Grid tied PV- Electric Vehicle Battery Charger using Bidirectional Converter

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Abstract- Research on renewable energy based Electric Vehicle battery charging system is booming in the automobile industry in the recent years. The intermittent nature of the renewable energy sources leads to the grid connected renewable energy systems for Electric vehicle battery charging applications. Hence, an Electric Vehicle battery charger using grid connected PV system is proposed in this paper. The proposed system is capable of charging the EV battery continuously irrespective of solar irradiations using dc-dc converter and bidirectional ac-dc converter. Sepic converter is preferred for dc-dc converter and Line commutated converter is used as a bidirectional ac-dc converter with the help of the proposed bidirectional configurator in the charging system. During sunshine hours, PV array power generated is used to charge the EV battery alone and during peak sunshine hours, apart from charging of EV battery, the excess PV array power is fed to the single phase utility grid. During low and non sunshine hours, the EV battery charging was supported by the utility grid through bidirectional ac-dc converter. The proposed electric vehicle battery charger is simulated in the MATLAB/Simulink environment and the dynamic response of the system was studied and its results are furnished in this paper.

Keywords Electric Vehicle Battery, Bidirectional ac-dc converter, Line commutated converter, Photovoltaic array, Sepic converter, Utility grid.

1. Introduction

In the last decade, transportation sector is booming with the development of Electric Vehicle (EV) as an option to reduce the global climate change due to CO_2 emissions from the conventional internal combustion (IC) engine vehicles [1]. Battery charging facility plays a vital role in the growth of EV in the automobile industry [2]. Recently, renewable energy based battery charging stations are developing rapidly worldwide [3]. Among various renewable energy sources, PV array installation is easy and also the continuous price reduction of PV modules makes it more attractive. Hence, PV array based EV battery charging is adopted by many EV users [4-5]. Although, aforementioned EV battery charging system has many advantages like easy installation, low maintenance cost and clean charging system, it has the disadvantage of intermittent nature and non-availability during night [6-7]. To overcome these disadvantages, there is a need for alternate source of energy during non sunshine hours [8-9]. Thus, grid connected PV-EV battery charging system is proposed in this paper.

The proposed system can charge the EV battery from PV array and grid during sunshine hours and low or non-sunshine hours respectively. Also, this system has the advantage of reducing the electricity bills to the users by feeding the excess PV generated power to the grid during peak sunshine hours. To integrate PV array, utility grid and EV battery, there is a need for intermediate dc-dc converter and bidirectional ac-dc converter [10-12].

Among various dc-dc converters, sepic converter is preferred in the proposed system due its advantages like (i) capability of operating in boost and buck mode (ii) providing output voltage with the same polarity as input voltage [13]. Silicon controlled rectifier (SCR) based line commutated converter (LCC) is used as a bidirectional ac-dc converter.

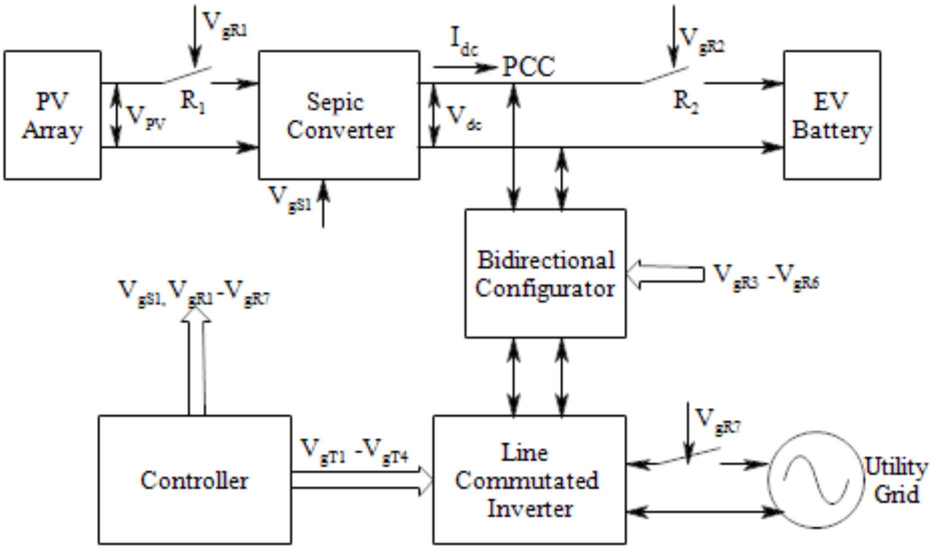


Fig. 1. Block diagram of the EV battery charger

In order to operate LCC in bidirectional mode, a bidirectional configurator is proposed in this charging system. It can operate both in rectifier and inverter mode depending on the firing angle of SCRs, α. Thus, during peak sunshine hours, LCC works in inverter mode with α > 90° in order to feed the excess PV array generated power to the utility grid. During non-sunshine hours, LCC works in rectifier mode with α < 90° to charge the EV battery from the utility grid. Also, LCC has the added advantage of self-grid synchronizing capability inherently [14-15]. Thus, an uninterruptable grid connected PV system with sepic converter and line commutated converter is proposed to charge the EV battery.

2. Description of the Proposed System

The proposed EV battery charger consists of a PV array, a sepic converter, Line commutated converter, bidirectional configurator, an Electric Vehicle battery, single phase utility grid, relays and controller as shown in Fig. 1. Description of each blocks depicted in Fig. 1 are explained in the following sub-sections.

2.1. Sepic Converter

The sepic converter consists of one IGBT switch, one diode, two inductors and two capacitors as shown in Fig. 2. The duty cycle of sepic converter is adjusted using the PI controller to provide constant output voltage at the point of common coupling (PCC), V_{dc} irrespective of the PV array voltage to charge EV battery in the constant voltage charging method. The voltage gain of the sepic converter is provided as follows [16]:

$$\frac{V_{dc}}{V_{pv}} = \frac{\delta}{1-\delta} \tag{1}$$

where, δ is the duty cycle of sepic converter, V_{PV} is the PV array voltage. The inductors and capacitors of sepic converter are designed as per the equations below:

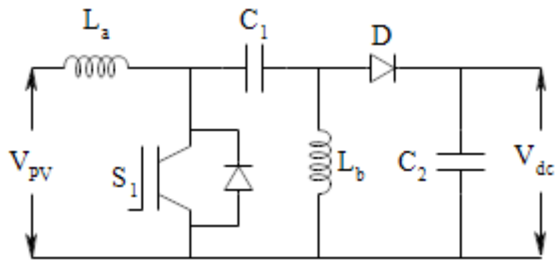


Fig. 2. Circuit diagram of sepic converter

$$L_a = L_b = \frac{V_{PV\,\min}\delta_{\max}}{2\Delta i_{PV} f_s} \tag{2}$$

$$C_1 = \frac{I_{dc}\delta_{\max}}{\Delta V_{C1} f_s} \tag{3}$$

$$C_2 = \frac{I_{dc}\delta_{\max}}{\Delta V_{dc} f_s} \tag{4}$$

Where, V_{PVmin} is the minimum PV array voltage, Δi_{PV} is the input current ripple, f_s is the switching frequency, I_{dc} is the current flowing through the PCC, ΔV_{C1} is the capacitor, C_1 voltage ripple, ΔV_{dc} is the output voltage ripple, and δ_{max} is the maximum duty cycle which is given by

$$\delta_{max} = \frac{V_{dc} + V_D}{V_{PVmin} + V_{dc} + V_D} \tag{5}$$

where, V_D is the diode voltage drop. As per the IEEE standards, the inductors value of Sepic converter is chosen to have a minimum of 5 % of input current ripple and the input and output capacitor values are chosen to have a minimum of 5 % of input and output capacitor voltage ripples in order to reduce the ripples in output current and voltage waveforms.

2.2. Line Commutated Converter

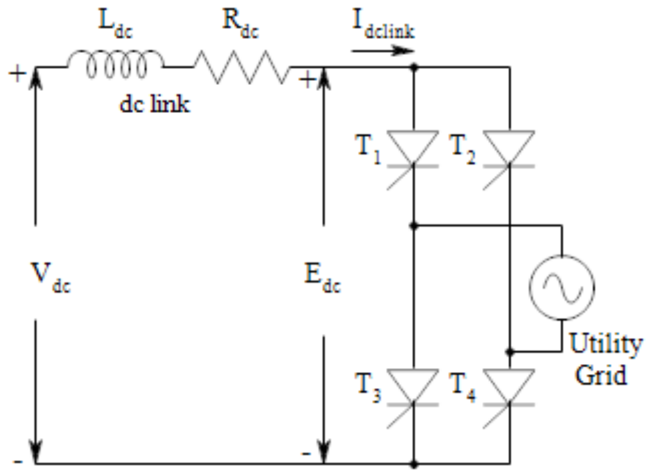


Fig. 3. Circuit diagram of Line commutated converter configured as inverter

The schematic diagram of LCC configured as inverter is shown in Fig. 3. It consists of 4 SCR switches and a dc link inductor, L_{dc} with internal resistance R_{dc}. During $\alpha > 90°$, LCC operates in inverter mode to feed power to the grid from PV array, provided $V_{dc} > E_{dc}$. Whereas, during $\alpha < 90°$, LCC operates in rectifier mode reversing the polarity of dc link voltage, E_{dc} which in turn necessitates the reversal of polarity of V_{dc} for supplying the power from grid to EV battery. This is accomplished by the proposed bidirectional configurator which is explained in the following sub-section 2.3. The dc link voltage of LCC, E_{dc} is given by [17]

$$E_{dc} = \frac{2V_m}{\pi}\cos\alpha \tag{6}$$

Where, V_m is the peak amplitude of ac voltage and α is the firing angle of SCR switches.

The dc link inductance, L_{dc} is designed for continuous conduction using the following equation [18]

$$L_{dc-critical} = 3.18\frac{E_{dc}}{I_{dclink}} \tag{7}$$

2.3. Bidirectional Configurator

The proposed bidirectional configurator consists of 4 relays which are arranged in such a way to make LCC to work as a bidirectional ac-dc converter as shown in Fig. 4. This bidirectional configurator ensures the bidirectional flow of power from PCC to grid in inverter mode and from grid to PCC in rectifier mode. During inverter mode, relays R_3 & R_4 are closed to interconnect the point 'A' of PCC to point 'C' of dc link and interconnect the point 'B' of PCC to point 'D' of dc link respectively. During this mode, relays R_5 & R_6 remain open as shown in Fig. 5(a). As mentioned in the sub-section 2.2, during rectifier mode, polarity of V_{dc} has to be reversed and hence, the point 'A' is connected to point 'D' and point 'B' is connected to point 'C' by closing relays R_5 and R_6 respectively while opening the relays R_3 and R_4 as shown in Fig. 5(b) to ensure the charging of EV battery from utility grid during this mode.

2.4. Controller

The controller in the proposed system generates the gate pulses to the sepic converter, LCC, bidirectional configurator and additional relays. A PI controller is designed to generate the gate pulses to the sepic converter switch by adjusting the duty cycle to maintain constant voltage at the PCC irrespective of the solar irradiation conditions. The firing pulses to the SCR switches of LCC are generated with $\alpha > 90°$ to operate LCC in inverter mode to feed the PV array power to the utility grid during peak sun-shine hours or full charge condition of EV battery.

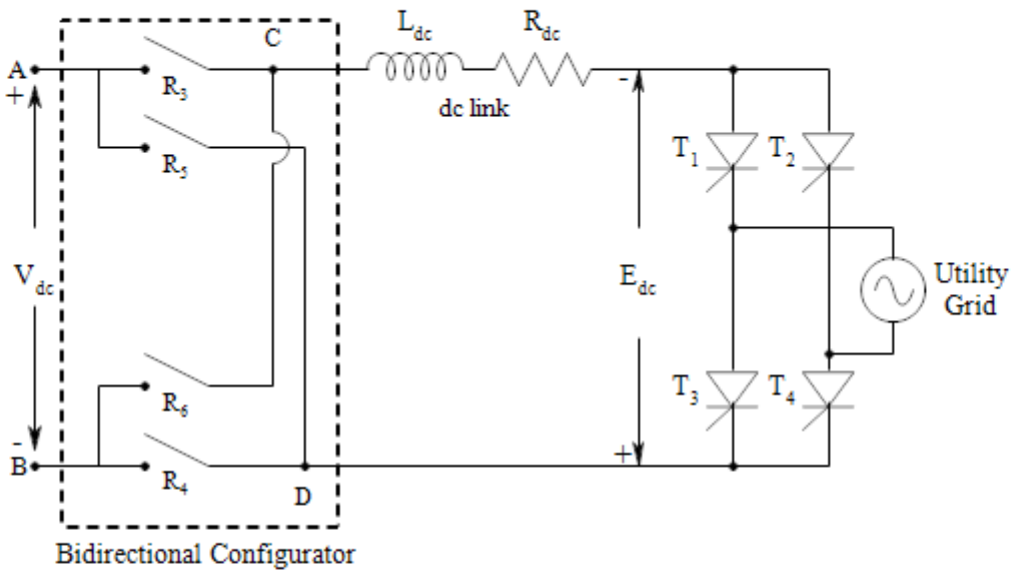


Fig. 4. Schematic diagram of bidirectional cofigurator

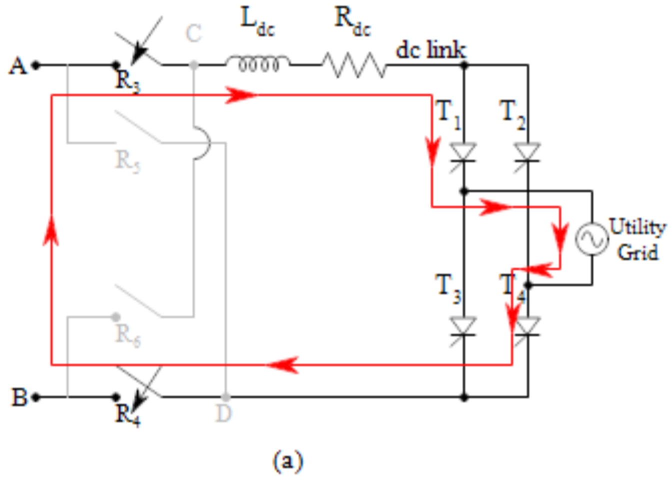


Fig. 5. Schematic diagram of LCC configured as (a) inverter & (b) rectifier

The firing pulses of LCC are generated with $\alpha < 90°$ to operate LCC in rectifier mode to charge EV battery from utility grid during low solar irradiation conditions. Controller generate control signals to operate the bidirectional configurator relays and additional relays depending on the PV array power generated and the state of charge (SOC) of EV battery. The working of the proposed EV battery charger is explained in detail in Section 3.

3. Working of the Proposed EV Battery Charger

Working of the proposed system is explained in 4 different modes of operation depending on the solar irradiation conditions and SOC of EV battery viz (i) mode 1 (P-V), (ii) mode 2 (P-VG), (iii) mode 3 (G-V) and (iv) mode 4 (P-G).

3.1. Mode 1: Forward PV-EV battery charging mode (P-V)

During normal sun-shine hours, solar power generated is sufficient to charge only EV battery in this mode. During this mode, the relays R_1 and R_2 are closed in order to transfer power from PV array to charge EV battery. Other relays in bidirectional configurator R_3 - R_6 and relay R_7 are open isolating the LCC and utility grid from the system.

3.2. Mode 2: Forward PV- EV battery & Grid mode (P-VG)

During peak sunshine hours, excess power generated from the PV array is fed to the utility grid apart from charging EV battery in this mode. In order to transfer the PV array power to EV battery and to the grid, relays R_1, R_2 and R_7 are closed in addition to closing of bidirectional configurator relays R_3 & R_4 to configure the LCC as line commutated inverter (LCI) as shown in Fig. 3 in this mode.

3.3. Mode 3: Reverse grid- EV battery charging mode (G-V)

During low sunshine hours and night time, solar power generated is insufficient to charge EV battery. Hence, grid power is used to charge EV battery in this mode with relays R_2 and R_7 closed. In order to transfer power from utility grid to the EV battery, R_5 & R_6 relays in the bidirectional configurator are closed to configure LCC as rectifier in this mode. Relay R_1 was opened to isolate PV array from the proposed charging system in this mode.

3.4. Mode 4: PV- grid mode (P-G)

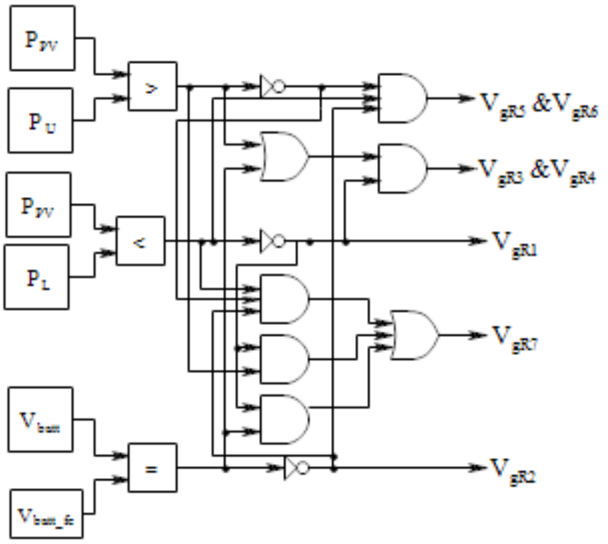
When EV battery is fully charged, EV battery has to be disconnected from the charging system and thus the solar power generated is fed to the grid alone in mode 4. In this mode, operations of relays are same as in mode 2 other than opening of relay R_2 to isolate EV battery from the proposed system.

The detailed working of controller which plays a vital role in the working of the proposed charging system in different modes of operation is explained in the next section.

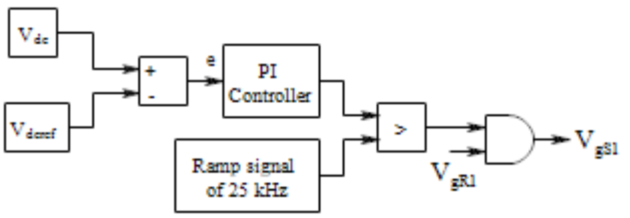
4. Design of Controller

Controller of the proposed system generates gate pulses to the sepic converter switch and generates firing pulses to the SCR switches in the Line commutated converter. Also, it controls the relays, R_1, R_2, R_7 and relays in bidirectional configurator R_3, R_4, R_5 and R_6 depending on the PV array irradiation conditions, viz (i) P_L is the low PV array power generated at specified lower irradiation limit (ii) P_U is the PV array power generated at specified upper irradiation limit. Operating conditions of relays in bidirectional configurator and other relays in the proposed system are provided in Table 1 for different modes of operation.

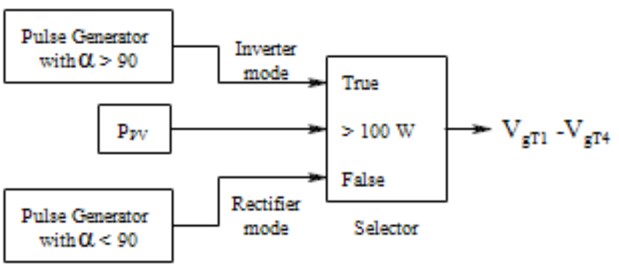
During $P_L < P_{PV} \leq P_U$, PV array with SEPIC converter is connected to EV battery alone by closing relays R_1 and R_2. The charging system is disconnected from the grid by maintaining the relays R_3, R_4, R_5 & R_6 in bidirectional configurator and relay R_7 in open state. During $P_{PV} > P_U$, control signals are generated to close the relays R_1, R_2, and R_7 and relays R_3 & R_4 in bidirectional configuartor to charge EV battery and feed excess power to the grid. Whereas, during $P_{PV} < P_L$, PV array is isolated from the charging system by opening the relay R_1 and the EV battery gets charged from the power supplied by the utility grid by closing the relays R_5 & R_6 and opening relays R_3 & R_4 in bidirectional configurator with relay, R_7 closed.



(a)



(b)



(c)

Fig. 6. Schematic diagram of (a) Relay controller (b) Sepic converter controller and (c) LCC controller

When EV battery is fully charged, battery voltage reaches its full charge voltage, $V_{batt\text{-}fc}$ during which the EV battery is disconnected from the charging system by opening the relay R_2. Generation of control signals to operate relays is shown in Fig. 6(a). PI controller generates gate pulses to the MOSFET switch of sepic converter to maintain constant voltage at PCC by changing the duty cycle of the gate pulses depending on the PV array voltage as shown in Fig. 6(b). Also, controller generates firing pulses to the LCC depends on the PV array generated power. If $P_{PV} > P_U$, controller generates firing pulse with $\alpha > 90°$ to SCR switches T_1 and T_4 and to the switches T_2 and T_3 with 180° phase shifted from that of the T_1& T_4 firing pulse to operate LCC in forward inverter mode for feeding the excess PV array power to the single phase utility grid. If $P_{PV} < P_L$, controller generate firing pulse with $\alpha < 90°$ to switches T_2 and T_3 and firing pulse to the switches T_1 and T_4 are provided with 180° phase shift from that of T_2 and T_3 firing pulses to operate LCC in reverse rectifier mode to charge EV battery from single phase utility grid as shown in Fig. 6(c).

Table 1. Operation of relays in the proposed system

EV Battery SOC, 1: fully charged, 0: Not fully charged
Relay conditions, 1: closed, 0: open

Modes	Irradiation Condition	EV Battery SOC	Relays			Bidirectional Configurator Relays	
			R_1	R_2	R_7	R_3 & R_4	R_5 & R_6
P-V	$P_L < P_{PV} \leq P_U$	0	1	1	0	0	0
P-VG	$P_{PV} > P_U$	0	1	1	1	1	0
G-V	$P_{PV} < P_L$	0	0	1	1	0	1
P-G	$P_{PV} > P_L$	1	1	0	1	1	0
Null	$P_{PV} < P_L$	1	0	0	0	0	0

5. Simulation Studies and Results

The proposed EV battery charging system is simulated in the simulink environment of MATLAB software. The proposed system is modeled using power MOSFET, 4 Thyristor switches, step up transformer, inductors, L_1& L_2 each of 0.5 mH and L_{dc} of 5 mH and capacitors, C_1 of 850 µF, C_2 of 750µF available in SimPowerSystem blockset in simulink library. Controller is developed using PWM generator, pulse generator, logic gates, comparator, multiplier and PI controller available in the Simulink library.

PV array model (two 250 W panels each with open circuit voltage, V_{oc} of 37.25 V and short circuit current, I_{sc} of 8.75 A are connected in parallel) is integrated with the developed sepic converter and Line commutated converter along with the battery model available in Simulink library for developing the proposed EV battery charging system as shown in Fig. 7.

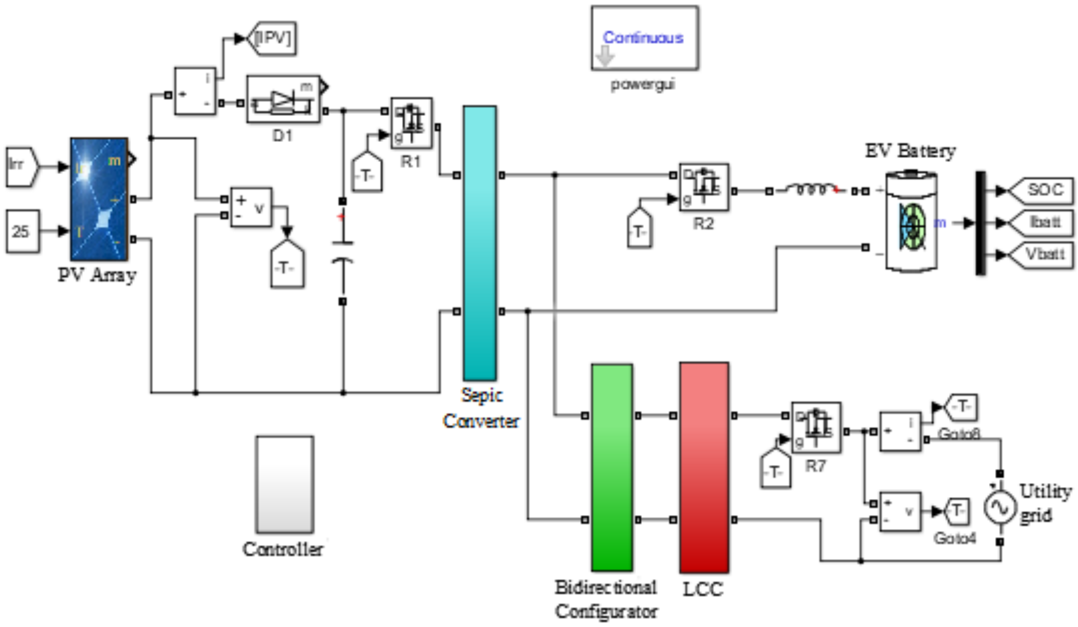


Fig. 7. Simulation model of proposed EV battery charger

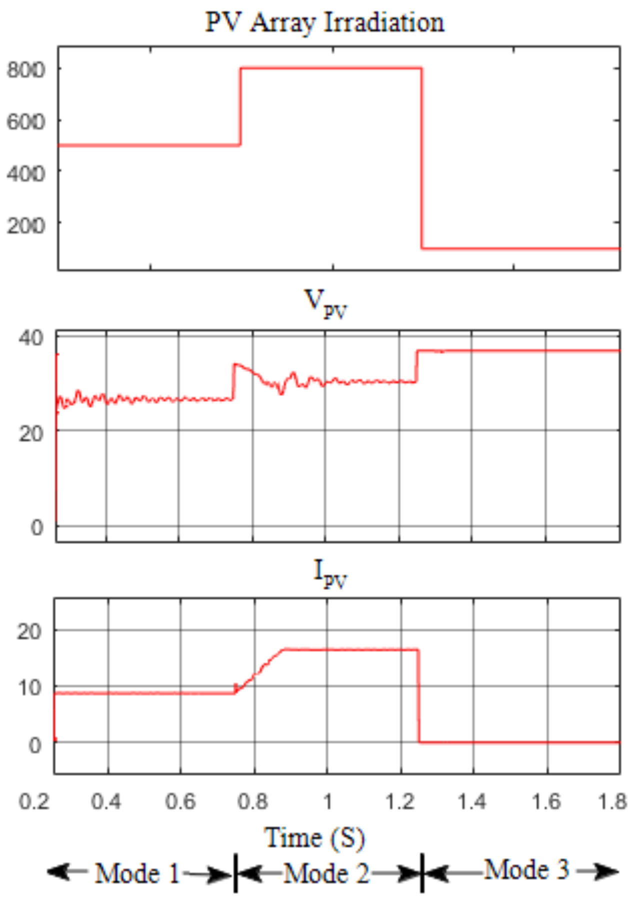


Fig.8. Waveforms of PV array irradiation, PV array voltage, V_{PV} and PV array current, I_{PV}

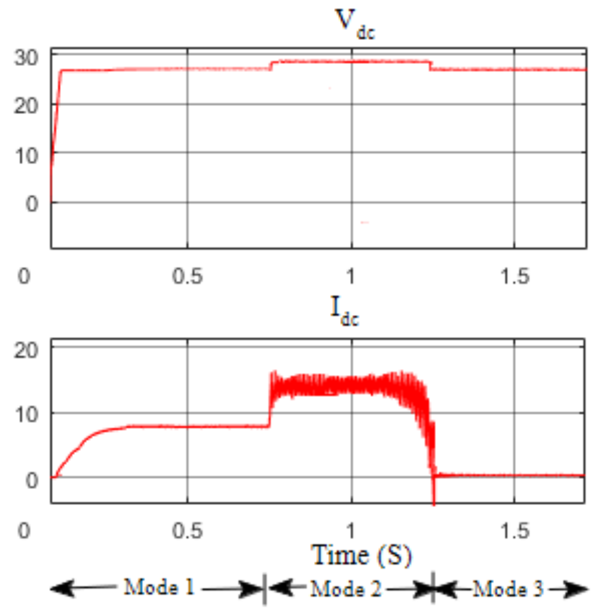


Fig. 9. Waveforms of sepic converter output voltage, V_{dc} and output current, I_{dc}

The dynamic response of the system was investigated using the developed simulation model for PV array irradiation of 500 W/m^2, 800 W/m^2 and 100 W/m^2 in mode 1: (P-V), mode 2: (P-VG) and mode 3: (G-V) respectively. The simulation results showing PV array voltage, V_{PV} and current, I_{PV} waveforms along with the solar irradiation in all the 3 modes are depicted in Fig. 8. Figure 9 shows the sepic converter output voltage at PCC, V_{dc} and current, I_{dc} waveforms and the EV battery SOC, battery voltage, V_{batt} and current, I_{batt} waveforms are shown in Fig. 10. The dc link voltage, E_{dc} and current, I_{dclink} of LCC and the grid voltage, V_{grid} and current, I_{grid} are depicted in Fig.11.

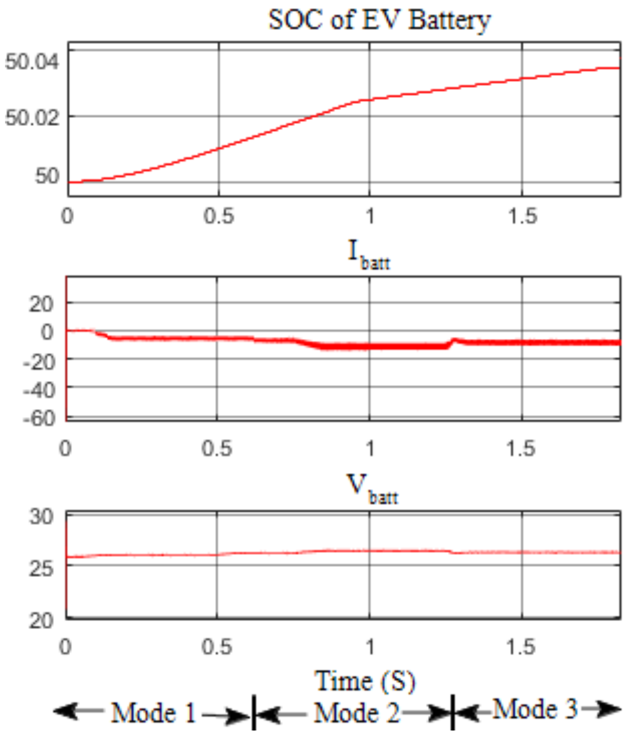


Fig. 10. Waveforms of EV battery SOC, Voltage, I_{batt} and current V_{batt}

From Fig. 8, 9, 10 and 11, it can be seen that, in mode 1, PV array voltage of 31.64 V and current of 7.27 A contributing to the power of 230 W is step down to a voltage of 26.64 V and current of 8.169 A by the sepic converter to charge EV battery alone as the PV array generated power is sufficient to charge EV battery only. In this mode, the proposed charging system is isolated from the grid which is depicted by the grid current of 0 A from Fig. 11.

In mode 2, PV array voltage of 34.6 V and current of 13.58 A is bucked to a constant voltage of 26.7 V at the sepic output terminal with the current of 16.53 A which is supplied to both EV battery and grid. In this mode, LCC operates in inverter mode at the constant firing angle α = 120° producing a negative dc link voltage, E_{dc} being less than the voltage at PCC of 26.7 V ensuring that the power is fed to the grid through a step-up transformer of 1:5 turns ratio. A power of 208 W is fed to a single phase 230 V grid at a current of 0.919 A. In this mode also, EV battery gets charged with the battery voltage of 26.6 V and current of 8.2 A.

In mode 3, PV array power is insufficient to charge EV battery and hence, the PV array is isolated from the charging system which is indicated by the increase in the PV array voltage to its open circuit voltage of 37.8 V and current being reduced to 0 A. EV battery is charged from the grid power in this mode operating LCC as rectifier with firing angle α = 30° indicated by the positive E_{dc} as shown in Fig. 11. From Fig. 10, it is evident that EV battery gets charged which is indicated by the increase in SOC and negative battery current in all the three modes irrespective of the solar irradiation conditions.

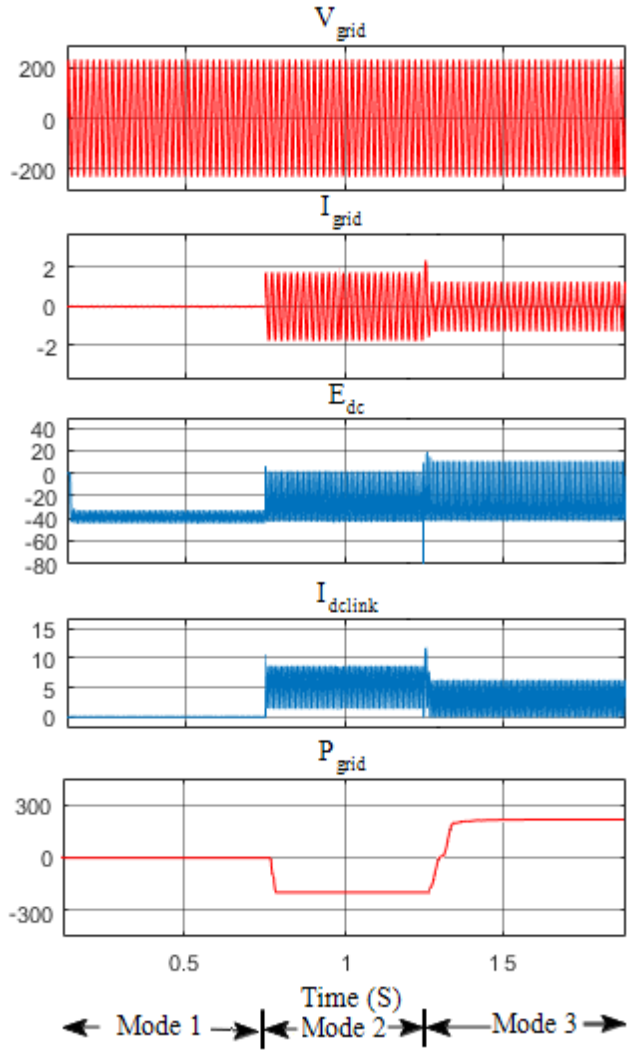


Fig. 11. Waveforms of grid voltage, V_{grid}, grid current, I_{grid}, dc bus voltage, E_{dc} current, I_{dclink} and grid power, P_{grid}

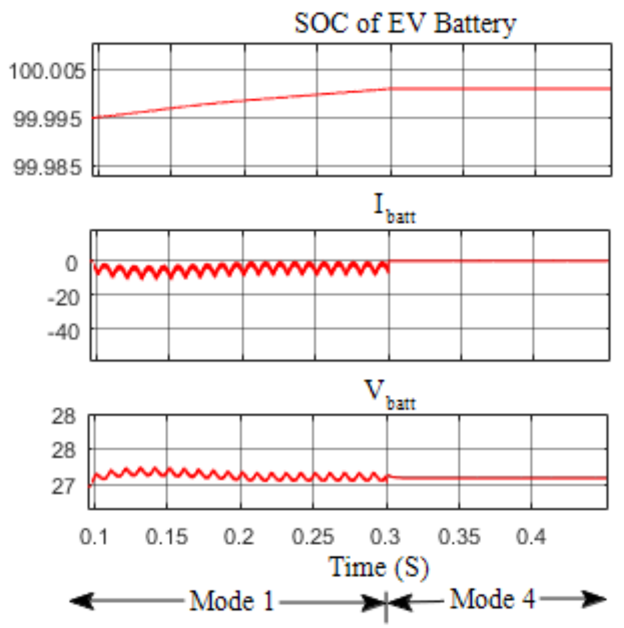


Fig. 12. Dynamic response of EV battery waveforms from Mode 1 to Mode 4

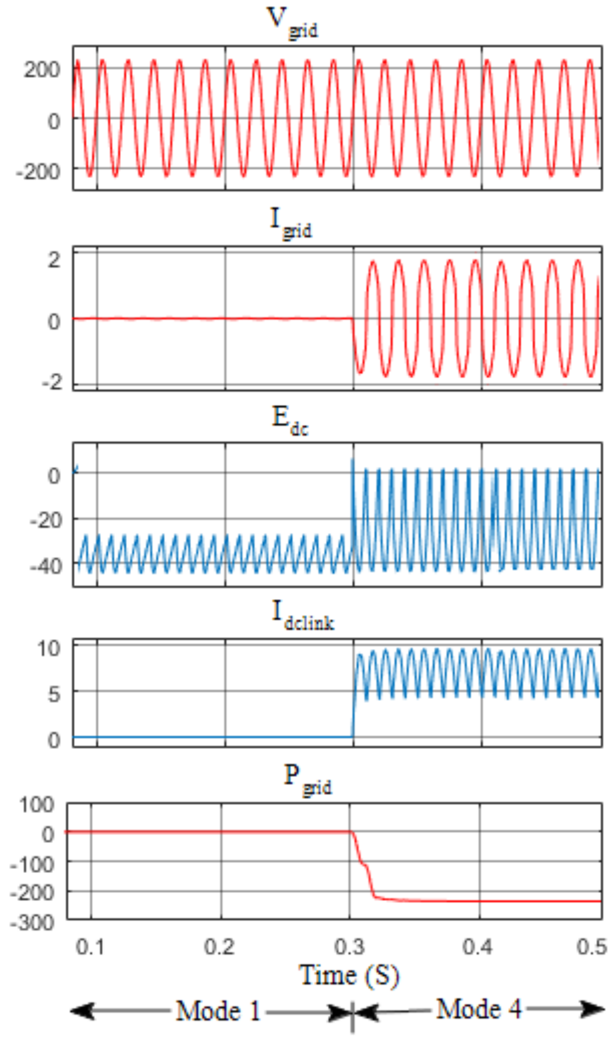


Fig. 13. Dynamic response of grid voltage & current and dc bus voltage & current waveforms from Mode 1 to Mode 4

Table 2. Comparative results in 4 modes of operation

Parameters	P-V mode	P-VG mode	G -V mode	P-G mode
Irradiation (W/m^2)	500	800	100	500
V_{PV} (V)	31.64	34.6	35.2	31.64
I_{PV} (A)	7.27	13.58	0	7.27
P_{PV} (W)	230	469.8	0	230
V_{dc} (V)	27.74	26.7	26.2	27.74
I_{dc} (A)	8.169	16.53	7.76	8.169
V_{batt} (V)	26.64	26.6	26	27.4
I_{batt} (A)	8.169	8.2	7.76	0
P_{batt} (W)	217.62	218.12	202	0
V_{grid} (V)	230	230	230	230
I_{grid} (A)	0	0.979	0.95	0.95
P_{grid} (W)	0	208	217	217

Also, the dynamic response of the charging system when the SOC of EV battery reaches 100 % is observed as transition from mode 1 to mode 4. During mode 1 at an irradiation of 500 W/m^2, EV battery alone gets charged from PV array generated power and the charging system is isolated from the grid. In this mode, if SOC of EV battery reaches 100 %, EV battery is disconnected from the charger which is depicted in Fig. 12 by the constant fully charged battery voltage of 27.4 V and zero battery current. Also, the PV array generated power is fed to the grid is represented by the negative grid power, P_{grid} in Fig. 13. Comparison of input and output parameter values in 4 different mode of operation of the proposed EV battery charger is presented in Table 2.

6. Conclusion

In this paper, an off-board EV battery charger fed from grid connected PV system is proposed. This paper discusses the flexibility of the system for uninterruptable charging of EV battery in constant voltage charging method irrespective of the irradiation conditions. The proposed system is capable of charging EV battery and supply power to the grid with the help of bidirectional configurator during peak sun-shine hours and also EV battery gets charged from the grid during low and non sun-shine hours. The proposed charging system is designed and simulated in simulink environment of the MATLAB software and the dynamic results are furnished for the four modes of operation. The simulation results presented in this paper emphasize the effectiveness of the proposed charger.

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