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New Perspectives for Vehicle-to-Vehicle (V2V) Power Transfer

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***Abstract*—This paper presents a comparison between different possibilities for the vehicle-to-vehicle (V2V) power transfer between two electric vehicles (EVs). The traditional V2V operation mode is performed through a common energy aggregator, such as the electrical power grid, consisting of a combination of the vehicle-to-grid (V2G) and grid-to-vehicle (G2V) operation modes. The traditional V2V power transfer is based on four power conversions, since each on-board EV battery charger is comprised by two power converters (dc-dc and dc-ac). In this context, this paper proposes new perspectives for the V2V power transfer, both in ac and dc, focusing in the V2V power transfer using dc power (dcV2V). The proposed methods discard the need for an energy aggregator connection, being possible to directly connect two EVs, charging one EV from the other. Furthermore, the proposed dcV2V method allows the reduction of four power conversions to a single one, allowing to increase the overall efficiency of the power transfer between EVs, An efficiency-based evaluation of the different V2V methods is performed, supporting the benefits of dcV2V.**

Index Terms*—Electric Vehicles (EVs), Battery Charging, Vehicle-to-Vehicle (V2V), Power Transfer, dcV2V.

I. Introduction

Electric vehicles (EVs) represent a key agent in the present society, contributing to mitigate the greenhouse gases emission and the fossil fuels exploration [1][2]. Since the energy storage elements of an EV are electrochemical batteries, their resupplying process, i.e., the charging process, is accomplished by drawing electrical current, which can be performed through a connection with the power grid and the appropriate power converters. However, the power grid is prone to failure if several connected EVs are charging simultaneously, whereby it is mandatory to schedule properly the charging process of the EVs [3][4]. Several battery charging strategies for EVs considering grid congestion have been reported in the literature [5][6][7]. Besides the grid congestion problem, the EV battery charging process, if not performed accurately, can degrade the power quality of electrical systems. Therefore, the EV battery charging must be performed with sinusoidal current and high power factor from the grid side, preserving the power quality of the electrical system [8].

Due to the referred aspects, operation modes regarding the EV and its interaction with the power grid have been proposed in the literature apart from the traditional grid-to-vehicle (G2V), such as vehicle-to-grid (V2G) [9] and vehicle-to-home (V2H) [10][11][12], proving the flexibility of the EV. In fact, EVs can also be used to enhance the power quality of an electrical installation, adjusting its power factor and mitigating harmonic currents [13][14][15] or compensating for voltage sags [16]. Moreover, EVs can be used to interface renewable energy sources with the power grid [17][18], representing an important asset for microgrids [19][20]. Thereupon, the flexibility and bidirectional power flow capability that characterize EVs place them as a vital agent towards power grid support [21][22].

Besides the G2V, V2G and V2H operation modes for power transfer concerning EVs, the vehicle-to-vehicle (V2V) operation mode can also be considered. This operation mode has been proposed in the literature as a power exchange between EVs connected to an energy aggregator [23][24][25], and research has been performed concerning energy price optimization [26][27][28][29][30]. This operation mode is suitable for military applications as an alternative to diesel generators, in which the stopped EVs can be used to establish a microgrid, combining the V2G and V2V modes [31]. Although V2V contributes to alleviate the energy demand from the power grid, it can be improved if the power transfer is accomplished directly between the EVs without any connection to the power grid. Besides, this approach can be useful in remote areas and/or if the batteries of an EV are completely discharged, making it impossible for the EV to reach any charging station. The direct V2V strategy is addressed in [32] and [33], and it is put in practical use in [34]. However, no further investigation has been performed about the V2V operation mode in the power electronics perspective.

In this context, this paper focuses on the different possibilities of V2V power transfer taking into consideration the power converters comprising the on-board EV battery chargers. Since these are constituted by a front-end ac-dc converter and a back-end dc-dc converter, different possibilities can be attained for power transfer between two EVs, namely through ac or dc power. An efficiency evaluation of the analyzed possibilities is performed in order to support the direct V2V power transfer using dc power (dcV2V) in favor of the direct and indirect V2V methods using ac power.

The paper is structured as follows: Section II presents the V2V power transfer possibilities using ac power; Section III describes the V2V power transfer possibilities using dc power; Section IV depicts the simulation results of the different V2V power transfer methods, comparing the efficiency of both ac and dc approaches; lastly, Section V summarizes the conclusions of the developed work.

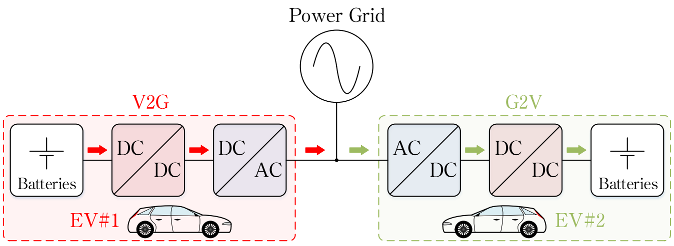

Fig. 1. Conventional indirect V2V power transfer (through an energy aggregator) based on the combination of V2G and G2V modes.

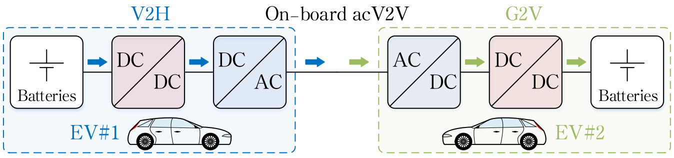

Fig. 2. On-board acV2V power transfer based on the combination of V2H and G2V modes.

II. AC VEHICLE-TO-VEHICLE POWER TRANSFER

This section presents the V2V power transfer using ac power, namely the traditional indirect approach (using the power grid as an intermediary point, i.e., V2G operation combined with G2V) and a direct approach that discards the connection to the power grid (V2H operation combined with G2V), labelled in this paper as acV2V. In the scope of this paper, it is considered the power transfer between two EVs only, with EV#1 transmitting power to EV#2 in all cases. Furthermore, it is considered that each EV is equipped with a battery charger, which is comprised by a front-end ac-dc converter and a back-end dc-dc converter. Both converters are bidirectional in order to support the V2G and G2V operation modes.

A. V2G Combined with G2V

The traditional concept of V2V is based on the combination of the operation modes V2G and G2V, where two EVs are connected to the power grid, as depicted in Fig. 1. Since EV#1 is the energy provider, it operates in V2G mode, injecting the energy stored in the batteries into the power grid. On the other hand, EV#2 operates in G2V mode, absorbing energy from the power grid and charging the batteries. Since both EVs are connected to the power grid, the power flow is regulated by controlling the currents in the ac side, which are phase shifted by 180º between both EVs. Provided that the current needed by EV#2 is equal in amplitude to the current produced by EV#1, the resulting current in the power grid is null, meaning that the energy required to charge the batteries of EV#2 is entirely furnished by EV#1. Consequently, the power grid is not overloaded, representing the essential focus of the V2V operation mode.

B. V2H Combined with G2V

Oppositely to the previous scenario, it is possible to perform a direct V2V power transfer using ac power (acV2V). As referred in [13], the V2H operation mode is related to isolated systems, i.e., without a power grid connection, whereby the EV is controlled to produce an ac voltage to feed electrical loads. This principle can be applied to V2V power transfer, in which EV#1 operates in V2H mode, functioning as a sinusoidal voltage source (Fig. 2). On the other hand, EV#2 operates in G2V mode, absorbing a sinusoidal current in phase with the voltage produced by EV#1.

The difference between the acV2V power transfer and the previous method resides in the connection to the power grid, which is inexistent in the acV2V. Due to the absence of a power grid connection, this possibility is considered as a direct V2V power transfer, since both EVs are exclusively connected to each other. This is a relevant approach in cases where the EV batteries are fully discharged and the EV has no possibility to move.

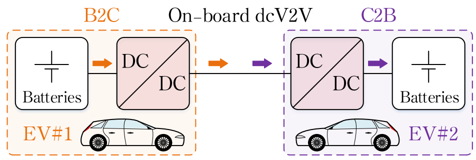

Fig. 3. On-board dcV2V power transfer using only dc-dc converters.

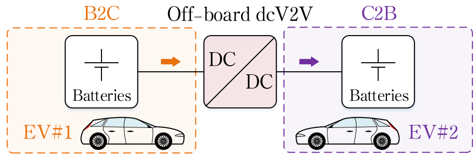

Fig. 4. Off-board dcV2V power transfer using an external dc-dc converter.

III. DC VEHICLE-TO-VEHICLE POWER TRANSFER

This section describes the V2V power transfer possibilities using dc power (dcV2V) instead of ac power, as opposed to the previous section. Despite the advantages of the direct V2V power transfer combining V2H and G2V, the possibilities using ac power need to perform four power conversions, either connected to the power grid or not. Since the batteries rely on dc power, it is advantageous to connect the EVs by the dc terminals, discarding the dc-ac and ac-dc power conversions. This can be attained by two means, namely: (1) Using the on-board dc-dc converter of both EVs, establishing a back-to-back connection between them; (2) Using an external dc-dc converter to interface the battery terminals of both EVs.

A. On-Board Dc-Dc Converters

As aforementioned, the on-board EV battery chargers considered in this paper allow a bidirectional power flow in order to support both V2G and G2V operation modes. Thus, the dc-dc converters comprising the battery chargers allow both charging and discharging of the batteries with controlled current or voltage. Consequently, if a second dc-dc converter is connected to the output of the first dc-dc converter, and both converters are bidirectional, a power exchange between the batteries of two EVs can be feasible, as shown in Fig. 3. The utilization of two cascaded dc-dc converters allows a bidirectional operation with a controlled charging current in a wide range of operating voltages, being possible for lower voltage batteries to charge batteries with a higher voltage. For this purpose, the EVs should be connected by the dc-links, i.e., the nodes that are common to the dc-dc and ac-dc converters of each battery charger. Hence, the subsequent external plug to be connected for enabling the dcV2V power transfer does not contain power converters nor any sophisticated hardware.

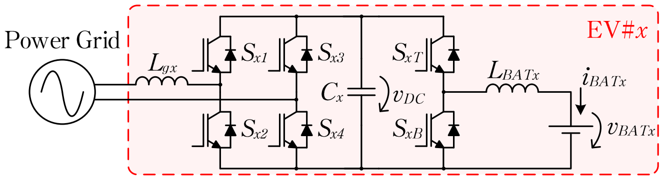

Fig. 5. Topology of EV#*x* on-board battery charger.

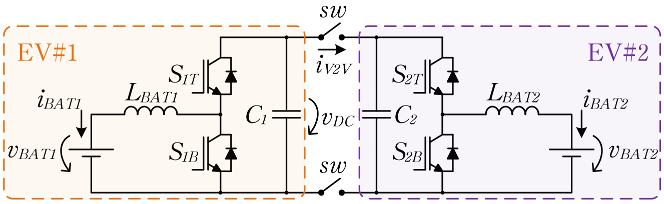

Fig. 6. Connection of the dc-dc converters used in the proposed dcV2V power transfer method between EV#1 and EV#2.

B. External Dc-Dc Converter

It is possible to perform a V2V power transfer with an external dc-dc converter instead of using the on-board EV battery chargers, which can be useful if galvanic isolation is required and/or for a significant voltage difference between the EVs batteries. For such purpose, the interface with the EVs should be performed directly to the batteries, as represented in Fig. 4. This strategy avoids entirely the operation of the on-board battery chargers, since the off-board dc-dc converter allows the operation with controlled current or voltage. Besides, the off-board dc-dc converter does not need a power source, since each terminal is connected to the batteries of each EV. Hence, a hypothetical power plug for enabling this mode of dcV2V power transfer could be comprised by power semiconductors and a high-frequency transformer only, which results in a relatively compact solution. Although the on-board battery chargers do not need to be used, which is useful for the EVs, the use of an external dc-dc converter carries additional costs compared to the on-board solution.

IV. Computational Simulation

This section presents the simulation results of the proposed dcV2V power transfer method, which is based on the use of the on-board dc-dc converters of the EVs. Moreover, an efficiency comparison is performed between the analyzed methods for V2V power transfer. The software PSIM v9.1 from PowerSim was used for performing the computational simulations.

A. On-Board EV Battery Chargers

Fig. 5 portrays the chosen topology for the on-board battery charger of a given EV#*x*, consisting of a full-bridge ac-dc converter (IGBTs S_{x1} to S_{x4}) and a two-quadrant buck-boost dc-dc converter (IGBTs S_{xT} and S_{xB}), the latter being one of the most common topologies for this purpose when no galvanic isolation is used. This converter allows a bidirectional operation with a single mode per current direction, hence the two-quadrant designation. When this converter is controlled to charge the batteries, it operates in buck mode; on the other hand, when the converter is controlled to discharge the batteries, it operates in boost mode. For enabling the proposed dcV2V power transfer method, the two EVs should be connected by the back-end dc-dc converters instead of the front-end ac-dc converters. If two buck-boost converters are connected in a back-to-back manner, sharing the same high-voltage side, a split-pi buck-boost converter is attained, as depicted in Fig. 6 [35]. This configuration represents the connection of two EV battery chargers by their dc-links, as referred in the previous section.

In order to assess the efficiency of the converter, the simulation model was implemented using the database version of IGBTs (IXYS model IXGH40N60C2), as well as the equivalent series resistance (ESR) of inductors and capacitors. For simplicity issues, the on-board battery chargers were considered to be equal between both EVs. Table I shows the main parameters of the developed simulation model.

Table I – Parameters Used in the Simulation Model

Parameter	Value
L_{gx}, L_{BATx}	500 μH
ESR(L_{gx}, L_{BATx})	100 mΩ
C_x	5 mF
ESR(C_x)	50 mΩ
Switching Frequency (f_{SW})	200 kHz

B. Operation Modes within dcV2V

Considering that the dc-dc converter of EV#2 operates in buck mode with controlled current, the arrangement of the two converters allows three operation modes for the dc-dc converter of EV#1: (1) boost mode with controlled current; (2) boost mode with controlled voltage; (2) no operation. Each mode is more appropriate for certain cases, depending on the voltages on the batteries. If the EV#1 battery voltage (v_{BAT1}) is close to the EV#2 battery voltage (v_{BAT2}), EV#1 can operate in boost mode with controlled current, whereby its supplied current (i_{BAT1}) will be similar to the current on the batteries of EV#2 (i_{BAT2}). In this mode, the dc-link voltage (v_{DC}) will be uncontrolled and dependent of i_{BAT1} and i_{BAT2}. On the other hand, if v_{BAT1} is significantly lower than v_{BAT2}, EV#1 must operate in boost mode with controlled voltage, so that v_{DC} can be sufficiently high to charge the EV#2 batteries with controlled current. Finally, if v_{BAT1} is significantly higher than v_{BAT2}, it can be advantageous to disable the EV#1 operation, since there is no need to step-up the voltage v_{BAT1}. This corresponds to a 0% duty-cycle in a boost converter, whereby its output voltage will be equal to the input voltage, i.e., $v_{DC} = v_{BAT1}$. This approach contributes to improve the power transfer efficiency and the current ripple of i_{BAT1}, since there are no switching currents on EV#1. Besides the three operation modes assuming a controlled current operation for EV#2, it is also possible to maintain EV#2 continuously enabled. This corresponds to a 100% duty-cycle in a buck converter, which brings the input voltage to the output. However, the output voltage is v_{BAT2}, whereby v_{DC} should have approximately the same value. Therefore, the controlled variable in this case is i_{BAT1}, while the value of i_{BAT2} will be imposed by the availability of EV#1. This approach can be useful if v_{BAT1} is significantly lower than v_{BAT2}, similarly to the constant voltage operation, since there is no need to step-down the voltage v_{DC}. For a better comprehension, Table II summarizes the four operation modes.

TABLE II – OPERATION MODES WITHIN DCV2V FOR EV#1 AND EV#2 ACCORDING TO THE BATTERIES VOLTAGE

CONDITION	EV#1 CONTROL	EV#2 CONTROL	v_{DC}
$v_{BAT1} \approx v_{BAT2}$	Current (i_{BAT1})	Current (i_{BAT2})	Uncontrolled
$v_{BAT1} < v_{BAT2}$	Voltage (v_{DC})	Current (i_{BAT2})	Controlled to v_{DC}*
	Current (i_{BAT1})	No Operation	v_{BAT2}
$v_{BAT1} > v_{BAT2}$	No Operation	Current (i_{BAT2})	v_{BAT1}

For the current and/or voltage control, predictive controls were implemented. For the current control, considering v_{Cx} the voltage that EV#x must produce, the following relation is valid:

$$v_{C_x} = L_{BATx}\frac{di_{L_{BATx}}}{dt} + v_{BAT_x}, \quad (1)$$

where i_{LBATx} is the current in the battery side inductor of EV#x. Considering a digital implementation, the following equations can be used to control the current during charging (buck mode) and discharging (boost mode), respectively:

$$v_{C_x} = v_{BAT_x} + L_{BATx}\, F_s\, (i_{BAT_x}{}^* - i_{BAT_x}) \quad (2)$$

$$v_{C_x} = v_{BAT_x} - L_{BATx}\, F_s\, (i_{BAT_x}{}^* + i_{BAT_x}), \quad (3)$$

where F_s is the sampling frequency of the digital control and $i_{BATx}{}^*$ is the battery reference current of EV#x.

For the voltage control, in which the controlled variable is v_{DC}, the dc-dc converter of EV#x is controlled as follows:

$$v_{C_x} = v_{DC}{}^* - v_{BAT_x}, \quad (4)$$

where $v_{DC}{}^*$ is the established dc-link reference voltage. In both cases, the obtained value for v_{Cx} is passed through a pulse-width modulation (PWM) scheme using a center-aligned triangular carrier with a fixed frequency of 200 kHz.

C. Simulation Results for dcV2V Power Transfer

The simulation results for the dcV2V power transfer using the two-quadrant buck-boost dc-dc converters were obtained using the four aforementioned operation modes. In the first three cases, v_{BAT2} starts with a value of 300 V and is charged with a 10 A constant current, yielding a power transfer of circa 3 kW, a typical rating of an on-board EV battery charger.

Fig. 7 shows the case when v_{BAT1} and v_{BAT2} have approximate values, with v_{BAT1} starting with 320 V. As it can be seen, i_{BAT1} is negative and has the same average value of i_{BAT2}. Besides, v_{BAT1} decreases and v_{BAT2} increases with time, meaning the power transfer between both batteries. On the other hand, v_{DC} increases, but its value is already low (around 325 V) considering that this voltage must be higher than v_{BAT1} and v_{BAT2} for the operation of the buck-boost converters. In this operation mode, the current in the connection of the EVs (i_{V2V}) has the same average value of 10 A of i_{BAT1} and i_{BAT2} and an even lower peak-to-peak ripple (40 mA against 50 mA and 120 mA, respectively).

Fig. 8 portrays the case when v_{BAT1} is significantly lower than v_{BAT2}, with v_{BAT1} starting with 200 V. In this case, EV#1 operates in constant voltage mode, controlling v_{DC} to an established reference value of 400 V. As it can be seen, v_{DC} has an average value of 395 V in the shown time interval, with EV#1 supplying a current of 15.5 A from its batteries. As expected, EV#2 draws a current of 10 A and v_{BAT2} increases. On the other hand, i_{V2V} has a pulsed waveform with values between 0 A and 12.7 A.

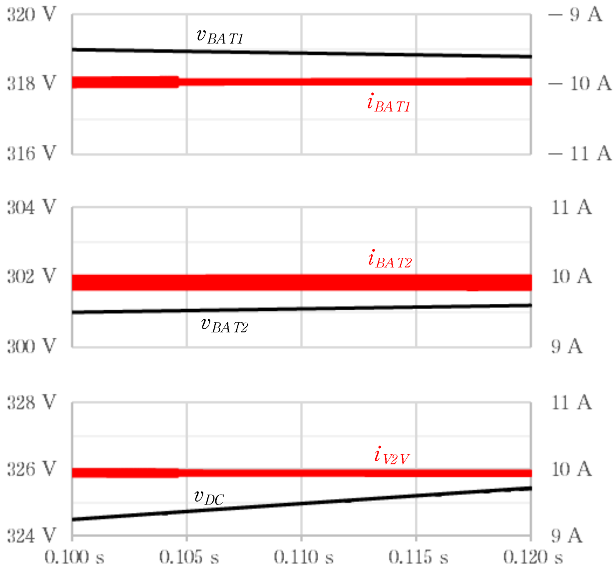

Fig. 7. Simulation results of the dcV2V power transfer in controlled current mode for both EVs (i_{BAT1} and i_{BAT2}).

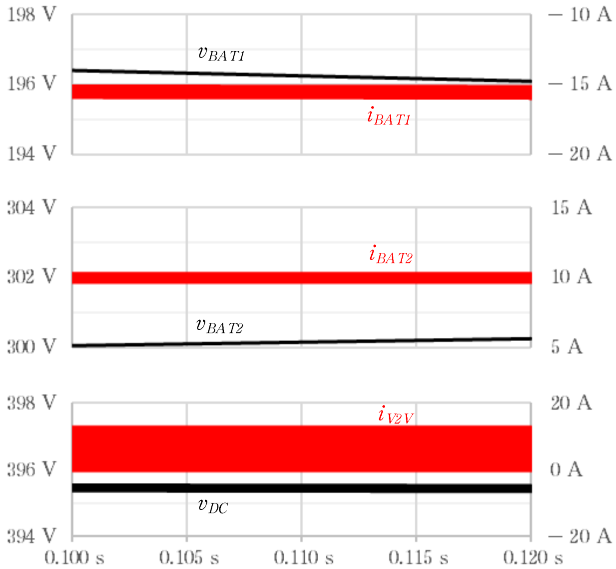

Fig. 8. Simulation results of the dcV2V power transfer in controlled voltage mode for EV#1 (v_{DC}) and controlled current for EV#2 (i_{BAT2}).

Fig. 9 depicts the case when v_{BAT1} is significantly higher than v_{BAT2}, with v_{BAT1} starting with 400 V. In this case, EV#1 has no switching operation, corresponding to a boost operation with a duty-cycle of 0%, i.e., the antiparallel diode of the IGBT S_{1T} is constantly conducting current. As such, the voltages v_{DC} and v_{BAT1} are nearly identical (differing due to the considered parasitic values in the simulation model), both decreasing according to the EV#1 discharging. The current i_{BAT2} is controlled to the average value of 10 A as expected, while i_{BAT1} has an average value of 7.5 A. It can be noted that the ripple of i_{BAT1} is significantly smaller in this operation mode (less than 0.5 mA peak-to-peak). As aforementioned, this is due to the absence of semiconductor switching in the EV#1 dc-dc converter. As occurred in the previous scenario, the current i_{V2V} is pulsed and its value oscillates between 3.7 A and 8.8 A.

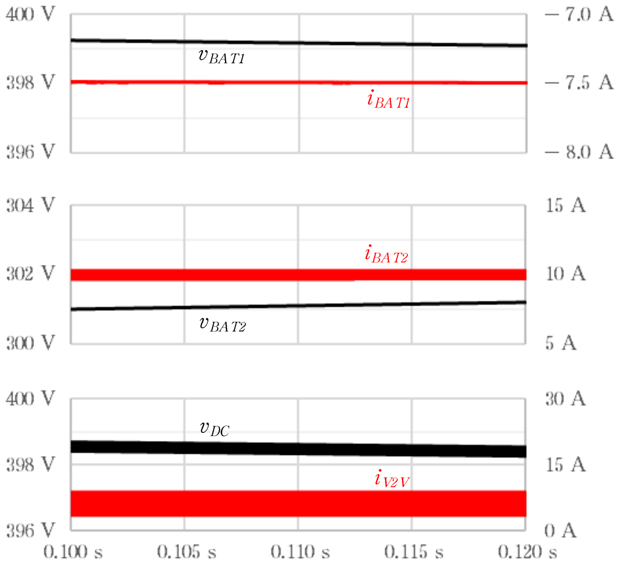

Fig. 9. Simulation results of the dcV2V power transfer with no operation for EV#1 and controlled current for EV#2 (i_{BAT2}).

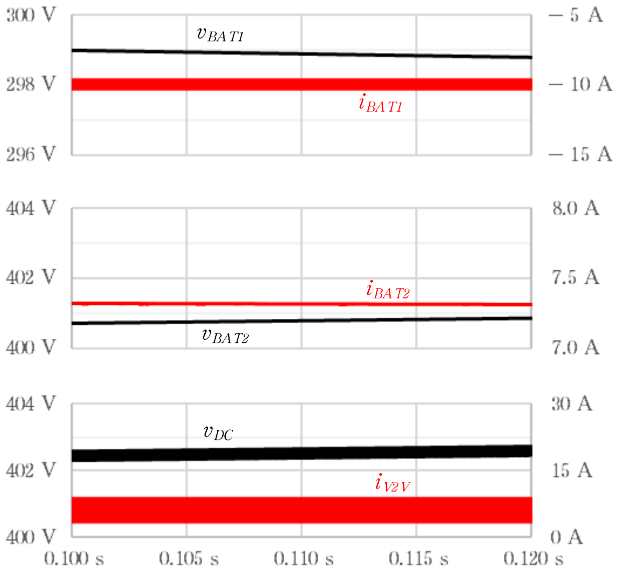

Fig. 10. Simulation results of the dcV2V power transfer in controlled current mode for EV#1 (i_{BAT1}) and no operation for EV#2.

Finally, Fig. 10 presents the fourth case, i.e., uncontrolled operation for EV#2. This mode is valid when v_{BAT1} is lower than v_{BAT2}, such as the second case (Fig. 8), whereby an initial value of 300 V was considered for v_{BAT1} and 400 V for v_{BAT2}. Similarly to the previous case (Fig. 9), only one converter is switching, with the difference that, in this case, the EV#2 dc-dc converter operates with a 100% duty-cycle, meaning that IGBT S_{2T} is constantly conducting current. Therefore, the controlled variable is i_{BAT1}, whose reference was established as 10 A in order to maintain an operating power of 3 kW. The current i_{BAT2} has an average value of 7.3 A that is indirectly imposed by EV#1, and its peak-to-peak ripple is about 0.3 mA due to the absence of the switching operation of the EV#2 dc-dc converter. Once again, it is possible to see the decrease in v_{BAT1} and the increase in v_{BAT2}, verifying the power exchange between both EVs. Concerning the voltage v_{DC}, a proximity with v_{BAT2} is noticeable, despite having a high-frequency component caused by the pulsed waveform of i_{V2V}, whose values vary between 3.7 A and 8.8 A.

The presented results prove the feasibility of the proposed dcV2V power transfer. In order to acknowledge the advantages of the proposed method (dcV2V) comparatively to the others, an efficiency comparison was performed for the same operating conditions. Table III depicts the obtained efficiency for each V2V method. As it can be noted, the dcV2V power transfer presents significantly higher efficiencies than acV2V, the worst value being attained with the traditional method based on the combination of V2G and G2V operation modes. In fact, the dcV2V efficiency can be further improved if the operation of one of the EVs is disabled, validating the superiority of the proposed method. It is worth to mention that a slightly better efficiency is attained when the disabled EV is the supplier (99.2% versus 99.1%), favoring the 0% duty-cycle boost operation rather than the 100% duty-cycle buck operation.

TABLE III – EFFICIENCY COMPARISON BETWEEN V2V POWER TRANSFER METHODS

METHOD	Traditional	acV2V	dcV2V		
OPERATION	V2G+G2V	V2H+G2V	BOTH EVS ON	EV#2 ON	EV#1 ON
EFFICIENCY	90.7%	95.0%	98.9%	99.2%	99.1%

V. CONCLUSIONS

This paper presented the traditional indirect and proposed direct perspectives for vehicle-to-vehicle (V2V) power transfer. V2V power transfer can be particularly useful when an electric vehicle (EV) has its batteries depleted and it is not possible to travel to a charging station. However, V2V can only be useful if it can be performed in a direct manner, i.e., without the need of an energy aggregator. Besides, the traditional indirect V2V method performs four power conversions (dc-dc, dc-ac, ac-dc, dc-dc), which decreases the power transfer efficiency between EVs. To overcome this issue, this paper presented a direct V2V method, the on-board dcV2V, with only two conversions (dc-dc, dc-dc). Simulation results proved the feasibility of the proposed method using four different operation modes. Moreover, a comparison between the traditional and proposed V2V power transfer methods was performed in terms of efficiency for the same operating conditions, where the effectiveness of the dcV2V method was verified. However, additional metrics will be used in further investigation in order to validate the benefits of the dcV2V method more confidently.

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