

An EV/PHEV Battery Charger Based on Sinusoidal-Ripple-Current Charging-Discharging Technique for V2G Applications

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Abstract—Sinusoidal-Ripple-Current (SRC) charging-discharging technique has distinct advantages compared to other techniques. The purpose of this paper is to design a bidirectional Battery Charger (BC) for an Electric Vehicle (EV) based on SRC technique. Sinusoidal current variations applied to the Li-ion battery in this technique negatively affect on the AC-side terminal of the BC, alternately change the output active power, power factor, and current of the AC-side terminal and therefore, worsen the power quality. On the other hand, the output active power and reactive power of the AC-side terminal (P_s and Q_s) must be regulated at constant values without any variations when the EV participates in (Vehicle-to-Grid) V2G technology. Therefore, a particular topology has been introduced and then, a novel control strategy has been defined for the BC of the EV in order to resolve the power quality problem and regulate P_s and Q_s at constant values. Finally, the simulation results confirm the validation of the proposed BC.

Index Terms—Active and reactive power control, bidirectional battery charger, charging-discharging technique, sinusoidal-ripple-current, vehicle-to-grid (V2G)

I. INTRODUCTION

Upgrading conventional distribution grids to MicroGrids (MGs) has been studied in the past few years. Electric Vehicles (EVs) and Plug-in Hybrid EVs (PHEVs) as one of the elements connected to the MGs, have drawn a great deal of attention, due to rising energy costs, concerns about fossil energy reserves, energy security, environmental and climate change issues and legislation, and growing consumer expectations [1]. Although a large number of PHEVs/EVs connected to the MG may lead to a huge threat to quality and stability of the power system, they have enough potential to be used as distributed energy storage units. The bidirectional active and reactive power transfer through bidirectional Battery Chargers (BCs) of EVs is referred as Vehicle-to-Grid (V2G) technology [1], [2]. Some possible services provided by this technology are: supply of peak power, supply of primary, secondary and tertiary frequency control, load leveling, and voltage regulation [3].

Intensive research efforts are being conducted to make such advanced technology a reality today. One of the essential steps to successfully implement V2G concept is to design appropriate bidirectional BCs for EVs whose control systems

regulate output active and reactive power of the AC-side terminal (P_s and Q_s) at requested values [4]–[7]. This task will be accomplished in this paper.

On the other hand, degradation on the battery during V2G technology makes it inconvenient and less preferable unless the battery performance and lifetime are under warranty. Thus, the bidirectional BCs should be designed based on a high-quality charging-discharging technique in order to obtain better battery performance and improve the battery lifetime.

Due to light weight, high power density, low self-discharge rate, and high operating voltage, utilization of Li-ion batteries as energy storage units of EVs has aggressively proliferated. Until now, some charging techniques for Li-ion batteries such as Constant-Current (CC) [8]–[10], Constant-Current Constant-Voltage (CC-CV) [8]–[10], pulse current [8], [10], [11], Reflex [8], [12], and Sinusoidal-Ripple-Current (SRC) [13], [14] have been proposed. Also, some discharging techniques for these batteries such as CC, pulse current, and SRC have been proposed [13]. Each charging or discharging technique has advantages and disadvantages.

In [14], SRC charging technique for Li-ion batteries has been investigated. The AC-impedance analysis has been used to explore the frequency f_m at which the AC impedance obtains its minimum value [14]. In [14], it has been proved that an optimal charging performance can be obtained when the Li-ion battery is charged based on SRC charging technique with f_m . Experiments have been shown that the charging time, charging efficiency, maximum rising temperature, and lifetime of Li-ion batteries are improved about 17%, 1.9%, 45.8%, and 16.1%, respectively, as compared with conventional CC-CV charging technique.

In [13], SRC discharging technique for Li-ion batteries has been investigated and it has been proved that an optimal discharging performance can be obtained when the Li-ion battery is discharged based on this technique with f_m . Experiments have been shown that this technique improves the discharging capacity, discharging efficiency, and rising temperature of Li-ion batteries about 1.3%, 1.32%, and 41.9%, respectively, as compared with conventional CC discharging technique.

Since this method has big distinct advantages in compar-

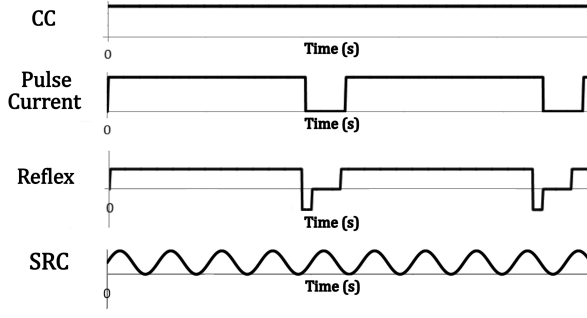


Fig. 1. Various types of charging-discharging battery current waveforms

ison with other charging and discharging techniques [13], [14], it has also been considered as a high quality charging-discharging technique in this research study. This charging-discharging technique can be used not only for EV BCs, but also for advanced battery systems.

As shown in Fig. 1, this technique applies a direct current (i_{DC}) with an alternating sinusoidal current (i_{AC}) with the frequency f_m . As a consequence of sinusoidal current variations applied to the Li-ion battery, the signal waveforms of delivered/extracted active powers to/from the Li-ion battery terminal and the AC-side terminal follow a sinusoidal shape. Such variations in P_s negatively affect on the AC-side terminal current, alternately change the Power Factor (PF) and the RMS value of the AC-side terminal current, and therefore, worsen the power quality. On the other hand, P_s and Q_s must be regulated at constant values without any variations when the EV participates in V2G technology. Thus, particular importance should be given to this power quality. Although this power quality has not been examined in details in the relevant studies conducted on SRC technique [13], [14], it has been investigated and solved in this paper.

The purpose of the study is to define a novel control strategy to resolve this power quality problem. For this purpose, a particular topology has been introduced in which one capacitor with two IGBT legs and two inductors are connected to the BC, and then are controlled according to the novel control strategy.

This work starts with a discussion about SRC technique in Section II. Then, Section III focuses on the model and control schemes of the DC-DC and DC-AC parts of the bidirectional BC based on SRC technique and finally, the paper will be concluded with relevant discussions on simulation results in Sections IV and V.

II. SRC CHARGING-DISCHARGING TECHNIQUE

Fig. 2(a) depicts the complete AC-impedance model for the Li-ion battery which includes an ohmic resistance (R_o), two double-layer capacitances (C_d' and C_d''), two charge transfer resistances (R_{ct}' and R_{ct}''), two inductances (L_d' and L_d''), and two Warburg impedances (Z_w' and Z_w'') [13], [14]. This circuit model can be simplified to the circuit model shown in Fig. 2(b) [13], [14]. The AC impedance for the Li-ion battery

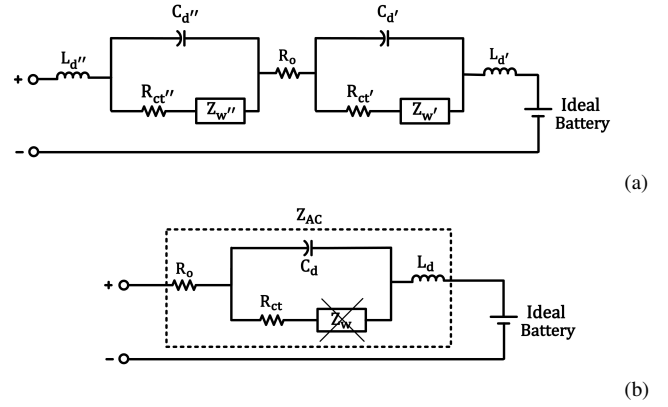


Fig. 2. Li-ion battery AC-impedance model: a) complete model and b) simplified model

is not affected by Warburg impedances only if the charging-discharging frequency is below 1Hz [13], [14]. If the charging-discharging technique is not CC, Warburg impedances can be neglected. Thus, the circuit model can be simplified again.

At the viewpoint of electrical circuit, different charging and discharging frequencies ($f_c = \omega_c/(2\pi)$) result in different AC impedances. To have the minimum AC impedance (Z_{min}), and as a result, the maximum energy transfer efficiency, the minimum energy loss, and finally, the best electrochemical reaction in both charging and discharging, f_c must be selected as follows [13], [14]:

$$f_c = f_m = \frac{1}{2\pi R_{ct} C_d} \sqrt{k-1} \quad (1)$$

where

$$k = \frac{\sqrt{2R_o R_{ct}^3 C_d^2 + 2L_d R_{ct}^2 C_d + R_{ct}^4 C_d^2}}{L_d} \quad (2)$$

The applied charging-discharging current can be written as: [13], [14]

$$i_{SRC} = i_{DC} + i_{AC} = I_0 + I_0 \cos(2\pi f_m t) \quad (3)$$

In the experiments conducted on the AC-impedance spectra of Li-ion batteries [13], [14], it has been revealed that f_m and $|Z|_{min}$ vary for different Li-ion batteries and vary as a consequence of temperature and State of Charge (SOC) [13], [14]. Therefore, the designer faces a great serious challenge. This challenge is how to find f_m for a specific Li-ion battery pack with a specific SOC at a specific temperature in extensive use. Thus, it is worth to study and develop an online adaptive tuning algorithm, which is able to explore f_m , in the future. It has been shown that f_m for different Li-ion batteries are commonly within 900 to 1200 Hz [13], [14]. f_m can be considered as a constant value to obtain a near-optimal charging-discharging performance [13], [14].

III. MODELLING AND CONTROL SCHEME

Fig. 3 depicts the most common three-phase conductive configuration of EV/PHEV battery chargers [15]–[18]. Fig. 4

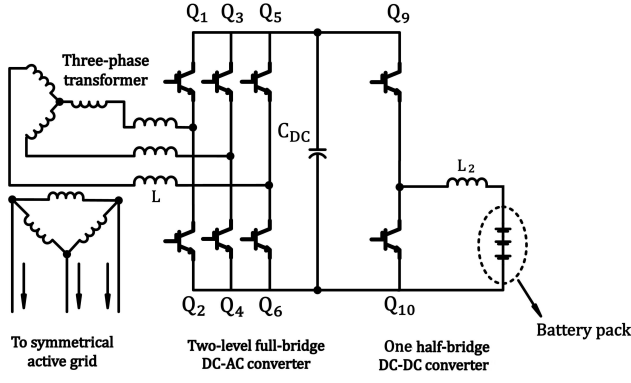


Fig. 3. A conventional topology for the EV bidirectional BC

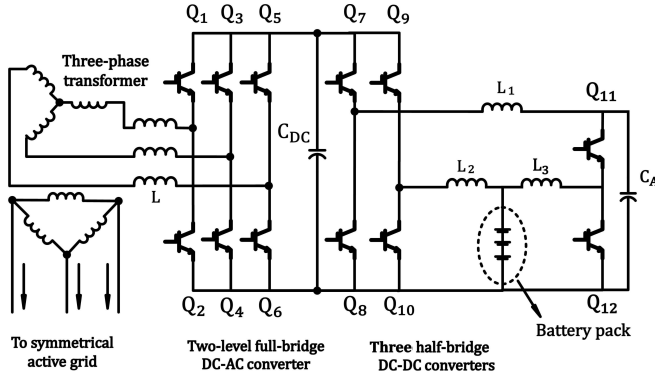


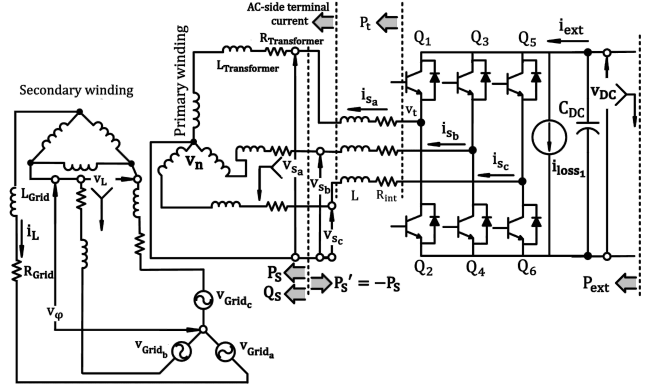
Fig. 4. Proposed topology for the EV bidirectional BC

proposes a particular configuration whose control system has been explained in this paper. It is preferred to have a part of the proposed system outside of the vehicle (off-board) [2] due to the relatively high power level, relatively heaviness and lack of space. It consists of a DC-DC part and a DC-AC part. The model and control of these parts will be explained in the following:

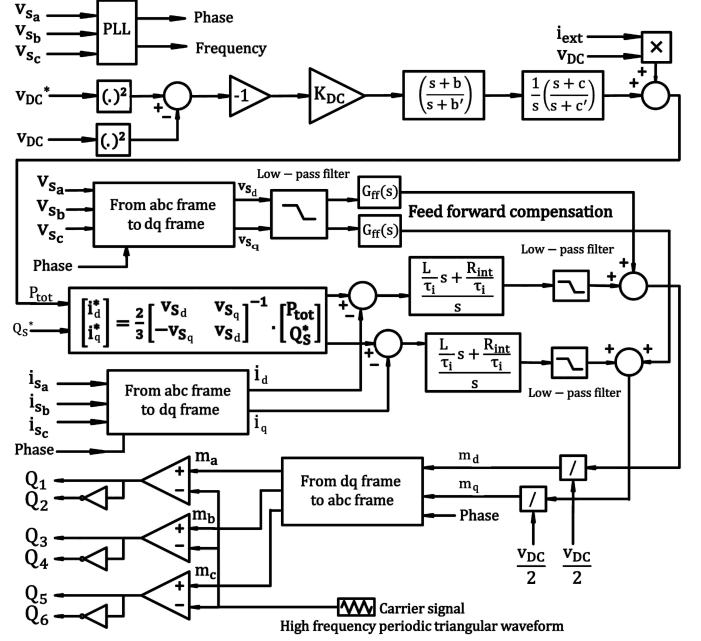
A. DC-AC Part

Fig. 5(a) shows the model of the DC-AC part. This part consists of whole the elements shown in the left side of the DC link capacitor in Fig. 4. Non-ideal characteristics of the switches impact on the design of controllers. To tackle this issue, the switching losses corresponding to each IGBT leg caused by the tailing current and reverse recovery current are modelled by a current source, connected in parallel with the DC link capacitor, whose amplitude is equal to $Q_{rr} + Q_{tc}/T_s$ [19]. Q_{rr} , Q_{tc} , and T_s are the reverse recovery electric charge of one IGBT, tailing electric charge of one IGBT, and the switching period, respectively. Since there are three legs in this part, the amplitude of the current source is equal to [19]:

$$i_{loss1} = 3 \frac{Q_{rr} + Q_{tc}}{T_s} \quad (4)$$



(a)



(b)

Fig. 5. DC-AC part: a) model and b) control system

The conduction losses corresponding to each IGBT leg caused by the internal resistance of the switches and inductors are modelled by the resistance R_{int} connected in series with each AC-side terminal [19].

The control system of the DC-AC part has been depicted in Fig. 5(b). First, the control system transforms the three-phase current i_s and voltage v_s from abc frame to dq frame. Moreover, there is a PLL to find the instantaneous phase and frequency of the applied three-phase voltage. It also includes two current control loops which receive the dq current references (i_{dref} and i_{qref}) and suggest the abc modulating signals (m_a , m_b , and m_c) transformed from dq frame. To make the current control loops independently of v_{DC} , they are divided by half of v_{DC} [19]. They are augmented by the feedforward compensation which has big distinct benefits [19]. i_{dref} and i_{qref} are calculated by the matrix equation,

shown in Fig. 5(b), so that P_s and Q_s follow P_{tot} and Q_s^* , respectively. The DC link voltage control system aims to suggest P_{tot} in order to regulate v_{DC} at v_{DC}^* with considering P_{ext} ($i_{ext} \times v_{DC}$) as a disturbance. P_{tot} becomes equal to P_{ext} when v_{DC} reaches its steady state condition (v_{DC}^*). With neglecting the switching and conduction losses, P_s becomes equal to P_{ext} in steady state condition of v_{DC} [19]. $i_{ext} \times v_{DC}$ or P_{ext} is imposed by the DC-DC part. Therefore, to have control over P_s and regulate it at P_s^* , the control system of the DC-DC part is needed. It determines the battery current references so that P_{ext} becomes equal to P_s^* [19]. Positive P_s^* discharges the Li-ion battery pack, while negative P_s^* charges it based on SRC technique.

B. DC-DC Part

Fig. 6(a) shows the model of the DC-DC part. This part consists of whole the elements shown in the right side of the DC link capacitor in Fig. 4. The switching and conduction losses corresponding to each IGBT leg are modelled, just as previously mentioned. So, we can write [19]:

$$i_{loss2} = 2 \frac{Q_{rr} + Q_{tc}}{T_s} \quad (5)$$

$$i_{loss3} = \frac{Q_{rr} + Q_{tc}}{T_s} \quad (6)$$

There are three IGBT legs in the DC-DC part. One of them (Q_7Q_8) belongs to the capacitor C_A and two of them (Q_9Q_{10} and $Q_{11}Q_{12}$) belong to the Li-ion battery pack modelled by the AC-impedance model.

According to Equation (3), the current of the Li-ion battery pack consists of two terms, i_{DC} and i_{AC} . Fig. 6(b) is the control system of the IGBT legs Q_9Q_{10} and $Q_{11}Q_{12}$ which regulates the current of the corresponding inductor i at i_{ref} . i can be i_{AC} or i_{DC} . i_{ref} can be i_{AC}^* or i_{DC}^* . i_{DC} and i_{AC} are controlled and imposed by the control system of Fig. 6(b) using the IGBT legs Q_9Q_{10} and $Q_{11}Q_{12}$, respectively. i_{AC}^* or i_{DC}^* must be determined as follows in order to regulate P_s and P_{ext} at P_s^* :

$$i_{Bat}^* = i_{DC}^* + i_{AC}^* = \left(-P_s^*/v_{Bat} \right) + \left(-P_s^*/v_{Bat} \right) \cos(2\pi f_m t) \quad (7)$$

Thus, the absorbed active power is given by:

$$P_{Bat} = P_{DC} + P_{AC} = v_{Bat} \times i_{Bat}^* \left(-P_s^* \right) + \left(-P_s^* \right) \cos(2\pi f_m t) \quad (8)$$

Fig. 6(c) is the control system of the IGBT leg Q_7Q_8 . It receives the filtered RMS value of v_A and regulates the RMS value of v_A at v_A^* . v_A^* must be greater than v_{Bat} and less than v_{DC}^* . This is due to the fact that an IGBT leg decreases the voltage level.

This control system with the topology proposed in Fig. 4 resolve the power quality problem and eliminate the negative effects of the sinusoidal variations in P_{Bat} and i_{AC} ; Because, the alternating active power in the second term of Equation (8) is supplied by only C_A and P_{ext} becomes equal to the

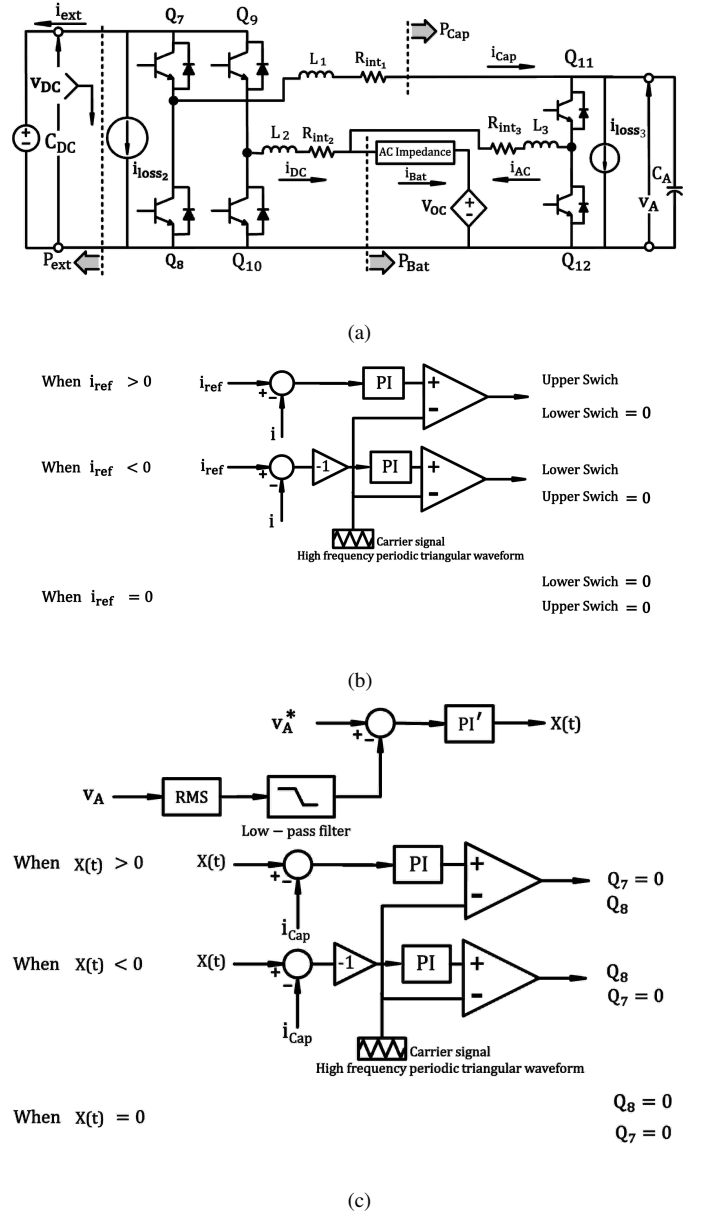


Fig. 6. DC-DC part: a) model, b) control system for the IGBT legs Q_9Q_{10} and $Q_{11}Q_{12}$, and c) control system for the IGBT leg Q_7Q_8

first term of Equation (8). In other words, there are not sinusoidal variations in P_{ext} and P_s , and as a result, the AC-side terminal current has a sinusoidal waveform and its RMS value is not changed. If the topology in Fig. 3 is used, P_{AC} must be supplied by the power system. Thus, P_{ext} will have a sinusoidal term. This worsens the power quality of the AC-side terminal current. This matter has been indicated in Fig. 10.

IV. SIMULATION RESULTS

The model and the control system of the bidirectional BC, which has already been explained in the form of DC-DC and DC-AC parts, are simulated by MATLAB/Simulink software with the parameters summarized in Appendix A.

P_s^* is changed from -19.2 kW to 19.2 kW at $t_0 = 0.6$ s. Q_s^* is changed from -10 kVAR to 10 kVAR at $t_0 = 0.4$ s and then, is changed from 10 kVAR to -10 kVAR at $t_0 = 0.8$ s. P_s^* and Q_s^* are independently set to validate the flexibility of the control system in switching among all the four quadrants of the P_s-Q_s plane. The positive P_s^* discharges the battery pack (after 0.6s), while the negative P_s^* charges it (before 0.6s) based on SRC technique as shown in Fig. 7. The signal waveforms in Fig. 7 are in agreement with Equations (7) and (8). Fig. 8 shows that the proposed BC is working under four different conditions within one second.

The capacitor C_A supplies P_{AC} and i_{AC} . The waveform of v_A has sinusoidal variations due to sinusoidal changes in i_{AC} and P_{AC} , as shown in Fig. 7(b) and 9(a). In spite of sinusoidal variations in v_A , applying i_{AC}^* does not change the RMS value of v_A ; Because the DC component (the mean value) of P_{AC} is equal to zero. But due to the switching losses caused by i_{loss3} and the conduction losses caused by R_{int3} , the RMS value of v_A decreases. Therefore, to maintain it at a constant value (v_A^*), the IGBT leg Q_7Q_8 has been used. The purpose of its control system is to keep the RMS value of v_A at 550V.

Fig. 10 compares two bidirectional BCs shown in Fig. 4 and Fig. 3. Fig. 10(a) corresponds to the AC-side terminal current of Fig. 4. Fig. 10(b) corresponds to the AC-side

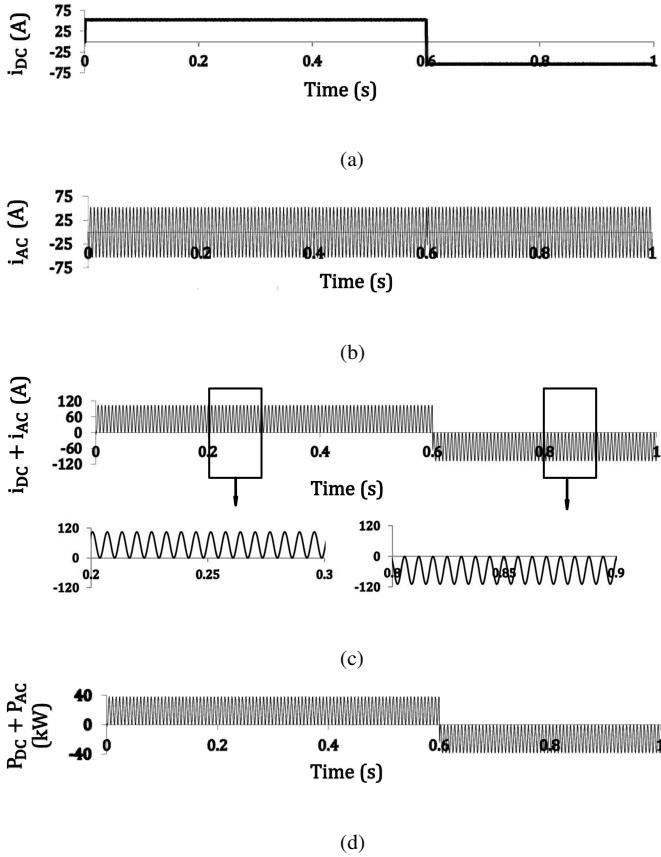


Fig. 7. Important signal waveforms of the battery pack of the BBC: a) DC component of the current, b) AC component of the current, c) summation of the AC and DC components of the current, and d) absorbed active power

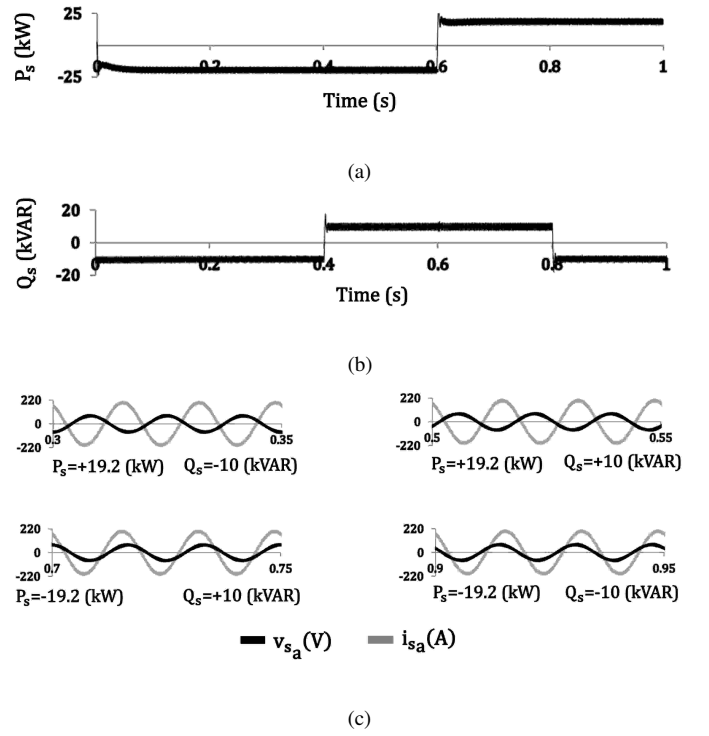


Fig. 8. Important signal waveforms of the AC-side terminal of the BBC: a) output active power, b) output reactive power, c) current and voltage

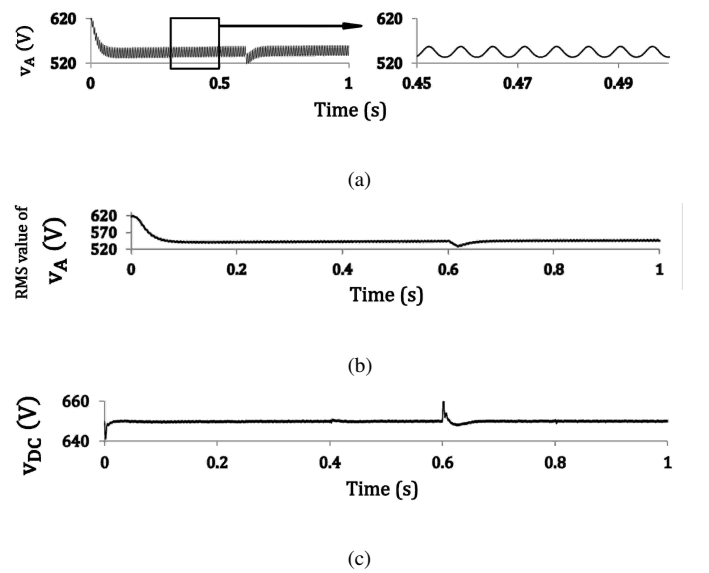


Fig. 9. a) v_A , b) RMS value of v_A , and c) DC link voltage

terminal current of Fig. 3. The simulation results prove that the proposed novel control strategy has resolved the mentioned power quality. The RMS value of the AC-side terminal current alternately changes for the conventional BC, while it is kept constant for the proposed BC.

V. CONCLUSION

SRC charging-discharging technique has distinct advantages compared to other techniques. The purpose of this paper was to

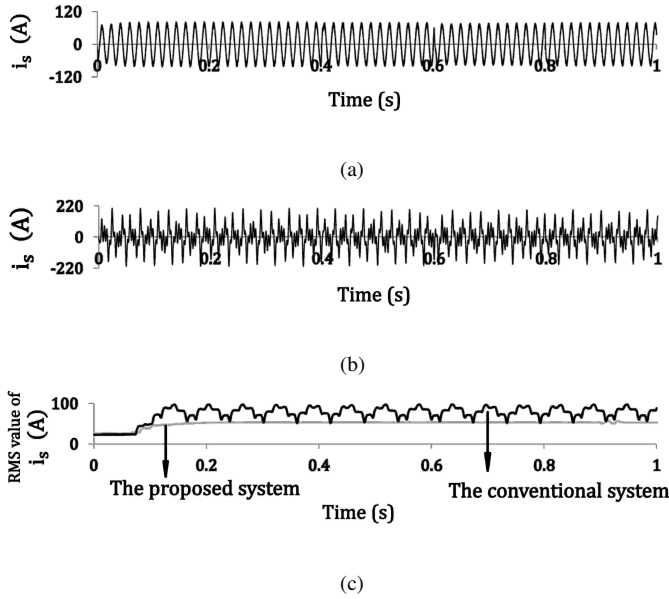


Fig. 10. Comparison of the proposed BBC and the conventional BBC: a) AC-side terminal current of the proposed BBC, b) AC-side terminal of the conventional BBC, and c) RMS value of these currents

design a bidirectional BC for an EV based on SRC technique. Sinusoidal current variations applied to the Li-ion battery in this technique negatively affect on the AC-side terminal of the BC, alternately change the output active power (P_s), power factor, and current of the AC-side terminal and therefore, worsen the power quality. On the other hand, P_s and Q_s must be regulated at constant values without any variations when the EV participates in V2G technology. Therefore, a particular topology was introduced and then, a novel control strategy was defined for the BC of the EV in order to resolve the power quality problem and regulate P_s and Q_s at constant values. Finally, the simulation results confirmed that the effect of sinusoidal current variations has been eliminated and the proposed BC can adjust P_s and Q_s at desired values.

APPENDIX A SOME IMPORTANT PARAMETERS

$$\begin{aligned}
 [L \ L_1 \ L_2 \ L_3 \ L_G \ L_d] &= [4 \ 3.3 \ 3.3 \ 3.3 \ 0.08 \ 0.0014516] \text{ mH} \\
 [C_{DC} \ C_A \ C_d] &= [3 \ 3 \ 35.67] \text{ mF} \\
 [v_{OC} \ v_{DC}^* \ v_A^*] &= [360 \ 650 \ 550] \text{ V} \\
 [f_0 \ f_s \ f_m] &= [60 \ 3420 \ 992] \text{ Hz} \\
 [T_i] &= [0.5] \text{ ms} \\
 [R_G \ R_o \ R_{ct}] &= [0 \ 0.03615 \ 22.51] \text{ m}\Omega \\
 [R_{int} \ R_{int1} \ R_{int2} \ R_{int3}] &= [2 \ 76 \ 76 \ 76] \text{ m}\Omega \\
 [b \ c \ b' \ c' \ K_{DC}] &= [230.198 \ 52.891 \ 390.9676 \ 1000 \ 325.5]
 \end{aligned}$$

The controllers shown in Fig. 6:

$$\begin{aligned}
 PI: & (100s + 0.001)/s \\
 PI': & (0.1s + 0.1)/s
 \end{aligned}$$

Time constants of low pass filters:

$$\begin{aligned}
 \text{in Fig. 5:} & \quad 0.001 \\
 \text{in Fig. 6:} & \quad 0.004
 \end{aligned}$$

Line to line nominal voltage of transformer: 480/240 V

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