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MODULE INTEGRATED HIGH GAIN DC-DC CONVERTER FOR SOLAR BASED EV CHARGING STATION

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ABSTRACT

Omnipresent charging infrastructure is a requisite for ensuring smooth transition to e-mobility. Reliable, sustainable, cost-effective and photovoltaic (PV) panel based charging of EV batteries could be befitting solution. This paper presents a PV module-integrated converter for EV charging station which can track maximum power point besides providing requisite high gain boost in voltage to a usable value even under intermittent conditions, i.e. insolation variation and partial shading conditions. The current control scheme evacuates the maximum available power amidst intermittent conditions. The performance of the system is evaluated under Matlab/Simulink environment. Presented simulation results show close conformity with design and validates the effectiveness of the system proposed.

Keywords: Module Integrated Converter, Incremental Conductance Algorithm, Insolation Variation, Partial Shading Condition, EV Charging.

NOMENCLATURE

Abbreviations	
EV	Electric vehicle
PV	Photovoltaic
MPPT	Maximum Power Point Tracking
R_{DS}(ON)	On state resistance
ESR	Equivalent series resistance
SI-PCCBC	Switched inductor based Parallel charged and cumulative boost converter
V_{OC}	Open-circuit Voltage
I_{SC}	Short-circuit Current
MPP	Maximum Power point
Symbols	
µH	Micro-Henry
µF	Micro-farad

1. INTRODUCTION

Electric Vehicles (EVs) are envisaged to provide a clean, energy efficient and noise-free means of transportation. The technology and infrastructure of charging station is the key enabler for smooth adoption of e-mobility. Fail safe EV charging facilities will be required at homes, workplaces, shops, metro stations, etc., requiring EV chargers to be robust, reliable, sustainable, cost-effective and utilizing renewable energy to have minimum carbon footprint. Among all the renewable energy resources, solar energy powered charging stations are most attractive option because of its high accessibility near load centres and a good compatibility with battery for storing the energy to offset seasonal and diurnal variations. On the other hand EV battery can also be used as energy storage with PV system, to offer portable power generation.

The current-voltage and power-voltage characteristics of a PV panel changes with environmental conditions, which affects the efficiency, durability, power handling capacity and reliability of the system. For efficient utilization of solar energy the assessment of solar radiation and maximum available power from the panels becomes paramount. Thus, various maximum power point techniques (MPPT) are reported for harvesting maximum power from PV panels [1]. But under some non-ideal conditions like insolation variation and shading of panels it alters the Maximum Power Point (MPP). Partial shading of PV panels often results in massive power dissipation in module, resulting in hotspot formation and cell breakdown [2]. The problem is circumvented by using bypass diodes in parallel with each module or part(s) of the module [3]. This results in removable of available amount of power from the module/part of module having shaded portion. This is reflected as multiple peaks and to maintain the best performance of the system, there is a growing trend to deploy more global MPP tracking algorithms [4]. Other envisioned solution is prescribed by connecting a module integrated DC-DC converter to each PV module, thereby eliminating mismatching related losses and also enhancing overall energy harvesting efficiency [5]. This approach presents “plug and play” concept thus enabling easy integration of PV modules in series or parallel combination depending upon user requirements. Key requirements for this approach includes high power density, modular, cost-effective, reliable and robust DC-DC converter [6]. On comparison with conventional method of centralized converter for tracking the MPP, using this approach can increase the harvested power from PV modules by over 30% [7]. Literature reveals various isolated and non-isolated topologies that can be used as module integrated converters [8-14]. Isolated topologies uses high frequency transformer to achieve high voltage gain ratio and galvanic isolation, which would require significant effort while dealing with leakage energy [8]. Non-isolated topology has advantages of higher efficiency, smaller volume, less number of components and easier to implement and control over isolated topologies [9]. Amongst non-isolated converters, boost converter is reported as most preferred module integrated converter (MIC) converter but its operation is restricted by higher duty cycle, since at higher duty, the efficiency of the system droops nosedive which may lead to severe reverse recovery problems thus increasing electromagnetic interference (EMI) levels [10]. Quadratic converters can provide large step-up voltage conversion ratios [11]; however, the switch voltage stress in quadratic converters is equal to the output voltage. Topologies based on capacitor-diode voltage multiplier can eliminate the above drawbacks, reduces the size and cost, and increases the efficiency and reliability [12]. However, these topologies cannot provide ultra-high voltage gains at moderate duty cycles leaving the devices under high stresses. Self-lift converters overcome the above issues, which use more number of inductors and capacitors to boost the voltage [13]. In [14-15], a switching inductor based converter is discussed in which inductors are charged in parallel and discharged in series thus resulting in higher voltage gain.

This paper presents a switching inductor based parallel charged and cumulative discharged boost converter (SI-PCCBC), with its analysis and control for solar powered EV charging station under intermittent conditions. The proposed converter feeds the connected load and the battery bank which is connected in parallel for pumping the energy in terms of current. The converter employs two switching inductor cells, where all the inductors in both the cells are coupled, making the system more modular and power dense. A simple control methodology is employed in the system which ensures the unperturbed operation of the system even if there is a change in MPP voltage of PV due to partial shading condition or change in MPP current due to insolation variation. The operating duty of the converter is governed by incremental conductance algorithm (InC) thus extracting maximum power from PV module. Its parallel charging and cumulative discharging characteristics ensures high voltage gain operation at lower duty, thus resulting in lesser stresses on the active devices. The designed system is simulated under MATLAB/Simulink environment to access the effectiveness of the system for partial shading conditions and conditions of insolation variation.

2. SYSTEM CONFIGURATION

Fig. 1 shows the basic configuration of the solar powered EV charging station. PV panels are connected through MPPT charge controllers (InC controlled SI-PCCBC) to evacuate maximum power to the DC-link which is maintained by a Master voltage source (Mass storage battery) maintained at 220 V DC. PV panel acting as current controlled converter Master charges the battery and deliver the power to EV under dynamically varying conditions, viz., insolation change and partially shaded conditions on each panel.

Fig. 2 shows the circuit diagram of SI-PCCBC utilizing PV panels to power DC link. SI-PCCBC charges all the coupled inductors in parallel when switch is ON and connects them in cascade when switches are turned off

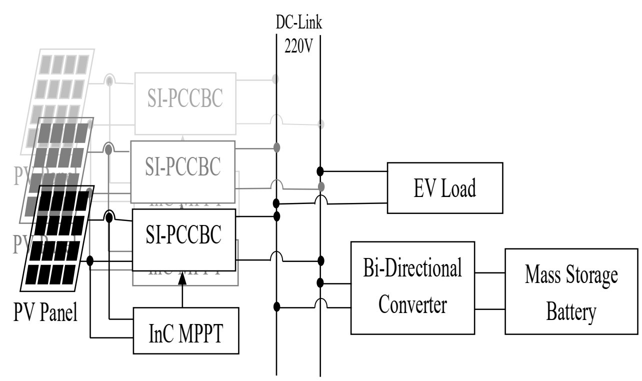


Fig 1 System Configuration having SI-PCCBC as MPPT Controller

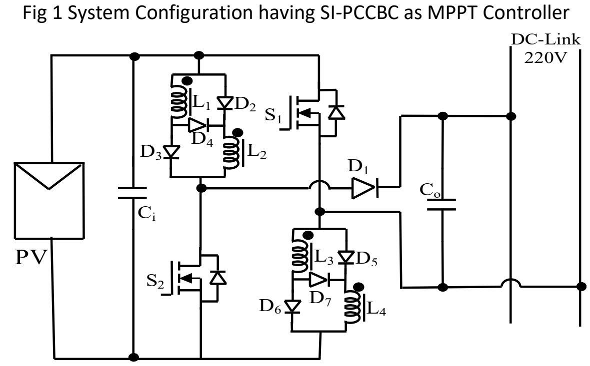


Fig 2 Switched Inductor based parallel charged Cumulative Discharged (SI-PCCBC)

to offer aggregated gain at the output. The converter is operated as current controlled source due to InC controller to charge the battery bank at DC-link. For clear understanding, the operation and control of the converter the analysis of the SI-PCCBC is done first and later the performance of the system is analyzed under two intermittent conditions, i.e. insolation variation which affects current level and partial shading condition which affects voltage level on the PV panel.

3. ANALYSIS

Fig. 3 (a, b) shows the circuit configurations of SI-PCCBC for depicting its modes of operations. For analyzing the steady-state characteristics, some assumptions are made:- ON-state resistance $R_{DS}(ON)$ of the switches and the equivalent series resistances (ESRs) of the coupled inductor and capacitors are ignored; the voltages across the capacitors are considered to be constant; and all the inductors are have same number of turns, thus $L_1 = L_2 = L_3 = L_4 = L$.

SI-PCCBC has two operating modes, viz., Mode 1 (where both the switches are closed); and Mode 2 (where both the switches are open).

Mode 1: When switches are closed the current flows through the inductors following short-circuited path and thus making diodes D_1, D_4 and D_7 reverse biased. Thus voltage equation around the path containing source, inductor L_1, L_2, L_3 and L_4 and switch S_1 and S_2 will be represented as:

$$v_{L_1} = v_{L_2} = v_{L_3} = v_{L_4} = V_{C_i} = L\frac{di_L}{dt} \quad (1)$$

Current flowing through capacitor C_i at the input side and C_o at the output side, respectively are:

$$i_{C_i} = I_i - 4i_L \quad (2)$$

$$i_{C_0} = -I_o \quad (3)$$

Mode 2: When both switches (S_1 and S_2) are opened, voltage polarity across the inductors (L_1, L_2, L_3 and L_4) reverses their polarity and gets connected in series since D_2, D_3, D_5 and D_6 becomes reverse biased. The cumulatively releases the energy and boosts the voltage at output, thereby transferring power to the load through forward biased diodes D_1, D_4 and D_7.

Keeping in view $v_{L_1} = v_{L_2} = v_{L_3} = v_{L_4} = v_L$ the boost in voltage is represented as:

$$v_{Ci} - v_{Co} = 4v_L = 4\,L\frac{di_L}{dt} \quad (4)$$

Current through capacitor C_i on the input side and through C_o at the output side, respectively are:

$$i_{C_i} = I_i - i_L \quad (5)$$

$$i_{C_0} = i_L - I_o \quad (6)$$

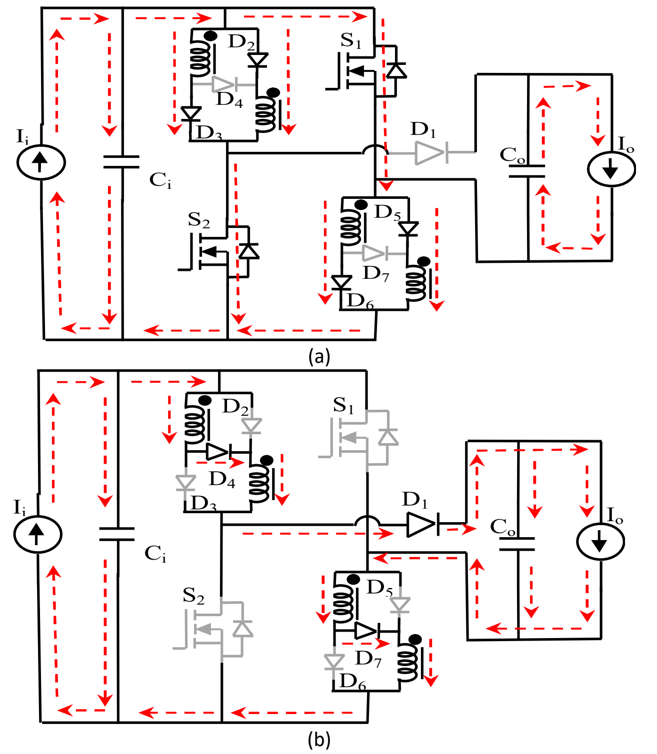


Fig 3 Modes of SI-PCCBC; (a) Mode 1: Switches S_1 and S_2 are closed; and (b) Mode 2: Switches S_1 and S_2 are open.

Using Volt-sec balance equation involving eqs. (1) and (4) representing Mode 1 and Mode 2 as:

$$(v_{ci})D + \left(\frac{v_{Ci}-v_{Co}}{4}\right)(1-D) = 0 \quad (7)$$

which gives the gain as:

$$\frac{v_{Co}}{v_{Ci}} = \frac{1+3D}{1-D} \quad (8)$$

Similarly, under current control operation, current-sec equations across capacitor (C_i) gives:

$$(I_i - 4i_L)D + (I_i - i_L)(1-D) = 0 \quad (9)$$

Giving, $I_i = (1+3D)i_L$ (10)

and current-sec equations across capacitor (C_i) gives:

$$(-I_o)D + (i_L - I_o)(1-D) = 0 \quad (11)$$

giving, $I_o = (1-D)i_L$ (12)

Thus, current gain is extracted as

$$\frac{I_o}{I_i} = \frac{1-D}{1+3D} \quad (13)$$

4. CONTROL STRATEGY

I-V and P-V characteristics of the PV Panel changes with environmental conditions and the incident solar influx which affects the generated power. Thus, staying on MPP point is requisite for extraction of maximum power from PV panel. For the PV-DC-Battery system, current control is preferable as battery acts like master maintaining the voltage at DC-link. Incremental Conductance (InC) algorithm is therefore used for MPP tracking as it provides higher accuracy during fast dynamics and employs current based control.

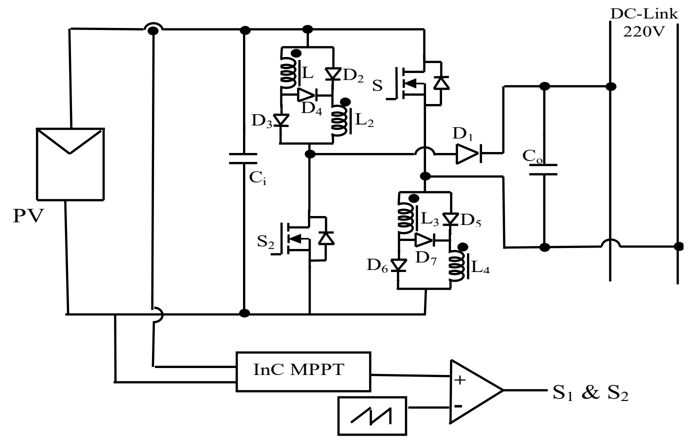


Fig 4 Circuit depicting control scheme of SI-PCCBC

InC algorithm works on following equation:

$$\frac{dP}{dV} = \frac{dI}{dV} = I + V\frac{dI}{dV} \quad (14)$$

For maximum power, $\frac{dP}{dV} = 0$ i.e. $\frac{dI}{dV} = -\frac{I}{V}$. If the operating point is to left of MPP then $\frac{dI}{dV} > -\frac{I}{V}$ and if the operating point is to the right of MPP, $\frac{dI}{dV} < -\frac{I}{V}$.

Duty obtained by using InC algorithm is compared with the carrier signal to produce switching signals for S_1 and S_2 as shown in Fig.4.

5. PERFORMANCE ANALYSIS

The converter is analysed and simulated under MATLAB/Simulink environment using InC algorithm. Photovoltaic panel NEOSOL TSE-300, having V_{OC} of 44.82 V and I_{SC} of 8.63 A, is interfaced with the converter.

The parameters of the system considered are:

Table 1: System Parameters

DC-Link [V]	*L_1, L_2, L_3, L_4* [µH]	*Turns Ratio* [N_1:N_2: N_3:N_4]	*C_i* [µF]	*C_o* [µF]	*Switching Frequency* [kHz]
220	100	1:1:1:1	330	330	50

The operation of the system is tested under insolation variation condition and later for shading condition as per pattern shown in Fig. 5.

Fig. 6 and 7 corresponds to I-V and P-V characteristics of the panel under different conditions. Fig. 6 shows I-V and P-V characteristics at different insolation, i.e. @ 1000W/m^2, @ 900W/m^2 and @ 800W/m^2, Fig. 7 represents the characteristics in three conditions, i.e., 1/3rd portion of panel is shaded, there exists two MPPs, while, when 2/3rd portion of panel is shaded there still exists two MPPs, if the two parts are equally shaded as shown in Fig. 7(b). If the two parts of panel are unequally shaded, then there exist three MPPs which are shown in Fig. 7(c).

The response of the converter connected to one panel under variable insolation (G) levels is shown in Fig. 8. The panel pushes 240 W with V_{MPP} of 36.5 V @ 800W/m^2, thus

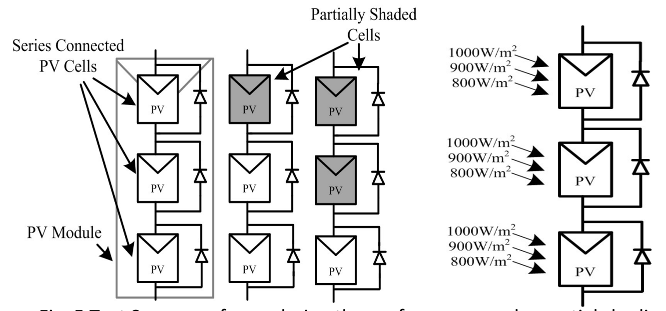
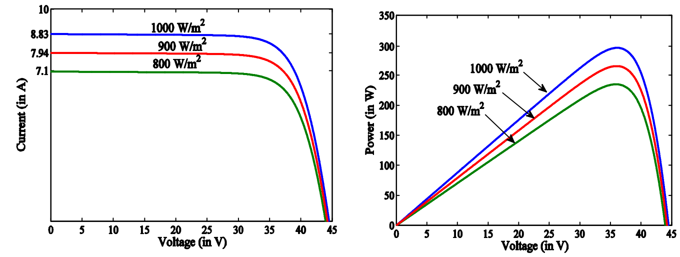
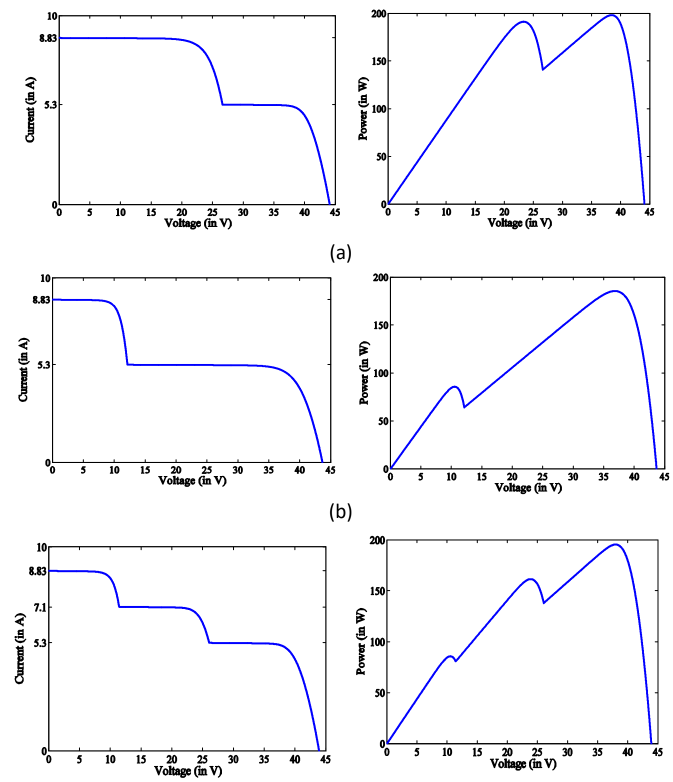


Fig. 5 Test Sequence for analyzing the performance under partial shading conditions of the PV Panel



(a) (b)

Fig. 6: I-V and P-V characteristics of PV panel for irradiance change



(c)

Fig. 7 I-V and P-V Characteristics of PV panel under Partial Shading Condition
(a) 1/3rd portion shaded; (b) 2/3rd portion shaded with equal shading;
(c) 2/3rd portion shaded with each portion having different insolation

making the converter to power the connected load with a contribution of 1.0 A together with battery, providing a contribution of 0.12 A. At t = 0.5 sec, insolation of panel is increased to 900W/m^2, which in turn increases the panel power to 270 W thereby increasing the contribution of the converter to 1.2 A which is used to feed the load and is utilized for accumulating charge on

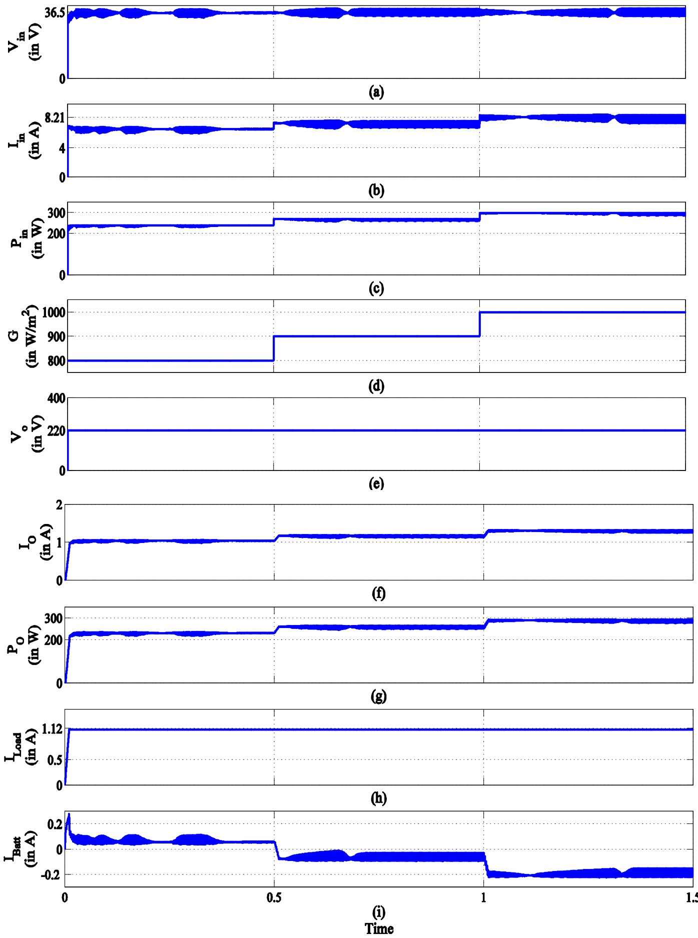


Fig. 8 Insolation Variation Condition: (a) Input Voltage (V_{in});(b) Input Current (I_{in}); (c) Input Power (P_{in}); (d) Insolation (G); (e) DC-link Voltage (V_o);(f) Output Current (I_o);(g) Output Power (P_o);(h) Load Current (I_{Load});(i) Current through Battery (I_{Batt})

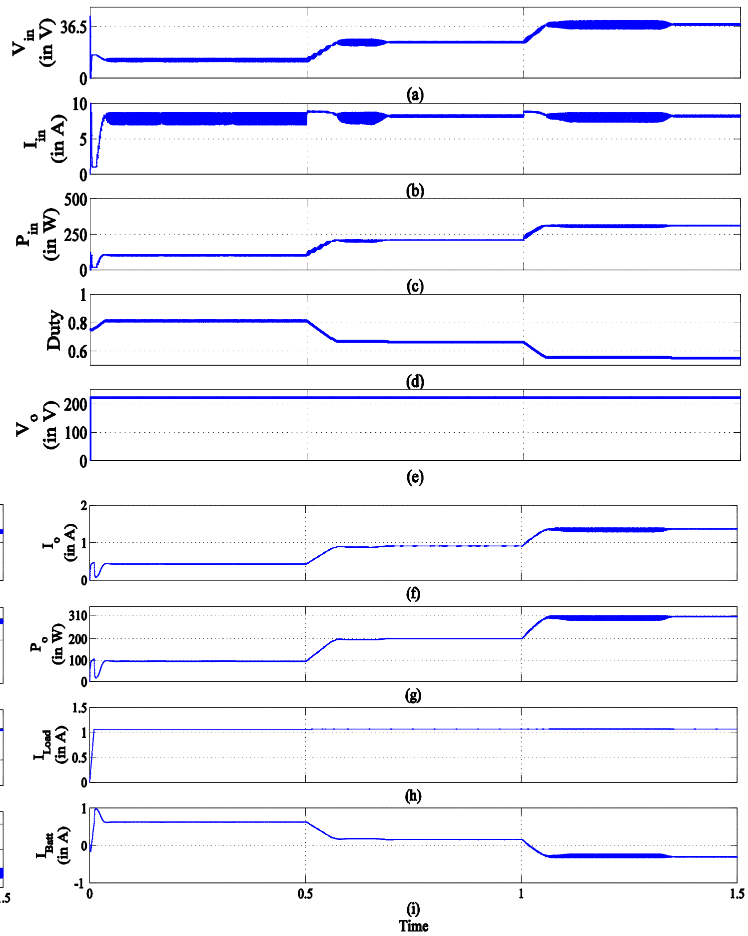


Fig. 9 Partial Shading(a) Input Voltage (V_{in});(b) Input Current (I_{in}); (c) Input Power (P_{in}); (d) Duty (D); (e) DC-link Voltage (V_o); (f) Output Current (I_o);(g) Output Power (P_o);(h) Load Current (I_{Load});(i) Current through Battery (I_{Batt})

the batteries at DC link. At t = 1 sec, output power of the converter increases to 300W. The output current of the converter increases to 1.3 A, thus feeding the load by 1.1 A current and also supplying to battery by 0.2 A.

Fig. 9 shows the dynamics of the system under shading conditions. Initially from t=0 sec to t = 0.5 sec, 2/3rd of the panel is considered, which represents low input condition (12.5 V) and input current is 8.21 A, thus converter contributes 0.5 A to load while battery is supporting to load by supplying 0.6 A. Operating duty is approximately 80 % to supply to load at 220 V. At t = 0.5 sec, when shading is suddenly reduced to 1/3rd portion of panel, output current of panel still hovers around 8.21 A, while the voltage gradually increases to 25.6 V. Thus power generated from the panel increases to 210 W with operating duty of 66%, making the converter to push 0.9 A to load and balance 0.2 A is supplied from battery. At t = 1 sec, when shading on the panel is removed, voltage gradually build up to 36.5 V which is the MPP voltage. The

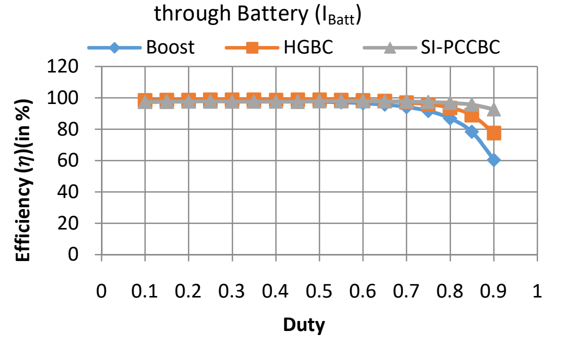


Fig. 10 Comparison of Efficiency of Boost, HGBC [14] and SI-PCCBC

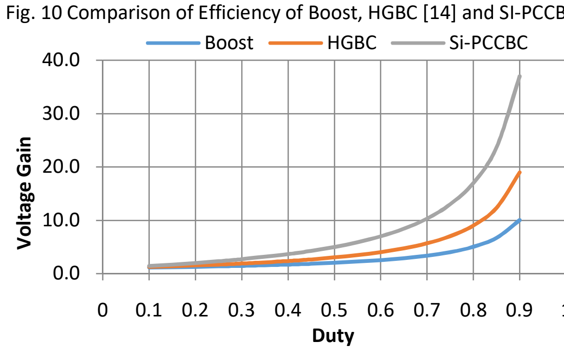


Fig. 11 Comparison of Voltage Gain of Boost, HGBC [14] and SI-PCCBC

converter feeds 1.1 A to the load and 0.3 A to charge the DC link.

Fig. 10 and 11 shows the comparison of the efficiency and voltage gain of the boost converter, HGBC and SI-PCCBC for a 300 W system. The graphs clearly shows the merit of SI-PCCBC over boost converter and PCCBC for high gain applications, viz, partial shading conditions.

6. CONCLUSION

A PV-Module integrated high gain boost converter is discussed in the paper for EV charging station. Results demonstrates the performance of the proposed converter to effectively track MPP for transfer power to the load with a simple current control scheme and boost the voltage upto usable value under both intermittent irradiation conditions and partial shading condition. Converter effectively utilizes switched inductor cell, with parallel charging of inductors and cumulative discharging ensuring high gain operation of the converter with robustness and modularity of architecture. The proposed converter is cost-effective, robust, power dense, modular and shall pave the way for better utilization of PV off-grid and on-grid applications.

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