Electric Vehicle Battery Charger with Vehicle-to-Vehicle (V2V) Operation Mode

Carlos F. V. Martins(✉), Tiago J. C. Sousa, and Delfim Pedrosa

ALGORITMI Research Centre, University of Minho, Guimarães, Portugal
a70902@alunos.uminho.pt

Abstract. This paper presents a validation based on simulation result of an electric vehicle (EV) battery charger for power transfer between two EVs (vehicle-to-vehicle (V2V) operation) using only one converter per EV. The traditional topology needs a connection between the EVs and the power grid, consisting in a combination of two operation modes (V2G and G2V). In addition, the power transfer is made using a total of four power converters, two dc-dc and two dc-ac power converters, which represents more energy losses. In contrast, the presented topology discards a connection with a power grid and the charging operation can be done anywhere through the connection between two EVs. Furthermore, the proposed topology only needs two dc-dc power converters, one per EV, allowing the power transfer between EVs becoming more efficient and useful.

Keywords: Electric Vehicles (EVs) · Battery charging · Vehicle-to-Vehicle (V2V) · Power transfer

1 Introduction

Nowadays, there is an urgent need for a growing concern for environmental sustainability and measures to be adopted for a better future for the Earth. Electric mobility, a growing concept associated with means of transportation, presents itself as an asset in order to reduce greenhouse gas emissions produced by internal combustion engine vehicles (ICEVs) into the atmosphere. However, for electric mobility to actively contribute to the mitigation of this problem, the main means that support it also need to be in constant evolution. One of the main problems it faces is the reduced number of functional charging stations that exist [1–3].

Electric vehicles (EVs) are nothing new among us, having been in existence for over 150 years, but only in the last few years they have presented themselves as a viable alternative to ICEVs in order to reduce emissions of greenhouse gases produced into the atmosphere and the fossil fuels exploration. Through the past years, the ICEV represents about 10% of the total greenhouse emissions every year, and, for that reason, it is a big concern to society to try to reduce that in every way as possible [4]. With the growing acceptance of EVs by society, electric mobility has undergoing an impressive growth

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and represents a key agent that helps to mitigate the ICEVs problems for the environment [5, 6].

For an EV to operate, an energy storage element is needed. The battery is the most used energy storage element in EVs, being classified as a secondary battery as it is rechargeable [7]. When used in an EV, its charging process is carried out through the connection to the power grid and its discharge process through the supply of energy for the EV to move, as well as to supply energy to another EV, home or power grid [8].

EV battery chargers can be classified as on-board or off-board, and also as conductive or wireless. Besides the traditional grid-to-vehicle (G2V) operation mode, in the literature can be found other operation modes such as vehicle-to-grid (V2G), vehicle-to-home (V2H) and vehicle-for-grid (V4G). These operation modes have in common the connection between an EV and a power grid, restricting the places to where EVs can be connected [9–14].

A power transfer between two EVs is a strong option to address the presented problems, namely the operation mode presented as vehicle-to-vehicle (V2V). In the literature can be found two concepts associated to V2V, one related to the communication between two vehicles (EV or ICEV) and another to the power transfer between two batteries of different EVs. The V2V operation mode can be used by connecting the EVs to the power grid or directly between them, as seen in Fig. 1. In the first case, the power transfer is carried out using four conversion stages (two stages for each EV), which is based in the combination of V2G and G2V operation modes, with one EV operating as an energy provider and the other as an energy receiver. For this reason, the power transfer efficiency is significantly decreased. In the second case, the power transfer can be performed using four or two conversion stages, being naturally more efficient if only two conversion stages are used. V2V is a recent operation mode and new developments and approaches are expected in the next years to increase the use of EVs and make them more efficient [15–19].

Considering the V2V operation mode and the different topologies proposed for it in the literature, this paper is focused on the power transfer between two EVs using only two conversion stages without external power converters, ensuring a greater efficiency and working only with dc power. The paper is structured as follows: Sect. 2 presents the adopted V2V topology for power transfer, Sect. 3 presents a simulation for the presented topology, and Sect. 4 summarizes the conclusions of the developed work.

2 Adopted V2V Configuration

This section presents the adopted V2V topology for power transfer, using only dc power and discarding the connection to the power grid by using a direct approach between two EVs. Throughout this section will be described how two EVs (EV#1 and EV#2) can transfer power between them only using the on-board dc-dc power converters. It is important to refer that the power converters present in each EV battery charging system are bidirectional to support the presented V2V topology.

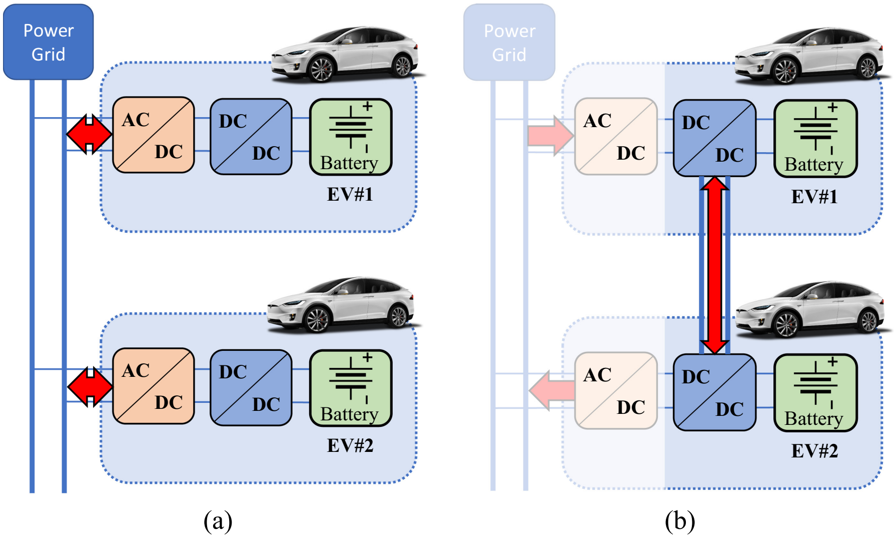


Fig. 1. Topologies of power transfer between two electric vehicles: (a) Conventional indirect V2V power transfer based on the combination of V2G and G2V modes; (b) Direct V2V power transfer using only the on-board dc-dc converters.

2.1 On-Board Dc-Dc Converters

As presented in Fig. 1, each EV battery charger contains a front-end ac-dc converter and a back-end dc-dc converter. Considering two EVs, with only one bidirectional dc-dc power converter in each EV, it is possible to perform charging and discharging processes of the batteries with controlled current, voltage or both, being possible to take this approach as the batteries operate in dc. When the two EVs are connected by the dc-link of battery chargers dc-dc converters, a power exchange between them can be performed, as shown in Fig. 1. Both EVs are connected by the dc-links between the nodes that are common to the front-end and back-end power converters of each battery charger. With two dc-dc converters connected, a bidirectional bridge is accomplished, and both can operate with fully control of charging and discharging current and voltage, being possible for an EV to charge the other under different operating conditions with a high-rate power transfer.

The choice of the bidirectional dc-dc converter for the topology to be implemented relies on the non-isolated buck-boost converter, which changes its operating mode depending on the semiconductor that is being switched. As can be seen in Fig. 2, the connection between the two non-isolated buck-boost converters through the dc-link of each one gives rise to a non-isolated bidirectional split-pi buck-boost dc-dc converter [20, 21].

3 Computational Simulation

This section presents the simulation of the presented V2V power transfer topology, considering the connection between two EVs only use the on-board bidirectional dc-dc power converter present in the battery charger. Each adopted model of the on-board battery charger is composed by a two-quadrant bidirectional buck-boost dc-dc power converter and a battery, simulating the EV battery charger. In Table 1 are present the adopted values to the power converter components.

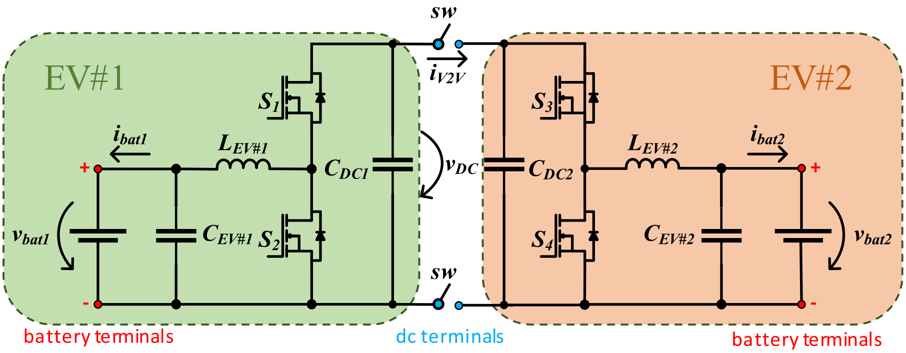


Fig. 2. Connection of the dc-dc converters used in the presented V2V power transfer method between two EVs.

To keep the simulation as real as possible for a power transfer between the batteries of EVs and to the charging and discharging processes, the battery model adopted in this paper is a Thevenin battery model, present in Fig. 3.

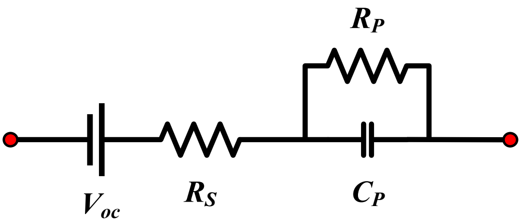


Fig. 3. Adopted Thevenin battery model.

As mentioned in [16], this battery model considers the dynamic operation of the batteries during the charging and discharging processes of an EV, which is enough to validate the presented V2V power transfer. The used parameters for the charging and the discharging process are present in Table 2. The chosen software to perform all the simulations is PSIM v9.1 from PowerSim.

3.1 V2V Operation Mode Conditions

Since V2V can guarantee bidirectional power flow between two EVs, four modes of operation for power transfer will be addressed to simulate all the battery conditions. However, to prove the operation of the adopted battery charger, different operating

Table 1. Component values used in simulation.

Variable	Value
L_{EV}	600 µH
C_{EV}	10 nF
C_{DC}	480.1 µH

Table 2. Battery simulation parameters.

Variable	Value
V_{oc}	200 V
R_s	80 mΩ
R_p	100 kΩ
C_P *(charging)*	0.2 F
C_P *(discharging)*	0.1 F

parameters will be defined to be assigned to each mode. Table 3 shows the four chosen operating modes and the different parameters defined for their operation, considering the EV user's needs and the battery conditions. In the Table 3, variables V_{bat1} and V_{bat2} represent the battery voltages of EV#1 and EV#2, respectively. The sign of the current i_{V2V} represents the power flow direction, indicating which EV is charging and discharging.

Table 3. Defined operation modes for V2V power transfer according to the batteries voltage.

Mode	V2V power transfer	Condition
I	$i_{V2V} > 0$	$V_{bat1} > V_{bat2}$
II		$V_{bat1} < V_{bat2}$
III	$i_{V2V} < 0$	$V_{bat2} > V_{bat1}$
IV		$V_{bat2} < V_{bat1}$

Being defined a maximum operating power of 3 kW for simulating the V2V power transfer, the nominal operating voltage and current values need to be defined. These values are scaled according to the desired requirements and for the operation of the V2V charging system under nominal conditions. In Table 4 are presented the voltage values and the charging and discharging current values for each battery.

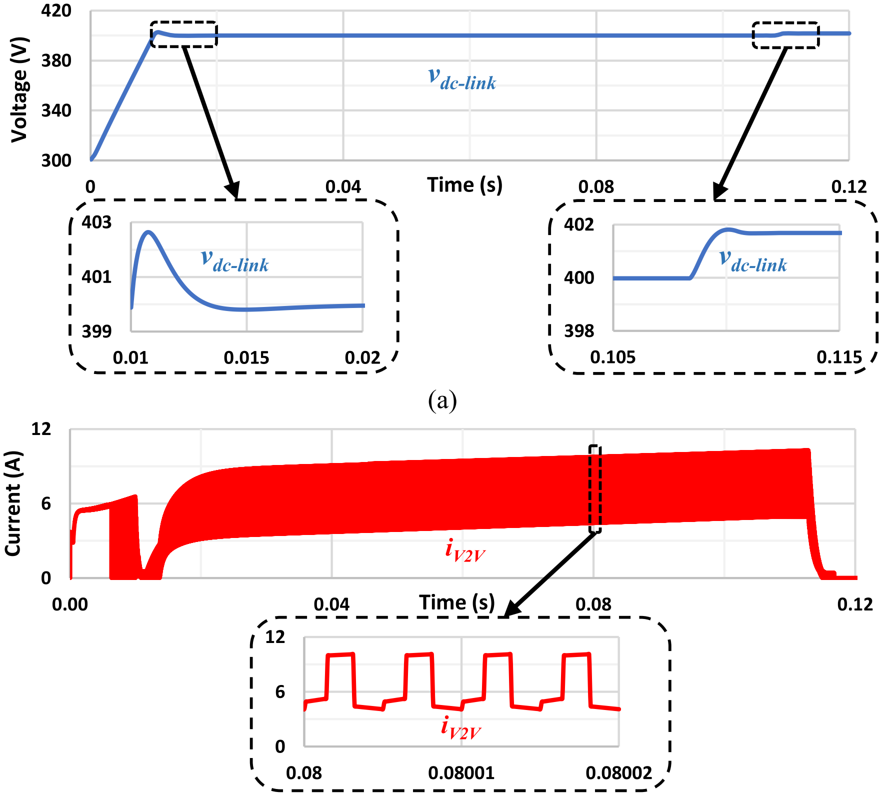
For a correct functioning of the implemented power converter, it is necessary to have a dc-link voltage higher than the battery voltage so that a controlled power transfer can exist. The reference voltage set for the dc-link was 400 V and needs to be controlled to remain constant. To ensure that the dc-link voltage and current remains at the defined reference value, a PI control technique using PWM modulation was used. To control the charging and discharging processes applied to each of the EV batteries, a method was adopted for each one. For the charging process, the constant current-voltage charging method was adopted and for the discharging process, which controls the dc-link, the constant power method was used. The constant power discharge method allows controlling the voltage and current of the dc-link simultaneously, resulting in a superior performance to the constant voltage method.

Table 4. Defined nominal operating values for the system.

Variable	Minimum	Maximum
v_{bat1}	150 V	300 V
v_{bat2}	150 V	300 V
i_{charge}	0 A	10 A
$i_{discharge}$	0 A	16 A

Figure 4 shows the result of the PI control technique applied to the discharging process, responsible for controlling the voltage and current in the dc-link. In Fig. 4(a) it is possible to verify that the dc-link voltage is controlled to 400 V, and it only suffers two voltage disturbances during the charging process. The first is related to the start of the charging process, started after the dc-link reaches 400 V, and the second when the charging is finished. Figure 4(b) portrays the current present in the connection between the two EVs during the power transfer. In the same way as in voltage, two disturbances are visible in its value, represent the beginning and the end of the power transfer.

Once the operating modes of the system have been defined and the nominal operating values and the control applied to its operating modes have been validated, the results obtained in the computational simulations for each of the assigned modes are then presented.



(a)

(b)

Fig. 4. Simulation result of the dc-link voltage control implemented for V2V power transfer between two EVs: (a) Dc-link voltage ($v_{dc\text{-}link}$); (b) Dc-link current (i_{V2V}).

Mode I

To perform the simulation for V2V operation in Mode I, the nominal operating values defined previously need to be in consideration. Figure 5 shows the charging process applied to EV#2 and the discharging process applied to EV#1, existing energy transfer from EV#1 to EV#2 in both mode I and mode II, according to the operating conditions defined in Table 3. In Fig. 5(a) it is possible to see the beginning of V_{bat2} charging process at 0.01 s, with a value of 200 V and constant current, and finished when it reaches 300 V at 0.113 s. During 0.108 s and 0.113 s, the charging process went from constant current to constant voltage, being terminated when the current reaches about 0 A. On the other hand, as shown in Fig. 5(b), V_{bat1} starts the discharging process with a value of 300 V and finishes with 290 V, validating the power transfer between both batteries.

Considering the voltage values of both batteries and that the charging method adopted is constant current, with a charging current of 10 A being defined, it is possible to verify that the discharging current will increase as the battery voltage drops while that the charging current remains constant throughout the entire process. The current i_{bat2}

(i_{charge}) has a current ripple peak-to-peak value of 500 mA and i_{bat1} ($i_{discharge}$) has a slightly higher current ripple peak-to-peak value of 700 mA.

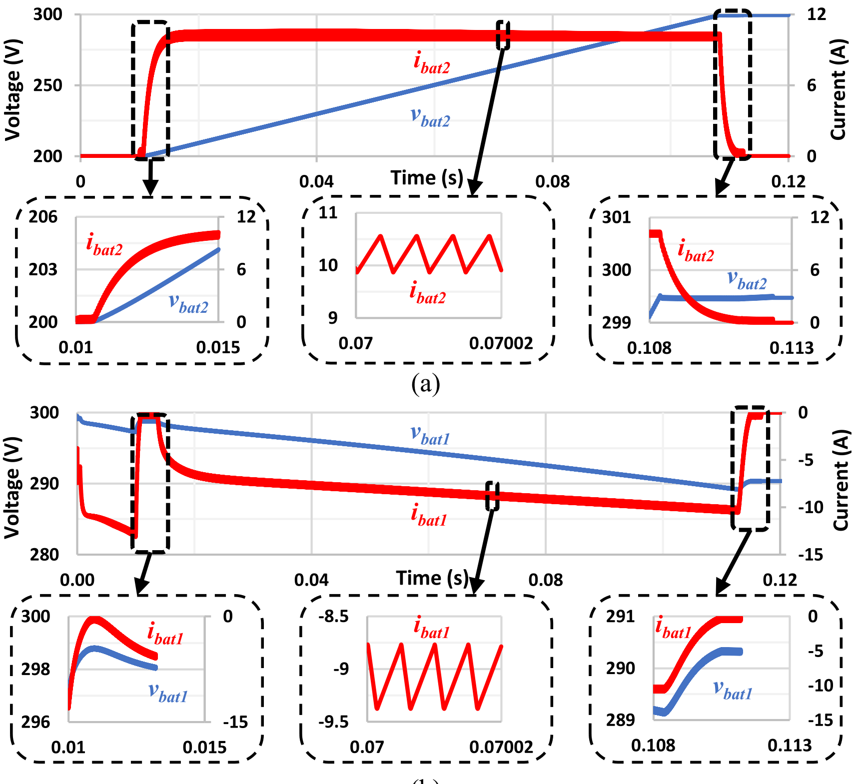
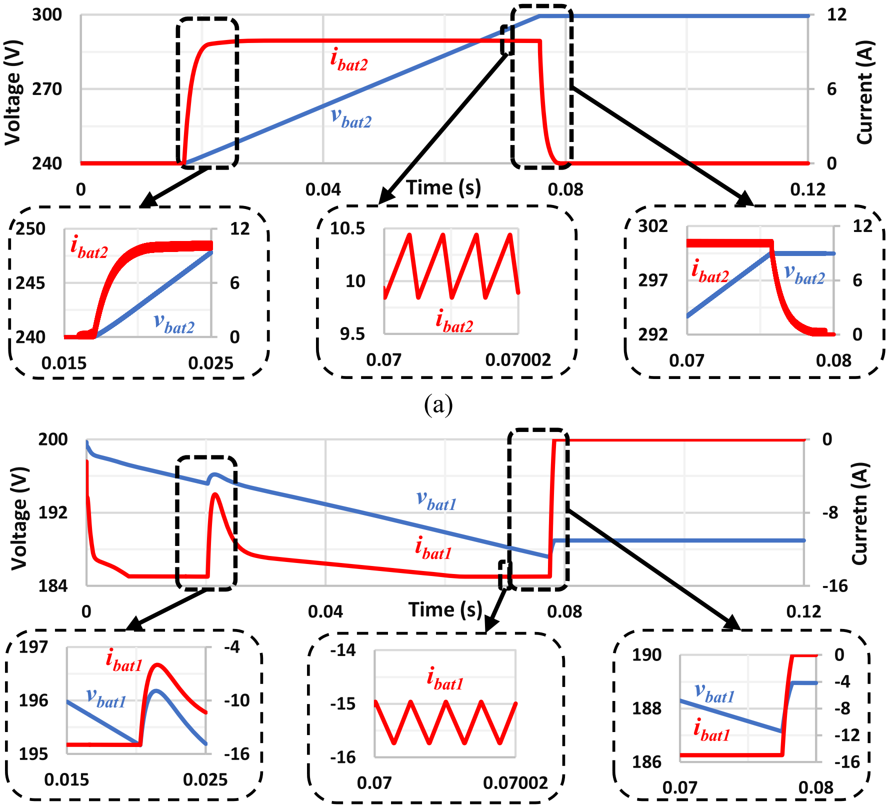


Fig. 5. Simulation results for V2V power transfer in mode I: (a) Charging process applied to EV#1; (b) Discharging process applied to EV#2.

Mode II

Respecting the same operating condition for energy transfer as in mode I, Fig. 6 shows the case for V2V power transfer in mode II. In Fig. 6(a), V_{bat2} starts the charging process at 0.015 s with a mean value of 240 V and finishes when it reaches 300 V at 0.076 s. As it can be seen in Fig. 5, the same process happens during 0.075 s and 0.08 s as in mode I. In mode II, V_{bat1} has lower voltage than V_{bat2}, and starts the discharging process with 200 V and finishes with 190 V. Comparing the mean value of charge and discharge currents obtained with mode I, it is possible to verify they have the same charge current (10 A), previously defined, but the discharge current has increased. In Fig. 6(a) it is possible to see the discharging process and to verify that the discharge current (i_{bat1}) reaches a value of 15 A, because the battery voltage in the process of discharging (V_{bat1}) is lower than in mode I, according to the operation condition present in Table 3, naturally increasing the current respecting the theory of the input power being equal to the output power. Comparing the current ripple with mode I, it is possible to verify that it is equal, although the discharge current (i_{bat1}) values are higher.



(a)

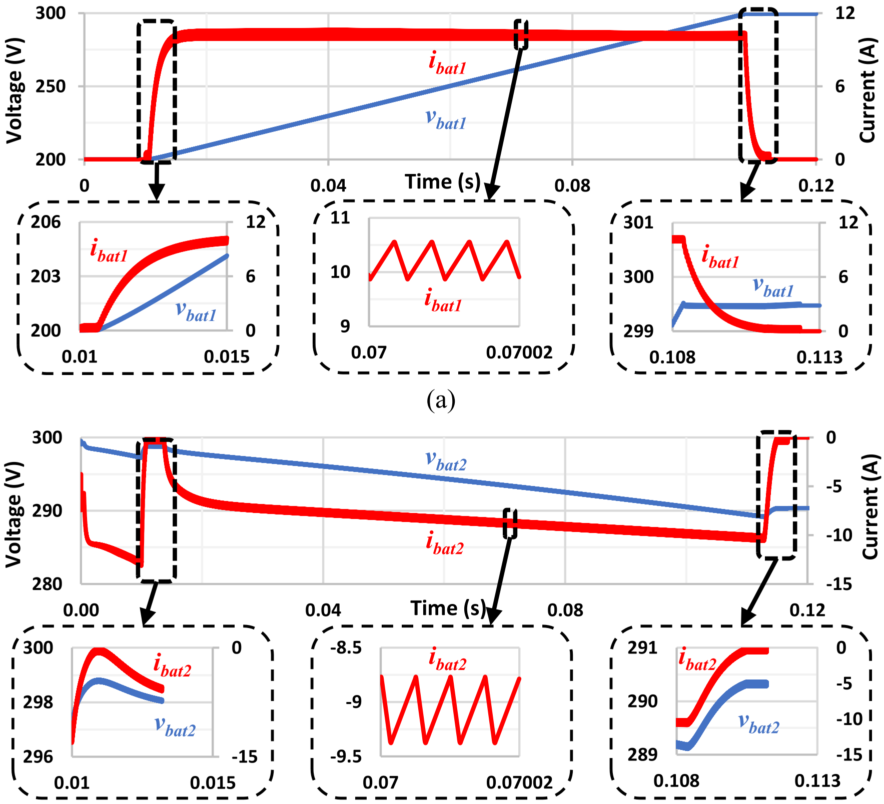
(b)

Fig. 6. Simulation results for V2V power transfer in mode II: (a) Charging process applied to EV#1; (b) Discharging process applied to EV#2.

Mode III

According to the condition previously defined for mode III and mode IV, the power transfer in these two modes will be performed from EV#2 to EV#1. The charging process is then applied to EV#1, while to EV#2 is applied the discharging process.

Figure 7 shows the result obtained during the simulation of V2V power transfer in mode III. In this mode, as the voltage applied to each battery is equal to mode I in their respective charging and discharging processes, the results obtained for one of the processes will be equal to mode I. Similarly, to the previous mode I, the current i_{bat1} has the same average values and a peak-to-peak ripple with value of 500 mA, while i_{bat2} has a value of 700 mA. As already mentioned, through a detailed analysis of the charging (Fig. 7(a)) and discharging (Fig. 7(b)) processes, the results obtained in mode III are the same as in mode I, proving the bidirectionality in power transfer and the topology adopted.



(a)

(b)

Fig. 7. Simulation results for V2V power transfer in mode III: (a) Discharging process applied to EV#2; (b) Charging process applied to EV#1.

Mode IV

Finally, the results obtained in operation mode IV are be analyzed, proving the functioning of all defined modes. By analyzing Fig. 8, it is possible to verify that the results obtained are equal to mode II, as expected. Figure 8(a) portrays the charging process and Fig. 8(b) the discharging process, verifying the power transfer from EV#2 to EV#1. It is also possible to verify that the obtained results present the same behavior as mode II although the direction of power transfer is different, which would be expected since the voltages defined for each battery are the same.

Once the computational simulations are presented for all four operation modes, it is possible to claim that the V2V topology, using only the dc-dc converters present in the charging system of an EV, allows power transfer between EVs with different battery voltages independently of the power flow direction.

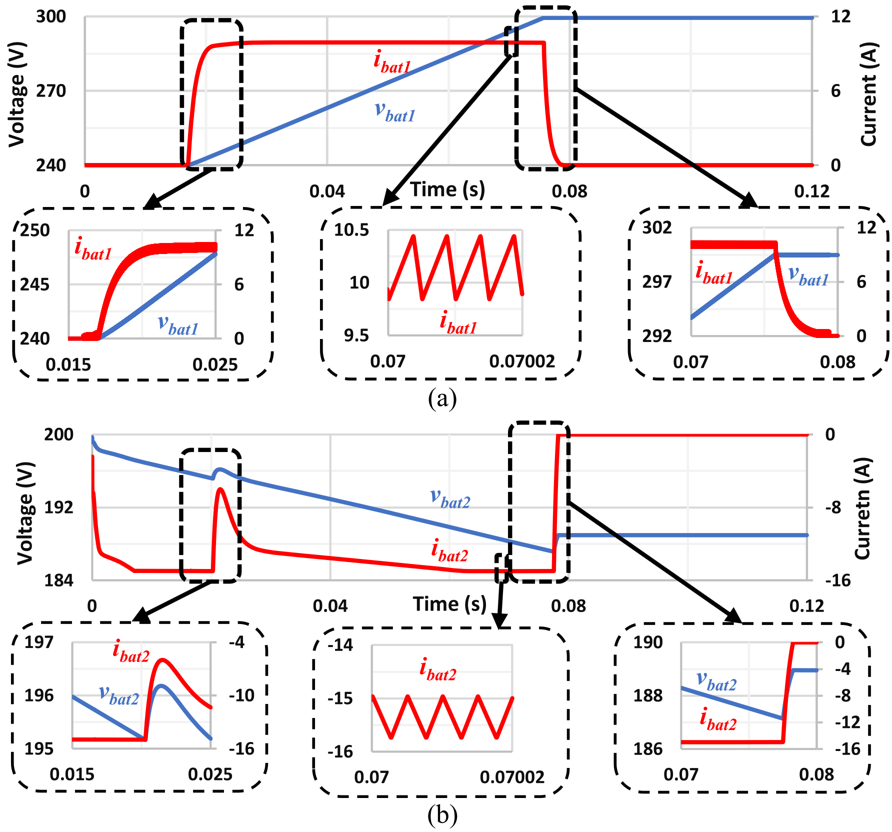


Fig. 8. Simulation results of the adopted topologies for V2V power transfer mode IV: (a) Discharging process applied to EV#2; (b) Charging process applied to EV#1.

4 Conclusions

This paper presents a validation based on simulation result of an EV battery charger for vehicle–to–vehicle (V2V) power transfer between two EVs without using additional power converters. The presented V2V operation is easy to implement, using only the dc-dc converters present in the on–board battery chargers of the EVs, and numerous advantages are associated with its use. Without the necessity to connect to a power grid, the EVs perform the power transfer through the direct connection of the dc–link of the on-board dc-dc converters. It should be noted that the direct connection via the dc-link is not available in nowadays EVs.

The implemented V2V configuration was validated through computational simulations. To prove the flexibility, safety and efficiency of the system, several operating modes were attributed to the adopted configuration. The defined operating modes were also intended to prove the bidirectional power transfer under different operating conditions, validating its operation with different voltage values assigned to the batteries. With the adopted procedures, the performed computational simulations and obtained results, the adopted V2V topology is then considered valid.

However, additional metrics will be used in further investigation in order to improve the power, safety and efficiency. Metrics with the adoption of new power converter topologies for on–board battery chargers, such as interleaved topologies, and advanced methods for controlling the current can be implemented.

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