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A Solar PV Based Smart EV Charging System with V2G Operation for Grid Support

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Abstract—**This paper presents a solar photovoltaic (PV) based electric vehicle (EV) charging system with the ability to charge the EV battery storage system and with vehicle to grid (V2G) operation to support power grid. The charging system consists of a solar PV array with a single-ended primary-inductor converter (SEPIC) DC-DC converter, a bidirectional DC-DC converter for EV battery charging and three-level inverter with LCL filter for grid interface and associated controllers. The SEPIC converter is controlled with maximum power point tracking algorithm to extract maximum power from solar PV array and charge EV battery through a bidirectional DC-DC converter and controller. The designed controllers are capable to provide uninterrupted charging and grid support to enhance grid performance under disturbance and variable PV generation. The charger is also enabled with V2G power transfer for active and reactive power support and enhancement of fault ride through capability for the distribution grid with renewable energy sources. The proposed system is implemented in MATLAB/Simscape environment and results confirm that the proposed solar PV based EV charging system can charge the EV and provide grid support under varying irradiance and grid disturbances.**

Keywords—Electric Vehicle, Solar Photovoltaic, Vehicle-to-Grid, EV charging system, Grid Support

I. INTRODUCTION

Recently, solar PV integrated EV chargers have gained popularity as a clean and environmentally friendly charging method to provide energy security and reduce carbon emission. Solar PV based EV charging system provides energy efficient techniques while allowing renewable energy resources to be utilised in the transportation system and power grid. The solar PV based EV charging infrastructure offers high efficient and reliable EV performance and ancillary services to the power system such as voltage and frequency regulation, peak shaving and bidirectional power flow to maintain the utility grid balance through the vehicle to grid (V2G) and grid to vehicle (G2V) operation [1],[2]. Furthermore, V2G operation serves as a controllable spinning reserve that is achievable with the smart grid. Coordinated charging systems can be used to improve grid operational performance through smart control of EV loads while minimizing charging costs by adapting various pricing policies [3].

However, large scale integration of EVs into the distribution grid (DG) create some challenges and issues. Firstly, the high EVs loads on the DG introduced unpredictable dynamic behaviours, increasing peak demand, power quality (PQ) impacts, harmonics, and high active power absorption [4]. Secondly, EVs contribute to carbon emission depending on the source of electricity used to charge battery, such as coal/gas-based power. Therefore, EVs can be charged in a more sustainable manner by using renewable energy sources such as solar PV to overcome grid-related impacts and indirect greenhouse gas emission from the EVs.

Solar PV energy based charging system is a sustainable option for the future of the EV market due to their high accessibility to EV users at low cost, simple implementation, and noiseless operation [5]. Solar PV systems are increasingly being installed as a stable and reliable power source [6] and as a result, PV energy can be used to decrease the EV dependency on grid power. Moreover, solar PV integrated EV battery can be used as energy storage to mitigate the impacts of solar PV power fluctuations and reduce high-level PV integration on the DG. Because large scale solar PV energy integration into the power grid can create significant challenges for the operation and stability of the distribution grid due to the intermittent nature of solar PV. However, solar PV power integration to the EV charging system increases power losses and contributes to system complexity due to the necessity of additional power controllers and conversion stages. As a result, designing a PV integrated EV charging system with multifunctional operating capability is essential to coordinate and control different sources [5] in the system. Furthermore, coordinated control of solar PV and EV can be used as a very effective method to reduce the solar PV impacts on the power grid and eliminate intermittency constraints of solar PV generation [7].

The EV chargers consist of many power electronic components, which make them high nonlinear loads due to the presence of switching semiconductor elements and operating principles on the grid [8]. Nonlinear loads can cause many PQ impacts on the power grid including system instability, increase harmonic distortion, DG overload, increase voltage and current distortion, reduce efficiency, failure of critical controls and increase mechanical stress. High integration of EVs significantly injects harmonics into the voltage and current profile of the DG [9]. The case study in [10] presented the analysis of the impacts of high penetration of EV on the DG, and used smart strategies to limit critical effects on the power grid. Unregulated and uncontrolled EV charging might lead to unexpected peak load at a certain time and PQ impacts, which can affect the grid power standards, phase imbalance, and also exceed the DG capacity and significantly effect on load performances [11]. A coordinated smart EV charging system was developed in [12] to reduce problems on low-voltage DG. It is required that EV charger be isolated from other power sources according to the key requirement of EV standards, and the ripple voltage and ripple current specifications and other EV charging standards should be met by all power converters. EV chargers must be able to meet IEEE-519 standards [13] in order to control PQ problems [11].

The power grid is likely to encounter more uncertainty and intermittency due to the growing utilization of PVs and EVs on the DG.

Many studies have contributed to the development of coordinated smart charging systems to mitigate PV and EV integrated impacts [14],[15],[16] while providing grid support. The [17] proposed a single phase solar PV integrated bidirectional EV charging system, that the solar PV array was directly linked to the DC-link by eliminating the PV array connected converter. The VSC was used to fulfil the MPPT from the solar PV and generate reference current for active and reactive grid power flow. A 10 kW PV based EV charger presented in [18] is able to increase power density with efficiency of 95% for PV to EV power flow. The proposed system used an interleaved boost converter for PV, bidirectional flyback converter for EV and VSC for the power grid with complex controlling algorithm and additional power electronic components. The [19] developed a coordinated charging system for EV charging/discharging to mitigate grid impacts. The solar PV array is linked to the DC-link via maximum power point tracking (MPPT) based DC-DC boost converter with additional low-pass filter. The coordinated PV based EV charging system in [20] used power conditioning structure to system control and EV charger was capable to mitigate uncertainty and intermittency impacts of PV to improve reliable power flow into the grid.

In this paper, the solar PV based smart EV charging system is proposed to achieve satisfactory operation of various functions with the combined control implementation. The smart charger was developed to charge the EV battery using solar PV power and enhance the grid support with V2G operation. A single-ended primary-inductor converter (SEPIC) is selected to connect the PV array to the DC-link due to its efficient voltage regulation, low ripple current and low electrical stress on the system components compared to the other DC-DC converters. The EV battery, solar PV array and power grid are interconnected on a DC-link through separate power converters with algorithm designs to EV charging and feed EV power to the grid. An LCL filter is integrated to improve the power factor and mitigate harmonics to improve power quality of the system. The main contributions of this paper are (i) Design and control of SEPIC DC-DC converter with MPPT to extract maximum power from the solar PV (ii) Design and control of a bidirectional DC-DC converter with smart charging/discharging algorithm for V2G operation and (iii) Modelling and control of voltage source converter and LCL filter to enhance the grid support.

The paper is organised as follows: Section-II explains the system structure and functions of PV based EV charging system, Section-III presents modelling, design and control of solar PV based EV charger, inverter, LCL filter and associate controllers. Results and discussion are presented in section IV and finally, the conclusions are presented in Section V.

II. System Structure

The proposed solar PV based EV charging system is shown in Fig 1 which includes PV array, DC-DC SEPIC converter with MPPT controller, bidirectional DC-DC converter and controller for EV battery charging/discharging, three-level inverter with controller for power grid interface. The solar PV power is used to charge the EV battery and feed other local loads. The SEPIC DC-DC converter for solar PV system is controlled with incremental conductance based maximum power point tracking (MPPT) algorithm to extract maximum power under varying solar irradiance. The grid connected voltage source converter (VSC) operates as an inverter to convert the DC voltage to AC voltage with required frequency and supply power into the grid from solar PV system or EV battery storage. The VSC is controlled to inject active or reactive power into grid and provide grid support under disturbances. The bidirectional DC-DC converter operates in buck mode while EV battery charging and boost mode while battery discharging when V2G operation is enabled. The controlling system made decisions to charge or discharge the EV battery through proper communication between PV, utility grid and EV. Table 1 shows the system specification including PV array, EV battery, inverter, LCL filter and power grid with associate converters.

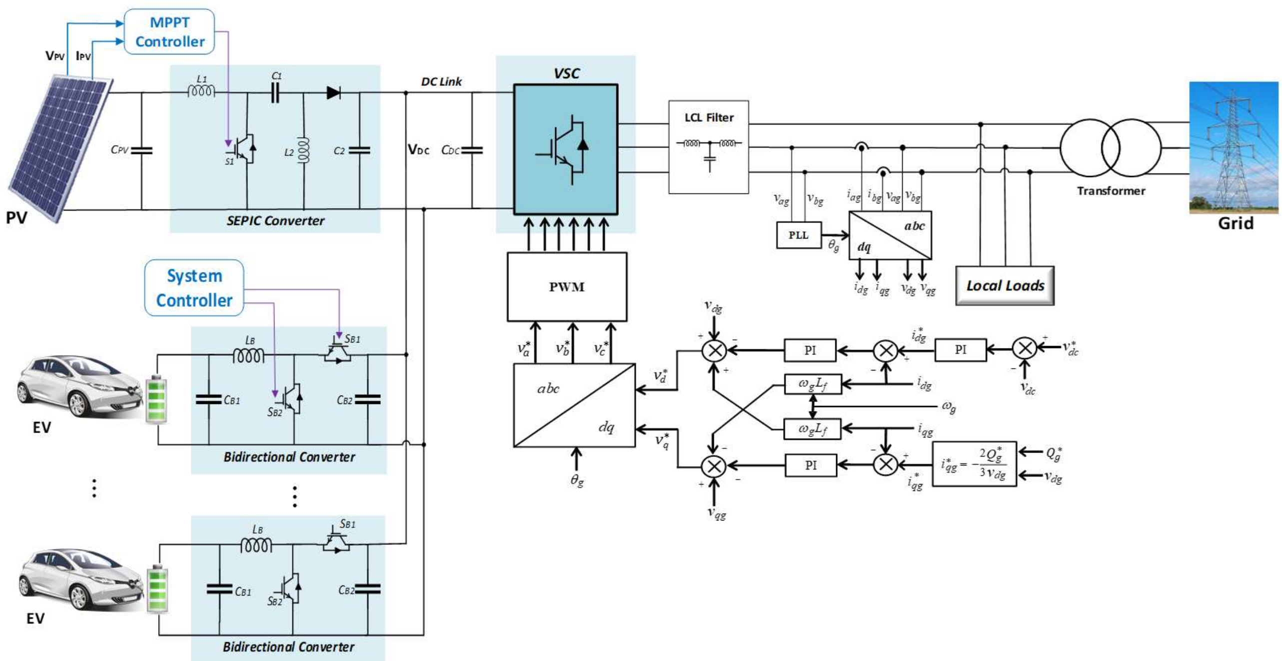

Fig. 1. System Configuration

III. Modleing, Design and control of Solar PV Based EV Charger

A. Control SEPIC DC-DC Converter with MPPT

The SEPIC DC-DC converter is controlled with incremental conductance based maximum power point tracking algorithm to extract maxim power under varying irradiance as shown in. The control block diagram of the PV array and MPPT controller are presented in the Figure 2. The output voltage of the SEPIC DC-DC converter is given by,

$$V_o = V_{in}\frac{D}{1-\text{D}} \tag{1}$$

where, V_{in} is input voltage and D is duty ratio. The switching frequency used for the SEPIC converter is 5 KHz.

The inductor L_1 and L_2 of the SEPIC converter are calculated with allowable percentage of current ripple through inductors where, Δi_L is peak to peak ripple current and f_{sw} is the switching frequency:

$$L_1 = L_2 = \frac{V_{in} * D}{\Delta i_L * f_{sw}} \tag{2}$$

The value of capacitors C_1 and C_2 for permitted ripple voltage are calculated as eq (3), where R is load resistor and ΔV_0= ripple voltage.

$$C_1 = C_2 = \frac{V_O * D}{R * \Delta V_0 * f_{sw}} \tag{3}$$

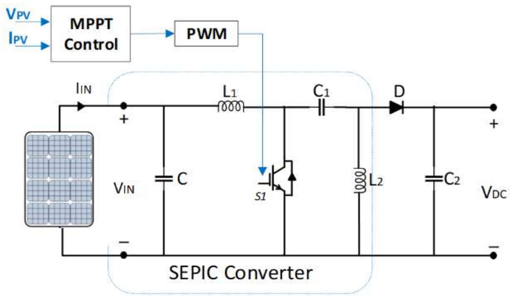

Fig. 2. Control of SEPIC DC-DC converter with MPPT

B. Control of EV Battery with Bidirectinal DC-DC Converter

The EV battery is connected to the bidirectional DC-DC converter which can operate as a buck or boost converter depending on the direction of power as shown in Figure 3. Buck mode is utilized to charge the battery when PV power is sufficient as well as SoC is lower than the threshold value (85%). The boost mode is enabled to discharge the battery when PV power is less than load power. Once PV power is unavailable and the battery SoC is higher than the threshold value, V2G operation is employed to enhance the grid support. The charging or discharging schedule is determined by the DC-DC bidirectional converter controller. The operating mode of bidirectional DC-DC converter depends on the PV power, load power consumption and state of charge (SoC) of the battery. As shown in Fig 3, upper level and the lower-level controlling logics of the DC-DC bidirectional converter is applied to produce signal for buck mode (Charging) and boost mode (discharging) of DC-DC converter. According to the decision made by the controller, either EV charging or V2G operation takes place, and the converter current is controlled. The flow chart of the battery charging and discharging operation is presented in the Fig 4.

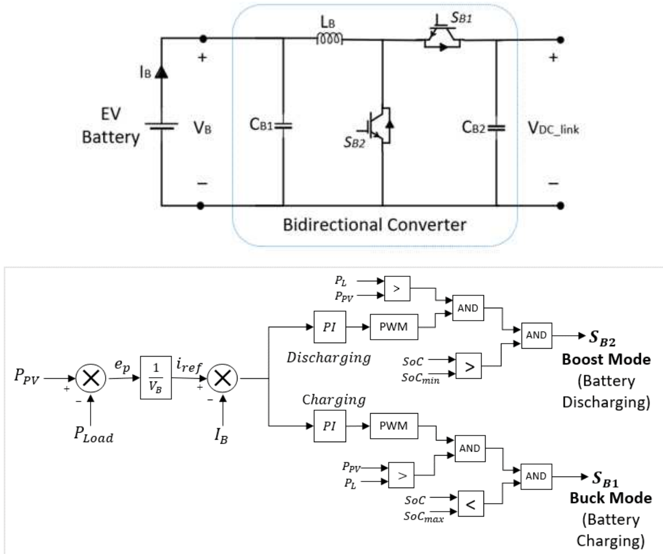

Fig. 3. Control of bidirectional DC-DC converter for EV charging and discharging modes of operation

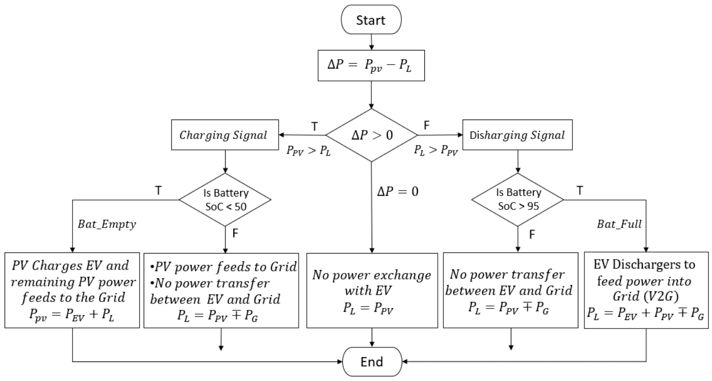

Fig. 4. Flow chart for operation of solar PV based EV charging system

C. Control of Voltage Source Converter

The control of VSC ensures voltage regulation of the DC-link (V_{dc}) and control active and reactive power flow into the grid by controlling d-axis and q-axis current. Since the EV charging system is combined with the PV array and grid, multimode operational capability is required of the charging system. The vector control strategy for VSC with decoupled current controller is presented in Fig 1. The VSC consists of DC-link voltage controller and two inner loops to control dq axis currents (i_{dg} and i_{qg}). The proportional integral (PI) controller is used to regulate the DC-link voltage by minimizing the error between V_{dc} and reference DC-link voltage (V_{dc}^*). The DC-link voltage controller provides the d-axis reference current (i_{dg}^*) according to the inverter operating condition. The q-axis current reference is calculated from reactive power reference Q_g^* and v_{dg}. The dq axis currents can be represented as,

$$\frac{di_{dg}}{dt} = (v_{dg} - v_{di} + \omega_g L_f i_{qg})/L_f \tag{4}$$

$$\frac{di_{qg}}{dt} = (v_{qg} - v_{qi} - \omega_g L_f i_{dg})/L_f \tag{5}$$

where, L_f is line inductance, ω_g is angular frequency of the grid. The voltage and current variables are transformed from abc to dq synchronous fames using grid voltage angel (θ_g). The phase locked loop (PLL) is used to detect θ_g

because voltage of the grid may consist of harmonics. The reference q-axis current can be calculated from

$$i_{qg}^{*} = -\frac{2Q_g^{*}}{3\, v_{dg}} \tag{6}$$

When inverter losses are neglected and $v_{qg} = 0$ and $V_{dg} = |V_g|$, the active power and reactive power are given by,

$$P_g = \frac{3}{2}\left(v_{dg} i_{dg} \right) = \frac{3}{2} |V_g| i_{dg} \tag{7}$$

$$Q_g = \frac{3}{2}\left(v_{dg} i_{qg} \right) = \frac{3}{2} |V_g| i_{qg} \tag{8}$$

The decoupled current controller is used to maintain *d* and *q* axes variables using two PI controllers because these variables depend on each other.

D. LCL Filter Design for Grid Side Inverter

The LCL filter is used reduce total harmonic distortion (THD) of inverter output voltage and current. The inverter side inductor is designed to reduce high-order harmonics of VSC current output, while the grid side inductor is designed to mitigate the grid-side current harmonics. The LCL filter consists of wye connected capacitors. The switching frequency, line frequency and converter power rating were considered as inputs for the design of the LCL filter. The resonant frequency of the LCL filter is chosen to be smaller than the switching frequency.

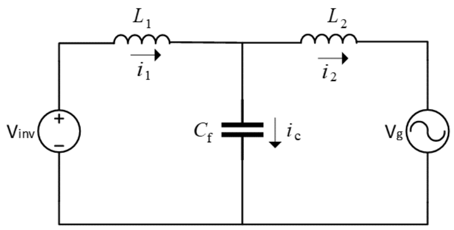

Fig. 5. Per phase model of the LCL filter

Impedance and capacitor base values can be calculated as,

$$Z_b = \frac{V_{gll}^2}{P_g} \tag{9}$$

$$C_b = \frac{1}{\omega_g . Z_b} \tag{10}$$

$$C_f = 0.05 \times C_b \tag{11}$$

where, Z_b and C_b are base values of impedance and capacitor, V_{gll} and P_g are line voltage and nominal grid power respectively. Also, $\omega_g = 2\pi f_g$; where f_g is the grid frequency. The variation of power factor for the grid is allowed up to maximum of 5% for filter capacitor design. The inverter side inductor is L_1. For the design constraints, ripple of 10% of the rated current is allowed. Therefore, L_1 and L_2 can be calculated as follows,

$$I_{max} = \frac{\sqrt{2}P_n}{3V_{ph}} \tag{12}$$

$$\Delta I_{Lmax} = 0.1 \times I_{max} \tag{13}$$

$$L_1 = \frac{V_{dc}}{6 f_{sw} \Delta I_{Lmax}} \tag{14}$$

$$L_2 = \frac{\sqrt{\frac{1}{K_a{}^2}+1}}{C_f\, \omega_{sw}{}^2} \tag{15}$$

where, K_a is the attenuation factor, and it is assumed to be 20% [21]. The L_2, and primarily used to mitigating harmonic around the switching frequency for LCL filter.

IV. Results and Discussion

The solar PV based EV charging system with associated power converter and controllers of Fig.1 is simulated in *MATLAB/Simscape* environment. The simulation has been conducted under varying irradiance, temperature, and grid disturbances. The sampling time for inner current control loops and outer voltage control loop are 10 μs and 100 μs, accordingly. The system parameters are shown in Table I.

Fig.6 shows the simulation results of solar PV array power and output voltage under varying irradiance and temperature. The irradiance is varied with the pattern of 1000 W/m^2 – 800 W/m^2 – 900 W/m^2 – 1000 W/m^2 as presented in Fig 6 (a), and varying temperature is shown in Fig 6 (b). The solar PV array supplies 20kW maximum output power and P_{pv} varies according to the irradiance changers as presented in Fig. 6 (c). The Fig.6 (d) shows the voltage output of PV (V_{pv}) at maximum power. When the temperature is increased from 25^{0}C to 45^{0}C at t=1.8 sec, the generated power by solar PV is reduced. Fig. 6(d) shows the duty cycle of DC-DC converter which is optimized by MPPT controller to extract maximum power from solar PV array.

Fig 7 represents simulation results for EV charging mode. At *t*=1sec, the irradiance decreases to 800W/m^2, battery current and power also decrease accordingly as shown in Fig 7(b) and (c). Then at t=1.2 sec, irradiance increases up to 900 W/m^2, the current and the power of the battery also increase as expected. Fig 7(d) shows SoC of the battery is increasing, which confirms the battery is being charged.

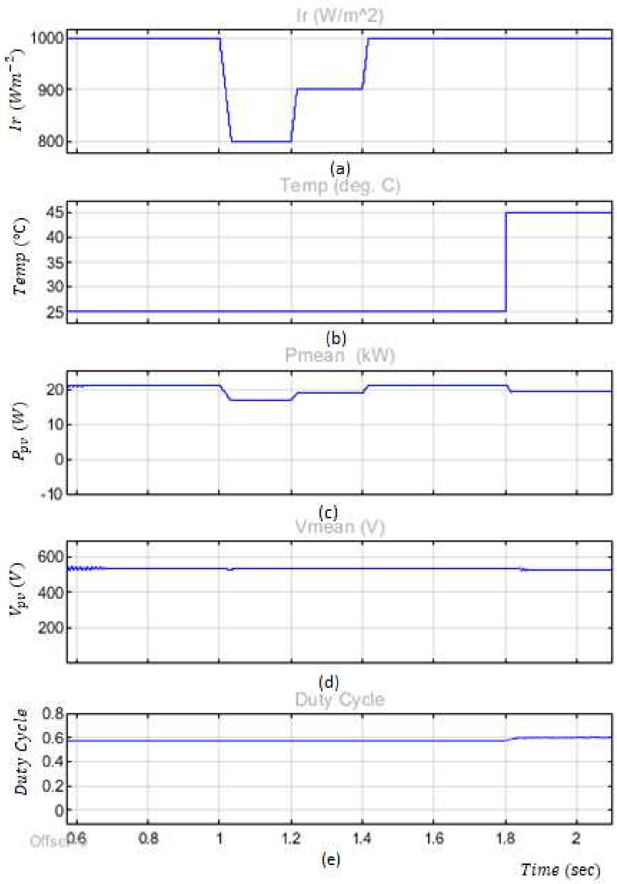

Fig. 6. PV Array Waveforms: (a) Solar Irradiance (W/m^2), (b)Temperature (^{0}C), (c) PV Power (W), (d) PV array Voltage (V) and (e) Duty Cycle.

Fig 8 shows the performance of solar PV system for grid connected mode. EV battery is off and total PV power is injected to the grid. Fig 8(a) shows that the V_{dc} follows its reference waveform and controls the DC-link voltage at 800V. Fig 8(b) and (c) shows the currents of d- axis and q- axis with their relative references and they are following respective references as well as control and regulate the grid active power flow as shown in Fig 8(d). The instantaneous grid voltage and current waveforms are shown in Fig 9(a) and (b).

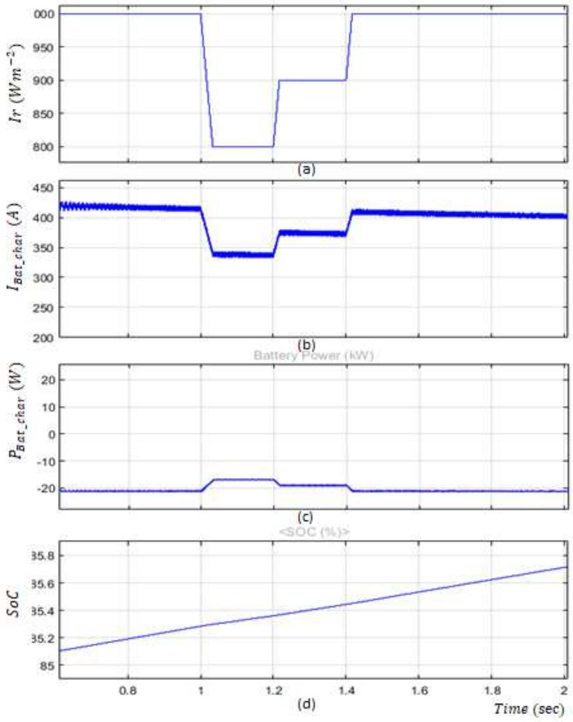

Fig. 7. EV battery charging using Solar PV System (a) solar irradiance (W/m[2]) (b) Charging current (A) (c) Charging power (W) and (d) Battery

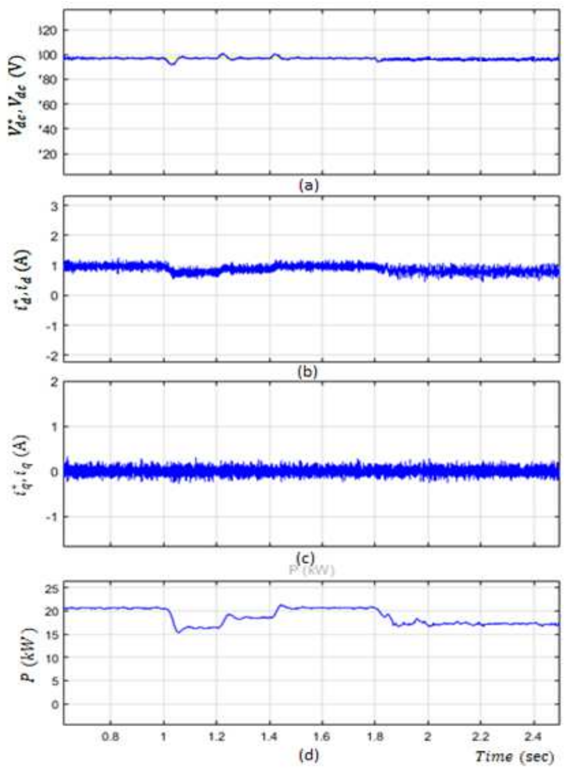

Fig. 8. Solar PV to Grid (a) DC-link voltage (b) d-axis current , (c) q-axis current (d) Grid Power (kW)

Fig 10 presents the results when vehicle to grid operation is activated to regulate voltage under grid disturbance. The grid voltage is changed to $\pm$ 4%, the inverter supply or absorb reactive power to regulate grid voltage. Fig 10(a) shows that the DC-link voltage perfectly follows its reference under variations at 800V with small variations during grid disturbances.. Fig 10(b) shows the grid voltage (V_{ac}) and it shows transients in V_{ac} when disturbances occur, and the controller regulates V_{ac} at a constant value, which demonstrates that the grid voltage is follows its reference. The currents of d axis and q axis are shown in Fig 10(c) and (d), illustrating that they follow their relevant references and regulate the power flow into the grid under varying irradiance and temperature values.

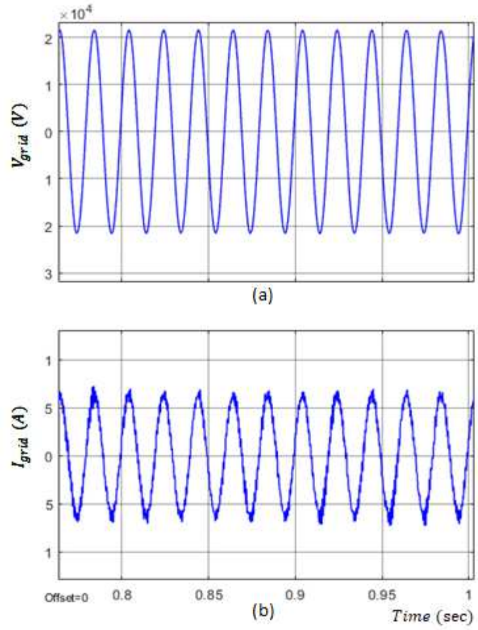

Fig. 9. Solar PV to Grid (a) Grid voltage (V) (b) Grid Current (A)

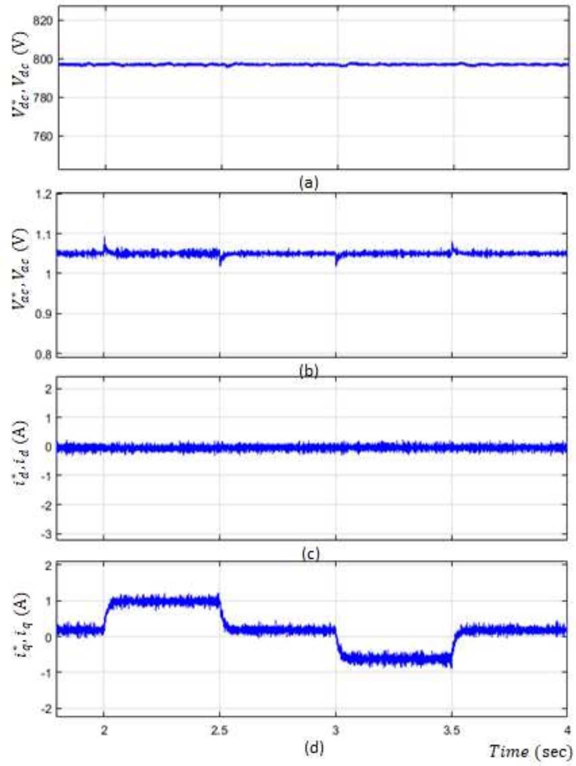

Fig. 10. EV battery discharging (V2G) (a) DC-link voltage (b) Grid Voltage (c) d-axis current, (d) q-axis current

TABLE I. SYSTEM PARAMETTERS

Solar PV system & SEPIC DC-DC converter		
PV	Power (P_{PV})	20kW
	Voltage (V_{PV})	547V
	$V_{dc-link}$	800V
SEPIC	L_1, L_2	300μH
	C_1, C_2	400μF
EV Battery and Bidirectional DC-DC converter		
EV battery	Voltage	40V
	SoC	85%
Bidirectional DC-DC Converter	L_B, C_{B1}, C_{B2}	160μH, 312μF, 300μF
	V_1 & V_2	800V & 40V
Inverter, Grid & LCL filter		
Inverter	V_{in} & V_{out}	800V DC & 415VAC
	$Frequency$	100 μHz
Grid LCL Filter	Line Voltage	415V
	Power (P_g)	600 kW
	Fund. Frequency (f_g)	50Hz
	Swit. Frequency (f_{sw})	5 kHz
	L_1 , L_2	225 μF , 109.7 μF
	C_f	554 μF

V. CONCLUCION

This paper presents a solar PV based EV charging system with V2G operation for grid support. The SEPIC DC-DC converter is controlled with MPPT to extract maximum power under varying irradiance and temperature. The PV based EV charging system can be used either to charge or discharge the EV battery according to the PV power availability and grid requirement via bidirectional DC-DC converter. The controllers perform well during both charging and discharging with small variations. The proposed charging system has been verified by extensive simulation results with all the stipulated control objectives. The presented results further verified that the designed controllers could manage the system power flow under different transients and charge/discharge currents of the battery, under all tested conditions. The inverter controller ensures the V2G operation to provide grid support under varying grid voltage. This topology reduces the cost and circuit complexity, while maintaining the PV array efficiency and uninterrupted charging with active and reactive power support into the grid.

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