High Gain Modified Boost Converter for Electric Vehicle Battery Charging

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***Abstract*—In this paper, a modified boost converter topology for electric vehicle charging from a photovoltaic source is proposed. The proposed topology offers higher voltage gain and lower ripple content over the conventional boost converter. Investigations into the characteristics of lithium battery load, selection of the photovoltaic panel rating are discussed. Simulation studies on the performance of conventional and modified boost converter are performed with a resistive load using MATLAB/ Simulink. Experimental results validate the simulation studies. The proposed topology has a single switch and results indicate higher voltage gain with a 22 V input stepped up to 51 V and higher output voltage with a 48 % moderate duty cycle.**

Keywords—Photovoltaic source; High Voltage Gain; Boost Converter; Modified Boost Converter; Electric Vehicle

I. INTRODUCTION

The rise in the standard of living has lead to the number of oil-based vehicles for personal transportation increasing enormously. The number of vehicles for private transport is increasing with the number of two-wheelers exceeding 169 million in 2016 alone and growing at a rate of 20% each year. This increase has lead to the requirement of valuable foreign exchange in the form of import of oils and also health risks due to emissions in the form of CO, CO_2, NO_2 Alternate would be migration to electric vehicle (EV). Government of India's National mission on electric mobility sets deployment targets of 6 to 7 million EV and hybrid EV's by 2020. Effective charging infrastructure is required to promote the growth of EV 's in the country. Range anxiety, higher initial cost and lack of adequate infrastructure support for charging of vehicles are the issues affecting the adoption of EV's. The already overburdened transmission network will not be able to cater to this huge demand hence alternate sources need to be explored. PV based systems can offer a viable alternative solution.

The photovoltaic (PV) system as a source is intermittent. Though the sun shines for more than 300 days in many parts of the country, the irradiance and temperature vary with time of the day and seasons. An extensive study on the representation of PV Panel with its single diode model was carried out in [1]. V-I characteristics of a panel depend on the number of cells in series, parallel combination (N_s, N_p), Series and parallel resistances (R_s, R_p), Latitude of the area and the angle of inclination. The PV and IV curves are highly dependent on the solar radiation values and also inversely proportional to temperature. The maximum power that could be obtained continuously varies throughout the day with a change in irradiation and temperature. A number of MPP topologies were developed, evaluated and implemented in literature [2,3,4] Perturb and Observe (P&O), Incremental Conductance [5], Direct Measurement (Open Circuit Voltage, Short Circuit Current), Lookup table, Parasitic Capacitance, Constant Voltage (CV), Constant Current (CC), Fuzzy [6] are some of the algorithms reported in the literature. P&O algorithm is best suited for rapidly varying irradiance conditions and has an ease of implementation due to the minimum number of sensors required. But conventional P&O also results in oscillations around the mean position. Modified P&O algorithms with estimated step size, adaptive P&O, and others are proposed to avoid the drift [7].

Battery as a load has a variable profile. The Battery can be modeled as an electrochemical model, Thevenin based electrical model and impedance based model. Large capacitor representing the battery capacity to store and release charge and smaller capacitor to represent surface capacitance in parallel, resistors representing different internal resistances of the battery are discussed in the literature [8].

The power converter should be capable of meeting the wide variations caused due to varying irradiance and providing dependable power. Buck, boost, buck-boost and flyback are the DC-DC converter topologies widely reported for extraction of maximum power. Conventional buck based topologies have inductor performing the dual function of energy storage and filtering. The conventional boost converter has inductor on the source side and hence requires filters on the load side. It offers a maximum gain of twice the input for higher efficiency with a limitation of 50% duty cycle.

A number of topologies for ripple minimization with interleaved [9,10], cascaded, coupled, synchronous rectification [11], switched capacitor based topologies are discussed in the literature. Z source based and switched capacitor topologies though offer high gain have a limitation of high input current ripple. Extremely high gain topologies discussed above with a quadratic and above gains require a very small duty cycle for low voltage EV battery based applications [12-16]. The size of the conductor increases and hence the losses.

The reconfigured topology discussed in this paper has both source side and load side inductors and yields lower ripples and offers a moderate gain which is linearly

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varying and not exponential as in the case of conventional topologies and hence more suitable for PV based EV applications.

II. Estimation and Characterization of Load and Source.

A. Characterization of lithium battery load

Lead Acid, Nickel-Cadmium, and Lithium-Ion are the conventional battery types used for rechargeable batteries in the industry. Lithium-ion based batteries have superior performance in terms of highest energy density (90 Wh / Kg), higher charge-discharge cycles (3000) and lowest self-discharge (2%) and facilitate fast charging and preferred in EV applications. Disadvantages of these batteries are higher cost and intolerance of higher temperatures.

Conventional two-wheeler EV's use 48 V Lithium-ion battery. 48V, 24 AH battery of Amptek as in Fig.1 was used for the present study. Charging characteristics from the vendor's battery charger (Conventional 230 V_{ac}/ 48 V_{dc}) is studied to understand the safe charging profile. The charging characteristics from the observations are plotted in Fig. 2 - 4. The study indicates a CC charging for 6 hrs with 3 A and 2 hrs with CV. when the terminal voltage reaches 54.5 V, the battery was cut off. The power requirement increases from 120 W initially to 145 W and then linearly falls to 20 W before the battery is cut-off.

Fig. 1 Lithium-Ion Battery 48 V, 1152 Wh, Used for Study

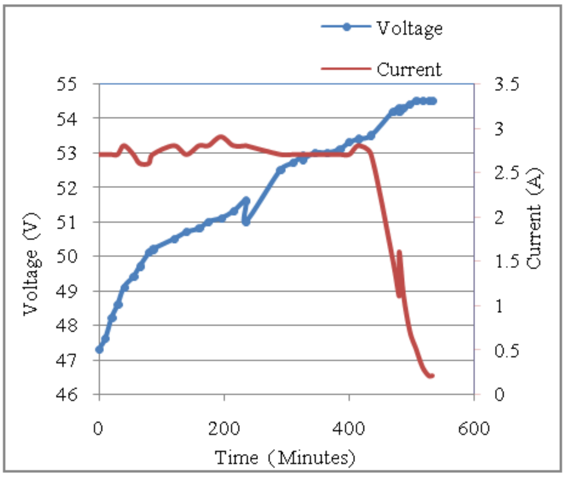


Fig. 2 VI Characteristics of Lithium Ion Battery

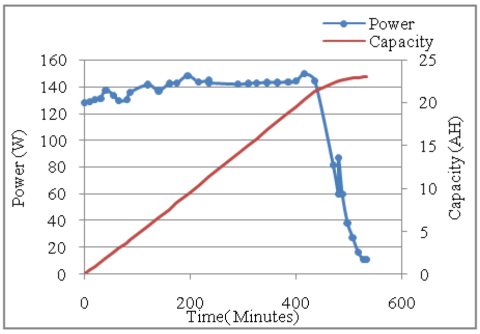


Fig. 3 Power and Capacity Vs. Time characteristics

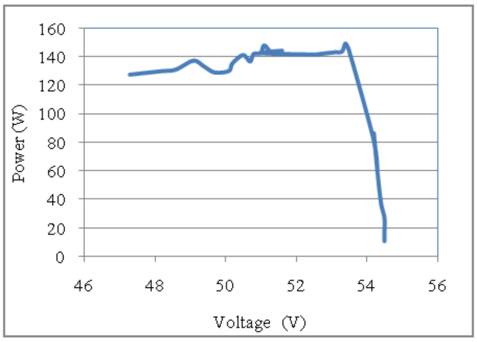


Fig. 4 Voltage vs. Power Characteristics

B. PV Panel Selection

The study of the nature of the load, indicated the source required could be over 150 W. The National Renewable Energy Laboratory (NREL) has made a detailed repository of temperature, irradiance, pressure, etc. data which can be used for the designing of the PV systems [17]. Data for the irradiance for the city Mangalore was downloaded from NREL, NSRDB data viewer and 3 years' data 2012-14 was collected analyzed. Estimation of energy output was plotted for the PV panels with 100 W, 150 W, 200 W, 250 W as in Fig. 5. It was found that a 200 W panel can charge 80% of the battery for the 8 months of the year except for the months of June to September where the irradiance falls below the average due to the rainy season.

From the MATLAB models, NREL 2014 details, Waaree panel of 200 W with the characteristics as in TABLE 1 was selected for further studies. By varying temperature, the characteristics of V_{MPP}, I_{MPP}, P_{MPP} were evaluated as plotted in Fig. 6.

From the data of Fig.7 it was observed that the PV Panels can be used to charge EV from morning 8.30 am when the irradiance exceeds 400 W/m^2 till evening 5.30 pm when the irradiance falls below the same for almost 10 months of the year.

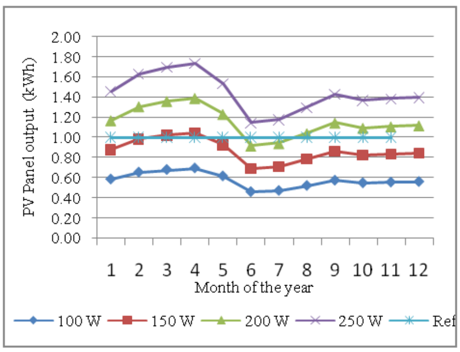


Fig. 5 Study for Determination of PV Panel Capacity

TABLE 1 WAAREE ENERGIES WU-200W PANEL

	200W
V_{OC}	**32 V**
I_{SC}	8.7 A
V_{MPP}	26 V
I_{MPP}	7.7 A
R_{SH}	42.5 Ω
R_{SE}	0.2608 Ω

Study of the characteristics indicate that with a rise in temperature, I_{sc} increases, V_{oc} reduces, power output and efficiency of the panel reduces. For a 200 W panel at 25°C temperature MPP voltage is around 27.7 V and at 40°C, it reduces to 24 V.

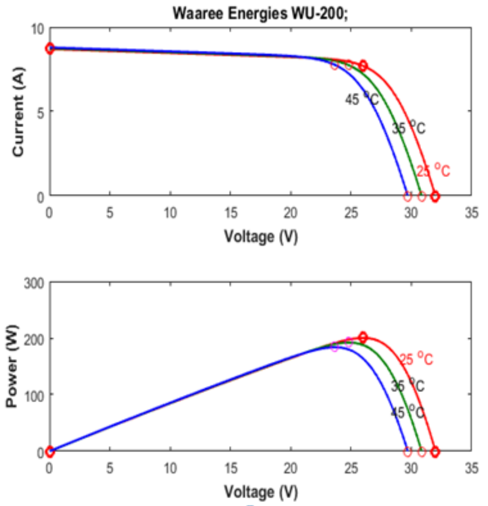


Fig. 6 PV Panel characteristics with change in temperature

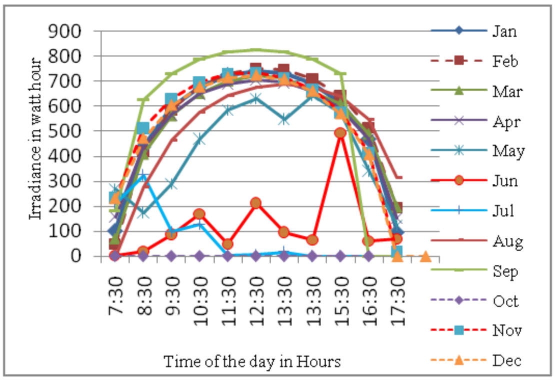


Fig. 7 Irradiance variation plot with the time of the day

From the NREL data, the normal room temperature in the city of Mangalore is found to be around 33 °C and PV panel temperature is considered to have 10 °C higher temperature than the room. For lower irradiance, the V_{MPP} further reduces.

Thus the voltage at MPP point could be variable from around 21V at 400 W/ m^2 irradiance to 27.7 V for 1000 W/ m^2. Observations made from the studies conducted on the PV panel indicate the requirement of a converter that can have a higher gain and charge a battery of 54 V with 21 V PV source. Conventional boost converter as in Fig. 8 might be required to be operated over 62 % duty cycle considering ideal conditions. Practically considering diode, inductor and switch drops and drop across ESR of the capacitor will require the system to operate at still higher duty cycle where efficiency reduces and the size of the components will increase.

III. BOOST CONVERTER

The operation of the conventional boost converter can be described with the assumptions that all the devices are ideal, losses across the devices are negligible and ESR of inductor and capacitor are neglected.

Mode1: Switch closed, Inductor charges, Capacitor supplies the load current.

Mode2: Switch open, Inductor discharges, the sum of input and voltage across the inductor appears across the output. Capacitor charges.

Gain is given by $\frac{Vo}{Vin} = \frac{1}{1 - d}$, where d is the duty cycle.

The operation of the conventional boost converter with a 21 V input was studied. Arduino board was used to generate a pulse of the required duty cycle with 30 kHz. Optocoupler 4N25A was used to provide the necessary isolation. As MOSFET IRF 740 needs a higher voltage to switch at high frequency, IR 2011 was used as a driver IC. The signals were observed on a DSO and shown in Fig. 9. The Input was stepped up to 42 V which matches with the expected results as in Fig.10.

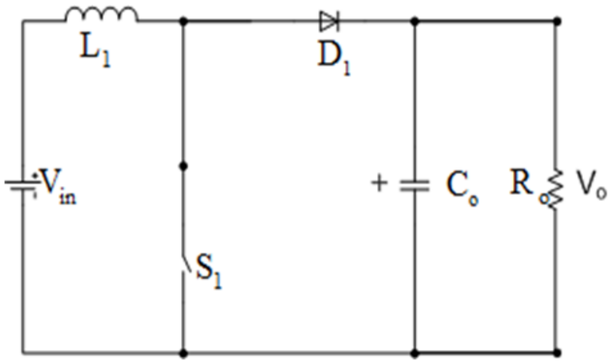


Fig. 8 Conventional Boost Converter

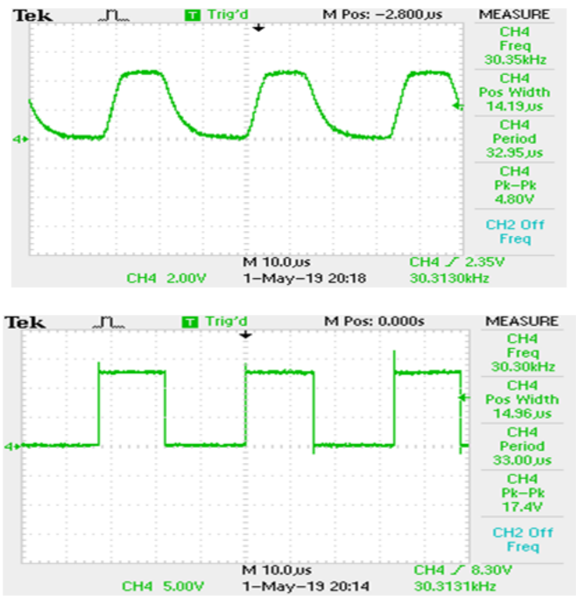


Fig.9 Opto Coupler output with 45% duty cycle

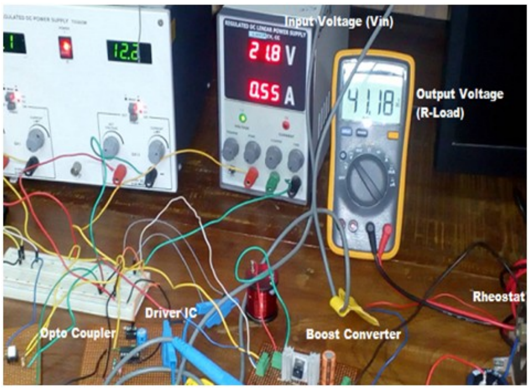


Fig.10 Driver Output

IV. Modified Boost Converter

A number of unidirectional and bidirectional high gain topologies are available in the literature. Most of the topologies are applied for a gain of over five and above which is required to step up low PV voltage to high dc link voltage through MPP extraction and processed further for inversion. The proposed topology in Fig.11 has additional two diodes, extra capacitor and an inductor as a gain cell for the realization of higher voltage gain. The proposed topology is represented in the figure below

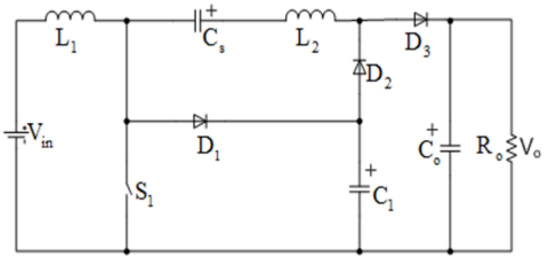


Fig. 11 Modified Boost Converter

The operation of the converter can be described as follows.

Mode 1: When the switch S_1 is closed, the inductor L_1 charges through the switch and the current through the L_1 increases. C_0 supplies the power to the load and get discharged. In addition, through the path D_2, L_2, the series capacitor gets charged through the switch S_1 connected to the ground. D_1 does not conduct as its anode gets reverse biased. The diode D_1 blocks the voltage of C_1 and needs to be rated at the load voltage.

Mode2: The switch S_1 is turned off. The current through the inductor now flows through D_1 and C_1 gets charged as the conventional boost converter with a gain $\frac{1}{1-d}$. The load voltage becomes the summation of V_{in} and V_{Cs}. The Conventional gain of the cell is $\frac{2}{1-d}$, But the loss due to the capacitor reverse biasing the diodes leads to a lower gain. The series capacitor and the inductor L_2 with diode block /switch is one of the types of gain cells as found in the literature which aids in achieving higher voltage gain [18].

A. Simulation Results of Modified Boost Converter

Simulation studies are conducted with MATLAB, Simulink Version R2015b. The simulation studies are performed with specifications as in TABLE 2 with dc source of 21 V and with a resistive load of 20 Ω. The converter gave an output of 60 V with 3.7 A of current with 48 % duty cycle. The study on the variation of output with duty cycle indicates the existence of linear the relation between the output and duty cycle, unlike the conventional boost converter which has an exponential relationship and reflected the functionality of high gain as in Fig. 12.

TABLE 2

Simulation & Hardware Parameters	
Inductors (L_1,L_2)	570µH, 270µH
Capacitors (C_s,C_O,C_1)	0.47 µF,220µF,1000µF
MOSFET	IRF 740
Diodes	UF5408

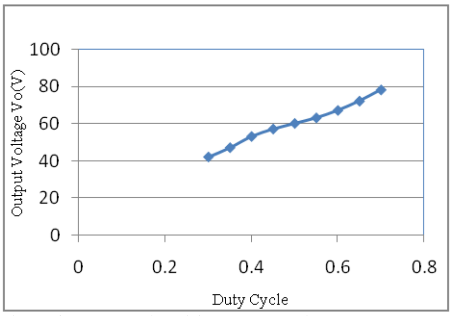


Fig. 12 Variation of Duty Cycle with Output Voltage

PV Panel of 200 W model of Waaree Energies was used as a source and Irradiance was set at 800 W/m^2. Studies were conducted with a resistive load of 17 **Ω**. At temperature 25 ^{o}C and 25% duty cycle the following results as in Fig. 13 were obtained. The panel with 27 V_{MPP}, 5.7 A current at 800 W/m^2 delivers 50V output voltage and 3 A current sufficient to charge the lithium battery. The results indicated a higher gain. In practical systems, the device drops, temperature effect, varying irradiance and the losses of the converter could lead to lower output, but the duty cycle can be increased to meet the requirements. As temperature and irradiance factors vary throughout the day, closed loop operation will be required for efficient power extraction.

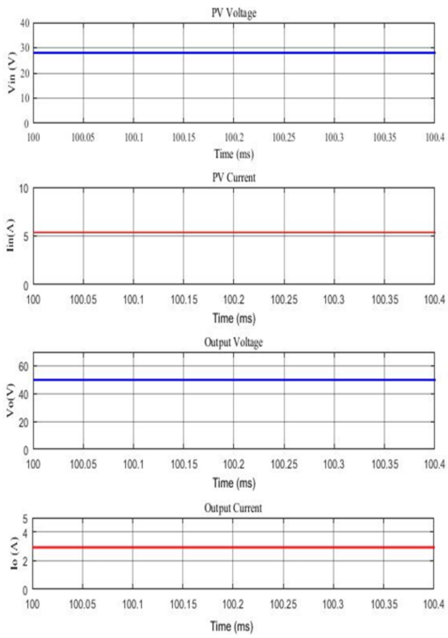


Fig. 13 PV Source and Resistive Load -Voltages and Currents

B. Hardware Results of Modified Boost Converter

To validate the simulation results, A 48% duty cycle pulse was generated using Arduino with a frequency of 30 kHz. Optocoupler is used for isolation and the driver circuit was connected to trigger the MOSFET. A Prototype of the modified boost converter as is rigged up with a resistive load and tested. The results were shown in Fig. 14 which indicate a higher gain over conventional boost converter.

The Study was performed with a constant duty cycle of 45% and input voltage was varied between 6 V and 22 V. The obtained values are plotted with a theoretical gain of conventional boost converter as in Fig.15. The results indicate modified boost converter offers a higher voltage gain over conventional converter and is suitable for PV applications. For a 48% duty cycle, the converter with 22 V input as in Fig. 16 gives an output voltage of 51 V and is suitable for 48 V EV battery charging.

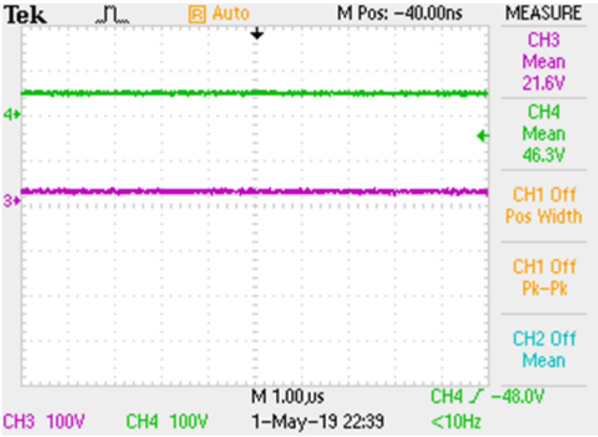


Fig. 14 Results of Modified Boost Converter at 45% duty cycle (Vin- 21.6V, Vo- 46.3V)

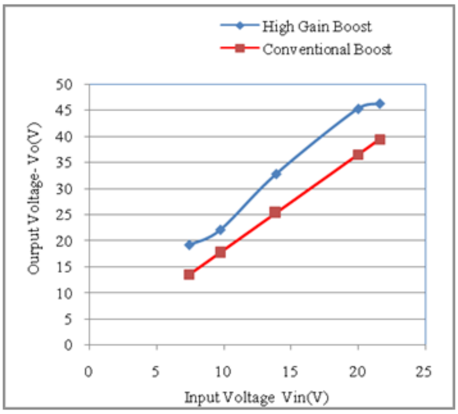
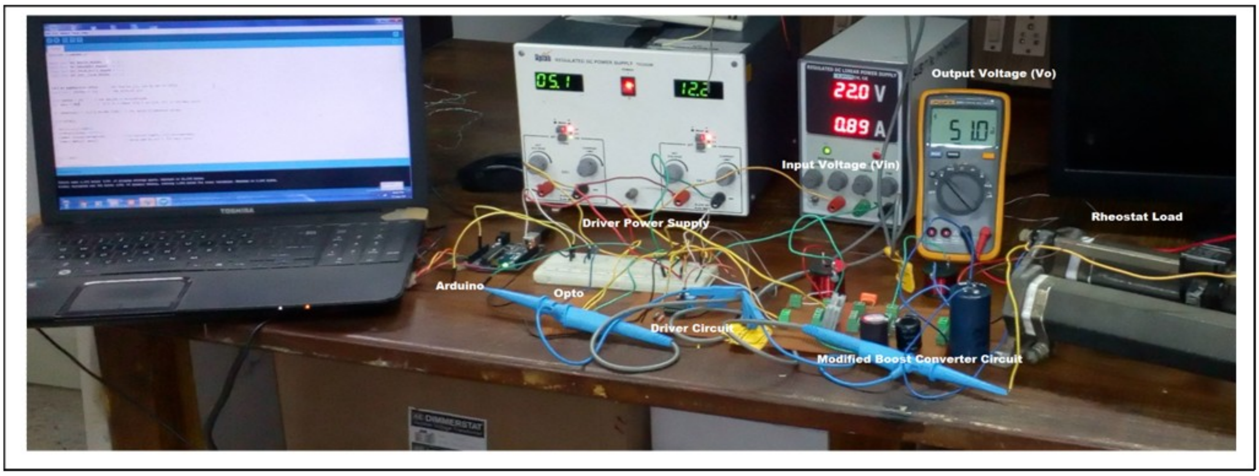


Fig. 15 Comparative study of modified boost converter with varying input (45% duty cycle)



V. Conclusion

In this paper, a unidirectional modified boost converter is proposed. Simulations results using MATLAB / Simulink are presented. The simulation studies of the open-loop operation of the proposed converter with PV source and resistive load are carried and were discussed. The simulation studies indicated a higher gain over a conventional boost converter. The Prototype of the conventional boost converter was tested and compared with the modified converter. Study on the variation of duty cycle with output voltage was carried out which has indicated a linear relationship between the duty cycle variation and the output voltage as in Fig. 14,15. The results indicate a higher voltage gain is achieved by the reconfigured modified boost topology and in agreement with simulation results. As the PV output depends on irradiance and temperature, closed-loop control is essential. Simulation studies with the appropriate algorithm are done and show promising results. The experimental validation for the closed-loop model is being investigated and will be presented in a future paper.

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