

# Power Conditioning of Distribution Networks via Single-Phase Electric Vehicles Equipped with Bidirectional Chargers

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**Abstract**— This paper presents the design of a single-phase electric vehicle (EV) on-board bidirectional charger with the capability of power conditioning. This charger can control its charging/discharging active power based on the demand of EV battery/network or load. Also, it controls reactive power and harmonic current based on the characteristics of the non-linear and linear loads. The topology of the proposed charger consists of the bidirectional AC/DC and buck-boost DC/DC converters, where it can operate in four quadrants in the active-reactive power plane with the capability of harmonic compensation. In the next step, this paper presents a suitable control strategy for the bidirectional charger according to the instantaneous active and reactive power (PQ) theory. Based on the PQ theory, the active and reactive power that include average and oscillatory components obtained based on the demand of non-linear/linear loads and EV battery. Then, the reference current of AC/DC converter of the charger and battery is obtained, and in the next step, the situation of the charger switches is determined using output signals of the proportional-integral and proportional-resonant controllers and pulse width modulation. Finally, the proposed approach is validated and implemented in the OPAL-RT to integrate the fidelity of the physical simulation and the flexibility of the numerical simulations.

**Index Terms**— Electric Vehicles (EVs), Bidirectional Charger, Power Conditioning, Active and Reactive Power Control, Harmonic Compensation, Three-Phase Instantaneous Active and Reactive Power (PQ) theory.

## NOMENCLATURE

### Acronyms

AC/DC	Alternating/Direct Current
DISCO	Distribution Company
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
HIL	Hardware-in-Loop
ICE	Internal Combustion Engine
PCC	Point of Common Coupling
PHEV	Plug-in Hybrid Electric Vehicle
PI	Proportional-Integral
PQ	Active-Reactive Power

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PR	Proportional-resonant
PWM	Pulse Width Modulation
SVC	Static Var Compensator
THD	Total Harmonic Distortion

### Subindexes

$a, b, c$	Indices of phase $a, b, c$
$d$	Duty cycle
$du$	Applied signal to PWM in the AC/DC converter
$I_{bt}, I_{bt}^*$	Battery current and reference current of battery
$IC, IC^{ref}$	Charger current and reference current of charger
$IC^p, IC^q$	Active and reactive components of charger current
$IL$	Consumption and injected harmonic current of EV
$K^p, K^i$	Proportional and integral coefficients
$P^{app}, Q^{app}$	Applied active and reactive power to charger
$P_{avg}, Q_{avg}$	Average active and reactive power
$PC_u$	Required active power of battery from network
$P_h, Q_h$	Active and reactive power due to harmonic frequency components
$PL, QL$	Active and reactive power of load
$P_{osc}, Q_{osc}$	Oscillatory active and reactive power
$P^{ref}, Q^{ref}$	Reference active and reactive power
$P_{2\omega}, Q_{2\omega}$	Active and reactive power due to unbalance system (negative and zero sequences)
$s$	Term of Laplace
$V_{dc}, V_{dc}^*$	DC-link voltage and reference DC-link voltage
$V_{dc}^{ref}$	Reference DC-link voltage
$V^{PCC}$	Voltage in the PCC
$\omega$	Network frequency
$\omega_c$	Resonant frequency in the PR controller

## I. INTRODUCTION

The electric vehicles (EVs), as alternatives for fossil fuel-based vehicles, are the new technology that is used for decreasing the environmental pollution. The EV includes conventional internal combustion engine (ICE) and the electrical motor, in which the required energy of the electrical motor is provided by embedded battery in EV. Also, some of EVs such as plug-in hybrid electric vehicles (PHEVs) are connected to the network to receive required energy for their batteries. But, it is noted that large number of EV connection to the network will cause increasing concerns and problems in the power system and/or distribution networks [1]-[3]. In addition, the EVs are connected to the network using chargers composed of AC/DC and DC/DC unidirectional converters. Hence, the EVs behave as non-linear loads in the network, and, they may inject harmonics to the network [4]-[5]. Also, the presence of the harmonic in the distribution networks causes reduction in the distribution transformers' lifetime and malfunctioning of some equipment [6]-[8]. Moreover, the

EVs with unidirectional charger act as passive loads, hence, the large number of EVs' connection to the network causes increased voltage drop and network power loss as well as overloading of distribution lines [9]-[10].

To reduce the harmonic injection into the network, researches have proposed to charge EVs by group [11] and change the charger structure [12]-[14]. In [11], the EVs are charged by the group, and accordingly it is proved that the total harmonic distortion (THD) of the EVs has been reduced with respect to the individual charging. Also, the authors of [12]-[14] have proposed bidirectional chargers including AC/DC and DC/DC bidirectional converters based on IGBT switches. Based on [12]-[14], this charger can control its active and reactive power as well as harmonic current, therefore, the EVs can improve the power quality and network indexes such as voltage. It is noted that although the authors of [12]-[14] have proposed EVs to decrease the harmonic current of the EVs, but in the power system, there are other non-linear loads such as the 6-pulse converter that causes increased concerns and problems about the power quality. In many research works [15]-[17], FACTS or custom power devices are used to decrease the negative impacts of these non-linear loads. Also, the FACTS can regulate the voltage at the point of common coupling (PCC) by injecting the reactive power as done in [15] and [16]. In [17], the capability of custom power devices such as D-STATCOM and active filter is presented. Based on [17], this device can control the harmonic and reactive power of the non-linear and linear loads. But, it is noted that the FACTS and custom power devices need high investment costs to be paid by one private company or distribution company (DISCO). In addition, the bidirectional charger used in the technology of vehicle-to-X (V2X), and the concept of V2X, which transmits electricity from an on-board battery to the electrical infrastructure, is expected to be key solutions for the smart grids. With V2X technology, we can use electricity stored in the batteries of EVs and PHEVs when necessary [18]. Furthermore, different control strategies can be implemented for EV bidirectional charger to use them as an active filter and a D-STATCOM. For instance, the strategy of instantaneous active and reactive power (PQ) theory has been expressed in [19]-[20]. This method is adopted to create the reference current generation schemes related to harmonic, active and reactive power and unbalance compensation. In [21]-[22], the synchronous reference frame (SRF) theory is used for reference current generation in active filter and D-STATCOM related to harmonic, reactive power and unbalance compensation of non-linear loads. Noted that different power decomposition theories are not suitable in the unity power factor operation, because, there are some limitations on occurring resonance effects [23]-[24]. Also, the frequency domain approaches such as fast Fourier transform (FFT), discrete Fourier transform (DFT) and recursive DFT (RDFT) lead to complex calculations which in turn increase the computational burden [21]. However, in [25]-[26], the conservative power theory (CPT) has been used for active filters. This method is the accurate current decomposition method and it has better features such as accurate estimation under ideal and non-ideal grid voltages with selective estimation of disturbing effect [25]-[26].

The main proposal of this paper is to activate the capabilities of the small scale distributed resources in the system to improve power quality and network indexes. In

other words, the EVs equipped with on-board bidirectional charger can control its battery power, reactive power and harmonic current of non-linear and linear loads. It is noted that the EVs' chargers can be installed on-board or off-board, where on-board charger is installed in the EV and off-board charger is installed in the electric vehicle supply equipment (EVSE). Moreover, this paper assumes that the metering point is point of consumption rather than PCC. Therefore, the EV controls its active power based on the demand of its battery, and regulates its reactive power and harmonic current based on the demand of loads. Thus, it is expected to reduce the reactive power and harmonic current in the network side. Accordingly, by this scheme the total cost of power quality and network indexes improvement would be mainly paid by loads rather than network operators. Finally, this paper presents the suitable control strategy for bidirectional charger for providing the capability of power conditioning (including active and reactive power and harmonic current control). The proposed scheme is applied to the three-phase system that non-linear and linear loads and EV are connected to the single phases. In the proposed strategy, both average and oscillatory components of the active and reactive powers are obtained using the three-phase instantaneous active and reactive power (PQ) theory. It is noteworthy that the main reason to use PQ theory is that this theory has a simple structure to be implemented with respect to the other control strategies. Thus, the applied active and reactive power to charger is calculated based on demand of EV and load. Finally, the reference current of AC/DC converter of charger and battery are obtained based on three-phase instantaneous PQ theory, and thus, the situation of charger switches are determined using proportional-integral (PI) and proportional-resonant (PR) controllers and pulse width modulation (PWM). Finally, the extensive studies and hardware-in-loop (HIL) simulations are presented, which prove the effectiveness of the proposed novel method. In summary, the main contributions of this paper are as follows: (i) using distributed resources for improvement of power quality and network indexes, and (ii) designing an on-board bidirectional charger for EVs to activate their capabilities in power conditioning.

The rest of the paper is organized as follows: Section II describes the proposed solution and system, and Section III expresses numerical simulations. Sections IV and V demonstrate experimental results and conclusions, respectively.

## II. PROPOSED SOLUTION

As in many works in the area, the bidirectional structure for AC/DC converter is used in this paper for power conditioning purposes of distribution networks, i.e., active and reactive power control and harmonic compensation of non-linear loads. Accordingly, a specific **control circuit** design for this converter has been proposed.

### A. Proposed topology

It is noted that this paper presents the active and reactive power control as well as harmonic current control simultaneously using electric vehicle. Also, EV includes the battery and charger from the network's view point. The bidirectional charger is used as shown Figure 1, in this paper, where it includes bidirectional AC/DC and DC/DC converters. Since the structure of the bidirectional AC/DC

converter is like D-STATCOM, active filter or others FACTS and custom power devices, therefore, this paper presents the active and reactive power control as well as harmonic current control simultaneously using EV. Also, the AC/DC converter is as full bridge converter that is comprised of a DC link capacitor, four transistors (MOSFETs or IGBTs), four diodes, and a coupling inductor as seen in Fig. 1. The topology is suitable for the proposed problem as done in [14] while it can provide low THD. Moreover, DC/DC converter is as half bridge bidirectional converter in this paper, and it has two transistors (IGBT or MOSFET), two diodes, a filtering capacitor and an inductor as shown in Fig. 1. It can transfer power in both directions. Also, it can only operate as a buck converter in one direction and as boost converter in the opposite direction [14].

The framework of the proposed EV on-board bidirectional charger has been illustrated in Fig. 1. It is noted that the charger has a single-phase structure as shown in Fig. 1. However, to have a generic comprehensive model, the three-phase and four wire system is considered for formulation as depicted in Fig. 2.

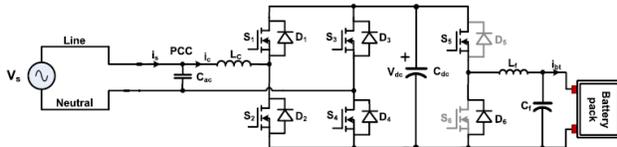


Fig. 1. The proposed structure of the on-board bidirectional charger [14].

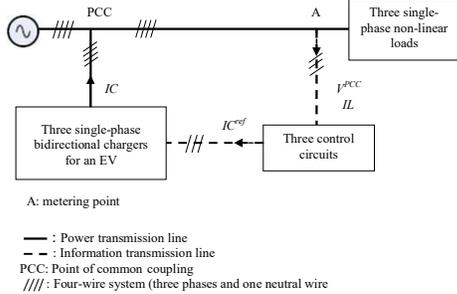


Fig. 2. The topology of proposed control scheme for EVs.

Accordingly, each phase includes one EV and a non-linear/linear load, thus, the proposed system includes three EVs and loads. Also, the network and source are three-phase and four-wire systems. Indeed, presenting the proposed framework on the single-phase system is much more compatible to investigate the EVs' capabilities in the active and reactive power control and harmonic compensation of non-linear loads. But, in this formwork, the sweeping model for the other studies such as three-phase system balance, power system stability has not been presented yet. Hence, in the following subsections, the sweeping model on the three-phase and four wire system is described. It should be noted that this paper investigates only the results of power conditioning (including active and reactive power control and harmonic control) or compensation for each individual EV. However, the model can be straightforwardly extended to consider a group of EVs.

### B. Control circuit for the proposed system

Based on Fig. 1, the charger includes AC/DC and DC/DC converters, hence, this section presents the control of AC/DC and DC/DC converters as well.

1) **The control circuit of AC/DC converter:** Fig. 3 shows the control circuit of the AC/DC converter. Based on this figure, the proposed control model includes three groups of parameters as follows:

**Metering parameters:** These parameters are shown in Fig. 3 with blue colour, and these parameters are metered voltage and current at different points. Based on Figs. 2 and 3, the metering points in the location of load and charger or EV are used for metering of load and charger currents (\$I\_L, I\_C\$), respectively. Also, metering point of voltage (\$V^{PCC}\$) is PCC of network, load and charger.

**Decision parameters:** These parameters are shown in Fig. 3 with orange colour, and these parameters are determined using user preferences. For example, \$PC\_u\$ is specified based on decision of EV's owner.

**Calculated parameters:** These parameters are calculated based on metering and decision parameters and their corresponding relationships.

Based on Fig. 3, the control circuit of AC/DC converter includes following blocks:

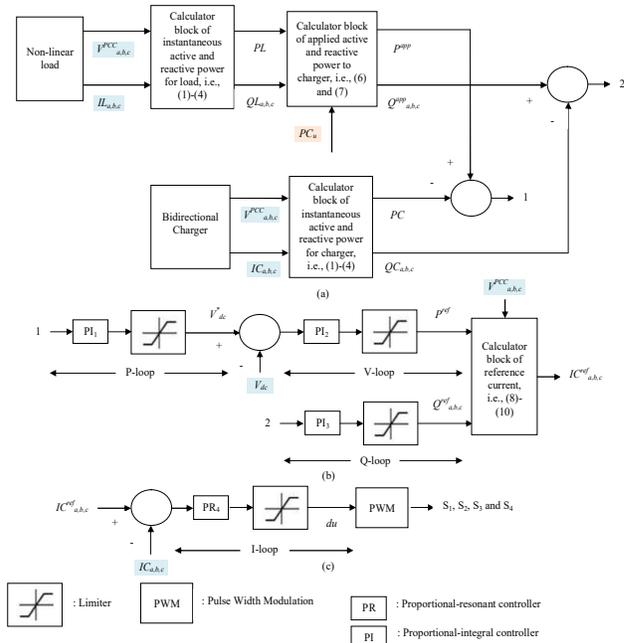


Fig. 3. The control circuit of the AC/DC converter, (a) calculating the charger power, (b) calculating reference current of the charger, (c) determining the situation of AC/DC converter switches.

**Calculator block of instantaneous active and reactive power:** The calculator block of instantaneous active and reactive power is used for the calculation of load and charger instantaneous active and reactive power based on Fig. 3. Accordingly, the input of this block is metering parameters such as PCC voltage and load (charger) current, and the output of this block is instantaneous active and reactive power of load or charge (EV). It is noted that active power is equal to dot (scalar) product ('.') of voltage and current vectors, and reactive power is equal to cross product ('×') of voltage and current vectors [17]. In other words, if the voltage and current vectors are defined as equations (1) and (2), respectively, the instantaneous active and reactive power will be calculated based on equations (3) and (4), respectively [17]. Therefore, the active power is as scalar and reactive power is as vector. Noted that \$I\_L\$ is used in the calculation of \$PL\$ and \$QL\$, and \$I\_C\$ is required to determine

the  $PC$  and  $QC$  in equations (3) and (4).

$$V^{PCC} = \begin{bmatrix} V_a^{PCC} & V_b^{PCC} & V_c^{PCC} \end{bmatrix} \quad (1)$$

$$I = [I_a \ I_b \ I_c] \quad \forall I \in \{IL, IC\} \quad (2)$$

$$P = V^{PCC} \cdot I = V_a^{PCC} I_a + V_b^{PCC} I_b + V_c^{PCC} I_c \quad (3)$$

$\forall I \in \{IL, IC\}, P \in \{PL, PC\}$

$$Q = V^{PCC} \times I = \begin{bmatrix} Q_a \\ Q_b \\ Q_c \end{bmatrix} = \begin{bmatrix} V_b^{PCC} & V_c^{PCC} \\ I_b & I_c \\ V_c^{PCC} & V_a^{PCC} \\ I_c & I_a \\ V_a^{PCC} & V_b^{PCC} \\ I_a & I_b \end{bmatrix} \quad (4)$$

$\forall I \in \{IL, IC\}, Q \in \{QL, QC\}$

It is noted that the equations (1) to (4) are based on three-phase instantaneous active and reactive power (PQ) theory [17]. However, if the proposed system has as single-phase, hence, it needs to implement single-phase instantaneous active and reactive power theory as presented in [27], [28]. Accordingly, the proposed system can be changed to single-phase system, while the calculator block of the instantaneous active and reactive power is based on single-phase instantaneous PQ theory. In addition, the scalar value of reactive power is needed in some cases, and it is obtained as follows [17]:

$$Q = \frac{Q_a + Q_b + Q_c}{\sqrt{3}} \quad Q \in \{QL, QC\} \quad (5)$$

Based on [17], the power is equal to summation of average power ( $P_{avg}$ ,  $Q_{avg}$ ) and oscillatory power ( $P_{osc}$ ,  $Q_{osc}$ ). The average power obtained based on the symmetrical (positive sequence) and fundamental frequency component of voltage and current, and the oscillatory power is equal to summation of power due to harmonic frequency components ( $P_h$ ,  $Q_h$ ) and power due to unbalance system (negative and zero sequences) that is shown as  $P_{2\omega}$  and  $Q_{2\omega}$ , and its frequency is equal to 200% of the fundamental frequency of the network ( $\omega$ ) [17].

*Calculator block of applied active and reactive power to charger:* The calculator block of the applied active and reactive power to charger is used for calculation of applied active and reactive power to charger based on Fig. 3. Based on Fig. 3, the input of this block is active and reactive power of the load ( $PL$ ,  $QL$ ) and required active power of battery from the network viewpoint that is demanded by EV user ( $PC_u$ ). Noted that the charger active power ( $PC_u$ ) is equal to the summation of the battery active power and charger active loss. The output of this block is applied active and reactive power of the charger ( $P^{app}$ ,  $Q^{app}$ ) that includes oscillatory active power of load ( $PL_h$ ,  $PL_{2\omega}$ ) and oscillatory ( $QL_h$ ,  $QL_{2\omega}$ ) and average ( $QL_{avg}$ ) reactive power of load (these terms are removed using charger), and required active power of battery from the network side. Therefore, the relationship between input and output of this block is as equations (6) and (7) for active and reactive terms, respectively.

$$P^{app} = a_1 PL_{avg} + a_2 PL_h + a_3 PL_{2\omega} + a_4 PC_u \quad (6)$$

$$Q_{a,b,c}^{app} = b_1 QL_{avg_{a,b,c}} + b_2 QL_{h_{a,b,c}} + b_3 QL_{2\omega_{a,b,c}} \quad (7)$$

In these equations, the coefficients of  $a_i$  and  $b_i$  are decision making parameters that are one or zero. But,

coefficient of  $a_4$  is equal to -1 while EV battery is in the discharging mode. It is noted that these parameters are determined based on the preferences of users. Moreover,  $PL_{avg}$  and  $QL_{avg}$  ( $PL_h$  and  $QL_h$ ) can be obtained using low-pass filter (high-pass filter) with low set-frequency (set-frequency is more than network frequency, i.e. 50 or 60 Hertz), where this filter is located after  $PL$  and  $QL$ , respectively. But,  $PL_{2\omega}$  and  $QL_{2\omega}$  are obtained using band-pass filter with the set-frequency of 100 to 120 Hertz [14]. In addition, the limits of the proposed charger are capacity and battery charge/discharge rate limits which expressed as  $(P^{app})^2 + (Q^{app})^2 \leq (SC)^2$  and  $DR \leq PC_u \leq CR$ , respectively.  $SC$  is charger capacity, and  $CR$  and  $DR$  are the battery charging and discharging rates, respectively [10]. In addition,  $Q^{app}$  is provided by the charger and it is not dependent of battery. But,  $P^{app}$  depends on active load and the required active power of battery from the network ( $PC_u$ ). Note,  $PL_{avg}$  is provided by the network, and  $PL_h$  and  $PL_{2\omega}$  are provided by battery in harmonic comparison mode. But, the values of  $PL_h$  and  $PL_{2\omega}$  are more less than  $PL_{avg}$ . Moreover,  $PC_u$  makes the SOC or DOD, because it is sent to battery from the network, or vice versa. Thus, this power changes the stored energy in battery, changing this energy causes changing of SOC or DOD. Since, this control action takes place in about 10 seconds, therefore, the SOC or DOD is almost constant. In other words, if the simulation times were about some hours, thus, the SOC and DOD would be changed during the control process as we studied it in our previous work [10]. Finally, it is noted that the models of the battery and EV's charger have been considered in this paper.

*Calculator block of reference current:* The calculator block of reference current is used for calculation of charger reference current. Based on Fig. 3, the input of this block is the reference active and reactive power of the charger, and the output of this block is the charger reference current. The proposed system as Fig. 2 is based on three-phase instantaneous PQ theory, hence, the calculator block of reference current is based on this theory. According to this theory [17], the reference current includes active ( $IC^p$ ) and reactive ( $IC^q$ ) components as equation (8), and these components are due to the active and reactive powers as equations (9) and (10), respectively.

$$IC_{a,b,c}^{ref} = IC_{a,b,c}^p + IC_{a,b,c}^q \quad (8)$$

$$IC^p = \frac{P^{ref}}{V^{PCC} \cdot V^{PCC}} V^{PCC} = \begin{bmatrix} IC_a^p & IC_b^p & IC_c^p \end{bmatrix}^T$$

$$= \frac{P^{ref}}{(V_a^{PCC})^2 + (V_b^{PCC})^2 + (V_c^{PCC})^2} \begin{bmatrix} V_a^{PCC} & V_b^{PCC} & V_c^{PCC} \end{bmatrix}^T \quad (9)$$

$$IC^q = \frac{Q^{ref} \times V^{PCC}}{V^{PCC} \cdot V^{PCC}} = \begin{bmatrix} IC_a^q & IC_b^q & IC_c^q \end{bmatrix}^T$$

$$= \frac{1}{(V_a^{PCC})^2 + (V_b^{PCC})^2 + (V_c^{PCC})^2} \begin{bmatrix} Q_b^{ref} & Q_c^{ref} \\ V_b^{PCC} & V_c^{PCC} \\ Q_c^{ref} & Q_a^{ref} \\ V_c^{PCC} & V_a^{PCC} \\ Q_a^{ref} & Q_b^{ref} \\ V_a^{PCC} & V_b^{PCC} \end{bmatrix} \quad (10)$$

Equations (1) to (10) are obtained based on PQ theory,

therefore, these equations should be changed in the other control methods based on the corresponding theory.

It is noted that the reference active and reactive power ( $P^{ref}$ ,  $Q^{ref}$ ) obtained with following formulations using suitable controller based on Fig. 3. Based on this figure, there are outer and inner loops for active power control, that the outer loop is used to satisfy active power condition (active power of charger output should be equal to applied active power to the charger) by modifying the set-point of DC-link voltage ( $V_{dc}^*$ ). Also, this loop is called active power loop that is shown as P-loop, and it includes proportional and integral (PI) controller as follows:

$$V_{dc}^* = K_{P-loop}^P (P^{app} - PC) + \frac{K_{I-loop}^I}{s} (P^{app} - PC) \quad (11)$$

The inner loop or DC voltage loop (V-loop) is used to follow  $V_{dc}^*$ , i.e., the voltage of DC-link should be equaled to  $V_{dc}^*$ . This loop uses PI controller that its output is reference active power as equation (12).

$$P^{ref} = K_{V-loop}^P (V_{dc}^* - V_{dc}) + \frac{K_{I-loop}^I}{s} (V_{dc}^* - V_{dc}) \quad (12)$$

Moreover, the reactive power control includes outer loop that is shown as Q-loop. This loop includes PI controller and it is used to satisfy reactive power condition (reactive power of charger output should be equal to the applied reactive power to charger) by modifying the reference reactive power as equation (13).

$$Q_{a,b,c}^{ref} = \left( K_{Q-loop}^P + \frac{K_{Q-loop}^I}{s} \right) \cdot (Q_{a,b,c}^{app} - QC_{a,b,c}) \quad (13)$$

Finally, the situation of AC/DC converter switches are determined using pulse width modulation (PWM). The input of PWM is current loop (I-loop) that is used to follow  $IC^{ref}$ , i.e., the current of the charger output should be equal to  $IC^{ref}$ . It is noted that this loop uses the proportional and resonant (PR) controller [29] that its output is applied signal to PWM ( $du$ ) as equation (14).

$$du_{a,b,c} = \left( K_{I-loop}^P + \frac{2K_{I-loop}^I \omega_c s}{s^2 + 2\omega_c s + (\omega)^2} \right) \cdot (IC_{a,b,c}^{ref} - IC_{a,b,c}) \quad (14)$$

2) **The control circuit of DC/DC converter:** Fig. 4 shows the control circuit of the DC/DC converter. Based on this figure, there are outer and inner loops for active power control, that the outer loop (Ib-loop) is used to satisfy DC voltage condition (voltage of DC-link should be equal to reference DC-link voltage or  $V_{dc}^{ref}$ ) by modifying the reference battery current ( $I_{bt}^*$ ).

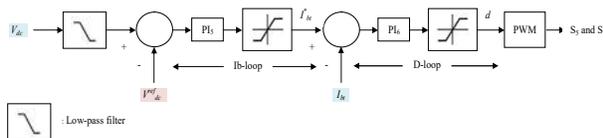


Fig. 4. The control block diagram of the DC/DC converter.

Also, this loop uses the proportional and integral (PI) controller as shown in equation (15), and it is used as a complement for the P-loop that its purpose is the establishment of balance between active power of the charger output and the applied active power to the charger.

$$I_{bt}^* = K_{Ib-loop}^P (V_{dc} - V_{dc}^{ref}) + \frac{K_{Ib-loop}^I}{s} (V_{dc} - V_{dc}^{ref}) \quad (15)$$

Regarding the voltage of the DC-link,  $V_{dc}$ , it depends on  $P^{app}$  and the current of battery. Thus,  $V_{dc}$  will be close to

$V_{dc}^{ref}$  (it is 400 V in this paper) by PI<sub>5</sub> controller or equation (15) based on Fig. 4. Also, DC link voltage that is related to  $P^{app}$  or  $P^{ref}$  ( $V_{dc}^*$ ) is extracted by PI<sub>1</sub> controller or equation (11), and it should be close to  $V_{dc}$  based on PI<sub>2</sub> controller or equation (12). Finally, based on equations (11), (12) and (15),  $V_{dc}^*$  should track  $V_{dc}^{ref}$ , therefore, with this method,  $V_{dc}$  is controlled to track the set-point  $V_{dc}^{ref}$ . In other words, the proposed system in Fig. 2 uses the DC-link voltage control to generate battery reference current ( $I_{bt}^*$ ) in the DC/DC converter. Note that if  $P^{app}$  increases/decreases, then,  $V_{dc}$  is increased/decreased to a new set-point based on the equations (11) and (12). This small increases/decreases in  $V_{dc}$  yields an increase/decrease in the battery current ( $I_{bt}$ ).

It is important to note that initial state of charge (SOC) and battery size of the EV do not affect the proposed strategy performance. In other words, the SOC is equal to the stored energy (E)/battery capacity (BC). The stored energy is expressed as  $E_t = E_{t-1} + \Delta t \times \eta PC_u$ , where  $\eta$  is charger round-trip efficiency and  $PC_u$  is the active power of battery or the charger. Thus, based on this equation, the SOC or depth of discharge (DOD) depends to time ( $\Delta t$ ) such as one hour. However, in this paper the simulation is run for 10 second. That is, the value of SOC is constant in this period of simulation. Thus, the changing of SOC or DOD is about zero. Also, the charge/discharge rates of the battery are considered in this paper, and they depend on  $PC_u$ , where  $PC_u$  has been explained in equation (6). The inner loop (D-loop) calculates duty cycle of DC/DC converter based on the error between reference and metering battery current using PI controlled and with equation (16). Finally, the duty cycle of DC/DC converter is applied to PWM for determination of the situation of AC/DC converter switches.

$$d = K_{D-loop}^P (I_{bt}^* - I_{bt}) + \frac{K_{D-loop}^I}{s} (I_{bt}^* - I_{bt}) \quad (16)$$

### III. NUMERICAL AND EXPERIMENTAL RESULTS AND DISCUSSION

#### A. Case study

To evaluate the capability of the proposed system with the simulation circuit in Fig. 5, the hardware-in-loop (HIL) simulation approach has been used. The real-time HIL method is used to emulate errors and delays that do not exist in the classical off-line simulations. Fig. 6 illustrates the HIL setup consisting of: (1) OPAL-RT as a Real-Time Simulator (RTS) which simulates the suggested circuit presented in Fig. 5; (2) a PC as the command station (programming host) in which the Matlab/Simulink based code will be executed on the OPAL-RT; (3) a router that is used as a connector of all the setup devices in the same sub-network. The OPAL-RT is also connected to DK60 board through Ethernet ports. More details about this setup can be found in [30], [31]. In other words, this method includes simulation and hardware parts, where Fig. 5 is in the simulation part and different controls are in the hardware part. Based on [30]-[31], the error of this method with respect to experimental platform is very low and accordingly this approach has been adopted in many research works in the area.

This simulation includes linear and non-linear loads. The linear load is as series circuit of resistance-inductance and the value of resistance and inductance is 8.7  $\Omega$  and 20 mH,

respectively. Also, the non-linear load is as a single-phase rectifier with series circuit of resistance-inductance in the output of single-phase rectifier, which the value of resistance and inductance is  $8.7 \Omega$  and  $20 \text{ mH}$ , respectively. The network voltage and frequency is  $120 \text{ V}$  and  $60 \text{ Hz}$ , respectively. Tables I and II present the bidirectional charger characteristics, and the PI/PR controller characteristics [14]. Also, the decision making coefficients of  $a_3$  and  $b_3$  are considered to be zero, because, this paper investigates the EV capability for active and reactive power control and harmonic compensation of non-linear load, that is, the system unbalance mode is not considered. Finally, the battery model has been presented in [32].

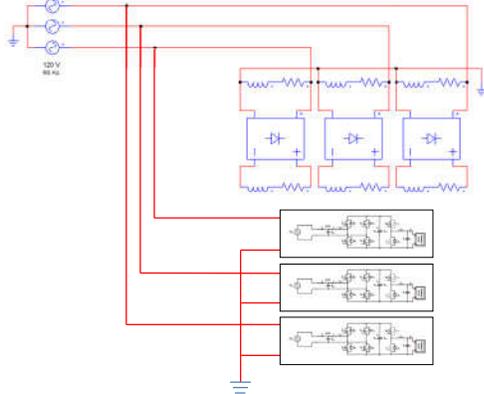


Fig. 5. Proposed circuit for the simulations.



Fig.6.The real-time experimental setup.

Table I. Characteristics of the bidirectional charger [14].

Parameter	Symbol	Value
Capacity	$SC$	$1.44 \text{ kVA}$
Battery charge/discharge rate	$CR/DR$	$1000/-1000 \text{ W}$
Supply voltage	$VC$	$120 \text{ V}$
Maximum current	$IC$	$12 \text{ A}$
Coupling inductance	$L_c$	$1 \text{ mH}$
Switching frequency of AC/DC converter	$f_{sw1-4}$	$10 \text{ kHz}$
DC-link voltage	$V_{dc}$	$400 \text{ V}$
DC-link capacitor	$C_{dc}$	$330 \mu\text{F}$
Switching frequency of DC/DC converter	$f_{sw5-6}$	$10 \text{ kHz}$
Battery side filter capacitor	$C_f$	$200 \mu\text{F}$
Battery side filter inductance	$L_f$	$400 \mu\text{H}$

Table II. Characteristics of PI and PR controllers [14].

Controller	Parameter	Value	
$PI_1$	P-loop	$K^P$	1
		$K^I$	20
$PI_2$	V-loop	$K^P$	1.5
		$K^I$	100
$PI_3$	Q-loop	$K^P$	0.1
		$K^I$	30
$PR_4$	I-loop	$K^P$	0.6
		$K^I$	500
		$\omega_c$	$3 \text{ rad/s}$
$PI_5$	Ib-loop	$K^P$	0.045
		$K^I$	0.5
$PI_6$	D-loop	$K^P$	0.01
		$K^I$	10

## B. Method

In this paper, the HIL simulation approach is used to obtain the proposed system results and investigate the capability of the EV charger. Also, the real-time HIL method is used to emulate errors and delays that do not exist in the classical off-line simulations.

1) *Investigating charger operating areas in the average power control condition:* In this section, the simulation results of the average active and reactive power control are expressed. Hence, the the decision making coefficients of  $a_2$ ,  $a_3$ ,  $b_2$  and  $b_3$  are equal to zero. Also, the different cases have been investigated as follows:

*Case I:* Investigating of simulation results in EVs are operated in the capacitive and charging modes.

*Case II:* EVs are operated in the inductive and charging modes.

*Case III:* EVs are operated in the capacitive and discharging modes.

*Case IV:* EVs are operated in the inductive and discharging modes.

The results of this section have been presented in Fig. 7. Accordingly, the average active and reactive loads are equal to  $7000 \text{ W}$  and  $3250 \text{ VAR}$  in the steady state condition. In the cases of I-IV, the charging/discharging active power is considered to be  $850 \text{ W}$  for each EV, and the total average reactive power of EVs is equal to the total average reactive power of loads ( $3250 \text{ VAR}$ ). Hence, in the steady state condition and based on Fig. 7, the average active power of EVs is  $2550 \text{ W}$  in the cases I and II, and it is  $-2550 \text{ W}$  in the cases III and IV. It is noted that the average active power of EVs shows the battery operation, i.e., if the average active power of EVs is positive (negative), thus, the EV's battery operates in the charging (discharging) mode. Moreover, the average active power of the network is  $9550$  and  $4450 \text{ W}$  for cases I-II and III-IV, respectively. In other words, the average active power of the network increases about  $36.5\%$  for cases I-II, and it reduces about  $36.5\%$  for cases III-IV with respect to the results of the load active power. It is noted that in the cases I and III, the EV charger operates in the capacitive mode. Hence based on Fig. 7, the average reactive power of EVs is equal to  $-3250 \text{ VAR}$ , and the average reactive power of the network is equal to zero in the steady state condition. Therefore, the EVs charger compensates all average reactive power of the loads. But, the EV charger acts in inductive mode for cases II and IV, hence, the average reactive power of EVs and network is equal to  $3250$  and  $6500 \text{ VAR}$  based on Fig. 7, respectively. Therefore, the average reactive power of the network increases about  $100\%$  with respect to the load reactive power.

Also, the time constant of charger active power is less than other parameters such as the network and load power and charger reactive power. Because, the number of calculator blocks is low for the calculation of the charger active power, but, the number of calculator blocks is high for the calculation of other parameters.

Based on Fig. 7, the EV charger can act as a power consumer or power producer with suitable control of its switches. This statement has been illustrated in Fig. 8 for one EV charger. According to this figure, the EV charger can be operated in all areas of PQ plane. It should be noted that the different values in Fig. 8 are obtained from the results of Fig. 7. Hence, EV can operate as capacitive, inductive and resistive loads or a complex of them based on

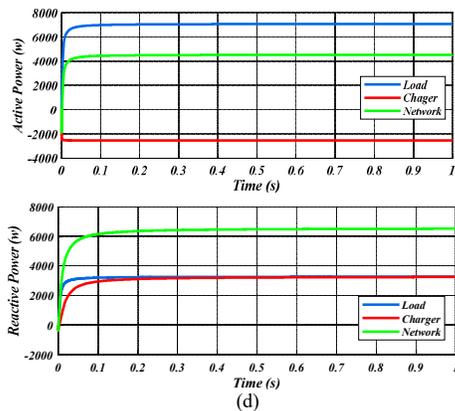
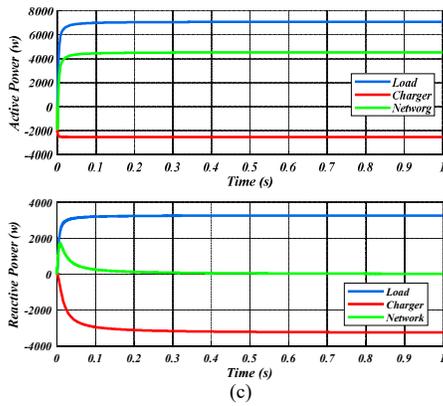
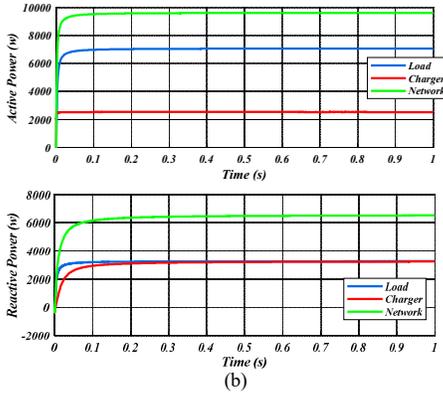
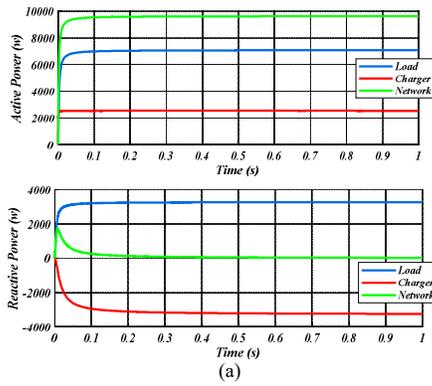


Fig. 7. Average active and reactive power for different parts of the proposed system, (a) Case I, (b) Case II, (c) Case III, (d) Case IV.

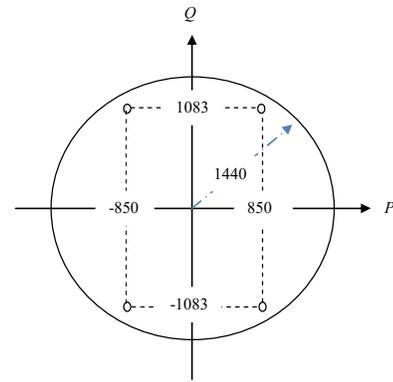


Fig. 8. Operating area of an EV in the PQ plane.

the right side of the operating areas in PQ plane of Fig. 8. In contrast, it can act as active power supply, reactive power supply, inductive load or complex of them based on the left side of operating areas in PQ plane of Fig. 8. Moreover, the operating area of EV charger is equal to inner areas and the border of circle with radius that is equal to charger capacity (1440VA for proposed system).

2) *Investigating harmonic compensation using EVs*: In this section, the simulation results for the harmonic compensation of the non-linear load using EV bidirectional charger have been presented. Accordingly, the coefficients of  $a_3$ , and  $b_3$  are equal to zero. Also, the following cases have been studied:

*Case I*: Investigating the proposed system without considering EVs.

*Case II*: Investigating the proposed system considering EVs that are operating as harmonic compensators in the capacitive and charging modes.

*Case III*: Investigating the proposed system considering EVs that are operating as harmonic compensators in the capacitive and discharging modes.

Fig. 9 shows the results of this section. As seen, the load current wave is not sinusoidal due to the presence of single-phase rectifier in the consumption side. Moreover, the load current magnitude for the harmonic orders 3, 5 and 7 is equal to 4, 2.5 and 1.8 A, that these values are high with respect to the load current magnitude at the fundamental frequency, i.e., 31 A. Because, the maximum current magnitudes are equal to 4%, 2%, 1.5%, 0.6% and 0.3% of current magnitudes at the fundamental frequency for  $h < 11$ ,  $11 \leq h < 17$ ,  $17 \leq h < 23$ ,  $23 \leq h < 35$  and  $h \geq 35$ , respectively based on standard of IEEE STD. P519.1/D9A [33], and  $h$  is the harmonic order. Also, in cases II and III, the charging/discharging active power is considered to 800 W for each EV, and the total average reactive power of EVs is equal to 3250 VAr. Finally, it is considered that the EVs can compensate all harmonics of the non-linear loads. Based on Fig. 9, the average network current wave is as sinusoidal wave, but, the average EV current wave is not as the sinusoidal wave in cases II and III. Because, the harmonic of the load side is compensated by EVs in these cases. It is noted that the network and EV currents include ripples mounted on the sinusoidal or non-sinusoidal waves due to switching of the charger switches. However, the magnitude of ripple can be reduced using suitable regulation of PI and PR controller parameters and inductance of  $L_c$ . In addition, the network current magnitude is reduced in harmonic frequency components with respect to the case I. Also, the

harmonic current magnitudes of the network satisfy IEEE STD. P519.1/D9A [33].

Table III presents the THD of the network current, DC-link voltage ( $V_{dc}$ ) and battery current for cases I to III. Based on the table, the network current THD is equal to 20% in case I, thus, it is high based on the standard of IEEE STD. P519.1/D9A. But, it is reduced about 57% in cases II and III with respect to the case I, and it satisfies the standard condition of IEEE STD. P519.1/D9A.

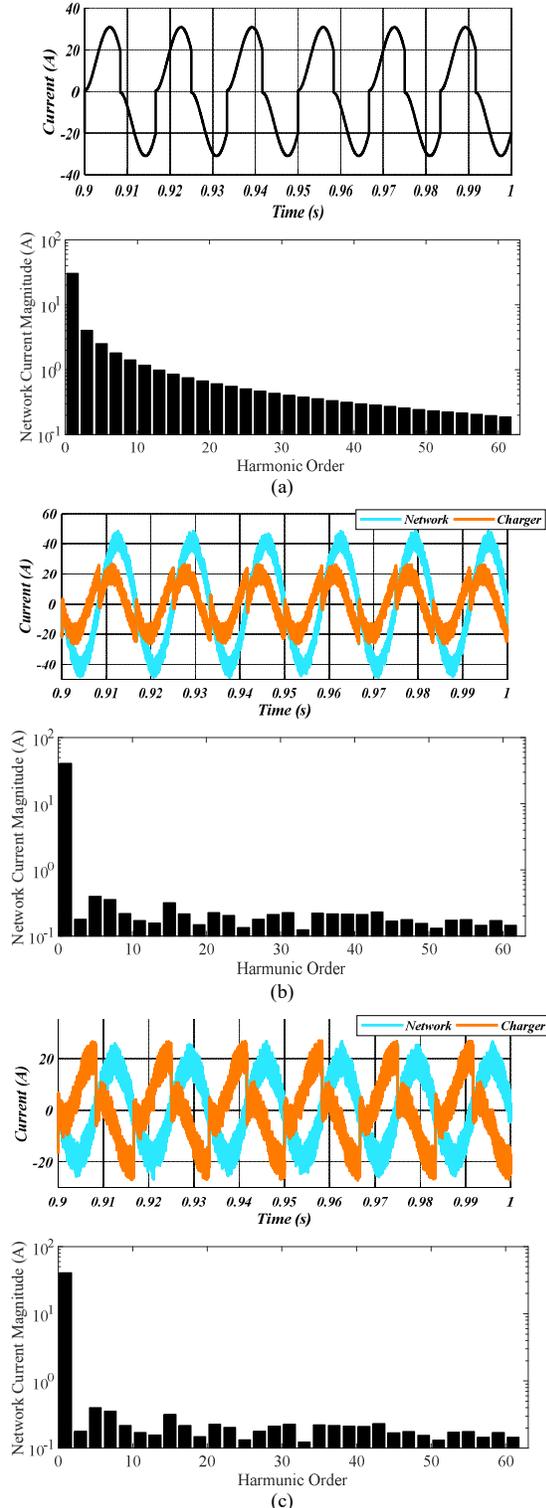


Fig. 9. Current and harmonic current for different parts of the network, (a) Case I, (b) Case II, (c) Case III.

Table III. Network current THD, DC-link voltage and battery current.

Case	Network current	DC-link voltage (V)		Battery current (A)	
	THD (%)	Value	Ripple	Value	Ripple
I	19.64	400	3	6.3	0.3
II	7.42	400	3	-7	0.35
III	8.54	400	3	-7	0.35

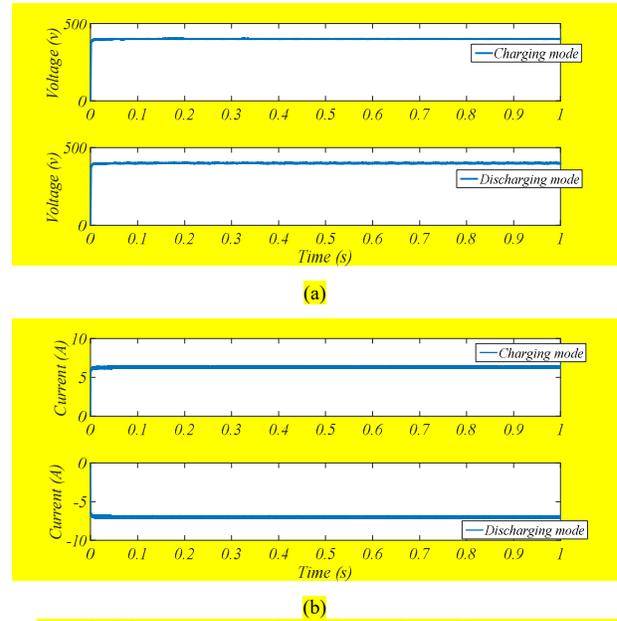


Fig. 10. DC side results in Cases II and III, (a) DC-link voltage, (b) battery current.

Moreover, the DC-link voltage is equal to 400 V for cases II and III in the steady state condition based on Fig. 10(a). Also, the time constant is much small for DC-link voltage according to this figure. As seen in table III and Fig. 10(b), the battery current is equal to 6.3 and -7 A for charging and discharging modes. Noted that if each EV injects or absorbs only 800 W to/from network, therefore, the current magnitude between network and charger is 6.66 A ( $800 \text{ W} / 120 \text{ V}$ ). However, due to the power loss of AC/DC and DC/DC converters provided by the battery, the battery current magnitude has been increased in the discharging mode with respect to 6.66 A. In addition, it is reduced in the charging mode with respect to 6.66 owing to the power loss of AC/DC and DC/DC converters provided by the network. Moreover, the battery current shows the battery operation, i.e., if the battery current is positive (negative), then, the EV's battery operates in the charging (discharging) mode. Finally, it is seen that the time constant is very small for the battery current based on Fig. 10(b).

3) *Comparison of results between different control strategies:* Table IV presents the results of this section including the network current THD and RMS, DC-link voltage and battery current with different control strategies based on PQ theory, SRF theory [22] and FFT [21] for cases II and III in the previous section (III-B-2). Also, it is noted that the all parameters of the proposed system are the same for all control strategies. The results in this table have been presented for three main parts as follows:

- Network current RMS and THD show the characteristics of the network or voltage source in Fig. 5, where as seen in the table, the network current RMS is the same for different control strategies while there are the same characteristics in Fig. 5 and the same demand from the

network by EVs and loads for all control strategies. Also, the network current RMS in the case II is more than case III, because the EVs receive the active power from the network in the case II, while they inject the active power into the network at the case III. In addition, the network current THD in the proposed control strategy (PQ theory) is suitable with respect to the SRF and FFT methods for cases II and III.

- In the DC-link part, the value and ripple of the DC-link voltage have been presented in Table IV. Indeed, the value of the DC-link voltage is the same for all control strategies and cases and it is equal to 400V, because the voltage of the DC-link should follow the reference voltage (400V based on Table I) according to equations (11), (12) and (15). In addition, the ripple of voltage in THE DC-link for THE proposed control strategy is low in comparison with the other control strategies.

- In the battery side, the value and ripple of battery current have been addressed in Table IV. The battery current value is the same in all control strategies since there is the same active power (charging in case II and discharging in case III) in battery side for all strategies. Also, the ripple of the battery current is low in the proposed method with respect to the SRF and FFT.

Finally, based on the results of this table, the proposed control strategy (PQ theory) has suitable results for different parameters as shown in table IV with respect to the SRF and FFT methods.

Table IV. Comparison between different control strategies.

Case II (EV is as harmonic compensator in the capacitive/charging modes)						
Method	Network current		DC-link voltage (V)		Battery current (A)	
	RMS (A)	THD (%)	Value	Ripple	Value	Ripple
Proposed strategy	28.4	7.42	400	3	6.3	0.3
SRF [22]	28.4	7.88	400	3.4	6.3	0.4
FFT [21]	28.4	7.57	400	3.6	6.3	0.45
Case III (EV is as harmonic compensator in the capacitive/discharging modes)						
Method	Network current		DC-link voltage (V)		Battery current (A)	
	RMS (A)	THD (%)	Value	Ripple	Value	Ripple
Proposed strategy	13.8	8.54	400	3	-7	0.35
SRF [22]	13.8	8.68	400	3.45	-7	0.45
FFT [21]	13.8	8.62	400	3.7	-7	0.55

#### IV. CONCLUSIONS

This paper designs an on-board bidirectional charger for a single-phase EV with the capability of power conditioning (including active and reactive power as well as harmonic current control). It is assumed that the general three-phase system includes some single-phase non-linear and linear loads and EVs. Accordingly, the proposed control strategy is based on the three-phase instantaneous PQ theory wherein the power (active and reactive) includes both average and oscillatory components. The average power is obtained based on the fundamental frequency and the positive sequence of the voltage and current signals, while the oscillatory power is obtained based on the harmonic frequency and the negative and zero sequences of voltage and current signals. Consequently, the situation of charger switches are determined using the proportional-integral and proportional-resonant controllers combined with PWM. Based on the numerical and experimental results, the EV bidirectional charger can operate in four quadrants in the

active-reactive (PQ) power plane, and it can compensate for the non-linear harmonic currents.

To have a further exploration in this area, the research work is underway to model the EVs in the context of the optimal harmonic power flow using new control strategy for the proposed charger and implement it in real cases.

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