Design Aspects and Different Control Strategy of Stand-Alone PV System by MPPT Technology

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Abstract: **Standalone Photovoltaic (PV) system requires a proper battery charge controller. In this paper an efficient battery charge controller using Buck-Boost regulator with Maximum Power Point Tracking (MPPT) is presented. The voltage command is determined by both the PV panel maximum power point tracking (MPPT) control loop and the battery charging loop. Here the controller is designed so as to balance the power flow from PV panel to the battery and load such that the PV power is utilized effectively. The design and simulation using MATLAB is presented in this work.**

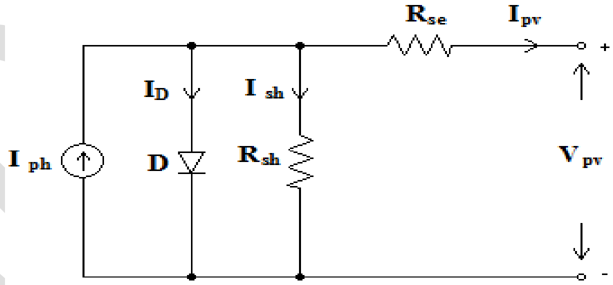
Keywords: Buck-Boost regulator, Maximum Power Point Tracking (MPPT), PI controller and Standalone Photovoltaic (PV) system.

I. INTRODUCTION

One of the most popular non conventional energy sources is the solar energy. Standalone PV system is the very popular way of utilizing solar energy. Photovoltaic panels are used to convert the solar energy into electrical energy. PV has nonlinear internal characteristics. The voltage-power characteristics of the PV panel is varied which depends upon insolation and temperature. Considering the high initial installation cost of the PV system, it is always necessary to operate PV at its Maximum Power Point (MPP). For this purpose dc-dc converter interface is required between PV and battery. The lifetime cost of the battery is high compare to the PV installation because of its limited service time. Battery life time is reduced if there is low PV energy availability for longer period or improper charging discharging. So the battery charging needs control for achieving high State of Charge (SOC) and longer battery life. Hence proper controller for battery charging is an inevitable need for this hour. The main function of the battery charging controller in standalone PV system is to fully charge the battery without permitting overcharging while preventing reverse current flow at night and deep discharge under load conditions. In this proposed system, the PV model, battery model and the battery charging system is implemented. Buck-Boost converter interface is used hence it is more suitable for battery charging. The purpose of the buck-boost converter used is to control the power flow from the PV panel to battery and load which requires MPPT control algorithm to find out the peak power of the PV panel. Perturb and Observe algorithm (P and O) is used for MPP tracking.

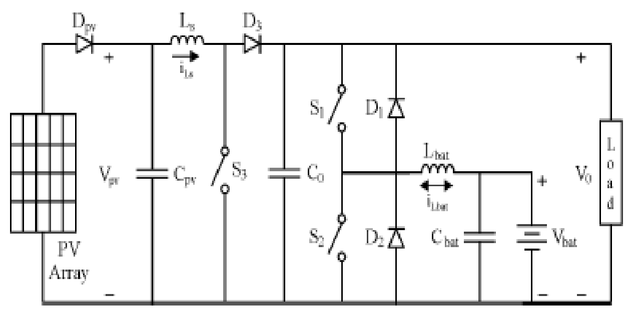
II. DESCRIPTION

The equivalent circuit of the PV cell is shown in Figure 1. PV cells are grouped in larger units called PV panels which are further interconnected in a parallel-series configuration to form PV arrays. To simulate the array, cell model parameters are properly multiplied by number of cells.

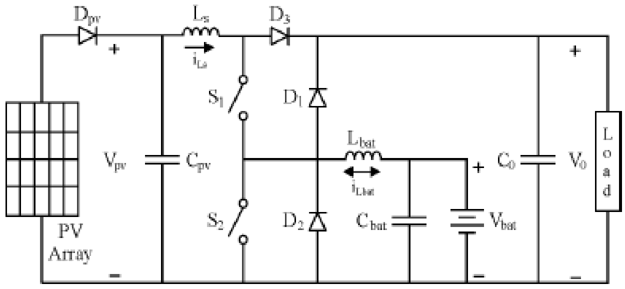


(Figure-1: Equivalent circuit of SPV panel)

The system presented in Figure-2 is an example of stand-alone PV system with two converters, an input boost converter for voltage regulation and a bi-directional converter for battery charge and to step up battery voltage to output dc bus. An appropriate displacement of C_0 and D_3 results in the Voltage Regulator - Battery Energy Storage System (VR-BESS) and allows the elimination of switch S_3. VR-BESS includes those two converters in a simple structure. Even so VR-BESS presents the same characteristics of two stages shown in fig. 2. The result of stand-alone PV system with VR-BESS can be seen in Fig. 3. This system is composed of two switches, three diodes, two inductors, two capacitors and a battery bank.



(Figure-2: Stand-alone PV system)



(Figure-3: Stand-alone PV system with VR-BESS)

The stand-alone PV system with VR-BESS can be differentiated into three different converters in the VR-BESS with different functions as follows.

(i) Input boost converter (voltage regulator)

The voltage regulator formed by switches S_1 and S_2, PV voltage V_{pv}, inductor L_s, diode D_3, capacitor C_0 and the load provides output voltage regulation. In this configuration switches S_1 and S_2 are turned on and off at the same time.

(ii) Buck converter (battery charger)

This is formed by PV voltage V_{pv}, inductor L_s, switch S_1, inductor L_{bat}, diode D_2, capacitor C_{bat} and the battery bank. This converter delivers into battery the excess of energy generated by PV array, extracting the maximum power.

(iii) Output boost converter (power compensator)

The boost converter formed by the battery bank, capacitor C_{bat}, inductor L_{bat}, switch S_2, diode D_1, capacitor C_0 and the load steps up battery voltage to output DC bus. This converter supplements the energy required by load when there is not enough insolation.

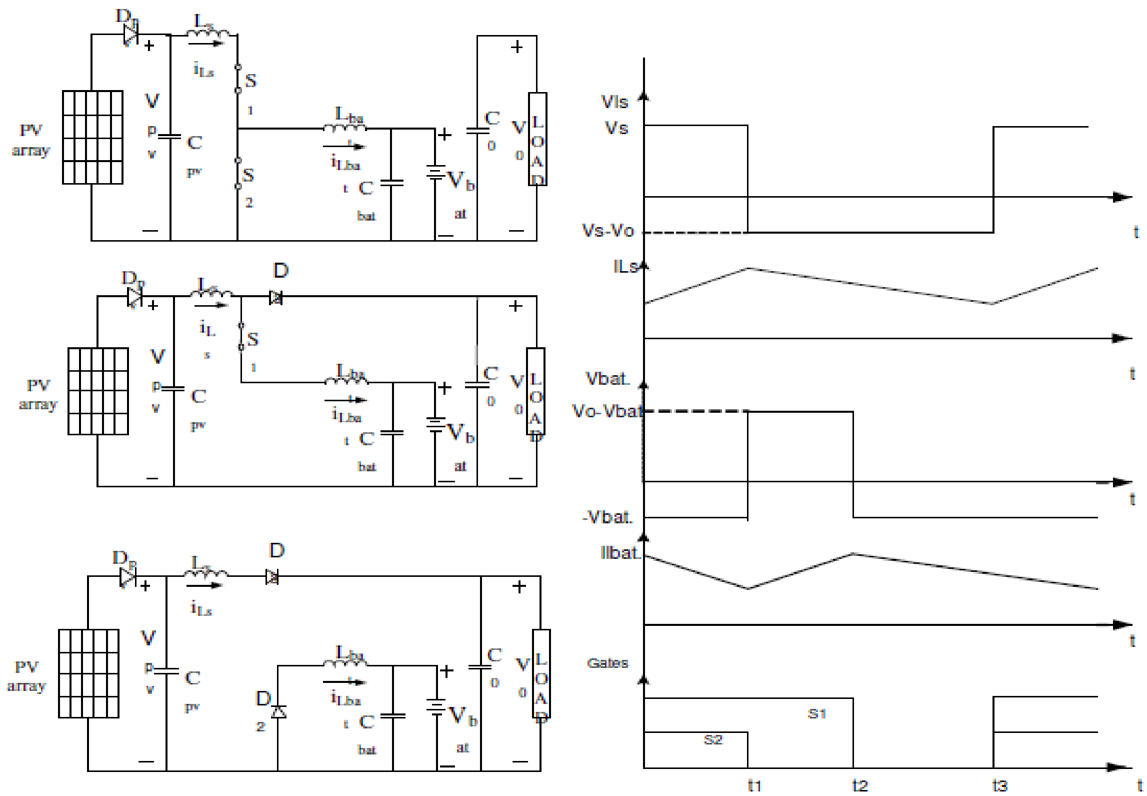
III. OPERATING PRINCIPLE

Depending on insolation condition, the proposed stand-alone PV system operates in one of the two modes of operation following

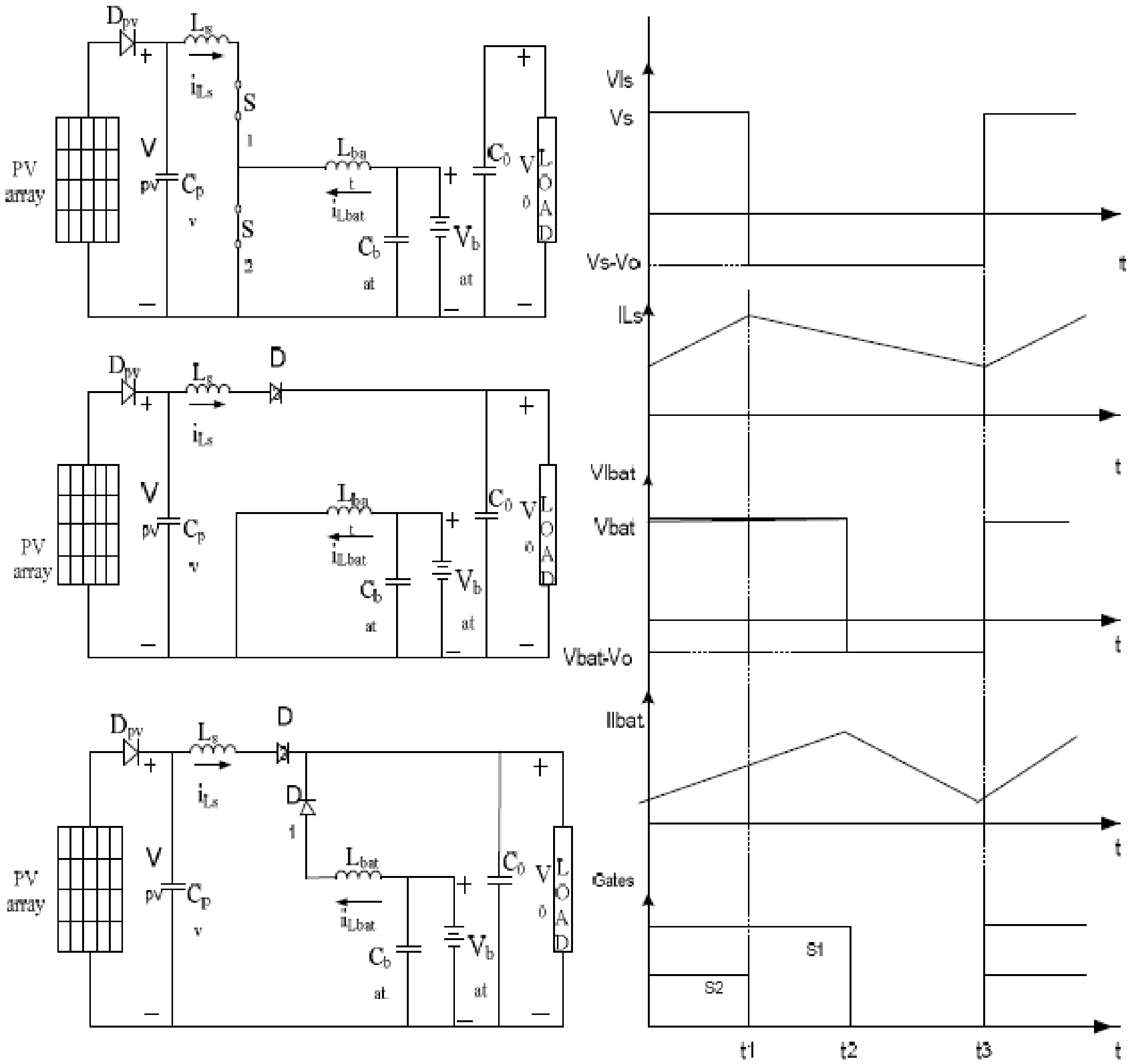
Mode 1 (Battery charge) In this mode the PV array generate sufficient energy to feed the load and charge battery.

Mode 2 (Power compensation) When the energy available in PV array is not sufficient to supply the load, the battery bank supplements the energy required by load. A particular operation in this mode occurs when there is no available energy at PV array. In this case the battery bank supplies full load current.

In continuous conduction mode the VR-BESS presents three operating stages. Assuming that devices used in the circuit are ideal and the filter capacitors C_0 and C_{bat} are assumed large enough to keep the voltages V_0 and V_{bat} constant, respectively, these stages are as follows:



(Figure- 4: Equivalent circuit and Theoretical wave forms for mode 1)



(Figure-5: Equivalent circuit and Theoretical wave forms for mode 2)

IV. PROBLEM FORMULATION

The design aspects of Standalone PV System are under the followings.

(A) Voltage and power levels considered

The parameters considered for simulation are as follows:
DC grid voltage, $V_S = 25V$
Battery bank open circuit voltage, $V_b = 24V$
Load voltage, Vo = 45 V
Maximum DC input power = 50W
Load power, P_O = 40-60 W
Switching frequency, f_s = 50 kHz

(B) Design of Inductor L_S:

The source side inductor, L_S value is designed in the way of designing inductor value for Boost converter. Here in mode1, DC source has to feed load with 40 W power and charge battery drawing 10 Watts power. In total a boost converter supplying 50W power. Parameters involved:
DC source voltage, $V_d = 25V$
Output voltage, Vo = 45V
Load power, $P_0 = 50$ W
Load current, $I_0 = 50/45 = 1.11$ A
As in Boost converter, $\frac{V_0}{V_S} = \frac{1}{1-D}$
1 – D = 25/45 = 0.55
D = 0.45
Inductor current, $I_L = \frac{I_0}{1-D} = \frac{1.11}{1-0.45} = 2.02\ A$
Considering 15% ripple in I_L, value of L_S needed is,

$$L_S = \frac{V_S D}{i_{LS} f_S} = \frac{25\times0.45}{0.303\times50000} = 0.75\ mH \qquad (1)$$

C) Design of Inductor L_b

The inductor value L_b is designed in the way of designing inductor value for Boost converter when battery is feeding the load in mode 2. In mode 2 load draws a power of 60W which is greater than DC source power (50W). Here 50W power is supplied by DC source and remaining 10W by battery.

Parameters (of boost converter formed by battery as source and load of 10W):

Battery voltage, V_b = 24 V

Output voltage, V_0 = 45V

Load power, P_0 = 10W

Load current, I_0 = 10/45 = 0.22 A

As in boost converter, $\frac{V_0}{V_b} = \frac{1}{1-D}$

1 – D = 24/45 = 0.53

D = 0.47

Inductor current, $I_L = \frac{I_0}{1-D} = \frac{0.22}{1-0.47} = 0.42\ A$

Considering 30% ripple in I_L, value of L_b needed is,

$$L_S = \frac{V_b D}{i_{Lb}\, f_S} = \frac{24\times0.47}{0.084\times50000} = 1.12\ mH \qquad (2)$$

D) Design of load side capacitor, Co

As load feeds from dc soure in boost converter operation, the capacitor across load can be determined in the following way:

Ripple in output voltage of boost converter,

$$\frac{v_0}{V_0} = \frac{D_1 T_S}{R_L C_0} \qquad (3)$$

From the above equation,

$$C_0 = \frac{D_1 T_S}{R_L \frac{v_0}{V_0}} \qquad (4)$$

Maximum value of C_o needs minimum value of R_L(60W load in mode 2).

$R_L = \frac{45\times45}{60} = 33.75\ \Omega$

Considering 1% ripple in output voltage, $C_0 = \frac{0.45\times20\mu}{33.75\times0.01} = 26.6\mu F$

Nearest available value is in practice is 47 µF. So final value of C_o is 47 µF.

E) Design of value of battery side capacitor, C_b

As battery charges from source in mode 1 through Buck converter operation, The capacitor across battery can be designed as capacitor across load in buck converter. Ripple in voltage across load terminals of Buck converter is

$$\frac{\Delta V_0}{V_0} = \frac{\pi^2}{2}(1-\Delta D)\left(\frac{f_c}{f_s}\right)^2 \qquad (5)$$

$$f_c^2 = f_s^2\left(\frac{\Delta V_0}{V_0}\right)\frac{2}{\pi^2(1-\Delta D)}$$

= 107788493

$f_c = 10382.12$ as

$$f_c = \frac{1}{2\pi\sqrt{L_b C_b}} \qquad (6)$$

$C_{b=}$ 300 µF

Nearest value of C_o in practice is 330 µF. So final value of C_o is 330 µF.

Duty Cycle of Switches:

Mode 1:

DC source voltage, V_s = 25 V

Load voltage, V_o = 45 V

Battery terminal voltage, V_{bat}= 24 V

Load power, P_o = 40 W

Battery power (charging), P_b = 10 W

Total power supplied by DC source = 40 + 10 = 50W

Source feeds load by supplying 40W power in Boost converter operation.

$\frac{V_0}{V_S} = \frac{1}{1-D_1}$

1 - D_1 = 25/45 = 0.55

D_1 = 0.45

Now D_1 is the duty ratio for switch S_2.

Battery gets charged from DC source in buck converter mode of operation.

$\frac{V_{ba\ t}}{V_0} = D = D_2 - D_1$

$D_2 - D_1 = \frac{V_{ba\ t}}{V_0} = \frac{24}{45} = 0.53$

D_2= D_1+0.53 = 0.98

Now D2 is the duty ratio for switch S_1.

Mode 2:

DC source voltage, V_s = 25 V

Load voltage, V_o = 45 V

Battery terminal voltage, V_{bat} = 24 V

Load power, P_o = 60 W

Power supplied by DC source (to load) = 50W

Battery power (discharging to load), P_b = 10 W

Total power supplied to load = 50 + 10 = 60W

Source feeds load by supplying 50W power in Boost converter operation.

$\frac{V_0}{V_S} = \frac{1}{1-D_1}$

D_1= 0.45

Now D_1 is the duty ratio for switch S_1.

Battery supplies load a power of 10W in Boost converter operation.

$\frac{V_0}{V_b} = \frac{1}{1-D_2}$

D_2= 0.47

Now D_2 is the duty ratio for switch S_2 from.

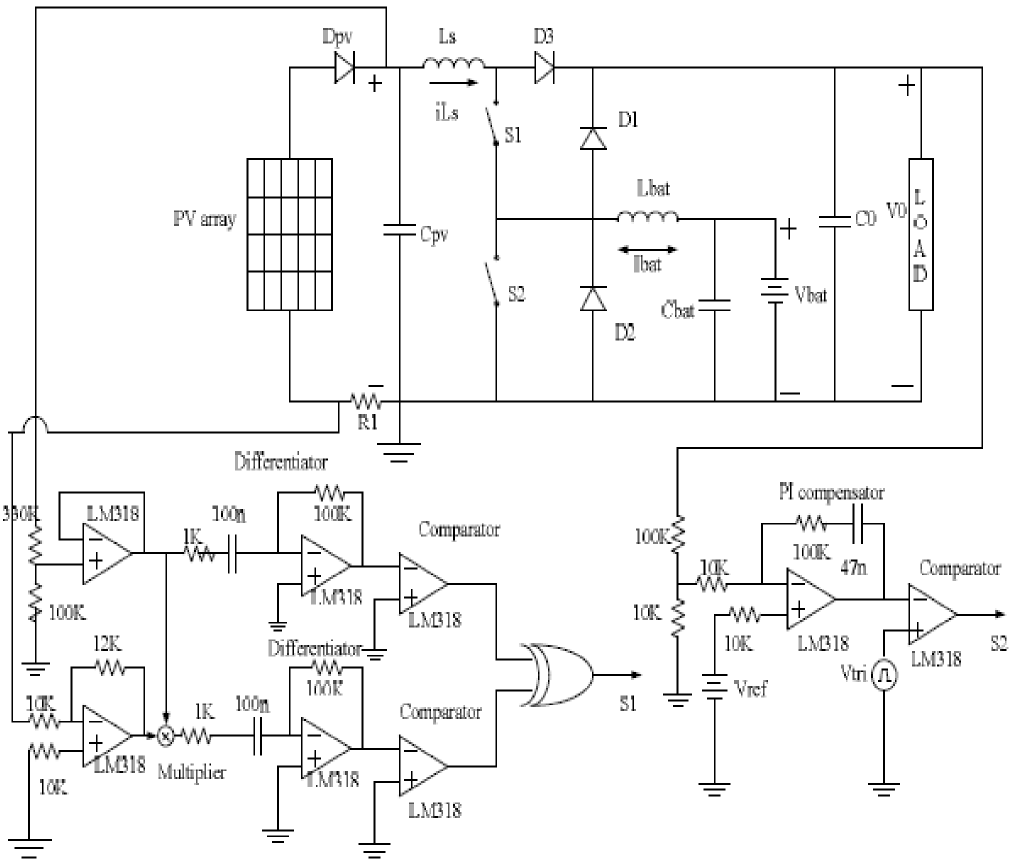
Load Resistance:

Mode 1: Load power, P_o = 40 w
Load terminal voltage, V_o= 45 v
Load resistance, R_L= 45^2/40=50.6 Ω

Mode 2 : Load power, P_o = 60 w
Load voltage, V_o= 45 v
Load resistance, R_L= 45^2/60= 33.7 Ω

V. SOLUTION METHODOLOGY

Proposed system in closed loop is having two controllers i.e., MPPT controller and output voltage controller. From these two controller's gate pulses are generating and giving to two MOSFET's. The below figure -6 is the orcad / pspice model of proposed system in closed loop manner.



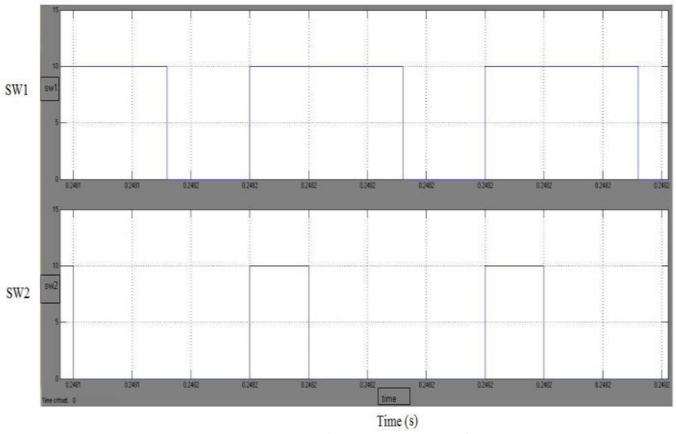
(Figure-6: Proposed stand-alone PV system in closed loop)

To increase and decrease the impressed voltage across the PV array, the capacitor C_{pv} is charged and discharged, respectively. That is done by adjusting the switch S_1conduction time. Maximum Power Point Tracker has been obtained using a control from nonlinear dynamics theory proposed in. This control strategy has been chosen due to the simple implementation with a few commonplace electronic components and its good tracking effectiveness and dynamic response.

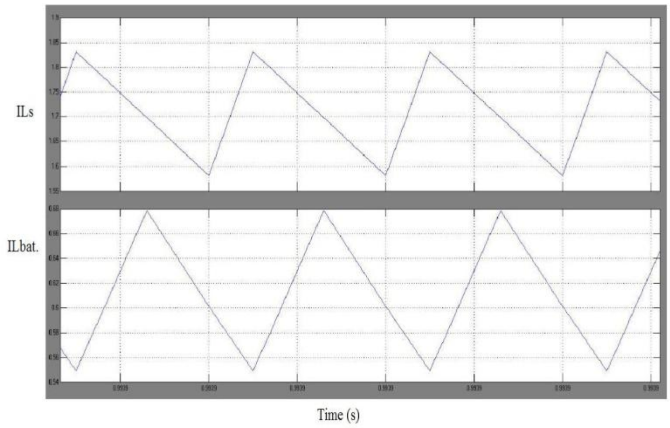
The controller can be implemented simply using two differentiators, two comparators, an exclusive-or gate (XOR) and an analogue multiplier to evaluate P=VI. In this MPPT control the turn off and turn on of the switch is done considering the sign of the dPpv/dt and dV_{pv}/dt, as used in perturb and observe method. The Proportional-Integral (PI) control was used to obtain regulated output voltage. The schematic of the MPPT and PI controls is presented in Figure-6.

It can be seen that the switches S_1 and S_2 control signals are generated by MPPT control and PI control, respectively. When $V_{pv}<V_{mpp}$, P_{pv} and V_{pv} decreases simultaneously $\left(\frac{dP_{pv}}{dt} < 0 \; and \; \frac{dV_{pv}}{dt} < 0\right)$ or increase simultaneously $\left(\frac{dP_{pv}}{dt} > 0 and \; \frac{dV_{pv}}{dt} > 0\right)$. In this case the signal resulted by multiplication of the signs of $\frac{dP_{pv}}{dt}$ and $\frac{dV_{pv}}{dt}$ in XOR gate turns OFF the switch S_1 so that capacitor C_{pv} can be charged, *dt* approaching the MPP. On the other hand, when $V_{pv}>V_{MPP,}$ P_{pv} decrease and V_{pv} increase . $\left(\frac{dP_{pv}}{dt} < 0 and \; \frac{dV_{pv}}{dt} > 0\right)$ or P_{pv} increase and V_{pv} decrease $\left(\frac{dP_{pv}}{dt} > 0 and \; \frac{dV_{pv}}{dt} < 0\right)$. Now, the switch S_1 is turn ON so that capacitor C_{pv} can be discharged, dt decreasing V_{pv} toward MPP. The system can operate either in mode 1 or mode 2. The controllers adjust automatically to the conditions. When the Stand-alone PV system with VR-BESS is operating in mode 1 the switch S_1 conduction time is greater than switch S_2 conduction time and for mode 2, the switch S_1 conduction time is smaller than switch S_2 conduction time.

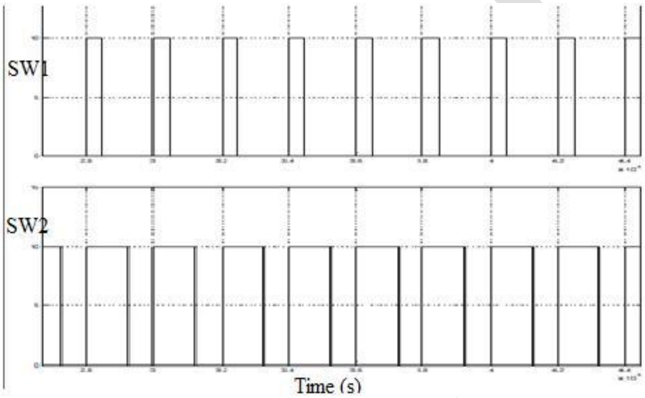
VI. RESULT



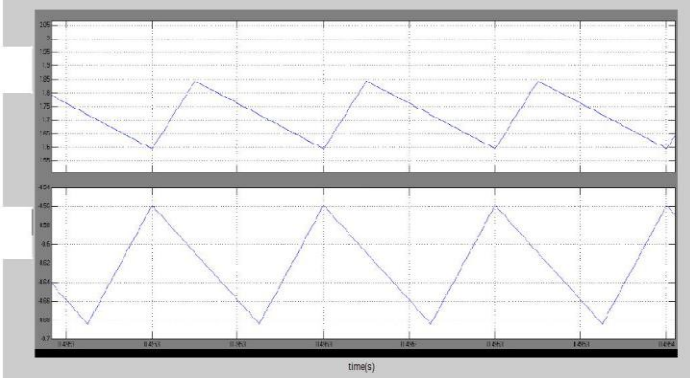
(Figure-7: Gate pulses for sw_1 and sw_2 for mode-1)



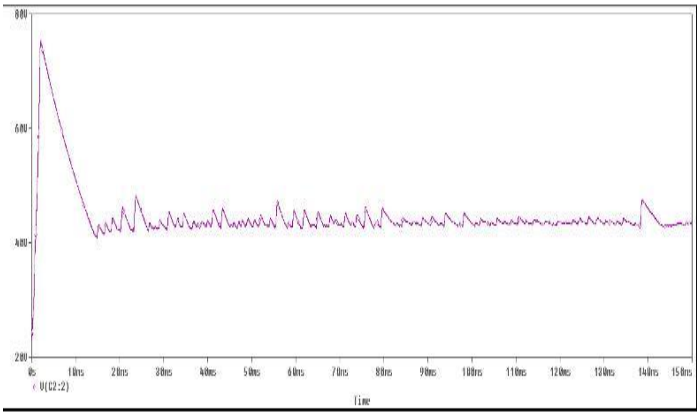
(Figure-8: Inductor Currents (I_{Ls}, $I_{Lbat.}$) for mode-1)



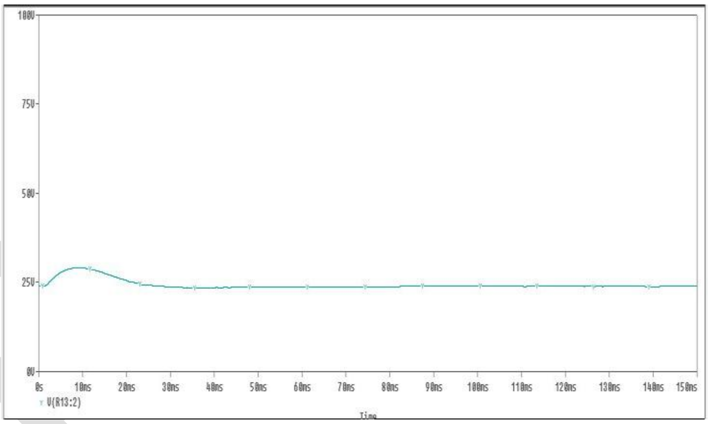
(Figure-9: Gate pulses to Sw_1 and Sw_2 for mode-2)



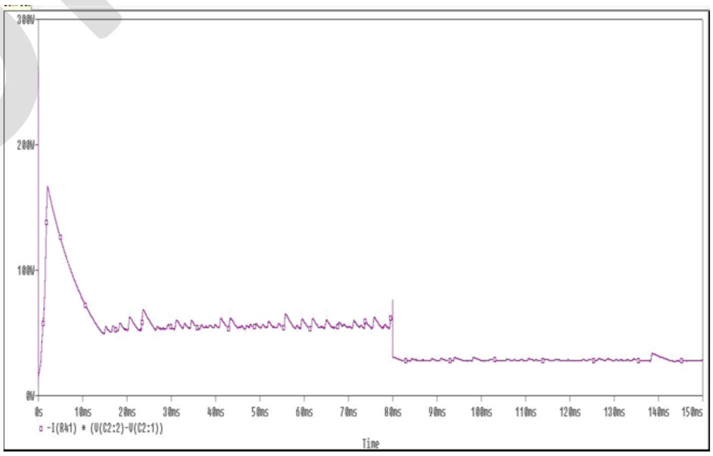
(Figure-10: Inductor currents (I_{Ls}, IL_{bat}).for mode-2)



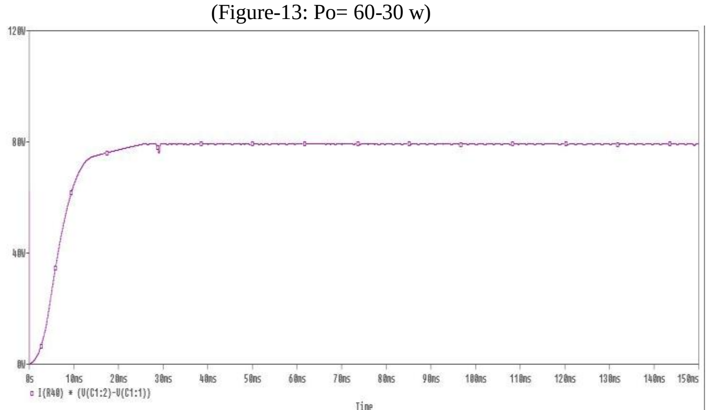
(Figure-11: Output voltage,V_O)



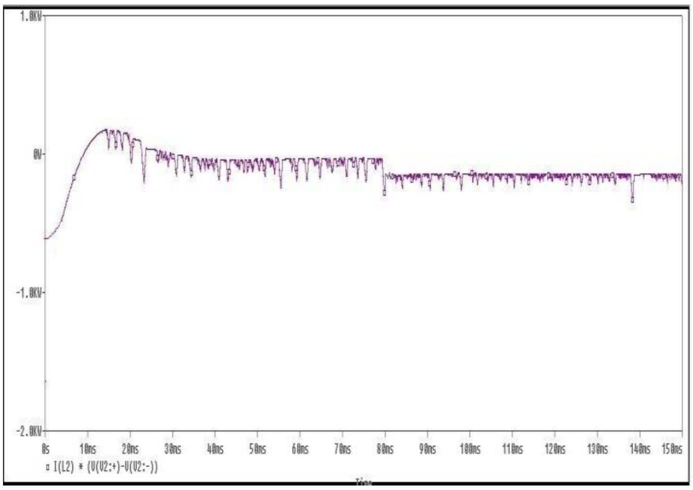
(Figure-12: Input voltage,V_{in})



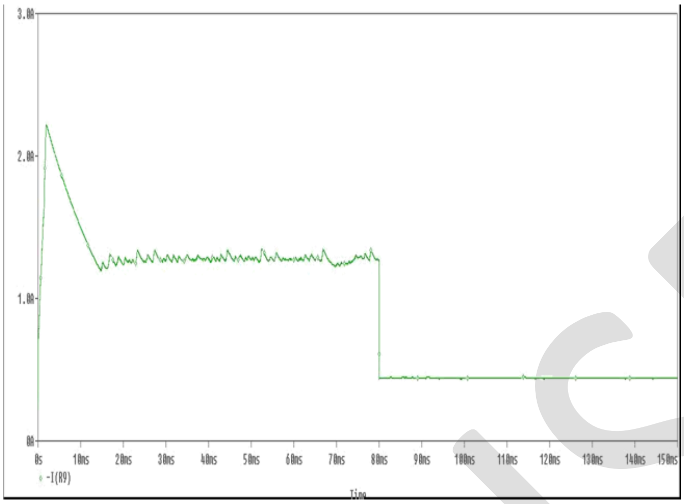
(Figure-13: Po= 60-30 w)



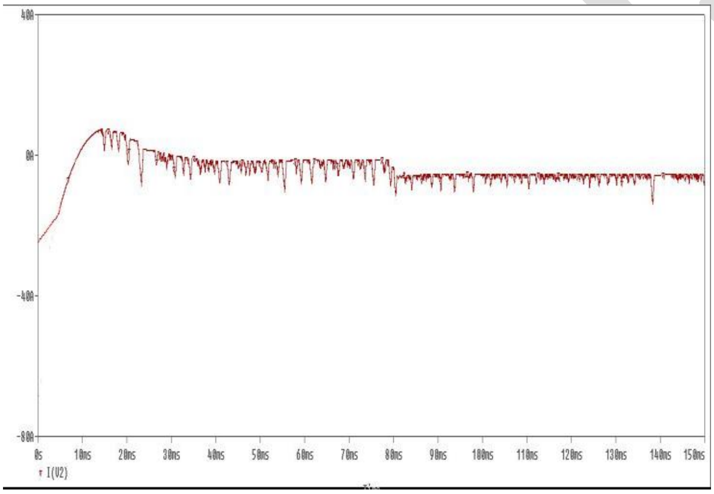
(Figure-14: Input power Pin)



(Figure-15: Battery power P_{bat}.)

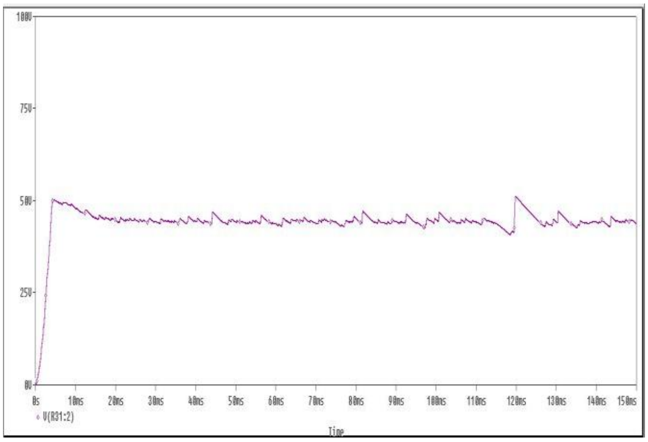


(Figure-16: Load current Io)

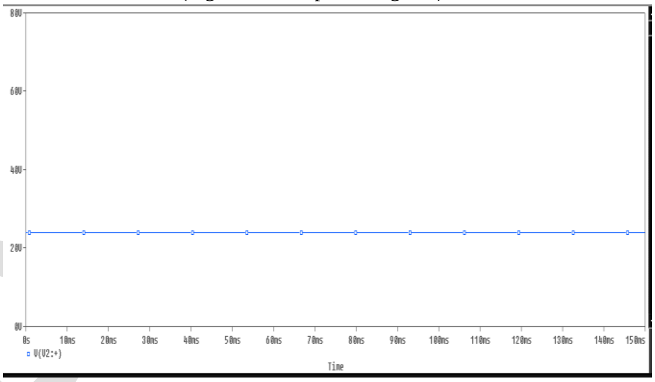


(Figure-17: Battery current I_{bat})

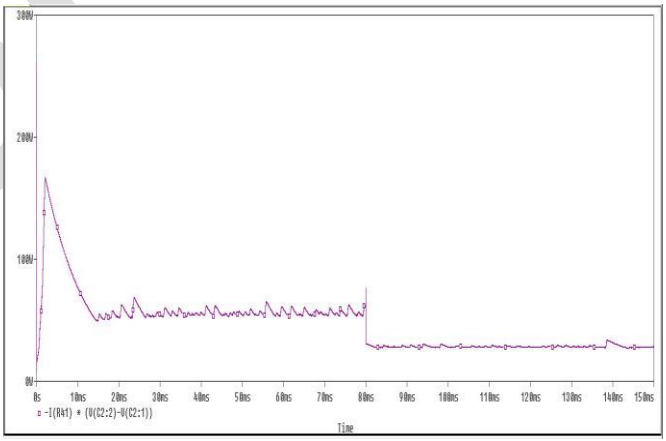
Figure 11 – 17 Shows the input, output and battery voltage, current and power waveforms for high solar intensity, i.e. with Isc=3A.



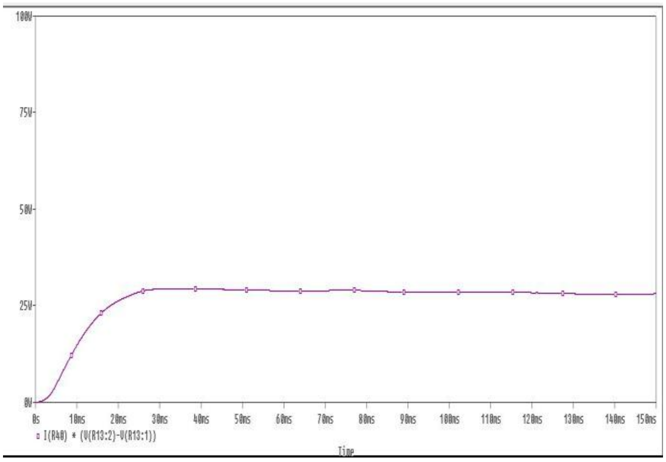
(Figure-18: Output voltage V_o)



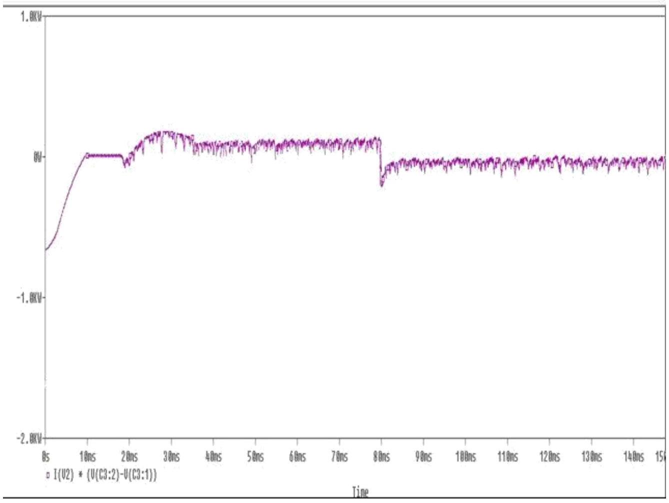
(Figure-19: Battery voltage V_{bat}.)



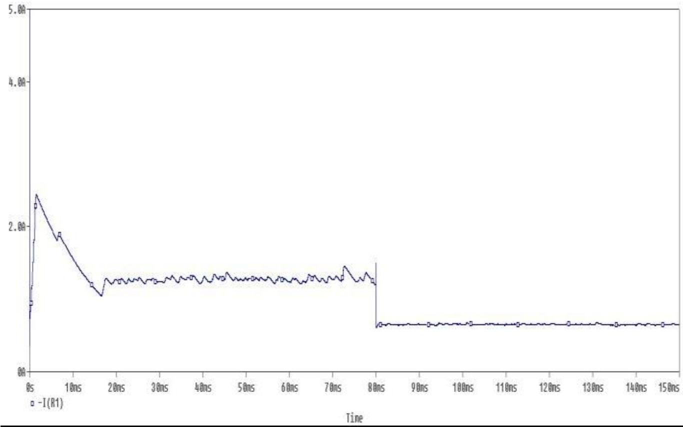
(Figure-20: Load power Po= 60-30w)



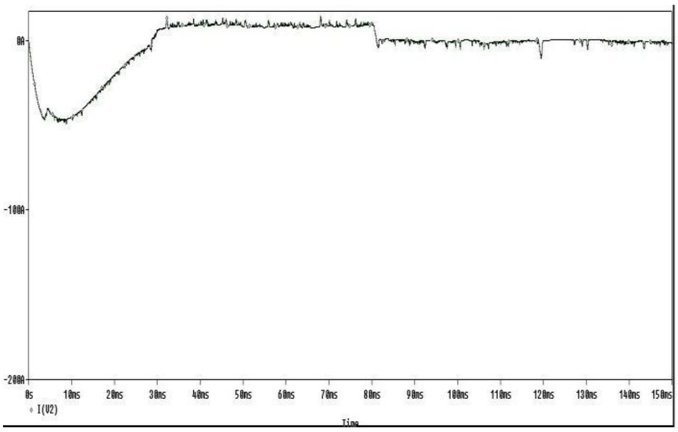
(Figure-21: Input power P_{in})



(Figure-22: Battery power Pbat.)



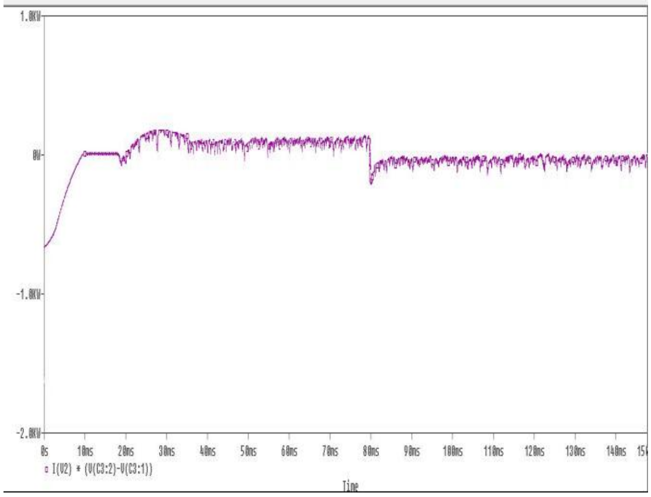
(Figure-23: Load current Io)



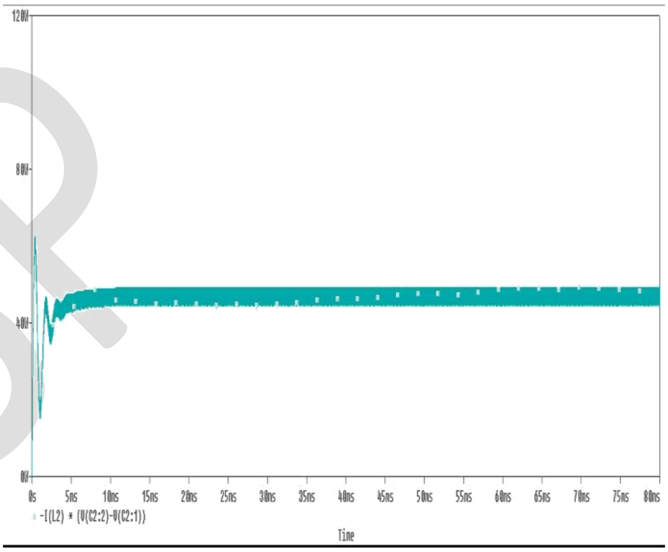
(Figure-24: Battery current I_{bat}.)

Figure 18 – 24 shows the input, output and battery voltage, current and power waveforms for high solar intensity, i.e. with Isc=2A.

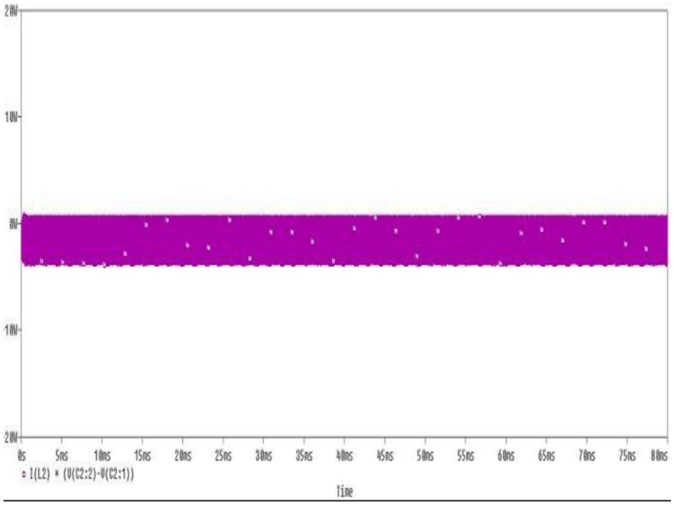
The System without MPPT is less charging and more discharging compared to with MPPT. We can observe below simulation results for I_{sc} =2A P_0=60W P_{in}=37W, P_{bat}.=23W; P_0=30W, P_{in}=37W, P_{bat}=7W.



(Figure-25: Battery Power in Closed loop P_{bat})



(Figure-26: Battery Power in Open loop P_{bat} = 60 W load)



(Figure-27: Battery Power in Open loop P_{bat} = 30W load)

VII. CONCLUSION

Standalone PV system with efficient battery charging controller by proper design equations has been presented in this work. The system has been simulated using MATLAB and the effectiveness of the proposed controller has been highlighted by checking the charging and discharging currents of the battery. PI controller used in this work can be replaced by sliding mode controller to get improved control action.

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