International Journal of Engineering & Technology, 7 (4.22) (2018) 215-220

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Design and Development of Buck/Boost Converter for Maintaining the Constant DC Supply to Meet the Load Requirement.

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Abstract

As the conventional sources are coming to an extent, the new research era has been started with renewable energy sources like solar, wind etc. But with solar, wind power generation is not maintained constant due to the considering parameters like the variation in day-to-day temperature and irradiance. In order to overcome these variations and to meet the required rated power of the PV System, Maximum Power Point Tracking (MPPT) technique has been implemented. The present work describes the design and implementation of photo voltaic (PV) system with Buck/Boost converter. PV system output voltage always varied with irradiance and temperature, to control the voltage use DC-DC buck/boost converter. With the help of DC-DC converter and mode transition from buck to boost vice versa to maintain DC bus voltage constant and feeds to DC loads. Experimental results obtained from a 2.5KW system have verified the discussion and feasibility.

Keywords: *PV System, Buck/Boost converter, DC load, Maximum Power Point Tracking (MPPT).*

1. Introduction

The necessity of new energy resources is go-on increasing in our day to day life as the shortage of fossil fuels and greenhouse effect. Thus, the renewable energy sources are playing a vital role for its important contribution of supply to the global requirement. In fact, the demand of solar, wind, ocean energy has increased drastically over the past decades. Due to the abundance available of solar energy, its growth rate has increased from 20% to 25% over the past 20 years [1]. Thus, the demand for the manufacturing of solar panels has got increased globally with the generation of 4800 GW of solar power. Due to this the consumption growth rate solar energy has got increased to 80% from 2004 to 2016. For improvement of cost, reliability and efficiency, A new research activities are adopted for benefit of PV System. Normally PV system output voltage is variable as well as smaller in magnitude compared to DC bus voltage shown in fig 1, so boost DC-DC converter is used to meet DC bus voltage. But in space applications [2], PV system output voltage may be higher than DC bus voltage buck DC-DC converter is used. These both operations can overcome with Buck-Boost converter but the problem with negative output voltage and duty ratio variations. In buck mode duty ratio varies from 0 to 0.5, boost mode duty ratio varies from 0.5 to 1. To avoid these problems, proposed Buck/Boost DC-DC converter with MPPT method is implemented. Whenever PV system output voltage is more than the DC bus voltage, Buck/Boost converter works in buck mode and duty ratio varied from 0.05 to 0.95 and PV system output voltage is lower than the DC bus voltage, Buck/Boost converter works in Boost mode and duty ratio varied from 0.95 to 0.05. The transition between Buck/Boost mode of an operational flowchart is proposed with Perturb and Observe (P&O) MPPT technique implemented.

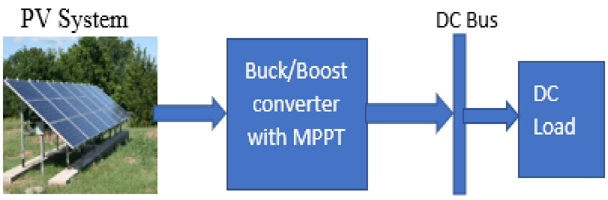

Fig.1: Configuration of DC Distribution system

2.PV system modelling

PV cells are made of semiconductor materials with crystalline, multi-junction and photochemical as the dominant materials. Many PV-Cells are silicon based but in the near future other thin film materials are likely going to surpass silicon PV cells in terms of cost and performance. The use of equivalent electric circuits makes it possible to model characteristics of a PV cell. The method used here is implemented in MATLAB simulations. The same modelling technique is also applicable for modelling a PV module and PV array. PV module is formed by the series and parallel connections of PV cells. Similarly, PV array consists of several photovoltaic modules in series and parallel connections. Series connections are responsible for increasing the voltage of an array whereas the parallel connection is responsible for increasing the current in the array.

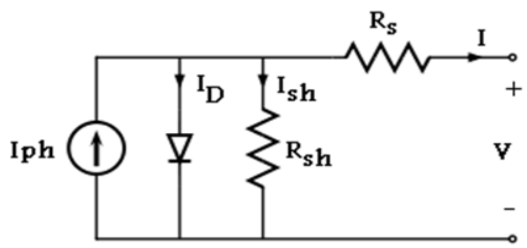

Fig: 2: Equivalent circuit of practical PV device

The circuit diagram of single diode model of the Ideal PV cell model and equivalent circuit of a practical PV device with series and parallel resistances shown in Fig2.The PV cell produces output current I is given by

$$I = I_{PV\,CELL} - I_d - I_{sh} \qquad (1)$$

Here

I is the PV output current in amps

I_d is the virtual diode current in amps and

I_{pvcell} is the current generated by the incident light

I_{sh} is the shunt current in the shunt resistance.

The diode current I_D is given the Shockley's diode equation as:

$$I_d = I_{oCELL}\left(e^{\frac{QV}{\alpha KT}} - 1\right) \qquad (2)$$

Where

I_{ocell} is the reverse saturation current/Leakage current of diode in amps,

Q is the electron charge ($1.602X\,10^{-19}$) in Coulombs,

V is the voltage of the PV cell across the diode in volts,

K is the Boltzmann's constant $1.31X10^{-23}$ in J/K,

α is the diode ideality constant

T is the junction temperature in Kelvin (K).

For this work purchased 10 panels with each panel rating 250Watt consisting in 60 cells made with Multi-Crystalline silicon material so total capacity of the 10 panels are 2.5KW and the specification are given below.

Open circuit voltage V_{OC} = 37.6 Volts,

Short circuit current I_{SC} =8.80Amps

Maximum power voltage V_{mp} = 30.23 Volts,

Maximum power current I_{mp} =8.27 Amps.

Table 1: Power ratings PV panel at 25^0C cell temp and different Irradiance level

Sl.No	Irradiance (Wb/m^2)	Max. Voltage (Volts)	Max. Current (Amps)	Max. Power (Watts)
1	200	30.23	1.6	48.5
2	400	30.23	3.29	99.5
3	600	30.23	4.97	150.4
4	800	30.23	6.64	200.7
5	**1000**	**30.23**	**8.27**	**250**

3.DC-DC buck/boost converter

The figure 3 shows the proposed Buck /Boost converter operated either fully buck converter for duty ratio 0.05 to 0.95 or boost converter for duty ratio 0.95 to 0.05. Depends on the PV system output voltage and DC bus voltage converter operated in buck/boost mode.

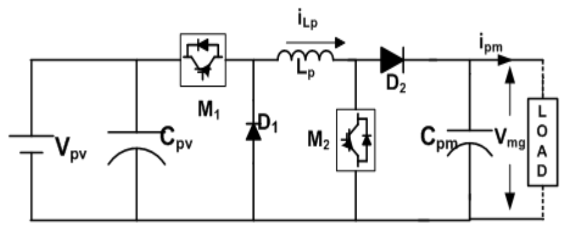

Fig:3: Proposed Buck/Boost DC-DC converter

The analysis assumes the inductor internal resistance R_{LP} and its inductance is L_P.

L_P= Inductance of inductor (H)

R_{LP}=Internal resistance of inductor(Ω)

PV voltage=V_{PV}, PV current =i_{PV}

M1= IGBT for buck operation

M2= IGBT for boost operation

D1, D2=Diodes for operating in M1, M2 in off duty conditions

C_{PV} =PV side capacitor

R_{M1}, R_{M2} =ON state resistance of IGBT s respectively

V_{D1}, V_{D2} = Forward voltage drops across diodes

i_{LP}= inductor current

V_{LP}=voltage across inductor

Complete circuit considering switch, diodes, inductor, and capacitor nonlinearities

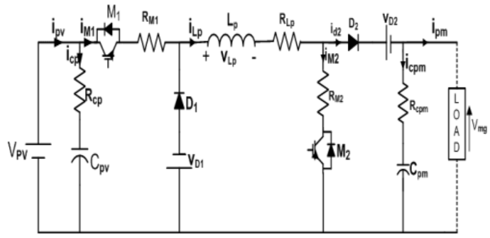

Fig:4: Buck/Boost DC-DC converter with nonlinearities

The main function of DC-DC converter is to get constant output from the PV system. The output of the PV array is given as an input for the converter and the output voltage of DC-DC converter is fed to DC bus voltage. If the output voltage of a PV array is much more than the DC bus voltage, in this case M_2 switch is turned off and the operation of the converter should be in buck mode otherwise boost mode.

Mode1: The power switch M_1 is turned on as shown in Figure.5. Analysis under Buck mode signal to M_2 is always low so this makes the diode D_2 conducts always during Buck mode. The magnetization of an inductance L_P is done by the voltage (V_{PV} – V_{pm}) through power diode D_2.

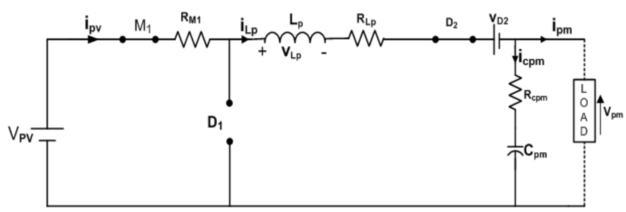

Fig 5: Buck operation while the switch M1 is on

$$V_{LP} = V_{PV} - i_{LP}R_{M1} - i_{LP}R_{LP} - V_{D2} - V_{pm} \quad (3)$$

$$i_{LPm} = i_{LP} - i_{pm} \qquad (4)$$

Mode 2: The M_1 switch is turned off as show in Figure 6. the magnetization of an inductance L_P is done by the output voltage Vo through the D_1 and D_2.

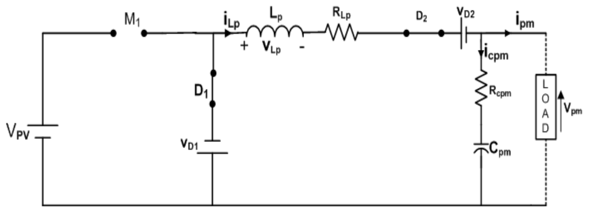

Fig: 6: Buck operation with switch M1 is off

$$V_{Lp} = -V_{D1} - V_{D2} - V_{pm} - i_{Lp}R_{Lp} \qquad (5)$$

$$i_{LPm} = i_{Lp} - i_{pm} \qquad (6)$$

Noticing that voltage across inductor over switching time is zero

$$V_{LP}D + V_{LP}D' = 0; \quad V_{pm}D + V_{pm}D' = V_{pm}$$

$$i_{LP}D + i_{LP}D' = I_{LP}\ ; i_{LPm}D + i_{LPm}\ D' = 0$$

From equations (3) & (5)

$$0 = V_{PV}\ D - i_{LP}(R_{M1}D + R_{LP}) - V_{D2} - V_{pm} - V_{D1}D'$$
$$V_{pm} = V_{PV}\ D - i_{LP}(R_{M1}D + R_{LP}) - V_{D2} - V_{D1}D'$$
$$V_{pm} = (V_{PV} - i_{LP}R_{M1} + V_{D1})D - i_{LP}R_{LP} - V_{D2} - V_{D1}$$

$$\frac{V_{pm} + i_{LP}R_{LP} + V_{D2} + V_{D1}}{V_{PV} - i_{LP}R_{M1} + V_{D1}} = D \qquad (7)$$

From the equation -------------- (5)

$$L\frac{di_{Lp}}{dt} = V_{LP} = -V_{D1} - V_{D2} - V_{pm} - i_{LP}R_{LP}$$

$$L\frac{\Delta i_{Lp}}{dt} = -V_{D1} - V_{D2} - V_{Pm} - I_{Lp}R_{Lp}$$

$$L = \frac{(-V_{D1} - V_{D2} - V_{Pm} - I_{Lp}R_{Lp})D'T_s}{\Delta i_{Lp}} \qquad (8a)$$

Another method

$$L\frac{di_{Lp}}{dt} = V_{LP} = V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - V_{D2} - V_{Pm}$$

$$L\frac{\Delta I_{Lp}}{DT_s} = V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - V_{D2} - V_{Pm}$$

$$L = \frac{V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - V_{D2} - V_{Pm}}{\Delta I_{Lp}} V_{Lp}D \times DT_s \qquad (8b)$$

From the capacitor current balance

$$I_{PM} = I_{Lp}$$

Output capacitor design

$$C\frac{dV_{pm}}{dt} = I_{Lp} + \frac{\Delta I_{Lp}}{2} - i_{pm}$$

$$C\frac{\Delta V_{pm}}{DT_s} = \frac{\Delta I_{Lp}}{2}$$

$$c = \frac{\Delta I_{Lp} \times DT_s}{2\Delta V_{Pm}} \qquad (9)$$

On the off chance that voltage of the PV panel is dependably lower than the bus voltage, the converter will be worked in boost mode. The M_1 switch is turned ON, in the boost mode of operation.

Mode 3: In mode 3 the M_2 switch is turned ON as depicted in figure. 7. the magnetization of an inductance L_P is done by the voltage of a PV panel V_{PV} through the M_1 and M_2 switches.

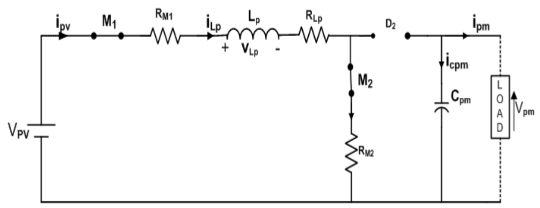

Figure7: Boost operation with switch M2 is on

$$V_{Lp} = V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - I_{Lp}R_{M1} \qquad (10)$$

$$i_{Lpm} = -i_{pm} \qquad (11)$$

Mode 4: In mode 4 the M_2 switch is turned OFF as shown in figure.8. The demagnetization of an inductance L_M is by the difference between voltage of the PV panel (V_{PV}) and DC bus voltage (V_o) through the M_1 switch and power diode D_2.

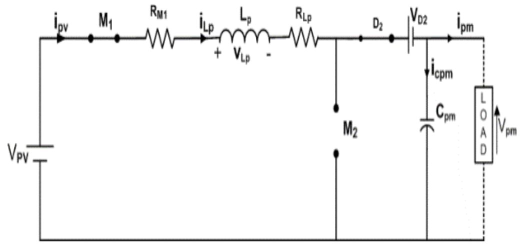

Fig 8: Boost operation with switch M2 is off

$$V_{Lp} = V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - V_{D2} - V_{Pm} \qquad (12)$$

$$i_{Lpm} = i_{Lp} - i_{pm} \qquad (13)$$

From equations (10) & (12)

$$V_{Lp}D' = V_{PV}\ D - i_{Lp}(R_{M1} + R_{Lp}) - i_{Lp}DR_{M2} +$$
$$V_{pv}D' - i_{Lp}D'(R_{M1} + R_{Lp}) - D'V_{D2} - V_{pm}D'$$
$$0 = V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - i_{Lp}DR_{M2} - V_{pm}D' - D'V_{D2}$$

$$0 = V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - i_{Lp}DR_{M2}$$
$$-V_{pm} + V_{pm}D - V_{D2} + V_{D2}D$$
$$(i_{Lp}R_{M2} - V_{pm} - V_{D2})D$$
$$= V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - V_{Pm} - V_{D2}$$

$$D = \frac{V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - V_{Pm} - V_{D2}}{(i_{Lp}R_{M2} - V_{pm} - V_{D2})} \qquad (14)$$

From equation (10) to find inductance L_p

$$L\frac{di_{Lp}}{dt} = V_{PV} - i_{Lp}(R_{M1} + R_{Lp}) - (i_{Lp}R_{M2})$$

$$L\frac{\Delta I_{Lp}}{DT_s} = V_{PV} - i_{Lp}(R_{M1} + R_{Lp} + R_{M2})$$

$$L = \frac{V_{PV} - i_{Lp}(R_{M1} + R_{Lp} + R_{M2})}{\Delta I_{Lp}} DT_s \qquad (15)$$

From equations (11) & (13)

$$i_{Lpm}D + i_{Lpm}D' = i_{LP}\ D' - i_{Pm} = 0$$

$$i_{Pm} = i_{LP}\ D' \Rightarrow i_{LP} = \frac{i_{Pm}}{D'}$$

To design capacitor

From equation (11)

$$C\frac{dV_{pm}}{dt} = -i_{pm}$$

$$C\frac{\Delta V_{pm}}{DT_s} = I_{pm}$$

$$C = \frac{I_{pm} \times DT_s}{\Delta V_{Pm}} \qquad (16)$$

3.1. Design of components under Buck converter:

Converter specifications
Input voltage (V_{pv}) =450V
Output voltage (V_{pm}) =400V
Output current (I_{pm}) =6A
Input current (I_{pv}) =5.46A
Switch on state resistance = $R_{M1} = R_{M2} = 0.5\Omega$
Forward voltage drops= $V_{D1} = V_{D2} = 1V$
Switching frequency f_{sw}=20KHz
Allowed Peak -Peak ripple for inductor current =0.5A
Allowed Peak-Peak ripple output voltage=2V

From the given information Duty ratio of the converter in Buck mode

$$I_{Lp} = I_{PM} (\text{for buck operation})$$

$$D = \frac{V_{pm} + i_{Lp}R_{Lp} + V_{D2} + V_{D1}}{V_{pv} - i_{Lp}R_{M1} + V_{D1}}$$

$$= \frac{400 + 6 \times 0.1 + 1 + 1}{450 - 6 \times 0.5 + 1} = 0.898$$

$$L \geq \frac{V_{pv} - i_{Lp}(R_{M1} + R_{Lp}) - V_{D2} - V_{pm}}{\Delta I_{Lp}} \times DT_s$$

$$= \frac{450 - 6(0.5 + 0.1) - 1 - 400}{0.5} \times \frac{0.898}{20 \times 10^3}$$

$$\geq 4.07 \text{ mH}$$

$$C \geq \frac{\Delta I_{Lp} \times DT_s}{2\Delta V_{pm}} = \frac{0.5 \times 0.898}{2 \times 2 \times 20 \times 10^3} \geq 5.612 \ \mu F$$

Voltage across M1 when it is OFF

$V_{M1} = V_{pv} + V_{D1} = 450+1 = 451V$

Peak current through M1 when it is ON

$$I_{M1} = I_{lp} + \frac{\Delta I_{lp}}{2} = 6 + \frac{0.5}{2} = 6.25A$$

Voltage across D1 when it is OFF

$$VD_1 = V_{pv} + R_{s1}(I_{lp} + \frac{\Delta I_{lp}}{2})$$

$VD_1 \geq 450 + 0.5(6.25)$ =453.125V

Peak current through D2 when it is in ON

$$I_{D2} = I_{lp} + \frac{\Delta I_{lp}}{2} = 6 + \frac{0.5}{2} = 6.25A$$

Design of components under Boost converter:
Let Input voltage (V_{pv}) =302V
Output voltage (V_{pm})==400V
Input current (I_{pv}) =8.27A $I_{lp} = I_{pv}$
Remaining all are same as buck converter

$$D = \frac{V_{pv} - i_{Lp}(R_{M1} + R_{Lp}) - V_{pm} - V_{D2}}{(i_{Lp}R_{M2} - V_{pm} - V_{D2})}$$

Duty Ratio $D = \frac{302 - 8.27(0.5+0.1) - 400 - 1}{(8.27X0.1) - 400 - 1}$ = 0.2597

Inductance Value

$$L \geq \frac{V_{pv} - i_{Lp}(R_{M1} + R_{Lp} + R_{M2})}{\Delta I_{Lp}} DT_s$$

$$\frac{302 - 8.27(0.5+0.5+0.1)}{0.5} X \frac{0.2597}{20X10^3} \geq 6.72\text{mH}$$

Capacitance value

$$C = \frac{I_{pm} \times DT_s}{\Delta V_{pm}}$$

$$C \geq \frac{I_{lp} D^1 + DT_s}{\Delta V_{pm}} \quad (I_{pm} = I_{lp} D^1)$$

$$C \geq \frac{8.27X(1-0.2175)X0.2597}{2X20X10^3} \geq 39.74\mu F$$

Voltage across switch M_2 when it is OFF

$$VM_2 = V_{pm} + VD_2 = 400 + 1 = 401V$$

Current through Switch M_2 when it is ON

$$IM_2 \text{ Peak} = I_{lp} + \frac{\Delta I_{lp}}{2}$$

$$= 8.27 + \frac{0.5}{2} = 8.52 \text{ A}$$

Voltage across D2when it is OFF

$$VD_2 = V_{pm} - I_{lp}R_{M2}$$

$$= 400 - 8.52X0.5 = 395.74V$$

Current through it when D2is conducting

$$I_{D2} = I_{lp} + \frac{\Delta I_{lp}}{2} = 8.27 + \frac{0.5}{2} = 10.25A$$

From the design parameters of Two modes of converters individually out of maximum values can be chosen.

Table II: Design parameters

$L \geq 7.606mH$	From Boost Mode
$C \geq 39.74\mu F$	From Boost Mode
V_{M1} = 451 V	I_{M1} = 6.25A
V_{D1} = 453.125V	I_{D1} = 6.25A
V_{M2} = 401V	I_{M2} = 8.52A
V_{D2} =395.74V	I_{D2} = 8.52 A

3.2. Transition from BUCK /BOOST Mode of Operation

The transition among buck and boost modes is a very critical control issue. In case the voltage of the PV array and the DC bus voltage are extremely each other, Due to malfunctioning of the power switches voltage and current oscillations may take place [3-4]. To meet the load requirement with PV system even in dual mode, proposed mode transition scheme as shown in Fig. 9. If PV array voltage is higher than the DC bus voltage, mode transition scheme selects buck mode and PV array voltage (V_{PV}) is approaching DC bus voltage (V_O), the duty ratio of M_1 will be raised to 99.5%. Then, the working mode is changed from buck to boost mode and the duty ratio of M_2 will be decreased to 0.05%.

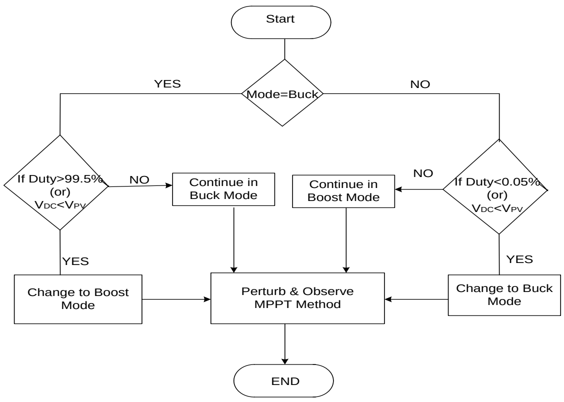

Figure 9: Step by step procedure for mode conversion

3.3 Maximum Power Point Tracking Algorithms

A good characteristics of PV arrays are converts only 30 to 40 percent of the occurrence solar irradiation into electrical energy. To get the maximum output power from the PV arrays use either Mechanical Tracking or Electrical tracking. Among those electrical tracking known as Maximum power point tracking technique. The source impedance of the circuit is matched with load impedance then only maximum power will be produced according to Maximum Power Transfer theorem. But in practical applications while tracking the maximum power point, the load impedances are not matched with source impedance. In the source side we use either buck / boost convertor with MPPT to enhance the required output voltage. This output voltage is used for different applications like lighting load, resistive load and motor load. For matching the impedances of load and source sides, by varying the duty ratio of the proposed converter appropriately [5]. Tracking the maximum power point (MPP) of a PV array is crucial part of a PV system. Many researchers have been developed and implemented new MPPT techniques. But the problem with convergence speed, cost, effectiveness, implementation hardware.

3.4. perturb and observe (p & o) algorithm:

In Perturb & Observe algorithm the controller adjusts the voltage by a small amount from the PV array and measures power perturbed by a small increment, if the difference in power is positive, then increase the PV array voltage by modification of duty ratio until the power reaches the maximum value [6].

If Power is negative, reduce the PV array voltage and observe the power upto change in power is zero, corresponding algorithm shown in fig 10.

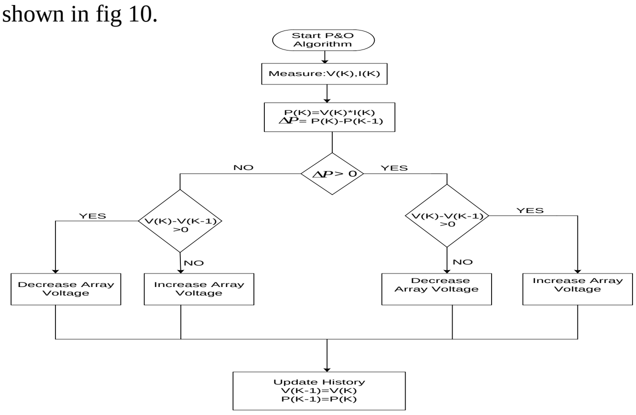

Fig 10: Flowchart of Perturb & Observe algorithms

4. Result analysis

The Proposed Buck/Boost Converter theoretical calculations are done, and system parameters are shown in table II. For implementation of this work, 10 solar panels are purchased and their power ratings at 25^0C cell temperature and different irradiance variations shown in table I, and solar panels available in figure 16. Normally PV output voltage varied due to weather conditions for meeting the load demand, buck/boost converter is designed and Simulation analysis has been carried out in different situations at t=0.3 sec PV system is ON, PV voltage more than DC bus voltage converter operated in buck mode, at t=0.4 sec PV system output voltage lower than DC bus voltage converter operated in boost mode, at t=0.5 sec boost with MPPT ON corresponding voltage , current and power wave forms shown in Figure 11 in MATLAB SIMULINK platform and hardware results are available in fig.14 & 15 without MPPT and With MPPT respectively. Comparison between solar output parameters without MPPT and with MPPT showed in Table:III

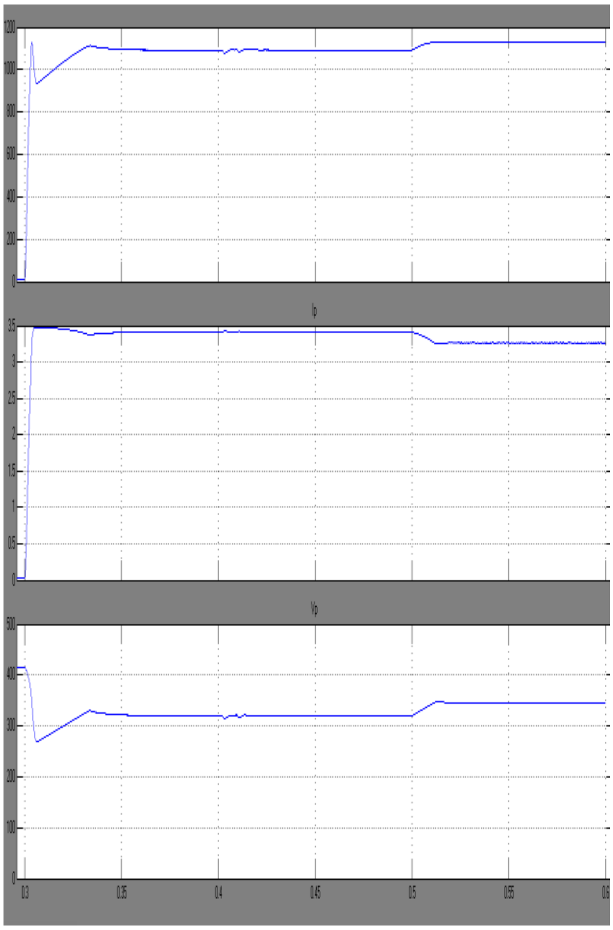

Fig:11: Simulation results of buck/Boost converter.

Based on the designed parameters experimental setup will established in Laboratory shown in figure 16 with input panels connected top of the EEE block shown in fig 16 and corresponding observations are Buck/boost mode of operation pulses shown in fig 12 and 13. Fig: 17. Shows the experimental setup established in Power Electronics and Drives Laboratory.

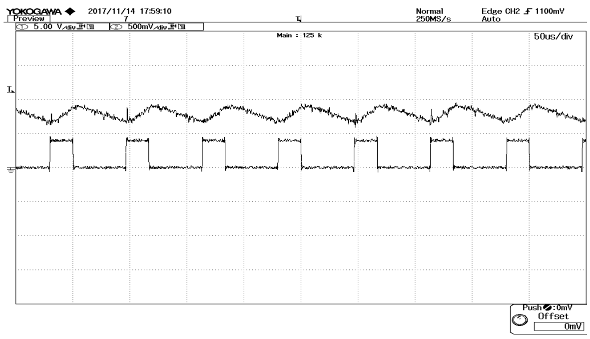

Fig: 12: Buck/Boost converter operated in Boost mode pulses

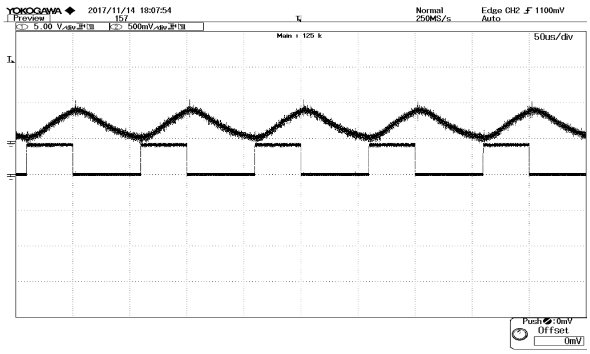

Fig:13 :Buck/Boost converter operated in Buck mode pulses

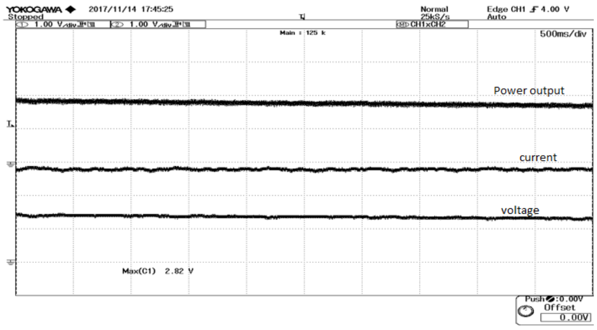

Fig: 14: PV system output voltage, current & power without MPPT ON

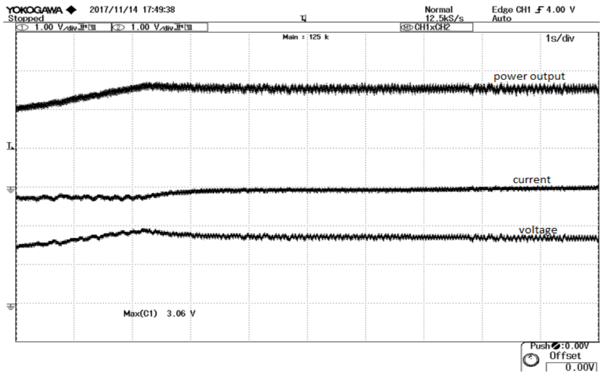

Fig: 15: PV system output voltage, current & power with MPPT ON

Fig: 16 :Solar Panels connected in series

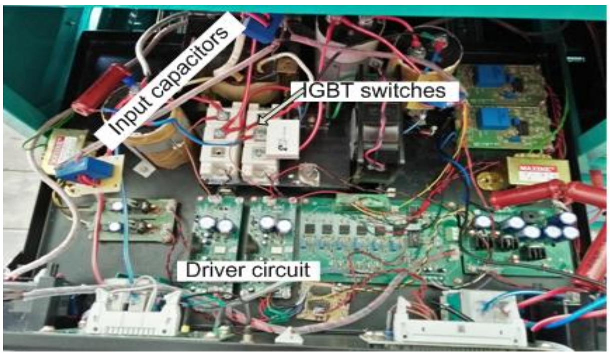

Fig: 17: Experimental setup established in Laboratory

Table-III: Comparison of solar output hardware and simulated results

Parameter	Solar Output without MPPT		Solar Output with MPPT	
	Simulated	Hardware	Simulated	Hardware
Voltage (V)	300	280	345	340
Current (I)	3	2.82	3.27	3.06
Power (W)	900	790	1128	1040

5. Conclusion

In this paper, the proposed Buck/Boost converter design and development for maintaining the constant DC supply to meet the load requirement with solar MPPT. Generally, solar output voltage is in deficient to the load requirement due to abnormal weather conditions like variable irradiance and variable temperature. For increasing solar output, we are incorporating with the perturb and observe based MPPT. But for some applications boost converter alone and buck converters alone are not meeting the load requirements, to provide the constant dc supply to the load. So, here, we are proposing the buck-boost converter in addition to the MPPT. Because, its duty cycle range can be controlled from 0 to 1. Where, which not possible with buck and boost converters alone. i.e. range of duty cycle can be varied from 0 to 0.5 for buck and 0.5 to 1 for boost converters alone. If this is the case, that the DC constant supply cannot be met. That the reason, a proposed buck/boost converter with MPPT is used. The main advantage of Buck /boost coveter is based on voltage levels of PV system and DC bus. That the corresponding results obtained from a 2.5KW system are verified with theoretical and practical validations.

Acknowledgment

This research is sponsored by means of the Science & Engineering Research Board under grant “Empowerment and Equity opportunities for Excellence in Science”, No SB/EMEQ-322/2014, Dairy No. SERB/F/344/2015-16 dated 14.05.2015.

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