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Comparative Analysis of Vehicle-to-Vehicle (V2V) Power Transfer Configurations without Additional Power Converters

Tiago J. C. Sousa
Centro ALGORITMI
University of Minho
Guimaraes, Portugal
tsousa@dei.uminho.pt

Luis Machado
Centro ALGORITMI
University of Minho
Guimaraes, Portugal
lmachado@dei.uminho.pt

Delfim Pedrosa
Centro ALGORITMI
University of Minho
Guimaraes, Portugal
dpedrosa@dei.uminho.pt

Carlos Martins
Centro ALGORITMI
University of Minho
Guimaraes, Portugal
a70902@alunos.uminho.pt

Vítor Monteiro
Centro ALGORITMI
University of Minho
Guimaraes, Portugal
vmonteiro@dei.uminho.pt

Joao L. Afonso
Centro ALGORITMI
University of Minho
Guimaraes, Portugal
jla@dei.uminho

***Abstract*— This paper presents a comparative analysis of power transfer configurations towards vehicle-to-vehicle (V2V) battery charging operation without using additional power converters, i.e., using just the on-board battery chargers of two electric vehicles (EVs). Three access interfaces were considered, namely the ac power grid interface, the dc-link interface and the dc battery interface, which allow the establishment of eight V2V configurations. The defined configurations are described and verified through computational simulations. A comparison is performed based on quantitative data, i.e., power transfer efficiency for a given output power range, and qualitative data, i.e., flexibility and safety. According to the obtained results, it can be concluded that each V2V configuration has its pros and cons regarding efficiency, number of possible quadrant operation and need for additional equipment.**

Keywords*— *Vehicle-to-Vehicle (V2V), Power Transfer, Electric Vehicles, Electric Mobility.

I. INTRODUCTION

The interface of electric vehicles (EVs) with the power grid has been an important research topic, with several operation modes being proposed besides the traditional battery charging (grid-to-vehicle (G2V)), such as vehicle-to-grid (V2G), vehicle-to-home (V2H) and vehicle-for-grid (V4G) [1]-[7]. All these operation modes have in common the fact of considering a connection between an EV and an electrical installation. Besides these, there is a proposed operation mode in the literature termed as vehicle-to-vehicle (V2V). The V2V designation is strongly associated to communication systems between vehicles in general (either EVs or internal combustion engine vehicles), but in the literature it was also proposed a V2V operation mode considering power transfer between the batteries of different EVs connected to the same power grid, as a peer-to-peer power exchange method. Based on this, these proposals consist actually of the combination of the operation modes V2G and G2V, with the first concerning the energy provider and the latter concerning the energy receiver [8]-[12].

A typical on-board EV battery charger contains a front-end ac-dc converter for the power grid interface and a back-end dc-dc converter for the battery interface. Hence, in the referred type of V2V power transfer, four power conversion stages are performed from one EV battery to the other. With this approach, the power transfer efficiency can be significantly decreased, even if each power converter is highly efficient. Moreover, the EVs must be connected to the same power grid in order to transfer power between their batteries. These two drawbacks can be overcome by using a direct V2V power transfer, allowing EVs to provide power to others without the need for a power grid [13]. In [14] is addressed the connection of two EVs by the ac side of each on-board battery charger with the power being transferred in dc. In [15] is analyzed the connection of two EVs by the dc-links of each on-board battery charger, with the resulting system acting as a four-quadrant bidirectional dc-dc converter. In [16] is studied a configuration that uses two dc-dc converters per EV, one isolated and the other non-isolated, while the front-end ac-dc converter was considered to be off-board. V2V operation through wireless power transfer is reported in [17]-[19], taking V2V a step further, allowing not only the power transfer between EVs in remote areas, but also the power transfer between EVs while travelling. In fact, a practical implementation of V2V power transfer between a Nissan Leaf and a Tesla Model S can be seen in [20] using a bidirectional charger. Based on the referred examples, the V2V concept is still recent and new developments are expected in the next few years.

However, in the literature regarding V2V power transfer can be found several types of connection between the two EVs. Taking into consideration the different possibilities, this paper presents an analysis and comparison of several approaches to attain a power transfer between two EVs without the need for external power converters, being used efficiency, flexibility and safety as metrics. In the scope of this paper, equal EVs were considered, i.e., with the same battery technology and the same nominal values, but with different levels of state-of-charge. The paper is structured as follows: Section II presents the analyzed configurations for the V2V power transfer; Section III presents a simulation analysis for the configurations; Section IV presents

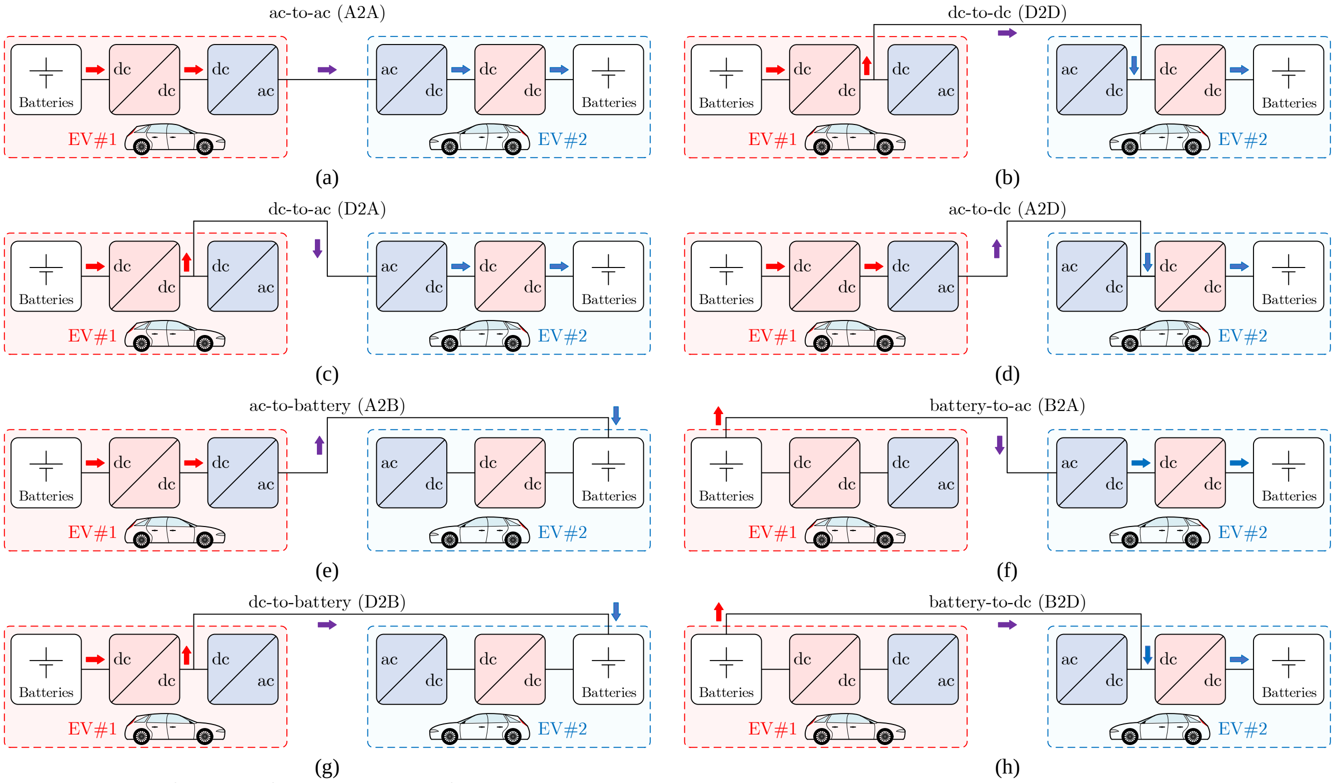

Fig. 1. Analyzed configurations for V2V power transfer between two EVs without using additional power converters: (a) ac-to-ac (A2A); (b) dc-to-dc (D2D); (c) dc-to-ac (D2A); (d) ac-to-dc (A2D); (e) ac-to-battery (A2B); (f) battery-to-ac (B2A); (g) dc-to-battery (D2B); (h) battery-to-dc (B2D).

a comparative analysis of the configurations; finally, Section V lists the conclusions of the investigation carried out.

II. V2V Configurations

This section presents the analyzed configurations for the V2V power transfer operation between two EVs without using additional power converters, i.e., using only the front-end ac-dc and back-end dc-dc converters existing in the on-board battery chargers. It should be noted that the battery chargers must allow bidirectional operation in order to fulfill the analysis made in this paper. Three access interfaces in each on-board battery charger were considered, with two of them being already present in the commercially available EVs (the dc battery terminals and the ac power grid interface terminals) and one additional access interface that is not externally provided in the existing on-board battery chargers (the dc-link terminals, i.e., the dc voltage that interfaces the front-end ac-dc and the back-end dc-dc converters). In the analysis developed in this paper, the ac power grid interface is coined as “ac (A)”, the dc-link interface is coined as “dc (D)” and the dc battery interface is coined as “battery (B)”. Based on the possible interface combinations between two EVs, five types of interface are feasible, with an eventual battery-to-battery (B2B) configuration being invalidated. However, among the five valid configurations, two of them are symmetrical and three are asymmetrical, which rises the possible configurations from five to eight. These configurations are illustrated in Fig. 1 and are explained in detail in the following subsections. It should be noted that the normal operation was considered to be the power transfer from EV#1 to EV#2.

A. *ac-to-ac (A2A) interface*

The ac-to-ac (A2A) interface can be accomplished by connecting the ac power grid interface of two EVs to each other, as shown in Fig. 1(a). The dc-dc converter of EV#1 controls the dc-link voltage, while the ac-dc converter is not switched but allowing the flow of current from the dc-link to the ac-dc converter of EV#2. On the other hand, in EV#2, the ac-dc converter is used as a passive rectifier, allowing the current to flow from the ac-dc converter of EV#1 to the dc-link of EV#2. Then, the dc-dc converter of EV#2 is used to control the battery charging of this EV. Since this configuration is symmetrical, the reverse operation, i.e., EV#2 supplying EV#1, will not be described.

B. *dc-to-dc (D2D) interface*

The dc-to-dc (D2D) interface cannot be accomplished with nowadays EVs, since the two battery chargers must be connected through the dc-links, as shown in Fig. 1(b). This configuration was initially proposed in [15]. The dc-dc converter of EV#1 controls the dc-link voltage, which in this case will be the intermediate voltage of the two EVs. On the other hand, the dc-dc converter of EV#2 is used to control the battery charging of this EV. Since this configuration is symmetrical, the reverse operation, i.e., EV#2 supplying EV#1, will not be described. Regarding this interface type, care should be taken in a practical implementation, since two dc-links with unknown and most certainly different voltages are connected in parallel. In this sense, an inrush current protection mechanism should be used.

C. dc-to-ac (D2A) and ac-to-dc (A2D) interfaces

The dc-to-ac (D2A) interface is a blend of the two previous ones, in which an EV (in this case EV#1) uses its dc interface (the dc-link terminals) and the other EV (EV#2) its ac interface, as can be seen in Fig. 1(c). The dc-dc converter of EV#1 controls the dc-link voltage, which once again will be the intermediate voltage of the two EVs. On the other hand, in EV#2, the ac-dc converter is used as a passive rectifier, such as in A2A, allowing the current to flow from the dc-link of EV#1 to the dc-link of EV#2. Then, the dc-dc converter of EV#2 is used to control the battery charging of this EV.

Conversely to the previous ones, this configuration is asymmetrical, i.e., despite this configuration being considered as D2A, the reverse operation is also possible, which would be termed as ac-to-dc (A2D) interface, as shown in Fig. 1(d). In this case, the dc-dc converter of EV#1 is used to control the dc-link voltage, while the ac-dc converter is not switched but allowing the flow of current, such as in A2A, but in this case from the dc-link of EV#1 to the dc-link of EV#2. Then, the dc-dc converter of EV#2 is used to control the battery charging of this EV.

D. ac-to-battery (A2B) and battery-to-ac (B2A) interfaces

Similarly to A2A, the ac-to-battery (A2B) configuration only uses currently available EV terminals, namely the ac power grid terminals in EV#1 and the dc battery terminals in EV#2, as it can be seen in Fig. 1(e). The dc-dc converter of EV#1 controls the dc-link voltage, while the ac-dc converter is used as a four-quadrant dc-dc converter, controlling the battery charging of EV#2. In this case, EV#2 does not use any converter.

As happens with D2A and A2D, this configuration is asymmetrical, i.e., despite this interface being considered as A2B, the reverse operation is also possible, which would be termed as battery-to-ac (B2A) interface, as shown in Fig. 1(f). In this case, the ac-dc converter of EV#2 is used to control the dc-link voltage in EV#2, while the dc-dc converter controls the battery charging in this EV. Conversely to the previously explained about A2B, the power converters of EV#1 are not used, but it should be referred that this can be applied to either EV#1 or EV#2 in any of the configurations (A2B or B2A), since all converters are bidirectional.

E. dc-to-battery (D2B) and battery-to-dc (B2D) interfaces

Among the considered configurations, the ones which use the lowest number of power converters are attained when the dc-link and the dc battery terminals are used. In dc-to-battery (D2B) configuration, visible in Fig. 1(g), only the EV#1 dc-dc converter is used. Since both input and output terminals of this converter are the batteries of the two EVs, only the battery charging or discharging current is controlled.

As happens with the previous configurations, this one is also asymmetrical, being possible to implement a battery-to-dc (B2D) interface, as it can be seen in Fig. 1(h). Despite the asymmetry, the operation of the converter is very similar, since its input and output consist of both EVs batteries. In this case, the only change is the converter that is used, i.e., either the power provider or the power receiver.

Despite the advantages in terms of converter count, D2B and B2D have a particular issue depending on the dc-dc converter used in the on-board battery charger. As normally two-quadrant dc-dc converters are used, the battery voltage of EV#2 should be higher than EV#1 in order to accomplish D2B operation. Conversely, in order to ensure B2D operation, the battery voltage of EV#1 should be higher than EV#2. If these constraints are undesired, it is possible to eliminate them if a four-quadrant back-end dc-dc converter is used.

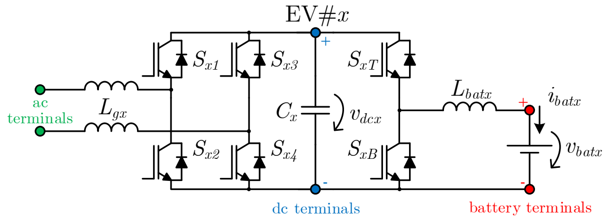

Fig. 2. Power topology of the on-board battery charger of each EV.

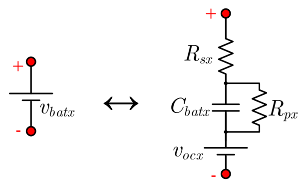

Fig. 3. Implemented Thevenin battery model.

TABLE I. SIMULATION PARAMETERS OF THE BATTERY CHARGERS USED FOR V2V POWER TRANSFER.

PARAMETER	VALUE	PARAMETER	VALUE
Initial v_{bat1}	300 V	ESR (L_{bat})	50 mΩ
Initial v_{bat2}	250 V	C	2 mF
v_{oc}	200 V	ESR (C)	20 mΩ
C_{bat}	1 F	L_g	300 µH + 300 µH
R_p	100 kΩ	ESR (L_g)	100 mΩ + 100 mΩ
R_s	100 mΩ	Switching Frequency	200 kHz
L_{bat}	200 µH	Sampling Frequency	100 kHz

III. SIMULATION ANALYSIS

This section presents the obtained simulation results of the analyzed configurations individually. In order to do so, power converter topologies needed to be chosen for the front-end ac-dc and back-end dc-dc converters. For simplifying issues, a full-bridge ac-dc and a two-quadrant buck-boost dc-dc converters were chosen. The total power setup of each EV on-board battery charger can be seen in Fig. 2, as well as the three possible access interfaces (ac, dc and battery) to use in the configurations.

The simulation models were developed in the software PSIM v9.1 from PowerSim and a database model of power semiconductors was used, aiming to consider switching and conduction power losses for a more realistic efficiency comparison. The equivalent series resistance (ESR) of inductors and capacitors was also considered. The used semiconductors were insulated gate bipolar transistors (IGBTs) HGTG20N60A4D from the manufacturer Fairchild Semiconductor with the respective antiparallel diodes. The power semiconductors are switched with a fixed-frequency pulse-width modulation (PWM) in all the converters, being used a deadbeat predictive current controller. The parameters considered for the converters can be seen in Table I.

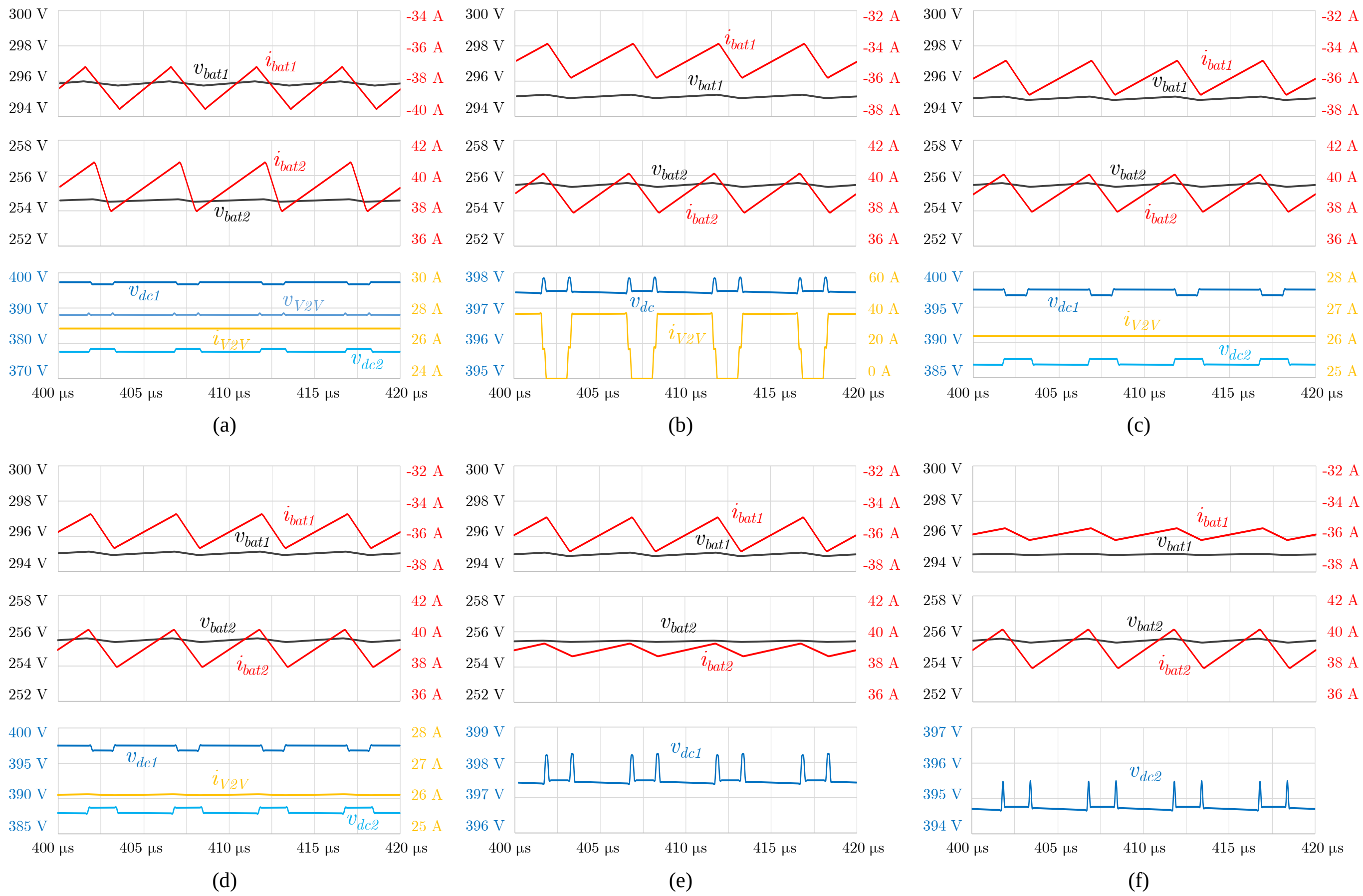

Fig. 4. Simulation results of the configurations for V2V power transfer between two EVs without using additional power converters: (a) ac-to-ac (A2A); (b) dc-to-dc (D2D); (c) dc-to-ac (D2A); (d) ac-to-dc (A2D); (e) ac-to-battery (A2B); (f) battery-to-ac (B2A).

Since the V2V operation mode comprises a power transfer between the batteries of two EVs, the battery model is of major concern towards a simulation analysis. Hence, a Thevenin battery model was used, as illustrated in Fig. 3, in order to consider the dynamic operation of the batteries, as well as the voltage rises (and drops) during charging (and discharging) operations. For the presented analysis, the EVs have the same characteristics. The used parameters are present in Table I.

In the analysis, seven cases were simulated, as it can be seen in Fig. 4 and Fig. 5. These cases represent the two symmetrical configurations (A2A and D2D) plus the doubled three asymmetrical ones (D2A/A2D, A2B/B2A and B2D). It should be noted that the complementary configuration of B2D (D2B) was not tested because the battery voltage is higher in EV#1 (the power provider) than EV#2 (the power receiver). As referred in section II.E, this condition only allows the B2D configuration. Moreover, the initial battery voltages of both EV#1 and EV#2 were kept unchanged due to consistency issues regarding the efficiency comparison. For all cases, it was considered that EV#1 provides power to EV#2. The output power in all cases is 10 kW, with each dc-link voltage being controlled to 400 V (when applicable).

A. *ac-to-ac (A2A) interface*

Fig. 4(a) shows the results of the A2A configuration, with the battery current of EV#1 (i_{bat1}) being negative and the battery current of EV#2 (i_{bat2}) being positive. The current in the connection of the two EVs (i_{V2V}) is positive, meaning that the current flows from EV#1 to EV#2. Besides, its ripple is negligible since the ac power grid coupling inductors of the two ac-dc converters are connected in series. In terms of voltages, the dc-link voltage of EV#1 (v_{dc1}) is controlled to 400 V, while the voltage at the connection point of the two EVs (v_{V2V}) is lower due to the voltage drops in the ac-dc converter and passive elements. Similarly, the dc-link voltage of EV#2 (v_{dc2}) is even lower due to the same reason. It can also be seen that the voltages of both batteries (v_{bat1} and v_{bat2}) present a small ripple due to the current ripple and the batteries internal resistance.

B. *dc-to-dc (D2D) interface*

Fig. 4(b) shows the results of the D2D configuration, again with i_{bat1} being negative and i_{bat2} positive. Accordingly, i_{V2V} is positive. In this case, since the dc-link voltage is common to the two EVs, only one voltage is represented (v_{dc}). Contrarily to the previous case, the current i_{V2V} is pulsed, since the dc-link is the output of a boost converter and the input of a buck converter. Provided that this is the current in the connection between the EVs, problems of electromagnetic interference (EMI) can be a major issue in a practical implementation.

C. *dc-to-ac (D2A) and ac-to-dc (A2D) Interfaces*

Fig. 4(c) shows the results of the D2A configuration. Due to the coupling inductors of the ac-dc converter of EV#2, the current i_{V2V} has a negligible ripple. It can be seen that v_{dc1} is

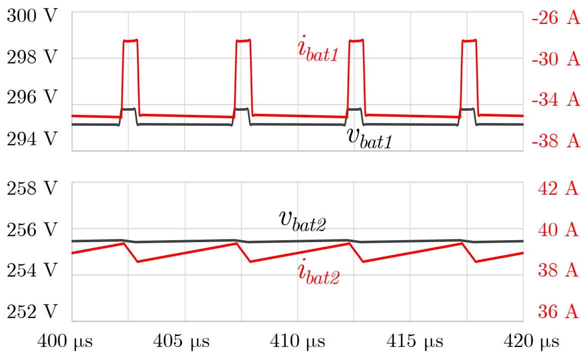

Fig. 5. Simulation results of the battery-to-dc (B2D) configuration for V2V power transfer between two EVs.

controlled to 400 V, and this is the voltage in the connection terminals of the two EVs ($v_{dc1} = v_{V2V}$). Therefore, v_{V2V} is not represented. As happened in A2A, $v_{dc2} < v_{dc1}$.

Fig. 4(d) shows the results of the A2D configuration. The obtained results are very similar to those of D2A (Fig. 4(c)), with the main difference being a slightly higher v_{dc2} voltage in the A2D case. This suggests that, for the operating conditions, lower voltage drops are attained when the ac-dc converter operates with an IGBT and a diode instead of with two diodes.

D. *ac-to-battery (A2B) and battery-to-ac (B2A) interfaces*

Fig. 4(e) shows the results of the A2B configuration. In this case, since the connection of the two EVs coincide with EV#2 dc battery terminals, v_{V2V} and i_{V2V} are not represented ($v_{V2V} = v_{bat2}$ and $i_{V2V} = i_{bat2}$). As aforementioned, the battery charging operation is assured by the EV#1 ac-dc converter operating as a four-quadrant dc-dc converter, using its power grid voltage sensor to measure v_{bat2} and its grid current sensor to measure i_{bat2}.

Fig. 4(f) shows the results of the B2A configuration. The main difference between the results of Fig. 4(e) and Fig. 4(f) is the on-board battery charger in operation, being used EV#1 in Fig. 4(e) (the power provider) and EV#2 in Fig. 4(f) (the power receiver). Besides, in the B2A case, $v_{V2V} = v_{bat1}$ and $i_{V2V} = i_{bat1}$.

E. *battery-to-dc (B2D) interface*

Fig. 5 shows the results of the B2D configuration. In this case, since only one converter is used (EV#2 dc-dc converter), with its input being the EV#1 battery and its output being the EV#2 battery, only two voltages and two currents are represented (v_{bat1}, i_{bat1}, v_{bat2}, i_{bat2}). Hence, this result shows the basic operation of a buck converter. Despite having a lower converter count, in this configuration the discharging current i_{bat1} is pulsed, as happens in the input current of a buck converter. Besides, since there is no current sensor in the dc-link, if the reverse operation is needed (EV#2 charging EV#1), the charging current is not directly controlled, being controlled the discharging current instead. As previously referred, due to the buck operation, this configuration is only possible if $v_{bat1} > v_{bat2}$. Therefore, the D2B configuration is not analyzed for the comparison made in this paper.

IV. Comparative Analysis

This section presents a comparative analysis of the configurations simulated in the previous section. A quantitative comparison is made based on efficiency for a given power range, but qualitative issues are also considered regarding flexibility and safety.

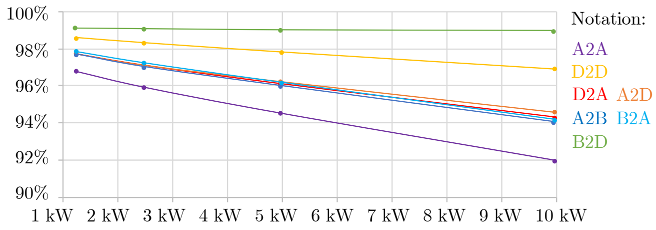

Fig. 6. Efficiency comparison of the analyzed configurations for V2V power transfer.

Fig. 6 shows the power transfer efficiency for the configurations simulated in the previous section, in this case being used four output power values (1.25 kW, 2.5 kW, 5 kW and 10 kW). It can be seen that the most efficient case is obtained with B2D, when only one converter is used. Conversely, the worst efficiency values are attained for A2A, as expected, since it is the operation mode that uses the highest number of converters (four). However, the most efficient operation modes have also disadvantages, while the least efficient ones can also present advantages regarding other metrics. For instance, A2A has inherent inrush current protection, since the on-board EV battery chargers are equipped to interface with an ac power grid, and does not present EMI issues as significant as in other configurations, such as D2D, because the current transferred between the EVs is dc with a negligible ripple. Table II shows a summary of the comparison for the configurations. It should be noted that the worst efficiency result (92%) is still more efficient than the traditional combination of V2G and G2V operation modes for V2V power transfer, as it can be seen in [15].

V. Conclusions

This paper presented a comparative analysis of configurations regarding vehicle-to-vehicle (V2V) power transfer without using additional power converters, i.e., only using the converters available on the on-board battery chargers of electric vehicles (EVs). Based on three access interfaces (ac, dc and battery) for the connection between two EVs, eight V2V configurations were considered. Among the eight configurations, two are symmetrical and six are asymmetrical. The symmetrical configurations are ac-to-ac (A2A) and dc-to-dc (D2D). The asymmetrical configurations are: dc-to-ac (D2A); ac-to-dc (A2D); ac-to-battery (A2B); battery-to-ac (B2A); dc-to-battery (D2B); and battery-to-dc (B2D)). These configurations were validated through computational simulations, and a comparison was performed in terms of efficiency, flexibility and safety, where it could be seen that the most efficient configurations present several disadvantages compared to the least efficient ones. It should be noted that one of the considered access interfaces for power transfer (the dc-link terminals) is not available in nowadays EVs. Thus, further investigation should be performed in order to verify if the dc-link availability by external connections is an advantageous step, given its advantages in terms of efficiency. On the other hand, based on flexibility and safety, the A2B configuration appears to be the most appealing one, despite its relatively low efficiency compared to the others. It should be noted that all the V2V configurations analyzed in this paper are highly efficient, with

TABLE II. COMPARISON OF THE ANALYZED CONFIGURATIONS FOR V2V POWER TRANSFER.

MODE	EFFICIENCY	ADVANTAGES	DISADVANTAGES
A2A	Low (92.01% - 96.81%)	• Only uses already available terminals • Four-quadrant operation • Inherent inrush current protection	• Redundant power conversions (lowest efficiency)
D2D	High (96.93% - 98.57%)	• Eliminates two redundant power conversions • Four-quadrant operation	• Does not use already available terminals • EMI issues due to pulsed transferred current • Requires additional inrush current protection
D2A/A2D	Medium (94.33% - 97.72%)	• Eliminates one redundant power conversion • Four-quadrant operation • Possible migration stage from A2A to D2D	• Does not use already available terminals (on one side) • One redundant power conversion
A2B/B2A	Medium (94.06% - 97.72%)	• Only uses already available terminals • Four-quadrant operation • Inherent inrush current protection • Eliminates two redundant power conversions • Uses the converters of only one EV	• One redundant power conversion
B2D	Highest (98.96% - 99.12%)	• Only one power conversion (highest efficiency) • Uses the converters of only one EV	• Two-quadrant operation • Does not use already available terminals (on one side) • Discharging current is not directly controlled • Pulsed discharging charging current • EMI issues do due to pulsed transferred current • Requires additional inrush current protection

the worst result being still more efficient than the traditional combination of vehicle-to-grid (V2G) and grid-to-vehicle (G2V) operation modes for V2V power transfer.

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