International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 07 | July - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

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 work 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. Furthermore, a scaled experimental prototype is developed to validate the proposed V2V method practically.

Proposed System

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]. 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 .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.

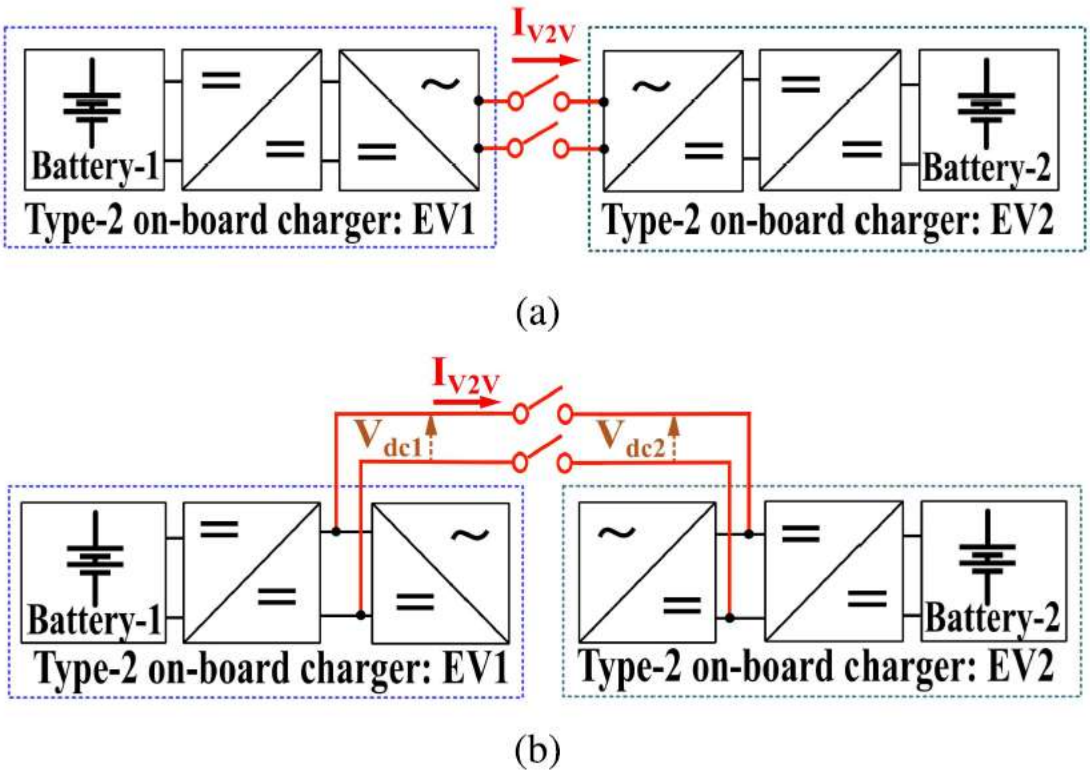

Fig. 1. V2V operations: (a) ac V2V operation and (b) dc V2V operation

This work 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. Furthermore, the proposed V2V approach utilizes the active rectifier stages as a connection interface to connect two EV batteries which in turn reduces the total conversion stages in the V2V energy transfer path. Reduced conversion stages reduce the overall active switches contributing to switching and conduction losses which significantly increases the efficiency. In the proposed V2V approach, mode selection logic is presented to decide buck/boost operating modes, based on the battery voltage levels and the power flow direction, based on the EV user's preference. Control of power flow in either direction provides greater irrespective of the difference in both EV battery voltage ratings.

The proposed V2V configuration is realized by connecting the existing type-2 charging ports of the provider-EV and th 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, $S1$ here) and bottom switch of the other phase (phase-c, $S6$ 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 $S1$, $S6$, 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

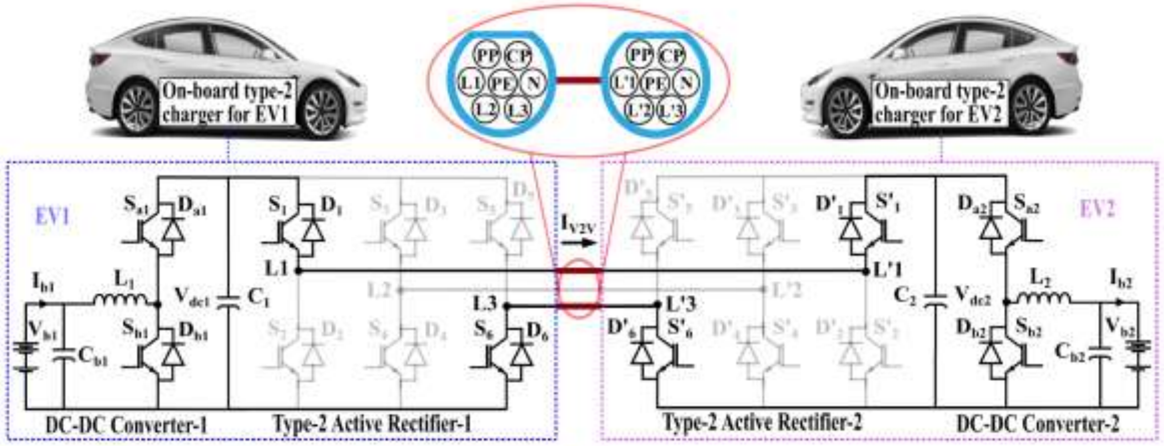

Fig. 2. Proposed topology for V2V operation.

A. V2V Scenario-1: Vbat1 < Vbat2

With the EV-1 battery voltage less than the EV-2 battery voltage and provider–receiver role, there are two possible 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 *Sb*1, inductor *L*1 stores energy from EV-1 battery, and the switch *Sa*1 is complimentary switched to *Sb*1 as shown in Fig. 3(a).

When *Sb*1 is turned OFF, *Sa*1 gets turned ON to transfer energy of EV-1 battery and inductor *L*1 to EV-2 battery through *S*1, *S*_ 1, *Sa*2, and inductor *L*2. To receive power from the dc-links, switch *Sa*2 is kept on throughout this V2V mode which makes *V*dc1 = *V*dc2 = *V*bat2 and switch *Sb*2 is complimentary switched to *Sa*2 as shown in Fig. 3(b).

2) Reverse Buck Mode (EV1 as Receiver 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 *Da*2 get forward biased as *V*bat1 < *V*bat2 leading to *V*bat2 = *V*dc1 = *V*dc and thus making EV-2 battery available for delivering power to EV-1 battery through the dc-link. During turn ON period of switch $Sa1$, the energy from the EV-2 battery is transferred to EV-1 battery through inductor $L1$, $Da2$, $S\_$ 1, and inductor $L2$ as shown in Fig. 4(a). During the turn OFF period of $Sa1$, theenergy in the inductor $L1$ freewheel through switch $Sb1$ which is complementary switched to $Sa1$ as shown in Fig. 4(b).

B. V2V Scenario-2: Vbat1 = Vbat2

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

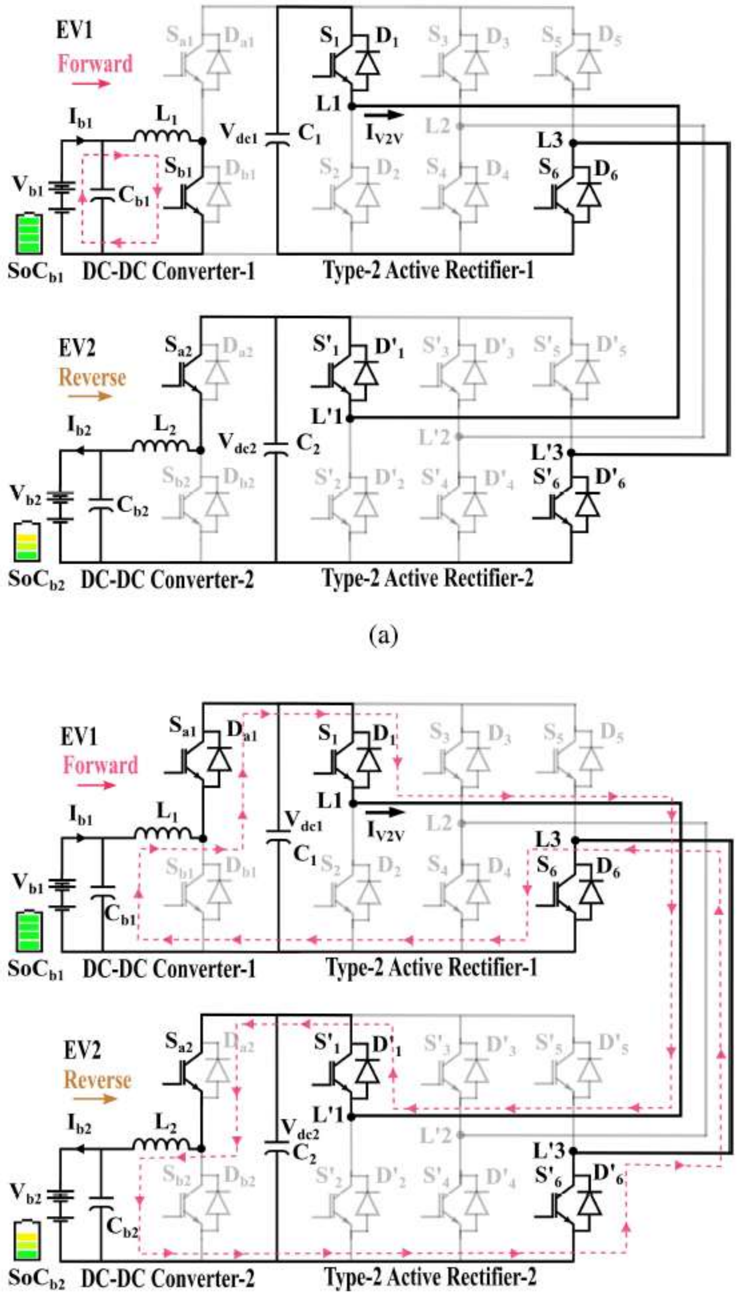

Fig. 3. Forward boost V2V mode with Vbat1 < Vbat2. (a) L1 stores energy from EV-1 battery. (b) Energy is transferred through dc-link to EV2.

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 I operated in the buck mode with closed-loop current control. During turn ON period of the switch *Sb*1, inductor *L*1 stores energy from EV-1 battery and switch *Sa*1 is complimentary switched to *Sb*1. At the same instant, the switch *Sb*2 of dc–dc converter-2 is also ON to freewheel the energy in inductor *L*2, and the switch *Sa*2 is complimentary switched to *Sb*2 as shown in Fig. 5(a). During the turn OFF period of *Sb*1 and *Sb*2, the switches *Sa*1 and *Sa*2 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*bat1 = *V*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: Vbat1 > Vbat2

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*bat1 < *V*bat2 but the power flow is reversed by operating the dc–dc converter-2 of EV-2 in the boost mode, and keeping the *Sa*1 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*bat1 < *V*bat2 but the power flow is reversed by operating the dc–dc converter-2 of EV-2 in the buck mode, and keeping the *Sa*1 of the dc–dc converter-1 of EV-1 always ON.

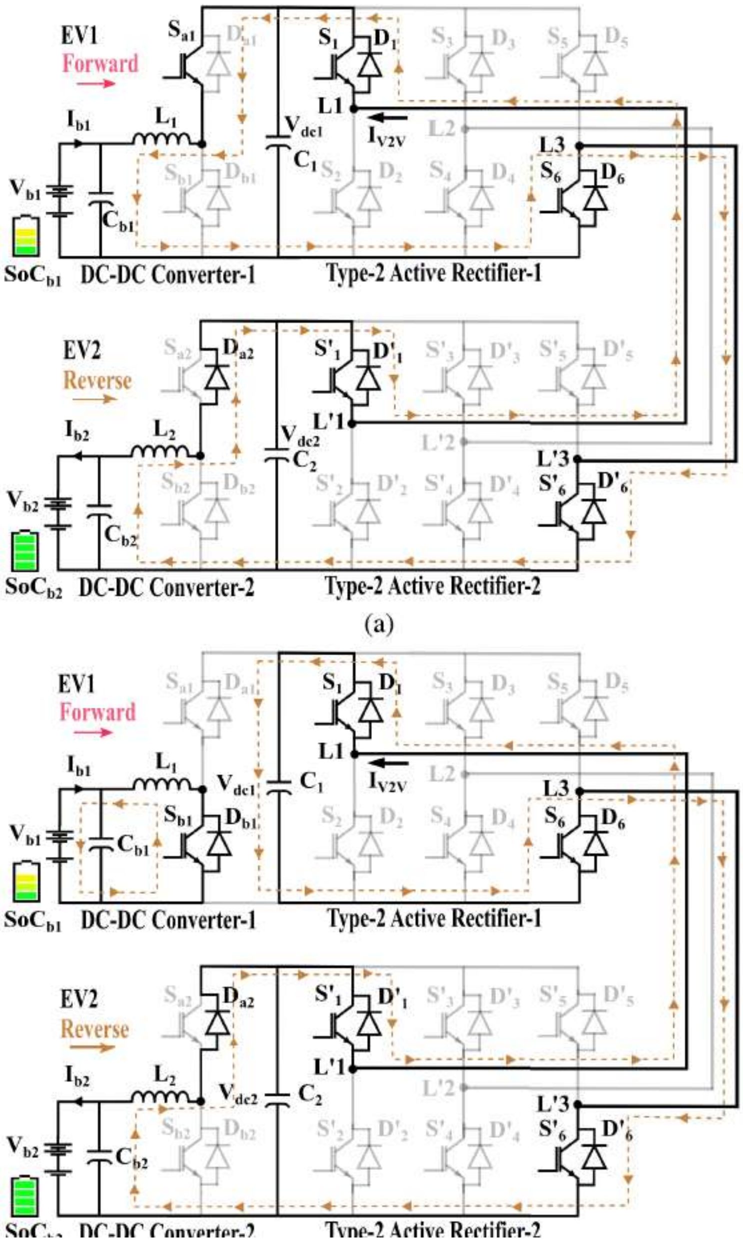

Fig. 4. Reverse buck V2V mode with Vbat1 < Vbat2. (a) L1 stores energy from EV-2 battery through dc-link. (b) Energy is stored from L1 to EV-1 battery through freewheeling

CONTROL SCHEME FOR THE PROPOSED V2V APPROACH

The charging rate and the amount of energy transferred during the proposed V2V approach are controlled by controlling the on-board converters. The mode selector flow shown in Fig. 6 decides the V2V mode based on the EV-1 and EV-2 battery values and the provider receiver information. Furthermore, depending on the mode of operation, the on-board charger converters are controlled for achieving the proposed V2V

A. Control of the Active Rectifiers as V2V Interface

Typically, during the normal three-phase ac charging through a type-2 charger, the active rectifier is controlled in d-q control mode to convert the three-phase ac to dc wit unity power factor operation at the grid terminals. During the proposed V2V charging, the active rectifier is re-utilized as an interface to access and connect the batteries of the two EVs. After the type-2 charger ports are connected for V2Vcharging, the gating pulse for the switches $S1$ and $S6$ of the active rectifier-1 of the EV-1 and the switches S_1 and S_6 of the active rectifier-2 are kept active high throughout the V2V charging for all the modes.

B. Control of DC–DC Converters

For the proposed V2V charging approach using the onboard chargers, the dc–dc converters of the type-2 chargers are closed-loop current-controlled. For forward boost and reverse buck mode control (Vbat1 < Vbat2): In these modes, the dc–dc converter-1's inductor current $IL1$ in forward or reverse direction is controlled inclosed-loop by feeding the error between the reference current $I * L$ and the actual inductor current $IL1$ to a PI controller to generate duty ratio for switch $Sa1$, and $Sb1$ is complimentarily switched to $Sa1$ as shown in Fig. 7. Gating signal to the switch $Sa2$ is kept active high throughout this mode. The current to control transfer function to the dc–dc converter-1 used to tune the PI controller is given in the following equation, where D is the duty ratio and $R2$ is the load resistance equivalent to charging current of the EV-2 battery The higher efficiency, lower losses, and convenience of connecting two EVs through the existing on-board type-2 charger ports make the proposed V2V approach more practically adaptable among EV users. In general, for the practical implementation of any V2V approach, access to the on-board instrumentation sensors and BMS controllers of the provide and receiver EVs are required to establish a communication between two EVs and to fetch the required parameters for V2V. These aspects of V2V are already discussed in [10]–[12], with details of game theory-based algorithms to match the receiver and the provider EVs with an assumption that the Fig. 6. Proposed V2V power transfer control flow. Fig. 7. Current control structure in forward boost and reverse buck modes (Vbat1 < Vbat2). bidirectional power converter interface for V2V is available. Practical implementation of the proposed V2V approach for commercial EVs assumes that communication between EVs and access to controllers and instrumentation sensors is readily available Depending on the battery voltage levels,provider, and receiver preferences, fetched using the on-board instrumentation sensors and EV user inputs, the V2V mode is decided, as shown in Fig. 6. Based on the mode of operation selected (e.g., forward boost), the power flow direction and the required amount of energy transfer are commanded through the on-board DSP controllers

SIMULATION DESIGN AND RESULTS

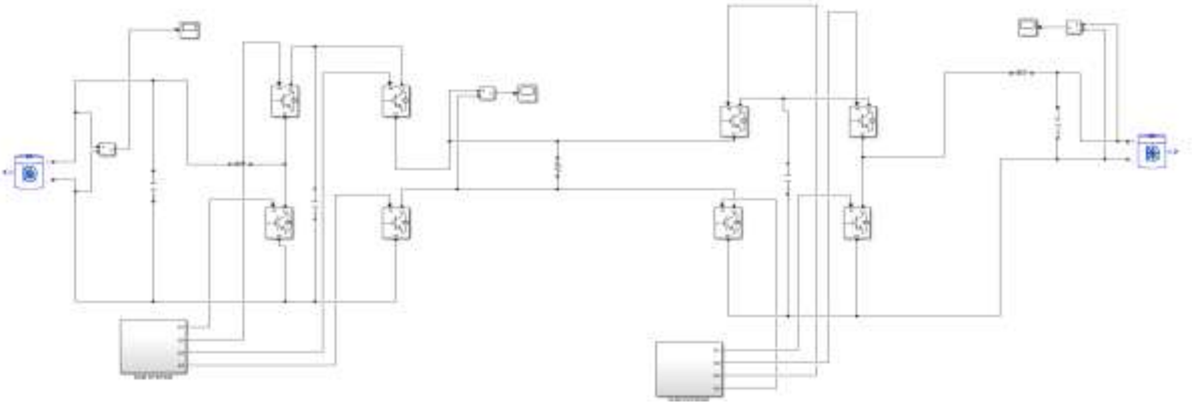

Figure 6.1 : Overall Simulink model

The simulation model represents a peer-to-peer Electric Vehicle (EV) charging system where one EV supplies power to another. This is designed to address scenarios such as emergency charging in remote locations. The simulation is developed in MATLAB/Simulink (version 2020b) .Both donor and receiver EVs are equipped with batteries rated at 48V, 100Ah, providing a balance between energy storage and portability.

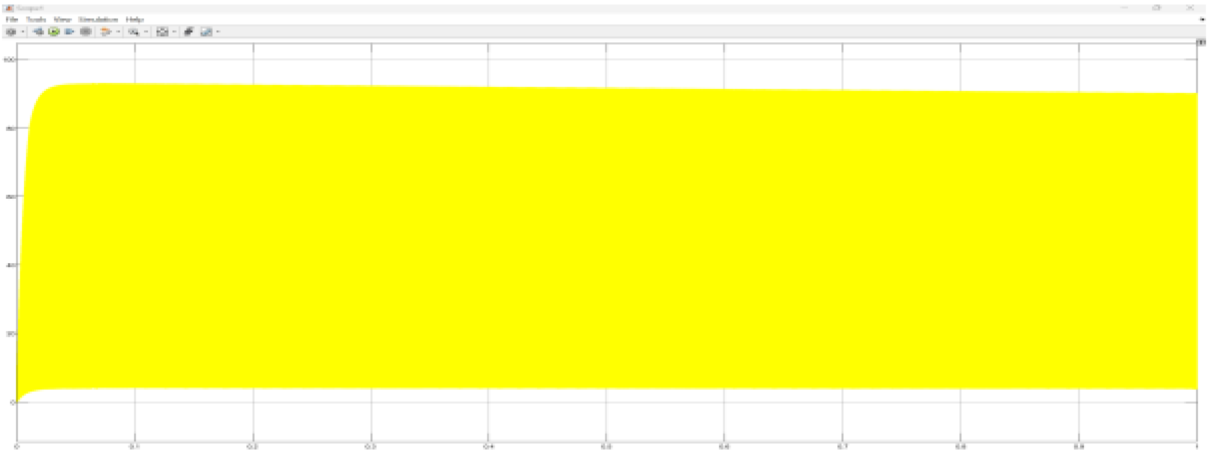

Figure 6.2 : Input voltage

The output voltage remains steady at 90V, with minimal fluctuations (less than ±1% ripple). The system reaches 90V within a few milliseconds, indicating a rapid stabilization by the converter's control algorithm.

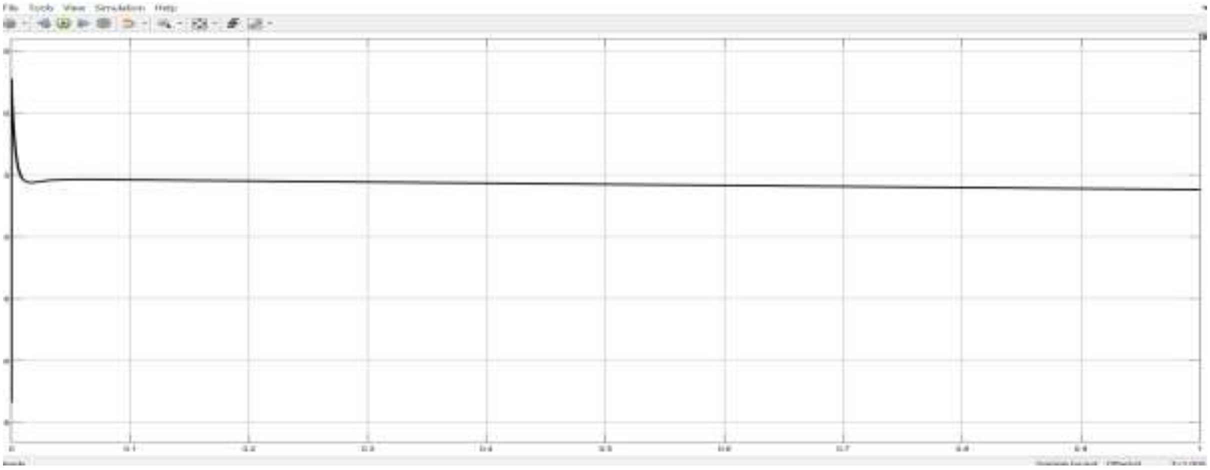

Figure 6.3: Buck mode

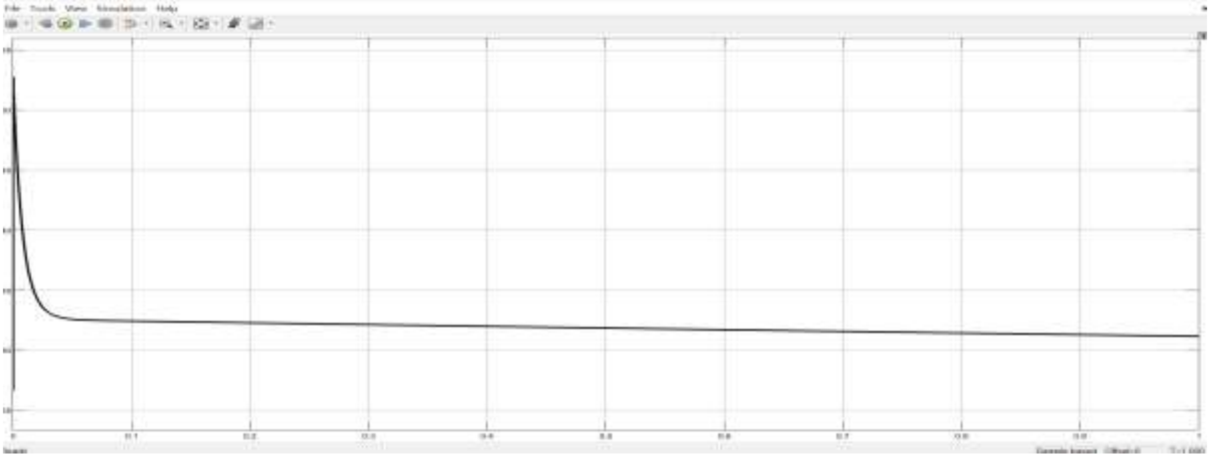

Figure 6.4: Boost mode

Similar to the 90V output, the 38V output maintains stability with negligible voltage ripples. The lower voltage level ensures safe and efficient charging for auxiliary systems. Slightly slower compared to the 90V output, as the lower voltage system typically has less aggressive control settings to ensure safety.

CHAPTER 7

CONCLUSION

This work 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 redundant power conversion stages were avoided, which improved the overall efficiency of the proposed V2V approach which is evident in the performance analysis. 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 and experimental results which prove the practical effectiveness without modifying the EV power architecture.

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