A novel auxiliary unit based high gain DC-DC converter for solar PV system with MPPT control

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ABSTRACT

Solar photovoltaic (PV) system becomes popular to generate the electricity in Asian region and helps to reduce the burden to utility. The power converter plays crucial role to interconnect with DC- grid. Traditional type power DC-DC converter can able to extract the maximum power from solar PV. However, most of the applications, it often fails to meet the voltage level of the DC bus and additional converter is required to boosting p the DC voltage. In order to overcome this drawback, this paper proposes a novel DC-DC converter to extract the maximum power from solar PV and helps to enhance the voltage level to meet the DC-bus. The PV and IV characteristics of practical solar PV cell and mathematical modelling have been done and implemented the same to proposed high gain converter. The maximum power point tracking (MPPT) algorithm and operation details are addressed and the detailed operation waveform of proposed high voltage gain DC-DC converter with mathematical evident is reported in this paper. The simulation study was carried out in the PSCAD/EMDTC software. From the measured results, it is investigated in further to validate the MPPT operation, gain values achievement and performance analysis of proposed converter. The corresponding explanations and results are presented in this article.

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1. INTRODUCTION

From the last few decades, the markets of renewable energy increases day by day due to global wise awareness on pollution free [1]. Contrasted with, the generation cost of solar PV gets reduced and improves the efficiency [2]. The power electronics converter plays a huge role in integrating the solar PV system to either off grid or on grid. The integration of grid connected mode is a complex task and many literatures of solving the issues are available in this study [3], [4]. The major concern of solar PV is extracting the maximum power throughout the day, especially varying climatic and load conditions. Many algorithms are proposed by several researchers, but still some adequate improvements are required on maximum power point tracking (MPPT) study [5]–[7]. The DC-DC converter is an essential portion to integrate with DC-grid or DC-bus. However, many applications, the voltage levels of load or bus voltage are higher than the output achieved by traditional type DC-DC converter. To increase the DC-output voltage a voltage gain, authors suggest a variety of DC-DC power converters [8], [9]. Revathi and Mahalingam [10] built a system with double inductor concept, a new high voltage gain DC converter is proposed. However, large duty ratios are required to build up higher voltage levels. Due to this, inductor core might get saturated and creates disturbances in the circuit. The coupling inductor approach often solves this duty ratio issues. But, due to leakage inductance property, the input current becomes discontinues and self-induced electromagnetic force (EMF) affects the performance of the converter output. And also, these types normally create electromagnetic interferences and additional snubbed circuit must be employed to arrest this EMI noise [11], [12]. Parastar and Seok [13] introduced high gain converter with cascaded configuration is proposed. It can solve the duty ratio issue but it requires more number of devices and increases the cost.

Apart these converters, switched capacitor configuration sustain the voltage boosting capability during low voltage solar PV generation [14], [15]. However, due to presence of more number of capacitors, the surge current may appear at every cycle and leads to damage the switches. Switched inductor type concept is also having unique feature and can produce higher voltage [16], [17]. But the switching stress is higher at large duty ratio and increases the switching losses and degrades the efficiency. The combination on switched capacitor and inductor type, basically hybrid structure has a great potential to neutralize the above points discussed from the literature [18], [19]. The hybrid structure produces a higher voltage at lower duty ratios, but input current (current in the inductor) is pulsating in nature and degrades the performance of converter under higher power ratings. From the detailed literature [20]–[25], it identified that certain improvement is required to boost up the voltage with improved performances of the converter. By setting this as a goal, this particular paper derives a novel auxiliary converter to boosting up the output DC voltage to higher level even under lower range of duty cycle. And also, this proposed converter can reduce the switching stress and input current ripples compared to reported converters. Thereby, the proposed converter can improve the efficiency. Therefore, this proposed converter is more suitable to solar PV system. Hence, perturb and observe (P&O) algorithm has been implemented to perform MPPT operation on solar PV system and validates the converter feasibility. In addition, this paper investigates the detailed operational waveforms and gain analyses are done. The solar IV and PV characteristics have been obtained after successful mathematical modeling of solar PV. Finally, the proposed work has been validated through simulation and experimental investigation.

2. PROPOSED AUXILIARY UNIT BASED CONVERTER

The configuration of novel auxiliary unit based high gain converter has been proposed in this paper as shown in Figure 1. There are two active switches and diodes with two inductors and capacitors combinations make the circuit to produce higher gain than the conventional approach. Normally, the switching inductor and capacitor networks can produce higher gain; however, it requires more number of components. But this proposed converter can able to produce higher gain due to auxiliary unit merged with existing switch, therefore number of switches has been reduced than conventional approach.

Basically, the switch S_1 and S_2 are helps to charge the inductor L_1 and L_2, respectively. But in this proposed circuit the capacitor C_1 is also gets charged through switch D_1 during off state of the switch. Therefore, the capacitor voltage is contributed to yield output voltage. The operational details of the proposed converter can be explained in two states.

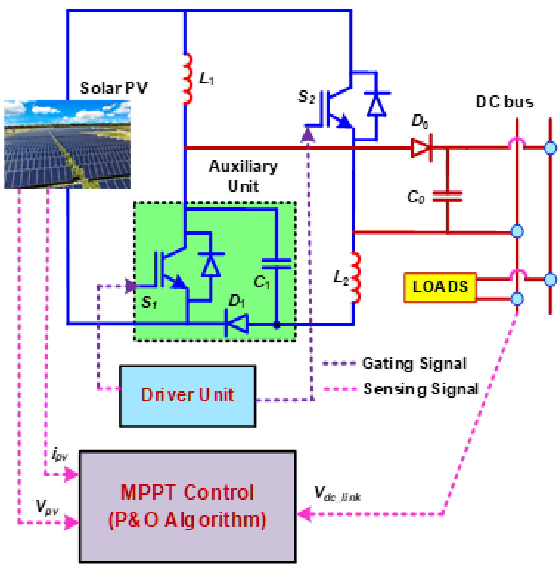


Figure 1. Circuit diagram of proposed auxiliary unit based high gain converter for MPPT operation

– Mode 1

When the switch S_1 (auxiliary unit switch) and switch S_2 are ON, the inductor L_1 on the auxiliary unit arm is charged linearly from the V_{in} and L_2 is gets charged with respect to V_{C1} and V_{in}, therefore V_{L2} is higher than V_{L1}. The inductor voltage across during charging is given as (1).

$$V_{L1} = L_1 \frac{di_{L1}}{dt} = V_i \tag{1}$$

The inductor voltage L_2 can be written as (2).

$$V_{L2} = L_2 \frac{di_{L2}}{dt} = V_i + V_{c1} \tag{2}$$

From (1) and (2), it is clear that the voltage across inductor L_2 is higher than that of voltage across inductor L_1. The current through the capacitor C_1 and C_0 (output capacitor) can be written as:

$$i_{c1} = C_1 \frac{dV_{c_1}}{dt} = -i_{L2} \tag{3}$$

$$i_{co} = C_o \frac{dV_{c_o}}{dt} = -i_o \tag{4}$$

– Mode 2

When the switches are OFF state, the stored energy of inductor is discharged. It produces higher voltage at output side. The inductor voltage and capacitor current can be expressed as (5).

$$\begin{aligned} V_{L1} &= L_1 \frac{di_{L_1}}{dt} = V_i - V_{c1} \\ V_{L2} &= L_2 \frac{di_{L_2}}{dt} = V_{c1} + V_o \\ i_{c1} &= C_1 \frac{dV_{c_1}}{dt} = i_{L1} - i_{L2} \\ i_{co} &= C_o \frac{dV_{c_o}}{dt} = i_{L2} - i_o \end{aligned} \tag{5}$$

The modes of operation and corresponding conduction states of the devices can be expressed in Table 1.

Table 1. Switching states in different modes

	Mode 1	Mode 2
S_1	On	Off
D_1	Off	On
D_o	Off	On

The functional voltage and current waveforms of the proposed auxiliary unit power converter are clearly picturized in Figures 2 (a) and 2 (b). During On state, the inductor current rise and corresponding voltage appears across the inductors are clearly mentioned in Figure 2. Similarly, when switch is on and off states, the elements current and voltages are indicated here. Under CCM, the capacitor voltage is a key factor to desire the output voltage. The voltage across the capacitor C_1 can be written as (6).

$$V_{c1} = \frac{1}{1-D} V_i \tag{6}$$

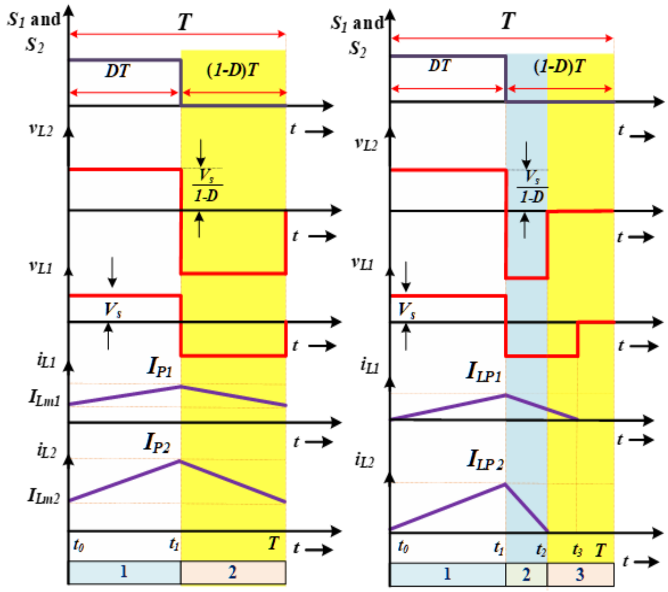
Basically, the average voltage of inductor is zero at every cycle, therefore based on the volt-second principle; the output voltage is written as (7).

$$V_o = \frac{DV_{pv} + V_{c1}}{1-D} \tag{7}$$

To determine the actual voltage gain ration, the expression (7) can be given as (8).

$$M_g = \frac{V_o}{V_{pv}} = \frac{1+D-D^2}{(1-D)^2} \tag{8}$$

Using (8), the maximum gain is obtained by setting the D to extreme level; however, the maximum D is restricted to 80% due core saturation. After this duty ratio, the core may get saturate for high power applications. For better view, three dimensionally the value of output voltage has been plotted with respect to variable source voltage and D as shown in Figure 3.



(a) (b)

Figure 2. The functional behavior of the auxiliary converter in (a) CCM and (b) DCM

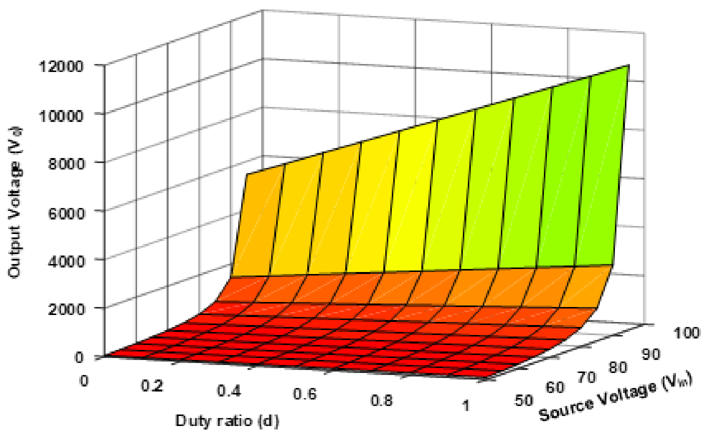


Figure 3. 3D plot of load voltage with respect to D and source voltage

3. IMPLEMENTATION OF SOLAR PHOTOVOLTAIC SYSTEM

In order to trap maximum power, the modeling of the solar PV must be analyzed. The single cell diode modeling has been considered, which has ideal and practical solar PV cell. It generates the current proposal to solar flux received through irradiation. The practical and idea solar cell circuit is shown in Figure 4.

$$I_o = I_{ph} - I_d - I_{sh} \tag{9}$$

Where, I_{ph} is solar PV current, I_d is the maximum possibilities of current (saturation) of diode and I_{sh} is the shunt resistance current. The relation between shunt current and current flow through diode can be written as:

$$I_{sh} = \frac{V+I_O R_{se}}{R_{sh}} \tag{10}$$

$$I_D = I_{sh}\left[exp\left(\frac{V+I_O R_S}{\eta V_T} - 1\right)\right] \tag{11}$$

where, V and V_T are the solar panel voltage and temperature dependent voltage, respectively. The series and shunt resistance can be represented as R_s and R_{sh}, respectively.

$$I_S = I_{sc} / \left[exp\left(\frac{V_{oc}}{\eta V_T} - 1\right)\right] \tag{12}$$

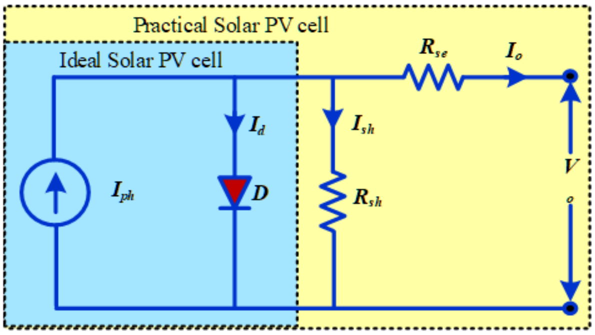
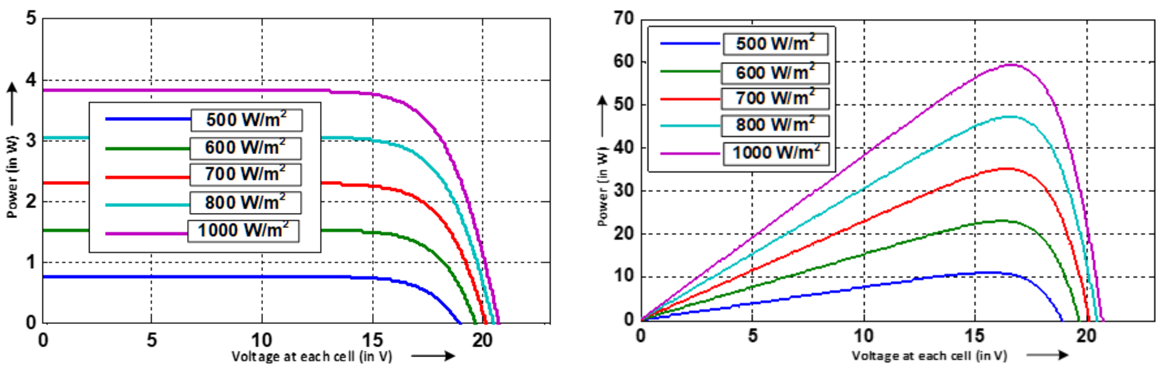


Figure 4. The realistic practical and ideal solar cell

After simplifying, the output current of load can be written as (13).

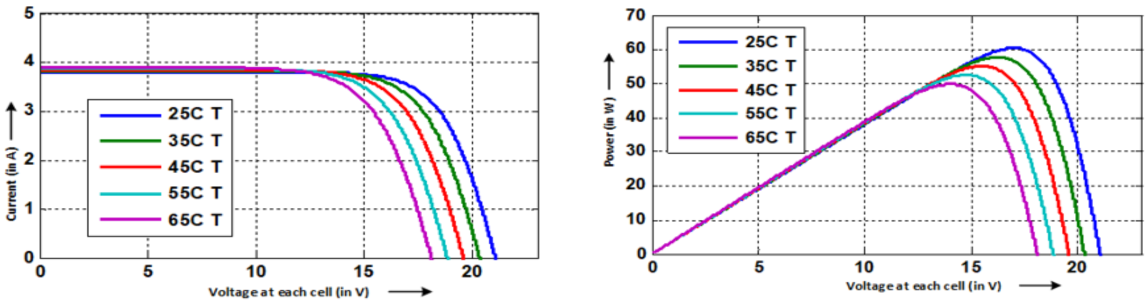
$$I_o = I_{ph} - I_{sh}\left[exp\left(\frac{V+I_O R_S}{\eta V_T} - 1\right)\right] - \frac{V+I_O R_{se}}{R_{sh}} \tag{13}$$

The mathematical modelling has been developed in simulation platform after incorporating all these expressions. From this, the IV and PV curve of solar PV system is measured and plotted, as presented in Figures 5 and 6, respectively. The current drastically gets affected with irradiation of solar PV as mentioned in Figure 5(a). Therefore, the power is also gets reduced proportional to the irradiation, which is clearly indicated in Figure 5(b). Similarly, the performance of solar PV under variable temperature condition is also simulated using mathematical modelling; the voltage across the solar PV cell gets varied in propositional to the temperature. It is clearly observed in Figure 6(a). And also, the power gets reduced at higher temperature, which is also observed and presented in Figure 6(b). After confirm the theoretical validation, the maximum power tracking algorithm has to be implemented to perform MPPT. There are many MPPT algorithm discovered in the past literature. But, the P&O algorithm is one of the most popularly used by many researchers since it has simplicity in control.



(a) (b)

Figure 5. Solar PV curves (a) IV characteristics with change in irradiation at uniform temperature and (b) PV characteristics with change in irradiation at uniform temperature



(a) (b)

Figure 6. Solar PV curves (a) IV characteristics with change in temperature at uniform irradiation and (b) PV characteristics with change in temperature at uniform irradiation

The detailed flowchart of P&O algorithm is illustrated in Figure 7. The voltage and current is gets adjusted automatically by adjusting the D value of the DC-DC power converter. The voltage deviation of the actual solar PV voltage from MPP voltage can be determined and suitable duty ratio can be generated through this P&O algorithm [22]. Using proposed high gain converter, the output voltage is controller such a way the solar PV MPP voltage and actual voltages are traced throughout the operation. Hence, MPP operation is achieved.

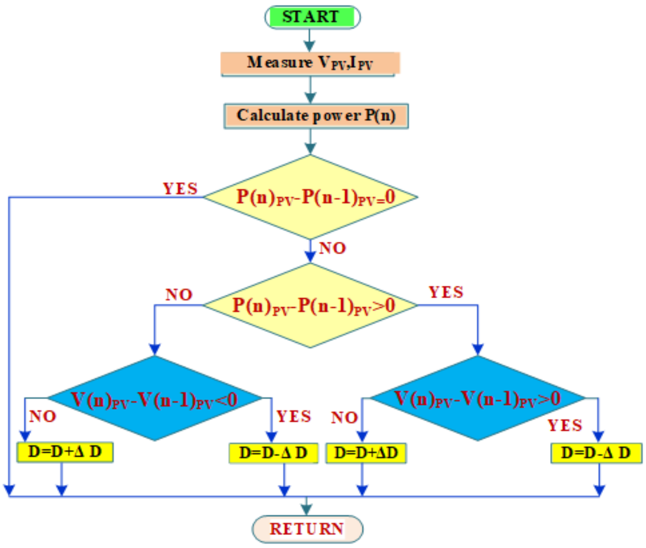
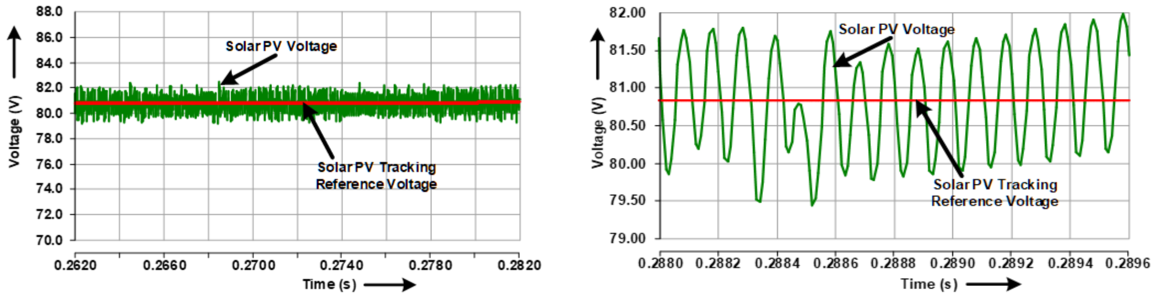


Figure 7. P&O algorithm

4. EXPERIMENTATION AND MEASURED RESULTS

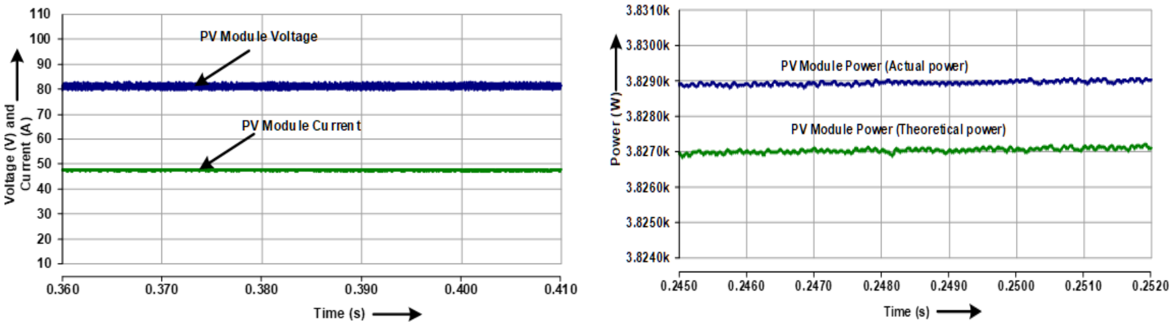
The simulation study has been investigated and results are observed and presented in this section. After implementing the P&O algorithm in the proposed auxiliary unit based high gain converter, the simulation results are observed for the solar PV actual voltage and MPP reference voltage. Under any situation, the solar PV actual voltage is tracking the MPP voltage, which is clearly observed in Figure 8(a). For better vision, the zoomed view of this MPPT operation is clearly shown in Figure 8(b).

Similarly, the solar PV voltage and current of is also presented in Figure 9(a). The practical parasitic elements of proposed high gain converter are identified for the given rating and it has been applied to the circuitry for investigation purpose. Therefore, the losses across the device are also applicable to the system. To visualize the power losses, the graphical view of actual and theoretical power levels is clearly shown in Figure 9(b). The basic output of P&O algorithm is reference voltage generation from IV characteristics different irradiation and temperature levels. After obtained this reference point of MPP voltage, it is compared with actual solar PV voltage. Based on the error, PI controller tunes the pulse width modulation (PWM) to produce required output. Finally, it is applied to the comparator section to obtain required duty ratio. The generation of this duty ratio from the relational operation of PI tuned output and reference frame signal are observed from simulation study and plotted in Figure 10. Furthermore, the generation of duty ratio is applied to the proposed auxiliary high gain converter and desired output voltage is achieved at output side. Practically, the performance of proposed converter has been investigated through simulation study. The capacitor voltage and inductor currents are measured during MPPT tracking operation and presented in Figure 11(a). And also, the current flow through capacitor C_1 and switch current is observed as shown in Figure 11(b).



(a) (b)

Figure 8. Simulation results of solar PV: (a) MPP tracking and (b) zoomed view of tracking



(a) (b)

Figure 9. Simulation results (a) PV module voltage and current (b) actual and theoretical value of PV power

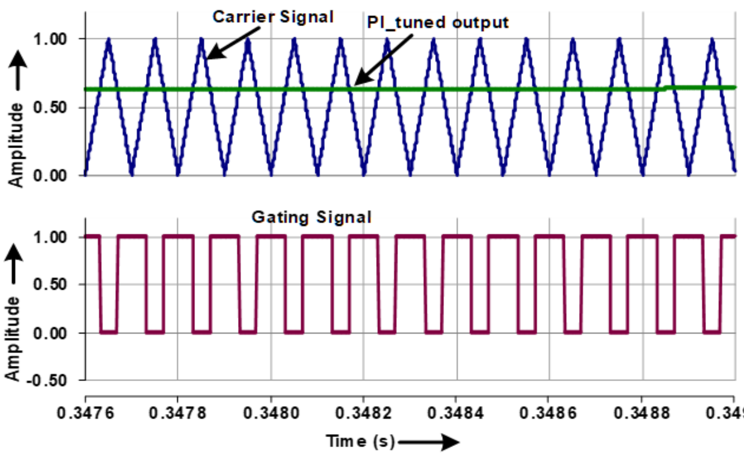
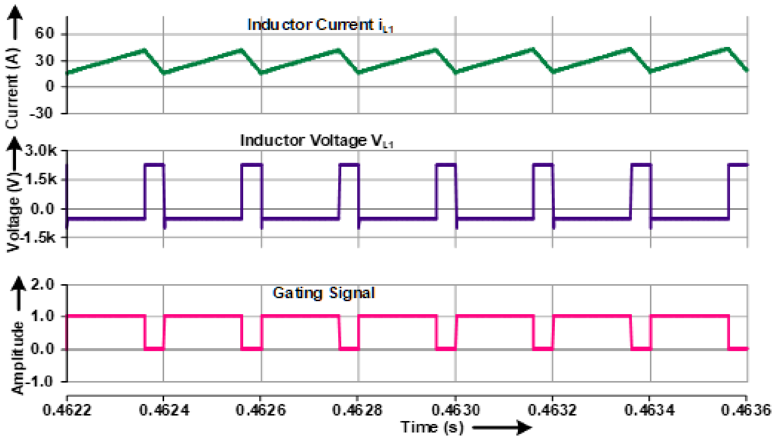
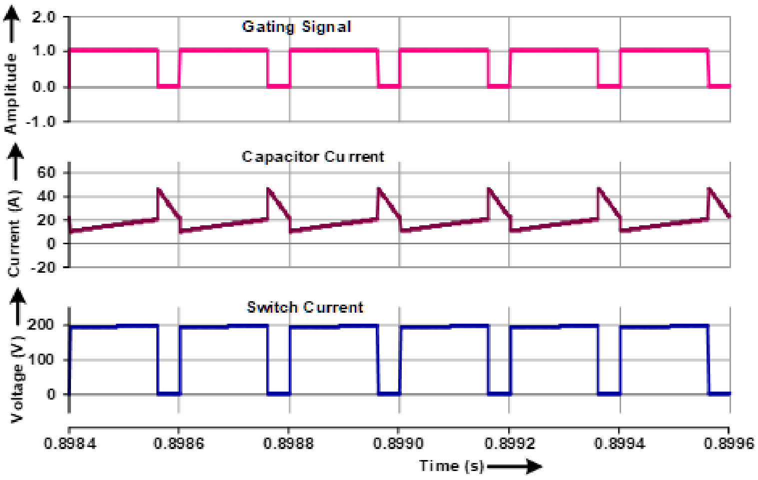


Figure 10. Measures results of gating signal generation using P&O control algorithm

Usually, the current rising of inductors and capacitors are common for most of the circuits. However, due to proposed circuit arrangement, it is vice versa as reported in theoretical explanation. This current rising of inductor and current falling of capacitor during switch ON condition is clearly visualized from these figures. Similarly, the current failing of inductor and current rising of capacitor can be clearly observed from Figure 11(a). And also, the current rising and falling of capacitor and switch currents are observed as shown in Figure 11(b).



(a)



(b)

Figure 11. Measures results of passive elements of proposed converter (a) voltage and current observation across the inductor and (b) current observation of capacitor and switch

After incorporating P&O control mechanism in the proposed high gain converter, the peak power can be extracted from the above solar PV with the various resistance of load. During change in load patterns, the IV characteristics of real time solar PV system is measured through simulation studies and presented in Figure 12. Different load line can be observed in the IV curve obtained during the operation. Each module voltage, and load voltage and power graphs are observed while execution of MPPT operation using proposed auxiliary converter, which is presented in Figure 13(a). It displays the voltage at the proposed auxiliary converter's input and output stages together with power measurements. The load power and generated power is almost equal due to lesser loss. Similarly, the under dynamic conditions, the simulation results are captured in Figure 13(b). The load voltage and power are higher under maximum solar irradiance conditions and lesser under minimum solar irradiance conditions. Since there are few losses on the converter, it ensures that the suggested auxiliary converter can perform more efficiently.

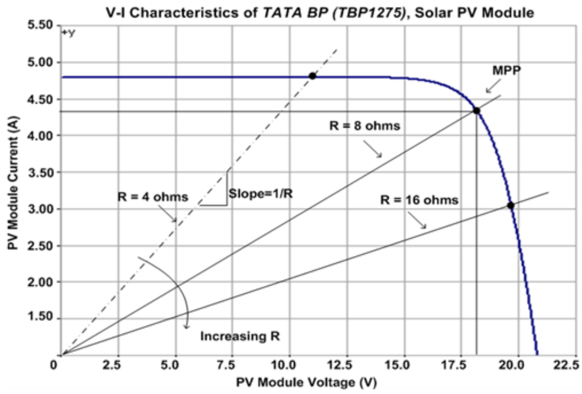
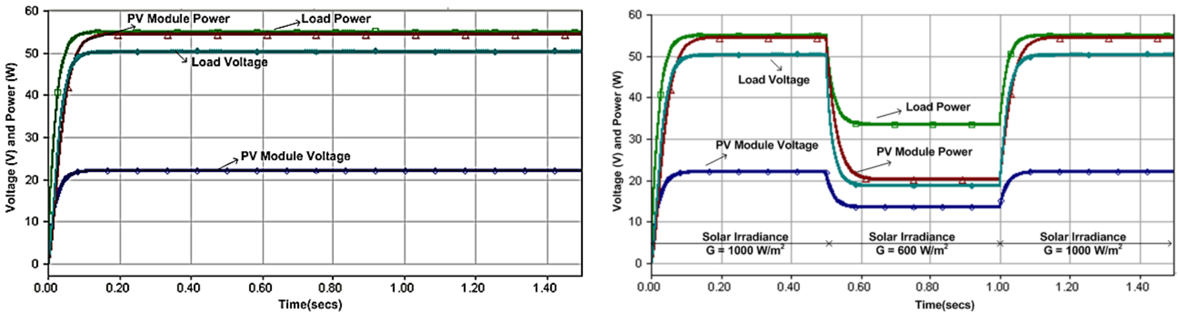


Figure 12. IV characterizes of solar PV with different load line



(a) (b)

Figure 13. Output voltages and power (a) during normal state conditions and (b) during stepped change in power conditions

5. CONCLUSION

This particular paper proposes novel auxiliary unit based high gain auxiliary power converter to trap the peak power generation point of solar PV. The detailed operational details of auxiliary converter have been investigated. The mathematical relations of the various elements involved in the proposed circuitry have been analyzed and gain ratio is derived. And also, the mathematical modeling of practical diode model has been developed and performance characteristics of solar PV are presented in this paper. In addition, the implementation of MPPT operation in the proposed auxiliary unit based high gain converter is investigated with detailed study. Finally, the simulation results are carried out and also implementation of MPPT operation in the proposed converter has been validated in normal state and dynamic conditions.

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