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AN IMPLEMENTATION OF SOLAR PV ARRAY BASED MULTIFUCTIONAL EV CHARGER

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ABSTRACT:

In this paper, a solar PV (Photo-voltaic) array based EV (Electric Vehicle) charger is proposed, which has a bidirectional flow of active and reactive powers. The proposed charger uses a solar PV array energy to charge the EV battery and to feed the grid with the remaining power. In this charger, the VSC (Voltage Source Converter) does the task of harnessing the maximum power from the solar PV array. At the time of high cost of energy, the charger has the provision to inject the battery energy into the grid to earn revenue. In addition to the active power exchange with the grid, the proposed charger also exchanges the reactive power with the grid, simultaneously. In all operating modes, the THD (Total Harmonic Distortion) of the grid current remains within the IEEE 519 standard. The proposed charger is designed for a single phase 230V, 50Hz supply and is experimentally validated in the laboratory.

Keywords— Electric vehicle, bi-directional charger, solar PV array, reactive power, power quality.

I.INTRODUCTION

In the current scenario, the electric vehicle is emerging as a promising solution to the problems caused by the fossil fuel powered vehicles [1]. However, the adaptability of EV (Electric Vehicle) in society, depends on the charging infrastructure [2]. The charging of EV requires a huge amount of electrical energy, which mostly comes from the coal/ gas based

power plants. Therefore, in the true sense, the EVs can be a green and clean alternative to the present transport system when the electrical energy required for charging of EV, comes from the renewable energy sources such as solar, wind etc. [3]. Gunter et al. [4] and Satpathy et al. [5] have proposed the solar PV array and wind energy based grid connected system. However, this requires the revamping of the transmission lines for carrying more power. It also incurs transmission power losses. On the contrary to this, Marra et al. [6] have proposed the implementation of the solar PV based charging station. The advantage of this kind of charging station is that the solar PV power is generated locally and used locally [7]. Because of this, the transmission lines need not to be upgraded for the high power. Moreover, the charging station does not require to draw power from the grid when the cost of energy is high [8]. Ma et al. [9] have proposed the use of office building and parking area for laying down the solar PV panels as these solar PV panels work as a shed and prevent the heating of the vehicles and buildings. Therefore, the use of solar PV array based charging station not only avoids the overloading of the grid but it also minimizes the operational cost of the charging station.

Several publications have been proposed in the area of solar PV array integration with the EVs, and many advantages have been listed in the literature. The coordinated operation of solar PV array and EV mitigates the impacts of solar PV generation on the utility, and it eliminates the problems caused by the solar PV intermittency [10]. Because, the EVs are parked for about 90% of their lifetime and EV battery stores a huge amount of energy, Verma et al. [11] have proposed to use the EV battery energy in vehicle-to-grid mode to support the grid. Kydd et al. [12] have proposed to use the unutilized solar PV inverter and EV batteries to deliver ancillary assistance to the grid. The reactive power is also a problem for the utility grid. To meet the reactive power demand of the distribution system, the utility installs the capacitor banks. Since the reactive power flow through the transmission lines from the source to the load end, the loss in the transmission line increases. Melo et al. [13] have proposed to provide the reactive power support to the grid using the voltage source converter (VSC). Nowadays most of the loads are nonlinear, and they draw non-sinusoidal current from the grid. Because of this, the harmonics are injected into the grid. Brenna et al. [14] have utilized the V2G functionality of the EV charger for improving the power quality of the grid.

In this proposed bidirectional charger, the boost converter is eliminated, and the solar PV array is connected directly to the DC bus of VSC. Here, in this topology, the VSC fulfils the task of harnessing maximum power from the solar PV array. Therefore, this charger is a retrofit solution to the existing single phase bidirectional charger with a modification in the control algorithm. The proposed charger has following distinctive features.



Fig. 1 System configuration of the proposed charger

• It uses the solar PV energy to charge the EV battery and uses the grid in case of insufficient the solar PV energy. The

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controller decides when to use the solar PV energy and when to use the grid energy.

- Along with the active power trade with the utility, the charger exchanges the reactive power with the grid using the VSC of the charger. Both active and reactive powers exchanges are possible even when the EV is not connected to the charger.
- The proposed charger eliminates the DC-DC boost converter used for MPPT in the conventional charger.
- While exchanging the active and reactive powers, the grid current THD remains within the limits of the IEEE 519 standard.
- To use the solar PV array efficiently, the control algorithm extracts the maximum power at all irradiance levels.

II. SYSTEM CONFIGURATION

The circuit topology of the proposed system is shown in Fig. 1. This system is a single phase bi-directional charger for an EV that integrates the solar PV array directly on the DC bus of the VSC. The proposed charger charges the EV battery using the solar PV power/the grid power and feeds the solar PV / EV battery power into the grid. The proposed charger is a twostage charger, i.e. a bi-directional AC-DC conversion followed bi-directional by the DC-DC conversion stage. The AC-DC conversion stage converts the input AC voltage into the DC voltage while charging the EV battery and works as an inverter to change the DC voltage into the AC voltage while feeding the solar PV power and EV power into the grid. The EV battery is connected to the output of the bidirectional DC-DC converter (BDDC). The DC-DC converter in this charger accomplishes the various tasks. While charging the EV battery, the DC converter works in buck mode and operates in boost mode while discharging the EV battery. Moreover, it also regulates the DC bus voltage and harnesses the maximum generated power from the solar PV array. The proposed charger is connected to the grid through the coupling inductor (Lc). A coupling inductor is needed to eliminate the harmonics and to smoothen the grid current. A ripple filter is also connected at the PCC (Point of Common

Coupling) to prevent the injection of switching harmonics generated by the switching of VSC into the grid.

III. CONTROL ALGORITHM

The charger is controlled to perform these required functions as follows, 1) energy balance in the system, 2) harnessing of maximum solar PV array power, 3) generation of reference grid current for both active and reactive power flow, 4) charging/discharging current control of EV by controlling the bi-directional DC-DC converter. The energy balance in the system and harnessing of maximum solar PV array power are attained by regulating the DC bus voltage. However, the active/reactive power control is achieved by the grid current control. The overall control of the charger is designed as, 1) energy management strategy of charger, 2) VSC control, and 3) bi-directional DC-DC converter control.

A. Energy Management Strategy of the Proposed Charger

The energy management strategy of the proposed charger is based on the constant DC bus capacitor voltage. The flow chart of the energy management under different operating conditions is shown in Fig. 2. The energy management in steady state is given as,

 $P_{PV}\pm P_B\pm P_s=0$

(1)

Here PPV, PB and Ps are solar PV array power, EV power and grid power, respectively. In this expression, the positive power represents the supplying of power, and negative power represents the consumption of power. This means that the EV and the grid can both supply and consume the power. The charger undergoes the transient caused by the change in solar irradiance and change in charging demand. The dynamic power management equation in case of solar irradiance change is given as,

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\Delta P_{PV} \pm \Delta P_B \pm \Delta P_s = 0 \tag{2}
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Since the solar irradiance is changing throughout the day, the charging of the EV battery should not be affected. Therefore, based on the energy management strategy, a series of event occurs to achieve the energy equilibrium in the system.

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Solar irradiance $\uparrow \rightarrow P_{PV} \uparrow \rightarrow$ power at DC link $\uparrow \rightarrow V_{dc} \uparrow$ $\rightarrow V_{dc}$ regulation $\rightarrow I_P \uparrow \rightarrow i_s^* \uparrow$ (3)

Similarly, the energy management in case of decreased solar irradiance is achieved as,

Solar irradiance
$$\downarrow P_{PF} \downarrow \rightarrow$$
 power at DC link $\downarrow \rightarrow V_{dc} \downarrow$
 $\rightarrow V_{dc}$ regulation $\rightarrow I_P \downarrow \rightarrow i_c^* \downarrow$ (4)

With the load change, the solar PV array power should not be affected, and series of events for energy management during these transients are as follows,

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charging power \uparrow \rightarrow I_B \uparrow \rightarrow power at DC link \downarrow \rightarrow V_{ck} \downarrow (5)

\rightarrow V_{ck} regulation \rightarrow I_P \downarrow \rightarrow i_s^* \downarrow

charging power \downarrow \rightarrow I_B \downarrow \rightarrow power at DC link \uparrow \rightarrow V_{ck} \uparrow

\rightarrow V_{ck} regulation \rightarrow I_P \uparrow \rightarrow i_s^* \uparrow
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B. VSC Control

The VSC control diagram is shown in Fig. 3. The purpose of the VSC control is to regulate the DC bus voltage and control the grid current for controlling the active and reactive power flow, thereby generating the switching pulses for the VSC. The DC bus voltage regulation is achieved by a proportional integral (PI) controller [15] used for minimizing the error between actual DC bus voltage (Vdc) and reference DC bus voltage (Vdc*). The MPPT (Maximum Power Point [16] Tracking) algorithm estimates the reference DC bus voltage (Vdc*) at which the peak power of the solar PV array is extracted. In the absence of the solar PV generation, the DC link voltage is regulated at 360V. The DC link reference voltage (Vdc*) is compared with the sensed DC link voltage (Vdc). The error voltage (Ve) of the DC link voltage, is the input of the PI (Proportional Integral) controller. The output of the PI controller gives the magnitude of the real power constituent (Ip) of the reference grid current (is *). The expression of PI controller in the discrete domain is given as,

 $I_{\mu}(k) = I_{\mu}(k-1) + k_{\mu\nu} \{V_{\nu}(k) - V_{\nu}(k-1)\} + k_{\mu\nu}V_{\nu}(k)$

Where Ve=Vdc* -Vdc, k and k-1 are sampling instants and kpd and kid are the proportional and integral gains of the controller. The amplitude of the reactive power constituent (Iq) of the reference grid current (is *), is obtained based on the reference reactive power command (Qcmd) and it is given as, $2 \times Q_{cont}$

(8)

Where Qcmd is the reference reactive power command. Whereas Vtm is the peak amplitude of the PCC voltage (vs).



Fig. 2 Power management strategy **IV. RESULTS AND DISCUSSION**

The charger is designed for single phase 230V 50Hz supply system. The open circuit voltage and short circuit current of solar PV array is 425V and 7A, respectively. However, the maximum power point voltage and current are 366 V and 6.6A, respectively. The lead-acid battery of 240V, 35Ah is used as an EV battery the experimental prototype. The in implementation of the proposed charger is done using the digital controller (dSPACE-1006). For the implementation of the control algorithm, the digital controller requires various (voltage and current) signals of the charger. Therefore, various voltage and current signal (analog) are acquired using the Hall Effect based voltage and current sensor. These signals are then converted into a digital signal using analog to digital converter (ADC). The digital controller uses the digital signal to implement the control algorithm and generate the switching pulses for VSC and DC-DC converter. The experimental waveforms of the proposed charger are shown in Figs. 5-11. The performance of the proposed charger is evaluated in both steady state and dynamic conditions. In steady state conditions, various modes of operation are considered such as, 1) EV is not connected to the charger and whole solar PV array generated power is fed into the grid, 2) the grid is not available and solar PV array generated power is consumed by the EV, 3) reactive power compensation of the charger along with the active power operation, and 5) solar PV array supplying power to EV and

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feeding power into the grid. The dynamic performance is evaluated under solar irradiance change and change in the battery charging current. During implementation, the solar PV array power (PPV), the power is drawn from the grid (Ps), the power drawn from the battery (PB), are considered positive. However, the power fed into the grid and the battery is considered negative.

A. Steady State Performance of Proposed Charger

The performance in the case when the state of charge (SOC) of the EV battery is more than 80%, and solar PV array is generating maximum power, are shown in Figs. 5. In this case, to avoid the overcharging of the EV battery and to utilize the solar PV array energy fully, the charger feeds the solar PV energy into the grid using VSC. Figs. 5(e)-(f) show that the solar PV array is generating 2.32kW. Out of 2.32kW, 2.29kW is fed into the grid at UPF. The voltage (VPV), current (IPV) and power (PPV) of the solar PV array, are shown in Figs. 5(e)-(f). However, the voltage (vs), current (is), and power (Ps) of the grid are shown in Figs. 5 (a)-(b). The charger is not injecting any voltage and current harmonics into the grid (despite the charger is having power electronic component), as shown by the grid voltage (vs) and current (is) total harmonic distortion (THD) in Figs. 5(c)-(d). Moreover, it is also not drawing any reactive power from the grid as justified by the displacement power factor unity (DPF) operation of the charger in Fig. 5 (b).

When the EV battery is discharged, and its SOC reaches below 20%, the EV battery takes power from the solar PV array for charging in the absence of the grid. The performance under this case is shown in Fig. 6. The voltage (VB), current (IB) and power of the EV battery (PB) are shown in Figs. 6 (a), (b). However, the voltage (VPV), current (IPV) and power of solar PV array (PPV) are shown in Figs. 6 (c), (d).



Fig. 5 Performance of solar PV feeding power into the grid when EV battery is fully charged, (a) vs and is, (b) Ps, (c)-(d) THDs of vs and is, (e) Vpv and Ipv,, (f) PPV



Fig. 6 Performance of charger when charging EV battery in absence of grid, (a)Vb and Ib, (b) PB, (c) Vpv and Ipv, (d) PPV



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Fig. 7 Performance of charger when feeding solar PV power into grid and charging EV battery, (a) vs and is, (b) Ps, (c)-(d) THDs of vs and is, (e) Vb and Ib, (f) PB, (g) PPV



Fig. 8 Performance of charger when feeding solar PV power and EV power into the grid, (a) vs and is, (b) Ps, (c)-(d) THDs of vs and is, (e) Vb and Ib, (f) PB



Fig. 9 Simultaneous active and reactive power operation during battery charging from solar PV, (a) vs and is, (b) grid active and reactive power, (c)-(d) THDs of vs and is, (e) Vb and Ib, (f) PB

During the day hour, sometimes the solar PV array generated power (PPV) becomes more than the charging demand (PB) due to increased solar irradiance level or decreased charging power demand. In this condition, the management strategy of the charger automatically feeds the surplus solar PV array power into the grid without derating the MPPT performance or altering the charging demand. The performance under this condition is shown in Fig. 7. The EV battery is taking 1.38kW of 2.44kW of solar PV generated power. The

voltage (VB), current (IB) and power of the EV battery (PB) are shown in Figs. 7(e), (f). The solar PV array power is displayed in Fig. 7 (g). Since the solar PV array power (PPV) is fed into the grid, the controller of the charger synchronizes the PCC voltage with the grid voltage as per the control algorithm is shown in Fig. 3. Figs. 7(a)- (b) show that the 898W is fed into the grid at UPF. The performance of the charger while feeding power into the grid in terms of THD of the voltage (vs) and current (is) are exhibited in Figs. 7(c)- (d). It shows that the THD of the grid voltage and current are less than 5% thus achieving the IEEE519 standard.

B. Dynamic Performance of Proposed Charger

During the operation, the charger is subjected to the transient caused by the continuously changing solar irradiance level due to the shading of the clouds and the change in the charging demand. Under these two transient conditions, the charger and the control of the charger should operate such that the maximum power is harnessed from the solar PV array at all irradiance level without disturbing the charging of the EV. Moreover, the flow of active power should be balanced in the system during transients. The performance under step change in solar irradiance level from 1000W/m2 to 500W/m2 and vice versa are exhibited in Fig. 10. Figs. 10(a)-(b) show the performance under step change in solar irradiance intensity from 1000W/m2 to 500W/m2. Due to a decrease in the solar irradiance intensity, the solar PV current (IPV) decreases. Moreover, the DC bus voltage (Vdc) also decreases from 372V to 351V to extract the maximum power at 500W/m2 . As a result, the solar PV generated power (PPV) decreases from 2.4kW to 1.2kW. As the charging of EV is undisturbed (as shown from IB in Fig. 10(a)), the power which is being fed into the grid decreases. Therefore, the grid current (is) reduces as shown in Fig. 10(a).

Similarly, in case of an increase in solar irradiance from 500W/m2 to 1000W/m2, the solar PV array power (PPV) increases from 1.2kW to 2.4kW as exhibited in Fig. 10 (c). In this condition, the DC bus voltage (Vdc)

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increases from 351V to 372V to continue the process of maximum power extraction. However, the charging of the EV does not get affected by the solar irradiance increase as shown by IB in Fig. 10 (d).

The performance under change in charging current is shown in Figs. 11 (a)-(c). Under this dynamic change, the charging current (IB) is decreased from 3A-1.5A and again it is increased from 1.5A-3A. Since the charging current (IB) of EV is decreased from 3A-1.5A, the energy management strategy maintains the power balance by feeding the extra power into the grid without disturbing the MPP operation of the solar PV array. Because of this, the grid current (is) increases as shown in Fig. 11(a). Similarly, when the charging current (IB) in increased from 1.5A to 3A, the grid current (is) reduces to maintain the power balance as solar PV array cannot supply more power as presented in Fig. 11 (b). Moreover, the DC bus voltage (Vdc) does not get affected by this disturbance as exhibited in Fig. 11 (c).





Fig. 10 Performance of charger under solar irradiance change, (a)-(b) solar irradiance decrease from 1000W/m2 - 500W/m2 , (c)-(d) solar irradiance increase from 500W/m2 - 1000W/m2



Fig. 11 Performance of the charger under change in battery current, (a) decrease in

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charging current from 3A-1.5A, (b) increase in charging current 1.5A-3A, (c) combined

waveforms

V. CONCLUSION

The performance of proposed single stage solar PV array based bi-directional EV charger has been presented under both active and reactive power flows. Test results have verified that along with performing its primary tasks of charging the EV battery, the proposed charger has integrated the solar PV array very efficiently. Moreover, the elimination of DC-DC boost converter has not affected the performance of the solar PV array, and VSC has performed the task of harnessing the maximum power from the solar PV array. The various steadystate and dynamic conditions results have proved the promptness of the controller, capability to maintain the sinusoidal grid voltage and current and power quality of the grid voltage and current within the IEEE 519 standard.

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