Development and Implementation of Control Algorithms For a Photovoltaic System

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***Abstract*—Photovoltaic (PV) system is one of the energy generation systems and produces direct current. The PV output is depending on solar irradiation and temperature. The arrangement of PV cells in series or in parallel, known as PV array. Maximum Power Point Tracking (MPPT) techniques like Incremental Conductance (Inc Cond) with fixed step size is used to extract maximum power from a PV system. Inc Cond control algorithm is compared with a MPPT PI controller. DC DC Boost converter steps up and regulates the PV output voltage to get a usable form of DC voltage. PV cell single diode model with a series and parallel resistances and a DC DC boost converter are developed and implemented, MPPT control algorithms are developed, compared and simulated in MATLAB/SIMULINK. Results are presented and discussed.**

***Index Terms*— DC DC boost converter, Incremental conductance, Maximum power point tracking, Photovoltaic, PI controller.**

I. INTRODUCTION

Solar power has exceptional potential as a renewable energy generation source due to the abundance of solar energy and the resulting emission free generation. The PV power generation is based on the principle of the photovoltaic effect[1]. With the advent of silicon p-n junctions, the photoelectric current is able to produce power due to inherent voltage drop across the junction. However, such power generation is well-known for the nonlinear relationship between the current and voltage of the photovoltaic cell. It is observed that, there is a unique point at which the photovoltaic cell produces maximum power. At this point, the rate of change of power with respect to the voltage is equal to zero. The advancements in the area of power electronics have made photovoltaic technology much more efficient and cost-effective.

Set of PV cells connected in series or in parallel known as PV array. PV cells are connected in a series fashion to obtain large output voltages, and connected in a parallel fashion to obtain large output currents. There are several issues in power management to improve the conversion efficiency of a PV array, maximizing PV power output[2]. PV array has to be operated at MPP in order to extract maximum power output. The maximum power of the PV array changes with climatic conditions, that means the output power of PV is always changing with weather conditions like solar irradiation and atmospheric temperature. The PV output current changes with solar irradiation levels, whereas the PV output voltage changes with temperature of the PV array. Thus, an important challenge in a PV system is to ensure the maximum energy generation from the PV array with a dynamic variation of its output characteristic when connected to a variable load[3]. A solution for this problem is the insertion of a power converter between the PV array and load, which could dynamically change the impedance of the circuit by using a control algorithm.

DC DC Converters are required to regulate the output voltage at a required level and to get a usable form of DC voltage[4]. Converters are classified mainly as buck, boost, buckboost and Cuk converters. The DC DC boost converter is a power electronic circuit, also called as a step up converter. It has a capability of providing an output voltage is higher than the input voltage.

A large number of techniques have been proposed for tracking of Maximum Power Point (MPP). Hill climbing, Perturb and Observe (P&O), Fuzzy logic methods are widely used as an MPPT controller because of their simplicity and easy implementation[5], [6]. The incremental Conductance algorithm is more complicated to develop the control algorithm compared with any other MPPT techniques[7]. In General Inc Cond algorithm with fixed step size is popular to track the MPP.

In this paper, a single diode model of a PV cell is implemented. DC DC boost converter is used to step up and regulate the PV output. MPPT control techniques used to track MPP, and results of Inc Cond MPPT and PI MPPT are provided and compared.

II. SINGLE DIODE MODEL OF A PV CELL

PV is one of the methods of renewable energy generations, which means generating electrical power by converting solar irradiation into direct current. Now, PV is one of the popular renewable energy generation sources due to the availability of solar energy and resulting emanation of free generation. The basic diagram of a PV cell is shown in Fig. 1.

When the solar irradiation falls on photovoltaic material, it will convert as a direct current. The current source is connected in parallel to a diode, and the current through the diode D is I_d and the diode is connected in a reverse direction to regulate the voltage of PV cell[8], [9].

Two resistors are connected, one is in series and the other one is in parallel to the current source. Generally R_{sh} is very high and R_s is almost equal to zero, then maximum current will flow to the output side[10], [11]. A series resistor R_s, which determines the downward slope of the I-V curve of the PV cell near V_{oc}. This value represents the internal resistance of the cell. A shunt resistor R_{sh}, which determines the slope of the line at the top of the I-V curve near I_{sc}[8]. This value controls the leakage current from the cell to ground, and is usually small enough to be neglected. The diode current equation is expressed as[2]

$$I_d = I_0[e^{qV_d/nkT} - 1] \quad (1)$$

Where, q = charge of the electron $(1.6X10^{-19}Col)$, V_d = Diode voltage, k = Boltzman's constant, $(1.3X10^{-23}J/K)$, T=Absolute temperature, n=Ideality factor, I_0=Saturation current.

Apply K.C.L. in PV cell, then the equation expressed as [1] when R_{sh} is not considered

$$I_{ph} - I_d = I_L \quad (2)$$

Substitute (1) in (2)

$$I_{ph} - I_0[e^{qV_d/nkT} - 1] = I_L \quad (3)$$

After mathematical calculations of (3), which can be expressed as

$$V_L = \frac{nkT}{q}\ln\left(\frac{I_{ph} - I_L}{I_0} + 1\right) - I_L R_S \quad (4)$$

The open circuit voltage V_{oc} can be expressed from (4) as

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_{ph}}{I_0} + 1\right) \quad (5)$$

The PV cell mathematical expression (when considering R_{sh}) is

$$V_L = \frac{nkT}{q}\left[\ln\left(\frac{I_{ph} - I_L}{I_0} + 1\right) - \frac{V_L + I_L R_S}{R_{sh}}\right] - I_L R_S \quad (6)$$

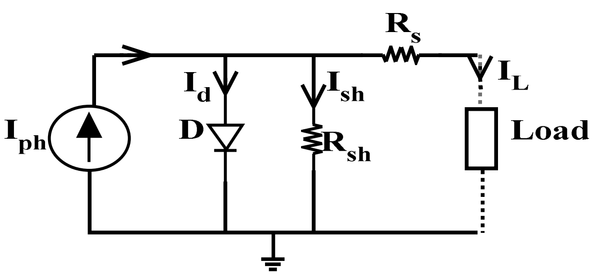

Fig. 1. Circuit of a PV cell single diode model

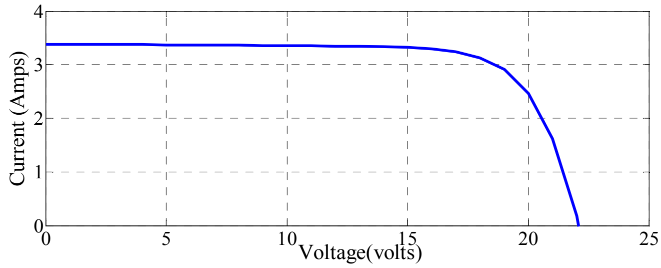

Fig. 2. I-V characteristic curve

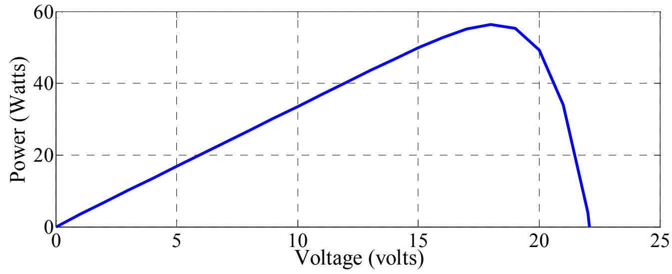

Fig. 3. P-V characteristic curve

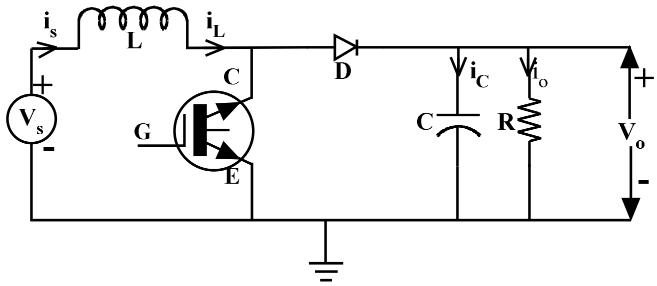

Fig. 4. Circuit of a Boost converter

After mathematical modeling of a PV cell, simulated in MATLAB/SIMULINK and obtained I-V and P-V characteristic curves at 25^o C temperature, irradiation at 1000. The waveforms shown in Fig. 2 and Fig. 3

III. DC DC BOOST CONVERTER

The DC DC boost converter is a power electronic device, also called as a step up converter, and it has a capability of providing an output voltage is higher than the input voltage[4]. The circuit diagram of a boost converter is shown in Fig. 4.

In boost converter an inductor is connected in series with supply V_s. A transistor is connected across the inductor and supply. A filter capacitor is connected across the load to make the output as smooth. The diode D blocks the reverse flow of current when the switch is turned ON. The equivalent circuit diagram of boost converter, when the transistor ON, is shown in Fig. 5.

When the transistor is turned ON, the current flows from the supply to the inductor L. At this condition the diode D is reverse biased and it does not conduct. Hence the inductor stores the current and the inductor current rises, and the capacitor C maintains the voltage V_o and supplies current i_o.

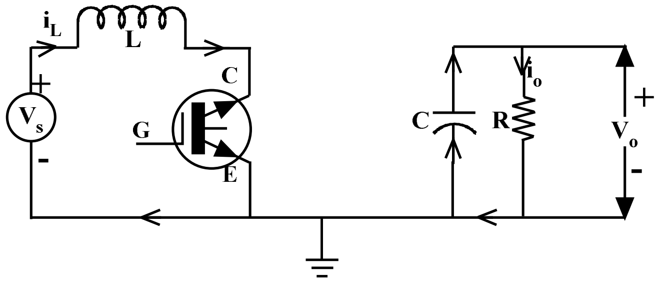

Fig. 5. Equivalent circuit when the transistor is ON

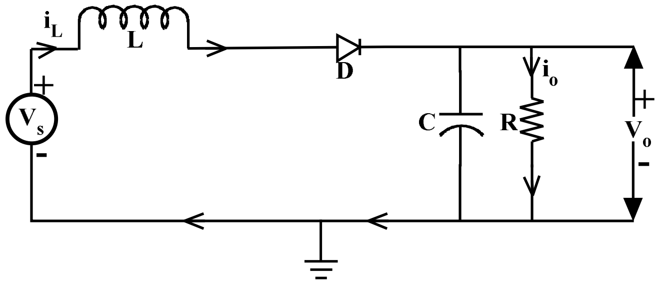

Fig. 6. Equivalent circuit when the transistor is OFF

The mathematical model of a boost converter when the transistor is ON can be simply expressed in state space as

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_0}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{CR} \end{bmatrix} \begin{bmatrix} I_L \\ V_0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_S \quad (7)$$

$$V_0 = \begin{bmatrix} 0 & -\frac{1}{CR} \end{bmatrix} \begin{bmatrix} I_L \\ V_0 \end{bmatrix} \quad (8)$$

When the transistor is turned OFF, the inductor generates a large voltage to maintain the current i_L in the same direction and now the diode D is forward biased and it starts conducting. The equivalent circuit diagram of boost converter when transistor OFF, is shown in Fig. 6.
Hence the output voltage can be expressed as

$$V_o = V_s + L\frac{di_L}{dt} \quad (9)$$

Thus the output voltage of the converter is higher than the supply voltage V_s, also called as step-up operation. The voltage induced in the inductor adds to the supply voltage and this total voltage appears as output voltage, at that situation the capacitor C also charges to the boosted voltage. The inductor and supply provides the energy to the load when the transistor is turned OFF. The current through the inductor decreases because its stored energy goes on reducing. After some time the transistor is again turned ON and the cycle repeats. The mathematical model of a boost converter when the transistor is OFF can be simply expressed in state space as

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_0}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{CR} \end{bmatrix} \begin{bmatrix} I_L \\ V_0 \end{bmatrix} + \begin{bmatrix} I_L \\ 0 \end{bmatrix} [V_S] \quad (10)$$

$$V_0 = \begin{bmatrix} \frac{1}{C} & -\frac{1}{CR} \end{bmatrix} \begin{bmatrix} I_L \\ V_0 \end{bmatrix} \quad (11)$$

IV. CONTROL TECHBNIQUES AND SIMULATION RESULTS

A. PI MPPT Controller

A proportional-integral (PI) controller is a generic control loop feedback mechanism, widely used in industrial control systems. A PI controller is the most commonly used feedback controller (closed loop), and it calculates an "error" value as the difference between a measured process variable and a desired set point or reference point[4].

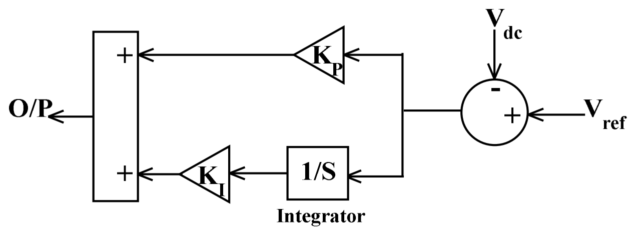

Fig. 7. PI controller

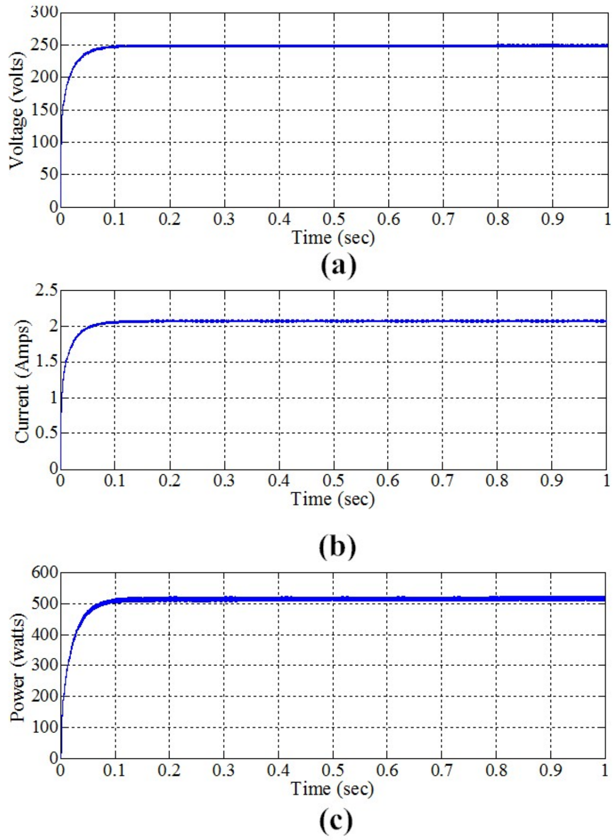

Fig. 8. PV array outputs with PI MPPT. (a) Voltage (b) Current and (c) Power

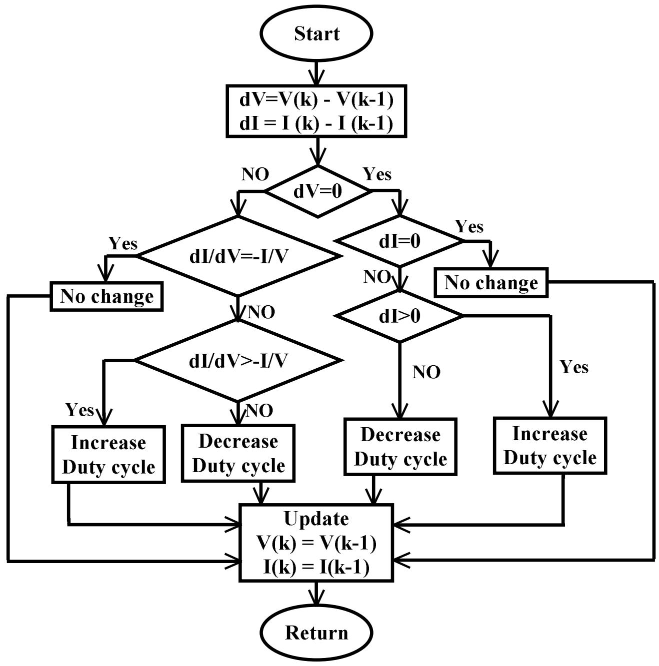

Fig. 9. Flowchart model of Inc Cond MPPT algorithm

The controller attempts to minimize the error by adjusting the process control inputs. A PI controller is used to track MPP because of simple operation past success record, ease of design and use, low cost and maintenance. MATLAB/SIMULINK PI controller model is shown in Fig. 7.

The PI controller calculation (algorithm) involves two separate constant parameters, the proportional, and the integral values denoted as K_P and K_I. These values can be interpreted in terms of time heuristically.P depends on the present error, I depends on the accumulation of past errors based on on current rate of change. The weighted sum of these two actions is used to adjust the process via a control element.

The PI controller output is given to a comparator to compare with the pulse width modulation (PWM) signal. The comparator output is fed to gate terminal of transistor in the converter. Implementation of the PI controller in MATLAB/ SIMULINK, is shown in Fig. 7. Heuristic values of K_P and K_I are 0.9 and 203 respectively to get undistorted output.

The reference voltage given to the PI MPPT controller is 250V, and outputs are collected at the load. The output voltage exactly reached to 250V, current 2.1A and power is 521W. The output waveforms of voltage,current and power are shown in Fig. 8. (a) , (b) and (c)respectively.

B. Inc Cond MPPT Controller

Inc Cond MPPT controller algorithm with a fixed step size tracks MPP accurately and tracking speed is high, when compared to the other MPPT techniques. The controller is connected in a open loop[7]. MPP tracker is achieved by connecting a DC DC converter in between the PV array and load. The controller measures the incremental changes in PV array current and voltage to predict the effect of voltage change. This method utilizes incremental conductance (dI/dV) of a PV array to compute the sign of change in power with respect to voltage (dP/dV). Inc Cond MPPT control algorithm is shown in Fig. 9.

The Inc Cond controller compares incremental conductance (ΔI/ΔV) to array conductance (I/V), and the difference of these two is zero then that voltage is MPP voltage, corresponding current is MPP current. Inc Cond controller maintains the MPP voltage until the irradiation changes and the process is repeated. MPP is located at the knee of the I-V curve, where the resistance is equal to the negative of differential resistance[7].

$$\frac{V}{I} = -\frac{V}{I} \tag{12}$$

The slope of the PV curve at MPP is equal to zero.

$$\frac{dP}{dV} = 0 \tag{13}$$

Mathematical calculations based on (13), finally

$$I + V\frac{dI}{dV} = 0 \tag{14}$$

Based on (12) and (13) if any small error occurs then (14) becomes

$$I + V\frac{dI}{dV} = e \tag{15}$$

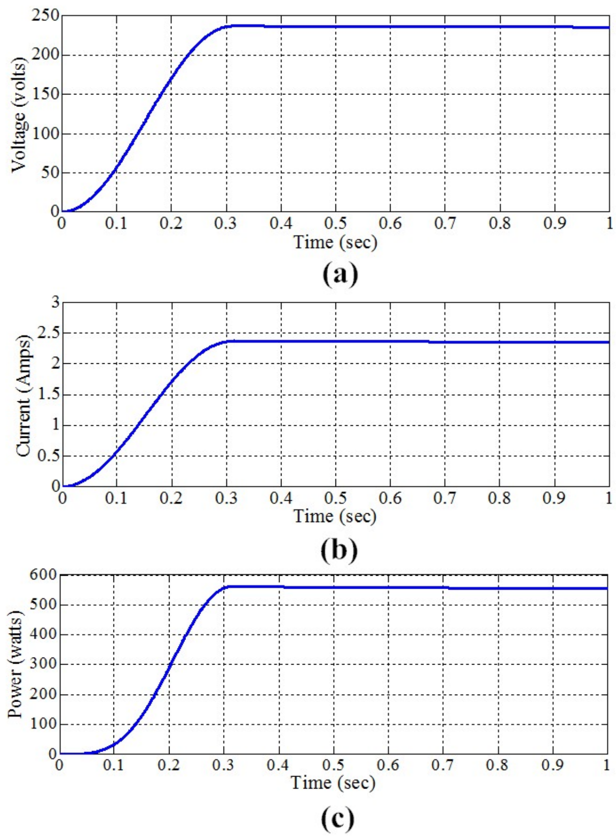

Fig. 10. PV array outputs with Inc Cond MPPT. (a) Voltage (b) Current and (c) Power

TABLE I
ELECTRICAL PARAMETERS OF PV ARRAY

Maximum power (P_{max})	56w
Voltage at MPP (V_{MPP})	18v
Current at MPP (I_{MPP})	3.13A
Open circuit voltage (V_{oc})	21.9v
Short circuit current (I_{SC})	3.46A

TABLE II
COMPARISON OF MPPT TECHNIQUES

	PI MPPT	Inc Cond MPPT
Output voltage	250v	235v
Output current	2.1A	2.4A
Output power	521w	563w

The error chosen on the basis of trial and error method and the error is 0.0024. According to the MPPT algorithm in the flowchart, duty cycle is calculated. Setting a new duty cycle in the system is repeated according to the sampling time. The output waveforms of voltage, current and power are shown in Fig. 10. (a) , (b) and (c)respectively.

The electrical parameters are tabulated in Table I, readings are taken from the resultant curves shown in Fig. 2 and Fig. 3. The MPPT techniques are compared in Table II. The parameter values of PI MPPT are collected from resultant curves shown in Fig. 8 (a), (b) and (c). And the parameter values of Inc Cond MPPT are taken from resultant curves shown in Fig. 10 (a), (b) and (c) respectively.

V. CONCLUSION

A PV cell is analyzed and developed with a series resistance and shunt resistance to extract the parameters like open circuit voltage, short circuit current, etc. PV cells are connected in series to accumulate voltage. The output of PV array is connected to a DC DC boost converter for voltage regulation. A PI MPPT controller and an Inc Cond MPPT controller techniques are used to get the useful form of output. Final results of both MPPT techniques are compared. The PI MPPT technique has taken less time to get steady state, and more power tracked with Inc Cond MPPT technique.

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