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Design and Implementation of Artificial Neural Network-Based Controllers for Electric Vehicle-to-Vehicle Energy Transfer via On-Board Converters

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Abstract
The design and implementation of controllers based on Artificial Neural Networks (ANN) for EV-to-EV energy transfer via On-Board Converters (OBCs) are the main objectives of this project. Improving the dependability and efficiency of energy transfer between electric vehicles is the goal. In order to efficiently manage the transfer process and optimize power flow, the study entails the creation and integration of ANN controllers. The usefulness of the suggested controllers in raising the general efficiency and dependability of EV-to-EV energy transfer is assessed through a thorough performance study. The results of this study, which were verified by a MATLAB/Simulink simulation study, advance the field of electric car technology and optimize energy transfer mechanisms for sustainable transportation networks.

Keywords: On-board type-2 AC chargers, vehicle-to-vehicle (V2V) charging, and electric vehicles (EV).

Introduction

The traditional charging methods for electric vehicles (EVs) include type-1 and type-2 AC on-board slow chargers with a power range of 3.3-19.4 kW. However, due to inadequate charging infrastructure, EV consumers still experience range anxiety. Vehicle-to-vehicle (V2V) charging is becoming a viable alternative for sharing energy between two EVs, with minimal infrastructure and expense. V2V energy sharing consists of two components: communication and power interface. Communication allows users to identify a match for energy sharing, choose a provider and recipient, and choose a tariff. Power interface regulates power flow direction according to the preferences of the receiver and provider, and a buck or boost conversion depends on the voltage level of the EV battery.V2V methods can be introduced by reusing on-board type-1 and type-2 chargers as power interfaces. This method reduces conversion efficiency due to cascaded converter losses and directly connects the two EVs' dc-links using mechanical switches. However, this method requires specialized design changes and extra charging ports to connect the dc-link terminals of the two EVs.The proposed V2V charging method for EVs directly connects the on-board type-2 chargers to the on-board type-2 power inlet ports, reducing the number of conversion stages in the energy transfer path. Efficiency is greatly increased when conversion steps are reduced, and mode selection logic determines buck/boost operating modes based on battery voltage levels and power flow direction. This allows EV consumers more flexibility to act as either a supplier or receiver.

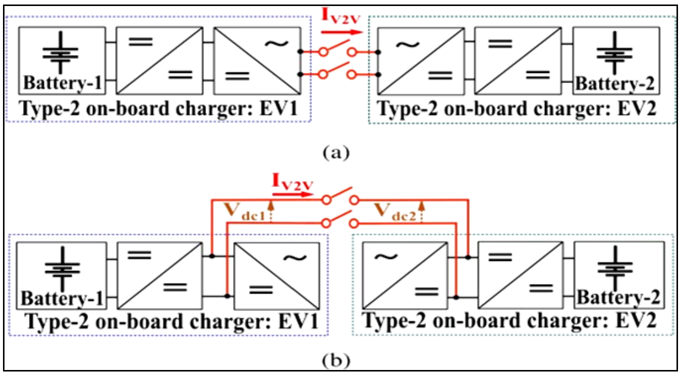

Fig 1: Shows the two types of V2V operations: (a) ac and (b) dc.

The article proposes a method to improve V2V efficiency by connecting two EV batteries via on-board active rectifier switches, instead of using off-board interfaces, contactor switches, or redundant power transfer stages. The method's control strategy, efficiency.

System Description

The receiver-EV and the provider-EV's current type-2 charging connectors are connected to create the suggested V2V setup. The three-phase active rectifier switches are used to connect the two EVs. The two EV batteries are directly connected through the intermediary dc-link of the provider and receiver EVs, as illustrated in Fig. 2, by turning on the top switch of one of the phases (phase-a, S1 here) and the bottom

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switch of the other phase (phase-c, S6 here) of the active rectifier-1 and the corresponding phase switches S1 and S6 of the active rectifier-2. During the V2V power transfer period, all four switches—S1, S6, S1, and S6—remain in the ON position. Regardless of the battery voltage levels of the two EVs, the suggested method of connecting them creates a dual bidirectional buck-boost converter that can be operated to transmit energy between them in any direction. The other switches of both type-2 chargers' active rectifiers are kept off during the V2V operation since they are being utilized as an interface to connect two dc-links rather than for their intended rectification function. The setup may function in one of the potential energy transfer modes, as explained below, depending on the battery voltage of two EVs.

A) V2V Scenario-1:

Vbat1 < Vbat2 As detailed below, there are two conceivable situations of boost and buck functioning with power flowing in either the forward or backward direction, respectively, when the EV-1 battery voltage is lower than the EV-2 battery voltage and provider–receiver role.

i). EV1 as the Provider and EV2 as the Receiver in Forward Boost Mode: In this mode, battery 1 has a lower voltage than battery 2, and EV1 is the charge giver while EV2 is the charge receiver. After two EV batteries are directly connected using the suggested method (by activating switches S1, S6, S1, and S6), the dc–dc converter-1 is operated in boost mode to step up the EV-1 battery voltage to the EV-2 battery voltage. As illustrated in Fig. 3(a), inductor L1 stores energy from the EV-1 battery during the switch Sb1's turn ON time, and the switch Sa1 is complimentary switched to Sb1. Through S1, S1, Sa2, and inductor L2, the energy of the EV-1 battery and inductor L1 is transferred to the EV-2 battery when Sb1 is turned off. As illustrated in Fig. 3(b), switch Sa2 is kept on throughout this V2V mode in order to accept power from the dc-links, resulting in Vdc1 = Vdc2 = Vbat2, and switch Sb2 is complimentary switched to Sa2.

ii). EV1 as the Receiver and EV2 as the Provider in Reverse Buck Mode: In this reverse buck mode, the switches S1, S6, S1, and S6 of the active rectifiers 1 and 2 are turned on to connect the EV batteries, just like in the forward boost mode. To move power from the EV-2 battery to the EV-1 battery, the dc–dc converter-1 is run in buck mode. As Vbat1 < Vbat2, the diode Da2 becomes forward biased, resulting in Vbat2 = Vdc1 = Vdc2, which frees up the EV-2 battery to supply power to the EV-1 battery via the dc-link. As seen in Fig. 4(a), the energy from the EV-2 battery is transferred to the EV-1 battery through inductor L1, Da2, S1, and inductor L2 during the switch Sa1's turn ON period.

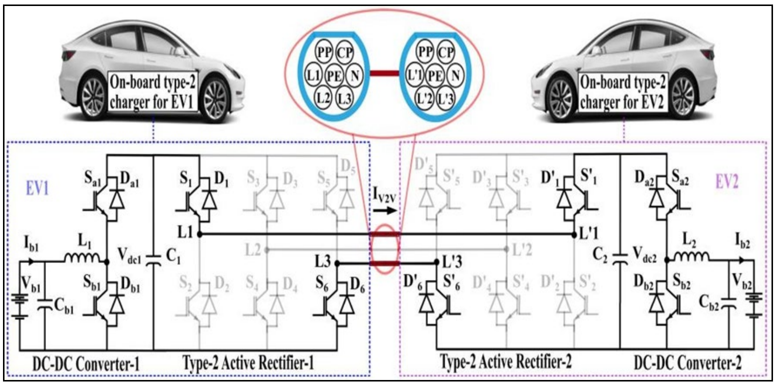


Fig 2: Proposed topology for V2V operation.

B) V2V Scenario-2:

Vbat1 = Vbat2 the dc-dc converters in this situation must be controlled, one in current-controlled boost mode and the other in current-controlled buck mode, because the voltages of the two EV batteries are equal.

i). EV1 as the Provider and EV2 as the Receiver in Forward Boost Style: Power transfer from EV-1 to EV-2 battery is accomplished in this mode with Vbat1 = Vbat2 by running the dc-dc converter-1 in boost mode and the dc-dc converter-2 in buck mode with closed-loop current regulation. Inductor L1 stores energy from the EV-1 battery during the switch Sb1's turn-on period, and switch Sa1 is complimentary switched to Sb1. As seen in Fig. 5(a), the switch Sa2 is complimentary switched to Sb2, and the switch Sb2 of the dc–dc converter-2 is also ON at the same time to freewheel the energy in inductor L2. As seen in Fig. 5(b), the switches Sa1 and Sa2 are activated to transfer energy from the EV-1 battery to the EV-2 battery via L1, S1, S1, and L2 during the turn OFF time of Sb1 and Sb2. This method can also be accomplished by using the receiver-side dc-dc converter in the current control mode and the provider EV side dc-dc converter in the voltage control mode to regulate the dc-link voltage at a greater voltage than the EV battery voltage.

ii). Using EV1 as the receiver and EV2 as the provider, reverse boost mode: While the power flow is reversed by operating the dc-dc converter-2 in boost mode and the dc-dc converter-1 in buck mode with closed-loop current management, this mode is comparable to the forward boost mode with Vbat1 = Vbat2. The power flow in this mode could also be managed using the voltage control mode.

C) V2V Scenario-3:

Vbat1 > Vbat2 With the direction of power flow inverted, the converter functions similarly to Scenario 1. 1) Reverse Boost Mode (EV1 as Provider and EV2 as Receiver): This mode is comparable to the forward boost mode with Vbat1 < Vbat2, but the power flow is inverted by running EV-2's dc-dc converter-2 in boost mode while maintaining EV-1's dc-dc converter-1's Sa1 always ON. In the Forward Buck Mode (EV1 as Provider and EV2 as Receiver), the power flow is reversed by running the dc-dc converter-2 of EV-2 in the buck mode while maintaining the Sa1 of the dc-dc converter-1 of EV-1 constantly ON. This mode is comparable to the reverse buck mode with Vbat1 < Vbat2.

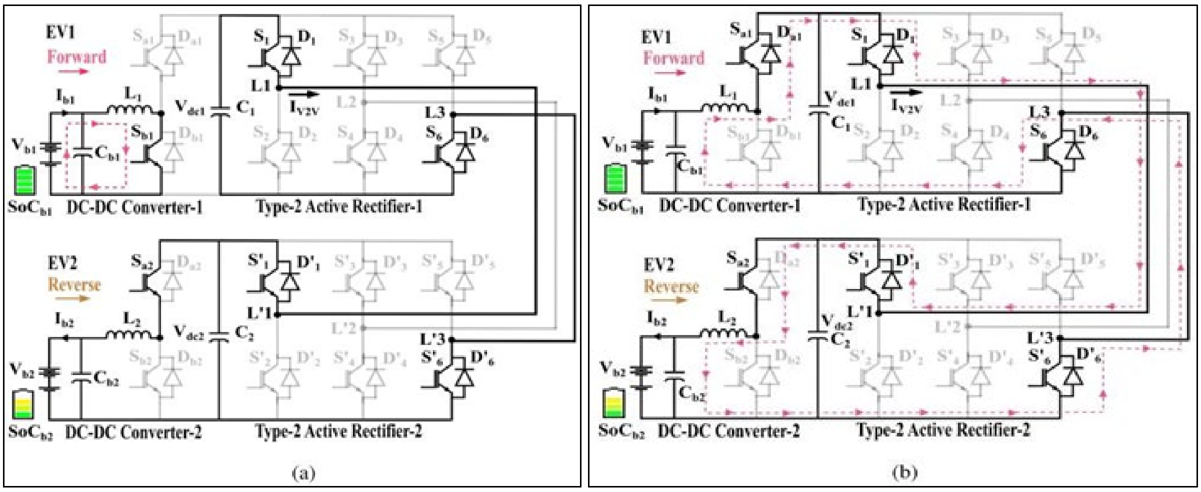


Fig 3: Forward boost V2V mode with Vbat1 < Vbat2. (a) The EV-1 battery's energy is stored in L1. (b) Energy is sent to EV2 via the dc-link.

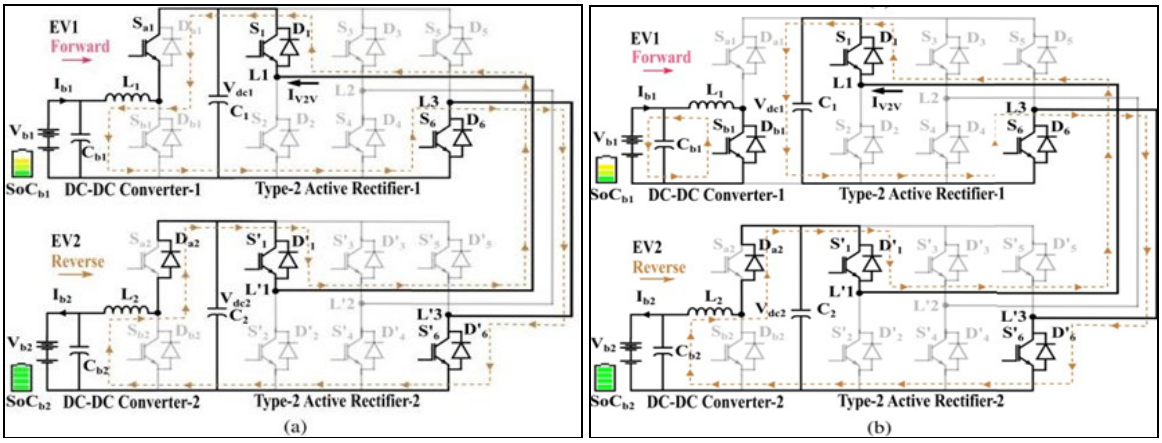


Fig 4: Reverse buck V2V mode with Vbat1 < Vbat2. (a) L1 uses dc-link to store energy from the EV-2 battery. (b) Freewheeling is used to store energy from L1 to the EV-1 battery.

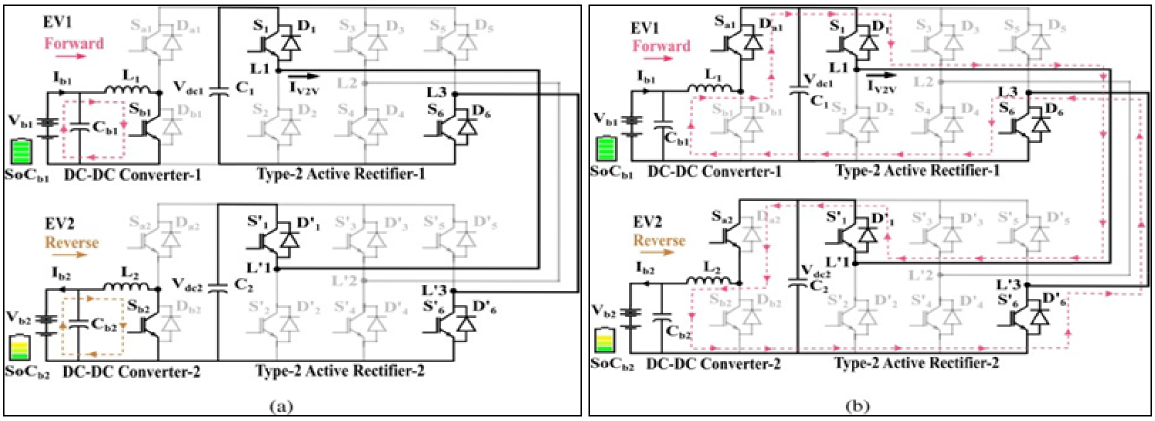


Fig 5: Vbat1 equals Vbat2 in forward boost V2V mode. (a) The batteries' energy is stored in L1 and L2. (b) Energy is sent to EV2 via the dc-link.

Control Scheme for the Proposed v2v Approach:

The on-board converters are used to regulate the charging rate and the energy transfer during the suggested V2V method. The EV-1 and EV-2 battery values as well as the provider receiver data are used by the mode selector flow seen in Fig. 6 to determine the V2V mode. Furthermore, depending on the mode of operation, the on-board charger converters are adjusted for reaching the proposed V2V as stated next in this section.

A. Active Rectifier Control via V2V Interface In order to convert three-phase ac to dc with unity power factor operating at the grid terminals, the active rectifier is usually regulated in d-q control mode during standard three-phase ac charging with a type-2 charger. The active rectifier is repurposed as an interface to connect and access the two EVs' batteries during the suggested V2V charging. The gating pulse for the switches S1 and S6 of the EV-1's active rectifier-1 and the switches S1 and S6 of the active rectifier-2 are maintained high during the V2V charging process for all modes after the type-2 charger ports are connected for V2V charging.

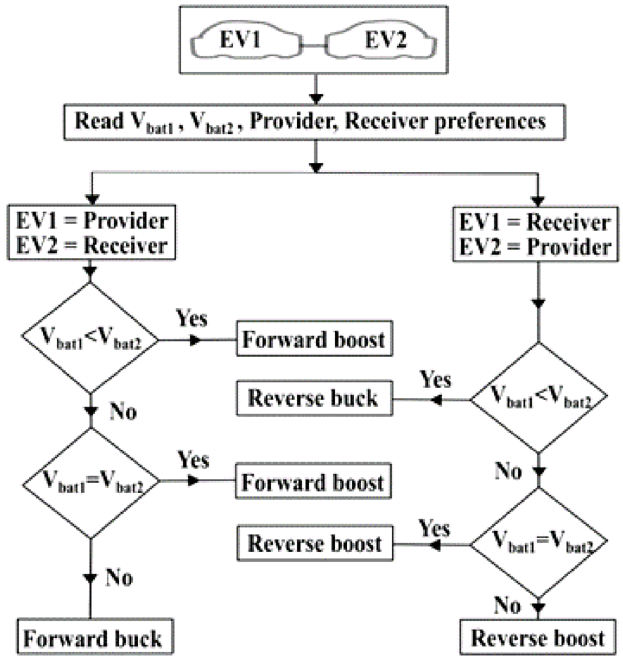


Fig 6: Shows the suggested control flow for V2V power transfer.

B. DC-DC Converter Control The type-2 chargers' dc–dc converters are closed-loop current-controlled for the suggested V2V charging method that makes use of the onboard chargers. For forward boost and reverse buck mode control (Vbat1 < Vbat2): In these modes, the inductor current IL1 of the dc–dc converter-1 is controlled in closed-loop by feeding a PI controller with the error between the reference current I ∗ L and the actual inductor current IL1 to generate duty ratio for switch Sa1. As illustrated in Fig. 7, Sb1 is complimentarily switched to Sa1. During this mode, the gating signal to the switch Sa2 is maintained at a high level. The following formula, where D is the duty ratio and R2 is the load resistance equal to the charging current of the EV-2 battery, provides the current to control transfer function to the dc–dc converter-1 used to tune the PI controller [20].

$$\frac{\widehat{I_{L1}}(s)}{\hat{d}(s)} = \frac{(C_1 V_{b1})s + 2(1-D)L_1}{(L_1C_1)s^2 + \frac{L_1}{R_2}s + (1-D)^2}.$$

Current of reference. The following formula is used to determine I ∗ L, where Tc is the preferred charging time and Ebat1 and Ebat2 are the kWh ratings of the EV-1 and EV-2 batteries, respectively. To determine the reference current, the lowest values between the two battery ratings and voltage levels are used.

$$I_L^* = \frac{\min(E_{\text{bat1}}, E_{\text{bat2}})}{\min(V_{\text{bat1}}, V_{\text{bat2}}) * T_c}.$$

The current rating Is1r of the on-board active rectifier IGBTs (S1, S6, S1, and S6) determines the maximum value of I ∗ L; if I ∗ L calculated from (2) is more than Is1r, the current reference will be caped to Is1r. The same control structure is utilized to control the IL2 in the forward orreverse direction for the forward buck and reverse boost mode with (Vbat1 > Vbat2) by creating the duty ratio for the switch Sb2, and switch Sa2 is complimentarily switched to Sb2. During this mode, the gating signal to switch Sa1 is kept high. Additionally, both dc–dc converters are run in current control mode to regulate IL1 and IL2 in the forward direction when using the forward boost mode with (Vbat1 = Vbat2).

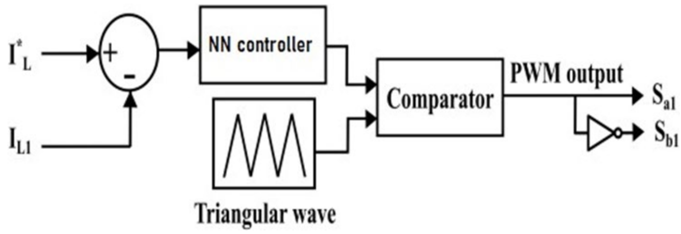


Fig 7: The forward boost and reverse buck modes' current control structure (Vbat1 < Vbat2).

There is a bidirectional V2V power converter interface available. The suggested V2V approach for commercial EVs is intended to offer a robust interface for the actual V2V power transfer through the hardware components of the on-board type-2 charger. It is assumed that communication between EVs and access to controllers and instrumentation sensors are easily accessible, as described in [10]–[12]. For V2V energy sharing, the receiver EV and the supplier EV are directly connected via the on-board type-2 charging connectors. As illustrated in Fig. 6, the V2V mode is determined by the battery voltage levels, provider, and receiver preferences, which are obtained by the on-board instrumentation sensors and EV user inputs. The on-board DSP controllers are used to command the direction of power flow and the necessary amount of energy transfer, depending on the mode of operation chosen (forward boost, for example). By activating the top and bottom switches on any two legs, the active rectifiers of both on-board chargers are managed to function as an interface. As mentioned in the first sections of this section, the battery side dc–dc converter of the on-board chargers is current-controlled to supply the necessary charge to the receiver EV after the dc-links of both chargers are connected. This depends on the V2V mode that is chosen.

Table 1: Simulation Parameters of the Proposed V2 V Approach

Parameter	Value
Battery-1 capacity (E_{bat1})	40 *kWh*
Battery-2 capacity *(E_{bat2})*	100 *kWh*
Battery-1 nominal voltage (V_{ba1})	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*
Li Internal resistance (R_1)	0.005 SΩ
L2 Internal resistance (R_2)	0.006 Ω
DC-link capacitor (C_1)	1000 *uF*
DC-link capacitor (C2)	1100 *uF*
DC-DC converter-1 capacitor *(Cb_1)*	5.6 *nF*
DC-DC converter-2 capacitor *(Cb2)*	5.8 *nF*

Artificial Neural Network (ANN) Controllers

One kind of control system that employs an artificial neural network (ANN) to manage a system or process is called an ANN controller. Comprising linked artificial neurons with the ability to learn and adjust to changing circumstances, the ANN controller is a computational model intended to mimic the activity of the human brain. Sensors that measure different aspects of the system under control, such temperature, pressure, or speed, send input signals to the ANN controller.

After processing these inputs, the ANN produces an output signal that is transmitted to an actuator or other control device to modify the behavior of the system. Applications for ANN controllers are numerous and include robotics, industrial automation, and self-driving cars. They are especially helpful when the system being controlled is complicated and challenging to simulate with conventional control methods. The capacity of ANN controllers to learn and adjust to shifting circumstances is one of their benefits. In order to reduce the error between the actual and projected outputs, the ANN modifies its weights and biases throughout the training phase after being given input-output pairs. Through this procedure, the ANN can discover the best control strategy for the system under control, which can subsequently be applied to modify the system's behavior in real time. All things considered, ANN controllers provide a strong and adaptable control strategy that may be applied to a variety of situations. ANN controllers are anticipated to grow even more potent instruments for resolving challenging control issues with continued study and development.

Working of ANN Controller:
One kind of control system that uses a neural network to learn and make choices based on incoming data is called an Artificial Neural Network (ANN) controller. The general steps involved in an ANN controller's operation are as follows:
Data Collection: Gathering information from the system or environment under control is the first stage in the procedure. The gathered information will be fed into the neural network.
Preprocessing: To prepare the gathered data for neural network input, it undergoes preprocessing. Scaling, normalization, and other data preprocessing methods might be included in this.

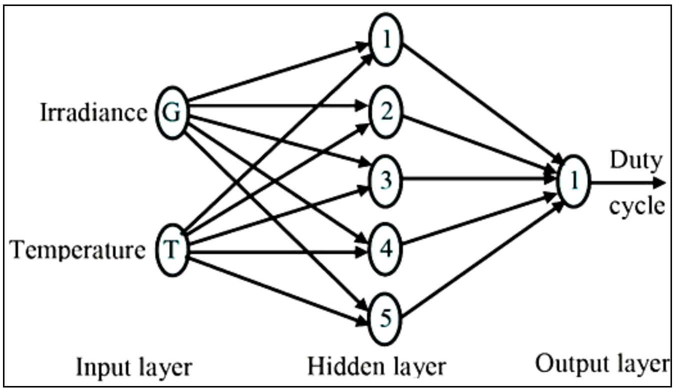
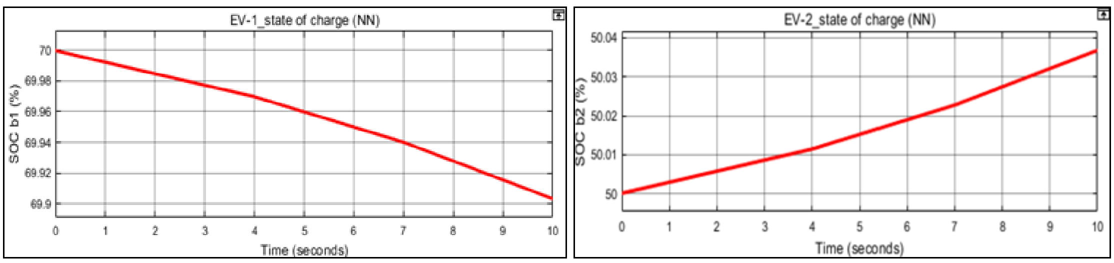


Fig 8: Structure of ANN controller

Design of Neural Network Architecture: The number of layers, the number of nodes in each layer, and the activation functions to be employed are all chosen while designing a neural network architecture.
Training: A dataset including input-output pairs is used to train the neural network. In order for the network to anticipate the output for new inputs with accuracy, the weights and biases must be adjusted.
Validation: A different dataset that wasn't used for training is used to verify the network's performance. This stage guarantees that the network can generalize to new data and is not overfitting to the training set.
Deployment: To make decisions based on the input data, the control system uses the trained neural network. The output of the neural network is utilized to manage the system under control, such a manufacturing process or a robot.
Monitoring and Optimization: The neural network is tuned to continuously increase its accuracy and efficiency while the system's performance is tracked. This stage could entail fine-tuning the neural network's parameters, training it on additional data, or changing the network's architecture.
An ANN controller's overall operation entails gathering and preprocessing data, creating and training a neural network, integrating it into the control system, and continuously assessing and enhancing its functionality to raise the accuracy and efficiency of the system.

Simulation Results and Discussion
Case 1:



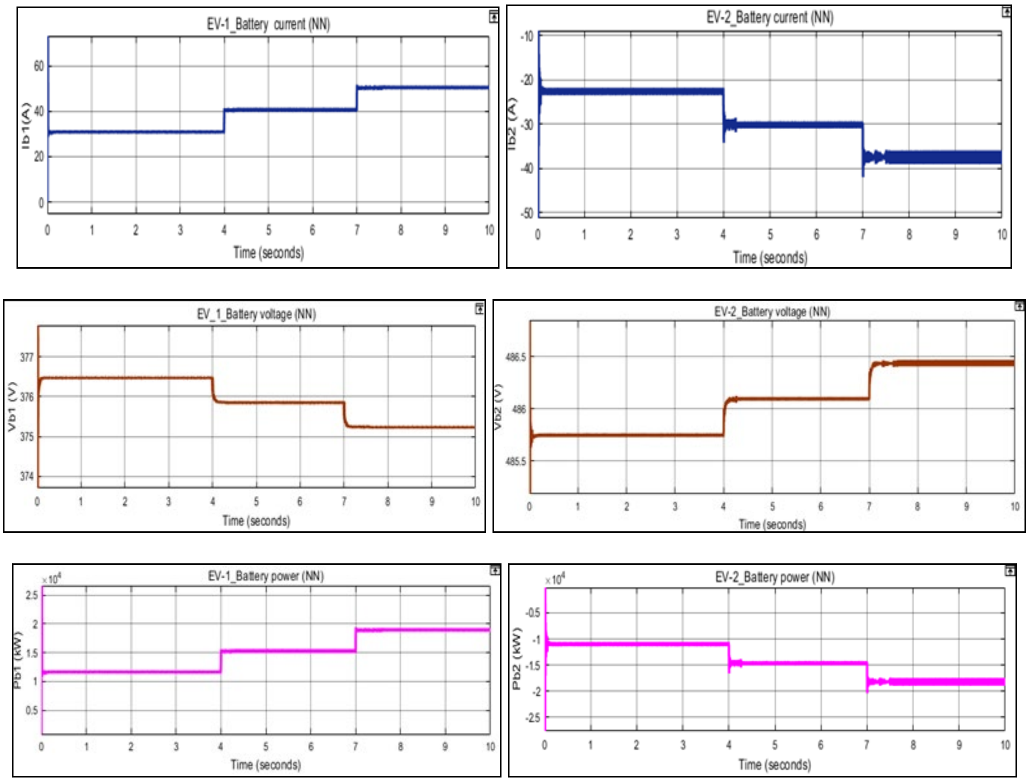
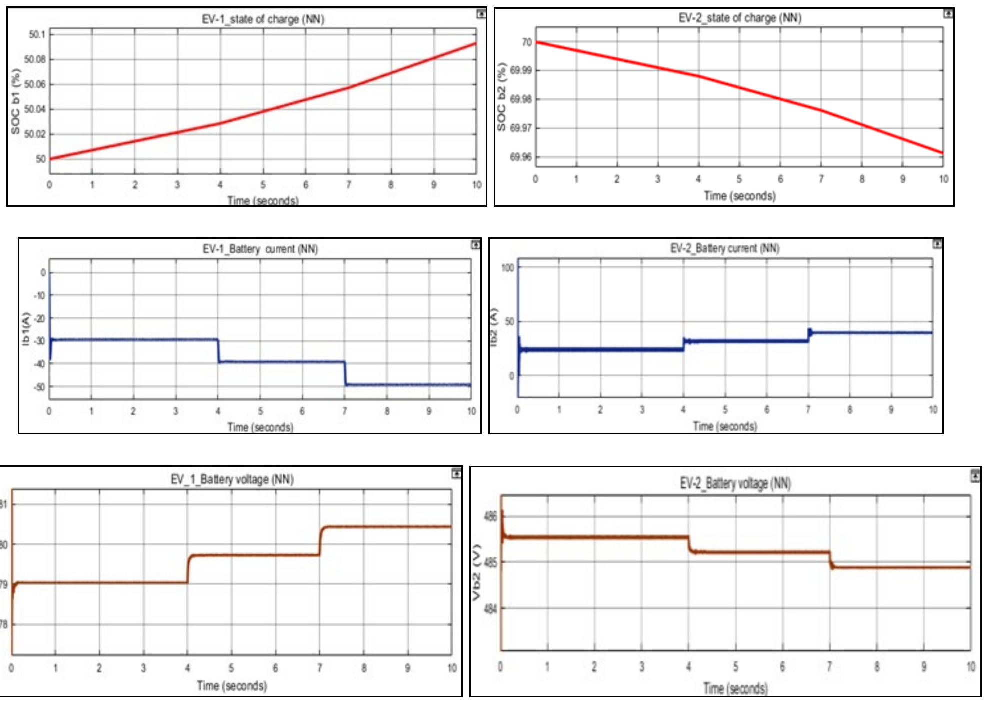


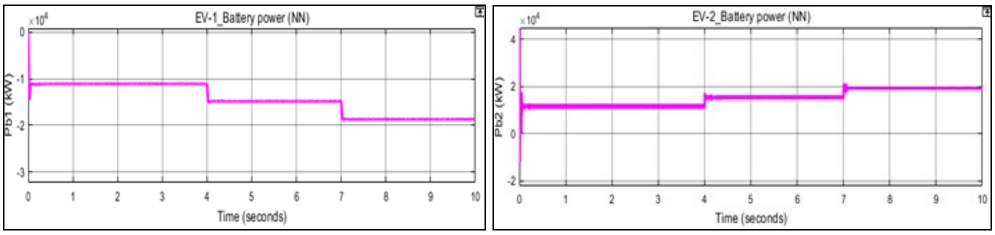
Fig 9: Results from simulations of the suggested V2V operation in forward boost mode with Vbat1<Vbat2.(a) SOC, voltage, current, and power waveforms of EV-1 battery. (b) SOC, voltage, current, and power waveforms of EV-2 battery.

In this operating mode, inductor current IL1 is controlled to transfer energy from the eV-1 to eV-2 battery. The discharge current Ib1 of the EV-1 battery is controlled by gradually increasing the initial reference inductor current IL*, which is set at 30A, in increments of 10A up to 50A. As shown in Fig. 9a, this control affects changes in EV-1's state of charge (SoCb1), voltage (Vb1), and discharged power (Pb1). As shown in Fig. 9b, the EV-2 battery experiences a concurrent increase in SoCb2, Vb2, and charged power (Pb2) due to a charging current Ib2. While both currents remain within the current rating of the active rectifier switches, positive battery currents indicate discharge and negative values indicate battery charging.

Case 2

Compared to forward boost mode, power flow is reversed in this operating state, although EV-1 and EV-2 battery voltage levels remain constant. As shown in Fig. 10a, the EV-1 battery is charged with current Ib1, increasing its voltage and state of charge (SOC). As shown in Fig. 10b, the EV-2 battery simultaneously suffers a discharging current Ib2, which causes variations in SOC and voltage in addition to the discharge power from the EV-2 battery.



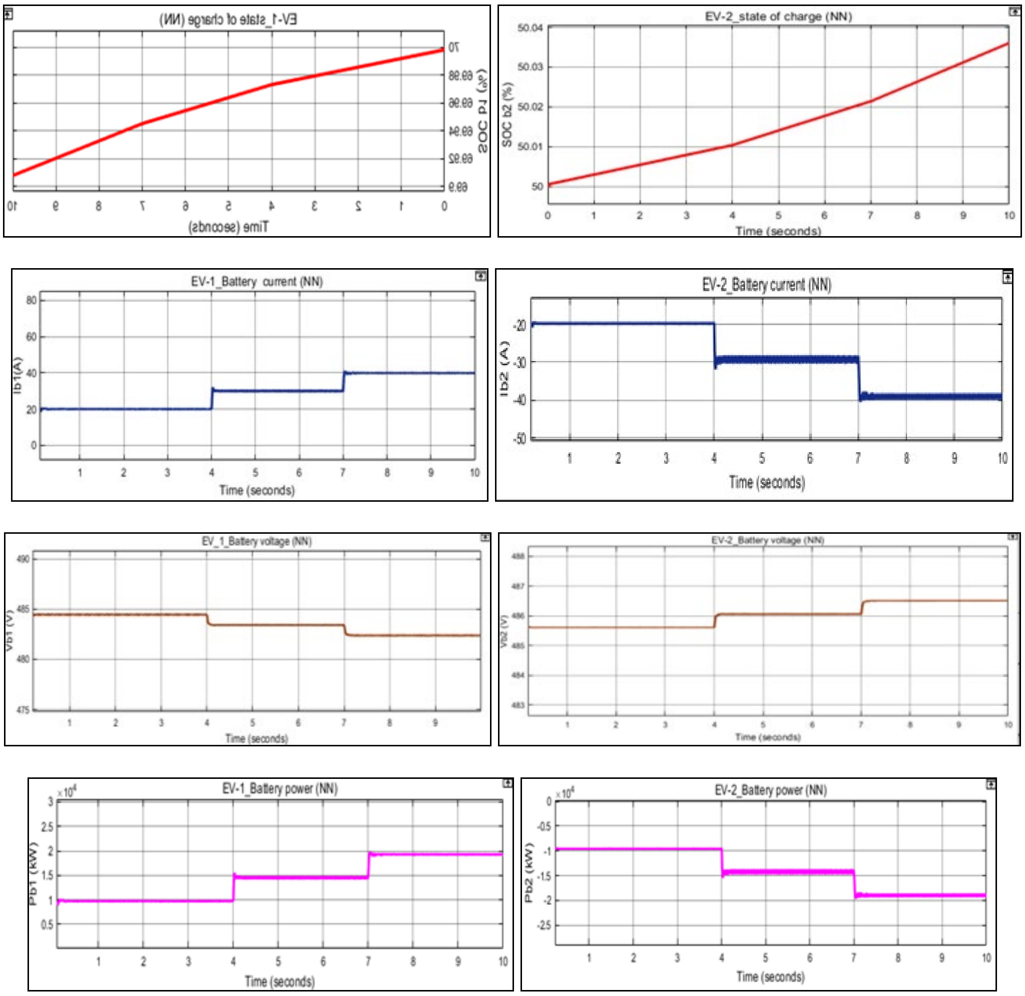


(a) **(b)**

Fig 10: Results from simulations of the suggested V2V operation with Vbat1 < Vbat2 in the reverse buck mode. (a) The EV-1 battery's state of charge, voltage, current, and power waveforms. (b) The EV-2 battery's state of charge, voltage, current, and power waveforms.

Case 3

In this mode, two identical electric vehicles with the same voltage levels exchange energy. IL1 and IL2 forward currents are controlled by a common current reference. Figure 11b shows the charging current and related changes in SOC and voltage for EV-2 batteries, while Figure 11a shows the discharge current of EV-1 batteries with variations in voltage, power, and SOC.



(a) **(b)**

Fig 11: The suggested V2V functioning in the forward boost mode with Vbat1 = Vbat2 was simulated. (a) EV-1 battery waveforms for state of charge, voltage, current, and power. (b) dc-link voltage, EV-2 battery SOC, voltage, and current.

Conclusion

To sum up, the use of Artificial Neural Network (ANN)-based controllers for energy transfer from electric vehicles to other vehicles via on-board converters has shown itself to be a very successful strategy. Through the use of MATLAB Simulink, the controllers showed notable gains in overall efficiency and power flow optimization in simulated scenarios. The ANN controllers' versatility and strong performance under a range of operational circumstances demonstrated its promise for real-world use. By offering a practical and effective way to optimize energy transfer processes, this research advances electric car technologies. To guarantee a smooth transition into developing electric vehicle systems, future research may concentrate on validating and improving the neural network models in the actual world. The study concludes that ANN controllers are a viable tool for improving the performance and sustainability of energy transfer systems between electric vehicles.

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