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A Single Switch DC-DC Converter for Photo Voltaic-Battery System

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ABSTRACT

A photo voltaic-battery powered, single switch DC-DC converter system for precise control of voltage for a low power application is presented in this paper. The converter is composed of buck converter and a buck-boost converter sharing a single switch. The converter allows you to implement maximum power point tracking, battery charging, and load voltage regulation simultaneously. The MPPT and load voltage regulation is achieved by controlling duty ratio and switching frequency of the switching pulse. Hence the buck converter will be working under discontinuous current conduction mode which enables to adjust the impedance by changing switching frequency and thus by achieving the MPP. Whereas the buck-boost converter will be working under continuous current conduction mode and output voltage regulation is done by changing duty ratio. The algorithm used for MPPT is incremental conductance algorithm which gives satisfactory results on most conditions. For the protection of battery from overcharging, the system will comes out from incremental conductance algorithm and provides a constant charging voltage the battery. The proposed system is tested under MATLAB SIMULINK 2016 and satisfactory results are obtained.

Keywords: dc-dc power conversion, maximum power point (MPP) tracking (MPPT), photovoltaic (PV) battery systems, single-stage single-switch converters (SSC), incremental conductance algorithm, variable –frequency control

I. INTRODUCTION

The energy demand of the world is increasing in an exponential rate. Due to the problems associated with fossil fuel and its unavailability in future led to vast extensive research and developments in renewable energy sources. One of those widely developed and researched areas is the solar energy conversion, especially energy production using photo voltaic cells. Since PV arrays are variable current sources from which the power transferred depends upon the output impedance of the solar array. Hence it is important to introduce a converter between PV array and output load [1]. The converter ensures the transfer of maximum power PV cell to output at all conditions.

One of the problems of introduction of the MPPT converter is requirement of additional converter, for providing the required voltage level to output. It results the increase in the size and cost of the whole system and due to the repeated power processing the efficiency of the system decreases [2]. Hence it is advantageous to process the MPPT technique and output voltage regulation using single stage converter, instead of two stage converter. The single stage converter is derived from two stage converter by combining the controlled switches of the converter. For the combining of the two controlled switches in to one, you need to have them sharing a common switch and combining them doesn’t alter the functions of the converter [3].

But one of the problems associated with single stage converters are high voltage stresses imparted on its components [4]. Hence it is very difficult to implement on high power applications. It is due to the currents from multiple source flows through it [5]. But the developments in microelectronics are continuously decreasing the turn on resistance of MOSFETs which gradually receding this restriction.

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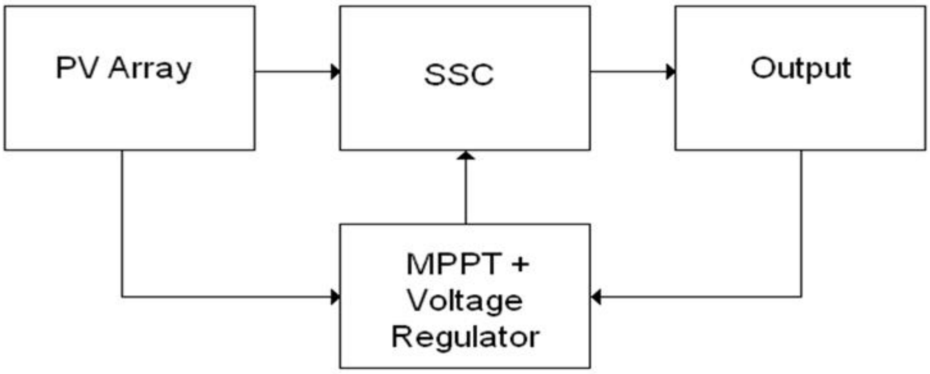

Fig 1. Block diagram of single Stage converter for photo voltaic system.

For the maximum power transfer from the PV array, suitable MPPT techniques must be used. There are various MPPT algorithms present in the industry ranging from simple to highly complex methods. The fractional open circuit voltage algorithm is one of the simplest and easiest methods to implement on most converter topologies [6]. The P & O algorithm is widely used on PV array application on grid connected as well as standalone system [7]. But its operating points never stabilize at a point and always oscillate around maximum power point. The incremental conductance algorithm avoids this problem and one of the accurate and stable methods [8]. But the traditional MPPT algorithms lacks under the partial shaded conditions. Hence advanced MPPT techniques like central point iteration methods which calculate the maximum power at different operating points and optimizes to single point [9].

By using the variable frequency control for MPPT algorithm, the high voltage stress problem can be reduced [10]. This paper utilizes the frequency modulation techniques for MPPT control by impedance matching and the output load voltage is regulated using normal duty cycle feedback control.

The circuit description and modes of working is given in section II. The section III explains the incremental conductance algorithm for MPPT tracking. The design of the converter is given in IV. The detailed analysis of the system is explained in section V. The section VI gives the conclusion of the work.

II. CIRCUIT DESCRIPTION AND MODES OF OPERATION

The circuit diagram of the single stage single switch converter given in Fig.2. It is derived from combining the switches of the buck and buck boost converter into one. It consist of inductor L_1 which controls MPPT and charges battery, inductor L_2 which transfers energy to the output load, a rechargeable battery V_b for stabilizing DC link voltage and stabilizing input and output powers, capacitor C_1 passing the ripple current to the battery, capacitor C_2 for absorbing the ripple current to the load. The switch S provides the returning path to both PV array and battery current. The diodes D_2 and D_3 provide the path to battery current on different occasions, when switch is on. The diode D_3 provides the energy transferring path from inductor L_1 to battery V_b, whereas the diode D_4 provides the linking between the output load and inductor L_2.

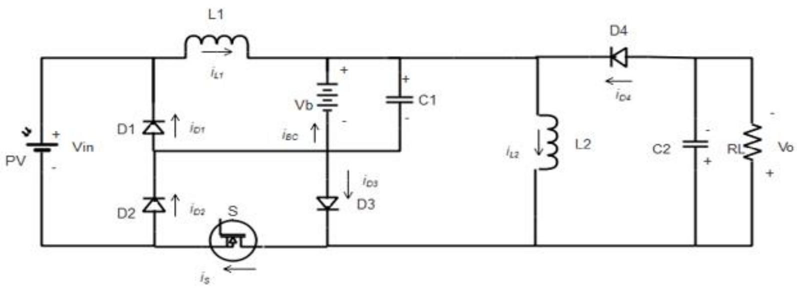

Fig 2. Single switch converter based on buck and buck-boost converter.

For the simplicity and ease of analysis under steady state, the PV array and battery are replaced by constant DC voltage sources. The diodes and controlled switch assumed to be ideal and the output capacitor C_2 is large enough so that output remains constant. The buck inductor L_1 works in discontinuous current conduction mode and the buck-boost inductor works under continuous current conduction mode.

The circuit is explained for different modes of operation for a switching cycle under steady state is given in Fig 3-6. The key waveforms of the converter are given in Fig 7. The converter operation can be divided in to four modes during a switching cycle under steady state.

Mode 1(T_0-T_1): In mode 1, switch is on. The diode D_2 is forward biased where as the diode D_1, D_3 and D_4 is reverse-biased. The PV cell supplies energy to both buck inductor (L_1) as well as boost inductor. The current through inductor L_1 is rises from zero since it is working in discontinuous mode of current mode. Since battery also supplies the energy to buck-boost inductor (L_2) apart from PV cell. Hence the current through L_2 is higher than that of current through L_1.

$$i_{L1} < i_{L2} \quad (1)$$

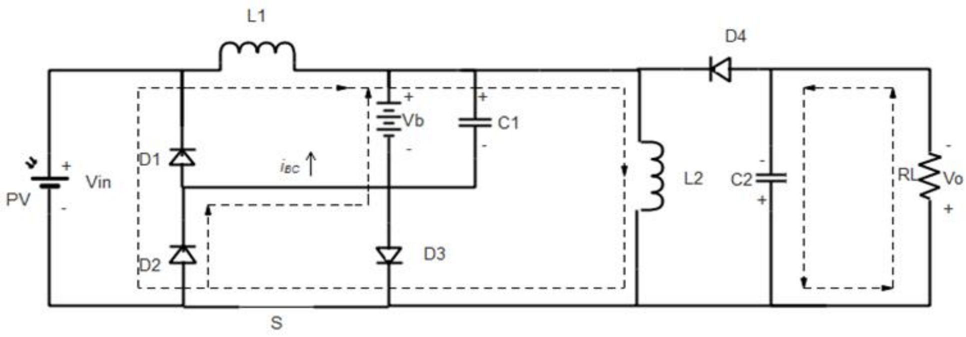

Fig 3. Circuit operation: Mode 1.

The current through L_2 is the sum of the current through L_1 and the battery discharging current.

$$i_{L2} = i_{L1} + i_B \quad (2)$$

The mode ends at T_1 when current through L_1 become equal to current through L_2.

Mode 2 (T_1-T_2): The mode 2 begins when current through L_1 becomes greater than L_2. It means in this mode the discharging battery on previous mode starts to get charged. The time T_1 is determined by the load requirement. In this mode the switch is still conducting and the diode D_3 gets forward biased, D_2 gets reverse biased and others remain in their previous state. This mode ends when the switch S gets turned off at T_2. The current through L_1 and L_2 reaches their maximum point at the end of this mode.

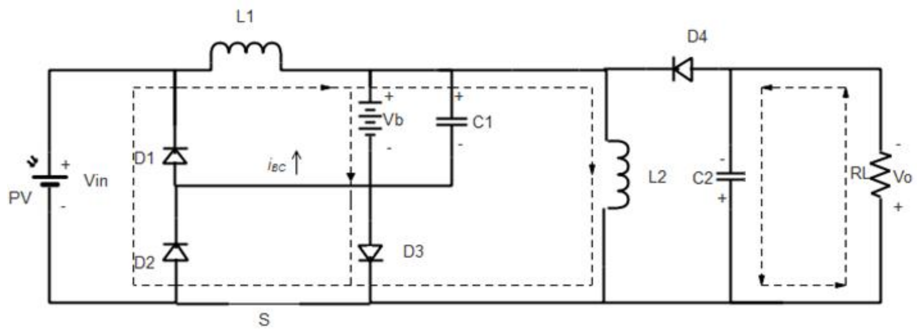

Fig 4. Circuit operation: Mode 2.

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$$i_{L1} > i_{L2} \quad (3)$$

The current through the L_1 is the sum of the current through the L_2 and the battery charging current.

$$i_{L1} = i_{L2} + i_B \quad (4)$$

Mode 3 (T_2-T_3): The mode 3 starts when switch gets turned off. The diode D_1 and D_4 gets forward biased and D_2 and D_3 are in reverse biased mode. The energy in inductor L_1 will now solely used to charge the battery and energy in L_2 will supply to the load.

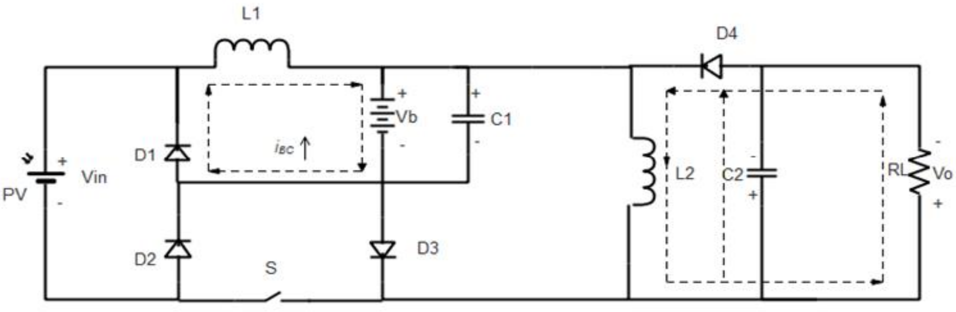

Fig 5. Circuit operation: Mode 3.

Mode 4 (T_3-T_4): This mode starts when the energy in inductor L_1 is completely transferred to battery and current becomes zero. In this mode only the inductor L_2 is transferring energy and supplies to load until the switch S gets turned on again.

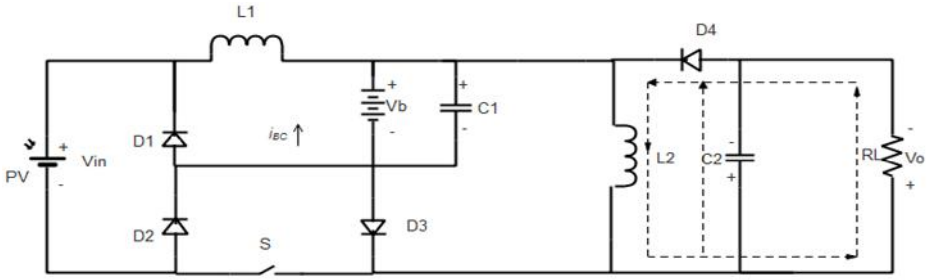

Fig 6. Circuit operation: Mode 4.

III. MPPT ALGORITHM AND OUTPUT VOLTAGEREGULATION

For the extraction of maximum power from PV array, Incremental conductance algorithm is used. In this method, the MPP is adjusted based up on the incremental and instantaneous conductance of the PV array. The flow chart for the algorithm is given in fig 8. For the MPPT algorithm, both PV array current and voltage needs to be measured simultaneously. In order to adjust the operating voltage of PV array, variable frequency control is used. It is achievable due to the discontinuous current conduction of the inductor L_1. The output to input gain (M) of the buck converter which constitutes the front end of the SSC under discontinuous conduction mode (DCM) is given by

$$M = \frac{V_B}{V_I} = \frac{2}{1+\sqrt{1+\frac{8L_1 f}{D^2 R}}} \quad (5)$$

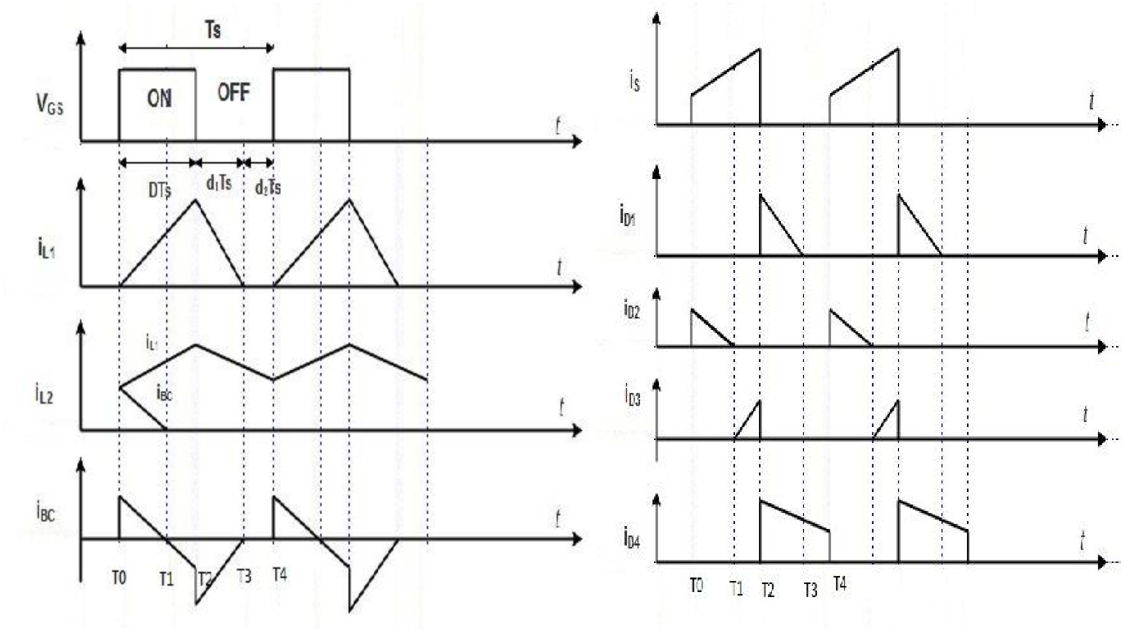

Fig 7. Waveforms of SSC.

Where D is the duty ratio of the switching pulse to the switch, f is the switching frequency, and R is the equivalent resistance of the battery which is an unknown quantity. Assuming that the system is loss less, the output power can be equated to input power. Then R can be approximately calculated as

$$R = \frac{V_b^2}{V_L\ I_L} \tag{6}$$

Where the product of V_{IN} and I_{IN} gives the input power. Substituting equation (6) in (5), and rearranging the terms, it can be derived that

$$\frac{V_L}{I_L} - \frac{V_b}{I_L} = \frac{2L_1 f}{D^2} \tag{7}$$

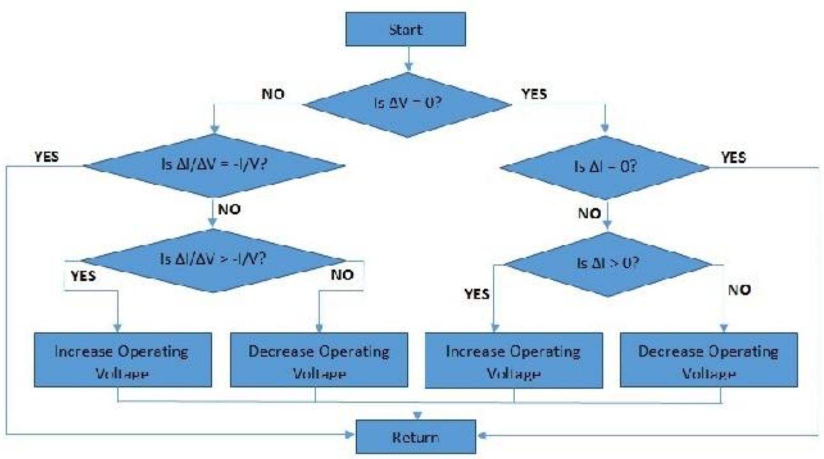

Fig 8. Flow chart of Incremental Conductance algorithm.

Since the PV array current which is a function of PV array voltage, the equation (7) shows that the PV array volt age is depend up on both duty ratio as well as switching frequency. Hence the MPPT can be achieved using either variable frequency control or duty cycle control. Since precise output voltage regulation is

needed, MPPT is achieved with variable frequency control. It is because the duty cycle control shows larger control range than variable frequency control. The output voltage regulation achieved by duty cycle control. Buck-boost converter constitutes the rear end of the converter. The buck-boost inductor operates in continuous conduction mode (CCM), hence the gain 'K' of the converter is given by

$$K = \frac{V_o}{V_b} = \frac{-D}{1-D} \qquad (8)$$

For the output regulation, closed loop operation with PI controller is used. For this operation actual voltage compared with required reference voltage and error is given to PI controller. The PI controller will produce the required duty ratio for the system to achieve the desirable voltage.

IV. DESIGN OF INDUCTORS

For the single switch converter, the buck inductor L_1 is designed such that it works under discontinuous mode of current conduction at all occasions. Hence the inductor is selected such that, its maximum value is given as

$$L_1 < \frac{V_b(1-D)}{2\,f_m \quad I_{L1,max}} \qquad (9)$$

Where $I_{L1,max}$ is the average current flowing through the inductor L_1 under maximum output power. V_b is the battery voltage and f_{max} is the maximum switching frequency.

The buck-boost inductor L_2 is designed such that, it always works under the continuous mode of conduction. Hence minimum value of the inductor L_2 is given by the inequality.

$$L_2 > \frac{V_b D(1-D)}{f_m \quad I_{o,m}} \qquad (10)$$

Where $I_{o,min}$ is the minimum load current and f_{min} is the minimum switching frequency.

V. SIMULATION AND RESULTS

Table I

Simulation Parameters

PV Open Circuit Voltage at STC(V_{OC})	21 V	Inductor (L_2)	1000 μH
PV Short Circuit Current at STC (I_{SC})	1.26 A	PV Capacitor	100 μF
PV Voltage at MPP at STC	17 V	Capacitor (C_1)	220 μF
PV Current at MPP at STC	1.1A	Capacitor (C_2)	470 μF
Inductor (L_1)	20 μH	Battery Voltage	12 V

The simulation model of single switch converter for PV battery system is developed in the MATLAB R2015/ SIMULINK environment. The parameters used for the simulation is given in table 1.

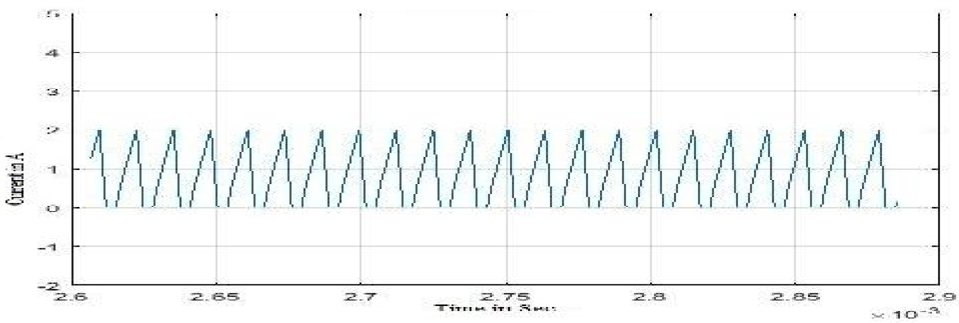

Fig 9. Simulation: Current through inductor L_1.

For the simulation, the switching frequency is limited to ran between 2 KHz to 120 KHz and MOSFET is used as the switching device. For the PI controller k_p and K_i is chosen as .02 and 3 respectively. The load is

purely resistive and its value is taken as 50 Ω. Fig 9 shows the current through the inductorL_1. Since it is selected as to work under DCM, the current is zero for some time in one cycle. It has peak current of 2A at the peak. The fig 10 shows the current through inductor L_2 and it is working under CCM.

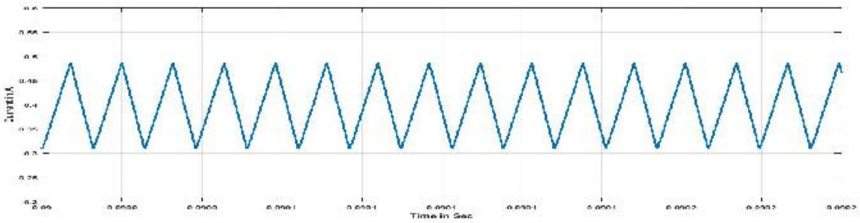

Fig 10. Simulation: Current through inductor L_2.

The simulation is done in two stages. At first, the irradiations is changed as 750 W/m^2, 500 W/m^2, 1000 W/m^2 respectively in successive steps in 0.04 seconds. The fig 11 shows the PV array power and its variation as the irradiance changes

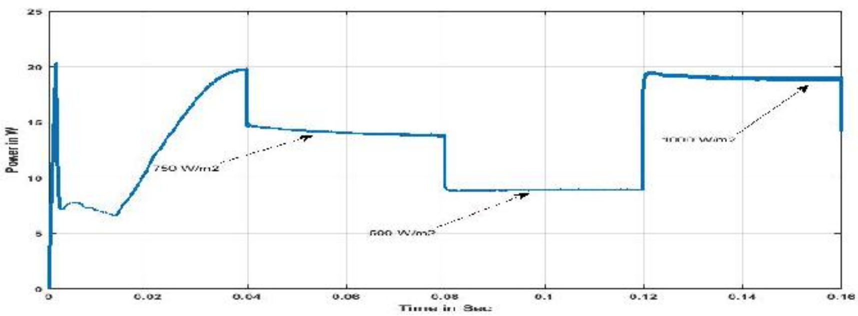

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Fig 11. Simulation: PV array power at MPP for different irradiance.

The irradiation and PV array power has direct relationship. Hence with the increase in irradiation, PV array power also increases. The fig 12 and 13 shows the corresponding PV array voltage and current at different irradiation.

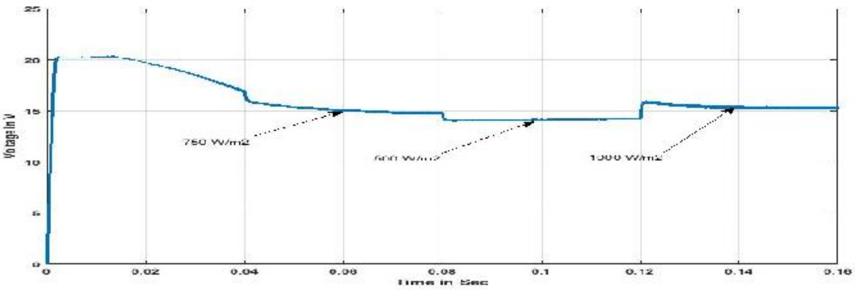

Fig 12. Simulation: PV array Voltage at MPP for different irradiance.

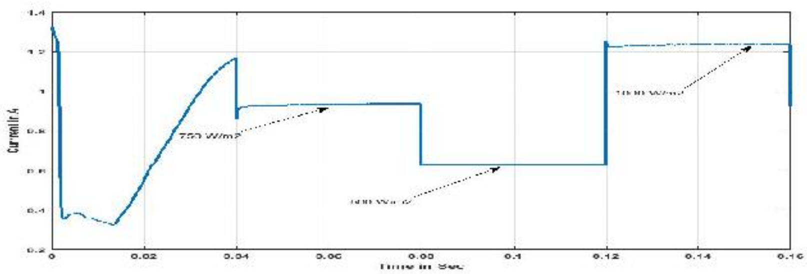

Fig 13. Simulation: PV array current at MPP for different irradiance.

The MPPT algorithm takes about 0.04 sec to determine the MPP at starting. It is because the changes in duty ratio to obtain the desirable output voltage. It is evident from the equation (7) that MPP is depends not only on switching frequency, but also depends on the duty cycle. Hence it is important to have fast response for the PI controller.

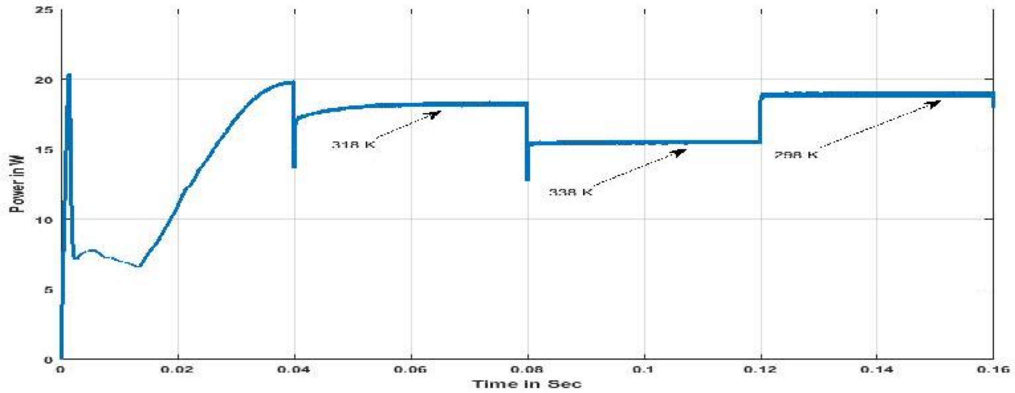

Fig 14. Simulation: PV array power at MPP for different temperature.

Similarly, in the second stage, temperature is varied and PV power is plotted. The temperature is varied in an interval of 0.04 sec as 318K, 338K, and 298K respectively. It is evident from the fig 14 that temperature and PV array power has inverse relationship. The fig 15 and 16 shows the PV array voltage and current at different temperatures. The changes in the temperature are less impact on the PV array voltage at MPP. But the current at MPP decreases for the PV array with temperature, even though it increases its short circuit current.

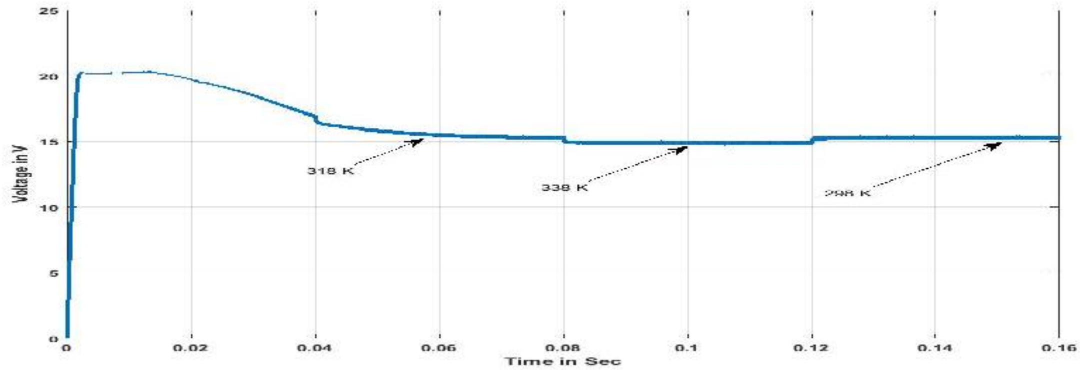

Fig 15. Simulation: PV array voltage at MPP for different temperature.

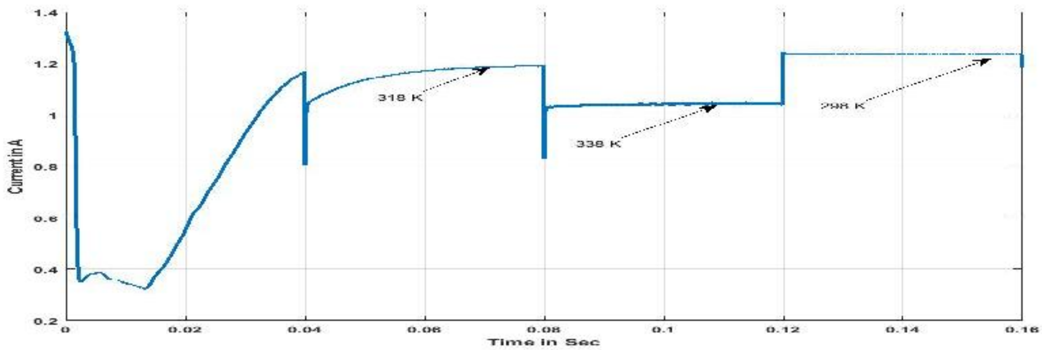

Fig 16. Simulation: PV array current at MPP for different temperature

Fig 17 shows the output voltage of single switch converter. The reference value set as -14 V and it takes 0.04 seconds to reach the desired value which effects the starting of MPPT algorithm. The output voltage has a negative polarity due to the buck-boost topology.

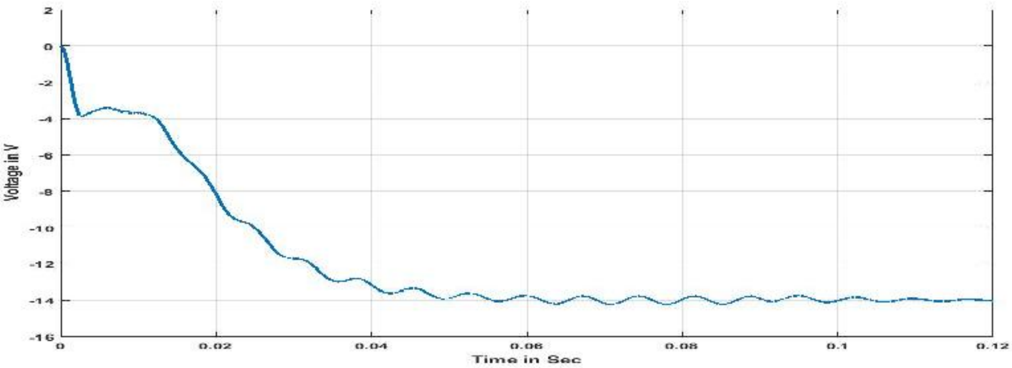

Fig 17. Simulation: Output voltage of SSC.

VI. CONCLUSION

A single switch converter for a PV battery system performing Maximum power point tracking, output voltage regulation, and battery charging is presented in this chapter. By avoiding the repeating power processing, the size and cost of the system decreases. It also increases the efficiency of the converter. The MPP is tracked using incremental conductance algorithm which reliable under all conditions. The MPPT is achieved using variable frequency control whereas the output voltage regulation is done by duty cycle control. But due to the high voltage stress problem, it can only be used for low to medium power applications.

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