Solar Powered LED Lighting with High Gain Boost Converter

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Abstract

High gain converters are extensively used in the solar powered Light-Emitting Diode (LED) lighting systems due to its several advantages, such as high voltage conversion, reduced voltage stress of power semiconductor devices as compared to conventional DC-DC converters. Solar energy is one of the sustainable energy resources and is able to collect the energy by using Photo-Voltaic (PV). In order to achieve high efficiency the PV should operate at maximum power point (MPP). This paper deals with the design of high gain DC-DC converter for solar powered LED lighting applications. The proposed configuration developed by voltage lift technique and has advantages of high voltage conversion ratio, economical, simple control and suitable for low and medium power applications. Different modes of the proposed topology are explained in detail with corresponding voltage and current equations. A simple Perturb and Observe (P&O) MPPT controller is applied for the proposed topology to control the output voltage from its non-linear characteristics of PV module. Simulation of high gain DC-DC converter and conventional DC-DC converter with 120 watts of LED load has been developed using MATLAB/Simulink software. Load has modeled by 120 LEDs in series-parallel combination by supplying 3.5 V & 20 mA for each LED. The results

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are evident that the proposed converter offers low voltage stress with high gain as compared with conventional DC-DC converters and hence increase the life span of LED lighting system.

Keywords: Solar PV panel, High voltage gain boost converter, MPPT, P&O Algorithm, LED Load.

1 Introduction

Nowadays Light Emitting Diode (LED) technology is becoming more popular and advanced technology for various lighting applications due to long life span, high resolution, save in energy and good color rendering [1–3]. Worldwide lighting system demands one fifth consumption of electricity for efficient lighting applications [4]. Automotive lighting, domestic lighting, traffic lighting, street lighting, decorative lighting are the applications of LED [5, 6]. Due to deficiency of conventional resources the demand on power production has increased in recent years. This situation leads to concentrate on the renewable energy sources to produce the electricity because of its eco-friendly and pollution less power generation [7, 8]. Solar photovoltaic [9], fuel cell, wind energy [10] are the few main renewable energy sources for power generation due to its universal existence. Many researchers prefer more on the expansion of photovoltaic (PV) technology due to its less maintenance and operational cost to produce the power generation [11].

PV system generates very low voltage due to its intermittent nature it is not suitable for different load applications. The brightness, colour and flickering levels of LEDs directly depend on its forward voltage and current, hence it needs to be controlled accurately. To improve the efficiency of LED lighting system, Maximum Power Point Tracking (MPPT) algorithms were used mainly to track the maximum operating point from the PV panel. Due to the variable temperature and irradiance the power generation also gets varied. In order to obtain the maximum power from PV system MPPT algorithm is necessary to track the optimal point [12]. There are many MPPT algorithms like Perturb & Observe (P&O) [13], Particle Swarm Optimization (PSO) [14], Incremental Conductance (INC) [15], Fuzzy Logic Controller (FLC) [16], Genetic Algorithm (GA), Neural Network (NN) [17], Cuckoo Search [18], Artificial Bee Colony [19], Adaptive Neuro Fuzzy Inference System (ANFIS) [20]. P&O algorithm is most preferable and widely accepted among various MPPT techniques mentioned in the literature because of its simplicity and ease to implementation [21]. This technique is used to perturb in given direction by observing the operating voltage from PV panel. When the

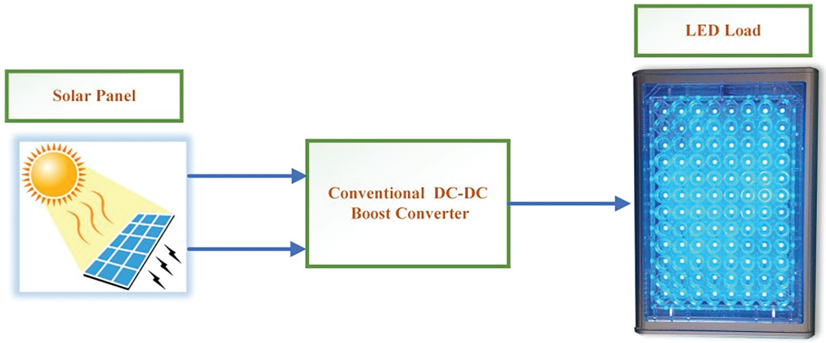

Figure 1 Solar powered LED lighting system using conventional boost converter without MPPT technique.

output power from the PV panel is raised, then the operating point is adjusted to maximum power point or else the direction of the operating point has to be reversed. The operating voltage measured by the photovoltaic system with MPPT technique is very less and not suitable for high voltage applications. To overcome this difficulty, the DC-DC converter topology is used to boost the voltage level from low to high based on the load condition, a steady DC voltage is needed for LED lighting applications [22]. There are many DC-DC converters have been proposed in literature like boost, buck, buck-boost, SEPIC, CUK, etc. to produce steady DC voltage. Figure 1 shows design of the solar powered LED lighting system using conventional boost converter without applying MPPT technique. It produces an unregulated low DC output voltage with high duty cycle. There are few converters that can achieve high voltage levels by increasing their duty cycle [23, 24]. Unfortunately, if the duty cycle is high the converter efficiency and gain voltage degrades noticeably. However, for efficient lighting applications, normal boost converter is not suitable because of its thermal management issues, low current handling capability and they are restricted by the effects of power semiconductor devices and Equivalent Series Resistance (ESR) of inductors and capacitors [25]. In order to achieve high efficiency and high voltage gain many power converters have been introduced at lower duty cycle [26]. High voltage gain is attained with low duty cycle of fly back converter [27–29], which can further increase the turn ratio of the transformer and voltage spikes across the switches.

Boost converter with switched capacitor and coupled inductor methods are proposed to get high voltage gain [30–32]. Whereas higher conduction losses

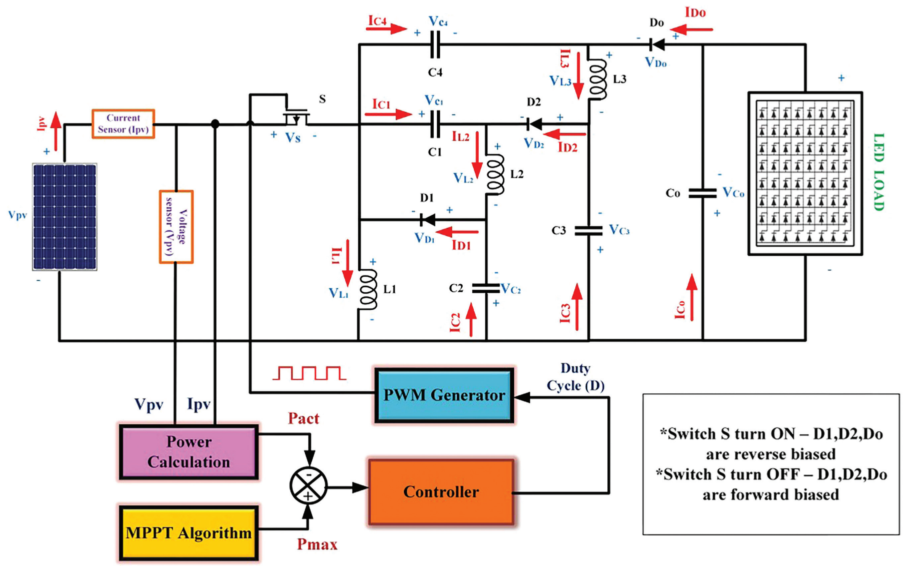

Figure 2 Proposed configuration of solar powered LED lighting system with MPPT technique.

and leakage inductance of the coupled inductor gives high spikes due to more number of switches. So, a novel transformer-less power converter is proposed with single switch to get high voltage gain with low switching losses [33]. The voltage gain is higher than conventional converters and simple in structure. The circuit is designed and operating in boost mode with high voltage gain for solar powered LED lighting controlled by MPPT technique as shown in Figure 2. It consists of a solar panel, efficient boost converter with high gain, maximum power point tracker and 120 watts of LED lighting load. Initially, both the current sensor and voltage sensor can sense the current and voltage from the solar panel and these are the inputs to the MPPT controller. These values can be varied according to the controller algorithm to track the MPP of solar panel for LED lighting. The duty cycle of power converter can be generated from the MPPT block. The proposed system is highly efficient and advisable for future work due to, its efficient energy balancing between power generation and consumption.

The surplus of the paper is structured as follows. Solar PV modeling is discussed in Section 2; design of proposed converter is covered in Section 3; MPPT control algorithm is explained in Section 4. Design LED lighting load described in Section 5. simulations and results are conferred in Section 6 and the conclusions summarized in Section 7.

2 Modelling a Solar Photovoltaic Panel

The design of précised solar PV cell with current source signifies the photocurrent of the cell. Intrinsic series resistance and shunt resistance of the cell are R_s, R_{sh} respectively. Practically, the arrangement of PV cells in the form of large units called PV modules [34]. The electricity can be obtained from PV generation system by using the PV arrays, which is the combination of series or parallel modules. The equivalent circuit of PV panel is shown in Figure 3.

The characteristic equations for both voltage & current of PV cell is given as photo current of module I_{ph} [35, 36]

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times I_r/1000 \tag{1}$$

Where I_{ph} = photo current of module; I_{sc} = short circuit current (A); K_i = short circuit current at temperature of 25°C & 1000 W/m^2 irradiation of PV cell; T = Temperature (K); I_r = irradiation of solar PV cell (W/m^2).

I_{rsat} is the reverse saturation current of PV module

$$I_{\rm rsat} = I_{sc}/[\exp(qV_{OC}/N_s knT) - 1] \tag{2}$$

Where q = electron's charge = 1.6×10^{-19} C; N_S = Number of series connected cells; n = diode's ideality factor; $k = 1.3805 \times 10^{-23}$ J/K k = Boltzmann's constant, V_{OC} = open circuit voltage (V).

The saturation current of module varies with the cell temperature, which is given by:

$$I_o = I_{rs}\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{q \times E_{g0}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \tag{3}$$

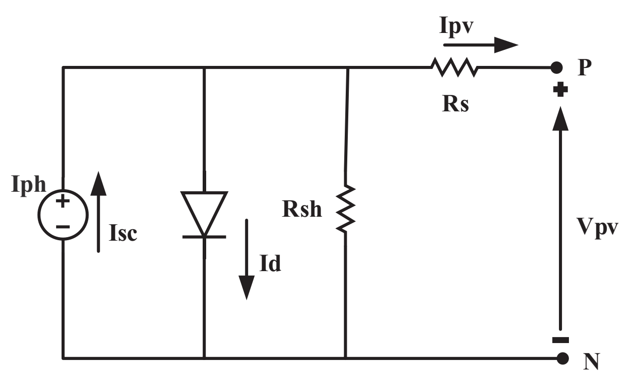

Figure 3 Equivalent circuit of solar PV panel.

Table 1 Design specification of Solar PV panel

Description of Parameters	Ratings
Maximum Power (P_{max})	150 W
Value of Voltage (V_{mp})	12 V
Value of Current (I_{mp})	12.25 A
Voltage at Open circuit (V_{oc})	12.47 V
Current at Short circuit (I_{sc})	14.62 A
No.of Cells	36 (4×9)
Temperature of Module	25°C
Irradiance	1000 W/m^2

Where E_{g0} = energy band gap of the semiconductor = 1.1eV; T_r = nominal temperature=298.15 K; The total output current of each module is

$$I = I_o \times N_P \times I_{ph} - N_P \times \left[\exp\left(\frac{V/N_S + I \times R_S/N_P}{n \times V_t}\right) - 1\right] - I_{sh} \quad (4)$$

Where

$$I_{shunt} = \frac{V \times N_{Parllel}/N_{Series} + I \times R_{Series}}{R_{shunt}} \quad (5)$$

$$V_t = \frac{k \times T}{q} \quad (6)$$

N_{Parllel} = number of parallel connected PV modules; R_{shunt} = shunt resistance (Ω); R_{series} = series resistance(Ω); V_t = thermal voltage of diode (V). A high gain boost converter is connected to the output of the solar panel to preserve a constant voltage across the DC link. The design specification of solar PV panel is given Table 1.

3 Design of Power Converter

The proposed converter consists of only one switch S, three diodes D_1, D_2 and D_o, three inductors L_1, L_2 and L_3, Five capacitors C_1, C_2, C_3, C_4 and C_o and LED load. The input voltage of solar PV panel and output voltage of power converter is V_{pv} and V_o respectively. The following assumptions are considered for the simplicity analysis of high gain boost converter.

i) The value of capacitors of proposed converter is very large, hence voltage across capacitors are assuming that they are constant.
ii) The main switch is considered to be an ideal one and the parasitic capacitance of the switch is neglected.

iii) The proposed power converter can be operated in boost mode of operation and chosen specifically in continuous conduction mode (CCM).

The voltage and current ripples across the capacitor and inductor are assumed very small. The analysis of the proposed converter depends on the switching states turn OFF and ON of metal oxide semiconductor field effect transistor is analysed with the help of Figure 2 and the steady state waveforms are clearly explained in Figure 4.

Mode-1 ($\mathbf{t_o \leq t \leq t_1}$): In the course of operation switch S is turned ON and the diodes D_1, D_2 and D_3 are reversed biased as shown in Figure 2 the input voltage of solar panel V_{pv} charges the inductors L_1, L_2 and L_3. The currents flowing through these conductors I_{L1}, I_{L2}, and I_{L3} increased linearly and the capacitors C_1 and C_4 are charged by the capacitors C_2 and C_3.

Mode-2 ($\mathbf{t_1 \leq t \leq t_2}$): In the course of operation, the switch S is turned off position and the diodes D_1, D_2 and D_o becomes turns on as shown in Figure 2. The inductors L_1, L_2 and L_3 are linearly demagnetized. Due to inductor L_1, the capacitors C_2 and C_3 are getting charged. Due to inductor L_2 the capacitor C_1 and C_4 are getting discharged.

3.1 Analysis of the Power Converter

The scrutiny of the power converter to be easier the inductors, capacitors and power semiconductor devices are assumed to be ideal and operating in CCM. The voltage transfer gain (M) of the converter is attained by applying volt-sec balance to the inductor $L_{1,}L_2$, L_3 by using we get

$$
\begin{aligned}
V_{L1} &= (V_{pv})\,(t_1 - t_0) + (-V_{C2})(t_2 - t_1) = 0 && (7)\\
V_{L2} &= (V_{c2} - V_{C1} + V_{pv})\,(t_1 - t_0) + (-V_{c1})(t_2 - t_1) = 0 \;\; or &&\\
V_{L2} &= (V_{c2} - V_{C1} + V_{pv})\,(t_1 - t_0) + (V_{c2} - V_{c3})(t_2 - t_1) = 0 && (8)\\
V_{L3} &= (V_{c3} - V_{C4} + V_{pv})\,(t_1 - t_0) + (V_{c1} - V_{c4})(t_2 - t_1) = 0 \;\; or &&\\
V_{L3} &= (V_{c3} - V_{C4} + V_{pv})\,(t_1 - t_0) + (V_{c3} - V_{c0})(t_2 - t_1) = 0 && (9)
\end{aligned}
$$

By solving (7), (8) and (9), the voltage across capacitors C_1, C_2, C_3, and C_4 are V_{C1}, V_{C2}, V_{C3}, V_{C4} can be obtained as follows.

$$V_{C1} = V_{C4} = \frac{2DV_{pv}}{1 - D} \tag{10}$$

$$V_{C2} = V_{C3} = \frac{DV_{pv}}{1 - D} \tag{11}$$

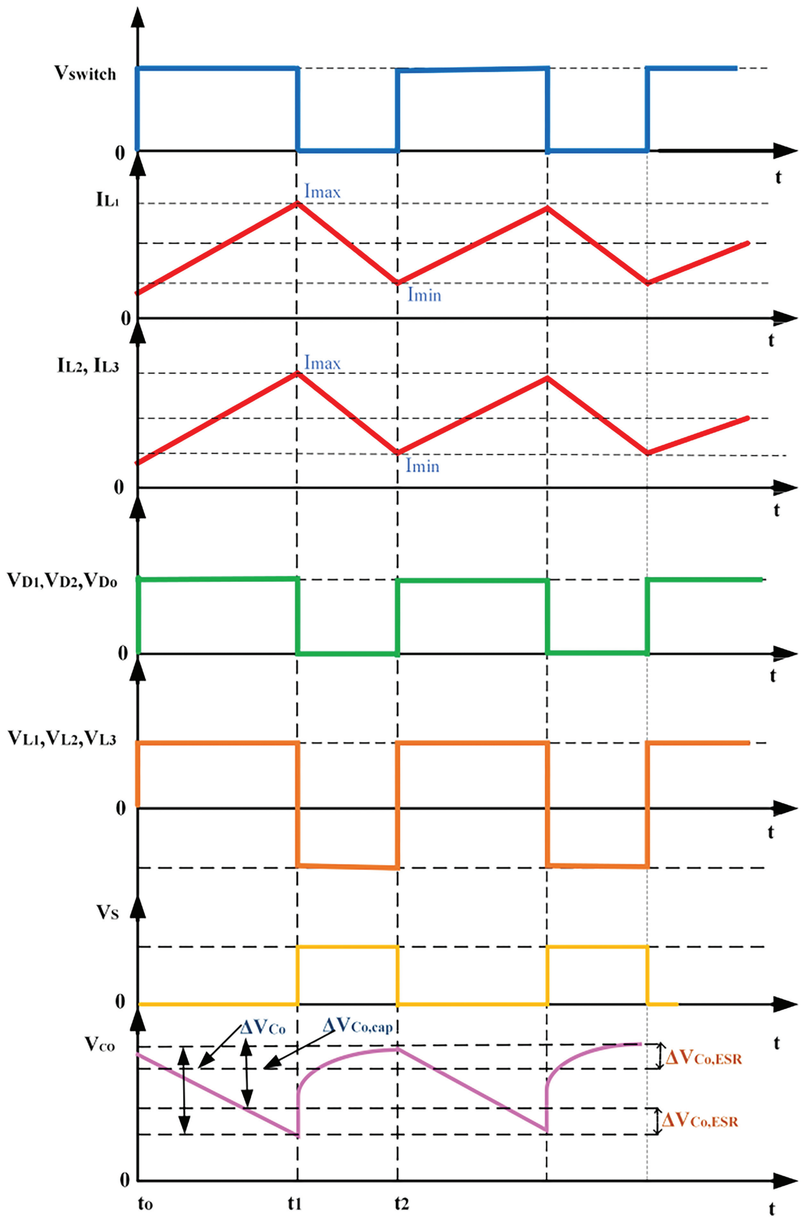

Figure 4 Steady state waveforms of proposed converter.

By solving Equations (10) and (11) the voltage gain of the power converter can be achieved as follows.

$$M = \frac{V_O}{V_{pv}} = \frac{V_{C3} + V_{C4}}{V_{pv}} = \frac{3D}{1 - D} \tag{12}$$

Voltage stress across the switch is specified by

$$V_S = \frac{V_{pv}}{1 - D} \tag{13}$$

The current flowing through the inductors L_1, L_2 and L_3 are I_{L1}, I_{L2}, and I_{L3} can be calculated by using following equations

$$I_{L1} = \left(\frac{1 + 2D}{1 - D}\right) I_o \tag{14}$$

$$I_{L2} = I_{L3} = I_o \tag{15}$$

Where

$$I_O = \frac{P_O}{V_O} \tag{16}$$

Voltage across the power semiconductor devices is less than the output voltage. By assuming the value of maximum current ripple of ΔI the inductor L will be calculated. The value of maximum input current ripple is assumed as 15% of its input inductor current. The value of the input inductors L_1, L_2, and L_3 are calculated by using Equations (17–19) respectively.

$$L_1 = \frac{DV_{pv}}{\Delta I_{L1} f_s} \tag{17}$$

$$L_2 = \frac{DV_{pv}}{\Delta I_{L2} f_s} \tag{18}$$

$$L_3 = \frac{DV_{pv}}{\Delta I_{L3} f_s} \tag{19}$$

The design of capacitors C_1, C_2, C_3, C_4, and C_o can be calculated by assuming the voltage ripple across the capacitors (ΔV) from Equations (20–22) respectively

$$\Delta V_{C1} = \Delta V_{C1,ESR} + \Delta V_{C1,cap} = \left(\frac{ESR_{C1} I_O}{1 - D} + \frac{DT_S V_O}{RC_1}\right) \tag{20}$$

$\tan \delta_{C1}$ = the dissipation factor
Where

$$ESR_{C1} = \frac{\tan \delta_{C1}}{2\Pi f_S} \tag{21}$$

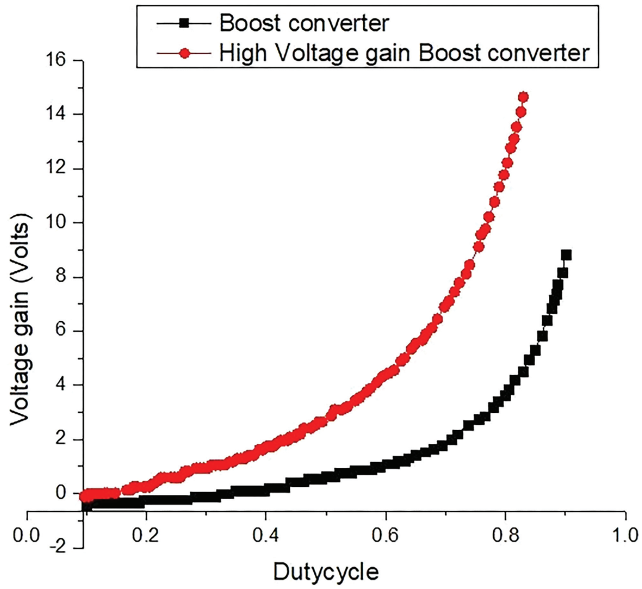

Figure 5 Comparison between both conventional and proposed topology of gain voltages at every duty cycle.

$$\begin{aligned}\Delta V_{C2,3,4,o} &= \Delta V_{C2,3,4,o,ESR} + \Delta V_{C2,3,4,o,cap} \\ &= \left(\frac{ESR_{C2,3,4,o}I_O}{1-D} + \frac{DT_S V_O}{RC_{2,3,4,o}}\right)\end{aligned} \tag{22}$$

The ESR of different capacitors like C_1, C_2, C_3, C_4 are can be calculated from the steady state waveforms respectively. In Figure 4 the clear measurements to calculate the exact value capacitor has been discussed from C_o waveform. In the same way from remaining capacitor's waveform the values of capacitors can be easily calculated. Figure 5 clearly shows that the voltage gain of the proposed converter is high at every duty cycle compared to conventional converter.

4 Efficient Control Algorithm

The efficient technique is proposed to track the maximum output power by adjusting the load of the photovoltaic system is called MPPT algorithm. MPPT can be achieved through the several ways like fuzzy logic, pilot cells, and neural networks. The utmost extensively used techniques are Perturb and

Observe (P&O) and Incremental Conductance (INC) algorithms because of these are economical [37]. Control algorithm is applied for the system due to its comfort of execution. The operation P&O algorithm is by measuring voltage and current of PV segment and then it will calculate the power from voltage and current.

This power compares with the previous value, if any deviation in the power means the voltage can altered. For example if the power of PV module is increased then the control algorithm corrects the operating point of the module in that direction; otherwise it operates in the opposite direction. These steps will continue until the power reaches at maximum level. The speed of the MPP is mainly depends on the perturbation of voltage, if the lower perturbation then the system response to reach MPP is to be low. If perturbation is larger than the system response to reach MPP is high. There is no need of previous knowledge on characteristics of PV in this control algorithm. The flow chart of P&O MPPT control algorithm is as shown in Figure 6.

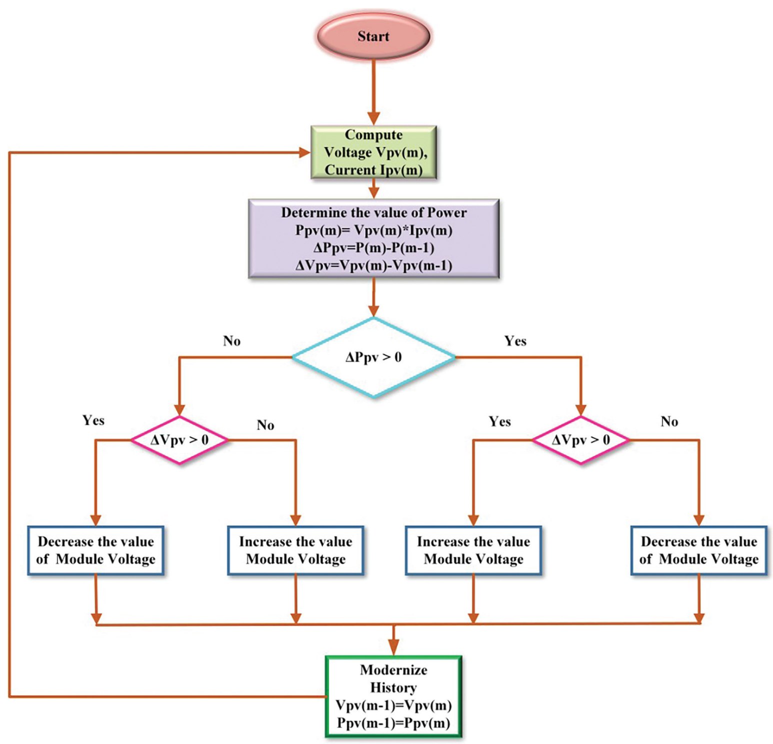

Figure 6 Flowchart of efficient control algorithm.

5 Design of LED Array

An effective brightness lighting load of 120 W can be provided by choosing White colour LEDs. The ratings of white LED are forward voltage and forward current are 3.5 V and 20 mA correspondingly. 120 numbers of LEDs are required to produce 120 W of lighting with the ratings what we have for white LEDs. These are arranged in 12×10 LED array arrangement. Every row contains 12 number of LEDs connected in series and the total current drawn from the source is 240 mA. To limit current flowing through LEDs of each and every row requires 330 Ω. Each resistor squanders 132 mW subsidizing a power loss of 1320 mW in the resistors and the LEDs dispels 8400 mW. Hence the overall power intemperate by the array is 9720 mW.

6 Simulation and Result Analysis

The modeling and simulation result comparison of the solar powered LED lighting system with conventional boost converter without MPPT Technique and efficient proposed power converter with MPPT Technique is made with MATLAB/Simulink software. The performance of control strategy has been analyzed. The basic simulation model diagram is as shown in Figures 1 and 2.

The design circuit of high voltage gain power converter produces a high efficient output compared to the conventional boost converter with the less duty ratio. In addition the power converter can reduce the ripples from output voltage and current waveforms.

The output voltage is not maintained constant and it was tested for constant PV panel irradiation. The output voltage of 48 V with load resistance of 19.2 Ω and duty ratio D = 0.75 set solar panel input voltage V_{pv} = 12 V of solar powered LED lighting system was tested at constant irradiation level without MPPT Technique as shown in Figure 7. As per the observation the output voltage is settled at 48 V (average) as shown in Figure 7(b). This conforms that the output voltage is matched the prediction value but at very high duty cycle D = 0.75. Correspondingly, Figure 7(c) shows the simulated output current 2.4 A at steady is observed. It is noticed that during this first test, MPPT is not achieved in terms of constant output voltage reaching its steady state within 0.10 sec. The waveform observed output power observed approximately 120 W at constant PV panel irradiation is shown in Figure 7(d).

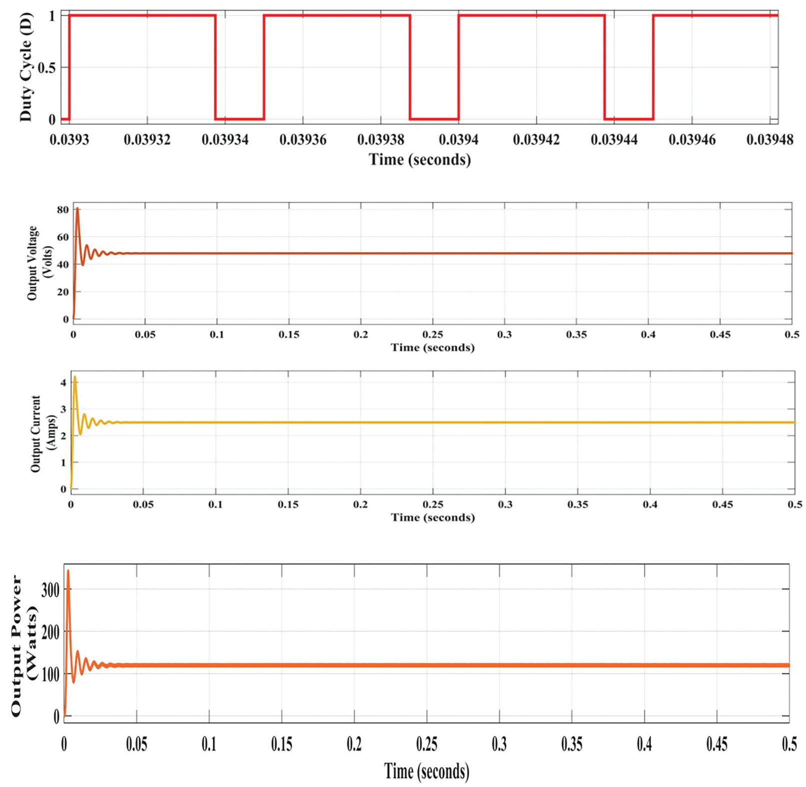

Figure 7 Output voltage, current and power of conventional boost converter without MPPT Technique.

Results are obtained under efficient proposed power converter at constant irradiation level conditions with MPPT Technique as shown in Figure 8. The figure shows the simulated output voltage (48 V) and output current (2.5 A) are achieved with low duty cycle D = 0.5 in Figure 8(b), Figure 8(c) and Figure 8(a). After which the output voltage and current stabilizes within 0.10 sec. The waveform output power at constant PV panel irradiation is also noticed closely to the value of 120 W is as shown in Figure 8(d).

The investigation confirms that the high voltage gain power converter harvests high efficiency, due to the fact that presence of passive components additionally (L, C). This essentially diminishes the switching, conduction

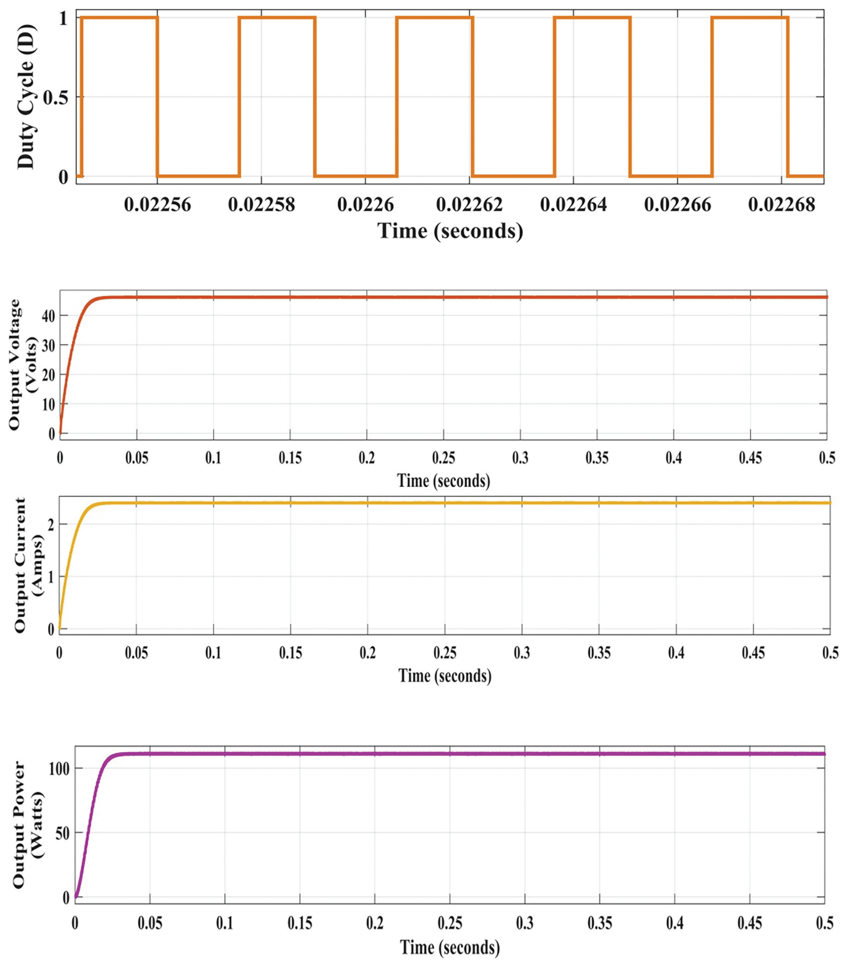

Figure 8 Output voltage, current and power waveforms of proposed power converter at constant irradiation level with MPPT Technique.

losses across the power switch. The voltage transfer gain which is really verified in Equation 12. Similarly proposed control algorithm is preserves constant output voltage of high gain boost converter beneath PV irradiation. The curves shown in Figure 9 noticed that the efficiency of the proposed converter with output power is higher compared to the conventional boost converter. The maximum efficiency of proposed converter is approximately 97%.

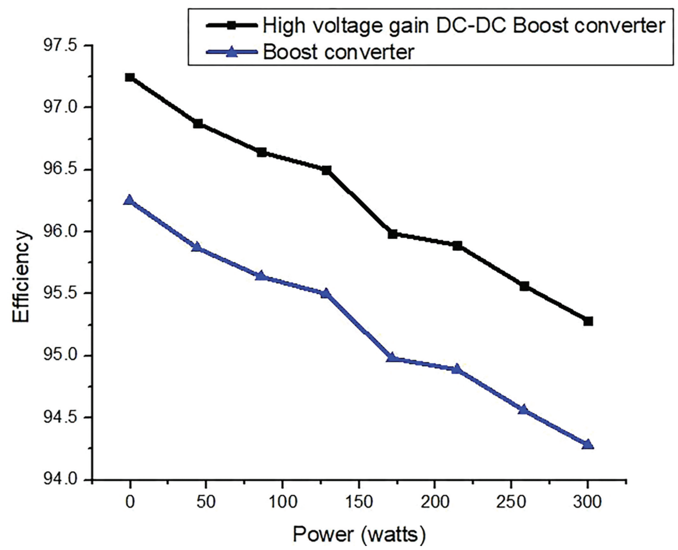

Figure 9 Comparison between efficiency versus power of the proposed power converter and boost converter.

7 Conclusion

In this paper, 120 W of solar powered LED lighting system is presented with an energy efficient fast tracking MPPT circuit at constant irradiation level with high gain power converter. The design of transformer less power converter is very simple and easy control. The current ripple has been reduced and contains lower voltage stress across the switch. The gain of the power converter is high associated to the traditional boost converter. The simulation results reveal that the MPPT controller has tracked the maximum power point faster and also clearly observed the performance characteristics of the power converter competed to boost converter.

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