OPTIMIZATION OF STAND-ALONE PHOTOVOLTAIC SYSTEM BY IMPLEMENTING FUZZY LOGIC MPPT CONTROLLER

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ABSTRACT

A photovoltaic (PV) generator is a nonlinear device having insolation-dependent volt-ampere characteristics. Since the maximum-power point varies with solar insolation, it is difficult to achieve an optimum matching that is valid for all insolation levels. Thus, Maximum power point tracking (MPPT) plays an important roles in photovoltaic (PV) power systems because it maximize the power output from a PV system for a given set of condition, and therefore maximize their array efficiency. This project presents a maximum power point tracker (MPPT) using Fuzzy Logic theory for a PV system. The work is focused on a comparative study between most conventional controller namely Perturb and Observe (P&O) algorithm and is compared to a design fuzzy logic controller (FLC). The introduction of fuzzy controller has given very good performance on whatever the parametric variation of the system.

ABSTRAK

Penjana photovoltaic (PV) adalah sejenis peranti tidak lelurus yang mempunyai spesifikasi volt-ampere yang bergantung kepada ketumpatan sinaran matahari. Oleh kerana titik maksimum kuasa berubah-ubah mengikut kecerahan sinaran matahari, maka ia adalah sukar untuk mencapai nilai padanan maksimum yang sah untuk setiap peringkat kecerahan. Oleh itu, pengesanan titik kuasa maksimum (MPPT) memainkan peranan penting dalam system kuasa photovoltaic (PV) kerana ia dapat memaksimumkan kuasa keluaran dari sistem PV untuk satu set keadaan dan seterusnya memaksimunkan kecekapan tatasusunan PV tersebut. Projek ini mempersembahkan satu pengesan titik kuasa maksimum (MPPT) yang menggunakan teori fuzzy logic untuk sistem PV. Kerja-kerja ini memfokuskan kepada satu kajian perbandingan antara pegawal paling konnventional iaitu P&O algoritma dan dibandingkan dengan rekabentuk pengawal fuzzy logic (FLC). Pengenalan kepada pengawal fuzzy logic telah memberikan prestasi yang sangat baik dalam apa sahaja perubahan parameter system tersebut.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

In the last years global warming and energy policies have become a hot topic on the international agenda. Developed countries are trying to reduce their greenhouse gas emissions. Renewable energy sources are considered as a technological option for generating clean energy. Among them, photovoltaic (PV) system has received a great attention as it appears to be one of the most promising renewable energy sources. Photovoltaic power generation has an important role to play due to the fact that it is a green source. The only emissions associated with PV power generation are those from the production of its components.

However, the development for improving the efficiency of the PV system is still a challenging field of research. MPPT algorithms are necessary in PV applications because the MPP of a solar module varies with the irradiation and temperature, so the use ofMPPT algorithms is required in order to obtain the maximum output power from a solar array.

Therefore, the motivation of this thesis is to obtain the maximum power point (MPP) of photovoltaic (PV) system by using Fuzzy Logic Controller (FLC). Hence, this thesis focused on the well-known Perturb and Observe (P&O) algorithm and compared to a design fuzzy logic controller (FLC). A simulation work dealing with MPPT controller, a DC/DC Boost converter feeding a load is achieved. The result will show the validity of the proposed Fuzzy Logic MPPT in the PV system.

1.2 Project Background

A photovoltaic system for isolated grid-connected applications as shown in Fig. 1.0 is a typically composed of these main components:

i. PV module that converts solar energy to electric power
ii. DC-DC converter that converts produced DC voltage by the PV module to a load voltage demand.
iii. Digital controller that drives the converter operation with MPPT capability.

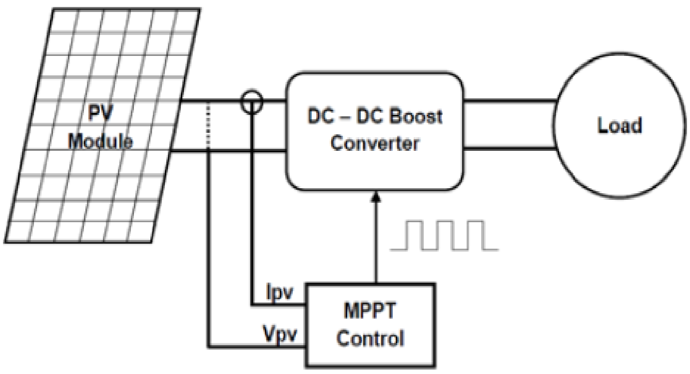

Fig. 1.0. Typical diagram of MPPT in a PV System

1.2.1 PV Equivalent Circuit

The model of solar cell can be categorized as p-n semiconductor junction; when exposed to light, the DC current is generated. As known by many researchers, the generated current depends on solar irradiance, temperature, and load current. The typical equivalent circuit of PV cell is shown in Fig. 2.0.

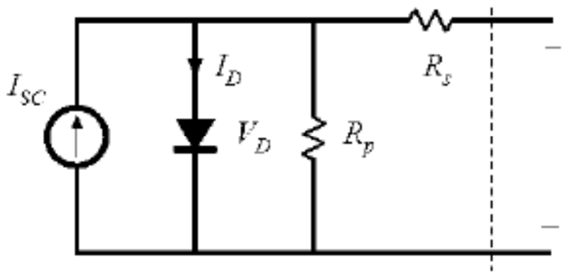

Fig. 1.1 Typical circuit of PV solar cell

The basic equations describing the I-V characteristic of the PV model are given in the following equations: [11]

$$0 = I_{SC} - I_D - \frac{V_D}{R_p} - I_{PV} \quad \text{...........(1.0)}$$

$$I_D = I_0(e^{V_D/V_T} - 1) \quad \text{...........(1.1)}$$

$$V_{PV} = V_D - R_S I_{PV} \quad \text{...........(1.2)}$$

Where:

I_{PV} is the cell current (A).

I_{SC} is the light generated current (A).

I_D is the diode saturation current (A).

R_s is the cell series resistance (ohms).

R_P is the cell shunt resistance (ohms).

V_D is the diode voltage (V).

V_T is the temperature voltage (V).

V_{PV} is the cell voltage (V).

1.2.2 PV Module Characteristic

The photovoltaic modules are made up of silicon cells. The silicon solar cells which give output voltage of around 0.7V under open circuit condition. When many such cells are connected in series we get a solar PV module. Normally in a module there are 36 cells which amount for a open circuit voltage of about 20V. The current rating of the modules depends on the area of the individual cells. Higher the cell area high is the current output of the cell. For obtaining higher power output the solar PV modules are connected in series and parallel combinations forming solar PV arrays. A typical characteristic curve of the called current (I) and voltage (V) curve and power (W) and voltage (V) curve of the module is shown is shown in Fig.1.2

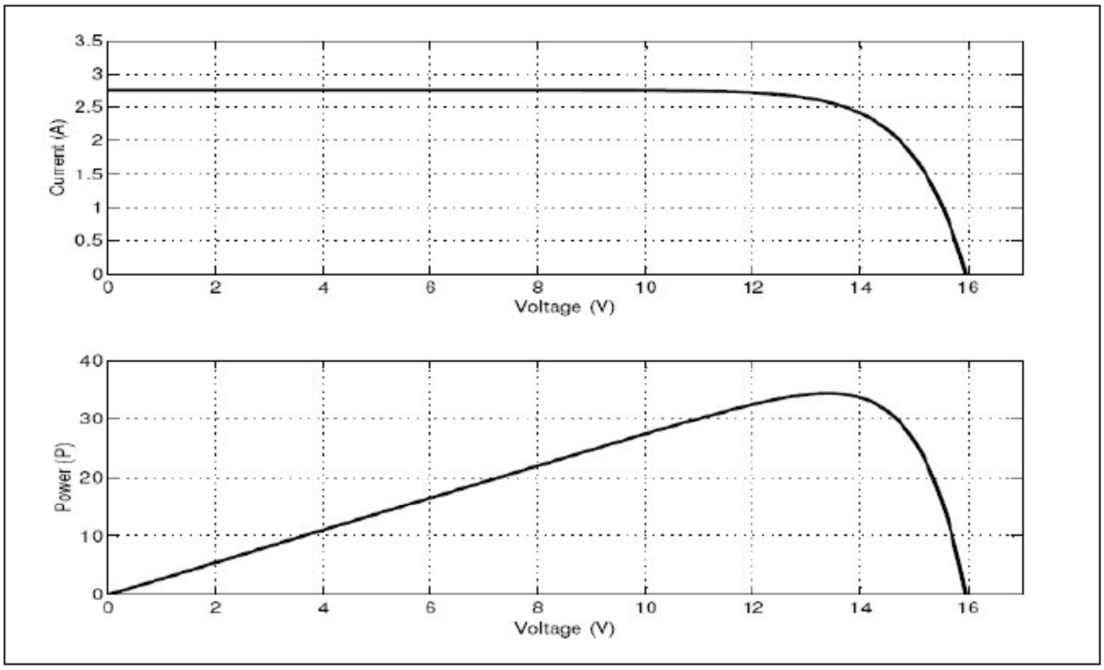

Fig.1.2 Characteristics of a typical solar PV module.

1.2.3 Need for Maximum Power Tracking

Power output of a Solar PV module changes with change in direction of sun, changes in solar insolation level and with varying temperature as shown in the Fig. 1.3&1.4.

As seen in the PV (power vs. voltage) curve of the module there is a single maximum of power. That is, there exists a peak power corresponding to a particular voltage and current. We know that the efficiency of the solar PV module is low about 13%. Since the module efficiency is low it is desirable to operate the module at the peak power point so that the maximum power can be delivered to the load under varying temperature and insolation conditions. Hence maximization of power improves the utilization of the solar PV module. A maximum power point tracker (MPPT) is used for extracting the maximum power from the solar PV module and transferring that power to the load.

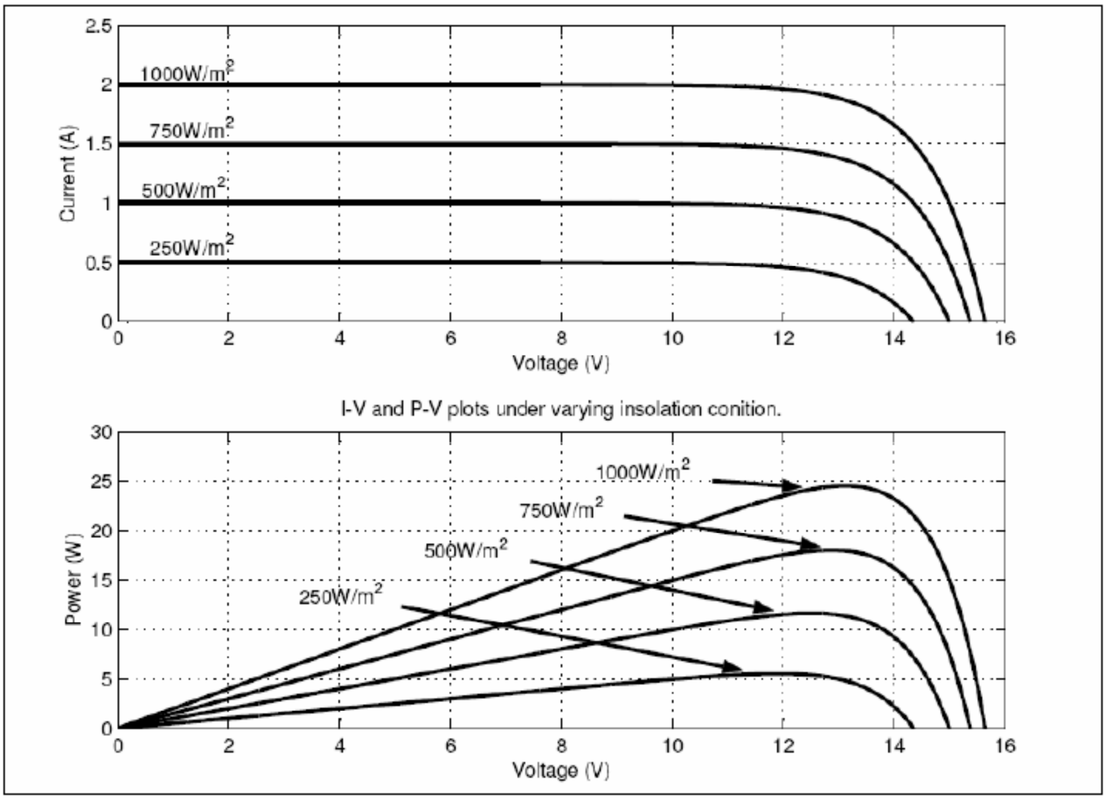

Fig.1.3 Changes in the characteristics of the solar PV module due to change in insolation level.

A dc/dc converter (step up/step down) serves the purpose of transferring maximum power from the solar PV module to the load. A dc/dc converter acts as an interface between theload and the module fig.1.5. By changing the duty cycle the load impedance as seen by the source is varied and matched at the point of the peak power with the source so as to transfer the maximum power.

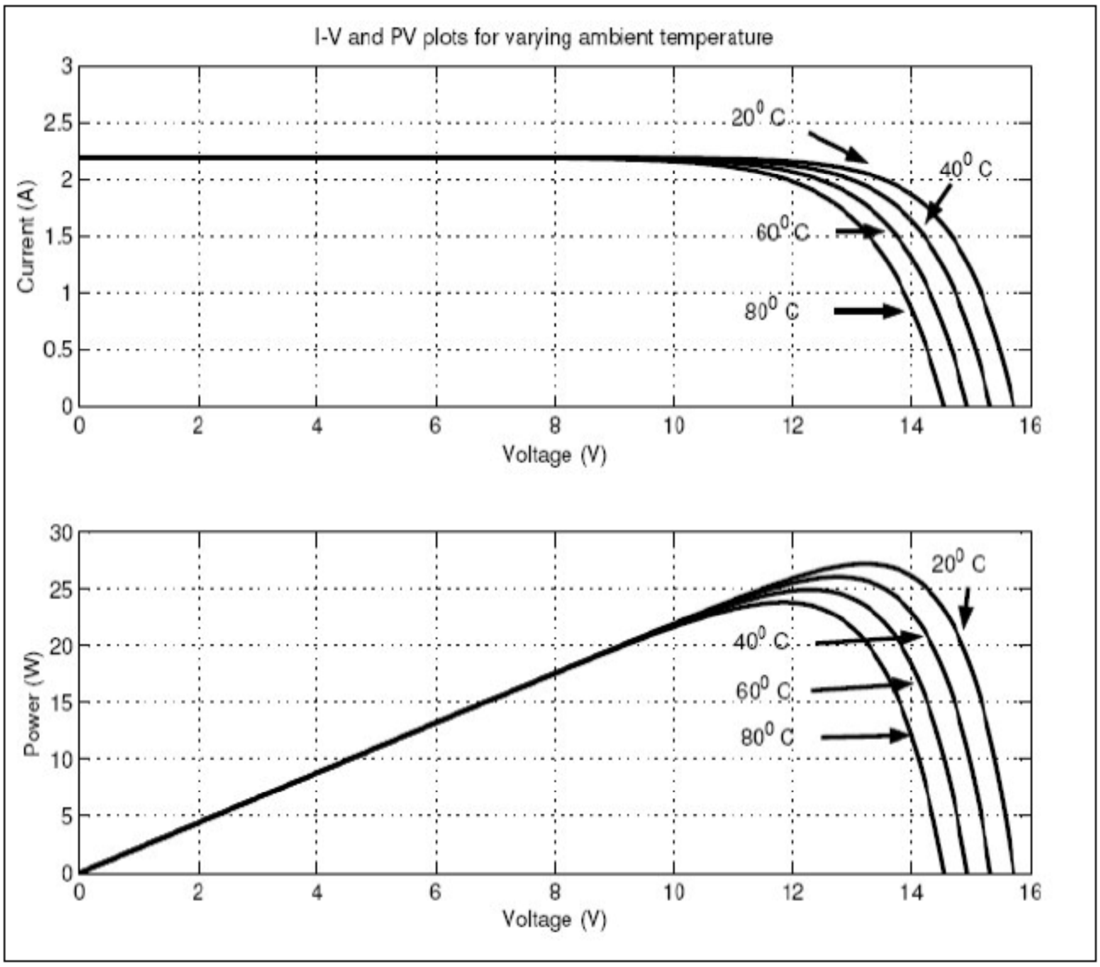

Fig.1.4 Change in the module characteristics due to the change in temperature

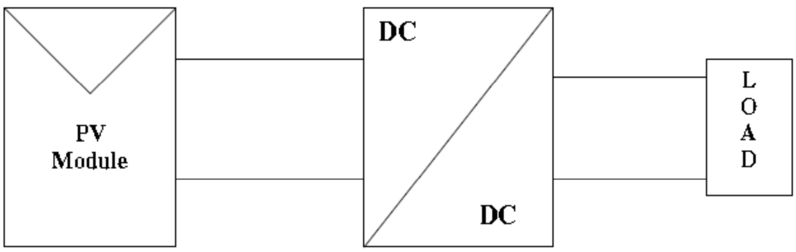

Fig.1.5 Block diagram of a typical MPPT system

1.2.4 How Maximum Power Point (MPP) is obtained.

The maximum power point is obtained by introducing a dc/dc converter in between the load and the solar PV module. The duty cycle of the converter is changed till the peak power point is obtained.

Considering a step up converter is used

$$Vo= (1/(1-D))*Vi\ldots\ldots(1.3)$$

(Vo is output voltage and Vi is input voltage)

solving for the Impedance transfer ratio

$$Ro = (1/(1-D))^2*Ri\ldots.(1.4)$$

(Ro is output impedance and Ri is input impedance as seen by the source.)

$$Ri = (1-D)^2*Ro\ldots\ldots.(1.5)$$

Thus output resistance Ro remains constant and by changing the duty cycle the input resistance Ri seen by the source changes. So the resistance corresponding to the peak power point is obtained by changing the duty cycle. As shown in the fig.1.6.

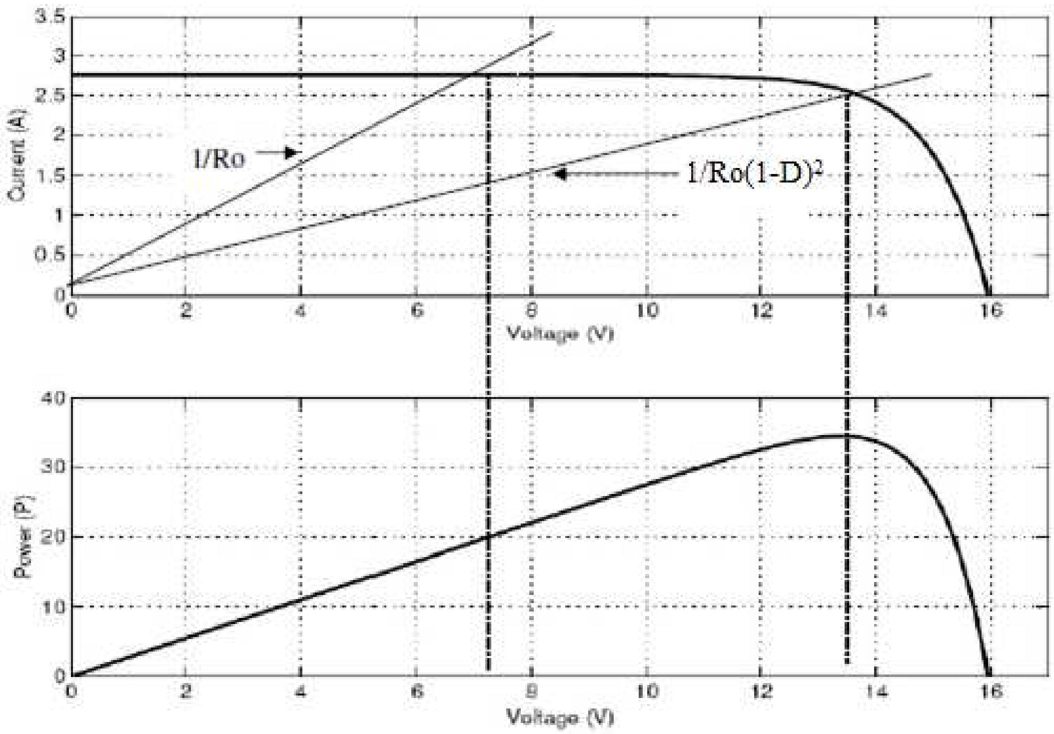

Fig.1.6 DC/DC converter helps in tracking the peak power point

1.2.5 Methods of Peak Power Tracking.

The peak power is reached with the help of a dc/dc converter by adjusting its duty cycle such that the resistance corresponding to the peak power is obtained. Now question arises how to vary the duty cycle and in which direction so that peak power is reached. Whether manual tracking or automatic tracking? Manual tracking is not possible so automatic tracking is preferred to manual tracking. An automatic tracking can be performed by utilizing various algorithms.

i. Perturb and observe [3],[4],[7].
ii. Incremental Conductance [5],[9].
iii. Parasitic Capacitance [9].
iv. Voltage Based Peak Power Tracking [9].

v. Current Based peak power Tracking [9].

vi. Computational Intelligent (e.g. fuzzy logic, neural network) [1],[2]

The algorithms are implemented in a microcontroller or a personal computer to implement maximum power tracking. The algorithm changes the duty cycle of the dc/dc converter to maximize the power output of the module and make it operate at the peak power point of the module. P&O and fuzzy logic algorithm are explained in detailed in the chapter 3.

1.3 Problem Statement

When a PV moduleis directly coupled to a load, the PV module's operating pointwill be at the intersection of its I–V curve and the load linewhich is the I–V relationship of load.

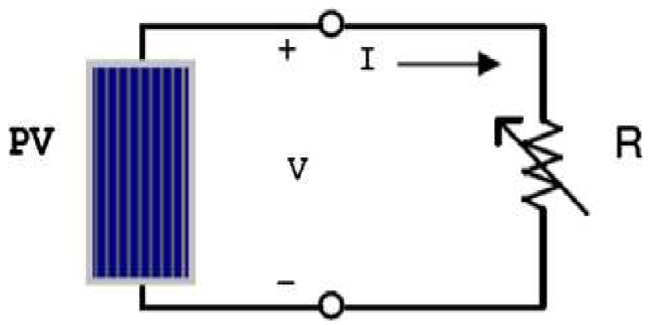

Fig. 1.7 PV module is directly connected to a (variable) resistive load.

In Fig. 1.7, a resistive load has a straight line with a slope of $1/R_{load}$ as shown in Fig. 1.8. In other words, the impedance of load dictates the operating condition of the PV module. In general, this operating point is seldom at the PV module's MPP, thus it is not producing the maximum power.

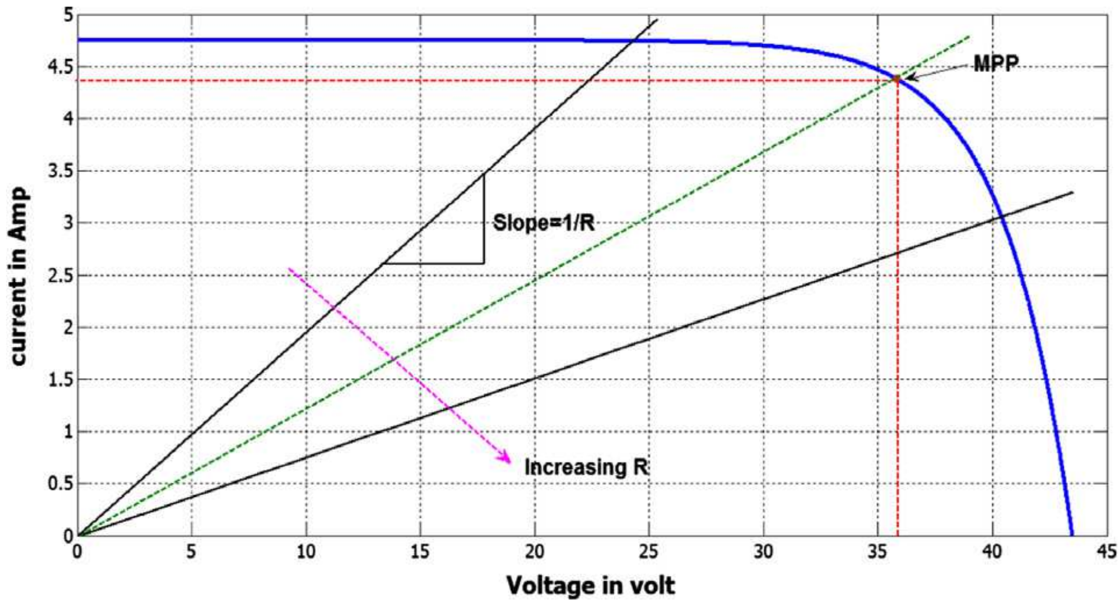

Fig. 1.8 I-V curve of PV module and various resistive loads

To mitigate this problem, a maximum power point tracker(MPPT) can be used to maintain the PV module's operatingpoint at the MPP. MPPTs can extract more than 97% of thePV power when properly optimized [51].

1.4 Project Objectives

The objectives of this project are:-

i. To track the maximum power point (MPP) of PV module by using Fuzzy Logic MPPT controller.
ii. To simulate and analyses the performance of Fuzzy Logic MPPT controller with other conventional controller.

1.5 Project Scopes

The scopes of this project are:-

i. To develop a SIMULINK model of PV module that converts solar energy to electric one.
ii. To develop a SIMULINK model of DC-DC boost converter that converts produced DC voltage by the PV module to a load voltage demand.
iii. To develop a SIMULINK model of Fuzzy Logic Controller (FLC) that drives the converter operation with MPPT capability.

CHAPTER 2

LITERATURE REVIEW

The following literature survey for the current report consists of various papers publishedin the IEEE conferences and the journals.

[1]. Control of DC/DC Converters for Solar Energy System with Maximum PowerTracking. [4].

ChihchiangHua and ChihmingShen.

The object of this paper is to analyze and design DC/DC converters of different types in asolar energy system to investigate the performance of the converters. A simple methodwhich combines a discrete time control and a PI compensator is used to track theMaximum power points (MPP's) of the solar array. The system is kept to operate close tothe MPPT's, thus the maximum possible power transfer from the solar array is achieved.The implementation of the proposed converter system was based on a digital signalprocessor (DSP). Experimental tests were carried out for buck, boost and buck-boostconverters using a simple maximum power point tracking (MPPT) algorithm. Theefficiencies for the system with different converters are compared. The paper is use full in evaluating the response of step up, step down converter for the MPPT system.

Paper proposes that the Step up converter is the best option for the use in the MPPT systemas it gives higher efficiency.

[2]. Maximum photovoltaic power tracking: an algorithm for rapidly changingatmospheric conditions.[5]

K.H. Hussein, I. Muta, I. Hoshino &, M. Osakada.

The authors have developed a new MPPT algorithm based on the fact that theMPOP (maximum peak operating point) of a PV generator can be tracked accurately bycomparing the incremental and instantaneous conductance of the PV array. The workwas carried out by both simulation and experiment, with results showing that thedeveloped incremental conductance (IntCond) algorithm has successfully tracked theMPOP, even in cases of rapidly changing atmospheric conditions, and has higherefficiency than ordinary algorithms in terms of total PV energy transferred to the load

[3]. Microcomputer Control of a Residential Photovoltaic Power ConditioningSystem. [5].

B.K. Bose, P.M. Szczesny and R.L. Steigerwald,

The authors discuss a control system of a residential photovoltaic system. The paper explains perturb and observe (P&O) algorithm and how can it be implemented using amicroprocessor. This paper is one of the basic papers which explain the Perturb andobserve algorithm. Also controller design using PI scheme is obtained.

[4]. An Improved Perturbation and Observe Maximum Power Point TrackingAlgorithm for PV Arrays. [8].

Xuejun Liu and A.C.Lopes,

The corresponding authors have proposed a new kind of maximum power point trackingalgorithm based on perturb and observe algorithm. The algorithm is fast acting andeliminates the need of a large capacitor which is normally used in perturb and observealgorithm to eliminate the ripple in the module voltage. The module voltage and currentthat are taken for processing are not averaged but are instantaneous this speed ups theprocess of peak power tracking. Also the paper implements the new algorithm on the real-time platform. The software used was dSPACE^{R}.

5]. Comparative Study of Maximum Power Point Tracking Algorithms Using anExperimental, Programmable, Maximum Power Point Tracking Test Bed. [9]

D. P. Hohm, M. E. Ropp.

The authors have compares all the different kinds of algorithm that are used for themaximum power point tracking. This helps in proper selection of the algorithm.Preliminary results indicate that perturb and observe compares favorably withincremental conductance and constant voltage. Although incremental conductance is ableto provide marginally better performance in case of rapidly varying atmospheric conditions, the increased complexity of the algorithm will require more expensivehardware, and therefore may have an advantage over perturb and observe only in largePV arrays.

[6]. Theoretical and Experimental Analyses of Photovoltaic Systems With VoltageandCurrent-Based Maximum Power-Point Tracking. [10]

Mohammad A. S. Masoum, HoomanDehbonei, and Ewald F. Fuchs.

Detailed theoretical and experimental analyses of two simple, fast and reliable maximumpower-point tracking (MPPT) techniques for photovoltaic (PV) systems are presented.Voltage-based (VMPPT) and the Current-based (CMPPT) approaches. Amicroprocessor-controlled tracker capable of online voltage and current measurementsand programmed with VMPPT and CMPPT algorithms is constructed. The load of thesolar system is either a water pump or resistance. The paper has given a simulink model of the DC/DC converter and a solar PV module.

[7]. Maximum Power Point Tracking using FuzzyLogic Control for Photovoltaic Systems. [11]

PongsakorTakun, SomyotKaitwanidvilai and ChaiyanJettanasen.

In this paper, a fuzzy logic control (FLC) is proposed to control the maximum power point tracking(MPPT) for a photovoltaic (PV) system. The proposed technique uses the fuzzy logic control to specify the size of incremental current in the current command of MPPT. As results indicated, the convergence time of maximum powerpoint (MPP) of the proposed algorithm is better than that of the conventional Perturb and Observation (P&O) technique.

[8]. Advanced Fuzzy MPPT Control Algorithm for Photovoltaic Systems. [12]

MayssaFarhatandLassaadSbita.

This paper presents an intelligent approach for the improvement and optimization of the PV control performances. A PV system topology incorporating maximum power point tracking controller (MPPT) is studied. In order to perform this goal a special interest was focused on the well known P&O algorithm and compared to a designed fuzzy logic controller (FLC). This paper presents a detailed study of the MPPT controller to insure a high PV system performance which can be selected for practical implementation issue. A simulation work dealing with MPPT controller, a DC/DC Boost converter feeding a load is achieved. Significant extracted results are given to prove the validity of the proposed overall PV system control scheme. The result show that the FLC has better performance and closed to the P&O ideal and FLC has better response time, less oscillation and much more accurate tracking.

The literature review consists of vast survey of papers from the various conferences. Theliteratures give sufficient idea about the basics of the MPPT algorithm and how the MPPtracking is takes place. Details of various algorithms that are used for the MPPTtechnique are discussed in the paper [9]. Also dc/dc converter design and various controlaspects for the dc/dc converter are discussed. Which type of dc/dc converter can givemaximum efficiency and which is the best choice for a given algorithm is discussed in the paper [4]. As discussed in [12] a dc/dc step up (boost) converter with Fuzzy Logic MPPT control algorithm gives higher efficiency than P&O algorithm. This algorithm is selected for the present work andis implemented in using a real timeinterface through microcontroller circuits.

CHAPTER 3

METHODOLOGY

3.1 Modeling PV Devices

The PV panel model is based on the recombination mechanism of p-n junctions. The I-V characteristic of the PV modules is extremely nonlinear and varies significantly with temperature and solar irradiation. These disturbances affect the normal operation of the PV panels and may lead to a tracking of incorrect maximum power point which gives the necessity for the development of an accurate mathematical model. The equivalent circuit of a PV cell is shown is shown in Fig.3.0.

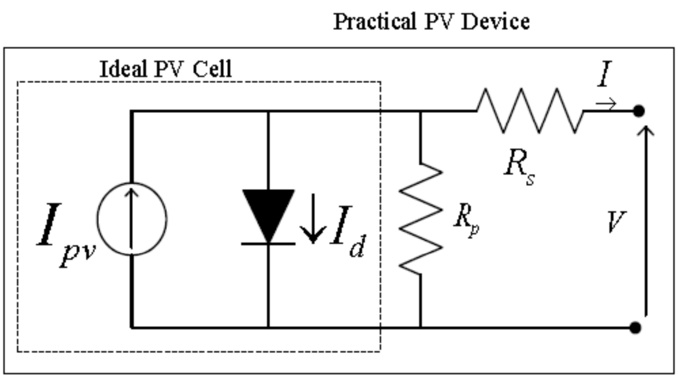

Fig.3.0The equivalent circuit of the Practical photovoltaic cell.

Fig. 3.0 shows the equivalent circuit of the ideal PV cell. The basic equation from the theory of semiconductors that mathematically describes the *I–V* characteristic of the ideal PV cell is

$$I = I_{pv,cell} - \underbrace{I_{0,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right]}_{I_d} \quad \ldots\ldots\ldots\ldots\ldots(3.0)$$

where I_{pv},cell is the current generated by the incident light (it is directly proportional to the Sun irradiation), I_d is the Shockley diode equation, I_0,cell is the reverse saturation or leakage current of the diode, q is the electron charge (1.60217646 × 10−19 C), k is the Boltzmann constant (1.3806503 × 10−23 J/K), T (in Kelvin) is the temperature of the *p*–*n* junction, and a is the diode ideality constant. Fig. 3.1 shows the *I–V* curve originated from (3.0).

Fig. 3.1. Characteristic *I–V* curve of the PV cell. The net cell current I is composed of the light-generated current I_{pv} and the diode current I_d .

The basic equation (3.0) of the elementary PV cell does not represent the *I–V* characteristic of a practical PV array. Practical arrays are composed of several connected

PV cells and the observation of the characteristics at the terminals of the PV array requires the inclusion of additional parameters to the basic equation

$$I = I_{\mathrm{pv}} - I_0 \left[\exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] - \frac{V + R_s I}{R_{\mathrm{p}}} \quad \text{..............(3.1)}$$

Where I_{pv} and I_0 are the photovoltaic (PV) and saturation currents, respectively, of the array and $V_t = NskT/q$ 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 PV and saturation currents may be expressed as $I_{pv} = I_{pv,cell}N_p$, $I_0 = I_{0,cell}N_p$. In (3.1), R_s is the equivalent series resistance of the array and R_p is the equivalent parallel resistance. This equation originates the *I–V* curve in Fig. 3.2, where three *remarkable points* are highlighted: short circuit (0, I_{sc}), MPP (V_{mp}, I_{mp}), and open circuit (V_{oc}, 0).

Equation (3.1) describes the single-diode model presented in Fig. 3.0. Some authors have proposed more sophisticated models that present better accuracy and serve for different purposes. For example, in [14]–[18] an extra diode is used to represent the effect of the recombination of carriers. A three-diode model is proposed in [19] to include the influence of effects that are not considered by the previous models.

For simplicity, the single diode model of Fig. 3.0 is proposed in this research. This model offers a good compromise between simplicity and accuracy [20], 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 [21]–[34].

Manufacturers of PV 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 PV array models cannot be found in the manufacturer's datasheets, such as the light-generated or PV current, the series and shunt resistances, the diode ideality constant, the diode reverse saturation current, and the band-gap energy of the semiconductor. All PV 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 MPP (V_{mp}), the current at the MPP (I_{mp}), the open-circuit voltage/temperature coefficient (K_V), the shortcircuit 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 condition or standard test conditions (STCs) 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 PV arrays.

Electric generators are generally classified as current or voltage sources. The practical PV device presents hybrid behavior, which may be of current or voltage source depending on the operating point, as shown in Fig. 3.2. The practical PV 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. Fig. 3.3 shows the structure of a PV cell. R_s basically depends on the contact resistance of the metal base with the *p* semiconductor layer, the resistances of the *p* and *n* bodies, the contact resistance of the *n* layer with the top metal grid, and the resistance of the grid. The R_p resistance exists mainly due to the leakage current of the *p*–*n* junction and depends on the fabrication method of the PV cell. The value of R_p is generally high and some authors [23]–[26], [29], [35]–[38] neglect this resistance to simplify the model. The value of *R*s is very low, and sometimes this parameter is neglected too [36], [39]–[41].

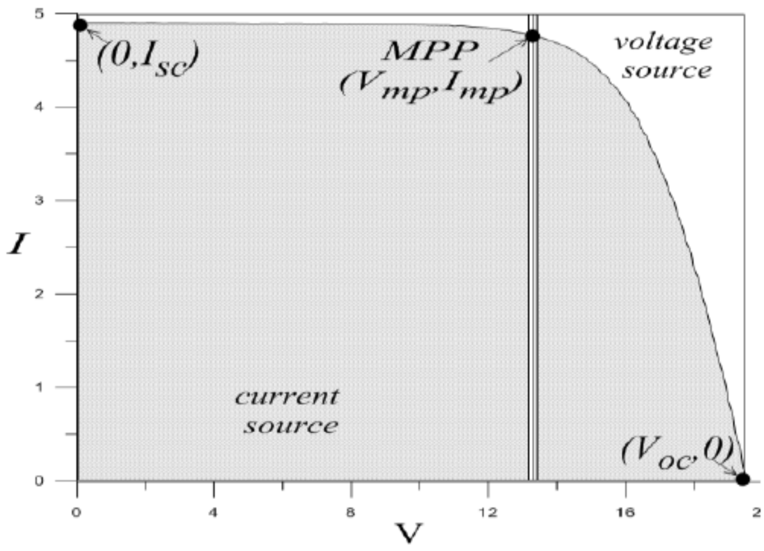

Fig. 3.2. Characteristic *I–V* curve of a practical PV device and the three *remarkable points*: short circuit (0, *I*sc), MPP (*V*mp, *I*mp), and open circuit (*V*oc ,0).

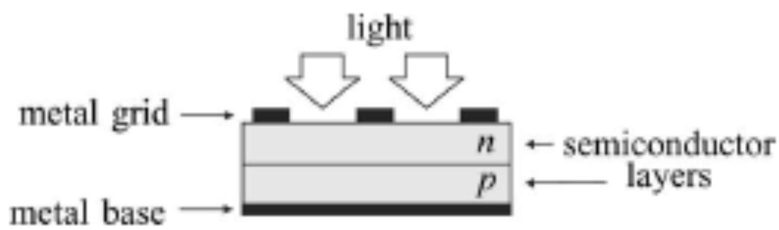

Fig. 3.3. Physical structure of a PV cell.

The *I–V* characteristic of the PV device shown in Fig. 3.2 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 inform 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 the modeling of PV devices because in practical devices the series resistance is low and the parallel resistance is high. The light-generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation [30], [42]–[44]:

$$I_{pv} = (I_{pv,n} + K_I \Delta_T) \frac{G}{G_n} \tag{3.2}$$

Where $I_{pv,n}$ (in amperes) is the light-generated current at the nominal condition (usually 25 ◦C and 1000 W/m2), $\Delta T = T - T_n$ (T and T_n being the actual and nominal temperatures [in Kelvin], respectively), G (watts per square meters) 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 as shown [42], [43], [45]–[48]:

$$I_0 = I_{0,n} \left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \tag{3.3}$$

whereE_g is the band-gap energy of the semiconductor (Eg = 1.12 eV for the polycrystalline Si at 25 ◦C [23], [42]), and $I_{0,n}$ is the nominal saturation current:

$$I_{0,n} = \frac{I_{sc,n}}{\exp(V_{oc,n}/aV_{t,n}) - 1} \tag{3.4}$$

With $V_{t,n}$ being the thermal voltage of N_s series-connected cells at the nominal temperature T_n .

The value of the diode constant *a* may be arbitrarily chosen. Many authors discuss ways to estimate the correct value of this constant [20], [23]. 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 [42] based on empirical analyses. As is given in [20], there are different opinions about the best way to choose *a*. Because *an*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* curve and varying *a* can slightly improves the model accuracy.

Modeling accurate Photovoltaic Arrays has been discussed in many papers. For the purposes of this research we will be using the method describer in [13]. This modeling algorithm includes only *Rs* and *Rp*, is assumed a very large value and it takes into consideration the effect of an array of solar modules and a panel of solar arrays. The PV datasheets always provide the following information:

i. Standard Operating Conditions: 25o C and 1000W/m2
ii. *Isc* at standard operating conditions.
iii. *Voc*at standard operating conditions.
iv. *Impp*: *I* at the maximum power point at standard operating conditions.
v. *Vmpp*: at the maximum power point at standard operating conditions.
vi. Kv: the open-circuit voltage/temperature coefficient.
vii. *Ki*: the shot-circuit current/temperature coefficient.
viii. *Pmaxe*: the maximum experimental peak output power at standard test conditions

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