International Journal of Advances in Engineering and Management (IJAEM)
Volume 5, Issue 3 March 2023, pp: 1958-1975 www.ijaem.net ISSN: 2395-5252

# A Novel Maximum Power Point Tracking based Solar Power System with Three-phase Voltage Source Inverter

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Date of Submission: 20-03-2023 Date of Acceptance: 30-03-2023

**ABSTRACT:**
The Arduino microcontroller based Maximum Power Point Tracking (MPPT) solar charge controller. The optimum solar photovoltaic power is extracted using the Perturb and Observe (P&O) MPPT algorithm. Whilst there are many MPPT solar charge controllers available in the market, the Arduino Nano based MPPT solar charge controller is an attractive method for MPPT controller due to its adaptability, simple, cheap, and durable with good performance for remote areas application with cheaper cost than conventional MPPT charge controllers. This system ensures maximum power is harvested from the photovoltaic panel and capable to charge the battery as well as maintain the battery health condition. The simulation result has shown the performance of the proposed P&O-SPWM controller is capable of tracking the photovoltaic maximum power point and extracting the maximum fundamental voltage with reduced ripples.

## I. INTRODUCTION

### 1.1 RENEWABLE ENERGY SOURCES

Energy is the keyword for our day-to-day life, as humans need it in the form of electrical, mechanical, thermal and chemical energy for various uses. World energy consumption has been increasing rapidly, since the industrial revolution introduced mechanized production methods. Though conventional energy sources like fossil fuel, coal, petroleum products and gases are used for generation of power, it is necessary to utilize the energy sources which are not only able to minimize the environmental pollution but also costs less than the conventional energy sources. Use of renewable energy protects the environment, by reducing the consumption of gaseous, nuclear material and emission of heat radiations. It is helpful in protecting the earth's atmosphere from global warming problem. It conserves non-renewable forms of energy, reduces environmental damage caused by exploration and extraction of fossil fuels, and minimizes exposure of people and wildlife to large conventional power plants.

The concept of renewable versus non-renewable energy resources provides the cornerstone of sustainability. A renewable energy system converts the energy found in sunlight, wind, falling-water, sea-waves, geothermal heat, or biomass into a form, such as heat or electricity. Most of the renewable energy comes either directly or indirectly from the sun and wind and it can never be exhausted. Therefore, they are called renewable energy sources. According to International Energy Agency (IEA), energy production from renewable sources would overtake the coal and become the world's number one source of electricity in the "early 2030s". The dominance of renewable source in the recent years has been driven by hydroelectricity and in the years to come, wind and solar will lead the way.

Figure 1.1 shows the global electricity generation by various sources from 2014 and projected up to 2040, which confirms the growing role of wind and solar energy sources. IEA has observed solar costs would fall by around 40% and onshore wind around 15% between 2014 and 2040.

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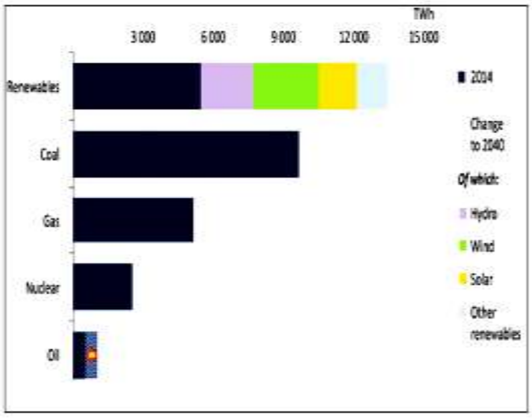


**(Source: IEA world energy outlook 2015)**
**Figure 1.1 Global electricity generations by various sources in 2014**

**(Terawatt hours) and its projected value up to 2040.**

Solar energy is one of the important sources of renewable energy. Solar energy, in the form of light and heat, helps to produce heat and electricity. Conversion of solar energy into electrical energy is done using a device called the photovoltaic (PV) cell, also called a solar cell. PV cells work by capturing the energy in the sun's radiation, called photons; the photons then dislodge electrons from the material inside the cell and the flow of electrons produces an electric current. Semiconductor material such as silicon acts as the best substance for forming p-n junction for this conversion of photon energy into electric current.

The performance of PV cell depends on the spectral distribution of solar radiation. The standard spectral distribution is mainly used as reference for the evaluation of PV cells. There are two standard terrestrial distributions defined by the American Society for Testing and Materials (ASTM). They are global and direct normal air mass AM1.5 spectral distributions. The solar radiation, which is perpendicular to a plane directly facing the sun, is known as direct normal. The global corresponds to the spectrum of the diffused radiations. Diffused radiations are the radiations which are reflected on earth's surface or influenced by atmospheric conditions. To measure the global radiations, an instrument named by pyranometer is used. This instrument is designed in such a way that it responds to each wavelengths and so that, a precise value for total power is obtained in any incident spectrum.

## 1.2 PHOTOVOLTAIC ENERGY SYSTEMS

The PV power systems have been gaining popularity more than other renewable sources because of their ease of installation and low maintenance requirement. Due to environmental and economic benefits, PV system is now widely utilized as a distributed energy resource in stand-alone mode and grid connected mode. Government of India is promoting energy harvesting from renewable sources, especially for solar power system by providing financial assistance. The problem of using PV power includes fluctuating power output from the PV panel due to unpredictable weather conditions. It results in tapping less than optimum value of power from the PV panel. In addition to this, the presently used DC-DC converters in PV power systems result high ripple content in the voltage and current. To overcome these issues, lot of research works is being done in PV power system throughout the world. The major research areas in PV power system are as follows:

- Development of new materials for increasing conversion efficiency of solar PV cell.
- Development of new technology for extracting the maximum power from the PV panel.
- Development of efficient power converter topology for PV Power system.
- Development of technology for reactive power management and harmonics reduction/elimination, while using PV power system and remote data logging/control of the solar PV power system.

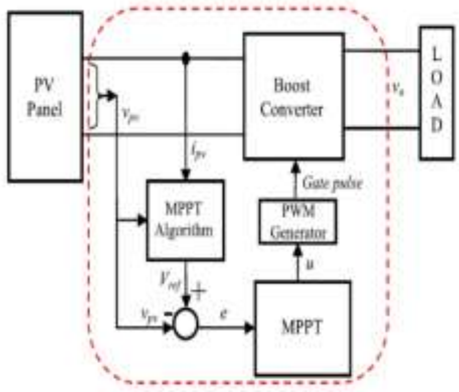


**Figure 1.2 Block diagram of standalone solar PV power system and**

**Highlighting major research work areas**

The solar power systems are usually used in the following main fields:

- Satellite applications, where the solar arrays provide power to satellites.
- Off-grid applications, where solar arrays are used to power remote loads that are not connected to the electric grid.

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- On-grid or grid connected applications, in which solar arrays are used to supply energy to local loads as well as to the electric grid.

The basic block diagram of the standalone solar PV power system highlighting the major areas of the research work done in the recent years to enhance its performance is shown in Figure 1.2. The components of solar PV system are described below in detail.

**1.2.1 Solar PV Cell**

PV cells are manufactured using photo sensitive materials. These cells absorb sunlight photons and liberate electrons from chemical bands. When the sunlight strikes the PV cell's surface, electrons are released from atoms. Electrons, excited by the light, move through the silicon. When these free electrons are captured, the result is an electric direct current that can be used as electricity.

Solar cells can be classified into first, second and third generation cells. The first generation cells also called conventional, traditional or wafer-based cells, which are made of crystalline silicon, the commercially predominant PV technology, that includes materials such as polysilicon and monocrystalline silicon. Second generation cells are thin film solar cells, which include amorphous silicon, Cadmium Telluride (CdTe) and Copper Indium Gallium Selenite (CIGS) cells and they are commercially significant in utility-scale PV power stations, for building integrated PV or to be used in small stand-alone power system.

**1.2.2 Maximum Power Point Tracking (MPPT) Algorithm**

Solar power is considered as a kind of clean power. The problems of using solar PV power include nonlinear current-voltage (I-V) and power-voltage (P-V) characteristics of PV panel as shown in Figure 1.2.2. At different irradiation levels and temperatures, power output of the PV panel varies. It is advantageous to extract the maximum amount of energy from the PV panel. This is possible, if tapping of energy is done at Maximum Power Point (MPP) at every instant.

Generally, the operating point of a PV module may not be at the MPP, but it can be shifted to MPP by using tracking algorithms. MPPT strategy is used to make the solar PV panel to operate at optimal power point, by delivering maximum power under various weather conditions. Different MPPT techniques have been proposed to increase the performance and efficiency of PV systems such as perturb and observe (P&O) method, Incremental Conductance (INC) technique, ripple correlation control method and lookup table method, etc. These methods differ in the number of sensors required, cost, convergence speed and complexity in hardware implementation.

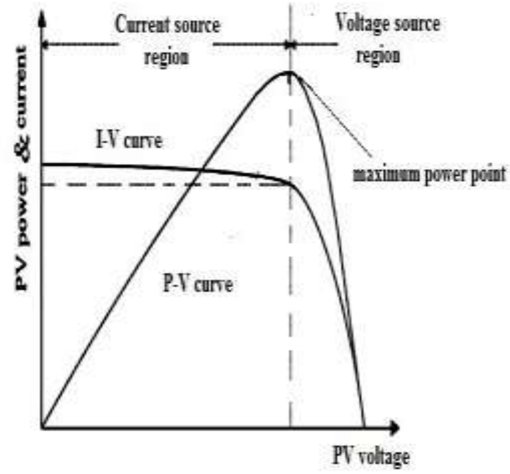


**Figure 1.3 I-V and P-V characteristics of solar PV panel**

**1.2.3 DC-DC Power Converters for PV System**

The basic element of the stand-alone solar PV power conditioning system is the DC-DC converter, which transfer power from the PV panel to the load optimally. However, switching operation results in voltage and current ripples, and this may be reduced by proper choice of converter. A DC-DC converter acts as an interface between the load and the PV panel. By changing the duty cycle of the converter, the load impedance as seen by the PV source is varied and matched at the point of the peak power so as to transfer maximum power to the load. Most of the research works done so far present an assessment on the performance of fundamental power converters used in solar PV power system in terms of its conversion efficiency, ripple content and stability.

Three fundamental configurations of DC-DC converters are buck, boost, and buck-boost converters. In DC–DC buck converter or step-down converter, the output voltage magnitude is always lower than the input voltage magnitude. Hence this topology can be used for connecting high voltages to low voltage loads or batteries. However, a boost converter has the ability to increase the input voltage based on duty cycle of the switch. A buck-boost converter can either buck or boost the input voltage. From the investigation and analysis of the fundamental converters, buck-boost converter is better than the others but, it has the drawback of having discontinuous current at the input and output side and reverse output voltage. To overcome this problem, higher order converters such as CUK, Single-Ended Primary-Inductor Converter (SEPIC) and LUO are deployed in solar PV system. They have main advantages of having continuous current at the converter input and output side. The higher order converters are less noisy, and have reduced ripple and higher conversion efficiency.

### 1.3 ORGANISATION OF THE THESIS

This thesis has been organized into five chapters reporting the complete research work, discussion and the analysis of results.

**Chapter 1** introduces briefly the role of renewable energy sources and the significance of solar power systems. Basic elements of standalone PV system and challenging issue in these elements for enhancing the performance of PV system are discussed.

**Chapter 2** The current topics of research in the field of performance improvement of PV system are presented through detailed literature survey. The objective of this thesis is reported at the end of the chapter.

**Chapter 3** describes the solar PV cell. It discusses the need of MPPT and gives the detailed study about the existing types of MPPT algorithms and various types of DC-DC converters used in PV system. Finally, the developed PV model is validated in the existing PV energy conversion system through MATLAB/SMIULINK environment. Its performance results are highlighted and analysed.

**Chapter 4** presents the simulation implementation of improved and simplified MPPT algorithm based solar PV module. The performance of proposed MPPT algorithm is compared with the results obtained from the existing conventional system.

**Chapter 5** presents the overall conclusion and summary of the thesis by highlighting the most important outcomes of each chapter. Guidelines for the future research work are also given at the end of the research work.

## II. LITERATURE SURVEY

Research works on the development of performance enhanced MPPT algorithms and appropriate DC-DC converters for stand-alone PV system, for its optimum performance are numerous. Only those important works, which are more related to the present work, are focused in this section. The literature survey is presented under the following topics:

### 2.1 Review on Modelling of PV Module

Rahman et al. (2013) have suggested a generalized mathematical model of PV panel. This proposed modelling technique determines the entire PV panel or module parameters such as, series resistance, shunt resistance and diode idealist factor at STCs without any explicit repetitive iteration method. This generalized model can be adopted for representing the performance of any PV panel at various operating conditions.

Maetal. (2013) have presented a new MPP DEM: Direct Estimation Method PV model, derived from the mathematical expressions of the electrical characteristics of the Rp-model. Since the temperature and the solar irradiance intensity have been taken into account in the estimation process, the method works for a variety of atmospheric conditions. The proposed method has shown its high-accuracy in off-line prediction performance.

Pandiarajan et al. (2011) have proposed step-by-step procedure for one-diode equivalent circuit modelling of PV module and it in order to study I-V and P-V characteristics. The proposed model is designed with a user-friendly icons and a dialog box like simulink block libraries.

Villalva et al. (2009) have proposed a method of modelling and simulation of PV arrays. The main objective is to find the parameters of the nonlinear I-V equation of PV panel by fitting the curve at three significant points: open circuit, peak power, and short circuit. Given these three points, which are provided by all commercial array datasheets, the method finds the best I–V equation for the single-diode solar cell model, for both series and parallel resistances configuration, and warranties that the maximum power of the model matches with the maximum power of the real array. With the parameters of the adjusted I-V equation, one can build a PV circuit model with any circuit simulator by using basic math blocks.

MATLAB-based modelling and simulation scheme, suitable for studying the I-V and P-V characteristics of a PV array under a non-uniform irradiation due to all irradiation condition include partial shading, was discussed by Patel et al. (2008). The simulated solar PV model conveniently interfaced with DC-DC converters.

Chowdhury et al. (2008) have developed a robust and very simple mathematical model of a polycrystalline PV array in MATLAB Simulink which has imposed low computational burden on the system and required low data storage. It can be represented by standard block set of MATLAB Simulink. The results clearly show that this model can be well utilized for detailed load performance analysis of PV arrays, and for studying elementary control strategies of PV plants.

### 2.2 MPPT Techniques

Sera et al. (2013) have investigated the two most well-known hill climbing MPPT algorithms (P&O and INC).These two methods are thoroughly analysed both from a mathematical and practical implementation point of view. Their mathematical analysis reveals that there is no difference between the two**.** This has been confirmed by experimental tests according to the EN 50530 standard.

Safari et al. (2011) have used INC MPPT in solar PV power systems using direct control method. This algorithm used to track MPP is precise under rapidly changing environmental conditions. It effectively tracks MPP quickly without oscillation. Its dynamic performance is satisfactory.

Deepak et al. (2015) have given a review of MPP tracking technique which may overcome the distraction of researchers while selecting MPPT technique because all the methods have their unique advantages and disadvantages which requisite a thorough and informative comparative analysis of different methods. This overview avoids the complication in the tiresome job of perfect choice of MPPT, and it will found to be worthy of complying all the desired attributes of the system.

Nafeh et al. (2007) have developed a new maximum power tracking algorithm based on the INC algorithm. The developed algorithm depends on the relationship between the load line and the tangent line angles of the I-V characteristic curve. The performance of the developed algorithm using mathematical models for the different system components is investigated.

Mei et al. (2011) have investigated a novel variable step-size incremental-resistance MPPT algorithm, which not only has the merits of INC algorithm but also automatically adjusts the step size to track the PV array MPP. This method is able to improve not only the steady-state performance but also the dynamic response.

Soon et al. (2015) have suggested a novel MPPT technique for efficiently extracting the maximum output power from a solar panel under varying meteorological conditions. In this proposed algorithm, the relationship between the load line and the I–V curve is used with trigonometry rule to obtain the fast response. The response of the proposed algorithm is four times faster than the conventional INC algorithm, during the load and solar irradiation variations.

Pakkiraiah et al. (2016) have reviewed research survey on various MPPT performance issues to improve the solar PV system efficiency. This work presents different types of PV panel systems, MPPT control algorithms, power electronic converters usage with control aspects, various controllers, filters to reduce harmonic content, and usage of battery system for the PV system.

Veerachary (2005) has proposed voltage-based power tracking for nonlinear PV sources using coupled inductor SEPIC converter. The proposed coupled inductor SEPIC converter is capable of reducing the ripple in the array current and improving the converter efficiency.

Rahimah et al. (2015) have developed the single sensor charging system with MPPT capability for standalone streetlight application. Using only one voltage sensor, the solar charger is able to operate in both MPPT and Constant Voltage (CV) charging mode. Hence high performance is provided at a low cost. For any given battery voltage and isolation level, the proposed control switches between MPPT and CV modes, optimize the power extracted from PV panel without compromising the battery's health.

### 2.3 DC-DC Power Converters for PV Application

Taghvaee et al. (2013) have reviewed the different non-isolated DC–DC buck, boost, buck–boost, CUK and SEPIC converters and their characteristics, to find a solution best suiting an application with MPPT. Review shows that there is a limitation in the system's performance according to the type of converter used. This review concludes that the best type of converter for PV system is the Buck–Boost DC-DC converter. This converter should be able to ensure optimum MPPT operation for any solar irradiation, cell temperature and load conditions.

Kolsi et al. (2014) have focused the effect of climatic conditions while designing two components (inductance, capacitance) for three topologies of DC-DC converters (Buck, Boost, Buck-Boost) commonly used in PV systems. When climatic conditions change, the boundary of inductance and capacitance parameters of DC-DC converter will change. These two parameters must be properly sized to achieve optimal efficiency of each converter.

Sivakumar et al. (2016) have presented an assessment of current and future trend of non-isolated DC–DC converters (Such as Buck–Boost, CUK and SEPIC) with various parameters and analysed using MATLAB Simulink. This helps to

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determine the suitable converter with a particular power rating for renewable energy based applications. In addition, the state space mathematical modelling of DC–DC converters is also presented and they will be useful in the design of controllers for different non isolated DC–DC converters.

**2.4 RESEARCH GAP IDENTIFICATION AND PROBLEM DEFINITION**

From the literature, it could be seen that still scope exists for reducing ripples in PV panel voltage and current and load side voltage and current. There is also scope for improving conversion efficiency and decreasing overall system cost of PV power system by proper choice of converter and by using suitable modified MPPT algorithms.

In general, the nonlinear I–V characteristic of the PV source makes the MPPT complex. To overcome this problem, conventionally several MPPT techniques have been used for maximizing the power extraction. These techniques vary in the number of sensors required, cost, convergence speed, and complexity in hardware implementation. Against this background, problems and prospects of several MPPT techniques reported in the literature are considered in this research work. A simple and modified Maximum Power Transfer Theorem (MPTT) based MPPT and Single Sensor Based (SSB) MPPT techniques are proposed. When proposing a MPP tracker for PV power system, the main job is to choose and design highly efficient converter, which reduces the ripple in current and voltage and increases the conversion efficiency.

Even though the modified MPPT with different DC-DC converter topologies are reported in literature for standalone PV system, there is lack of experimental analysis of different tracking control algorithms in terms of response speed, ripple content, conversion efficiency and cost of the PV system.

Therefore, this research work aims at bridging this gap by presenting simulation and experimental study of the proposed MPTT and SSB MPPT algorithms with higher order power converters such as DC-DC elementary LUO and interleaved LUO converter.

To designing more stable PV power system coupled to the load via DC-DC converter is another challenging task (controller design). This research work additionally covers the state-space averaging model of higher order DC-DC LUO converter used in the proposed PV power system. State space model as well as circuit model based simulation yields identical results. This modelling is helpful for identifying the stability region for typical power rating, when the input is within the specified range.

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**2.6 OBJECTIVES OF THE THESIS**

The main objectives of the research work are as follows:

- To develop a simplified MPPT technique and to verify its performance with the existing converter through MATLAB/SIMULINK.
- To study and evaluate the performance of the proposed PV power system using MATLAB/SIMULINK and compare its results with the conventional converter in terms of ripple current and voltage both in PV and load side, stress on the switch, conversion efficiency, and maximum power tracking capability. It is also experimentally implemented and the results are compared with those obtained through simulation.

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# III. MAXIMUM POWER POINT TRACKING FOR PV SYSTEM

## 3.1 INTRODUCTION

Literature reports voluminous research to improve the PV power system efficiency through material development, enhancing strategies for the efficient power point tracking and the development of efficient of DC-DC power converter topologies. Today's material technology assures only low to medium energy conversion efficiency PV cell. Hence, it is important to design high performance DC-DC converter and to propose efficient tracking algorithm. In which challenges arise on account of non-linear nature of I-V characteristics of PV system. The use of conventional power converters in PV system for MPPT, results in high ripple content in voltage and current. The problem gets worse because the output power of solar cells mainly depends on factors such as temperature and irradiance. Varying environmental conditions greatly affect the photovoltaic array output power.

The nonlinear I–V characteristics of the PV source make the MPPT complex. To overcome this problem, number of MPPT methods have been developed such as P&O, INC, ripple correlation control and lookup table method (Soon et al. 2013, Ishaque et al. 2014, Lin et al. 2011, Esram et al. 2006, Chung et al. 2003). Among these, the first two are the most commonly implemented methods in the existing PV systems. These methods vary in complexity, accuracy, speed, oscillation around the MPP, hardware implementation, and sensor requirement.

The artificial intelligence methods such as fuzzy logic and neural network are well adopted for handling nonlinearity in many applications. Though these methods are good in dealing with the nonlinear characteristics of the I–V curves of PV panel, they require extensive computation and the versatility of these methods is limited (Messai et al. 2011, Femia et al. 2007, Faraji et al. 2013). The lookup table method needs a prior knowledge of the PV array characteristics, so that, a clear mathematical function relating the output characteristics has to be predetermined. However, PV array characteristics depend on many complex factors such as temperature, partial shading, aging and a possible breakdown of individual cells. So, it is difficult to predict and store all the possible system conditions.

Modified algorithms have been introduced to improve the efficiency of MPPT algorithm in different aspects (Liu et al. 2008, Emad & Masahito 2010). INC algorithm with direct control method (Safari &Mekhile 2011, Liqun et al. 2013) eliminates additional control loop required for MPPT and shorten the computational time. In recent years implementation point of view, several MPPT algorithms such as Hill Climbing/P&O method, INC technique and artificial intelligence methods have been implemented using FPGA based controller because of its inherent features such as faster operation and optimized design of hardware architecture etc (Mellit et al. 2011, Khaehintung et al. 2006).

Electricity is one of the greatest inventions man has ever made, due to its very important role in socio-economic and technological development [1]. The need for electrical energy is increasing every year and also an increase in the government's construction of power plants.

The power plant relies on a thermal generator that can produce a large amount of power. On the other hand, thermal generators have several drawbacks, including air pollution, noise, waste, exhausted fuel, and expensive initial investment. Therefore, we need the alternative way to overcome these problems by utilizing renewable energy. One sustainable renewable energy, solar energy, is converted into electrical energy using the Solar PV System.

## 3.2 SINE WAVE INVERTER

Single-phase inverters are of three types i.e. square wave inverter, modified sine wave inverter, and pure sine inverter. The pure sine inverter is studied in this paper. The square wave or modified sine wave; these two types of inverters are cheaper and are not suitable for delicate electronic devices [3]. The output of pure sine wave inverter is a near-perfect sine wave. Pure sine wave inverters have fewer power losses and less heat generation [4]. The sine wave has minor harmonic distortion resulting in a very clean supply. It makes it most suitable for running electronic systems such as microwaves ovens, computers and motors and other sensitive equipment without causing problems or noise. Pulse Width Modulation (PWM) technique is best for sine wave generation.

A pure or true sine wave inverter changes or converts the DC supply into a near-perfect sine wave. The sine wave has minimal harmonic distortion, which results in a very clean supply [5]. It makes it suitable for working electronic systems such as computers, motors, and microwave ovens, and other sensitive equipment without causing problems like noise. Things like mains battery chargers also run better on pure sine wave converters. Ideally, the output waveforms of an inverter should be sinusoidal. However, the waveforms of efficient inverters are non-sinusoidal and contain specific harmonics [6]. Due to the availability of high-speed power semiconductor devices, the harmonic contents present in the output voltage can be minimized significantly by using switching techniques [7].

### 3.3 MAXIMUM POWER POINT TRACKING

The Power-Voltage or current-voltage curve of a solar panel, there is a peak operating point at which the Solar Panel delivers the maximum possible power to the load. This unique point is called the maximum power point (MPP) of solar panel. The photovoltaic nature of the solar panels makes the (Power-Voltage or current-voltage) curves depend on temperature and irradiance (the flux of radiant energy per unit area) levels. In other words depending on the amount of sunlight per unit area of the panels the curve will vary hence the peak point or MPP will vary accordingly. Therefore it can be deduced that the operating current and voltage which maximize power output will change with environmental conditions.

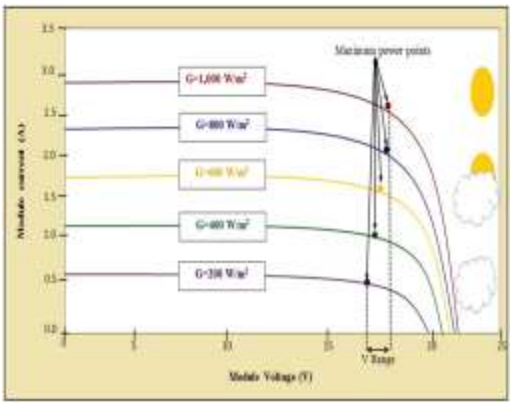

**Fig 3.1: Variation of maximum Power Point (MPP) at different sunlight conditions**

From the above Fig 3.1 it can be seen that the MPP depends on certain conditions such as the irradiance for instance which is given by the symbol ‘G’. At different values of G from the graph it can be seen how the values of MPP has slightly shifted. It is hence the work of charge controller using certain algorithm to calculate the MPP at every instance providing the maximum power hence making the system more efficient. In these applications, the load can demand more power than the PV system can deliver.

There are many different approaches to maximizing the power from a PV system, this range from using simple voltage relationships to more complexes multiple sample based analysis.

### 3.4 MPPT METHODS

There are some conventional methods for MPPT.

**1.** Constant Voltage method
**2.** Open Circuit Voltage method
**3.** Short Circuit Current method
**4.** Perturb and Observe method
**5.** Incremental Conductance method

### 3.4.1 Constant Voltage Method

The constant voltage method is quite a simple method but an inefficient method. This method simply uses single voltage to represent the $V_{mpp}$. In some cases this value is set by an external resistor connected to a current source pin of the control IC. For the various different irradiance variations in Fig 3.2, the method will collect about 80% of the available maximum power. The actual performance will be determined by the average level of irradiance. Since the maximum power point of a solar PVF module does not always lie between 70-80 percent of Voc, this is why the tracking efficiency is low in this case.

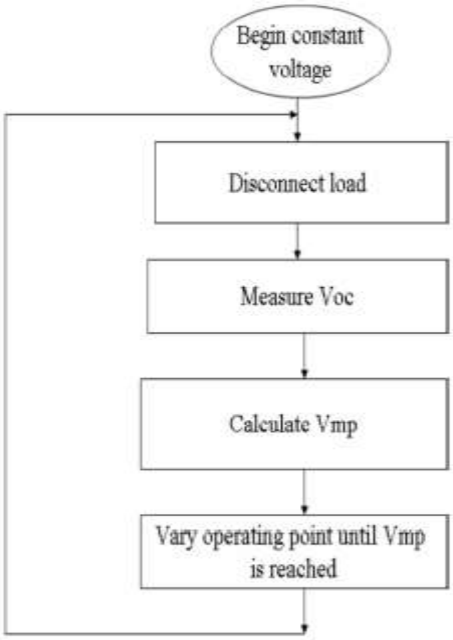


**Fig 3.2: Flowchart of constant voltage method**

### 3.4.2 Open Circuit Voltage Method

Another method which is similar to the constant voltage method but an improvement to it is the Open Circuit Voltage method which uses $V_{oc}$ to calculate $V_{mpp}$. Once the system obtains the $V_{oc}$ value, $V_{mpp}$ is calculated by,

$$V_{mpp} = k^* \, V_{oc}$$

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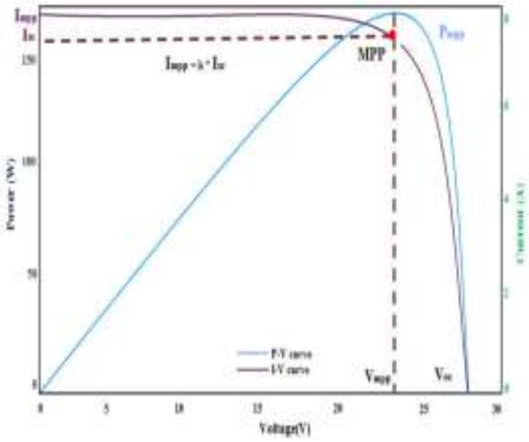


**Fig 3.3: I-V and P-V characteristics of Open circuit voltage method**

The $V_{oc}$ is the open circuit voltage of the PV Panel. The k value is typically between to 0.7 to 0.8 as it is always less than unity (commonly used as 0.76). It is necessary to update $V_{oc}$ occasionally to compensate for any temperature change. Sampling the $V_{oc}$ value can also help correct for temperature changes and to some degree changes in irradiance in Fig 3.3. Monitoring the input current can indicate when the $V_{oc}$ should be re-measured. The k value is a function of the logarithmic function of the irradiance, increasing in value as the irradiance increases.

### 3.4.3 Short Circuit Current Method

This technique is also referred to as the constant current method. The short circuit current method uses a value of Isc (Short Circuit Current) to estimate $I_{mpp}$ (Maximum power point current). The Isc is the short circuit current of the PV panel.

$$I_{mpp} = k \times I_{sc}$$

This method uses a short load pulse to generate a short circuit condition. During the short circuit pulse, the input voltage will go to zero, so the power conversion circuit must be powered from some other source. One advantage of this system is the tolerance for input capacitance compared to the Voc method in Fig3.4. The k values are typically close to 0.9 to 0.98 (always smaller than 1)

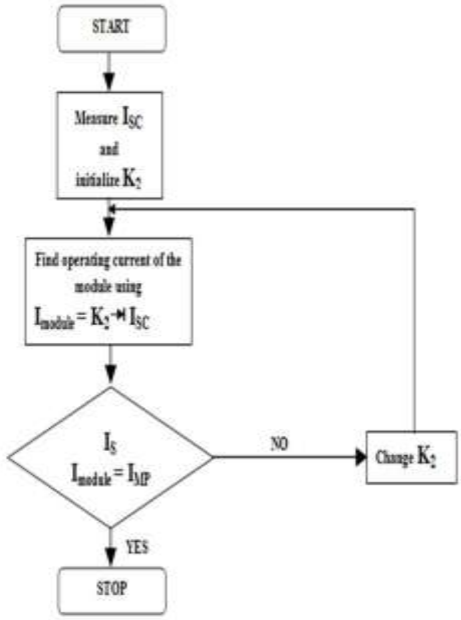


**Fig 3.4: Flowchart for Short circuit method**

### 3.4.4 Perturb and Observe Method

This method is a widely used approach to determine the MPP. In this method the controller adjusts the voltage by a small amount from the array and measures power, if the power increases, then there are further adjustments made in the direction until power no longer increases in Fig 3.5. This is called the Perturb and Observe Method. This method works by perturbing the system by increasing or decreasing the PV module operating voltage and observing its impact on the output power supplied by the module.

The voltage to a cell is increased initially, if the output power increase, the voltage is persistently increased till the point until the output power starts declining. Once the output power starts decreasing, the voltage to the cell is decreased until the point when the maximum power is reached. This process is continued until the MPPT is attained. This results in an oscillation of the output power around the MPP. The PV module's output power curve is a function of the voltage (P-V curve), at the constant irradiance and the constant module temperature; it is also assumed that the PV module is operating at a point which is away from the maximum power point. Now if the operating voltage of the PV module is perturbed by a minute amount the resulting power P is then observed. If it is seen that the P is positive, then in that case it is supposed that it has moved the operating point closer to the MPP. Hence further voltage perturbations in the same direction will continue moving the operating point toward the MPP. If the P is negative, in that case the operating

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point will be moving away from the MPP and the path of perturbation should be inverted to move back toward the MPP.

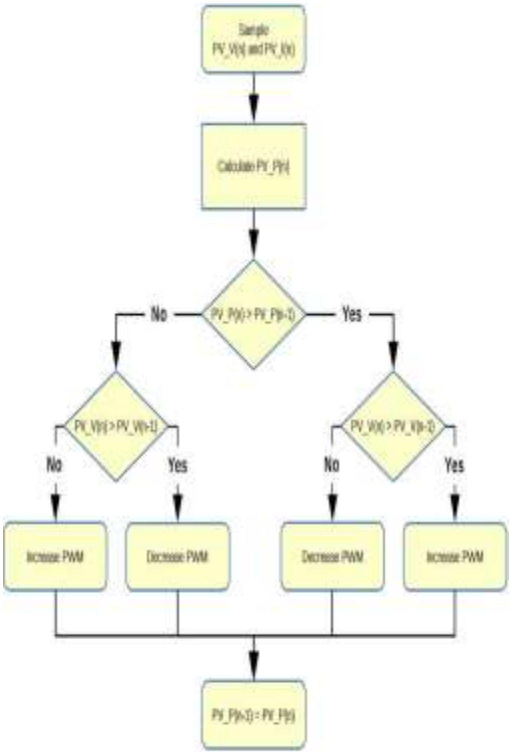


**Fig 3.5: Shows the flowchart of P&O**

### 3.4.5 Incremental Conductance Method

An observation based on a P-V characteristic curve the Incremental Conductance Method was planned. In 1993 when this algorithm was made it was intended to overcome some drawbacks of the P&O algorithm. The MPP can be calculated with the help of the relation between dI/dV and -I/V. The incremental conductance method is based on the fact that, the slope of the PV array of the power curve is zero at the MPP, positive on the left of the MPP and negative on the right on the MPP. This can be given by,

$$\frac{dP}{dV} = \frac{d(V.I)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV}$$

$$= I + V\frac{dI}{dV}$$

MPP is reached when dP/dV=0 and

$$\frac{dI}{dV} = -\frac{I}{V}$$

$$\frac{dP}{dV} > 0 \text{ then } V_p < V_{mpp}$$

$$\frac{dP}{dV} = 0 \text{ then } V_p = V_{mpp}$$

$$\frac{dP}{dV} < 0 \text{ then } V_p > V_{mpp}$$

So if the MPP lies on right side, dI/dV<-I/V and then the Photo Voltaic voltage must be reduced to reach the MPP. In order to find the MPP IC method can be used, it has been known to improve the PV efficiency, reduce power loss and also the system cost. When IC method is implemented in a microcontroller it is seen to produce a much more stable performance compared to P&O method.

The procedure starts with measuring the present values of PV module voltage and current. Then, it computes the incremental changes, dI (change in current) and dV (change in voltage), which uses the present and previous values of the voltage and current. With the help of the relationships in the equations mentioned above the main check is then done. If the condition satisfies the inequality equation shown above, it is assumed that the operating point is at the left side of the MPP thus must be moved to the right by increasing the module voltage. Similarly, if the condition satisfies the inequality equation, it is assumed that the operating point is at the right side of the MPP, thus must be moved to the left by decreasing the module voltage.

### 3.5 CONTROL SCHEMES

In Process industry generally, the processes are complex, having time delays, and may have different type of nonlinearities. Therefore, it is not always possible to control them with a classical control scheme such as a feedback control scheme. Therefore, to control such type of systems advance control schemes such as feedback plus feed-forward, cascade and cascade plus feed-forward may be required.

The most frequently implemented controller in different control schemes is the PID controller, due to its simple configuration and easy implementation (Astrom&Hagglund, 1995). A PID controller, also known as a three-term controller, has three principal control actions, i.e. the proportional action, the integral action and the derivative action.

All of these control actions are summed up together to obtain a single control effort. The proportional action provides a change in the manipulated variable relative to the error signal and is used to remove a large amount of error, the integral action provides a signal proportional to the time integral of error, and its main function is to reduce the steady-state error or offset, while the derivative action provides a signal proportional to the derivative of error and its function is to reduce maximum overshoot.

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### 3.5.1 THEORY OF CONTROLLER

A control system manages commands, directs, or regulates the behavior of other devices or systems using control loops. It can range from a single home heating controller using a thermostat controlling a domestic boiler to large Industrial control systems , which are used for controlling processes or machines. For continuously modulated control, a feedback controller is used to automatically control a process or operation. The control system compares the value or status of the process variable (PV) being controlled with the desired value or set-point (SP), and applies the difference as a control signal to bring the process variable output of the plant to the same value as the set-point. For sequential and combinational logic, software logic, such as in a programmable logic controller, is used.

## 3.6 CLASSIFICATION OF CONTROLLER

### 3.6.1 Open-loop and closed-loop control

In the case of linear feedback systems, a control loop including sensors, control algorithms, and actuators is arranged in an attempt to regulate a variable at a set-point (SP). An everyday example is the cruise control on a road vehicle; where external influences such as gradients would cause speed changes, and the driver has the ability to alter the desired set speed.

The PID algorithm in the controller restores the actual speed to the desired speed in the optimum way, without delay or overshoot, by controlling the power output of the vehicle's engine. Control systems that include some sensing of the results they are trying to achieve are making use of feedback and can adapt to varying circumstances to some extent. Open-loop control systems do not make use of feedback, and run only in pre-arranged ways.

### 3.6.2 Feedback control

In the case of linear feedback systems, a control loop including sensors, control algorithms, and actuators is arranged in an attempt to regulate a variable at a set-point (SP). An everyday example is the cruise control on a road vehicle; where external influences such as gradients would cause speed changes, and the driver has the ability to alter the desired set speed. The PID algorithm in the controller restores the actual speed to the desired speed in the optimum way Fig 3.6, without delay or overshoot, by controlling the power output of the vehicle's engine.

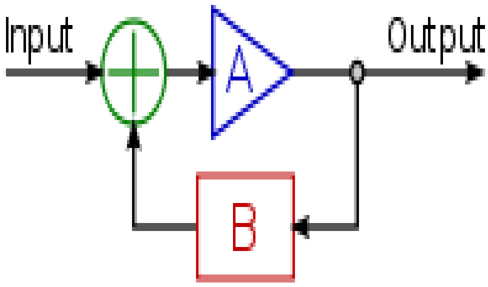


**Fig 3.6 : Basic feedback control**

Control systems that include some sensing of the results they are trying to achieve are making use of feedback and can adapt to varying circumstances to some extent. Open-loop control systems do not make use of feedback, and run only in pre-arranged ways.

### 3.6.3 Logic Control

Logic control systems for industrial and commercial machinery were historically implemented by interconnected electrical relays and cam timers using ladder diagram logic. Today, most such systems are constructed with programmable logic controllers (PLCs) or microcontrollers. The notation of ladder logic is still in use as a programming method for PLCs.

Logic controllers may respond to switches, light sensors, pressure switches, etc., and can cause the machinery to start and stop various operations. Logic systems are used to sequence mechanical operations in many applications. PLC software can be written in many different ways – ladder diagrams, SFC (sequential function charts) or statement lists.

Examples include elevators, washing machines and other systems with interrelated stop-go operations. An automatic sequential control system may trigger a series of mechanical actuators in the correct sequence to perform a task. For example, various electric and pneumatic transducers may fold and glue a cardboard box, fill it with product and then seal it in an automatic packaging machine. Programmable logic controllers are used in many cases such as this, but several alternative technologies exist.

### 3.6.4 On–off Control

A thermostat can be described as a bang-bang controller. When the temperature, PV, goes below a SP, the heater is switched on. Another

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example could be a pressure switch on an air compressor.
When the pressure, PV, drops below the threshold, SP, the pump is powered. Refrigerators and vacuum pumps contain similar mechanisms. Simple on–off control systems like these are cheap and effective.

### 3.6.5 Linear Control

Linear control systems use linear negative feedback to produce a control signal to maintain the controlled process variable (PV) at the desired set-point (SP).

### 3.6.5.1 Proportional control

Proportional control is a type of linear feedback control system in which a correction is applied to the controlled variable which is proportional to the difference between the desired value (setpoint - SP) and the measured value (Process Value - PV). Two classic mechanical examples are the toilet bowl float proportioning valve and the fly-ball governor. The proportional control system is more complex than an on-off control system like a bi-metallic domestic thermostat, but simpler than a proportional-integral-derivative (PID) control system used in something like an automobile cruise control. On-off control will work where the overall system has a relatively long response time, but can result in instability if the system being controlled has a rapid response time. Proportional control overcomes this by modulating the output to the controlling device, such as a control valve at a level which avoids instability, but applies correction as fast as practicable by applying the optimum quantity of proportional gain.

A drawback of proportional control is that it cannot eliminate the residual SP-PV error, as it requires an error to generate a proportional output. To overcome this the PI controller was devised, which uses a proportional term (P) to remove the gross error, and an integral term (I) to eliminate the residual offset error by integrating the error over time to produce an "I" component for the controller output. In some systems there are practical limits to the range of the manipulated variable (MV). For example, a heater can be off or fully on, or a valve can be closed or fully open. Adjustments to the gain simultaneously alter the range of error values over which the MV is between these limits. The width of this range, in units of the error variable and therefore of the PV, is called the proportional band (PB) which is the inverse of the proportional gain. While the gain is useful in mathematical treatments, the proportional band is often used in practical situations.

### 3.6.5.2 PID control

Apart from sluggish performance to avoid oscillations, another problem with proportional-only control is that power application is always in direct proportion to the error. In the example above we assumed that the set temperature could be maintained with 50% power. What happens if the furnace is required in a different application where a higher set temperature will require 80% power to maintain it? If the gain was finally set to a 50° PB, then 80% power will not be applied unless the furnace is 15° below set-point, so for this other application the operators will have to remember always to set the set-point temperature 15° higher than actually needed.

This 15° figure 3.7 is not completely constant either: it will depend on the surrounding ambient temperature, as well as other factors that affect heat loss from or absorption within the furnace.

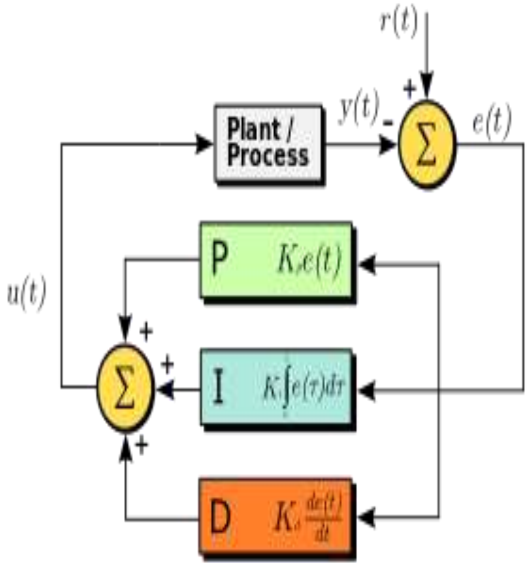


**Fig: 3.7 Block Diagram of PID Controller**

To resolve these two problems, many feedback control schemes include mathematical extensions to improve performance. The most common extensions lead to proportional-integral-derivative control, or PID control.

### 3.6.5.3 Derivative action

The derivative part is concerned with the rate-of-change of the error with time: If the measured variable approaches the set-point rapidly, then the actuator is backed off early to allow it to coast to the required level; conversely if the

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measured value begins to move rapidly away from the set-point, extra effort is applied-in proportion to that rapidity-to try to maintain it.

Derivative action makes a control system behave much more intelligently. On control systems like the tuning of the temperature of a furnace, or perhaps the motion-control of a heavy item like a gun or camera on a moving vehicle, the derivative action of a well-tuned PID controller can allow it to reach and maintain a set-point better than most skilled human operators could.

If derivative action is over-applied, it can lead to oscillations too. An example would be a PV that increased rapidly towards SP, then halted early and seemed to "shy away" from the set-point before rising towards it again.

**3.6.5.4 Integral action**

The integral term magnifies the effect of long-term steady-state errors, applying ever-increasing effort until they reduce to zero. In the example of the furnace above working at various temperatures, if the heat being applied does not bring the furnace up to setpoint, for whatever reason, integral action increasingly moves the proportional band relative to the setpoint until the PV error is reduced to zero and the setpoint is achieved.

**3.6.5.5 Ramp up % per minute**

Some controllers include the option to limit the "ramp up % per minute". This option can be very helpful in stabilizing small boilers (3 MBTUH), especially during the summer, during light loads. A utility boiler "unit may be required to change load at a rate of as much as 5% per minute (IEA Coal Online - 2, 2007)".

## IV. PERFORMANCE ANALYSIS OF SIMULATION RESULTS

The developed MATLAB Simulink model of the proposed system has PV module, the implementation of pure sine wave inverter, which can convert DC voltage to AC voltage at high efficiency and low cost. Solar-powered electricity generation is being favoured nowadays as the world increasingly focuses on environmental concerns. The designed inverter converted DC voltage into AC voltage for a small-scale off-grid solar PV system suitable for electrification in remote areas, pollution-free, and inexpensive. Its inverter uses a sinusoidal pulse width modulation technique and a simple circuit, consisting of only 2 MOSFET switches and 1 MOSFET driver. The H-bridge inverter's output is applied to a step-up transformer with a dual coil input and a single-coil output, and hence, we can create positive and negative sides of the wave.

Mitigate a voltage noise; a capacitor is parallelly installed at the secondary side of the transformer. Several simulations are performed to verify the effectiveness of the designed inverter using Proteus software, and continued hardware implementation. Based on some experiments we have done, the designed inverter produces a 30 V rms 50 Hz sine wave with very low harmonics distortion.

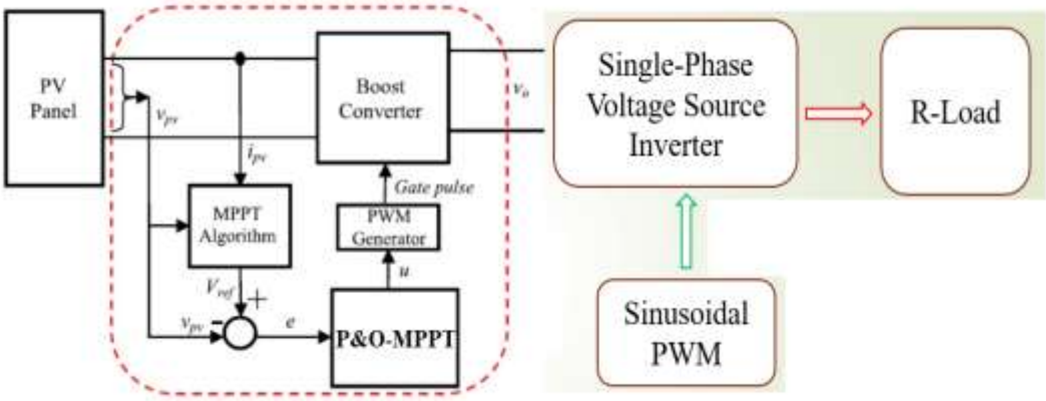


**Fig 4.1. Simulation block diagram of standalone solar PV power system**

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*Table 1. Parameter Specifications BP Solar SX3190 PV Module*

| Parameter Description | Rating |
|---|---|
| Maximum power ($P_{MP}$) | 560 W |
| Maximum current ($I_{MP}$) | 7.82945 A |
| Maximum voltage ($V_{MP}$) | 24.3003 V |
| Short circuit current ($I_{SC}$) | 8.51029 A |
| Temperature (T) | $25^0$C |
| Open circuit voltage ($V_{oc}$) | 30.6021 V |
| Parallel strings | 3 |
| Series-connected modules per string | 1 |
| Solar irradiation (G) | 1000 W/m$^2$ |

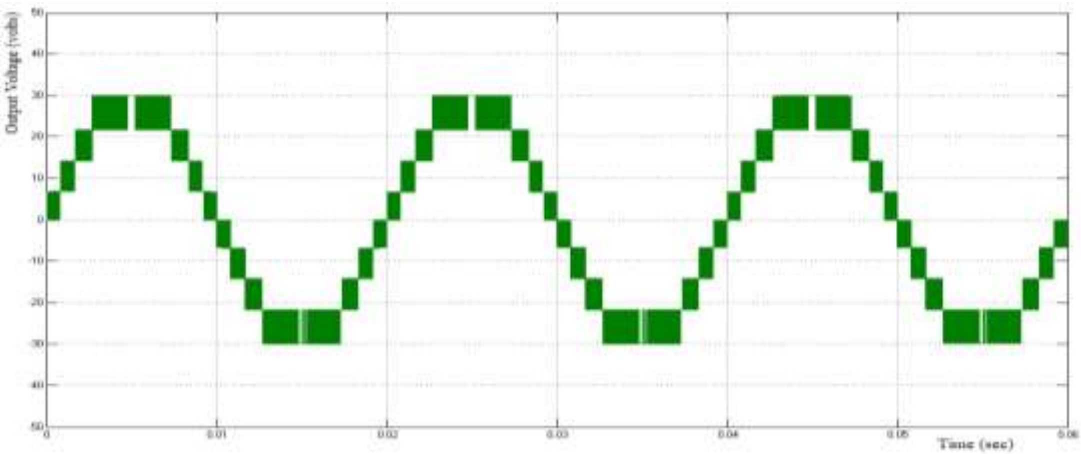


**Fig4.2. Inverter output Line to Line voltage at 500ohm**

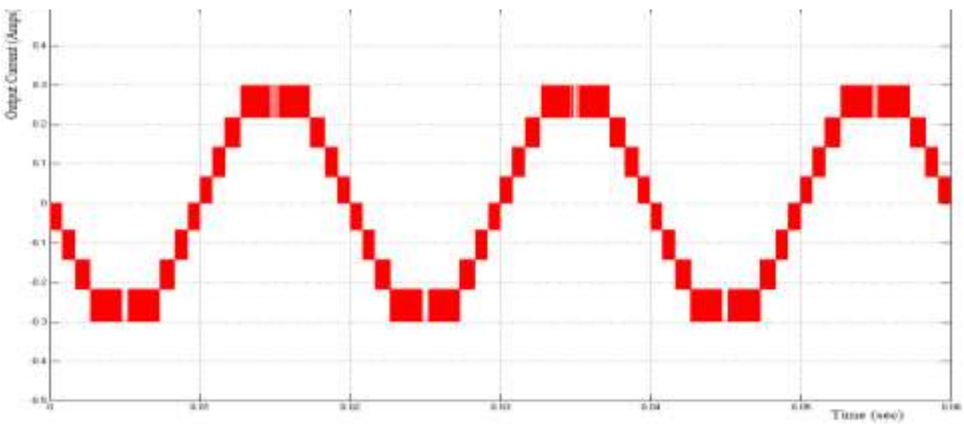


**Fig4.3. Inverter output Current at 500ohm**

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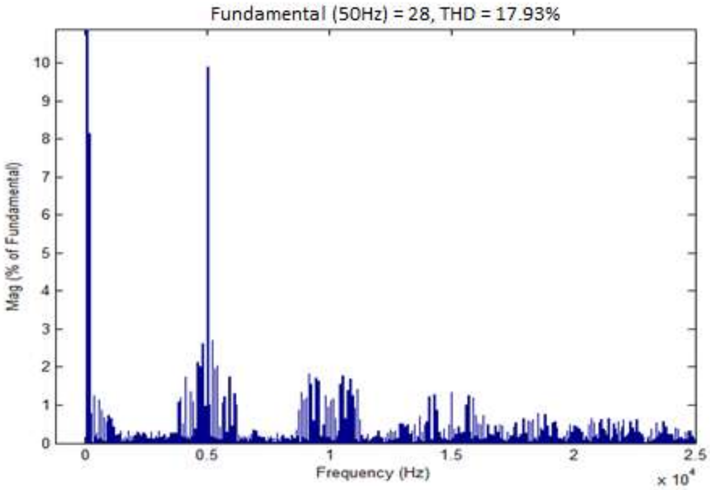


**Fig 4.4. THD - Output Voltage at 500ohm**

**Table4.1. Comparison of Fundamental Voltage Vs THD**

| **Simulation** | | |
|---|---|---|
| **R – Load (ohm)** | **Fundamental Output Voltage (Volts)** | **Total Harmonics Distortion (THD%)** |
| 250 | 29 | 19.28 |
| 500 | 28 | 17.93 |
| 750 | 27.8 | 15.49 |
| 1000 | 27 | 13.91 |
| 1500 | 26.5 | 11.98 |

## V. CONCLUSIONS AND FUTURE WORK

### 5.1 CONCLUSIONS

This thesis deals with the development of modified MPPT for maximum transfer of generated power from a solar photovoltaic panel and its performance evaluation. Different MPPT techniques and their relative merits and demerits are discussed in detail, along with DC-DC Boost converter and their influence on the optimum performance of the PV system. The performance of the existing and the proposed MPPT algorithms applied to DC-DC Boost converter based PV system are studied for various irradiation conditions both by simulation and through experimental implementation.

A modified P&O algorithm called MPTT based MPPT and SSB MPPT techniques are proposed and their performance to effectively track the MPP of solar PV panel using DC-DC Boost converter under changing environments are evaluated. Simulation results demonstrate the capability of the proposed system eliminating undesirable ripples in the converter and PV panel. The proposed algorithms are simple to implement and cost effective. The MPPT technique does not require current sensor for maximum power tracking.

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Performance analysis of the conventional DC-DC Boost converter with PV panel is carried-out. Ripple content in voltage and current, current stress on switching devices are investigated. The feasibility of the MPPT algorithm and tracking capability of both the topologies are verified under various load conditions.

**5.2 FUTURE WORK**

On the basis of investigation carried out in this thesis, the following suggestions are provided for further research:

1. In the present work, the application is restricted to DC systems only. The proposed MPPT technique has enormous scope of application in systems requiring DC to AC conversion. Therefore, the proposed MPPT techniques can also be used for the large solar PV based grid interactive system, where slight increase of power generation has a great significance. This may require two stage state space analyses of the system since grid interaction is dynamic.
2. The switching loss of an DC-DC Boost converter increases with the number of switching devices such as MOSFETs and diodes when number of channels is increased to handle large power. For such a converter, soft switching techniques can be applied.
3. This research analysis may also be extended for partial shading conditions in PV panel.
4. The proposed Maximum Power Transfer Theorem (MPTT) and Single Sensor Based (SSB) MPPT techniques may also compare with artificial intelligence techniques such as fuzzy logic and neural network based MPPT techniques used in standalone PV system.
5. This work can be taken to next level involving multi criteria and probability estimate based decision making in MPPT algorithm. This will be useful for widely spaced energy collection and storage from distributed PV system.

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