Middle-East Journal of Scientific Research 25 (2): 408-416, 2017
ISSN 1990-9233

DOI: 10.5829/idosi.mejsr.2017.408.416

Analysis and Implementation of MPPT Technique and Battery Voltage Regulation System for a Standalone Solar PV System

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Abstract: This paper presents an analysis of MPPT based Solar PV system harvesting maximum power from solar energy under dynamically varying atmospheric conditions and also includes the analysis of battery voltage control algorithm to control the charging and discharging characteristics of battery for superior performance of battery used in the standalone system for constant availability of power supply. The solar PV system includes Perturb and Observe MPPT method to extract maximum power from the PV array under varying atmospheric condition and a battery which is used as a backup source for solar energy. In this paper, MPPT method is implemented for solar PV system using Cuk Dc-Dc power converter for improved conversion efficiency. Cuk converter is chosen to provide better output voltage with reduced ripples and increased efficiency. It mainly includes the analysis of MPPT based solar charge controller regulating the voltage from the solar PV system to the battery. The simulation is done using MATLAB Simulink and also experimentally verified.

Key words: Insolation · High voltage disconnect · Low voltage disconnect · Low voltage reconnect · Maximum Power Point Tracking (MPPT) · Charge controller · Solar PV system

INTRODUCTION

Non-Conventional energy sources which are inexhaustible and pollution-free have gained its importance due to raising energy demand and depletion of fossil fuels [1]. Among which solar energy can supply about 20, 000 times the energy requirement of mankind on the earth if harnessed and replaces the demand for conventional energy sources. The operating efficiency of solar PV cell depends upon the varying atmospheric conditions mainly insolation and temperature. Thus, the efficiency of solar PV cell is improved by employing a concept known as Maximum Power Point Tracking (MPPT). The main objective of MPPT is to improve the output power of PV cell by tracking the maximum operating point under varying atmospheric conditions. There are several methods for tracking maximum power point (MPP) from solar PV cell depending upon their complexity, cost, implementation, accuracy and speed of convergence such as constant voltage method, incremental conductance (IC), perturb & observe (P&O), artificial intelligence methods such as Fuzzy logic and neural network.

In In constant voltage method, the pragmatic values maintaining the PV terminal voltage are around 70 to 80 % of its open circuit voltage. The main drawback of this method is PV terminal voltage varies frequently with change in temperature [2]. In Incremental Conductance method, the MPP is reached when the slope of PV power is zero with respect to PV terminal voltage. The drawback of this method is it causes digital resolution error in implementation [2]. There are some artificial intelligence method such as Fuzzy logic and neural network which requires more knowledge on data computation and data storage. And, it also requires high cost processor for its successful implementation [3, 10-11]. Though evolutionary algorithm such as particle swarm optimization technique provides more accuracy in tracking the MPP but it is highly dependent on technical knowledge of the designer to compute the tracking error [4, 14]. The above mentioned drawbacks can be overcome by Perturb & Observe method, it is simple to implement and involves less complexity. It mainly operates based upon the perturbation in its operating voltage by adjusting the duty ratio [5]. The integral part of MPPT is the DC-DC power converter which has to be chosen

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optimally. Among all the power converter topologies, Cuk converter is chosen because of its continuous input and output current characteristics, reduced ripples and increased voltage gain with high conversion efficiency [4]. In order to supply power to load continuously even under poor insolation conditions, battery is used as a backup source for solar photovoltaic system [6]. Depending upon the charging and discharging characteristics of battery, the life time of solar batteries varies. The frequent charging and discharging of solar battery results in shorter life time. It is also necessary to control the over-charging and deep-discharging of battery to increase its life time[10]. Hence, in order to increase the operational characteristics of battery for increased lifetime, voltage control algorithm is developed. This paper mainly includes Perturb & Observe MPPT method to continuously monitor the varying atmospheric condition and correspondingly generates the duty ratio for the Cuk converter for obtaining maximum power from solar PV system and to store the energy in battery and supplying the stored energy to load for efficient operation of solar PV system. The performance of battery is also improved by controlling charging and discharging characteristics of battery for enhancing the life time of battery.

In this paper, section II describes about Solar PV cell and its characteristics, section III explains briefly the operation of perturb & observe MPPT method, section IV includes the ephemeral description of Cuk converter, section V describes the operation of battery and battery voltage controller, section VI includes the simulation analysis of the standalone solar PV system including MPPT and Battery Voltage regulation in Matlab/Simulink environment and section VII includes the experimental analysis.

Solar PV Cell and its Characteristics: The simplified equivalent circuit diagram of solar PV cell is shown in Fig.1. It consists of current source generator connected in parallel with the non-linear junction diode and a shunt resistance. When light falls on the PV cell, it generates a current (I), generally known as short circuit current (I_{sc}) which is equal to the sum of light generated current (I_L), diode current (I_D) and the shunt current (I_{sh}) [7].

$$I = I_L - I_D - I_{sh} \tag{1}$$

And the diode current I_D is given by,

$$I_D = I_o\left(e^{\frac{qv}{kT}} - 1\right) \tag{2}$$

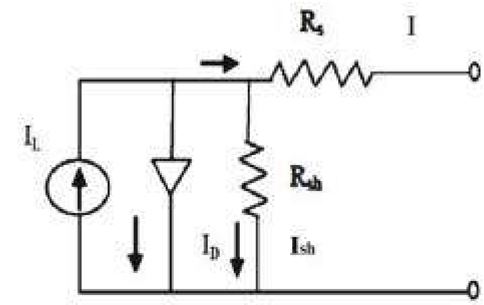

Fig. 1: Simplified Equivalent Circuit Diagram of Solar PV cell

The PV cell characteristics determines the amount of open circuit voltage (V_{oc}) and short circuit current (I_{sc}). The maximum amount of power which can be generated from solar PV cell is determined by the largest rectangle which can be fit with in the VI characteristics of the cell as shown in Fig. 2.

$$P_{mpp} = V_{mpp} * I_{mpp} \tag{3}$$

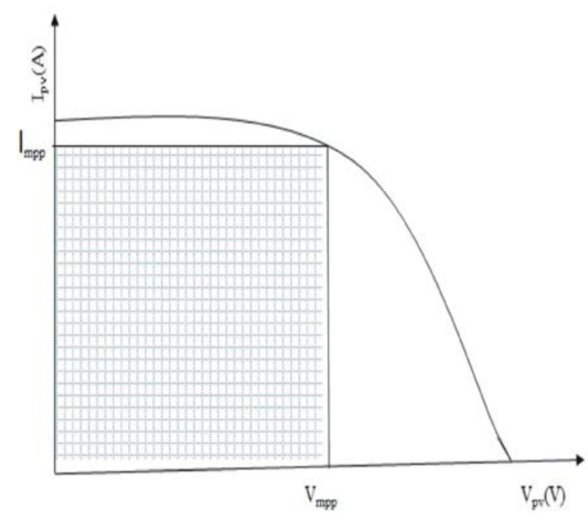

Fig. 2: V-I characteristics of Solar PV cell

Perturb & Observe MPPT Method: The conversion efficiency of solar PV cell is low under varying atmospheric conditions. Hence, in order to improve the efficiency of a solar PV cell, the maximum power point tracking (MPPT) method is employed to extract the maximum power from PV cell by matching the load impedance (R_o) with the PV panel impedance (R_{in}) [6]. The basic block diagram of the solar PV system with

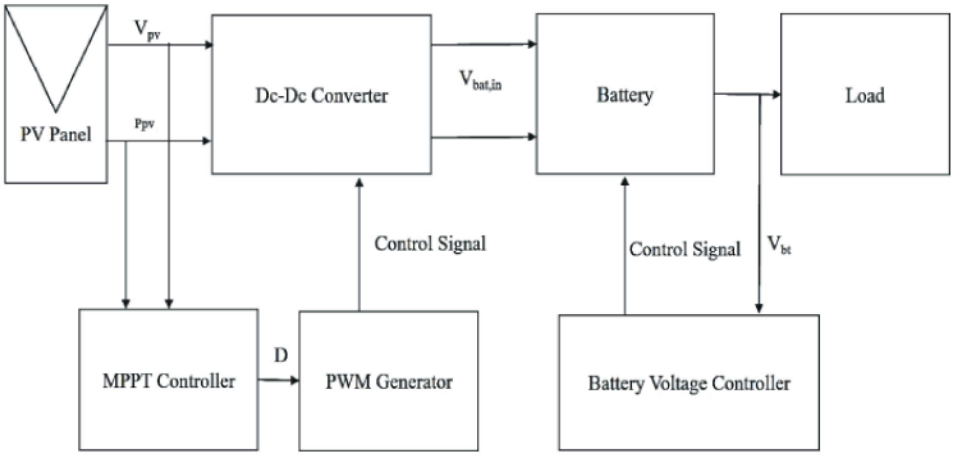

Fig. 3: Block diagram of solar PV system with MPPT and battery voltage controller

MPPT and battery voltage controller is shown in Fig. 3. The MPPT system consists of DC-DC Converter and a controller to generate the control signal to adjust the duty cycle (D) of the converter based upon the solar PV output voltage (V_{pv}) /current (I_{pv}) and PV output power (P_{pv}). In this paper, Cuk DC-DC converter is used, where the load impedance of Cuk converter is to be matched with the PV panel impedance. The Load impedance of Cuk Converter is obtained from the following equations (4) to (7).

$$R_o = \frac{V_o}{I_o} \tag{4}$$

The output voltage (V_o) and current (I_o) of Cuk Converter is given by,

$$V_o = V_{pv}\left(\frac{-D}{1-D}\right) \tag{5}$$

$$I_o = I_s\left(\frac{-(1-D)}{D}\right) \tag{6}$$

From (4),

$$R_o = \left(\frac{D}{1-D}\right)^2 R_{in} \tag{7}$$

P&O MPPT method operates based upon the perturbation of PV array output power with respect to the perturbation in PV array output voltage and continuously observes the variation of PV array operating point for the varying atmospheric conditions [9]. According to this method, at MPP the derivative of PV power with respect to PV voltage is zero and its operation is explained using the flowchart as shown in Fig. 4.

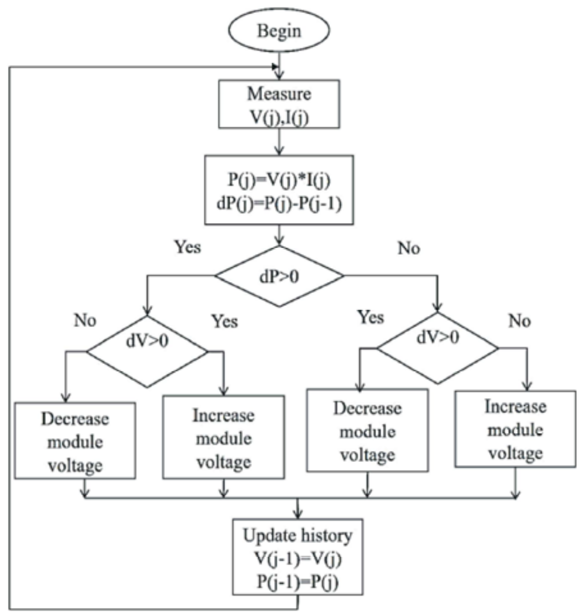

Fig. 4: Flowchart of P&O MPPT Method

This method is simple to implement with reduced complexity [8]. It mainly operates based upon the following conditions as given in (8) to (10).

$$\frac{dP}{dV} > 0 \text{, Left of MPP } (V_{pv} < V_{mpp}) \tag{8}$$

$$\frac{dP}{dV} = 0 \text{, At MPP } (V_{pv} = V_{mpp}) \tag{9}$$

$$\frac{dP}{dV} < 0 \text{, Right of MPP } (V_{pv} > V_{mpp}) \tag{10}$$

The above condition is defined using Fig. 5; at MPP the PV voltage (V_{pv}) generated is the maximum voltage (V_{mpp}) which could be obtained from solar PV panel, when V_{pv} becomes less than the V_{mpp}, the local MPP is obtained in the left side of the actual MPP and similarly, when V_{pv} becomes greater than the V_{mpp}, the local MPP is obtained in the right side of the actual MPP and the P&O algorithm is developed to always maintain V_{pv} equal to V_{mpp}.

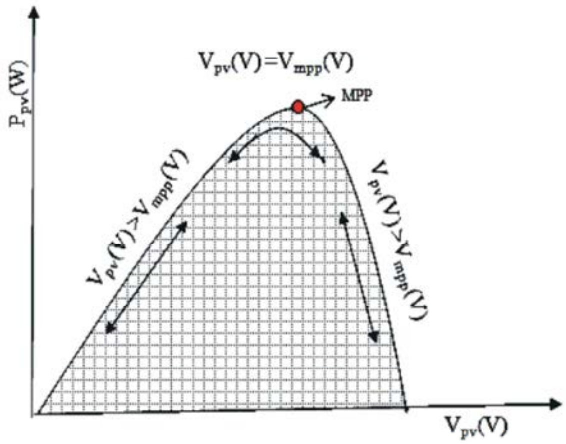

Fig. 5: PV Characteristics curve tracking MPP

CUK Converter: Cuk converter provides the output voltage magnitude less than or greater than the given input voltage. The functional schematic diagram of Cuk converter is shown in Fig.6. When the switch Q1 is on, the current I1 develops the magnetic field across the inductor in the input side and the diode D1 is reversed biased, the energy is dissipated from the storage elements towards the output element. Similarly, when the switch Q1 is off, the inductor L1 maintains the current flowing through it and the energy is dissipated through C1 towards the output element.

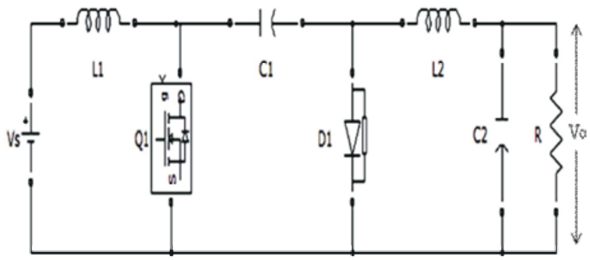

Fig. 6: Functional Schematic Diagram of Cuk Converter

Based upon the principle of energy conversion [13], the voltage gain of Cuk Converter is given by equation (11).

$$\left(\frac{Vo}{Vg}\right) = -\left(\frac{D}{1-D}\right) \quad (11)$$

The output voltage can be controlled by controlling the duty ratio, D as shown in equation (12).

$$\begin{aligned} D &< 0.5, [Vo < Vg] \\ D &= 0.5, [Vo = Vg] \\ D &> 0.5, [Vo > Vg] \end{aligned} \quad (12)$$

Battery Charge Controller: Battery serves as a storage medium for solar PV system and also helps in maintaining the power balance of the demand system. The life time of battery is less than the life time of solar PV cell. Hence in order to improve the efficiency of battery, design of battery is chosen to be optimum [10]. The operational characteristics of battery employed in solar PV system mainly depends upon the type of battery, design of battery, depth of discharge and number of days of autonomy. The life time of battery is improved for ensured performance by controlling the over-charging and deep discharging of batteries using a charge controller. In this paper, Lead acid battery is employed because of its low self-discharge rate. The operation of battery charge controller is explained in flowchart shown in Fig. 7.

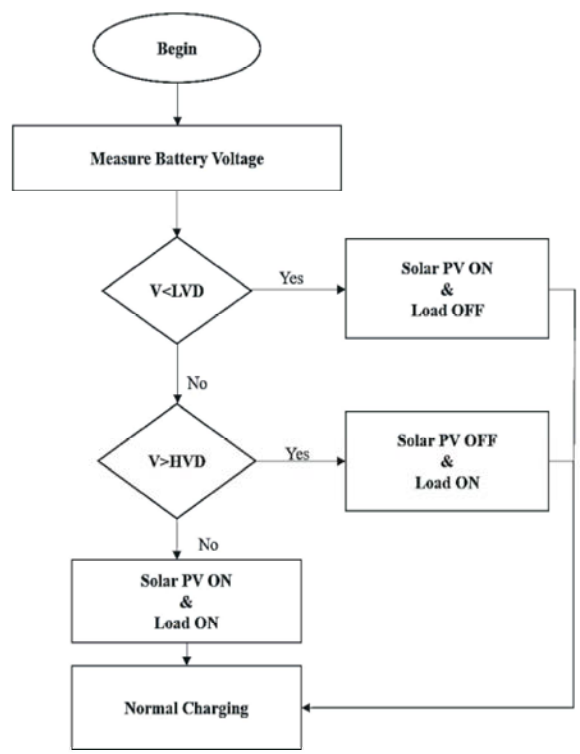

Fig. 7: Flowchart of Battery Charge Controller

It basically operates based upon three operating points such as Low voltage Disconnect (LVD), High Voltage Disconnect (HVD) and Low Voltage Reconnect (LVR) Point as shown in Table 1.

Table 1: Battery Control Points in terms of Voltage

Control Set Points	Voltage Set Pionts
HVD	11.8V
LVD	<10V
LVR	10V

Simulation Results: The simulation analysis of the standalone solar PV system is executed using MATLAB Simulink is shown in Fig. 8. It includes electrical circuit of solar PV module, Cuk converter, battery and control algorithm, provided the converter specifications are chosen from Table 2. The output voltage and current of PV module is directly fed as input to the converter and controller. The load is supplied only when the battery is completely charged to its nominal value.

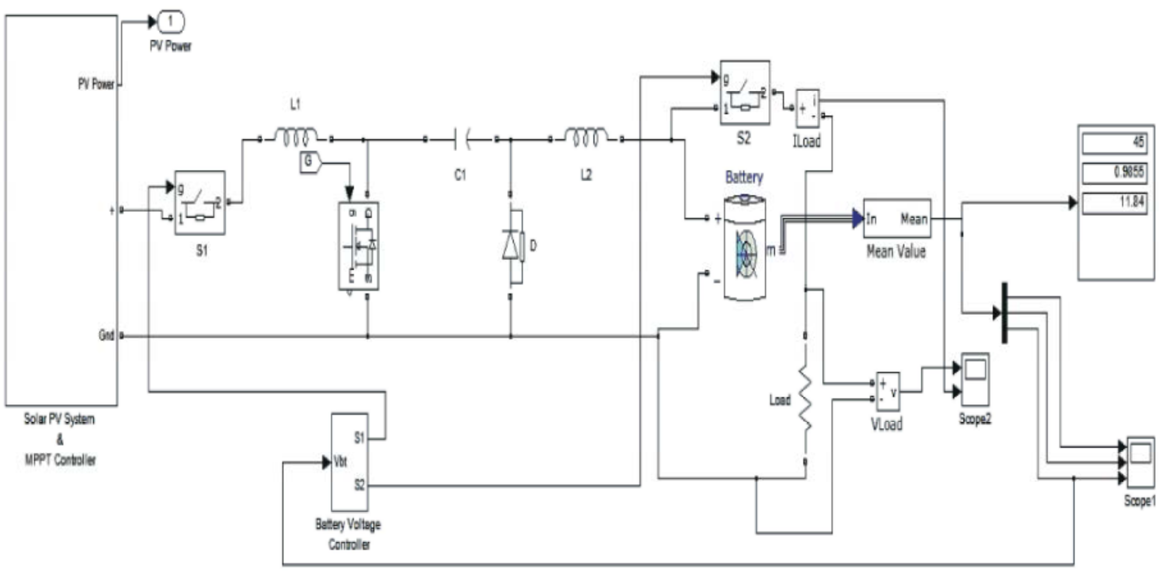

Fig. 8: Simulation of solar PV system for a standalone system

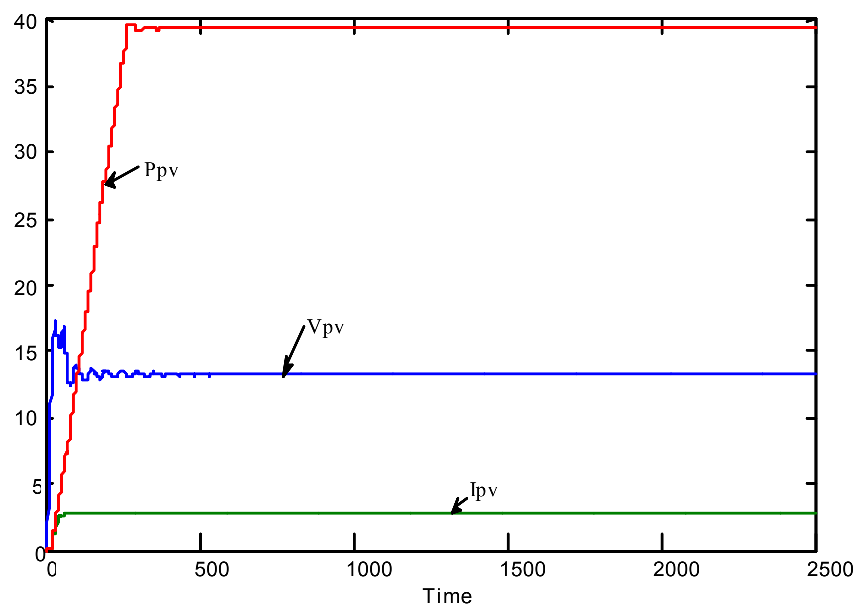

Fig. 9: Voltage, Current and Power of solar PV system for insolation of $1000W/m^2$

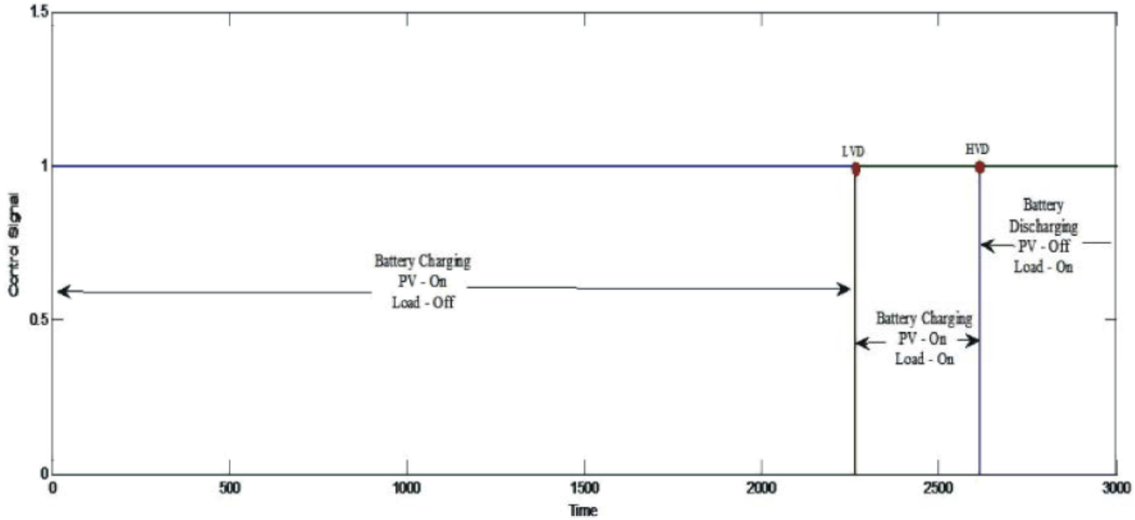

Fig. 10: Output of battery voltage controller

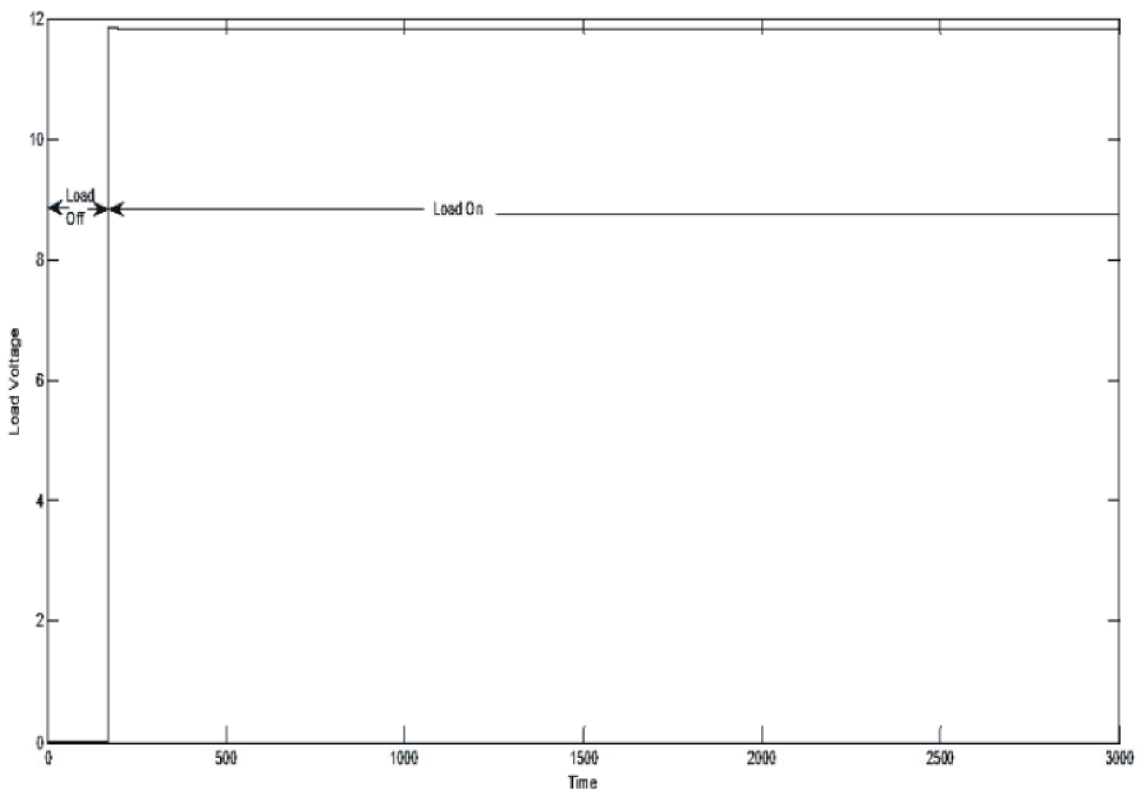

Fig. 11: Load Voltage of solar PV system with battery charge controller

The simulated results of solar PV system with battery charge controller is shown in Fig. 9-11. Voltage, current and power of solar PV system for insolation condition of 1000W/m^2 are shown in Fig. 9.

Fig. 10: shows the output of battery voltage controller. It includes the sequence of battery charging and discharging such that up to LVD point only PV source is utilised to charge the battery, when it reaches LVR, load gets connected to the battery and it's charged using PV source and when it attains HVD, PV source voltage gets disconnected and only battery discharges to the load.

The output result of load voltage is shown in Fig. 11. Initially, the load remains disconnected the supply and when the battery is charged to its maximum capacity (LVR), the load gets connected to the supply.

Experimental Results: The functional characteristics and the performance of the standalone solar PV system are verified using the prototype model shown in Fig. 12. PIC 16F877A microcontroller is used to generate the control signal for the Cuk converter based upon the MPP. PIC 16F872 is used to generate the control signals to control the operation of battery.

Fig. 12: Hardware setup for Cuk Converter based solar PV system for standalone system

Fig. 13: Execution of standalone solar PV system with Battery Voltage Controller

The regulated voltage from Cuk converter based solar PV system is used to charge the battery. The Cuk converter specifications are shown in Table 3. The real time monitoring and controlling of battery charging and discharging is implemented using two relays: one at coupling point of PV voltage to the Cuk converter and other at coupling point of battery to the load. These relays are operated based upon the set points as shown in Table 1. The execution result is shown in Fig. 13.

The experimental result for solar PV system with battery voltage controller along with operation of load for varying conditions of battery charging and its corresponding load variation is shown in Fig. 12. Channel 1 (CH1) corresponds to PV voltage produced for varying insolation conditions and channel 2 (CH2) corresponds to varying load voltage corresponding to the battery characteristics. Initially, when PV voltage is generated it starts charging the battery and the load remains disconnected from the supply. The experimental results for solar PV system with Battery voltage controller is shown in Fig. 14-16. When the battery voltage reaches LVR point, the load gets connected with the supply as shown in Fig. 14. Now, the PV voltage generated charges the battery and the load remains connected to the battery continuously.

At HVD point, the battery is completely charged to its maximum capacity, hence battery is disconnected from the PV source but the load is still connected to the battery. At LVD point, the battery is completely discharged and the load is disconnected from the supply as shown in Fig. 15 and gets reconnected again when PV source charges the battery reaches the LVR point.

The act of solar PV system without and with battery for various insolation condition is shown in Table 2. Thus, without a battery storage system, load is supplied with varying supply voltage which easily reduces the life of load whereas, using a solar PV system with battery provides nearly a constant supply voltage to load.

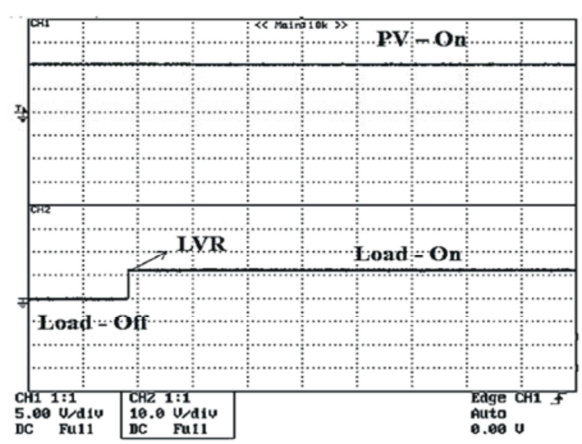

Fig. 14: System Operating Condition- Before and After LVR point

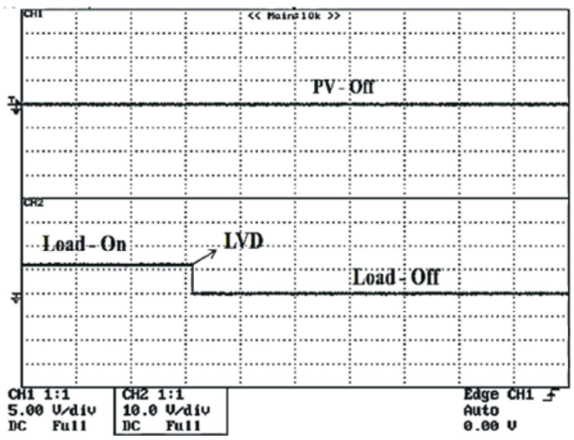

Fig. 15: System Operating Condition- Before and After LVD point

Table 2: Comparison of SPV system with & without Battery

Insolation	SPV system without Battery			SPV system with Battery		
	V_{in}	V_L	I_L	V_{in}	V_L	I_L
1000	20.08	18.95	1.579	12.88	11.48	0.9562
900	19.85	18.72	1.56	12.81	11.47	0.9559
800	19.54	18.41	1.535	12.74	11.47	0.9556
700	19.08	17.97	1.497	12.67	11.46	0.9552
600	18.28	17.18	1.432	12.61	11.46	0.9549
500	16.48	15.41	1.284	12.54	11.46	0.9545

Thus, the performance of SPV system with battery is better than the one without battery and the battery characteristics is also well equiped with battery voltage regulation system.

CONCLUSION

In this paper, solar PV system is actively employed with MPPT controller for harvesting the maximum power from solar PV system which enhances the conversion efficiency with simple implementation and reduced costs and also the battery voltage control algorithm for controlling the charging and discharging characteristics of battery which provides enhanced operating characteristics of battery for its superior performance. It is also tested using a system consisting of a solar PV cell, Cuk converter, battery and load. The performance of battery is also confined based upon its operating set points at which the load is connected and disconnected from the system. The simulation and experimental results are also verified and proven to be satisfactory. Thus, employing this method will enhance the performance of solar PV system and the maximum power extracted can also be utilised efficiently using battery storage system.

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