CHAPTER-I
INTRODUCTION

1.1 GENERAL

Due to accessibility and moderate cost of renewable energy resources in deserted and far-flung area, as compared the conventional solutions, their applications in standalone systems have been increasing exponentially. Considering the rapid consumption of fossil energy sources, the hybrid renewable systems are about to have great share in future's energy supply [1]. Alternative energy sources are inherently non-polluting and continuous free in their availability, [2]. However, their applications in conventional distribution systems are limited due to high initial cost and reliability issues [3-12].

An easy and effective approach in utilizing solar energy is to convert it directly to electrical energy using Photovoltaic (PV) technology [4]. According, it is anticipated that PV systems will become one of the main energy resources to full fill the global energy requirement by the end of this century [5].

Other methods such as wind power plants, fuel cells batteries, and solar-heat plants are also considerable and are usually combined with photovoltaic (PV) units in order to increase system reliability [6]. An important and growing concern has been the approach used to design and control renewable hybrid systems. Different methods for modelling and controlling power production systems are possible by combination of two or more renewable energy systems [7].

The most important and considerable issues about these environmentally friendly systems are their cost and reliability [8]. Nowadays the PV and wind generators are widely use in many applications such as water pumping, illumination [9], electricity supply in outlying areas and supplying communication systems.

To include power shortage capability, diesel generators may be used in parallel. Considering the importance of synchronized operation between diesel generators and renewable supply system, the maintenance costs is be noticeable [9]. In this research work an effective methodology for design and modelling of photovoltaic power generation system is carried including their planning.

To extract the maximum available energy under different environmental conditions, voltage-based maximum power point tracking (VMPPT) of PV system [10] are implemented in this work.
1.1.1 Key Issues in Photovoltaic Power Generation

Following are main issues in solar photovoltaic power generation.

Environmental and Economical Importance.

Solar energy has both the environmental and the economical importance to every nation. Hence, the solar power plays a key role in cost effectiveness of any nation economy; creates a direct employment of manpower and to foster the development of micro – industries. The most important factor driving solar energy generation system is whether the energy it produces is economical. Although there are factors other than economics that enter a decision of when to use solar energy; i.e. no pollution, no greenhouse gas generation, security of the energy resource etc., the design decisions are almost exclusively dominated by the ‘level of energy cost’. This similar economic parameter, gives the expected cost of the energy produced by the solar energy system, averaged over the lifetime of the system. Hence, solar energy power system is a very clean energy that if given financial support by the government and industrialist to reduce the cost of implementing the solar panels for industrial, commercial and residential consumers.

Abundant Supply
Solar power could meet today's total electricity demand by PV systems covering only 0.4% of the nation in a high-sunlight area such as the Southwest — an area about 100 square miles. These panels, in reality, will be installed across the country on roofs and other structures close where it is consumed. Technologies such as PV roof shingles, windows, and flexible fabrics that are easily and cheaply integrated into new and existing buildings are emerging.

Secure and Stable Supply
Because solar power is generated domestically, often at the site where it will be consumed, prices and supplies are immune to blackouts, international uncertainty and does not rely on long-distance supply networks.

Cleaner Air
Solar power does not pollute air or water. It replaces electricity generated from facilities powered by coal, natural gas and other non-renewable fuels, eliminating threats to public health such as carbon monoxide, particulate, and toxic chemical emissions from those facilities. Additionally, when a solar power replaces electricity from a coal-fired power plant it also eliminates a potential source of sulphur emissions - a major component of acid rain.

Reducing Global Warming
Solar power does not produce CO$_2$ or any other greenhouse gases, thus helping to reduce the risk of climate change.

1.2 SOLAR PHOTOVOLTAIC POWER GENERATION

Solar power is produced by photovoltaic, or "PV", solar panels and other devices that capture the energy in sunlight and convert it to electricity. This electricity can then be fed directly to consumers, an electric power grid, or a storage device. Typically, solar panels are installed on the roof of residential or domestic buildings, and use the power generated to meet the owner's energy needs and provide surplus electricity to the grid. Other applications include heating water and providing power in areas where electricity connections are not available, such as on road signs, cellular phone towers, and satellites [11, 12].

Photovoltaics are array of cells containing a solar photovoltaic material that converts solar radiations in to direct current electricity. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, microcrystalline silicon, cadmium telluride, and copper indium selenide/sulphide [13, 14]. Photovoltaic production has been doubling every two years, increasing by an average of 48% each year since 2002, making it world’s fastest growing energy technology.

Solar energy is often talked of in the context of other renewable energy technologies that also have distributed energy generation potential. A photovoltaic system is a system which uses solar cells to convert solar energy into electricity. Due to the low voltage of an individual solar cell (typically 0.5V), several cells are combined into photovoltaic modules, which are in turn connected together into an array. The electricity generated can be either stored, used directly (standalone plant) or fed into a large electricity grid powered by central generation plants (grid-connected/grid-tied plant) or combined with one or many domestic electricity generators to feed into a small grid (hybrid plant) [15].

Photovoltaic electricity has many advantages over conventional electricity. Firstly, it has renewable energy input i.e. solar energy. It is not geographically limited. PV systems can have capacities ranging from mW to GW. On the other hand, only large capacity conventional electricity generation systems are economical. PV systems have very low maintenance and operation costs and are economically benign.

Recent years have seen rapid growth in the applications of PV systems in residential homes, industry, commercial buildings and water pumping, lighting, heating etc. in developing
countries. A typical block diagram of solar photovoltaic power generation system has been shown in Fig.1.1

![Block Diagram of Isolated Photovoltaic Power Generation System](image)

Installations of PV on to buildings that are connected to the electricity grid have been taken up largely in countries like Japan, Germany, Switzerland, USA, etc. In grid connected systems, PV systems supply electricity to the building and any day-time excess may be exported to the grid. Batteries are not required because the grid supplies any extra demand. However, the battery storage can be there to provide power outside daylight hours. Solar PV modules can be retrofitted on to a pitched roof above the existing roof-tiles, or the tiles replaced by specially designed PV roof-tiles or roof-tiling systems.

For many years, solar energy has been the power supply of choice for industrial applications, where power is required at remote locations. This means in these applications that solar power is economic, without subsidy. Most systems in individual applications require a few kilowatts of power. The examples are powering repeater stations for microwave, TV and radio, telemetry and radio telephones. Solar energy is also frequently used on transportation signalling e.g. offshore navigation buoys, lighthouses, aircraft warning lights on pylons or structures, and increasingly in road traffic warning signals.

For larger electrical loads it can be cost effective to configure a hybrid power system that links the PV with a small diesel generator. On an office building, atria can be covered with glass/glass PV modules, which can be semi-transparent to provide shaded light [16]
1.3 SCOPE OF PROPOSED RESEARCH WORK

The basic objective of carrying out this research is to develop an isolated power generation system by using non conventional energy recourses like solar energy. This work is beneficial in number of ways

**Rural Electrification**

Developing countries where many villages are often more than five kilometres away from grid power have begun using photovoltaic. In remote locations in India a rural lighting program has been providing solar powered LED lighting to replace kerosene lamps. The solar powered lamps are sold at about the cost of a few months’ supply of kerosene. These are areas where the social costs and benefits offer an excellent case for going solar though the lack of profitability could relegate such endeavours to humanitarian goals.

**Solar Roadways**

A 72 km section of roadway in Idaho is being used to test the possibility of installing solar panels into the road surface, as roads are generally unobstructed to the sun and represent about the percentage of land area needed to replace other energy sources with solar power.

**Solar Satellite**

The design studies of large solar power collection satellites have been conducted for decades. The idea has been first proposed by Peter Glaser, then of Arthur D. Little Inc; NASA conducted a long series of engineering and economic feasibility studies in the 1970s, and interest has revived in first years of the 21st century. From a practical economic viewpoint, the key issue for such satellites appears to be the launch cost. Additional considerations include developing space based assembly techniques, but they seem to be less a hurdle than the capital cost. These will be reduced as photovoltaic cell costs are reduced or alternatively efficiency increased.

1.4 CHAPTERS OUTLINES OF THESIS

Contents of the thesis has been divided in to following chapters
Chapter-1: This Chapter introduces the different aspects of solar photovoltaic power generation. The issues related with solar photovoltaic power generation and the scope of the present research work is included in this chapter.

Chapter-2: This chapter presents exhaustive literature review on solar photovoltaic power generation and different photo voltaic configurations, different methods of maximum power point tracking. DC-DC Converters and identified research area.

Chapter-3: This chapter presents the detailed modelling of the photovoltaic array using MATLAB/SIMULINK. This photovoltaic model is flexible in terms requirement of power generation according to the requirement of power generation. The solar module can be arranged in series and in parallel. Detailed analysis of results has been performed for different arrangements under variation of solar radiation and ambient temperature.

Chapter-4: This chapter presents the design, modelling and control of isolated solar photovoltaic power generation system (500W) for domestic and commercial applications. The proposed generating system configuration boosts the low voltage of photovoltaic (PV) array using a dc-dc boost converter to charge the battery at 96V and to convert this battery voltage into high quality 230V rms ac voltage at 50Hz for feeding autonomous loads without any intermediate conversion stage and a filter.

Chapter-5: This chapter includes with a solar power generation system (500W). An isolated solar photovoltaic (PV) power generation system is designed and modelled using a dc-dc Cuk converter and a single phase sine wave voltage source (VSI) inverter. The proposed system boosts the low voltage of photovoltaic (PV) array using dc-dc boost converter to charge the battery at 24V, which is then converted into high quality 380V dc voltage using an isolated dc-dc Cuk converter. This dc voltage of 380 V is converted to single phase 230Vrms value using a single phase sine wave VSI.

Chapter-6: This chapter presents the important findings of the investigations and bring out the main conclusions of the work. It also inlists the scope of the further work in this area.
CHAPTER - II

LITERATURE REVIEW

2.1 GENERAL

Present days the use of non conventional sources to generate electricity is gaining ground due to its pollution free nature and availability of resources. In this research work the objective concentrated is on to develop an isolated solar power generation system for low power applications. In April 1995 N.Jeenkins[8] develops photovoltaic system for small scale remote power supplies.

Then after that 2003, Ahmed and Sulaiman proposed the design and proper sizing of solar energy system for electricity production. Abdin, Osheiba and Khater explain modelling and optimal controllers design for a stand alone PV generating unit [9]. Then after that Bin, Hongxing, Hui and Xianbo presented computer aided design for pv- wind hybrid system [17].

After that in 2007 Ashok presented an optimized model for community based hybrid energy system [18]. In 2008 Soysal and Soysal have presented a residential model for PV power generation. In this they have discussed the pre-design study for site selection, an assessment of the solar and wind potential at the selected location, the system outline, experience gained during the design and construction phase, and an assessment of the system performance based on collected output data.

2.2 PV SYSTEM CONFIGURATIONS

There are different types of photovoltaic configuration system, the brief description of these configurations are as.

**Standalone systems**: A standalone system as shown in Fig.2.1 does not have a connection to the electricity mains. Standalone systems vary in size from watches or calculators to remote buildings or spacecraft. If the load is to be supplied independently of insolation, the generated power needs to be buffered with a battery. Where weight is not an issue (e.g. buildings) lead acid batteries are used. A charge controller may be incorporated in the system to a) avoid battery damage by excessive charging or discharging and b) optimizing the production of the cells or modules by maximum power point tracking (MPPT).
In small devices (e.g. calculators, parking meters) only DC is consumed. In larger systems (e.g. buildings, remote water pumps) AC is usually required. To convert the DC from the modules or batteries into AC, an inverter is used [19].

**Hybrid systems:** A hybrid system combines PV with other forms of generation, usually a diesel generator. In which a biogas is also used. The other form of generation may be a type able to modulate power output as a function of demand. However more than one renewable form of energy may be used e.g. wind. The photovoltaic power generation serves to reduce the consumption of non renewable fuel [19].

![Diagram of stand-alone PV systems with optional generator for back-up](image)

**Fig. 2.1** stand-alone PV systems with optional generator for back-up[13]

**Grid-connected/Grid-tied System:** A grid connected system (Fig.2.2) is connected to a large independent grid (typically the public electricity grid) and feeds power into the grid. Grid connected systems vary in size from residential (2-10kWp) to solar power stations (up to tens of GWp). This is a form of decentralized electricity generation. In the case of residential or building mounted grid connected PV systems, the electricity demand of the building is met
by the PV system. Only the excess is fed into the grid when there is an excess in generation. The feeding of electricity into the grid requires the transformation of DC into AC by a special, grid-controlled inverter.

![Diagram of grid-connected PV System]

**Fig. 2.2** Simplified grid-connected PV Systems [13]

**Small scale DIY (Do-it-yourself) solar systems:** With a growing DIY-community and an increasing interest in environmentally friendly "green energy", some hobbyists have endeavored to build their own PV solar systems from kits. Usually, the DIY-community uses inexpensive and/or high efficiency systems (such as those with solar tracking) to generate their own power. As a result, the DIY-systems often end up cheaper than their commercial counterparts. Often, the system is also hooked up unto the regular power grid to repay part of the investment via net metering. These systems usually generate power amount of ~2kW or less. Through the internet, the community is now able to obtain plans to construct the system (at least partly DIY) and there is a growing trend toward building them for domestic requirements. The DIY-PV solar systems are now also being used both in developed countries and in developing countries, to power residences and small businesses.

### 2.3 SOLAR POWER GENERATION

The photovoltaic effect is the electrical potential developed between two dissimilar materials when their common junction is illuminated with radiation of photons. The photovoltaic cell, thus, converts light directly into electricity. The PV effect has been discovered in 1839 by French physicist Becquerel [20] It remained in the laboratory until 1954, when Bell Laboratories produced the first silicon solar cell.
It soon found application in the U.S. space programs for its high power capacity per unit weight. Since then it has been an important source of power for satellites. Having developed maturity in the space applications, the PV technology is now spreading into the terrestrial applications ranging from powering remote sites to feeding the utility lines.

2.4 DC-DC CONVERTERS
This section provides a comparative study as shown in Fig.2.3, to choose a suitable converter topology for the applications of the maximum power point tracking. Nonisolated as well as isolated dc-dc converters are widely used in stand-alone and grid connected photovoltaic power systems because of their simplicity and efficiency. As one knows that for solar photovoltaic application the output of solar panel is not regulated and it also depends on weather conditions. So in order to the solar panel output regulated and always tracks maximum power one may use different converter topologies and different control algorithms. Generally we use buck, boost, buck-boost, sepic, flyback, push pull topologies of dc- dc converters. According to the relevance of the operation one may use various isolated or non isolated topologies [20]. For low power application, the topology is based on a half bridge on the primary and a current-fed push-pull on the secondary side of a high frequency isolation transformer. Achieving bidirectional flow of power using the same power components provides a simple, efficient and galvanically isolated topology that is specially attractive for use in battery charge/discharge circuits in dc UPS.

![Classification of dc converter](image)
The development of various converter topologies for various low power applications like in telecommunication, applications under wide load variation with high frequency and wide load variation with high efficiency is done [21,20]. Various development work like dc–dc converter for CMOS applications, inductor current analysis for isolated and non-isolated dc–dc converter, design of high precision measurement dc–dc converter, development of full bridge converter for wide range variation in solar panel voltage and load is developed. Concept of zero current and zero voltage switching are used in these converters to reduce switching losses [22]. Power management of different types of converters for renewable energy, intelligent dc–dc converter for space application, zero current transition in full bridge dc–dc converter and digital control in stand-alone dc–dc converter have been developed in [19,20].

2.5 MAXIMUM POWER POINT TRACKING

The photovoltaic generator exhibits a non-linear I-V characteristic and its maximum power point (MPP) vary with solar Insolation. An intermediate switch-mode dc–dc converter is required to extract maximum power from the photovoltaic array. The operating point at maximum power in systems based on PV modules depends on solar-radiation level, operating temperature and load current. After the development in dc–dc converter design for various applications, concentration is focused on maximum power point tracking [23] which is analysed for maximum power tracking. In this maximum power is tracked with the help of artificial neural network and, fuzzy logics and maximum power tracking for partially shadow condition. A new technique based on current control is proposed [24]. Then performance evaluations is carried for MPPT devices from various methods of maximum power point tracking has been introduce with real time estimation of solar characteristics and then used them for maximum power point tracking. Different patent for power conditioning, solar test circuit, power maximizing circuit has been evaluated and implementation of different algorithms with the help of microprocessor, controller [24]. Evaluation of controller performance for maximum power point tracking is carried out in the available literature.

2.5.1 Maximum Power Point Tracking Methodologies

While the I–V curve for a photovoltaic cell, module, or array defines the combinations of voltage and current that are permissible under the existing ambient conditions, It does not by itself tells us anything about just where on that curve the system will actually be operating. This determination is a function of the load into which the PV delivers their power. Just as PVs have an I–V curve, so do loads. When the I–V curve for the load is plotted onto the same
characteristic having the I–V curve for the PVs, the intersection point is the one spot at which both the PVs and load are satisfied. This is called the operating point as shown in Fig. 2.4.

**Fig. 2.4** A PV module with a resistive load.

Consider a resistive load that is connected to PV module as shown in Figure 2.4. PV I-V curve gives different combinations of voltage and current that are permissible as the PV output. Output power is the product of this voltage and current and is maximum for a particular combination. This point on the curve is known as maximum power point (MPP). $V_m$ and $I_m$ are voltage and current respectively at the MPP. Resistor I-V curve with slope $1/R$ intersects PV I-V curve at the operating point which is different in this case from MPP. Efficiency of module decreases as the operating point moves away from MPP. As Figure 4 shows, with a fixed resistance the operating point slips off the MPP as conditions change and the module becomes less and less efficient [25].

**Fig. 2.5** The efficiency of a PV module with a fixed resistance load.
A device called a maximum power point tracker (MPPT) is used, the purpose of which is to keep the PVs operating at their highest efficiency point at all times. A buck boost dc-dc converter having PV array as source and a motor as load is shown in Figure 2.6. The work of the switch control is to open and close the switch in a way that operating point matches with the MPP. The MPP at a particular condition is identified, keeping the PV output voltage at \( V_m \) and appropriately lowering or raising the voltage using a buck boost converter to match with the load voltage, required duty ratio switching signal is given to the switch [26].

![Buck-boost converter](image)

**Fig. 2.6** A buck-boost converter used as a maximum power tracker

Figure 2.7 shows voltage and current at the MPPT output and their relation with the PV voltage and current. D is the duty ratio of the switch.

![Diagram of MPPT](image)

**Fig. 2.7** The MPPT of voltages and currents
Some of the popular MPPT schemes are:

- Hill climbing method
- Incremental conductance method
- Constant voltage method
- Modified hill climbing method
- β method
- System oscillation method
- Ripple correlation method
- Perturbation and Observation (P&O)
- Artificial intelligent method

2.6 IDENTIFIED RESEARCH AREAS

The identified research areas in this field are domestic use of solar power generation system in stand alone manner. Moreover to develop some technique to make overall system economical. The use various control algorithm techniques to control this power generation system. In addition power quality aspect is the area in which work can be done in respect to this power generation system.

2.7 CONCLUSIONS

Extensive literature review has been presented with special focus on DC-DC Converters, maximum power point tracking, and solar photovoltaic. Special thrust has been given to isolated solar photovoltaic power generation. On the basis of this literature survey research area are identified to investigate in this work.
CHAPTER-III
MODELING OF SOLAR PHOTOVOLTAIC ARRAY

3.1 GENERAL
In the first step to accomplish the research work, the objective has been on the solar power generation. In this, the first step is to model the solar photovoltaic array in MATLAB/SIMULINK. But first theoretical modelling of solar array is presented, which is used developing the model in Photovoltaic array.

3.2 THEORITICAL MODELING OF SOLAR ARRAY [27-30]
A simplified expression [27] describes the relationship between voltage (V) and current given by an electrical equivalent circuit photovoltaic module, as given Eq. (3.1). The \( n_{pp} \) and \( n_{ss} \) parameters represent the number of cells connected in parallel and in series, respectively; \( R_P \) and \( R_S \), are the parallel and series resistances associated to the PV module, \( K \) is the Boltzmann constant (\( 1.38 \times 10^{-23} \text{ /K} \)) and \( q \) is the charge on an electron. Factor \( A \) is called ideal factor, which determines the deviation of the characteristics of an ideal p–n junction, and \( I_0 \) is the reverse saturation current, which depends on the module temperature. \( I_{PV} \) represents the current (photo-current) generated by solar radiation (G) [27].

Such a current shows a linear relation with respect to radiation and temperature. Eq. (3.1) this curve is I-V curve of the P-V module and the multiplication result of both magnitudes gives the supplied power as in Eq. (3.2) and (3.3). This curve changes depending on the incident irradiance and the cell temperature. Each curve presents a maximum power point (MPP, point of coordinate VP), which gives the required maximum power point for an optimum use of the module.

The MPP is calculated solving Eq. (3.3) with the condition given Eq. (3.4). Other two important points of this curve are the open-circuit voltage (Voc) and the short-circuit current (Isc). The voltage in an open circuit represents the maximum voltage given by the panel to a zero current (without load), while the short circuit current represents maximum removable current of the module.

\[
P = V [n_{pp} \{I_{PV} - I_0 e^{q(V/n_{ss} + R_S I/n_{pp})/AKT} (V/n_{ss} + R_S I/n_{pp})/R_P\}] \tag{3.1}
\]

\[
P = VI \tag{3.2}
\]

\[
P = V \{n_{pp} [I_{PV} - I_0 e^{q(V/n_{ss} + R_S I/n_{pp})/AKT + 1} - (V/n_{ss} + R_S I/n_{pp})/R_P] \tag{3.3}
\]
\[ \frac{dp}{dv} = 0 \]  

\[ I_{o,n} = \frac{I_{SC,n}}{\exp\left(\frac{V_{OC,n}}{aV_{t,n}}\right) - 1} \]  

\[ \text{fig. 3.1 Equivalent electrical circuit of pv module} \]

### 3.3 MATLAB/SIMULINK MODEL OF PHOTOVOLTAIC ARRAY[28]

A photovoltaic (PV) system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells may be grouped to form panels or arrays. The voltage and current available at the terminals of a PV device may directly feed small loads such as lighting systems and DC motors.

More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid-connected systems, and mainly to track the maximum power point (MPP) of the device.

In order to study electronic converters for PV systems, one first needs to know how to model the PV device that is attached to the converter. The PV devices present a nonlinear I–V characteristic with several parameters that need to be adjusted from experimental data of practical devices. The mathematical model of the PV device may be useful in the study of the dynamic analysis of converters. In the study of MPP tracking (MPPT) algorithms and mainly
to simulate the PV system and its components using circuit simulators. The basic equation (3.6) of the elementary photovoltaic cell does not represent the I-V characteristic of a practical photovoltaic array.

\[ I = I_{PV,cell} - I_{0,cell} \left[ \exp \left( \frac{qV}{akT} \right) - 1 \right] \]  

(3.6)

Practical arrays are composed of several connected photovoltaic cells and the observation of the characteristics at the terminals of the photovoltaic array requires the inclusion of additional parameters to the basic equation [3.6]

\[ I = I_{PV} - I_0 \left[ \exp \left( \frac{V + R_s}{V_a} \right) - 1 \right] \frac{V + IR_s}{R_p} \]  

(3.7)

Where \( I_{PV} \) and \( I_0 \) are the photovoltaic and saturation currents of the array and \( V_t = N_s kT/q \) is the thermal voltage of the array with \( N_s \) cells connected in series. Cells connected in parallel increase the current and cells connected in series provide greater output voltages.

If the array is composed of \( N_p \) parallel connections of cells the photovoltaic and saturation currents may be expressed as: \( I_{PV} = I_{PV,cell} N_p \), \( I_0 = I_{0,cell} N_p \). In Eq. (3.4) \( R_s \) is the equivalent series resistance of the array and \( R_p \) is the equivalent parallel resistance as in Eq.(3.7). This equation originates the I-V curve seen in Fig. 3.10, where three remarkable points are highlighted: short circuit (0, \( I_{SC} \)), maximum power point (\( V_{MP} \), \( I_{MP} \)) and open-circuit (\( V_{OC} \), 0). Eq. (3.4) describes the single-diode model presented in Fig 3.1.

Some authors [30] have proposed more sophisticated models that present better accuracy and serve for different purposes. Three-diode model is proposed to include the influence of effects which are not considered by the previous models. For simplicity the single-diode model of Fig. 3.1 is studied in this work. This model offers a good compromise between simplicity and accuracy and has been used by several authors in previous works, sometimes with simplifications but always with the basic structure composed of a current source and a parallel diode. The simplicity of the single-diode model with the method for adjusting the parameters and the improvements proposed in this work make this model perfect for power electronics designers who are looking for an easy and effective model for the simulation of photovoltaic devices with power converters. Manufacturers of photovoltaic arrays, instead of the I-V equation, provide only a few experimental data about electrical and thermal characteristics. Unfortunately some of the parameters required for adjusting photovoltaic
array models cannot be found in the manufacturer’s data sheets, such as the light-generated or photovoltaic current, the series and shunt resistances, the diode ideality constant, the diode reverse saturation current, and the band gap energy of the semiconductor.

All photovoltaic array datasheets bring basically the following information: the nominal open-circuit voltage $V_{oc,n}$, the nominal short-circuit current $I_{sc,n}$, the voltage at the maximum power point $V_{mp}$, the current at the maximum power point $I_{mp}$, the open-circuit voltage/temperature coefficient $K_V$, the short-circuit current/temperature coefficient $K_I$, and the maximum experimental peak output power $P_{max,e}$. This information is always provided with reference to the nominal or standard test conditions (STC) of temperature and solar irradiation.

Some manufacturers provide I-V curves for several irradiation and temperature conditions. These curves make easier the adjustment and the validation of the desired mathematical I-V equation. Basically this is all the information one can get from datasheets of photovoltaic arrays. Electric generators are generally classified as current or voltage sources. The practical photovoltaic device presents a hybrid behaviour, which may be of current or voltage source depending on the operating point, as shown in Fig 3.1.

The practical photovoltaic device has a series resistance $R_s$ whose influence is stronger when the device operates in the voltage source region and a parallel resistance $R_p$ with stronger influence in the current source region of operation. The $R_s$ resistance is the sum of several structural resistances of the device [29].

The $R_p$ resistance exists mainly due to the leakage current of the $p$-$n$ junction and depends on the fabrication method of the photovoltaic cell. The value of $R_p$ is generally high and some authors neglect this resistance to simplify the model. The value of $R_s$ is very low and sometimes this parameter is neglected too [30]. The I-V characteristic of the photovoltaic device shown in Fig 3.1 depends on the internal characteristics of the device ($R_s$, $R_p$) and on external influences such as irradiation level and temperature.

The amount of incident light directly affects the generation of charge carriers and consequently the current generated by the device. The light-generated current ($I_{pv}$) of the elementary cells, without the influence of the series and parallel resistances, is difficult to determine.

Datasheets only provide the nominal short-circuit current ($I_{sc,n}$), which is the maximum current available at the terminals of the practical device. The assumption $I_{sc} \approx I_{pv}$ is generally
used in photovoltaic models because in practical devices the series resistance is low and the parallel resistance is high. The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following Eq. (3.8).

\[ I_{pv} = \left( I_{pv,n} + K \Delta T \right) \frac{G}{G_n} \]  

(3.8)

where \( I_{pv,n} \) [A] is the light-generated current at the nominal condition (usually 25 °C and 1000W/m2), \( \Delta T = T - T_n \) being \( T \) and \( T_n \) the actual and nominal temperatures [K]), \( G \) [W/m\(^2\)] is the irradiation on the device surface, and \( G_n \) is the nominal irradiation.

The diode saturation current \( I_0 \) and its dependence on the temperature may be expressed by Eq. (3.4). The saturation current \( I_0 \) of the photovoltaic cells that compose the device depend on the saturation current density of the semiconductor (\( J_0 \), generally given in [A/cm\(^2\)]) and on the effective area of the cells.

The current density \( J_0 \) depends on the intrinsic characteristics of the photovoltaic cell, which depend on several physical parameters such as the coefficient of diffusion of electrons in the semiconductor, the lifetime of minority carriers, the intrinsic carrier density, and others.

This kind of information is not usually available for commercial photovoltaic arrays. In this report the nominal saturation current \( I_{0,n} \) is indirectly obtained from the experimental data through Eq. (3.5), which is obtained by evaluating Eq. (3.2) at the nominal open-circuit condition, with \( V = V_{oc,n}, I = 0, \) and \( I_{pv} \approx I_{sc,n} \) as in Eq. (3.9).

The value of the diode constant \( a \) may be arbitrarily chosen. Many authors discuss ways to estimate the correct value of this constant, [11]. Usually \( 1 \leq a \leq 1.5 \) and the choice depend on other parameters of the I-V model. Some values for \( a \) are found in based on empirical analysis.

\[ I_{0} = I_{0,n} \left( \frac{T_n}{T} \right) \exp \left[ \frac{qE_x}{ak} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right] \]  

(3.9)

As [30] says, there are different opinions about the best way to choose \( a \). Because \( a \) expresses the degree of ideality of the diode and it is totally empirical, any initial value of \( a \) can be chosen in order to adjust the model.

The value of \( a \) can be later modified in order to improve the model fitting if necessary. This constant affects the curvature of the I-V characteristic and varying \( a \) can slightly improves the model accuracy. The electricity available at the terminals of a photovoltaic array may directly
feed small loads such as lighting systems and DC motors. Some applications require electronic converters to process the electricity from the photovoltaic device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid connected systems and mainly to track the maximum power point (MPP) of the device.

Photovoltaic arrays present a nonlinear I-V characteristic with several parameters that need to be adjusted from experimental data of practical devices. The mathematical model of the photovoltaic array may be useful in the study of the dynamic analysis of converters, in the study of maximum power point tracking (MPPT) algorithms and mainly to simulate the photovoltaic system and its components using circuit simulators. This work presents in details the equations that form the I-V model and the method used to obtain the parameters of the equation. The aim of this paper is to provide the reader with all necessary information to develop photovoltaic array models and circuits that can be used in the simulation of power converters for photovoltaic applications.

Fig. 3.2 MATLAB Based Modeling of the System
Calculation of overall module current \( I_m = I_{pv} - I_d (N_{ss} \times N_{pp}) \)

Calculation of \( I_{pv} \) (single module):

Calculation of \( I_o \) (single module):

Calculation of saturation current \( (I_o) \) and photovoltaic current \( (I_{pv}) \)

Fig-3.3 MATLAB /Simulink Modell of PV array

By substitution the desired data in model one can get output. This modelling is useful when one have number of array connected in series and in parallel.

one can also modify it for a single photovoltaic array. Now one can perform simulation when 15 arrays are connected in series and 2 are in parallel. These analyses are done on sm 60 module.
3.3.1 MATLAB/SIMULINK Model for Single Module

When one is going to model a single module, the terms Nss and Npp will we remove from the equation of total module current given by Eqn 3.10.
\[ I = n_{pp} [I_{PV} - I_0 e^{\frac{q(V/n_{ss} + R_s/n_{pp})}{AKT}} (V + R_s I/n_{pp})] \]  \hspace{1cm} (3.10)

So now for single module the value of the total current of solar module is given by Eq.(3.11)
\[ I = [I_{PV} - I_0 e^{\frac{q(V+n_{ss})}{AKT}} (V+n_{ss})] \]  \hspace{1cm} (3.11)

Photovoltaic current (Ipv) and Reverse Saturation current (Io) will remain same; the MATLAB/SIMULINK model of the single module is given in Fig 3.5.

Fig.3.5 Simulink model for a single module
3.4 RESULTS AND DISCUSSION

The current voltage (I-V) characteristic of PV array is shown in Figure 3.6. The current axis (where V=0) is the short circuit current Isc and intersection with the voltage axis (where I=0) is the open circuit voltage Voc. at maximum power point power Pm the current is Im and voltage is Vm as shown in Fig.3.7
3.4.1 Effect of Solar Radiation and Temperature

Traditionally measurements of PV electrical characteristics are made at reference incident radiation at 1000W/m$^2$ and an ambient temperature of 25$^\circ$C. Measurement of current and voltage at these reference conditions are often available at open circuit condition, short circuit condition and maximum power condition. Fig.3.8 shows the I-V characteristic when temperature is constant and effect of radiation is observed. As the radiation is decreased the value of short circuit current is decreased with small change in open circuit voltage.

![Figure 3.8](image)

**Fig. 3.8 Effect of Intensity variation on V-I characteristic of solar array**

Effect of change in temperature is shown in Fig.3.9 when radiation held constant. As the temperature increases it leads to decrease in open circuit voltage and slightly increase in short circuit current. This corresponding change can be shown in Fig. 3.10 and Fig.3.11 respectively. In Fig.3.10 one can observe that at constant radiation with increase in temperature decrease the open circuit voltage and hence the available power is reduced. In Fig. 3.11 as constant temperature, decreased in solar radiations decreased the short circuit current and hence the available power is reduced. The temperature dependence of maximum power point efficiency of a module is an important parameter in estimating the system performances.
Fig. 3.9  Effect of temperature variation on V-I characteristic of solar array

Fig 3.10  Effect of Temperature variation on P-V characteristic of solar array
Fig. 3.11 Effect of Temperature variation on P-V characteristic of solar array
For a single array the simulink model modified. Now experiment is done with only a single module consists of 36 cells in series. No array is connected in series or in parallel. Then the characteristics obtains between voltage and current and between power and voltage is obtained are shown in Fig.3.12 and Fig.3.13.
3.5 CONCLUSIONS

In this chapter a MATLAB/SIMULINK based photovoltaic model is developed. This model has the flexibility in terms of its power. The output of this photovoltaic module can be increased or decreased according to the requirement of the isolated or grid connected solar power generation system. The output characteristic obtained from this photovoltaic model is comparable with standard results. Now this developed MATLAB model of this photovoltaic system with maximum power point tracking is ready to interface with next stage of electrical power generation.
CHAPTER-IV

SOLAR PHOTOVOLTAIC POWER GENERATION USING BOOST INVERTER

4.1 GENERAL

The ever-increasing demand for conventional energy sources like coal, natural gas and crude oil is driving society towards the research and development of alternate energy sources. Many renewable energy sources such as wind energy and solar photovoltaic (PV) are now well developed as the cost effective solution and are being widely used in many applications. These energy sources are preferred for being environmental friendly. The PV energy has become one of the most promising sources of energy due to the fact that PV energy is free and sustainable. Besides this, PV is scalable from very small to very large and easy to integrate with existing power converters [25]. Generally the solar power generation consists of a PV array, a dc-dc converter and an inverter. The classical inverter gives the output voltage lower than the dc link voltage due to this the size of output transformer is increased thus the overall cost of the system increases and efficiency decreases. A solar PV power generation system shown in Fig.4.1, for a standalone small residential load of 500 W is designed, modeled and simulated using MATLAB/SIMULINK. First the dc output voltage from the PV array is given to the boost dc-dc converter which boosts the output voltage of the PV array as well as it regulates its output voltage irrespective of the variation in solar radiation and temperature. This dc-dc converter is controlled with PWM control technique to charge the battery. A small and cheap capacitor can further smoothen the PV current and voltage for the selection of the power MOSFETs and driver [31]. In most applications, the PV array acts as a power source to energize devices capable of storing electricity and/or a utility grid. However, the capacity of solar generation systems depends heavily on the presence of light. At night, a current could flow back into PV cells from the bus; however, reverse current must be avoided because it causes leakage loss, extensive damage, or could even cause a fire [32]. The blocking diode is effective to prevent reverse current flow. In the selection of blocking diodes, the boost converter topology shows significant advantages over the buck converter. In the boost converter topology, the freewheel diode serves as the blocking diode to avoid the reverse current. Irrespective of variation in solar radiation and temperature, the system should always track maximum power to make the system more efficient. This research work presents a maximum power point tracking (MPPT) scheme based on perturbation and observation (P&O) technique. As the photovoltaic being
intermittent source of power, cannot meet load demand all the time of the year. The energy tracking storage is therefore, a desired feature to incorporate with renewable power system, particularly in standalone plant. It significantly improves the supply availability. Then the dc voltage available at terminals of the battery is fed to a dc-ac boost inverter. This inverter converts 96 V dc voltages in to 230 V rms which is readily available for residential loads without using any transformer. So by using this technique it reduces the cost of the overall system as well as an increased efficiency. The boost inverter [33, 34] is used in this PV power generation with a storage battery and such wide dc-ac conversion is achieved without using a step-up transformer. This PV power generation system is designed, modeled and simulated with resistive, inductive, nonlinear loads and single phase induction motor load. Detailed analysis is presented in subsequent sections.

4.2 SOLAR CELL CHARACTERISTICS

A solar PV cell consists of the semiconductor material which converts solar radiation into the dc current using the photovoltaic effect. The most important qualities of a solar cell are described by the I–V characteristic. By connecting solar cell in series a solar PV module is formed, and this module has 36 cells. For desired output voltage and current, the proposed solar PV power generation system consists of five modules in parallel and three modules in series. This arrangement is called solar array. A simplified expression describes the relationship between voltage (V) and current (I) given by an electrical equivalent circuit PV module shown in Fig.4.2 as,

\[
I = n_{pp}[I_{PV} - I_D(e^{(V/n_{ss} + R_S/I_{pp})/AKT} - 1) - (V/n_{ss} + R_S/I_{pp})/R_P]
\]  

(4.1)
where \( n_{pp} \) and \( n_{ss} \) parameters represent the number of cells connected in parallel and in series, respectively. \( R_P \) and \( R_S \), are parallel and series resistances associated to the PV module. \( I \) is the output current of solar array and \( V \) is the output voltage of solar array. \( K \) is the Boltzman constant \((1.38 \times 10^{-23} /K)\) and \( q \) is the charge on an electron. Factor \( A \) is called an ideal factor, which determines the deviation of the characteristics of an ideal p–n junction, and \( I_D \) is the reverse saturation current, which depends on the module temperature. \( I_{PV} \) represents the current (photo-current) generated by solar radiation. The power developed from PV array is given as,

\[
P = V[n_{pp}(I_{PV} - I_D(e^{q(V/n_{ss} + R_SI/n_{pp})/AKT})/(V/n_{ss} + R_SI/n_{pp})/R_P)]
\]

(4.2)

The maximum power condition can be described as,

\[
dP/dV = 0
\]

(4.3)

Eq. (4.1) models the I-V curve of the PV module and a multiplication of both magnitudes gives the supplied power as given in Eqn. (4.2). This curve shown in Fig.4.11 changes depending on the incident irradiance and the cell temperature. Each curve presents a maximum power point (MPP) which gives the required maximum power for an optimum use of the module. The MPPT is calculated solving Eqn. (4.2) with the condition given in Eqn. (4.3). Other two important points of this curve are the open-circuit voltage \( V_{oc} \) and the short-circuit current \( I_{sc} \). The voltage in an open circuit represents the maximum voltage \( V_{oc} \) given by the panel to a zero current (without load), while the short circuit current \( I_{sc} \) represents maximum removable current of the module.

The temperature dependence of maximum power point efficiency of a module is an important parameter in estimating the system performances.
### 4.3 MAXIMUM POWER POINT TRACKING

In order to track maximum power irrespective of the variation in solar radiation and temperature, the perturbation and observation method is utilized. Fig. 4.3 shows the flow chart of the algorithm. It is an iterative method of obtaining MPPT.

![Conventional Perturbation and Observe Algorithm flow chart](image)

**Fig.4.3 Conventional Perturbation and Observe Algorithm flow chart**

It measures the PV array characteristics, and then perturbs the operating point of the PV generator to encounter the change direction. The maximum power point is reached when $\frac{dP_{PV}}{dV_{PV}} = 0$. Where $P$ is the output power and $V$ is the output voltage of PV array. As the power-voltage relationship of a typical PV module is not linear therefore the maximum power point can always be tracked if condition $\frac{dP}{dV} = 0$ is met for any solar radiation or
temperature [35]. The advantages of this method are that a previous knowledge is not required of the PV generator characteristic, and it a relatively simple method.

### 4.4 DESIGN OF BOOST DC-DC CONVERTER

Fig. 4.4 shows the boost converter used in this system. Since the output voltage is higher than the input voltage, it is called a boost converter. It is implemented by using a diode and a MOSFET. In the boost converter the average output current is less than the average inductor current, and a much higher rms current would flow through the filter capacitor due to this reason a large value of the inductor and filter capacitor is required than those of buck converter [20].

Here a series connection of a dc–dc converter output with a photovoltaic panel is proposed for high efficiency. Each panel is connected in series to a dc–dc converter. The switching frequency (\(F_{sw}\)) of converter is 50 kHz and output current ripple (\(\Delta i\)) and voltage ripples (\(\Delta v\)) are considered 10% and 5% respectively. The design parameters of the boost converter are given below. The duty cycle of a boost converter is given by as,

\[
\text{Duty cycle (D)} = 1 - \left(\frac{V_{in}}{V_o}\right)
\]

\[(4.4)\]

where \(V_{in}\) is input voltage of the boost converter which is the output of PV array. For this analysis the \(V_{in}\) is varying between 58-64 Volts and \(V_o\) is the output voltage of boost
converter, which is constant at 96 Volts. From Eqn. (4.4) the value of duty cycle (D) is varies between 0.33-0.39. The value of an inductor for the boost converter is given by as,

\[
Inductance\ L = \frac{V_{pv}D}{2\Delta i_{Fsw}} \tag{4.5}
\]

where D is duty cycle, \(V_{in} = V_{pv}\) is output voltage from PV array, \(\Delta i_1\) is output current ripple. For this analysis the value of \(\Delta i_1\) is considered 5% and \(F_{sw}\) is switching frequency and the value of \(F_{sw}\) is used 50 kHz. The value of inductance (L) from Eqn. (4.5) is 2.12 mH. The output capacitor for a boost converter is given by as,

\[
Output\ capacitance\ C_2 = I_{oD}/(\Delta V_{Fsw}) \tag{4.6}
\]

where \(I_o\) is the output current and \(\Delta V\) output voltage ripple. The value of this \(\Delta V\) is taken 10% and value of output current (\(I_o\)) is considered as 5.2 A. The value of output capacitor (\(C_2\)) from Eqn. (4.6) is calculated as 343µF. The output of the solar array is connected to a dc- dc boost converter. This converter boosts the voltage of solar array from 63.5 V to 96 V.

**4.4.1 MATLAB/SIMULINK Model of Boost dc-dc Converter**

![Fig.4.5 MATLAB based Simulation Model for Proposed Boost Converter with Solar Array and Storage Battery.](image)

The MATLAB/SIMULINK models of proposed boost converter with its control scheme are given in Fig.4.5. This MATLAB/SIMULINK model of a boost converter is used to charge a storage battery. The input supply to this boost converter is the output of the photovoltaic model which is incorporated with maximum power point tracking to track the maximum power irrespective of the variations in solar radiations and ambient temperature. The switching frequency of this dc-dc converter is 50 kHz. The output of this converter is used to
charge the storage battery at 96 volts. The switching frequency of 50 KHz is realized using MOSFET as switch.

### 4.4.2 Proportional Integral Voltage Controller

The proportional plus integral controller produces an output signal consisting of two terms - one is proportional to voltage error signal and other proportional to integral of error signal. The output of the PI controller is as

\[ u(t) \propto (e(t) + \int e(t) dt) \]  \hspace{1cm} (4.7)

\[ u(t) = k_p e(t) + \left(\frac{k_p}{T_i}\right) \int e(t) dt \]  \hspace{1cm} (4.8)

where, \( K_p \) = proportional gain, \( e(t) \) is then voltage error signal between boost converter output voltage and reference voltage and \( T_i \)=integral time. The advantages of both P-controller and I controller are combined in this PI controller. The proportional action increases the loop gain and makes the system less sensitive to the parameter variation of system parameters. Integral action reduces or eliminates the steady state error. The output of boost converter is compared with the reference value then the error of this comparison is fed to PI controller. Then the output of a PI controller is compared with a waveform generated with the help of repetitive sequence wave form .Then after this comparison the gating pulse is generated in order to control the DC-DC Boost converter. As there is any change in the input voltage of the dc-dc boost converter, the output of the converter also changes but this control circuit regulates the output of the converter irrespective of the variations in the input to the dc-dc converter

### 4.5 DESIGN OF STORAGE BATTERY

The solar energy is not available all the time. Therefore in order to meet the demand of the load at the time when there is no sun an energy storage system is designed so that the additional generated power with the increased in solar radiation is stored into the battery as shown in Fig.4.6. Since the battery is an energy storage unit, its energy is represented in kWh when a capacitor is used to model the battery unit. The value of capacitance is given as,

\[ C_b = \frac{(kWh \times 3600 \times 1000)}{0.5(V_{oc\text{max}}^2 - V_{oc\text{min}}^2)} \]  \hspace{1cm} (4.9)

where \( V_{oc\text{max}} \) is the maximum voltage at the terminals of the battery when it is fully charged and \( V_{oc\text{min}} \) is the minimum voltage at the terminals of the battery when it is fully discharged.
In this Thevenin’s equivalent model of the battery [36,37] where $R_s$ is the equivalent resistance (external + internal) of parallel/series combination of a battery, which is usually a small value. For this analysis $R_s=0.01\Omega$. The parallel circuit of $R_b$ and $C_b$ is used to describe the stored energy and voltage during charging or discharging. $R_b$ in parallel with $C_b$, represents self discharging of the battery. Since the self discharging current of a battery is small, the resistance $R_b$ is large and the typical value of $R_b$ for this battery is used $10k\Omega$. Here the battery is considered of having $500W$ for $8$ Hrs peaking capacity, and with the variation in the voltage of order of $85.6$ V-$101.6$ V. The calculated value of $C_b$ for this battery from Eqn. (4.9) is calculated as $C_b=9615.38$ F.

### 4.6 DESIGN AND ANALYSIS OF BOOST INVERTER

The boost inverter consists of two individual dc-dc boost converters, as shown in Fig.4.1. In this inverter topology, both individual converters are driven by two $180^\circ$ phase-shifted dc-biased sinusoidal references which differential output is an ac output voltage [38, 39]. The idea of controlling the phase shift between two boost dc-dc converters in order to achieve a dc-ac inverter is also provided by the theory of phase-modulated inverters, which is presented and analysed in [40]. The boost dc-ac inverter exhibits several advantages, the most important of which is that it can naturally generate an ac output voltage from a lower dc input voltage in a single power stage. This boost inverter achieves dc-ac conversion by connecting the load differentially across two dc-dc converters and modulating the dc-dc converter output voltage sinusoidally. The reduced number of switches that are required (only four) and the quality of the output voltage sine wave are additional advantages reported in the literature [33, 38, 40, 41]. Basic working principle is illustrated in Fig.4.7 voltage $V_1$ is the output of converter A and $V_2$ is the output of converter B. The load is differentially connected across
these converters with respect to ground, as a result one gets differential ac voltage $V_1-V_2$ across the load. The conduction mode is given as,

$$V_1/V_{in} = 1/(1-D)$$  \hspace{1cm} (4.10)

where $D$ is duty cycle. $V_1$ is the voltage across capacitor $C_1$ and $V_{in}$ is the input voltage to boost inverter. As two converters are 180° out of phase the output voltage is given as,

$$V_O=V_1-V_2=\{V_{in}/(1-D)\}-\{V_{in}/D\}$$  \hspace{1cm} (4.11)

$$V_O/V_{in} = (2D-1)/ \{D \cdot (1-D)\}$$  \hspace{1cm} (4.12)

The MATLAB/SIMULINK model of the boost inverter is given in Fig.4.8. In this model a sliding mode control scheme is used for the control of the boost converters. This dc-ac boost inverter is designed for a power of 500W, single phase, 230V, 50Hz residential load. The dc link voltage of 96V from a storage battery is converted to a 230V rms, 50Hz output to feed different types of loads.

![Fig.4.7 Basic Principle of the Boost dc-ac Inverter](image)
Control Technique for Boost Inverter

For the purpose of optimizing the dynamics, a sliding mode control is used to control the boost inverter. The main advantage of this control scheme is its robustness for plant parameter variation which leads to steady state response in an ideal case [41, 42]. The typical sliding mode control scheme is shown in Fig. 4.9. The boost dc-ac converter includes dc link voltage $V_{in}$, input inductors $L_1$ and $L_2$, power switches $S_1$-$S_4$, transfer capacitors $C_2$ and $C_2$, freewheeling diodes $D_1$-$D_4$ and load resistance $R_L$. The main purpose of the controllers A and B is to make possible the capacitors voltages $V_1$ and $V_2$ to follow sinusoidal reference accurately. For a desirable response of output voltage, the sliding surface equation in state space is expressed by linear combination of state variable error is as

$$S(I_{c1}, V_1) = K_1 I_{c1} + K_2 I_{c2} = 0$$  \[(4.13)\]
where $K_1$ and $K_2$ are the gains and $\Delta_1$ and $\Delta_2$ are feedback current and voltage error respectively.

\[ \Delta_1 = I_{L1} - I_{Lref} \]  \hfill (4.14)

\[ \Delta_2 = V_1 - V_{ref} \]  \hfill (4.15)

By substituting Eqns. (4.13) and (4.14) in (4.12) one gets,

\[ S(I_{L1}, V_1) = K_1(I_{L1} - I_{Lref}) + K_2(V_1 - V_{ref}) \]  \hfill (4.16)

The system behaviour is completely determined by coefficients $K_1$ and $K_2$, which must be selected to satisfy existence and ensure stability and fast response, even for large supply and load variations. The signal obtained in Eq. (4.15) is fed to hysteresis loop, which generates the pulse to control semiconductor device.

### 4.7 RESULTS AND DISCUSSION

The results of the solar photovoltaic power generation system are comprise of various stages, like results from solar array, results of DC-DC boost converter with solar panel and storage battery. Solar photo voltaic power generation system.

#### 4.7.1 Characteristics of the Solar Array

The typical voltage versus current and voltage versus power curves are shown in Fig.4.10 and Fig.4.11 respectively. Fig. 4.10 shows that the operating point at which the solar generator can deliver maximum power for a given radiation intensity is near the bend of characteristic. Three points of the curve are of particular interest open circuit voltage ($V_{oc}$) short circuit current ($I_{sc}$) and maximum power point (MPP). Fig.4.12 shows the I-V characteristic at
different value of solar radiations and different values of solar temperature. Fig.4.13 shows the P-V characteristic at different values of solar radiations and at different values of solar temperature. It is possible to notice that the solar array behaves as a current source left at (MPP), and it considers that the voltage source behaviour right at MPP. From Figs. 4.12, 4.13 it is observed that for each curve of solar irradiation, there is a specific voltage for which the array operates at proper maximum power point. This is the optimum voltage for the operation of the solar array [28]. Considering that most of the loads supplied by PV system operate with constant voltage, it is necessary to track the maximum power point tracking (MPPT) condition of the solar array regardless the load voltage.

![Fig.4.10 I-V and Fig.4.11 P-V Characteristic of Solar Array](image)

![Fig.4.12. I-V Characteristics with Different Radiation and Temperature](image)
4.7.2 Performance of Boost Converter with Solar Array and Storage Battery

The results of this boost dc-dc converter are shown in Fig.4.14. In this figure, an input to the boost converter ($v_{in}$), the value of output current ($i_o$), output voltage ($v_o$), inductor current ($i_l$) and corresponding voltage across capacitor ($v_c$) and diode ($v_d$) are shown under stranded temperature and radiation conditions (i.e. 25°C and 1000w/m$^2$). Fig.4.15 shows the simulation results of a dc-dc boost converter with variation in solar radiation and temperature at radiation of 400W/m$^2$ and temperature of 25°C. The dc-dc converter is responsible for the regulation of the output voltage at peak power point while also providing a constant voltage for charging a battery. The PWM control is provided in order to regulate the output voltage of the boost converter. In order to generate gating pulse for the MOSFET the error voltage between reference value and the converter output voltage is given to a PI (proportional integral) controller. Then this error voltage is compared using a comparator to a repetitive sequence wave of switching frequency. Then ON/OFF pulse is generated which controls the dc-dc converter [21]. The solar array voltage and current with respect to time are also shown at 1000W/m$^2$25°C at standard test conditions (STC) and also at 400W/m$^2$ and 25°C. This boost converter converts input voltage of 64 V to 96 V in order to charge storage battery connected to the output of the boost converter. The control of the boost converter regulates the output of the boost converter irrespective of the variations in the solar radiations and temperature. As solar radiation and temperature controls the output of the solar array.
Fig. 4.14 Output of the Boost Converter with Solar Array and Battery at Standard Conditions
Fig. 4.15. Output of Boost Converter with Solar Array under Variation in Solar Radiation and Temperature
4.7.3 Performance of Boost Inverter

The optimum component values of $L_1$, $L_2$, $C_1$ and $C_2$ obtained from the design and fine tuned based on simulation results. The simulation of the complete system is carried out in the MATLAB/SIMULINK environment. Resistive (R), inductive, non-linear type loads and single phase induction motor load are considered for the investigation as an isolated operation of solar photovoltaic system with the proposed system. The simulation results are discussed in terms of output voltage, output current, and voltage THD at various loads.

4.7.4 Performance of Generation System at Resistive Load

The performances of the boost inverter at resistive load are shown in Fig. 4.16. The voltages across $C_1$ and $C_2$ current across inductor $L_1$ and $L_2$ are shown Fig. 4.16. The voltage THD calculated on this load are only 0.99% which is quite reasonable. The THD of the voltage is shown in Fig. 4.17. Under variable load condition, as the load varies the value of output current change accordingly and compensates for the change in the load without affecting the output voltage profile. The detailed results are given in Fig. 4.18.

![Fig. 4.16 Performance of dc-ac Boost Inverter](image.jpg)
Fig. 4.17 Wave form and Harmonics Spectrum of Load Current at Resistive Load of 500 W

Fig. 4.18. Performance of dc-ac Boost Inverter Variable Load
4.7.5 Performance of Generation System at Inductive Load

These results have been shown in Fig.4.19. The THD of the output voltage in this case is 0.81%.

![Fig4.19. Wave form and Harmonics Spectrum of load Voltage at Inductive Load](image)

4.7.6 Performance of Generation System at Nonlinear Load

In Fig.4.20, a nonlinear load is shown which consists of a diode rectifier, resistance and capacitance. The results with this load have been shown in Fig.4.21. The current THD is calculated about 51.4% the value of R is 86 Ω and the value of C is 100µF. The voltage THD observed to the order of 1.85% and shown in Fig.4.22.

![Fig4.20 Non linear load](image)

![Fig4. 21 Wave form and Harmonics Spectrum of load Current at non Linear Load](image)
4.7.7 Performance of Generation System when Single Phase Induction Motor is connected as Load

When a single phase induction motor is connected as the load to this solar power generation system, the behavior of this load is given in Fig. 4.23. Where corresponding main winding current ($I_m$), auxiliary winding current ($I_a$), motor speed ($W$), and the developed torque ($T_e$) are presented. Moreover corresponding harmonics in the motor current is also shown in Fig. 4.24. The THD in motor current is 4.92%.
4.8 CONCLUSIONS

This solar power generation system has been found economical and efficient conversion system for converting the output dc voltage from PV array in to ac 230V rms, 50Hz. The output power of solar PV power generation system is used to feed a single phase residential load at 230 V. The boost inverter used here has economical as well as technical advantages over conventional voltage source inverter. A simulation result on different loads has been observed well within acceptable range.
CHAPTER- V

SOLAR PHOTOVOLTAIC POWER GENERATION USING CUK CONVERTER AND SINGLE PHASE UNIPOLAR VOLTAGE SOURCE INVERTER

5.1 GENERAL

In this chapter an isolated solar photovoltaic (PV) power generation system is designed and modeled using a isolated dc-dc Cuk converter and a single phase sine wave voltage source (VSI) inverter. The proposed dc-dc converter system boosts the low voltage of photovoltaic (PV) array using dc-dc boost converter to charge the battery at 24V, which then converted into high quality 380V dc voltage using an isolated dc-dc Cuk converter. This dc voltage of 380 V is converted to single phase 230Vrms 50Hz using a single phase sine wave VSI. A maximum power point tracking (MPPT) algorithm is proposed with series connection of a dc–dc converter with a PV panel for high efficiency. The proposed solar photovoltaic power generation system is given in Fig.5.1.

This approach increases the efficiency of the energy conversion in PV array to the load. The output ac voltage total harmonic distortion (THD) obtained using this configuration of Fig.5.1 is quite acceptable. The complete system is designed and modelled in MATLAB/SIMULINK and simulated results are presented to demonstrate its satisfactory performance.

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Fig5.1 Solar power generation using cuk converter
5.2 DESIGN OF SOLAR ARRAY SYSTEM

The first major part is the heart of the model, the PV array, which appears as a block with three external inputs irradiance, ambient temperature and array voltage. The two external outputs are the cell temperature and array current as shown in Fig.5.2.

The PV array model gives the user a great flexibility as it allows the user to modify the model in such a way that it will accept a set of irradiation and temperature data at the inputs 1 and 2 respectively. This gives the user direction into what data requires at the inputs of the model to get the desired outputs. The internal of the PV array can be understood via a broken down structure known as the hierarchical structure of the array model [27].

![Fig. 5.2 Model of BP 280 PV Array](image)

The array model BP 280 PV [27] has been used to carry out all the simulations throughout this research work.

The model parameters for the BP 280 PV module used are as follows

\[
\begin{align*}
I_{ir} &= \text{Inverse diode saturation current at reference temperature} = 3.047 \times 10^{-7} \text{ A} \\
I_{SCR} &= \text{Short-circuit current under STC} = 4.92 \text{ A} \\
I_t &= \text{Short-circuit current temperature coefficient} = 1.7 \times 10^{-3} \text{ A/K} \\
A &= \text{Diode ideality factor} = 1.043 \\
T_r &= \text{Cell reference temperature} = 300 \text{ K} \\
\text{NOCT} &= \text{Normal operation cell temperature} = 43 \text{ K} \\
E_G &= \text{Band gap for semiconductor material silicon} = 1.11 \text{ eV} \\
R_{SH} &= \text{Cell shunt resistance} = 50 \text{ Ω}
\end{align*}
\]
\( R_S = \text{Cell series resistance} = 5.0 \text{ m}\Omega \)

\( N_S = \text{Number of cells in series} = 36 \)

\( N_P = \text{Number of cells in parallel} = 1 \)

\( M_S = \text{Number of modules in series} = 1 \)

\( M_P = \text{Number of modules in parallel} = 1 \)

MATLAB modeling of array is explained in the following section by broken down PV array in hierarchical governing equations describing the I-V characteristics.

### 5.2.1 MATLAB Simulink Model of PV Array

The single-diode model of a typical PV cell has three inputs and two outputs Fig.5.3. Photovoltaic arrays are represented by the number of modules connected in series \( M_S \) and the number of modules in parallel \( M_P \), where the photovoltaic array voltage and current are given as

\[
V_{\text{array}} = V_{\text{cell}} * N_S * M_S \tag{5.1}
\]

\[
I_{\text{array}} = I_{\text{cell}} * N_P * M_P \tag{5.2}
\]

![General Model of Array showing Input and Output](image)

Fig. 5.3 General Model of Array showing Input and Output

The external inputs

\[ G = \text{Irradiance (W/m2)} \]

\[ T_a = \text{Ambient Temperature (K)} \]

\[ V_{\text{array}} = \text{Array Voltage (V)} \]

The external inputs
\( T_c = \) Cell Temperature (K)
\( I_{array} = \) Array Current (A)

### 5.2.2 MATLAB Simulink Model of PV Module

Photovoltaic modules are modelled as a series/parallel connection of cells, as expressed by the following equations for the photovoltaic module voltage and current, respectively:

\[
V_{module} = V_{cell} \times N_S \tag{5.3}
\]

\[
I_{module} = I_{cell} \times N_P \tag{5.4}
\]

These parameters can be set internally in the model as shown in Fig.5.4, by selecting the mask parameters the following block will appears as

![Function Block Parameters: PV array](image)

**Fig. 5.4 Block Parameter Subsystem Mask**

Where

- \( N_S = \) Number of cells in series
- \( N_P = \) Number of cells in parallel
- \( M_S = \) Number of modules in series
- \( M_P = \) Number of modules in parallel
This process simply involves increasing the number of cells in series and parallel, until the desired systems size is reached [28].

### 5.2.3 MATLAB Simulink Model of PV Cell

The simulation model of the photovoltaic array is based on the standard single-diode representation of a silicon photovoltaic cell as shown in Fig. 5.5.

![Single Diode Equivalent Circuit of PV cell](image)

**Fig. 5.5 Single Diode Equivalent Circuit of PV cell**

From this circuit, the describing equation for output current for the Photovoltaic cell as

\[
I_c = I_{SC} G_N + I_i (T_c - T_R) - I_{Diode} \left( \frac{V_c + I_c R_S}{R_{sh}} \right)
\]  

(5.5)

Where

- \(I_c\) = load current (A)
- \(V_c\) = load voltage (V)
- \(I_{SC}\) = short circuit current at STC (A)
- \(G_N\) = normalized radiation (W/m²)
- \(I_i\) = short circuit current temperature coefficient (A/K)
- \(T_c\) = cell temperature (K)
- \(T_R\) = cell reference temperature (K)
- \(I_{Diode}\) = diode current (A)
- \(R_S\) = series resistance (Ω)
$R_{SH} = \text{Shunt resistance (}\Omega\text{)}$

$I_{LG} = \text{Light generated current}$

PV cell consists of all the governing equations, describing the I-V characteristics of a crystalline silicon photovoltaic cell. Fig.5.6 shows the developed simulink model of the PV cell.

![Simulink model of PV cell](image)

Fig. 5.6 PV Cell Model Developed in Simulink

The Photovoltaic cell current is found by applying Kirchhoff’s current law (KCL) to the Single diode equivalent circuit of the PV cell as

$$I_{cell} = I_{LG} - I_D - I_{RSH} \quad (5.6)$$

And
\[ v_{sat} = \frac{V_{app}}{M_iN_s} \]  

(5.7)

### 5.2.4 Calculation of \( I_{LG}, I_D \) and \( T_C \)

Light-generated current as is given as

\[ I_{LG} = I_{SCR} \times G_N + I(T_C - T_r) \]  

(5.8)

The developed model of light generated current in simulink models shown in Fig.5.7

![Simulink Diagram](image)

**Fig. 5.7 Light Generated Current in Simulink**

The normalized irradiance \( G_N \) is calculated from:

\[ G_N = \frac{G}{1000W/m^2} \]  

(5.9)

The diode current is calculated as:

\[ I_D = I_0 \left[ e^{\frac{q(V_{app} + I, V_{app})}{akT}} - 1 \right] \]  

(5.10)

Inverse saturation current of the p-n junction is expressed as:

\[ I_0 = I_{0,n} \left( \frac{T_n}{T} \right) \exp \left[ \frac{qE_T}{ak} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right] \]  

(5.11)

MATLAB model representing the above equations is shown in figure 5.8.
In addition, the cell temperature as shown in Fig. 5.8B is calculated as [30]:

$$T_c = T_s + \frac{G}{800} (\text{NOCT}-20)$$  \hspace{1cm} (5.12)

Using the above equations the photovoltaic cell current equates can be expressed as:

$$I_{cell} = I_{cell}^* + \frac{V_{cell} + I_{cell} R_s}{R_{cell}}$$ \hspace{1cm} (5.13)

From the above equation, it can be seen that the photovoltaic cell current is a function of itself, forming an algebraic loop, which can be solved conveniently using SIMULINK [29].
5.3 DESIGN OF BOOST CONVERTER

Fig.5.9 shows the boost converter used in this system and Fig 5.10 shows it’s control scheme. Since the output voltage is higher than the input voltage, it is called a boost converter. It is implemented by using a diode and a MOSFET. In the boost converter the average output current is less than the average inductor current and a much higher rms current would flow through the filter capacitor due to this reason a large value of the inductor and filter capacitor is required than those of buck converter[20].

![Diagram of Boost Converter](image)

**Fig. 5.9.** Boost dc–dc converter topology used as photovoltaic power interface

5.3.1 Design Equations of Boost Converter

Here a series connection of a dc–dc converter output with a photovoltaic panel is proposed for high efficiency. Each PV panel is connected in series to a dc–dc converter. The switching frequency ($F_{sw}$) of converter is 50 kHz and output current ripple ($\Delta i_l$) and voltage ripples ($\Delta v$) are considered 10% and 5% respectively. The design parameters of the boost converter are given below. The duty cycle of a boost converter is given by as,

$$Duty\ cycle\ (D) = 1 - \left(\frac{V_{in}}{V_o}\right) \quad (5.15)$$

where $V_{in}$ is input voltage of the boost converter which is the output of PV array. For this analysis the $V_{in}$ is varying between 18-21 Volts and $V_o$ is the output voltage of the boost converter, which is constant at 24 V. From Eqn. (5.15) the value of duty cycle (D) is varies between 0.33-0.39. The value of an inductor for the boost converter is given by as,

$$Inductance\ L = \frac{V_{pv}D}{(2\Delta i_lF_{sw})} \quad (5.16)$$

where D is duty cycle, $V_{in} = V_{pv}$ is output voltage from PV array, $\Delta i_l$ is output current ripple. For this analysis the value of $\Delta i_l$ is considered 5% and $F_{sw}$ is switching frequency and the
value of $F_{sw}$ is used 50 kHz. The value of inductance (L) from Eqn. (5.16) is 0.45 mH. The output capacitor for a boost converter is given by as,

$$\text{Output capacitance } C_2 = I_o D / (\Delta V F_{sw})$$  \hspace{1cm} (5.17)

where $I_o$ is the output current and $\Delta V$ output voltage ripple. The value of this $\Delta V$ is taken 10% and value of output current ($I_o$) is considered as 5.2 A. The value of output capacitor ($C_2$) from Eqn. (5.17) is calculated as 100µF. The output of the solar array is connected to a dc-dc boost converter. This converter boosts the voltage of solar array from 16 V to 24 V. The MATLAB/SIMULINK models of proposed boost converter with its control scheme are given in Fig.5.11.

### 5.3.2 Proportional Integral Controller for Boost Converter

The proportional plus integral controller produces an output signal consisting of two terms - one is proportional to error signal and other proportional to integral of error signal. In PI controller

$$u(t) \propto \{e(t)+\int e(t)dt\} \hspace{1cm} (5.18)$$

$$u(t) = K_p e(t) + (K_p / T_i) \int e(t)dt \hspace{1cm} (5.19)$$

Where, $K_p$ = proportional gain
And $T_i$=integral time.

The advantages of both P controller and I controller are combined in PI controller .The Proportional action increases the loop gain and makes the system less sensitive to the parameter variation of system parameters. Integral action reduces or eliminates the steady state error [21]. The output of a Boost converter is compared with the reference value then the error of this comparison is feed to the PI controller.

Then the output of PI controller is compared with a carrier wave form generated with the help of repetitive sequence wave form .Then after this comparison the gating pulse is generated in order to control the dc-dc Boost converter. As there is any change in the input voltage of the dc-dc boost converter, the output of the converter also changes but this control scheme regulates the output of the converter irrespective of the variations in the input to the dc-dc converter.
5.3.3 MATLAB/SIMULINK Model of Boost Converter with Solar Panel and Storage Battery

The MATLAB/SIMULINK models of the proposed boost converter with its control scheme are given in Fig.5.13. This MATLAB/SIMULINK model of the boost converter is used to charge a storage battery. The input supply to this boost converter is the output of the photovoltaic model which is incorporated with the maximum power point tracking to track the maximum power irrespective of the variations in solar radiations and ambient temperature. The switching frequency of this dc dc converter is 50 kHz. The output of this converter is used to charge the storage battery at 24 V. The switching frequency of 50 kHz is realized using MOSFET as switch.
5.4 DESIGN OF STORAGE BATTERY

The solar energy is not available all the time of the day and in night so in order to meet the demand of the loads at the time when there is no sun an energy storage system is designed so that the additional generated power with the increased in solar radiation is stored into the battery as shown in Fig.5.12. Since the battery is an energy storage unit, its energy is represented in kWh when a capacitor is used to model the battery unit. The capacitance can be determined from eqn. (5.20). In the Thevenin’s equivalent model of the battery [36,37] where $R_s$ is the equivalent resistance (external + internal) of parallel/series combination of a battery, which is usually a small value. The parallel circuit of $R_b$ and $C_b$ is used to describe the stored energy and voltage during charging or discharging. $R_b$ in parallel with $C_b$, represents self discharging of the battery, since the self discharging current battery is small, the resistance $R_b$ is large. Here the battery is considered of having 500W for 8 Hrs peaking capacity, and with the variation in the voltage of order of 20.4 V-26.4V.

\[
C_b = \frac{(kWh \times 3600 \times 1000)}{[0.5(V_{oc,\text{max}}^2-V_{oc,\text{min}}^2)]} \tag{5.20}
\]

\[
C_b = 102564.102 \text{F}
\]
5.5 DESIGN OF ISOLATED CUK DC–DC CONVERTER

According to study at the combination of the boost converter and buck converter, the Cuk converter as shown in Fig.5.13 has one switch only Fig.5.14 shows its operation. It transfers energy by a capacitance between input and output, which helps to minimise volume and increase power density. In the PV grid-connected power generation control systems; it’s usually required that there is no direct electrical connection between the PV arrays side and electro-side. The isolated Cuk converter circuit introduces isolated transformer between input and output of the power supply, which realizes the electrical isolation between the primary and secondly winding [43]. The duty cycle and formulas of this Cuk converter is given as

\[ V_o = D \frac{N_1}{N_2} \frac{V}{(1 - D)} \]  
\[ L_1 = \frac{V_o D}{F_s M_L} \]  
\[ L_o = \frac{V_o (1 - D)}{F_s M_{L0}} \]  
\[ C_1 = \frac{V_o (N_1 / N_2)^2 D^2}{RF_s (1 - D) \Delta V_c} \]  
\[ C_2 = \frac{V_o D}{RF_s \Delta V_c} \]  

Fig.5.12 Schematic Diagram of Storage Battery

Fig.5.13 Cuk dc–dc Converter Topology
5.5.1 Principle of Operation Isolated Cuk Converter

During switch $S_1$ turn-on, the equivalent circuit of isolated Cuk circuit is shown in Fig. 5.14, the arrow in this figure means the current direction of the loop. Supposed that the circuit is working at a steady state, during switch $S_1$ turn on, input voltage $v$ is connected to inductor $L_1$ and charge it directly and terminals of $C_1$ are connected to the primary wind of transformer $T$, $C_1$ is discharging[43]. The current induced by secondary winding charge the load. At this time, $C_1$ and $C_2$ are all discharging, $C_2$ and the transformer secondary winding supply energy to inductor $L_2$ and load. The clamp diode turns off because of anti-emitting. During switch $S_1$ turn-off, the equivalent circuit of isolated Cuk circuit is shown in Fig. 5.15, the arrow in the Fig. means the current direction of the loop. The inductor $L_1$ and source $v$ releases energy. One part of the energy is sent to $C_1$, is saved in $C_1$, another part is sent to $C_2$ via transformer $T$. At the same time, inductor $L_2$ releases the stored energy to the load. In order to get the desired output of Cuk converter the PWM control is implemented [44].

![Fig. 5.14 Cuk dc-dc converter topology when $s_2$ is off](image)

![Fig. 5.15 Cuk dc-dc converter topology when $s_1$ on](image)

The duty cycle of this cuk converter is given by

$$D = \frac{t_{on}}{T} = \frac{t_{on}}{T_{on} + T_{of}} = f_s T_{on}$$

(5.26)
5.5.2 MATLAB/SIMULINK Model of Isolated DC-DC Cuk Converter

In the MATLAB/SIMULATION model of isolated cuk dc-dc converter consists of of input capacitor C1, inductor L1, high frequency transformer, output inductor L2, output capacitor and a high frequency switching device is used in order to control the Cuk converter. The switching frequency of this Mosfet is 100 kHz. PWM control technique is used in order to provide control to the converter circuit. In converter circuit a PI controller is used. The output of the converter is compared with reference value and error of this comparison is fed to PI controller and this is compared with repeating sequence wave form and this comparison generates the gate pulse which controls the converter. The MOSFET is device which can be used to generate the switching pulse of 100 kHz.

5.5.2 DESIGN OF HIGH FREQUENCY TRANSFORMER [45, 46]

The design of a high frequency transformer is most important part of isolated Cuk dc-dc converter design. With the isolated cuk converter applications one can have high range conversion of dc input. This high frequency transformer is designed at a frequency of 100 kHz. The design equation for different parameters are given as under.
Total Time Period, $T$

$$T = \frac{1}{f_{SW}} \text{ Sec} \quad (5.27)$$

Maximum Switch on Time, $T_{ON}$

$$T_{ON} = T_{D_{\text{Max}}} \text{ Sec} \quad (5.28)$$

Minimum Duty Ratio, $D_{\text{MIN}}$

$$D_{\text{Min}} = D_{\text{Max}} \left( \frac{V_{\text{Min}}}{V_{\text{Max}}} \right) \quad (5.29)$$

Total Secondary Power, $P_0$

$$P_0 = I_0 (V_0 + V_d) \text{ watts} \quad (5.30)$$

The Maximum Input Current, $I_{\text{in}}$

$$I_{\text{in max}} = \frac{P_0}{\eta V_{\text{Min}}} \text{ amps} \quad (5.31)$$

The Primary Voltage, $V_p$

$$V_p = V_{\text{Min}} - V_{\text{av}} \text{ volts} \quad (5.32)$$

Required Primary Inductance, $L$

$$L = \frac{V_p L_{\text{in}}}{I_{\text{out}}} \text{ henry} \quad (5.33)$$

Primary Peak Current, $I_{pk}$

$$I_{pk} = \frac{I_{\text{in max}}}{D_{\text{Max}}} + \frac{\Delta I}{2} \text{ amps} \quad (5.34)$$

The rms Current $I_{\text{rms}}$

$$I_{\text{rms}} = \sqrt{I_{pk}^2 - (I_{pk})(\Delta I) + \frac{(\Delta I)^2}{3}} \text{ amps} \quad (5.35)$$

Total Energy Handling Capability in Watt-Seconds

$$E = \frac{L_{\text{rms}}^2}{2} \text{ Ws} \quad (5.36)$$

Electrical Condition $K_e$

$$K_e = 0.145 P \Delta B \ast 10^{-4} \quad (5.37)$$

Core Geometry $K_g$

$$K_g = \frac{E^2}{2dK_e} \text{ cm}^2 \quad (5.38)$$

Number of Primary Turns $N_p$

$$N_p = 1000 \left( \frac{I_{\text{in max}}}{I_{\text{av}}^2} \right) \text{ Turns} \quad (5.39)$$

Current Density $J$

$$J = \frac{2E10^4}{B_{\text{in}} A_p K_e} \text{ amps/cm}^2 \quad (5.40)$$

Incremental Permeability Constant $A_u$
The Primary Wire Area, \( A_{pw} \)
\[
A_{pw} \ (\text{B}) = \frac{I_{pw} N_s}{J} \ \text{cm}^2
\]  
(5.44)

Primary Winding Resistance, \( R_p \)
\[
R_p = \text{MLT} \times N_s * 10^{-6} \ \text{ohms}
\]  
(5.45)

The Primary Copper Loss, \( P_p \)
\[
P_p = I_{pw}^2 R_p \ \text{Watts}
\]  
(5.46)

Total Secondary Turns, \( N_s \)
\[
N_s = N_p \left( V_o + V_d \right) \left( \frac{1 - D_{\text{max}}}{V_p D_{\text{max}}} \right) \ \text{turns}
\]  
(5.47)

Secondary Peak Current, \( I_{spk} \)
\[
I_{spk} = \frac{2I_0}{(1 - D_{\text{max}} D_w)} \ \text{amps}
\]  
(5.48)

Secondary rms Current, \( I_{rms} \)
\[
I_{rms} = I_{spk} \sqrt{\frac{(1 - D_{\text{max}} D_w)}{3}} \ \text{amps}
\]  
(5.49)

Secondary Wire Area, \( A_{sw(B)} \)
\[
A_{sw(B)} = \frac{I_{sw}}{J} \ \text{cm}^2
\]  
(5.50)

Total Winding Resistance, \( R_s \)
\[
R_s = \text{MLT} \times N_s * 10^{-6} \ \text{ohms}
\]  
(5.51)

Total Secondary Loss, \( P_s \)
\[
P_s = I_s^2 R_s \ \text{Watts}
\]  
(5.52)

Secondary Winding Inductance of Transformer, \( L_s \)
\[
L_s = L_p \left( \frac{N_s}{N_p} \right)^2
\]  
(5.53)

Magnetising current of Transformer \( L_m \)
\[
L_m = \frac{N_s I_p}{N_p (1 - D)}
\]  
(5.54)

5.5.3 Control of dc-dc Cuk converter

The proportional plus integral controller produces an output signal consisting of two terms - one is proportional to error signal and other proportional to integral of error signal. In PI controller
\[
u(t) \propto \{e(t) + \int e(t) dt\}
\]  
(5.55)
\[ u(t) = K_p e(t) + \left( \frac{K_p}{T_i} \right) \int e(t) dt \]  

where, \( K_p \) = proportional gain  
and \( T_i \)= integral time.  
The advantages of both p-controller and I-controller are combined in PI controller. The proportional action increases the loop gain and makes the system less sensitive to the parameter variation of system parameters. An Integral action reduces or eliminates the steady state error [21].

5.6 DESIGN OF SINGLE PHASE INVERTER AND CONTROL CIRCUIT

The four-switch single-phase inverter proposed in this thesis is a prime candidate for use in single households and small businesses. Its compact size and compatibility with existing electrical standards make its integration easy. However, little work is available on characterizing the system from a controls point of view. In particular balancing the two outputs with an uneven load is a concern. This thesis uses a nodal and loop analysis to formulate a mathematical model of the four switch single-phase inverter. Non-linear times invariant model is constructed for circuit simulation the details are found in real circuits are as.

5.6.1 Design of VSI

The intent of the controller is to achieve the best performance out of the most economical system. Generally speaking the best performance means low total harmonic distortion (THD) of the sinusoidal output. The output impedance for any type of the voltage source is always important. Here low output impedance insures that the output waveform will exhibit low THD and accurate RMS voltage value under a variety of load conditions [21].

5.6.2 Design of Output Filter

Output filter selection is an important part of the system design. A smaller output filter provides lower output impedance, but at the expense of higher harmonics and distortion due to voltage ripple from inadequate attenuation of the switching frequency [45]. In general a voltage source would be better with a larger capacitor at the output, but peak IGBT currents necessitate the need for a reasonably sized output inductor.

\( L_f \) is the filter inductor which filters the high switching frequency component present in the current waveform fed into the grid. For design, it requires the cut off frequency \( f_c \) to be lesser than the switching frequency \( f_s \). Thus, the design value of \( L_f \) is given by

\[
L_f = \frac{1}{(2 \pi f_c)^2 C_f}
\]
A block diagram representation of a single-phase inverter is given in Fig.5.1. The inverter consists of four switching devices connected in the form of a bridge. The single-phase inverter in the unipolar switching scheme as shown in Fig.5.17

5.6.3 Design of Controller

To produce a sinusoidal output voltage waveform of variable frequency and amplitude, a sinusoidal reference signal (Vref) is compared with the triangular waveform (Vtri). The amplitude modulation index (MA), which controls the rms value of the output voltage, is defined as

\[ M_A = \frac{V_{\text{ref}}}{V_{\text{tri}}} \]  

Equation (5.57) refers to the peak amplitudes of the signals. Leg A and B of the full-bridge inverter are controlled separately by comparing Vtri with Vref and Vtri with -Vref. The resulting waveforms are used to control the switches as follows:

In leg A

\[ V_{\text{ref}} > V_{\text{tri}} : G_{S1} \text{ on} \]  

\[ V_{\text{ref}} < V_{\text{tri}} : G_{S4} \text{ on} \]

and

In leg B

\[ -V_{\text{ref}} > V_{\text{tri}} : G_{S3} \text{ on} \]  

\[ -V_{\text{ref}} < V_{\text{tri}} : G_{S2} \text{ on} \]

Note that GS4 and GS2 are automatically created as the inversion of GS1 and GS3, respectively [47].

Fig.5.17 Unipolar Control Scheme for Single Phase VSI Inverter
5.7 MATLAB/SIMULINK Model of solar power generation system

The complete models of solar power generation system are given in Fig.5.18 and as a part of subsystem1 and subsystem2 are shown in Fig.5.19A and Fig.5.19B respectively.

Fig.5.18 MATLAB/SIMULINK Model of Complete Solar Photovoltaic Power Generation

Fig. 5.19-A MATLAB/SIMULINK Model of Subsystem 1 used in Fig.5.22
5.8 RESULTS AND DISCUSSION

The Results of a solar photovoltaic power generation system are discussed in this section. This solar power generation system consists of three main stages.

5.7.1 Characteristics of Solar Array Used

Parameters of model used are,

\[ N_s = \text{Number of cells in series} = 36 \]

\[ N_p = \text{Number of cells in parallel} = 1 \]

\[ M_s = \text{Number of modules in series} = 1 \]
M_P = Number of modules in parallel = 1

The PV model is simulated for different environment conditions. Figures 5.20 and 5.21 show PV array characteristics at different ambient temperatures and insolation, respectively.

Fig.5.20 Array Characteristic at Different Temperatures and Isolations
Fig.5.20 and Fig.5.21 show that the operating point at which the solar generator can deliver maximum power for a given radiation intensity is near the bend of characteristic. Three points of the curve are of particular interest: open circuit voltage \(V_{oc}\), short circuit current \(I_{sc}\), and maximum power point \(MPP\). Fig.5.20 shows the I-V characteristic at different values of solar radiation and different values of solar temperature. Fig.5.21 shows the P-V characteristic at different values of solar radiation and at different values of solar temperature. It is possible to notice that the solar array behaves as a current source left at \(MPP\), and it considers that the voltage source behaviour right at \(MPP\). From Figs. 5.20, 5.21 it is observed that for each curve of solar irradiation, there is a specific voltage for which the array operates at proper maximum power point.

This is the optimum voltage for the operation of the solar array [28]. Considering that most of the loads supplied by PV system operate with constant voltage, it is necessary to track the maximum power point tracking (MPPT) condition of the solar array regardless the load voltage.
Fig. 5.21 PV Array Characteristic at Different Temperatures and Isolations

5.8.2 Performance of Boost Converter with Solar Panel and Storage Battery

The results of this boost dc-dc converter are shown in Fig. 5.22. In this figure, an input to the boost converter \( (v_{in}) \), the value of output current \( (i_o) \), output voltage \( (v_o) \), inductor current \( (i_l) \) and corresponding voltage across capacitor \( (v_c) \), diode \( (v_d) \), voltage across mosfet \( (V_m) \), Power\( (P) \) are shown under stranded temperature and radiation conditions (i.e. 25\(^{0}\)C and 1000w/m\(^2\) ). The dc-dc converter is responsible for the regulation of the output voltage at peak power point while also providing a constant voltage for charging a battery. The PWM control is provided in order to regulate the output voltage of the boost converter. In order to generate gating pulse for the MOSFET the error voltage between reference value and converter output voltage is given to a PI (proportional integral) controller.

Then this error voltage is compared using a comparator to a repetitive sequence wave of switching frequency. Then ON/OFF pulse generates which controls the dc-dc converter [21]. This boost converter converts input voltage of 16-21 V to 24 V in order to charge storage battery connected to the output of the Boost Converter. The control of the boost converter regulates the output of the boost converter irrespective of the variations in the solar radiations and temperature. As solar radiation and temperature control the output of the solar array.
Fig. 5.22 Output of boost converter with MPPT and Storage Battery

5.8.3 Performance of Cuk Converter

When the output of the boost converter with solar panel and storage battery is feed to Cuk converter, the Cuk converter converts this input voltage of 24 V in high quality 380 V D.C.
voltage. The corresponding results are shown in Fig.5.23. In which output voltage (Vo), input voltage (Vi), voltage across diode (Vd) as per represents of the system.

![Diagram](image)

**Fig.5.23** Results of Isolated DC-DC Cuk converter

### 5.8.4 Performance of Solar power Generation System

The solar power generation system is analysed and simulated using MATLAB/SIMULINK as shown in Fig.5.18, at different conditions load like resistive load, non-linear load, dynamic load and induction motor as load on solar power generation system and order of harmonics is calculated in each above case.

#### 5.8.4.1 Resistive Load

The of complete solar power generation system when applied a resistive load of 500W is shown in Fig.5.24 and corresponding order of current harmonics shown in fig.5.30 the THD is well within desirable range. The value of R is considered 105.4 ohms for power of 500 W.

#### 5.8.4.2 Non linear Load

When a non linear load is applied on the solar power generation system, the output is shown in fig. 5.26 and corresponding order of current and voltage harmonics is shown in fig.5.28 and Fig.5.29. The THD corresponding to this non linear load is 149.72% the value of R is 105.4 ohms and value of C is 500μF for a load of 500 W
5.8.4.3 Dynamic Load

When a dynamic load of 500W is applied on the inverter the output is shown in Fig.5.27. When a sudden load increases and corresponding current increases and output voltage remains unchanged.

Fig.5.24 Output of Complete Solar Photovoltaic Power Generation System at Resistive Load
Fig. 5.25 Output of Generation Restive Load at the Instant when Load is Switched On

Fig 5.26 Voltage and load current output of Generation System at Non-Linear Load

Fig 5.27 Voltage and load current output of Generation System at Variable Load
5.9 CONCLUSIONS

In this topology of solar power generation system by using an isolated Cuk converter and boost dc-dc converter to feed ac load, an effective control technique has developed to demonstrate the satisfactory performance of the system. The performance which has been carried out on this solar power generation system for feeding different types of loads has been well within desirable range.
CHAPTER-VI

MAIN CONCLUSIONS AND SUGGESTIONT FOR FURTHER WORK

6.1 GENERAL

The objective of this research work has been on the investigation of various type of isolated solar photovoltaic power generation system. In order to cater the high demand of electricity and reduce the effects of global warming, solar PV is extensively used.

Following are the main objective on which detailed work has been carried out.

(1) Modelling of solar photovoltaic panel in MATLAB/SIMULINK has been carried out which is governed by solar radiation and ambient temperature with implementation of maximum power point tracking.

(2) Design and modelling in MATLAB/SIMULINK models of various type of DC-DC converter like boost converter, isolated DC-DC Cuk converter have been carried out in detail.

(3) Design of storage Battery with different capacity to provide load leveling in isolated applications.

(4) Design, analysis and control of DC to AC boost inverter and single phase voltage source inverter with unipolar switching to feed local ac loads.

6.1 MAIN CONCLUSION

In this research work two different types of solar photovoltaic power generation system has been developed and simulated using MATLAB/SIMULINK the main conclusions of this research work are the following

1) The first isolated solar photovoltaic power generation system using a boost converter and boost inverter has been designed, modelled for domestic point of view for 500W. An analysis has been carried out on this solar photovoltaic power generation system in feeding of resistive loads, inductive loads, and non-linear loads. The results of this isolated solar photovoltaic power generation system well within the suitable range and THD of output ac voltage have been found below 5%.

2) The second isolated solar photo voltaic power generation system using a boost converter and an isolated Cuk DC-DC converter has designed, modelled for domestic load of 500W. This isolated solar photovoltaic power generation system has been analysed for resistive loads, inductive loads and non-linear loads. The results have been found satisfactory well within the reasonable limits and THD of the output ac voltage well below 5%.

6.2 SUGGESTIONS FOR FURTHER WORK

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Although two systems has been analysed in this research work the areas for further work, can be suggested as.

1) As a part of further work different topologies can be worked out by using different type of dc-dc converters available in the literature.
2) The hybrid power generation system consisting of PV solar and wind energy can be designed, modelled and hardware could be implemented.
3) Some control strategies could be work out for the control of these isolated generating system.
REFERENCES.


APPENDIX-1
\[ Iscn = 8.21; \quad \text{%Nominal short-circuit voltage [A]} \]
\[ Vocn = 32.9; \quad \text{%Nominal array open-circuit voltage [V]} \]
\[ Imp = 7.61; \quad \text{%Array current @ maximum power point [A]} \]
\[ Vmp = 26.3; \quad \text{%Array voltage @ maximum power point [V]} \]
\[ P_{\text{max},e} = Vmp \times Imp; \quad \text{%Array maximum output peak power [W]} \]
\[ Kv = -0.123; \quad \text{%Voltage/temperature coefficient [V/K]} \]
\[ Ki = 3.18 \times 10^{-3}; \quad \text{%Current/temperature coefficient [A/K]} \]
\[ Ns = 54; \quad \text{%Number of series cells} \]

%%% Array with Nss x Npp modules
\[ Nss = 15; \]
\[ Npp = 2; \]

%%% Constants
\[ k = 1.3806503 \times 10^{-23}; \quad \text{%Boltzmann [J/K]} \]
\[ q = 1.60217646 \times 10^{-19}; \quad \text{%Electron charge [C]} \]
\[ a = 1.3; \quad \text{%Diode constant} \]

%%% Nominal values
\[ Gn = 1000; \quad \text{%Nominal irradiance [W/m^2] @ 25°C} \]
\[ Tn = 25 + 273.15; \quad \text{%Nominal operating temperature [K]} \]

%%% Adjusting algorithm
% The model is adjusted at the nominal condition
\[ T = Tn; \]
\[ G = Gn; \]
\[ Vtn = k \times Tn / q; \quad \text{Thermal junction voltage (nominal)} \]
\[ Vt = k \times T / q; \quad \text{Thermal junction voltage (current temperature)} \]
\[ Ion = Iscn / (\exp(Vocn/a/Ns/Vtn) - 1); \quad \text{Nominal diode saturation current} \]
\[ Io = Ion; \]

% Reference values of Rs and Rp
\[ R_{s,\text{max}} = (Vocn - Vmp) / Imp; \]
\[ R_{p,\text{min}} = Vmp / (Iscn - Imp) - R_{s,\text{max}}; \]

% Initial guesses of Rp and Rs
\[ Rp = R_{p,\text{min}}; \]
\[ Rs = 0; \]
\[ tol = 0.001; \quad \text{%Power mismatch Tolerance} \]
\[ P = [0]; \]
\[ error = Inf; \quad \text{%dummy value} \]

% Iterative process for Rs and Rp until \( P_{\text{max},\text{model}} = P_{\text{max},\text{experimental}} \)
\[ \text{while (error > tol)} \]
% Temperature and irradiation effect on the current
dT = T - Tn;
Ipvn = (Rs+Rp)/Rp * Iscn; % Nominal light-generated current
Ipv = (Ipvn + Ki*dT) *G/Gn; % Actual light-generated current
Isc = (Iscn + Ki*dT) *G/Gn; % Actual short-circuit current

% Increments Rs
Rs = Rs + .01;

% Parallel resistance
Rp = Vmp*(Vmp+Imp*Rs)/(Vmp*Ipv-Vmp*Io*exp((Vmp+Imp*Rs)/Vt/Ns/a)+Vmp*Io-
Pmax_e);

% Solving the I-V equation for several (V,I) pairs
clear V
clear I

V = 0:.1:35; % Voltage vector
I = zeros(1,size(V,2)); % Current vector

for j = 1 : size(V,2) %Calculates for all voltage values

% Solves g = I - f(I,V) = 0 with Newtonn-Raphson

g(j) = Ipv-Io*(exp((V(j)+I(j)*Rs)/Vt/Ns/a)-1)-(V(j)+I(j)*Rs)/Rp-I(j);
while (abs(g(j)) > 0.001)

g(j) = Ipv-Io*(exp((V(j)+I(j)*Rs)/Vt/Ns/a)-1)-(V(j)+I(j)*Rs)/Rp-I(j);
glin(j) = -Io*Rs/Vt/Ns/a*exp((V(j)+I(j)*Rs)/Vt/Ns/a)-Rs/Rp-1;
I_(j) = I(j) - g(j)/glin(j);
I(j) = I_(j);
end

end % for j = 1 : size(V,2)

plott = 1; %Enables plotting during the algorithm execution
if (plott)

%Plots the I-V and P-V curves

figure(1)
grid on
hold on
title('I-V curve - Adjusting Rs and Rp');
xlabel('V [V]');
ylabel('I [A]');
xlim([0 Vocn+1]);
ylim([0 Iscn+1]);

%Plots I x V curve
plot(V,I,'LineWidth',2,'Color','k')

%Plots the "remarkable points" on the I x V curve
plot([0 Vmp Vocn],[Iscn Imp 0],'o','LineWidth',2,'MarkerSize',5,'Color','k')

%Power x Voltage
figure(2)
grid on
hold on
title('P-V curve - Adjusting peak power');
xlabel('V [V]');
ylabel('P [W]');
xlim([0 Vocn+1])
ylim([0 Vmp*Imp+1]);
end % if(plot)

% Calculates power using the I-V equation
P = (Ipv-Io.*exp((V+I.*Rs)/Vt/Ns/a)-1)-(V+I.*Rs)/Rp).*V;
Pmax_m = max(P);
error = (Pmax_m-Pmax_e);
if (plot)
%Plots P x V curve
plot(V,P,'LineWidth',2,'Color','k')

%Plots the "remarkable points" on the power curve
plot([0 Vmp Vocn],[0 Vmp*Imp 0],'o','LineWidth',2,'MarkerSize',5,'Color','k')
end % if (plot)
end % while (error>tol)

%% Outputs

% I-V curve
figure(3)
grid on
hold on
title('Adjusted I-V curve');
xlabel('V [V]');
ylabel('I [A]');
xlim([0 Vocn+1])
ylim([0 Iscn+1]);
plot(V,I,'LineWidth',2,'Color','k') %

plot([0 Vmp Vocn ],[Iscn Imp 0 ],'o','LineWidth',2,'MarkerSize',5,'Color','k')

% P-V curve
figure(3.4)
grid on
hold on
APPENDIX-2
A. The Parameter For Solar Panel
Nominal short circuit current(A) $I_{scn} = 3.8$, Nominal array open circuit voltage(V) $V_{ocn} = 21.1$, Array current @maximum power point(A) $I_{mp} = 3.5$, Array voltage @maximum power point(V) $V_{mp} = 17.1$, Voltage /temperature coefficient(V/K) $K_v = -80e^{-3}$, Current /temperature coefficient(A/K) $K_i = 0.003$, Number of series cell=36

A. Parameters For Dc-Dc Boost Converter
$D=0.427-0.338, K_v = 0.056, K_p = 0.015, F_{sw} = 50$ kHz

B. Parameters For Storage Battery
$R_b=10k\Omega, R_s=0.01\Omega, V_{oc} = 96$ V

C. Parameters For Dc-ac Boost Inverter
$C_1 = C_2 = 200\mu F, L_1 = L_2 = 700\mu H, K_1 = 0.2, K_2 = 0.24, F_{sw} = 30$ KHz, $P=500$ W, 230 V
APPENDIX-3

A The Parameter For Solar Panel
Nominal short circuit current(A)\(I_{scn}=3.8\), Nominal array open circuit voltage(V)\(V_{ocn}=21.1\), Array current @maximum power point(A)\(I_{mp}=3.5\), Array voltage @maximum power point(V)\(V_{mp}=17.1\), Voltage /temperature coefficient(V/K) \(K_v=-80e^{-3}\), Current /temperature coefficient(A/K) \(K_i=.003\), Number of series cell=36.

A. Parameters for dc-dc boost converter
\[D=0.427-0.338, K_i=0.056, K_p=0.035, F_s=50 \text{ KHz}\]

B. Parameters for storage battery
\[R_b=10K\Omega, R_s=0.01\Omega, V_{oc}=24\text{V}\]

C. Parameters for isolated cuk dc-dc converter
\[C_1=C_2=1\text{mF}, 65.7\mu\text{F}, L_1=L_2=11\text{mH}, 19\text{mH}, K_p=0.000035, K_i=0.07, F_{sw}=100 \text{ KHz}\]

D. Parameters for single phase inverter
\[K_{i_1}=8, k_{p_1}=8, L_f=0.5\text{mH}, C_f=6\mu\text{f}, K_i_2=10, k_{p_2}=.9, 500W, 230V \text{ RMS}\]

E. Parameters high frequency transformer [9,10]
\[f_s=100\text{KHz}, V_1=25\text{V}, V_2=380\text{V}, R_1=1.4e-005\text{ohm}, R_2=0.0058999\text{ohm}\]
\[L_1=2.26e-007\text{H}, L_2=5.89999e-006\text{H}, R_m=100\text{ Ohm}, L_m=0.002866\text{ H}\]
LIST OF PUBLICATIONS


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