International Journal of Engineering & Technology, 7 (4.6) (2018) 510-519

International Journal of Engineering & Technology

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

Research paper

Level Boosting DC-DC Converter for Solar Energy Conversion System

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Abstract

The conversion of light energy into electrical energy has extensively increasing because it offers less pollution and its wide availability. Maintaining the constant DC output power from the panel is the key issue in solar PV system. Solar irradiation and temperature of the solar cells are the two factors effects the output of the PV modules, in the proposed converter. To get better conversion gain ratio the Switched Inductor/Capacitor Branch is replacing the existing inductor in the conventional boost converter. The conduction loss can be lessened by adopting the switch with low resistance. In addition, the reverse-recovery issue of the diodes is eliminated, and thus, the efficiency can be further improved. In this paper, Perturb and Observe (P&O) algorithm is used along with proposed boost converter to track the MPPT from the solar cell and to improve the DC output by providing suitable duty cycle. The number of components used in converter has been reduced and converter efficiency is improved. The proposed work is verified through MATLAB/SIMULINK.

***Keywords**: Duty cycle, DC-DC converter, Switched Inductor/Capacitor Branch, MPPT*

1. Introduction

The key concern inside the power sector is that the everyday expanding power demands however the bother of enough resources to satisfy the power requirement utilizing the standard energy sources. Demand has expanded for renewable sources of energy to be utilized alongside typical systems to fulfill the energy demand. Renewable sources like wind energy and solar energy are the prime energy sources that are being used. The nonstop utilization of fossil fuels have caused the fossil fuel deposit to be decreased and has radically affected the environment draining the biosphere and in total adding to global warming. Solar energy is luxuriously possible that has made it feasible to procure it and use it legitimately. Solar energy will be an independent generating unit or will be a grid connected generating unit relying upon the convenience of the grid nearby. So it will be accustomed to power rural areas wherever the supply of grids is to a great degree low. Another favorable position of utilizing solar energy is that the moveable operation at whatever point wherever necessary.
In modern power applications, boost converter is one amongst the most significant and wide used devices. Many applications require high step-up, DC-to-DC converters. The applications like renewable energy systems, fuel cells, and UPS system. By and by, because of the impact of power switches, the Equivalent Series Resistance (ESR) of the inductors and capacitors and rectifier diode, the step-up voltage gain is lessened. Likewise, the serious reverse-recovery and electromagnetic interference issues because of extraordinary duty cycle operation [4]. It is anything but difficult to modify the turns ratio of the forward and fly back converters to accomplish a high step up voltage gain. Be that as it may, the main switch will endure high power dissipation and high voltage spike caused by the leakage inductor of the transformer [7].
In spite of the fact that the active clamp-circuits and non-dissipative snubber circuits can be utilized, the cost is expanded because of high side driver and the additional power switch [15]. Many step- up converters have been proposed, to boost the conversion efficiency and accomplish a high step-up voltage gain [3]-[5], [24]. A high step-up voltage gain can be accomplished by the utilization of the switched-capacitor [19], [22], [24], [25], [27] and voltage-lift [2]-[5] procedures. However, the switch will suffer conduction loss and high charged current. To attain a high step-up gain, the converters use the coupled-inductor technique [4], [24], [25]. Nonetheless, the switch will endure conduction loss and high charged current. To accomplish a high step-up gain, the converters utilize the coupled-inductor method [4], [24], [25]. However the main switch experiences a voltage spike influences the conversion efficiency due to the leakage inductor. To defeat this, the converters utilizing a coupled inductor with an active-clamp circuit have been proposed [15], [16]. In addition, a few converters with a passive clamp circuit to decrease the voltage stress on the main switch [24], [25]. The auxiliary side of the coupled inductor of an integrated boost fly back converter is utilized as a fly back converter [15]. Hence, it can increase the voltage gain. Likewise, the leakage inductor energy is reused to the output load directly, restricting the voltage spike on the main switch. By the turns ratio of the coupled inductor, the voltage stress on the main switch can be balanced. It has been suggested that the secondary side of the coupled inductor can be utilized as

fly back and forward converters to accomplish a high step-up gain [15], [17]. Numerous converters that are proposed to combine output -voltage stacking to enhance the voltage gain [14]. Moreover, a high step-up boost converter has been recommended that uses multiple coupled inductors with output stacking [5], [16]. This paper proposes a level boosting DC-DC converter to accomplish high step-up voltage gain and efficiency. The proposed converter includes one capacitor, three inductors and three diodes to accomplish high step-up voltage gain. Perturb and Observe technique is utilized alongside the proposed boost converter to track the MPPT from the solar panel. To enhance the dc output by giving appropriate duty cycle.

2. Operation of Boost Converter

The input voltage magnitude is stepped up to the required magnitude without utilizing the transformer by the use of Boost converter. The principle parts of a basic boost converter are a diode, an inductor and a high frequency switch as appeared in Fig.1. These are in a synchronized way; the load is fed a voltage more noteworthy than the magnitude of the input voltage. The duty cycle of the switch is controlled to control the voltage change. Boost converter can be operated in two modes. During ON state, the source charges the inductor through the switch and the flow of current to the load is limited by the diode and the capacitor satisfies the demand of the load. At the point when the turn is OFF the diode is forward biased. The inductor releases and together with the source charges the capacitor and takes care of the load demand.

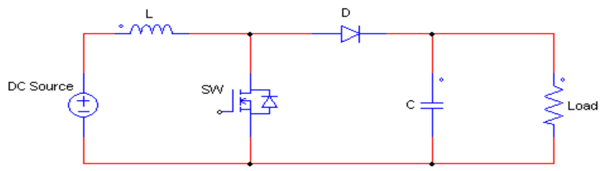


Fig. 1: DC-DC boost converter

The solar cell efficiency is very low, in order to enhance the efficiency a few strategies are to be embraced to coordinate the source and load appropriately. One such common method is Maximum Power Point Tracking (MPPT). This strategy is utilized to track the maximum possible power from the variable source. The I-V curve of the PV systems is non-linear, consequently making it hard to be utilized power a specific load. This is done by using a boost converter whose duty cycle is changed by utilizing an MPPT algorithm. Among several techniques mentioned, the Perturb and Observe (P&O) method and the Incremental Conductance (In Cond) algorithms are the most commonly applied algorithms. In the P&O method only one voltage sensor is used to sense the PV array voltage and hence the cost of implementation is less. In this project Perturb and Observe (P&O) algorithm is used along with a newly proposed boost converter to track the MPPT from the solar cell and to improve the dc output.

3. Operating Principle of Proposed Converter

Fig.2 shows the topology of the proposed converter which, is composed of solar PV array as input, one main switch, three inductors L_{f1},L_{f2}, L_{f3}, one capacitor C_1, three diodes D_1, D_2 and D_3, output diode D_O and output capacitor C_O.

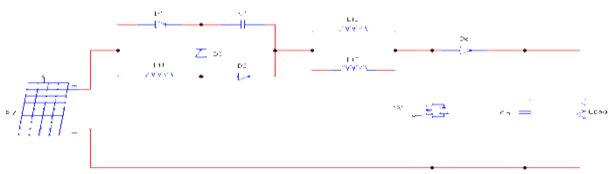


Fig. 2: Schematic diagram of proposed level boosting DC-DC converter

Fig.3 shows the simplified diagram of proposed converter. The solar PV array is considered as DC voltage source V_S which, is the input to the converter circuit. The low conducting resistance $R_{DS(ON)}$ can be adopted to reduce the conduction loss. Switched inductor branch in series with coupled inductors which have been introduced in the proposed converter. By replacing the inductor of the traditional DC-DC converter with the switched inductor/capacitor branch in series with coupled inductors. The original voltage-clamp circuit was first proposed in [16] to recycle the energy stored in the leakage inductor. Based on the topology, the proposed converter combines the concept of coupled-inductor and switched-capacitor techniques. The switched-capacitor technique in [19] has proposed that capacitors can be parallel charged and discharged in series to achieve a high step-up gain.

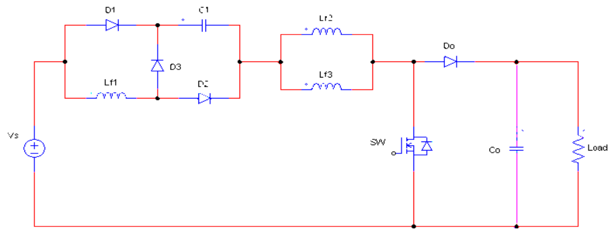


Fig. 3: Simplified diagram of proposed level boosting DC-DC converter

Based on the concept, the proposed converter puts the capacitor C_1 and inductor L_{f1} in the switched inductor/capacitor branch and the inductors L_{f2}, L_{f3} are connected them parallel which is in series with the switched inductor/capacitor branch. Thus, inductor L_{f1} and capacitor C_1 are charged in parallel and are discharged in series by the diodes when the switch is turned on and turned off, the high gain is achieved significantly. Also, the voltage stress of the switch can be reduced and the conduction losses can be low.

4. Operation of Boost Converter

The modes of operation of the proposed converter are presented in this section. The following analysis contains the explanation of the power flow direction of each mode.

a) Mode I (Charging Mode)

The proposed converter has two modes of operations. Mode I occurs when switch SW is ON, this causes diodes D_1 and D_2 to be turned ON and diode D_3 to be turned OFF. Thus the two branches of inductor, capacitor L_{f1} and C_1 are charge in parallel and simultaneously the coupled inductors L_{f2} and L_{f3} charge in parallel. The diode Do restricts the flow of current from the source to the load and the demand of the load is met by the discharging of the capacitor C_O. Fig. 3 (a) shows the proposed converter circuit when the switch is turned ON. Inductor voltage and capacitor current in this mode are given in Equations (1) and (2).

$$V_L = \frac{V_S}{2} \quad (1)$$

$$I_C = \frac{-V_o}{R} \quad (2)$$

b) Mode II (Discharging Mode)

Mode II occurs when switch SW is turned OFF, this causes diodes D_1 and D_2 to be OFF and diode D_3 is ON, and hence the two branches of inductor, capacitor L_{f1} and C_1 discharge in series and the coupled inductors L_{f2} and L_{f3} in parallel. In this mode of operation, the switch is open and the diode Do is forward biased. The inductors and capacitor now discharges and together with the source charges the capacitor and meets the load demands. The load current variation is very small and in many cases is assumed constant throughout the operation. Figure 3 (b) shows the proposed converter circuit when the switch is turned OFF.

Inductor voltage and capacitor current in this mode are given in Equations (3) and (4)

$V_S = 3V_L$

Here, $V_C = V_L$, since inductor and capacitor stores equal energy

$$V_L = \frac{1}{3}(V_S) \tag{3}$$

$$Ic = I - \frac{Vo}{R} \tag{4}$$

Here, I is the total current through the circuit.

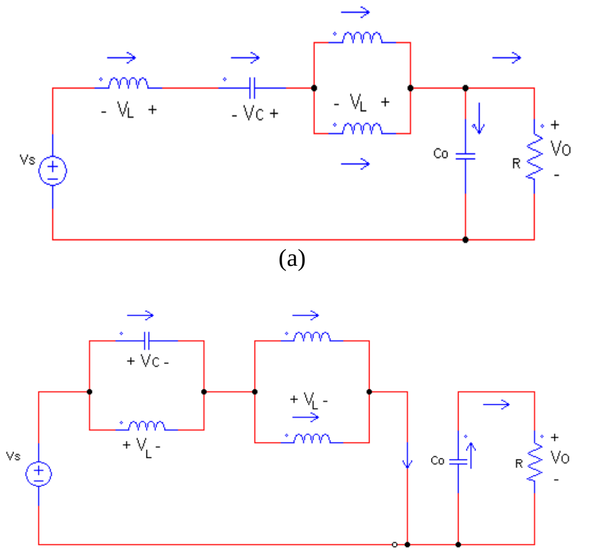


Fig. 3: (a) Mode I Operation of proposed converter (b) Mode II Operation of proposed converter

5. Perturb and Observe Algorithm for Proposed Converter

The demand of the solar photovoltaic generation systems being increased for both standalone and grid connected PV systems. An efficient Maximum Power Point Tracking (MPPT) technique is necessary to track the maximum power at all environmental conditions. Perturb and Observe (P&O) method is applied for the proposed converter to extract maximum power point from the PV module. The Perturb and Observe algorithm is used to provide suitable duty cycle to the proposed boost converter.

In this technique, the controller modifies the voltage by a small amount from the array and measures power; if the power increments facilitate changes toward that path are attempted until power no longer increases. This is called Perturb and Observe strategy and is most normal, in spite of the fact that this technique can bring in oscillations of power output. Flow chart and Simulink diagram of Perturb and Observe method are shown in below Fig. 4 & 5 respectively.

Perturb and Observe is the most commonly used MPPT method due to its ease of implementation. Perturb and Observe method may result in top-level efficiency, provided that a proper predictive and adaptive hill climbing strategy is adopted [18]. The PV voltage and current are received from sensors by the controller where the MPPT control can adjust the duty cycle using Perturb and Observe method. The Perturb and Observe method sense the voltage and current from the PV array and then measures the power. If P(k)-P(k-1) is not zero then go for condition. Based on that, condition voltage is adjusted.

The Perturb and Observe algorithm for the proposed boost converter is implemented using the Embedded MATLAB function of Simulink as shown in Fig. 5, where the codes written inside the function block are utilized to vary certain signals with respect to the input signals.

6. Steady state analysis of the proposed converter

In the Mode-I operation, when the switch is turned 'ON'. Thus the following Equations can be formulated based on the converter circuit as shown in the Fig. 3 (a):

$V_s = V_L + V_L = 2V_L$

Here, $V_C = V_L$, since inductor and capacitor stores equal energy

Voltage across inductor,

$$V_L = \frac{V_S}{2} \tag{5}$$

The energy input to the inductor from the source during period 'Ton'is,

Win= [Voltage across 'L']* [Average current through 'L']*Ton

$$W_{in} = \left[\frac{V_s}{2}\right] * \left[\frac{I_1+I_2}{2}\right] * T_{on} \tag{6}$$

In the Mode-II operation when the switch is turned 'OFF'. Thus the following Equations can be formulated based on the converter circuit as shown in the Figure 3 (b):

By applying KVL,

$V_0 = V_S + 3V_L$

Voltage across the inductor,

$$V_L = \frac{V_0 - V_S}{3} \tag{7}$$

The energy released by the inductor to the load during the 'T_{off}' is,

W_{off} = [Voltage across 'L']* [Average current through 'L']* T_{off}

$$W_{off} = \left[\frac{V_0 - V_S}{3}\right] * \left[\frac{I_1+I_2}{2}\right] * T_{off} \tag{8}$$

Assumed as system to be lossless system by considering W_{in} and W_{off} are equal

Then, by equating Equations (6), (8) as,

$W_{in} = W_{off}$

$$\frac{V_S}{2}\left[\frac{I_1+I_2}{2}\right] * T_{on} = \left[\frac{V_0 - V_S}{3}\right] * \left(\frac{I_1+I_2}{2}\right) * T_{off}$$

By cancelling the common terms on both sides, we get,

$$\frac{V_S}{2} * T_{on} = \frac{V_0}{3} * T_{off} - \frac{V_S}{3} * T_{off}$$

By taking V_O term outside,

$$\frac{V_0}{3} * T_{off} = V_S\left[\frac{T_{on}}{2} + \frac{T_{off}}{3}\right]$$

$$V_o = \left[\frac{3V_S}{2} * \frac{T_{on}}{T_{off}}\right] + V_S$$

$$V_o = V_S\left[1 + \frac{3}{2} * \frac{T_{on}}{T_{off}}\right]$$

The total time period,

$$T = T_{on} + T_{off} \tag{9}$$

From the above Equation T_{on} = T - T_{off}, so the above Equation is written as,

$$V_o = V_S\left[1 + \frac{3}{2} * \frac{T - T_{off}}{T_{off}}\right]$$

$$V_o = V_S\left[1 + \frac{3}{2}\left(\frac{T}{T_{off}} - 1\right)\right]$$

By simplifying the above expression, V_o is obtained as

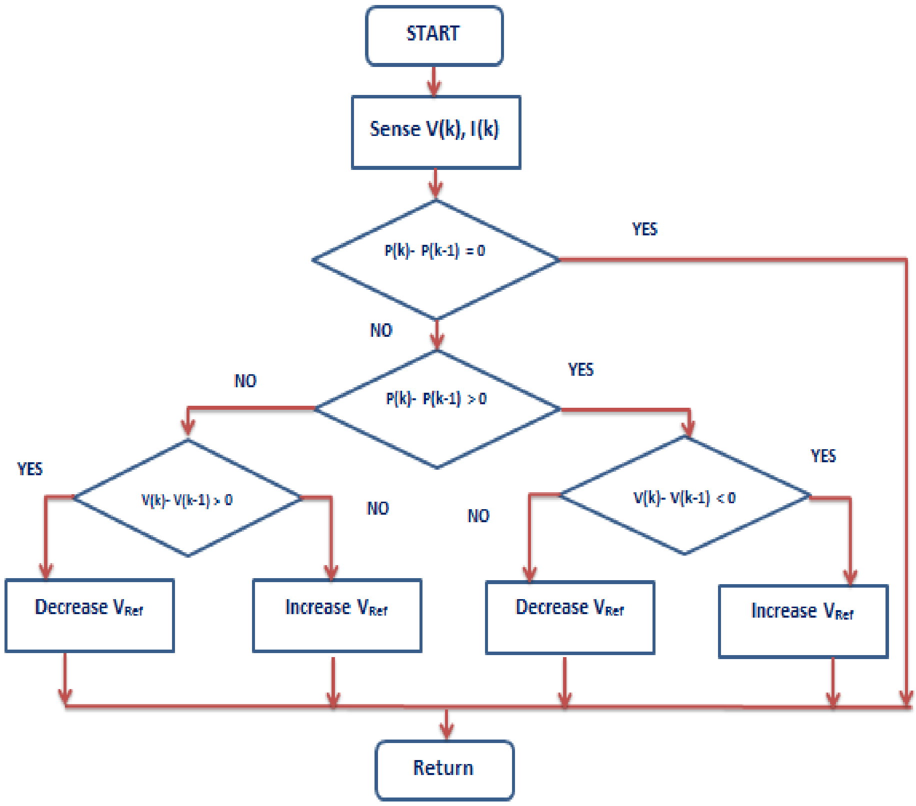


Fig. 4: Flowchart for Perturb and Observe method

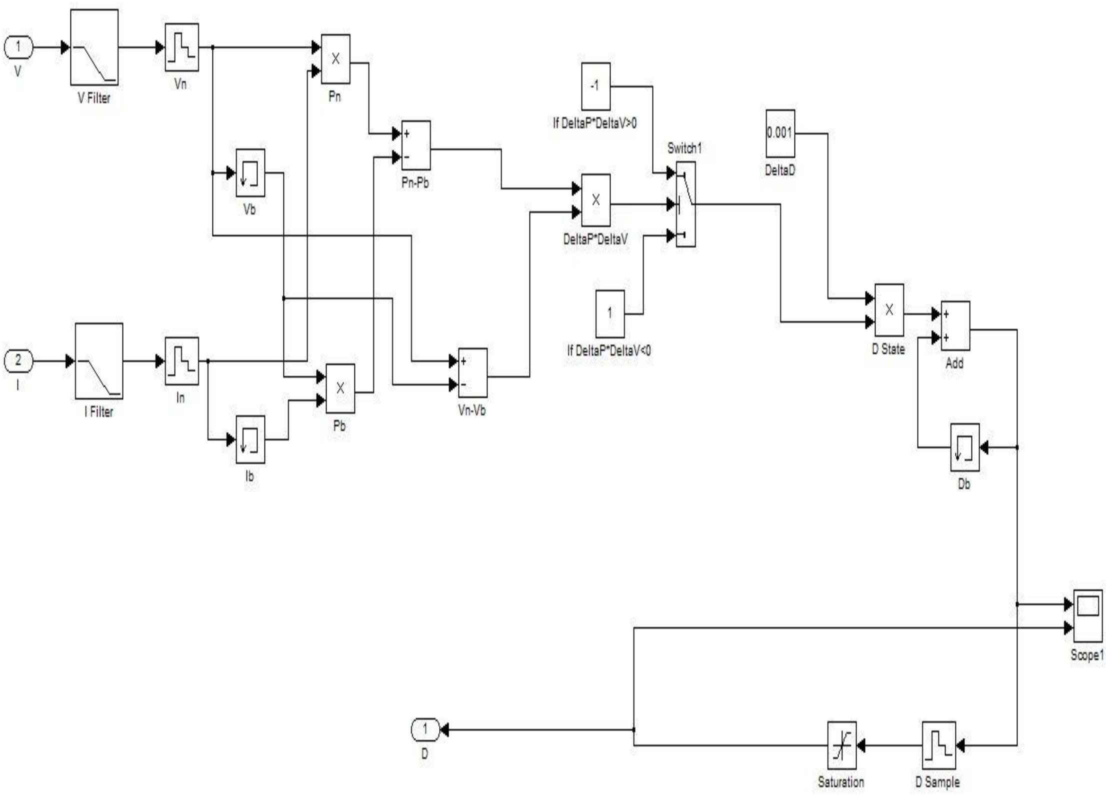


Fig. 5: Simulink diagram for Perturb and Observe method

$$V_o = V_S\left[\frac{3}{2} * \frac{T}{T_{off}} - \frac{1}{2}\right]$$

Substituting Equation (9) in the above expression,

$$V_o = V_S\left[\frac{3}{2} * \frac{T}{T - T_{on}} - \frac{1}{2}\right]$$

From the definition,

Duty cycle, $D = \frac{T_{on}}{T}$ (10)

By substituting the Duty cycle 'D' in the above expression,

$$V_o = \frac{V_S}{2}\left[\frac{3}{1-D} - 1\right]$$

After simplification we get the output voltage V_o as obtained below,

Output Voltage, $V_o = \frac{V_S}{2}\left[\frac{2+D}{1-D}\right]$ (11)

From the above expression the voltage gain of the proposed converter is obtained by

$G = \frac{V_o}{V_S} = \frac{1}{2}\left[\frac{2+D}{1-D}\right]$; 'D' is the Duty cycle (12)

If switch is always OFF, D = 0 and V_o=V_S

If switch is always ON, D =1 and V_o=∞

In practical, switch is turned ON and OFF, so that D is variable and the required step up output voltage more than the source voltage is obtained.

From the above Equation (11), the Duty cycle is obtained as,

$$V_o = \frac{V_S}{2}\left[\frac{2+D}{1-D}\right]$$

By cross multiplying the above Equation, we get,

$$2[V_o - DV_o] = 2V_S + DV_S$$

$$2V_o - 2V_S = DV_S + 2DV_o$$

Taking 'D' as common in the above expression, Duty cycle 'D' as obtained below,

$D = \frac{(V_o - V_S)}{V_o + \frac{V_S}{2}}$ (13)

Calculation of Efficiency:

Average inductor current or input current

$I_{in} = \frac{I_o}{1-D}$ (14)

Efficiency (E) of the Converter is,

$$E = \frac{\text{Input power} - \text{Losses}}{\text{Input power}}$$

$$E = \frac{P_{in} - [P_S + P_L + P_D]}{P_{in}}$$

Where,

The power input = Pin

The power loss in Switch is, $P_S = R_{on} * D * \left[\frac{I_o}{1-D}\right]^2$

The power loss in Inductor is, $P_L = R_L * \left[\frac{I_o}{1-D}\right]^2$

The power loss in Diode is, $P_D = \left(R_d * {I_o}^2\right) + (V_f * I_o)$

Switch ON condition losses:

In the proposed converter when the switch is turned ON the power loss occurs in the components L_{f1}, L_{f2}, and L_{f3}, D_1, D_2, D_3 and switch. Power loss in switch occurs only when switch is turned ON.

By substituting Equation (14) in above expressions,

$P_S = R_{on} * D * {I_{in}}^2$ (15)

$P_L = 3R_L * \left[\frac{I_{in}}{2}\right]^2$ (16)

The power loss in the input side diode is given by,

$P_{Di} = 2\left(R_d\left[\frac{I_{in}}{2}\right]^2 + V_f\left[\frac{I_{in}}{2}\right]\right)$ (17)

The load side isolated, so that output side diode losses does not occur.

Switch OFF condition losses:

The switch is turned OFF, hence no current flow through the switch thus no power loss in the switch. Only the power losses in the components L_{f1}, L_{f2}, L_{f3}, D_3 and diode D_o at the output side.

$P_L = R_L * {I_{in}}^2 + 2R_L * \left[\frac{I_{in}}{2}\right]^2$ (18)

Input side diode losses,

$P_{Di} = R_d * {I_{in}}^2 + V_f * I_{in}$ (19)

Output side diode losses,

$P_{D0} = R_d * {I_0}^2 + V_f * I_0$ (20)

7. Results and Discussion

The fundamental issues of PV generation are efficiency and power quality. Fig. 6 shows a proposed level boosting DC-DC converter for solar energy conversion system. The proposed system consisting of solar PV module, DC-DC converter and control circuit. PV power sources are usually integrated with control algorithms that have the task of ensuring Maximum Power Point (MPP) operation. In this paper the Perturb and Observe of MPPT is used along with the proposed converter. The proposed converter was simulated in MATLAB /Simulink which is given in Fig. 6 that includes the solar PV module circuit subsystem (MATLAB model), DC-DC Boost converter, and P&O algorithm. Fig. 6.1 and 6.2 shows the MATLAB models for solar PV subsystem, Perturb and Observe (P&O) algorithm and pulse generation using MPPT algorithm respectively.

PV module is modelled based on the electrical equations to provide voltage and current to the boost converter. For PV module, the temperature is constant at 25°C and the irradiation (G) level is 1000 W/m2. The PV voltage equals approximately 75 V and PV current equals approximately 12.3 A. The PV voltage and current are received from sensors by the controller where the MPPT control can adjust the duty cycle using Perturb and Observe. High perturbation is chosen when the operating point is far from MPP and low perturbation is chosen when the operating point is nearer to MPP. When the obtained tracked power is equivalent or close-by actual maximum, the variation in the duty cycle is least such that the memory increase value is chosen. Fig. 8 shows the MPPT control output signal, which is the desired duty cycle for the proposed converter.

For the proposed converter there are two modes of operation and Fig. 3 (a) and 3 (b) shows the operating stages of each mode. The operating modes charging and discharging modes are described in section III. Fig. 9 shows the typical waveforms of the proposed level boosting DC-DC converter under full load condition. The waveforms of input side capacitor voltage V_{Cin}, current through inductors L_{f2}, L_{f3}, output side diode current I_{Do} and output side capacitor voltage V_{Co} are shown in below figure. The current through both inductors L_{f2} and L_{f3} are equal. These waveforms show that inductors and capacitors are charged in different time durations. When the switch is turned ON, the inductors L_{f1}, L_{f2}, L_{f3} and capacitor C_1 are charged in parallel at the same time the diode current I_{Do} is zero because diode is reverse biased. However, the charged inductors and capacitors in the switched inductor branch are discharged during the switch OFF period.

The output side diode is forward biased during the switch turn-off period. The current IDo is flows through the diode Do. The output capacitor Co is charged during the switch off period. Whenever the switch is ON the output is isolated from the circuit at that time duration the output capacitor Co discharges the energy to the load to meet the load demand. The reverse-recovery problem is alleviated by the coupled inductors.

The responses of the proposed converter are shown in Fig. 10. The output voltage, output current and output power of the converter are given below. Circuit parameters for the proposed converter are L_{f1}=L_{f2}=L_{f3}= 100 µH, Co= 0.2 mF and switching frequency of 40 kHz. Comparison between traditional boost converter, switched inductor boost converter and proposed level boosting dc-dc converter is listed in Table 1.

Fig.6: Level Boosting DC-DC converter using P&O algorithm

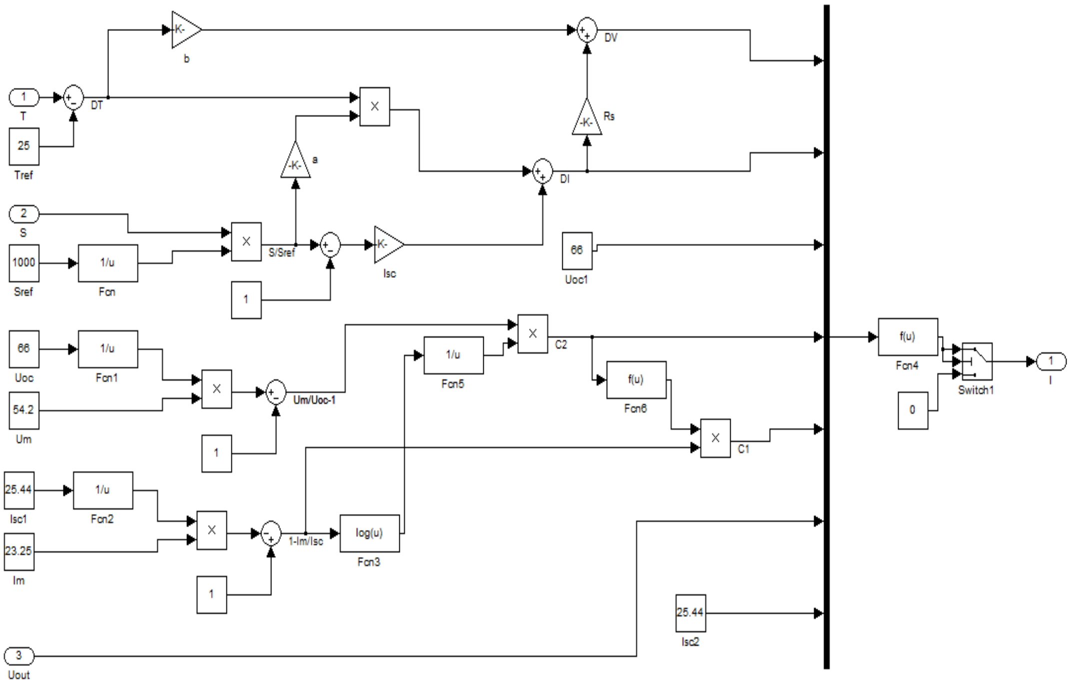


Fig.6.1: MATLAB model for solar PV subsystem

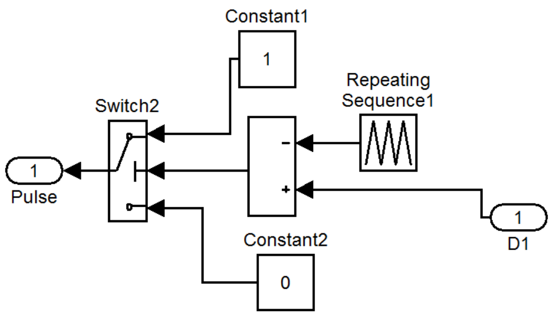
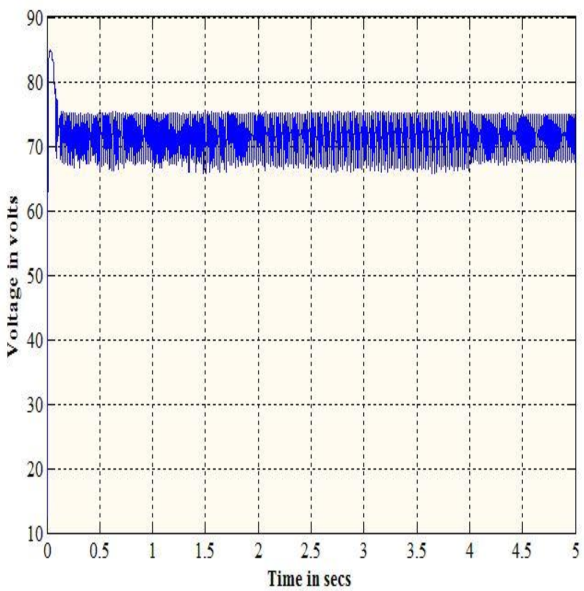
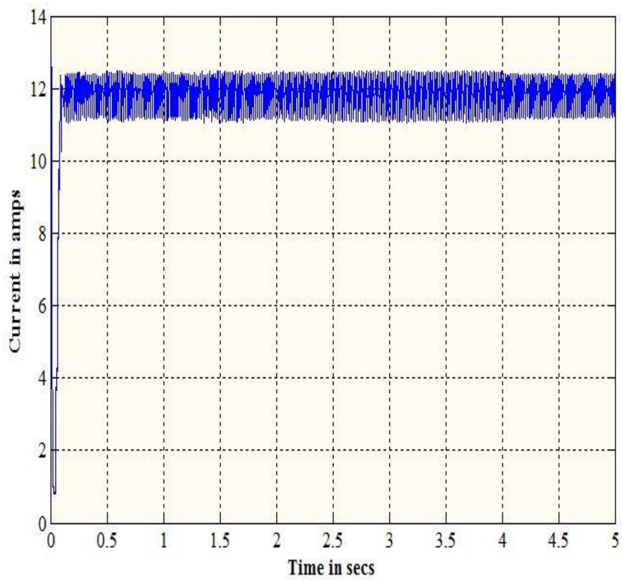


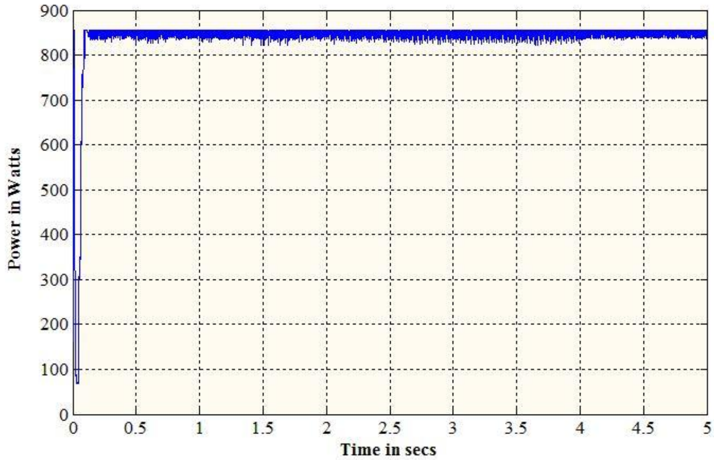
Fig.6.2: Pulse generation circuit



(a)



(b)



(c)

Fig.7: PV array output (a) voltage (b) current (c) power

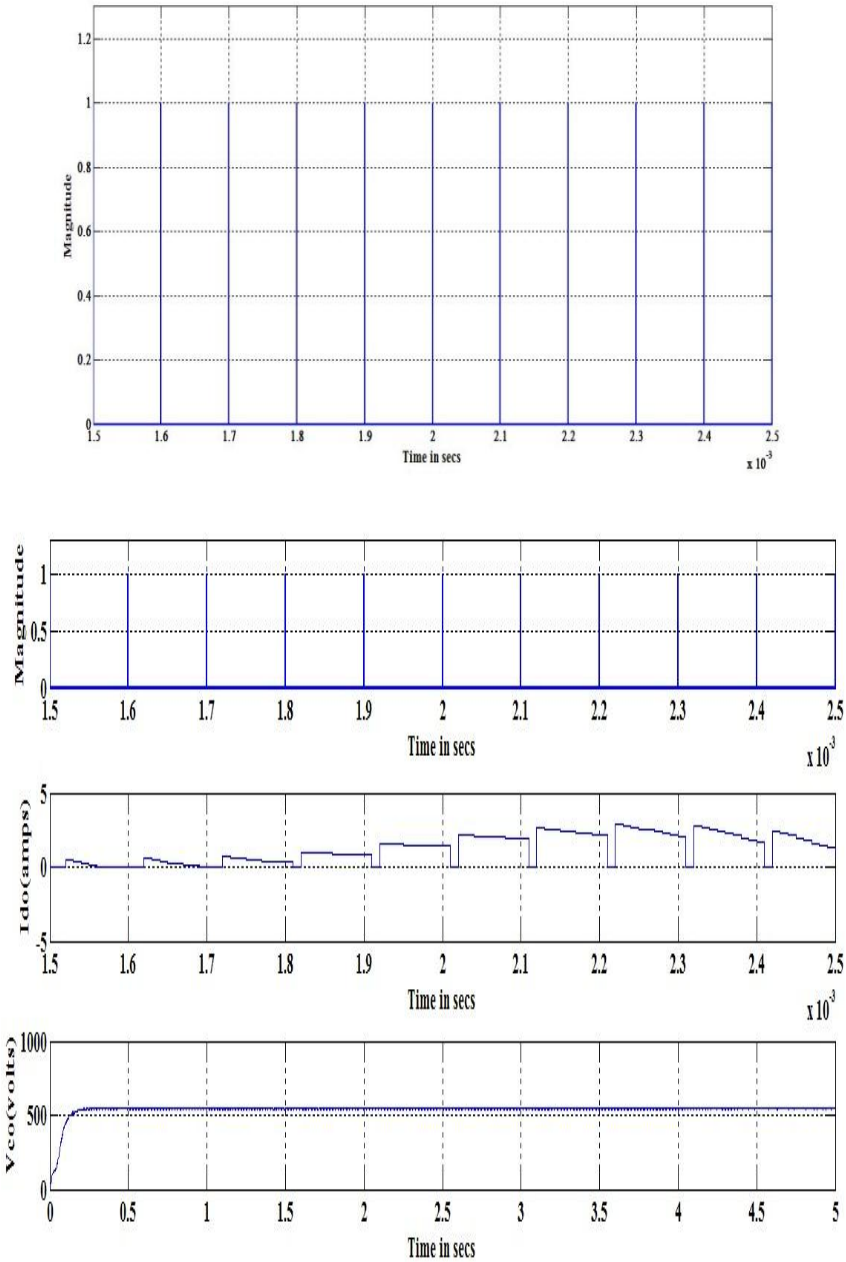


Fig.8: Maximum power point tracking control output

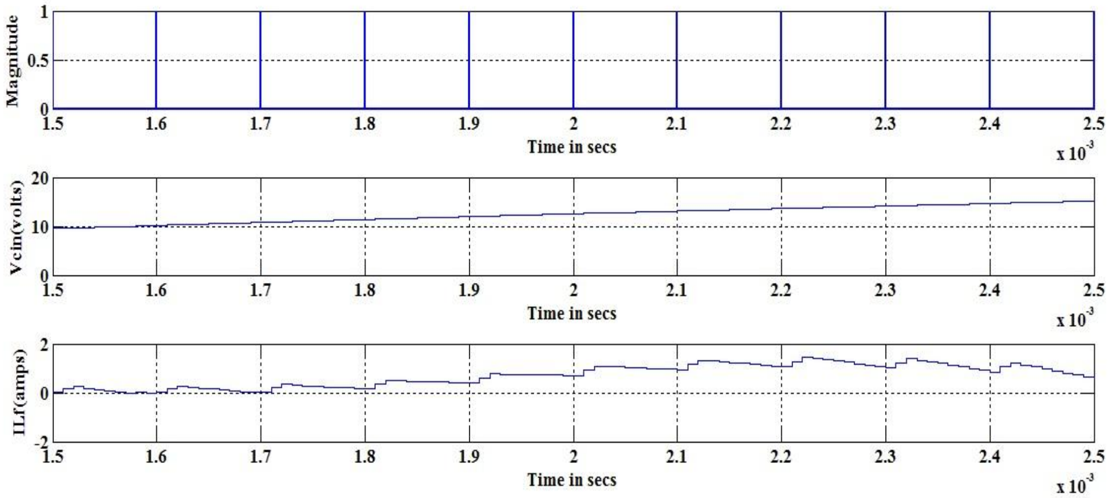
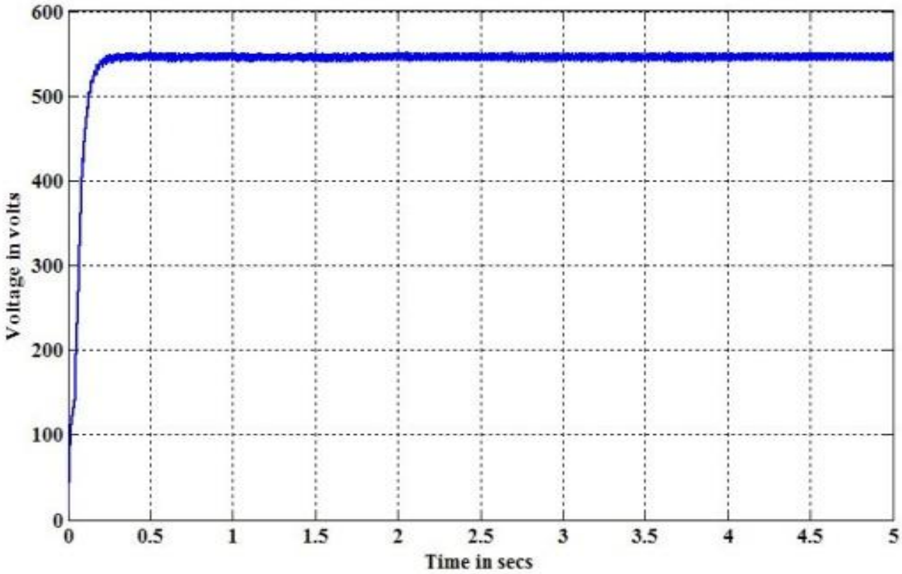
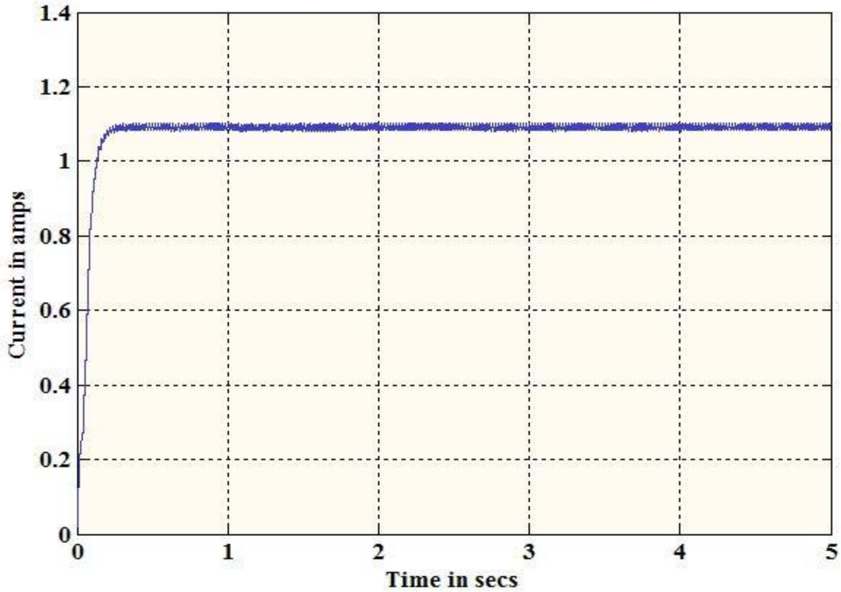


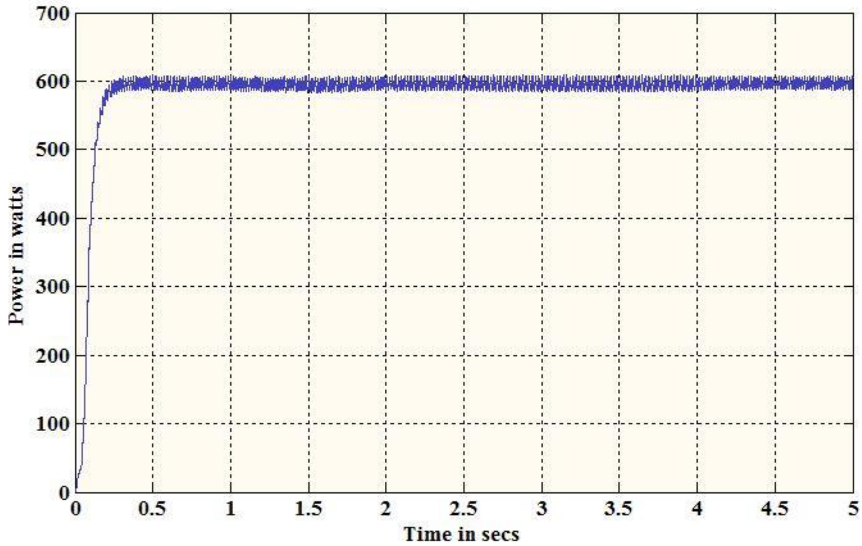
Fig.9: some typical waveforms of the proposed level boosting DC-DC converter



(a)



(b)



(c)

Fig.10: Proposed converter output (a) voltage (b) current (c) power

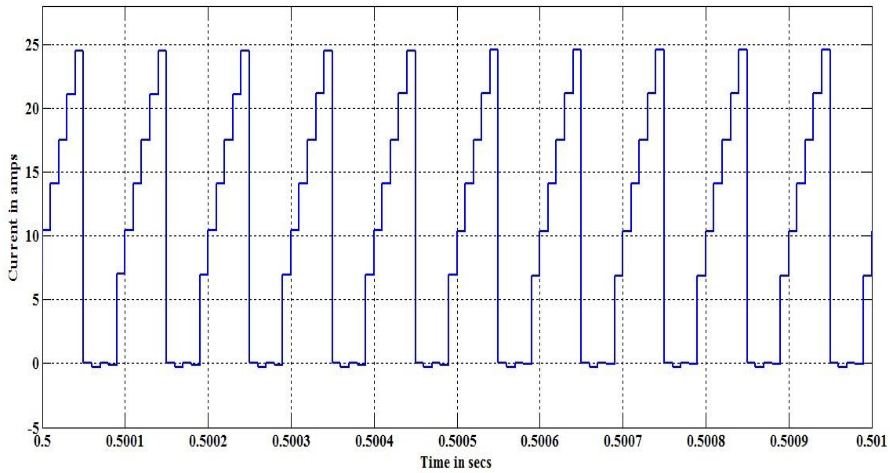


Fig.11: Switch SW current

Table 1: Comparison of proposed converter and existing converter

Parameter	Traditional boost converter	Switched inductor boost converter	Proposed boost converter
Input power(watts)	726	569	832
Output voltage(volts)	373	430	552
Output current(amps)	1.24	0.86	1.1
Output power(watts)	465	371	608
Voltage gain	4.97	5.73	7.35
Efficiency (%)	64	65.2	73

The voltage gain of the proposed level boosting converter is more than the switched inductor boost converter and the traditional boost converter. The voltage gain is high for the proposed converter, so the proposed converter is suitable for a low voltage source to grid connection. Similarly the output current of the proposed converter is desired value. As compare to other two converters, the proposed converter has improved output voltage, output power and efficiency.

8. Conclusion

A Level Boosting DC-DC Converter was proposed, which has vast dc-dc conversion ratio at desired duty cycle. The proposed converter utilizes capacitor, inductor in the switched branch which is in series with the parallel connected inductors, charged in parallel and discharged in series to accomplish high step-up voltage gain. The proposed converter is appropriate for a low voltage source to grid connection. Perturb and Observe (P&O) is applied for the proposed converter to extricate maximum power point from the PV module. The steady state analysis of voltage gain and efficiency are talked about. The voltage stress on the main switch can be diminished by choosing the low voltage rating and low on-state resistance levels R_{DS}(on) switch can be chosen. The voltage gain and power output of the converter are enhanced by utilizing least number of components in the proposed converter.

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