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Simulation of 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). ExistingV2V 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 V2Vcharging 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.

INTRODUCTION

ELECTRIC VEHICLE

Electric vehicles (EV), those that use electric motors instead of gasoline motors, have become very popular. Those who strive to protect the environment and go green love electric vehicles. But many would be surprised to learn that the EV isn't a new invention. While history is uncertain about who actually created the very first EV, what is certain is that there were electric motors in use as far back as the early 1800s. One known electric motor was created in 1828 by Anyos Jedlik. He made a small model car that could move on its own via a small electric motor. Sometime between 1832 and 1839, a larger electric motor created by Scottish inventor Robert Anderson was used to drive a carriage.

Of course, while these EV didn't exactly gain widespread use, they did spark the imaginations of others. In 1835, two small-scale EVs were created, one in Holland and one in the United States by Thomas Davenport. Davenport and would later create the first electric car to run on batteries, although these batteries were non-rechargeable and were unable to give the car much range. Others, including French inventor Gaston Plante, worked on better batteries, but still fell short of a practical vehicle.

In the early 1900s, American inventors return to the EV. Around this time, William Morrison created what many consider the first practical electric car, although it still lacked range. Hybrids were also created during this time to solve a number of issues with the EV.

1.1 TODAY'S ELECTRIC VEHICLES

Today, electric vehicles are more popular than they've ever been, and many are capable of driving fairly good distances on their batteries. The Tesla Roadster became available in 2008. While far from perfect, it was able to cover more than 200 miles on one charge of the battery. It was followed fairly quickly by the Mitsubishi i-MiEV in Japan. The development and release of these two vehicles, but especially of the Tesla, marked the beginning of the modern EV period.

Other major car companies quickly began working on their own electric cars. Many already produced hybrids, so the technology was already widespread. GM released the Chevrolet Volt, while Nissan released the Leaf, an all-electric five door hatchback. However, much like the Tesla, the major developments in EV are coming from smaller companies. The Better Place network created the first EV with a swappable battery.

There are a number of reasons to buy an EV. The engines are very quiet, and the ride is very smooth. They actually have a higher torque than most people expect, too, because the power is sent straight to the wheels. There's no need to visit a gas station, either, and while drivers do have to pay for the electricity used in charging the car, it's less than gas prices.

On the downside, EVs are not for everyone yet. Most are limited to about a 100 mile range, and it often takes about an hour of charging for one vehicle to travel 25 miles. EVs are also quite expensive, although Tesla is working on one that will be around $20,000. The lack of a diverse market leaves few choices for consumers, too.

1.2 ALTERNATIVES TO THE ELECTRIC VEHICLE

While EVs are quite popular, they may not be for everyone. There are some alternatives to electric cars that may interest some drivers. The electric scooter or moped, for example, provides some of the same benefits of an EV with a much smaller price tag. Riders can also make use of the bicycle lane and don't have to worry about parking. Of course, it doesn't do well in the rain.

Some companies are experimenting with using solar panels as a way to charge EVs. They have looked at placing solar cells directly on vehicles or on vehicle charging stations. While this is still a type of EV, the use of solar cells instead of plugging in means the car can charge whenever it's in sunlight, alleviating some of the battery life issues.

Hydrogen is a potential alternative fuel source that a number of companies are currently researching. It's emissions-free and is most often created by using a technique known as steam reformation. This transforms methane into hydrogen. Currently, most of this hydrogen is used in refining petroleum and processing foods, but it has been used as a power source in space flight for decades.

There are a number of other alternative fuels currently being studied. The Energy Policy Act of 1992 lists fuels such as Biomethane, drop-in biofuels, and biobutanol as potential fuel sources. However, while they have been used to power a vehicle, much more research and development is needed before they become commercially viable power sources.

The Basics of Hydrogen Fuel – A summary of using hydrogen as fuel by the U.S. Department of Energy.

Hydrogen Fuel Cells – How this energy source works

Emerging Technologies – This article discusses many different alternative energy sources for both vehicles and other uses.

Hydrogen and Fuel Cells – – A look at producing and using hydrogen.

1.3 THE FUTURE OF EV

While the future of EVs may have been debatable ten years ago, it's obvious that they're now here to stay. However, there's some question as to what kind of form EVs will take in the future. Many people still cite the high cost and low range as the reason why they haven't purchased an EV. That may change, though, as the market becomes more competitive. In 2014, Tesla released all of their patents on their EV technology. This means any company that wants to use or improve upon Tesla's electric motors is free to. CEO Elon Musk said the company hopes others will see ways of improving on their technology, which can only benefit the EV industry and the average customer

Experts in the field expect vehicles to easily get 400 miles to a charge within 10 years, while others believe that the cost of the lithium-ion batteries used in most EVs will decrease to the point that the vehicles are much more affordable.

However, many auto manufacturers aren't quite ready to give up on gas. Because the average driver is much more comfortable and familiar with gasoline-powered cars, many aren't ready to lose their safety net. The allure of cheap fuel is tempting to many, though, which is why hybrids are selling very well. This transitional vehicle is likely to continue to become more and more popular, especially as mileage increases.

There are a few types of EV technology, the most common are plug-in electric hybrid vehicles (PHEV), range extender electric vehicles (REEVs) and battery electric vehicles (BEVs). In this introduction, we're going to be focusing more on the latter: BEVs. However, we'll tell you a little bit about the hybrids too because we're good like that.

A vehicle propelled by an electric motor, rather than a traditional petrol or diesel engine. The electric motor is powered by rechargeable batteries that can be charged using household mains electricity via an EV charge point at home or at a more powerful EV charge station at work or in the street.

Battery electric vehicles

Battery electric vehicles use electricity, which is stored in a battery pack to power an electric motor and turn the wheels. When depleted, the batteries are recharged using grid electricity from a dedicated charging unit. You refuel the EV by plugging it into the charging unit or charging station, much like charging a mobile phone.

Plug-in hybrid electric vehicles

The same technology exists in hybrid vehicles, alongside a small petrol or diesel engine that also connects to turn the wheels when the battery is depleted. This powers the car at cruising speed, and batteries either provide power until depleted or extra power when accelerating. Batteries can recharge themselves when the car is decelerating or when plugged in. Hybrid technology means less pollution from the exhaust pipe, and can save you money if you charge the battery before each journey.

Range Extender Electric Vehicle

With the range extender vehicles, the petrol or diesel engine only kicks in when the battery is depleted, and instead of supplying locomotion to the wheels it instead recharges the battery which drives the car forward through the electric motor. The combustion engine is designed to be used on the odd occasions that the journey is too far for the electric battery to satisfy, and helps to alleviate some concerns with range limitations of battery electric vehicles.

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1.4 ELECTRIC VEHICLE TYPES

To decrease the dependence on fossil fuels and to promote sustainable transportation automobiles industries are migrating from ICE (Internal Combustion Engine) based vehicle to electric vehicles. These electric vehicles based on the propulsion system can be classified into various types as follows,

Pure Electric Vehicle (PEV)

Hybrid Electric Vehicle

Plug-in Hybrid Electric Vehicle

Pure Electric Vehicles (PEV)

These PEVs based on the energy storage units are categorized as battery powered EV (BEV), Fuel cell powered EV (FCEV), Ultracapacitor EV (UCEV). BEVs are powered solely by socket electricity without any ancillary source of propulsion (ICE). Generally, gearbox is not required for EVs because of the high torque in electric motors. When comparing it with internal combustion engines (~30-45%), the efficiency (~90 %) is high with respect to electric motors. Fig 1.1 shows the schematic diagram of the battery electric vehicle. These battery electric vehicles (BEVs) require less maintance and are more reliable. These vehicles can be charged during braking or from renewable sources such as solar, wind etc.,

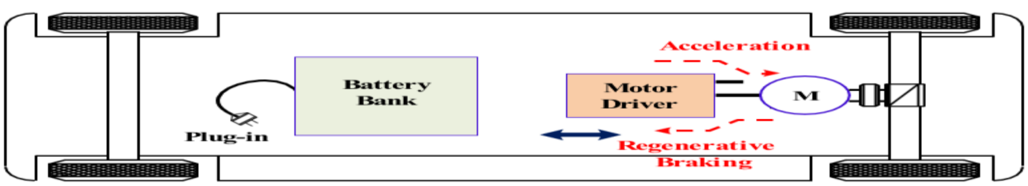

Fig 1.1 Schematic Diagram of Battery Powered Electric Vehicle

Hybrid Electric Vehicles (HEV)

HEV are driven by an internal combustion engine (ICE) in combination with single or additional energy stored in battery bank. The batteries in these vehicles are charged by regenerative braking or by ICE. The additional power required for driving EV is provided by electric motor. Fig 1.2 depicts the hybrid electric vehicle schematic arrangement. There exists two types of HEVs, such as plug-in HEV and range extended HEV (RHEV). Based on the connection of motor and engine they can be further classified as parallel hybrid vehicles, and

series hybrid vehicles.

Schematic diagram of series hybrid electric vehicle system is shown Fig 1.3 in which electric drive motor controls the wheels. Internal combustion engine (ICE) powers the generator to drive the electric motor. It permits the rejection of gearbox and the deacceleration depends upon the charged power from the battery.

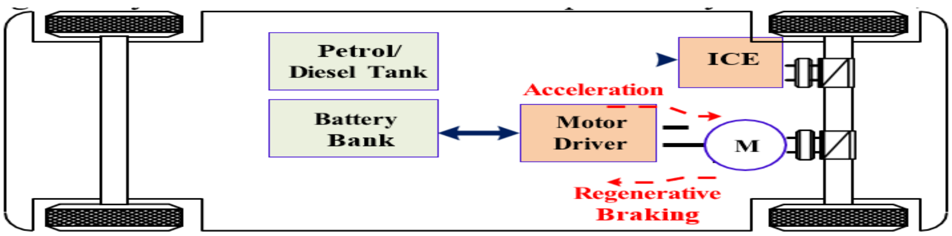

Fig 1.2 General Block Diagram of Hybrid Electric Vehicle

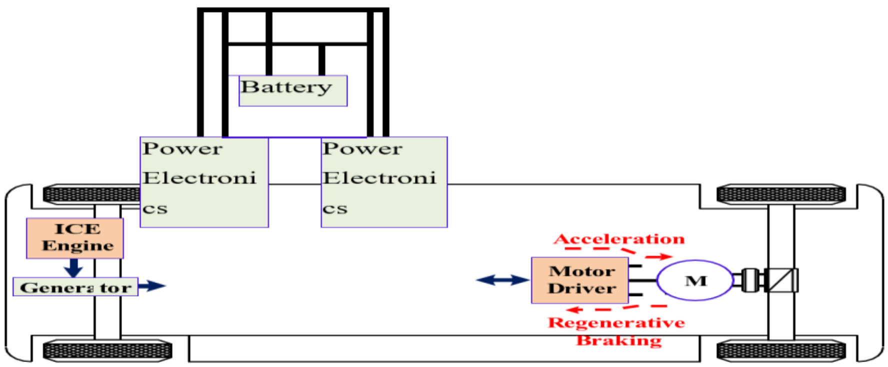

Fig 1.3 Series Hybrid Electric Vehicle Topology

Fig 1.4 shows the parallel hybrid vehicle in which the internal combustion engine (ICE) operates in parallel with electric motor and utilizes an automated gearbox. These type of EVs can run with fossil fuel or with electricity or with the combination of both.

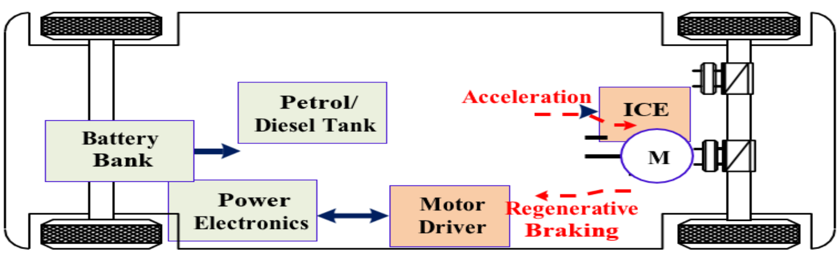

Fig 1.4 Parallel Hybrid Electric Vehicle Topology

Plug-in Hybrid Electric Vehicle (PHEV)

The block diagram of the PHEV is shown in Fig. 1.5. It consists of both ICE and Electric motor drive unit. The drive power is shared by either ICE or Electric motor. During the starting period, the battery power is utilized and whenever high load/torque is needed the ICE operation will take place. The onboard charger unit will provide the charging of battery unit which can be directly interfaced with power grid.

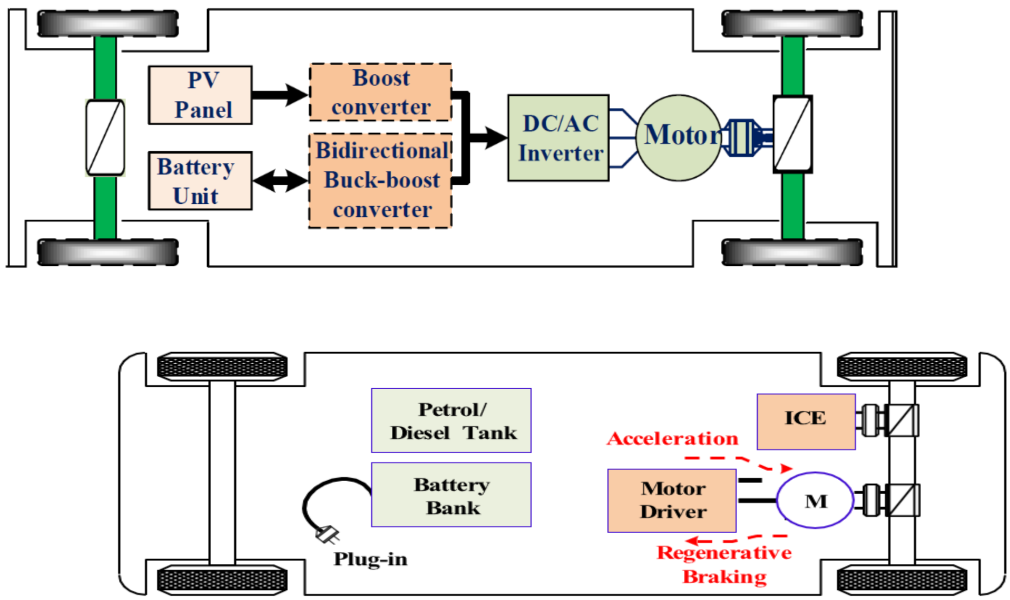

Fig 1.5 Plug-in Hybrid Electric Vehicle Topology

1.5 ELECTRIC VEHICLE OPERATION PRINCIPLE

Hybrid electric vehicles (HEVs) can be of two different types. Chemical energy stored in rechargeable battery power pack is used for battery-based electric vehicles and pure electric vehicles. EV requires DC converters to integrate the sources such as a photovoltaic cell (PV) or Fuel Cell (FC) and the drive system. An efficient DC power converter is required to propel the motor drive system without much power losses.

In the case of EV, this power electronic converter must possess the bidirectional capability while interfacing the energy resources with the battery and the motor drive system. Thus the conversion of conventional vehicular systems into electric, hybrid electric vehicles can be achieved by adding energy storage units such as batteries and ultra capacitors.

Fig 1.6 General Block Diagram of DC/DC Two Input Converter Integrated EV

Fig 1.6 illustrates the EV block diagram of the existing two input DC/DC converter for electric vehicle applications. When adequate amount of PV power is available, the battery is in charging conditions and the vehicle accelerates with the input of PV source. When sufficient PV power is not available, the battery is in discharging condition and the vehicle accelerates with the input of battery bank.

The main contribution blocks of electric vehicles are DC/DC power converter and DC/AC inverter. Mostly, EV utilizes only a single input and single output conventional DC/DC power converter and additional bidirectional buck-boost converters are utilized in the battery management system.

1.6 MOTIVATION

Electric Vehicle-to-Vehicle (V2V) charging is emerging as a transformative solution to address the growing need for efficient and flexible energy sharing among electric vehicles (EVs). Traditional charging infrastructures often limit the ability of EVs to share power, leading to challenges in managing energy distribution during long trips or in areas with limited charging stations. Existing V2V approaches, while promising, introduce additional space, weight, and costs due to off-board power-sharing interfaces or inefficient power conversion processes. This adds a layer of complexity for EV owners and diminishes the overall feasibility of widespread adoption. The need for a more streamlined and cost-effective solution is critical to overcoming these challenges and enabling more seamless energy sharing among EVs. The proposed direct battery-to-battery V2V charging method addresses these issues by eliminating redundant power conversion stages and utilizing the existing type-2 AC charger input ports, ultimately enhancing V2V energy transfer efficiency. This innovative approach has the potential to revolutionize how EVs interact, offering a more practical and energy-efficient solution that can be validated both through simulations and real-world experiments.

1.7 OBJECTIVE

The objective of this work is to develop a novel and efficient method for Vehicle-to-Vehicle (V2V) charging that eliminates the inefficiencies and additional costs associated with existing V2V power-sharing approaches. Specifically, the proposed method aims to bypass the redundant power conversion stages involved in traditional systems by directly connecting the batteries of two electric vehicles (EVs) through their type-2 AC charger input ports and switches. By optimizing the use of the existing onboard charger components and minimizing power conversion losses, the objective is to significantly improve the efficiency of energy transfer between EVs. This method will be validated through detailed MATLAB/Simulink simulations, as well as the development and testing of a scaled experimental prototype to ensure practical feasibility and effectiveness in real-world applications.

PROPOSED SYSTEM

Basically, the on-boardtype-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 3.1(a) where in the provider EV battery dc output is first converted into single-phase ac using the bidirectional two-stage on-boardtype-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 3.1(b) However, practically, there is no direct access to the dc-link of battery side dc–dc converters for establishing the presented direct connection.

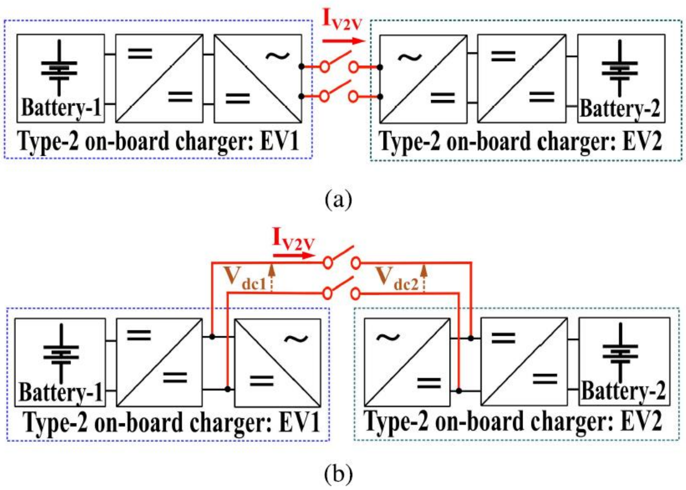

Fig 3.1 V2V operations: (a) ac V2V operation and (b) dc V2V operation

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 the receiver-EV. The two EVs are connected by utilizing the three phase 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-2directly connects the two EV batteries through the inter mediate dc-link of provider and receiver EVs .

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

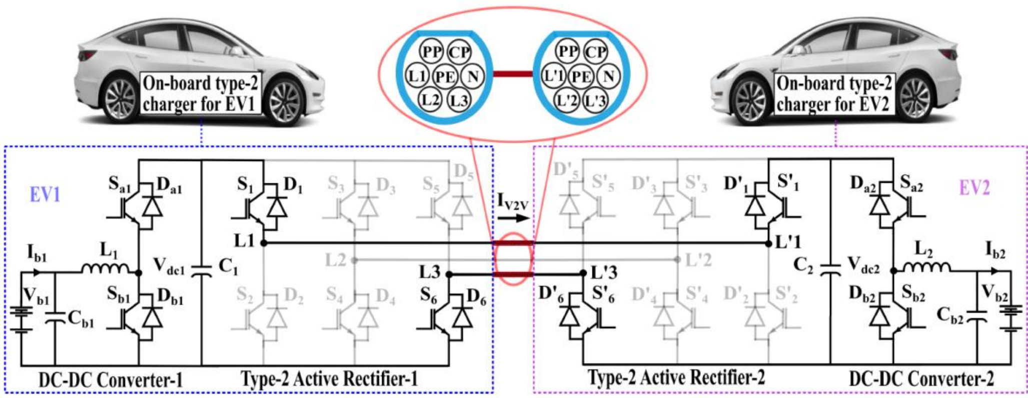

Fig 3.2 Proposed topology for V2V operation.

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 EV2is charge receiver with battery-1 having lower voltage thanbattery-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 theEV-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 Fig3.3(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 Fig3.3(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 *Sa*1, the energy from the EV-2 battery is transferred toEV-1 battery through inductor *L*1, *Da*2, *S*_1, and inductor *L*2 as shown in Fig3.4(a). During the turn OFF period of *Sa*1, the energy in the inductor *L*1 freewheel through switch *Sb*1 which is complementary switched to *Sa*1 as shown in Fig3.4(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 current controller boost mode and the other in current-controlled buck mode.

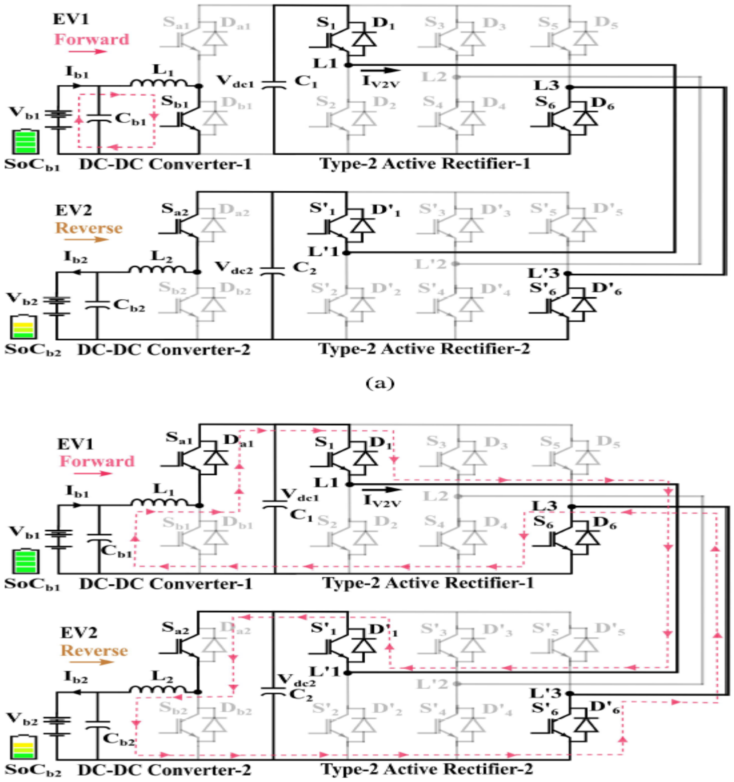

Fig 3.3 Forward boost V2V mode with Vbat1 < Vbat2. (a) L1 stores energy from EV-1 battery. (b) Energy is transferred through dc-link to EV2.

1) Forward Boost Mode (EV1 as Provider and EV2 as Receiver):

In this mode with Vbat1 = Vbat2, power transfer from EV-1 to EV-2 battery is achieved by operating the dc–dcconverter-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–dcconverter-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 Fig3.3(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 Fig3.3(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 Vbat1 = Vbat2 but the power flow is reversed by operating the dc–dc converter-2 in boost mode and the dc–dc converter-1is 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 theScenario-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 Vbat1 < Vbat2 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.

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2) Forward Buck Mode (EV1 as Provider and EV2 as Receiver): This mode is similar to the reverse buck mode with Vbat1 < Vbat2 but the power flow is reversed by operating the dc–dc converter-2 of EV-2 in the buck mode, and keeping the Sa1 of the dc–dc converter-1 of EV-1 always ON.

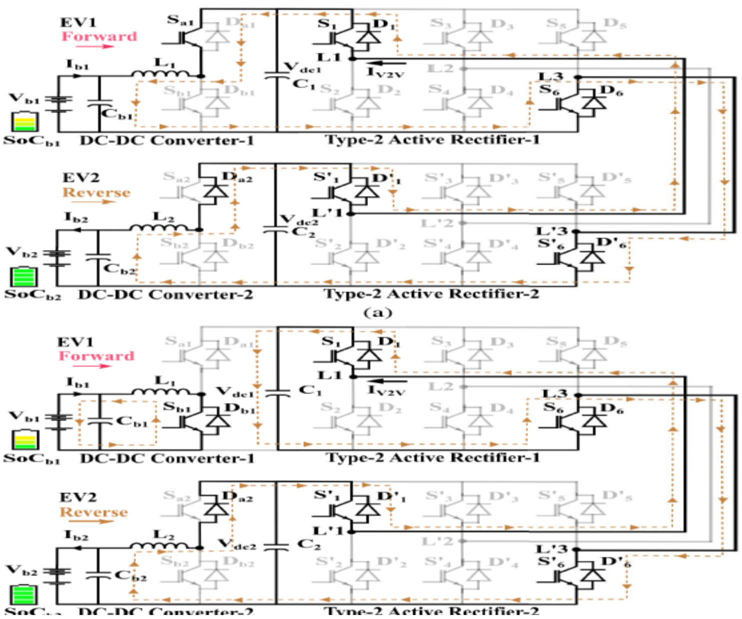


Fig3.4 Reverse buck V2V mode with Vbat1 < Vbat2. (a) L1 stores energy from EV-2 battery through dc-link. (b) Energy is stored from L1 to EV-1 battery through freewheeling

CONTROL SCHEME FOR THE PROPOSED V2VAPPROACH

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 Figure 3.3(a) 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

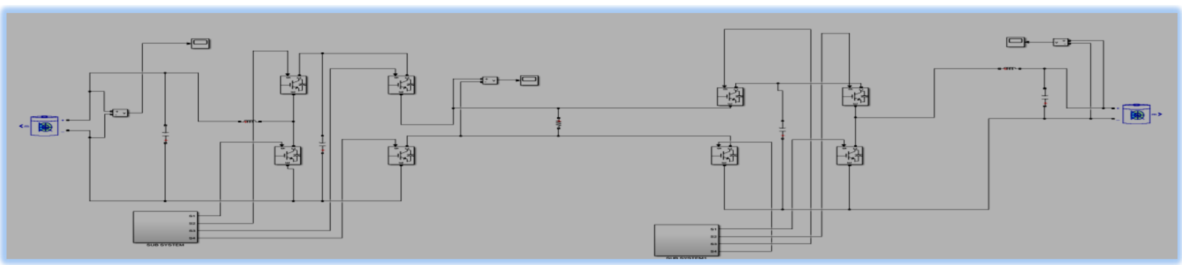
3.1.1. Control of the Active Rectifiers as V2V Interface

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 with 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 V2Vcharging for all the modes.

3.1.2. 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 in closed-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 Gating signal to the switchSa2 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 *R*2 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-2charger 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 forV2V. These aspects of V2V are already discussed with details of game theory-based algorithms to match the receiver and the provider EVs with an assumption that the Fig 3.3 Proposed V2V power transfer control flow. Fig3.4 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.

OVER ALL SIMULATION MODEL:



MATLAB Simulink.

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 V2Vapproach 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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