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Electric Vehicle-to-Vehicle Energy Transfer Using On-Board Converters

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ABSTRACT-Electric vehicle-to-vehicle (V2V) charging is a recent approach for sharing energy among electric vehicles (EVs). Existing V2V approaches with an off-board power-sharing interface add extra space and cost for EV users. Furthermore, V2V power transfer using on-board type-2 chargers reported in the literature is not efficient due to redundant conversion stages. This article proposes a new method for V2V power transfer by directly connecting the two EV batteries together for sharing energy through the type-2 ac charger input ports and switches. The active rectifiers of on-board type-2 chargers are not used for rectification during V2V charging, instead only a few switches are used as interfaces to connect the two EV batteries together, to avoid redundant power conversion and associated losses which effectively improve the overall V2V efficiency. The possible V2V charging scenarios of the proposed V2V approach are validated using a MATLAB/Simulink simulation study.

INDEX TERMS-Electric vehicle (EV), on-board type-2 ac charger, vehicle-to-vehicle (V2V) charging.

I. INTRODUCTION

In recent days, vehicle-to-vehicle (V2V) charging is emerging as an alternate method to share energy between two EVs, in the case of non availability of both the ac grid and the dc fast-charging stations. The V2V charging allows EV users to cooperatively share energy with each other with minimum infrastructure and cost and reduce range anxiety. Mainly there are two aspects to V2V energy sharing: first, the communication aspects of V2V, which provides a platform for EV users to interact with each other to find the energy sharing match, to decide provider and receiver preferences, and tariff.

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In [1]–[4] game theory-based algorithms to match the receiver EV, provider EV, the nearest meeting point, and the communication aspects of the V2V are presented.

The second important aspect of V2V is the power interface for the actual power transfer, that is, controlling the direction of power flow based on the receiver and provider preference, and a buck or boost conversion based on the EV battery's voltage level. Using the ac power grid as a common energy aggregator with off-board bidirectionalpower converters for accomplishing an indirect V2V energy transfer is one of the basic V2V approaches presented in [5] and [6] where the conversion efficiency is low due to multiple redundant conversion stages.

Basically, the on-board type-1 and -2 chargers consist of an ac to dc converter (active rectifier) stage followed by a dc–dc converter [for constant current and constant voltage (CCCV) charge control]. In [10], a V2V charging approach by connecting the type-1 charger input ports of the two EVs is presented as shown in Fig. 1(a), wherein the provider EV battery dc output is first converted into single-phase ac using the bidirectional two-stage on-board type-1 ac charger. This ac power output of the provider EV is fed as input to the two-stage on-board type-1 converter to charge the receiver EV battery. Cascaded converter losses due to redundant conversion stages lead to lower V2V charging efficiency in [10]. In [5], V2V charging by directly connecting the dc-link of the two EVs using mechanical switches is presented as shown in Fig. 1(b). However, practically, there is no direct access to the dc-link of battery side dc–dc converters for establishing the presented direct connection. Thus, the V2V approach presented in [5] is not a practically feasible solution without customized design modifications and additional charging ports for bringing out the dc-link terminals of the two EVs.

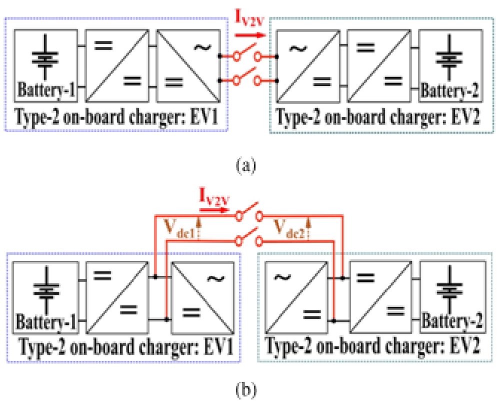

Fig. 1.V2V operations: (a) ac V2V operation and (b) dc V2V operation

This article proposes a V2V charging approach for EVs through the on-board type-2 chargers by directly connecting the on-board type-2 power inlet ports, which eliminates the need for external hardware or additional power inlet ports for V2V operation. The proposed approach of connecting the two EV batteries through on-board active rectifier switches

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eliminates the need for an off-board V2V interface unlike [8], additional contactor switches in contrast to [5], redundant power transfer stages compared to [10], and associated losses that improve the overall V2V efficiency.

The rest of the article is structured as follows. In Section II, the power converter configuration and its operating modes for possible V2V modes of the proposed approach are discussed. The control scheme for the proposed V2V approach is described in Section III. Performance improvement of the proposed V2V with respect to efficiency and other aspects are discussed in detail in Section IV in addition to simulation results. The experimental validation of the proposed V2V approach with a scaled lab prototype is discussed in Section V. Finally, the article is concluded in Section VI.

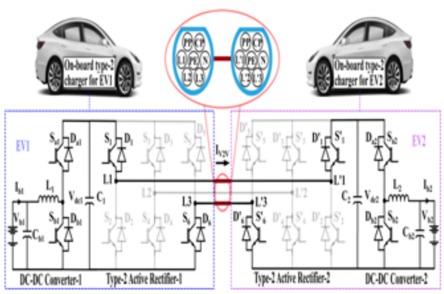

Fig.2.BLOCK DIAGRAM OF THE SYSTEM

II. PROPOSED V2V APPROACH

The proposed V2V configuration is realized by connecting the existing type-2 charging ports of the provider-EV and the receiver-EV. The two EVs are connected by utilizing the threephase active rectifier switches. Turning ON the top switch of one of the phases (phase-a, S_1 here) and bottom switch of the other phase (phase-c, S_6 here) of the active rectifier-1 and the respective phase switches $S_1$and $S_6$of the active rectifier-2 directly connects the two EV batteries through the intermediate dc-link of provider and receiver EVs as shown in Fig. 2. The four switches S_1`, $S_6$`, S_1`` and $S_6$are kept ON throughout the V2V power transfer duration. The proposed way of connecting the two EVs realizes a dual bidirectional buck-boost converter that can be controlled to transfer energy between two EVs in either direction regardless of their battery voltage levels.

As the active rectifiers of both the type-2 chargers are used as an interface to connect two dc-links instead of their actual purpose of rectification, other switches of both the active rectifiers are kept OFF throughout the V2V operation. Based on the battery voltage of two EVs, the configuration may operate in one of the possible energy transfer modes as discussed below.

A. V2V Scenario-1: $V_{bat1} < V_{bat2}$

With the EV-1 battery voltage less than the EV-2 battery voltage and provider–receiver role, there are two possible

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scenarios of boost and buck operation with power flow in forward or reverse direction, respectively, as explained below.

1) Forward Boost Mode (EV1 as Provider and EV2 as Receiver): In this mode, EV1 is charge provider and EV2 is charge receiver with battery-1 having lower voltage than battery-2. Once the direct connection of two EV batteries through the proposed approach (by turning on the switches S_1, S_6, S_1, and S_6), EV-1 battery voltage is stepped up to the EV-2 battery voltage by operating the dc–dc converter-1 in the boost mode. During the turn ON period of the switch S_{b1}, inductor L_1 stores energy from EV-1 battery, and the switch S_{a1} is complimentary switched to S_{b1} as shown in Fig. 3(a). When S_{b1} is turned OFF, S_{a1} gets turned ON to transfer energy of EV-1 battery and inductor L_1 to EV-2 battery through S_1, S_1', S_{a2}, and inductor L_2. To receive power from the dc-links, switch $Sa2$ is kept on throughout this V2V mode which makes $V_{dc1} = V_{dc2} = V_{bat2}$ and switch S_{b2} is complimentary switched to S_{a2} as shown in Fig. 3(b).

2) Reverse Buck Mode (EV1 as and EV2 as Provider): Similar to the forward boost mode in this reverse buck mode, the EV batteries are connected by turning on the switches S_1, S_6, S_1, and $S_6$of the active rectifier-1 and 2. The dc–dc converter-1 is operated in buck mode to transfer power from EV-2 battery to EV-1 battery. The diode D_{a2} gets forward biased as Vbat1 < Vbat2 leading to Vbat2 = Vdc1 = Vdc2 and thus making EV-2 battery available for delivering power to EV-1 battery through the dc-link. During turn ON period of switch S_{a1}, the energy from the EV-2 battery is transferred to EV-1 battery through inductor L_1, D_{a2}, S_1, and inductor L_2 as shown in Fig. 4(a). During the turn OFF period of S_{a1}, the energy in the inductor L_1 freewheel through switch S_{b1} which is complementary switched to S_{a1} as shown in Fig. 4(b).

B. V2V Scenario-2: $V_{bat1} = V_{bat2}$

In this scenario as both EV battery voltages are equal, the dc–dc converters need to be controlled, one in currentcontrolled boost mode and the other in current-controlled buck mode.

1) Forward Boost Mode (EV1 as Provider and EV2 as Receiver): In this mode with $V_{bat1} = V_{bat2}$, power transfer from EV-1 to EV-2 battery is achieved by operating the dc–dc converter-1 in the boost mode and the dc–dc converter-2 is operated in the buck mode with closed-loop current control. During turn ON period of the switch S_{b1}, inductor L_1 stores energy from EV-1 battery and switch S_{a1} is complimentary switched to S_{b1}. At the same instant, the switch S_{b2} of dc–dc converter-2 is also ON to freewheel the energy in inductor L_2, and the switch S_{a2} is complimentary switched to S_{b2} as shown in Fig. 5(a). During the turn OFF period of S_{b1}

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and S_{b2}, the switches S_{a1} and S_{a2} gets turned on to transfer energy from EV-1 battery to EV-2 battery through L_1, S_1, S_1, and L_2 as shown in Fig. 5(b). This mode can also be achieved by operating provider EV side dc–dc converter in the voltage control mode to regulate the dc-link voltage at a higher voltage than the EV battery voltage and receiver-side dc–dc converter in the current control mode.

2) Reverse Boost Mode (EV1 as Receiver and EV2 as Provider*):*This mode is similar to the forward boost mode with $V_{\text{bat1}} = V_{\text{bat2}}$ but the power flow is reversed by operating the dc–dc converter-2 in boost mode and the dc–dc converter-1 is operated in buck mode with closed-loop current control. Voltage control mode could be used to control the power flow in this mode as well.

C. V2V Scenario-3: $V_{bat1} > V_{bat2}$

The converter operation in this scenario is similar to the Scenario-1 with the power flow direction reversed.

1)Reverse Boost Mode (EV1 as Receiver and EV2 as Provider): This mode is similar to the forward boost mode with $V_{\text{bat1}} < V_{\text{bat2}}$ but the power flow is reversed by operating the dc–dc converter-2 of EV-2 in the boost mode, and keeping the S_{a1} of the dc–dc converter-1 of EV-1 always ON.

2)Forward Buck Mode (EV1 as Provider and EV2 as Receiver): This mode is similar to the reverse buck mode with $V_{\text{bat1}} < V_{\text{bat2}}$ but the power flow is reversed by operating the dc–dc converter-2 of EV-2 in the buck mode, and keeping the S_{a1} of the dc–dc converter-1 of EV-1 always ON.

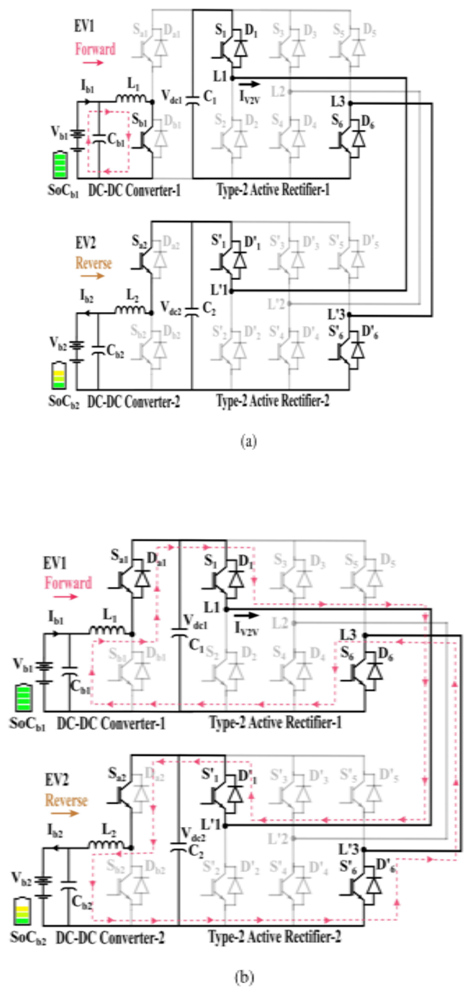

Fig. 3. Forward boost V2V mode with $V_{\text{bat1}} < V_{\text{bat2}}$. (a) L1 stores energy from EV-1 battery. (b) Energy is transferred through dc-link to EV2

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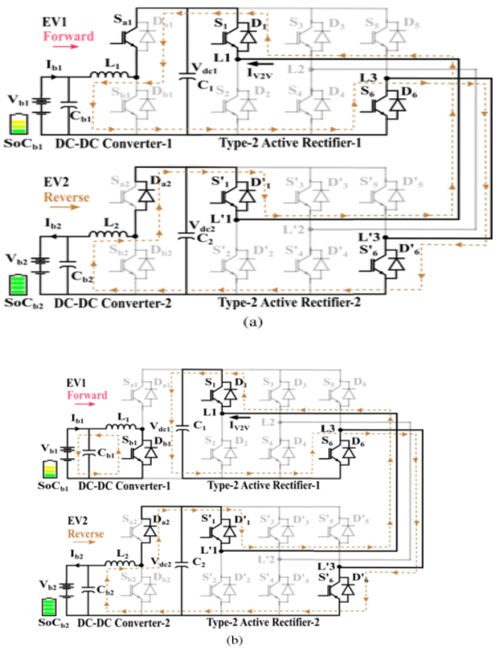

Fig. 4. Reverse buck V2V mode with $V_{\text{bat1}} < V_{\text{bat2}}$. (a) L1 stores energy from EV-2 battery through dc-link. (b) Energy is stored from L1 to EV1 to battery through free wheeling

III. SIMULATION RESULTS

The proposed V2V approach is validated through MATLAB/Simulink. The simulation parameters considered for designing the EV-1 and EV-2 on-board chargers are given in Table I.

TABLE - I

SIMULATION PARAMETERS OF THE PROPOSED V2V APPROACH

Parameter	Value
Battery-1 capacity (E_{bat1})	40 kWh
Battery-2 capacity (E_{bat2})	100 kWh
Battery-1 nominal voltage (V_{bat1})	350 V
Battery-2 nominal voltage (V_{bat2})	450 V
Switching frequency (f_{sw})	20 kHz
Filter inductor (L_1)	0.5 mH
Filter inductor (L_2)	0.6 mH
L_1 Internal resistance (R_1)	0.005 Ω
L_2 Internal resistance (R_2)	0.006 Ω
DC-link capacitor (C_1)	1000 uF
DC-link capacitor (C_2)	1100 uF
DC-DC converter-1 capacitor (C_{b1})	5.6 nF
DC-DC converter-2 capacitor (C_{b2})	5.8 nF

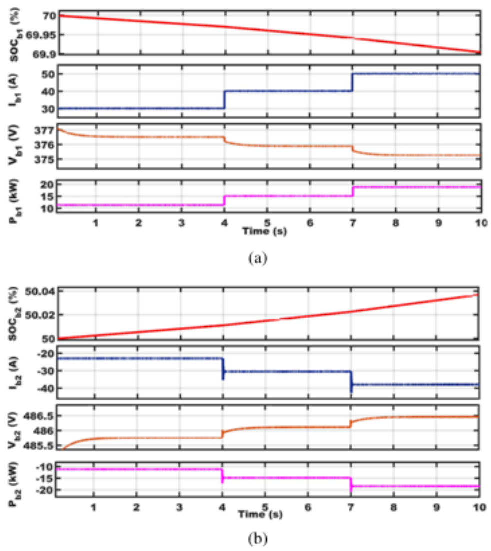

Fig.6. Simulation results of the proposed V2V operation in forward boost mode with $V_{\text{bat1}} < V_{\text{bat2}}$. (a) SOC, voltage, current, and power waveforms of EV-1 battery. (b) SOC, voltage, current, and power waveforms of EV-2 battery

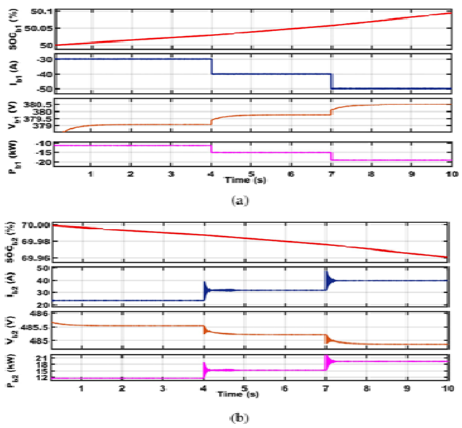

Fig.7.

Simulation results of the proposed V2V operation in the reverse buck mode with Vbat1 < Vbat2. (a) SOC, voltage, current, and power waveforms of the EV-1 battery. (b) SOC, voltage, current, and power waveforms of the EV-2 battery.

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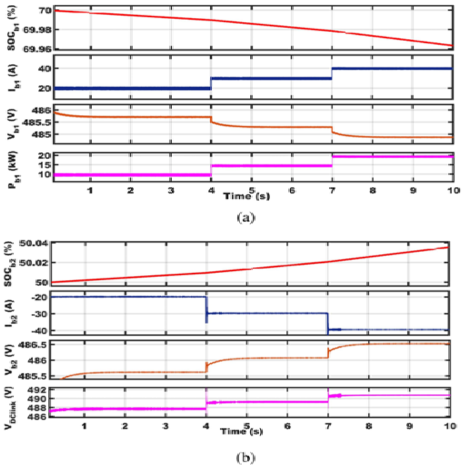

Fig.8. Simulation results of the proposed V2V operation in the forward boost mode with Vbat1 = Vbat2. (a) SOC, voltage, current, and power waveforms of EV-1 battery. (b) SOC, voltage, current of EV-2 battery, and dc-link voltage.

IV. CONCLUSION

This article proposes a direct V2V charging approach for power transfer between two EVs without the need for external hardware or additional charging ports. It is an emergency rescue charging solution in the case of non-availability of ac grid and dc fast-charging stations. Connecting two EV batteries directly through the on-board charger ports leads to significant hardware infrastructure savings. The proposed V2V approach mitigates range anxiety and cooperatively shares energy between EV users with minimum infrastructure and cost. The proposed V2V method is validated through simulation in MATLAB/Simulink.

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