"DESIGN AND SIMULATION OF BIDIRECTIONAL DC-DC BUCK AND BOOST CONVERTER WITH BATTERY INTEGRATION"

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ABSTRACT

The increasing demand for efficient energy management systems has led to the development of bidirectional DC-DC converters, which are crucial for applications involving energy storage systems like batteries. This paper presents the design and simulation of a bidirectional DC-DC buck and boost converter integrated with a battery, aimed at optimizing power flow between a DC source and the battery. The proposed converter operates in both buck and boost modes, allowing seamless transition between charging and discharging operations of the battery. The buck mode steps down the input voltage to charge the battery, while the boost mode steps up the battery voltage to meet the load requirements when discharging. The converter's bidirectional capability enables its use in hybrid electric vehicles, renewable energy systems, and uninterrupted power supplies (UPS), where energy storage and management are critical. The design is simulated using MATLAB/Simulink, which allows for a detailed analysis of its performance, including voltage regulation, efficiency, and response time under various load conditions. Key parameters such as inductor sizing, switching frequency, and duty cycle control are optimized to achieve high efficiency and minimal switching losses. The results demonstrate that the proposed bidirectional converter effectively manages power flow while maintaining battery health through controlled charge-discharge cycles. This paper concludes that integrating a bidirectional DC-DC converter with a battery enhances system flexibility and efficiency, making it a viable solution for modern energy management challenges.

Keywords- Bidirectional DC-DC converter, Buck-boost converter, Battery integration, Energy storage, MATLAB/Simulink, Power management, Voltage regulation, Hybrid electric vehicles, Renewable energy, Charge-discharge cycle.

1. Introduction

Automobiles are the most contemporary kind of vehicle transportation, and vehicles have been influencing human civilisation for generations, reaching beyond a few small settlements[1]. Because traditional cars burn petrol, diesel, or natural gas and emit toxic exhaust components including carbon dioxide (CO2), sulphur dioxide (SO2), and nitrogen oxides, their growing use is endangering both the environment and human health [2]. As seen in Figure 1, the transport sector in the EU is responsible for around 25% of greenhouse gas (GHG) emissions. GHG emissions in the transport sector rose up to 36% between 1990 and 2010, whereas GHG emissions from other sources decreased by 15% during same time. Conventional vehicle replacement is becoming more important in order to address this issue and uphold the regulations of the signed "Doha Amendment to the Kyoto Protocol (2012)."[3].

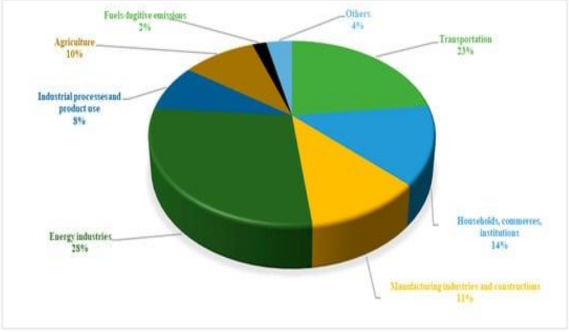

Fig 1 2017 Greenhouse gas emissions by sector according to the Intergovernmental Panel on Climate Change [4].

The mass consumption of EVs, which rely on low GHG emission, has excellent potential to significantly reduce the use of GHG-emitting transportation fuels [5]. Therefore, the vehicle industries have had little option but to shift towards EV powertrains. Moreover, as shown in Figure 2, EV trading is forecast to increase by a further 75% within the next two years. According to the 2017 International Energy Agency (IEA) report, research needs to be conducted focusing on the BEV and PHEV powertrains to meet the demand slope in coming years[6], whereas FCEVs are an underdeveloped area to date due to the high cost of fuel cells, production, transportation and storage of hydrogen, and the life cycle and reliability of the fuel cells [7].

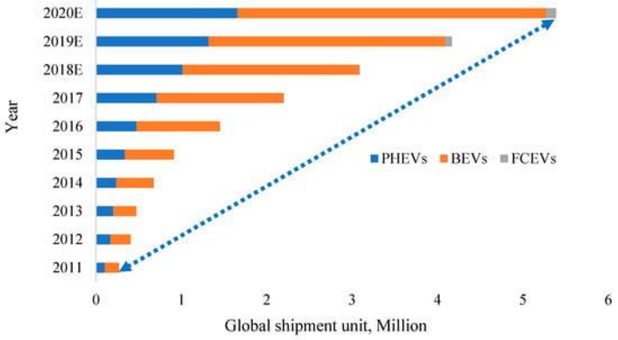

Fig 2 Estimated global shipments of EVs and PHEVs (2017 International Energy Agency (IEA) report [8].

State-Of-The-Art Ev Charging

A section of the electrical grid located in a public parking lot, business building street, or residential garage is known as an EV charging station. Both methods of charging are possible: dc charging is regarded as Level-3 charging that necessitates off-board chargers, whilst ac charging often specifies Level-1 and Level-2 charging for on-board chargers. Since Level-1 charging offers the lowest power level, it is the slowest of all [9]. Residential structures are often where it is put, and charging takes place at night. With an input voltage 120Vac or 230Vac, a Level-1 AC charger can provide around 1.92kW of power [10].

A common J1772 connector may be used to connect to the EV's ac port [11]. Level-2 ac chargers are mostly used in commercial locations like shopping centres, offices, and so on, and may provide up to 20kW of power. Current Level-2 charging stations need 208Vac or 240Vac as input voltage [12]. While the IEC62196-2 Type-2 plug is taken into consideration for Level-2 ac charging in Europe, the SAEJ1772 Type-1 or proprietary Tesla plug is the Level-2 charging connection in the United States [13]. Level-3 dc fast chargers, which can handle power in the range of 50kW to 300kW, have grown in popularity as a result of the restricted power rating and longer charging time of on-board Level-1 and Level-2 ac chargers [14]. They can charge the current EV batteries in 30 minutes and provide dc voltage of around 300V or greater, up to 800V [15]. Because of the high power flow, chargers are positioned outside to minimise the vehicle's weight and volume [16]. EVs often come equipped with an internal on-board charger. off-board dc fast chargers connect straight to the EV battery, eschewing the onboard charger [17]. While CCS combo 3, CHAdeMo, and the Tesla supercharger are used in Europe, CCS combo 1, CHAdeMo, and the Tesla supercharger are taken into consideration for Level-3 dc charger connectors in the US [18]. DC ultra-fast charging, which allows EV batteries rated at 400kW or more to be completely charged in 10 minutes, has emerged as a viable way to further lessen range anxiety among EV drivers and to be very competitive with the IC engine-based refuelling procedure [19].

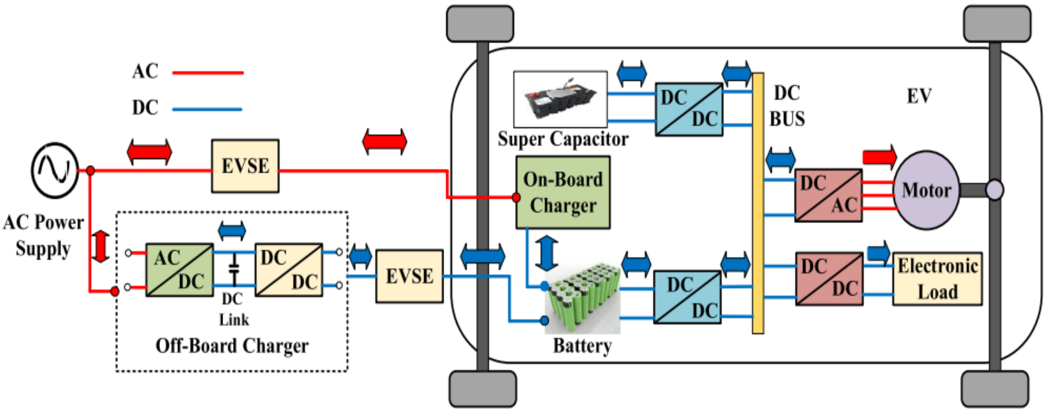

Fig Electric vehicle (EV) charging system including off-board and on-board charger [20].

Electric Vehicle Fast-Charging Technology and System Structure

1. Charging Level of Electric Vehicles

There are two types of EV charging systems: slow-charging and fast-charging. Level 1 and Level 2 on-board charging systems are often referred to as slow-charging systems. It takes around 8 to 10 hours for Level 1 on-board charging systems to completely charge a power battery [21]. Their output power is typically less than 10 kW, and they are mostly used in residential structures. On the other hand, Level 2 charging systems charge batteries more quickly than Level 1 systems. Their output may exceed 20 kW, and they are often seen in public spaces like malls [22]. On-board charging systems are one of the two primary topologies for slow-charging systems that are now available [23]. One is a single-stage architecture that includes a high-frequency DC/DC converter and an unregulated rectifier. This topology encompasses half-bridge, full-bridge, push-pull, flyback, and forward. Although single-stage topologies have the benefits of being compact, simple, and having fewer components, they may readily contaminate the grid since they are directly linked to it[24]. The second is a two-stage charging system that has a DC/DC converter in the backstage and power factor correction in the front stage. Although the two-stage charging method is expensive and inefficient, it can successfully handle the problems of low power factor and significant harmonic pollution. Although more sophisticated control techniques, like BP neural network PID control methods and fuzzy adaptive PID control methods, have also been developed and can greatly alter the charging output characteristics, the traditional PID control method is still frequently used for slow-charging systems [25].

2. Electric Vehicle Fast-Charging System Architecture

EV charging systems generally have a centralized layout in a specific area, and the power supply typically employs AC coupling or DC coupling, that is, multiple independent charging systems use the common AC bus or common DC bus to obtain power. The configuration is shown in Figure 3

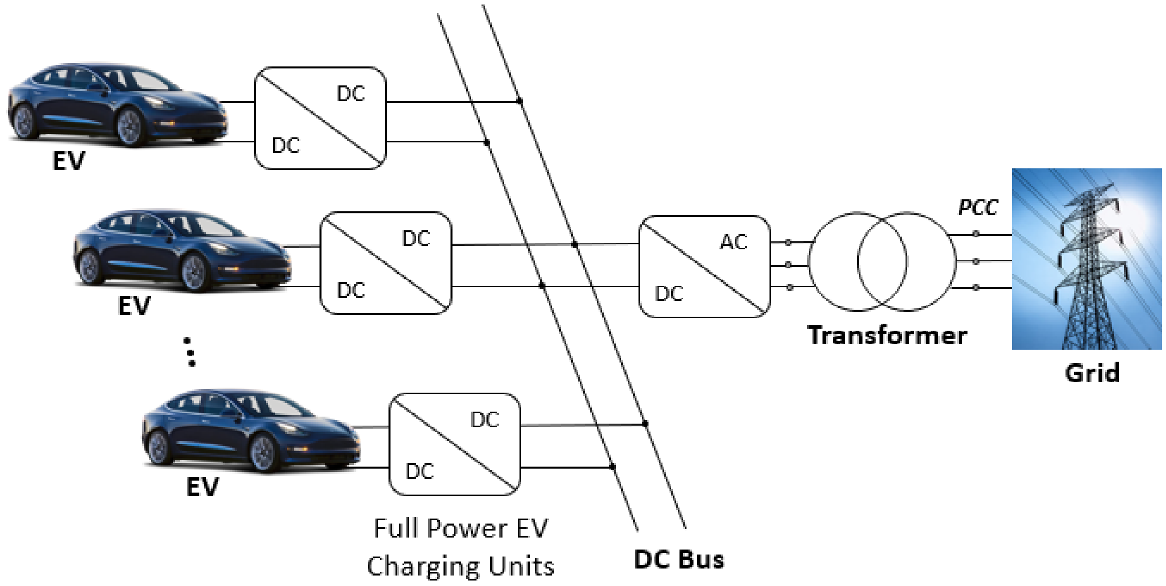

Fig 3 Architecture of conventional EV charging station [26].

In the AC-coupled configuration, a low-frequency transformer is used to connect the medium-voltage grid to the common coupling point of the charging system to supply power to each independent charging system. Each charging system consists of an AC/DC converter and a DC/DC converter [27]. Many charging systems use the AC coupling configuration because the converter technology is mature and the AC distribution system is stable. However, the overall complexity of system control is high since the power flow between the grid and the EV must pass through the AC bus and multiple AC/DC and DC/DC converters[28]

Table 1. Charging specifications of the manufactured EVs in current market.

Model	Battery Capacity (kWh)	AC Charging Rate (kW)	DC Fast Charging Rate (kW)	Range (miles/km)	Charging Time (AC)	Charging Time (DC Fast)
Tesla Model 3 (Long Range)	75	11.5	250	358 mi / 576 km	~7-8 hours (0-100%)	~30 min (10-80%)
Nissan Leaf (e+ Tekna)	62	6.6	100	239 mi / 385 km	~10-11 hours (0-100%)	~40-45 min (10-80%)
Chevrolet Bolt EV	66	7.2	55	259 mi / 417 km	~10 hours (0-100%)	~1 hour (10-80%)
Ford Mustang Mach-E (Extended Range)	98.8	10.5	150	300 mi / 483 km	~9-10 hours (0-100%)	~45 min (10-80%)
Hyundai Kona Electric	64	7.2	77	258 mi / 415 km	~9.5 hours (0-100%)	~47 min (10-80%)
Volkswagen ID.4 Pro	82	11	135	275 mi / 443 km	~7.5 hours (0-100%)	~38 min (10-80%)
Audi e-tron	95	11	150	222 mi / 357 km	~9-10 hours (0-100%)	~30 min (10-80%)
Porsche Taycan 4S	93	11	270	227 mi / 365 km	~9 hours (0-100%)	~22.5 min (10-80%)
BMW i4 (eDrive40)	81.5	11	200	301 mi / 484 km	~8-9 hours (0-100%)	~31 min (10-80%)
Lucid Air (Pure)	88	19.2	300	410 mi / 660 km	~6 hours (0-100%)	~20 min (10-80%)

Electric Vehicle Charging Technologies

A number of variables, such as the depletion of fossil fuels, clean environmental principles, government incentives, growing charging infrastructure, and intelligent control propulsion tactics, are contributing to the present industry's push towards electrified transportation [29]. Furthermore, the proliferation of fast charging stations will pave the way for EV charging to become as commonplace at current service stations as ICE car refuelling. This section provides an overview of EV charging technologies, including topics such as the state of the art, various EV kinds, charging levels, modes, and connection and battery types [30].

1. Current State of Ev Charging Technology

Global EV sales in 2021 reached a record 6.6 million, double from the year before. In the first quarter of 2022, 2 million electric cars were sold worldwide, a 75% increase over the same period in 2021 [31].

According to predictions, 58% of cars are anticipated to be EVs by 2040, and the worldwide EV fleet is estimated to reach 230 million vehicles by 2030 [32]. In 2021, there will be more than 16.5 million battery electric vehicles on the road worldwide, a huge increase over prior years. China has the biggest EV market, with total EV sales of 9.4 million in 2021, or 50% of the worldwide EV stock [33].

With 2.3 million light-duty EVs sold annually, Europe has the second-largest EV market, while the US has the third-largest EV market [34]. Governments and commercial players are now paying close attention to electric transport as a means of achieving carbon neutrality by 2040 via steady policy support, government incentives, and government subsidies. reaching 2040 carbon neutrality with steady government subsidies, incentives, and policy assistance [35].

2. Types Of Electric Vehicles

The EV is made up of a high-voltage battery pack with a charging system and one or more electric motors. Depending on the kind of EV, the electric motor may either run entirely on electricity or an internal combustion engine. During the vehicle's braking and deceleration, the electric motor also serves as a generator, supplying electricity to charge the battery via a bidirectional DC-AC converter. On the other hand, when driving mode is engaged, the converter permits electricity to go from the battery to the motor [17]. A charging system uses electric energy to replenish the battery pack. As seen in Fig. 2, EVs are divided into two categories based on their present stage of development: hybrid vehicles and all-electric vehicles (AEVs), which are distinguished by the extent of their energy consumption [36].

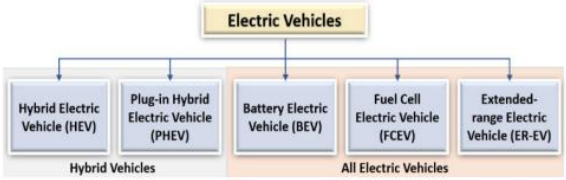

Fig 4 Types of electric vehicles

Table 2 Charging station classification based on charging power level

Charging Station Type	Charging Level	Power Output (kW)	Charging Voltage (V)	Current Type	Charging Time	Common Use Cases
Level 1 (AC Charging)	Slow Charging	1.4 - 3.7 kW	120 V (North America)	AC (Alternating)	8-20 hours (0-100% for 40-60 kWh battery)	Home charging, overnight charging
Level 2 (AC Charging)	Standard Charging	7.2 - 22 kW	240 V (NA), 230 V (EU)	AC (Alternating)	4-8 hours (0-100% for 40-60 kWh battery)	Home, public, workplace charging
DC Fast Charging	Level 3	50 - 100 kW	200-500 VDC (Direct)	DC (Direct)	30-90 minutes (10-80%)	Public charging stations, highway rest stops
Ultra-Fast Charging	Level 3+	100 - 350+ kW	400-1000 VDC (Direct)	DC (Direct)	15-30 minutes (10-80%)	Highway corridors, long-distance travel
Tesla Supercharger V3	Level 3	Up to 250 kW	400-500 VDC (Direct)	DC (Direct)	~20-25 minutes (10-80%)	Tesla-specific fast charging

Electric Vehicle Charging Topologies

To optimise energy efficiency while meeting the constraints of both EVs and the utility grid, several charging topologies, control techniques, converters, power needs, and charging stations have been developed in response to the growing popularity of EVs [37]. The construction and charging arrangement of EVs have been summed up in a number of publications [38]. A high-voltage battery pack to support moderate currents, an onboard charger, a battery management system, driving inverters [39], DC-DC converters, and high voltage loads like heaters and cooling systems make up the powertrain of contemporary PEVs . EVs rely heavily on energy storage technologies such as fuel cells, supercapacitors, and high-voltage battery packs [40].

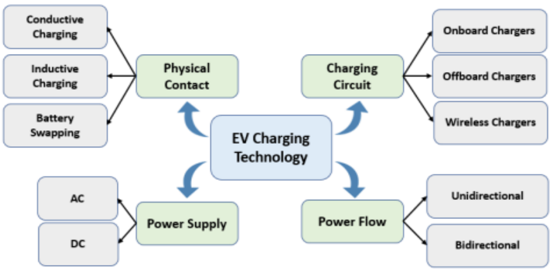

Fig 5 Classification of charging technologies used in electric vehicles [41].

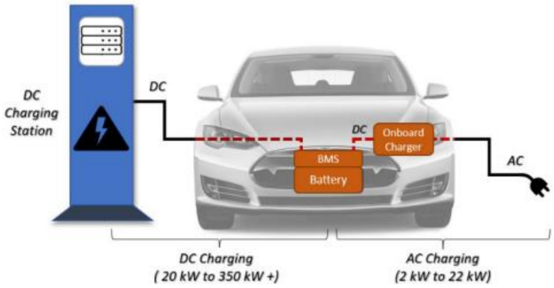

Fig 6 Onboard and offboard charging systems of electric vehicle [42].

This study presents a thorough analysis of conductive charging technology. Customers have a lot of options when it comes to charging their cars at home or at public charging stations since many manufacturers equip their cars with both AC and DC chargers [43]. While level 2 and level 3 or DC fast chargers are located at public charging stations, level 1 or level 2 chargers are intended to be used for EV charging at home. A large variety of EV models are compatible with the majority of EV chargers [44]. EV manufacturers provide their vehicles with both AC and DC chargers to facilitate onboard or offboard charging. Additionally, a variety of AC and DC power converters are included in EV battery chargers to provide great efficiency, dependability, and power density, either via coordinated or uncoordinated management [45]. In order to recharge the battery pack with certain power ratings, standards, and components, EV chargers use either AC or DC power supply. The most popular technique for charging EVs is AC charging, which involves converting AC to DC within the vehicle using an onboard charger before charging the battery [46].

1. Grid-To-Vehicle and Vehicle-To-Grid Mode

Depending on the charging setup that is included into the EV, the power flow direction might be either unidirectional or bidirectional. With a simpler control system, the unidirectional charging system makes use of a unidirectional DC-DC converter in the onboard charger and an AC-DC rectifier on the grid side. Bidirectional EV chargers, on the other hand, may use off-board chargers with a bidirectional AC-DC converter and a bidirectional DC-DC converter to transmit power to the utility grid (discharging) and EV battery (charging). The majority of the charger fleet runs in G2V mode, which charges the battery using locally produced or grid-supplied power using a minimal amount of hardware and a simple management system. Because of its straightforward design, a unidirectional charging method tends to reduce battery deterioration and makes connecting issues easier. To cut down on weight, volume, expense, and losses, unidirectional converters are implemented in a single step. Additionally, active front-end unidirectional converters may enable reactive power by regulating the current's phase angle without drawing power from a battery. Power grid needs may be met with a high penetration of unidirectional chargers without the expense, security risks, and performance problems of bidirectional chargers [47].

2. Onboard Chargers

Because of their constrained size, weight, volume, and power, Level 1 and Level 2 chargers may use the onboard chargers' unidirectional or bidirectional power transfer capabilities. A DC-DC stage at the rear end and an AC-DC stage at the front end are the two-stage converter topologies used by the majority of onboard chargers. In onboard chargers, a boost converter that functions as a PFC is fed by a grid-connected frontend passive rectifier. then uses a DC connection to provide the proper power to the inbuilt DC-DC converter so that the battery may be charged. Multilevel converters, half-bridges, or full-bridges may all be used to accomplish the front-end rectifier step. Compared to offboard chargers, onboard charging takes greater charging time since it delivers less power transmission[48].

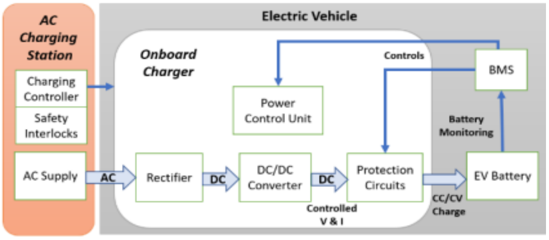

Fig 7 Configuration of conventional onboard EV.

In general, onboard EV chargers may be classified as single-phase or three-phase, unidirectional or bidirectional. Recently, a variety of onboard chargers have been released as the best way to address the widespread use of EVs. A specialised onboard charger is used to charge EV batteries using the traditional manner. conventional or specialised onboard chargers consist of two converters utilised for motor control and battery charging. Due to a number of limitations, like as the vehicle's weight, volume, and cost, dedicated onboard chargers have restricted power transmission capabilities. integrated onboard chargers, which are closely coupled with an electric motor via a single AC-DC converter, have been developed to get around the restrictions. By eschewing large parts and specialised setups, integrated chargers can use the current propulsion system for battery charging. The following section provides an overview of specialised and integrated onboard charging systems [49].

Dedicated Chargers

Using Level 1 and Level 2 charging standards, AC power is contingent upon the charging mechanism. From 3.6 kW single-phase chargers to 22 kW three-phase chargers, the power output has been increasing. An onboard charger performs pertinent conversions, including AC-DC and DC-DC power conversions, and a specialised charger attaches directly to the AC wall socket (Mode 1 or 2). In order to lessen the effects of power quality on the grid, modern onboard chargers adhere to IEC 61000 standards. The maximum AC charging power levels for commercial EVs are 22 kW (32A and 400V three phase) because of the vehicle's weight and space constraints. Dependency on the charging outlet, battery voltage restrictions, DC control with an AC voltage controller, and ground reference incompatibility are the primary issues with onboard chargers. Furthermore, the vehicle's size and weight may rise as more components are added, and strict safety regulations must be followed at high power levels. There are dedicated 22 kW DC chargers placed in homes, offices, flats, and retail malls.

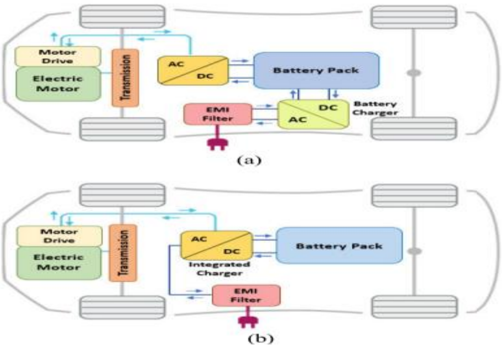

Fig 8 Configuration of onboard power electronic interface: (a) Dedicated onboard charger (b) Integrated onboard chargers.

Topologies for Ac–Dc Conversion Stage

The technical specifications of several front-end ac-dc rectifier topologies are covered in this section. The topologies that are shown here are ideal for quick charging in DC. It is possible to increase the rectifiers' power rating to satisfy the needs of dc rapid charging by using a modular approach and appropriate design [46].

1. Three-Phase Buck Type Rectifier

Achieving power factor correction (PFC), low THD, high efficiency, and high-power density are the key prerequisites for an ac-dc rectifier in the EV charging station. Three-phase buck type rectifier (TPBR) is a proper choice for the acdc power stage since it can deliver these features [50]. Moreover, TPBR provides inherent inrush current free startup, wider output voltage control range, phase leg shoot through protection, and overcurrent protection circuit. Besides, input current can be controlled without closed-loop configurations. Conventional six switch TPBR consisting of three legs and one freewheeling diode has been depicted [51].

Along with the reconstruction of the circuit, corresponding space vector pulse width modulation (SVPWM) strategy results in lower voltage stress than the input phase voltage on the switches. Furthermore, a transfer matrix-based digital controller has been designed that reduces the input current THD and output voltage ripple under unbalanced ac input condition without any sophisticated calculation or phaselocked loop (PLL) [52]. Another issue for TPBR while operating in high frequency is caused by distributed parasitic capacitances between the dc link output and the ground, leading to input current distortion especially at light load condition. In study, authors have introduced a novel structure to suppress the high frequency input current and thereby, the input THD is reduced. In general, high stepdown voltage gain is preferred, if multiple EVs available in the road are considered including their variation in terms of battery range [53].

2. Swiss Rectifier

With eight switches, the Swiss rectifier (SR) is another kind of TPBR that has reduced conduction, switching loss, common-mode noise, and efficiency. of the switches in contrast to TPBR with six switches. Because of its circuit design, SR may use dc-dc converter control techniques. Furthermore, SVPWM may be avoided for SR, making control easier. High power, high bandwidth, reduced filter requirements, reduced current and voltage ripple, and increased reliability are all benefits of interleaving SRs [54]. With a rated power of 8 kW, the work in offers SR with an interleaved dc-dc output stage that can attain 99.3% efficiency. Multilevel three-phase SR can also guarantee high power operation, but controlling the circuit becomes too difficult. Full-bridge SR, which takes electrical isolation and ZVS switching into account, has been shown in to greatly increase efficiency and dependability with better grid power quality. The fact that SR only permits unidirectional power flow is one of its main drawbacks. To enable V2G functioning, bidirectional SR may be created at the expense of additional electrical components and a complex structure [55].

3. Vienna Rectifier

When compared to a three-phase boost PFC rectifier, the three-phase Vienna rectifier (VR) operates similarly; however, the power flow is unidirectional. While VR still has the advantages of three-level converters, it also has some of their common disadvantages, such as the need for dc-link capacitors. Due to its straightforward control mechanism, high power density, high power efficiency, fewer switches, unity power factor, very low THD, and neutral connection-free construction, VR is often used in high power applications [56]. Furthermore, no dead zone switching drive is needed, and the voltage stress on the switches is half of the dc link voltage [66]. Since the VR requires about half as much boost inductance as two-level rectifiers, a reduced volume of the VR may be achieved.

Three boost inductors at the input, six fast rectifier diodes, six switches (two switches per leg), and two split capacitors at the output make up the three-phase VR. Furthermore, VR may be used with a bipolar dc bus layout, which improves power flow capabilities while keeping the dc-dc power stage's step-down ratio low. To avoid input current distortion, the bipolar dc bus structure's voltage imbalance must be corrected [57].

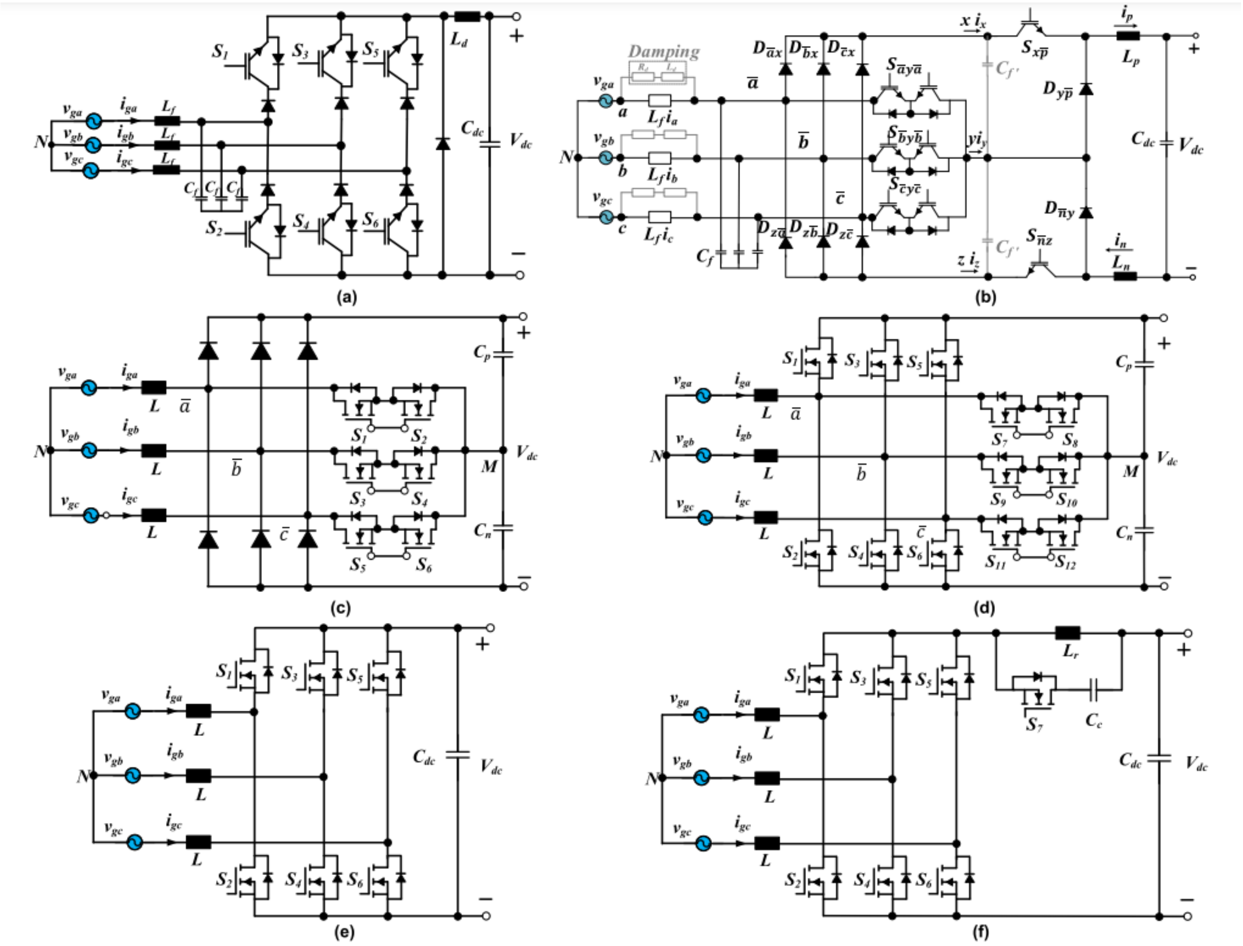

Fig 7 Circuit schematics of AC-DC power stage: (a) Three-phase six switch buck type rectifier. (b) Swiss rectifier. (c) Three-phase Vienna rectifier. (d) Three-phase bidirectional Vienna rectifier. (e) Three-phase six switch boost rectifier. (f) ZVS enabled three-phase boost rectifier [58].

4. Three-Phase Boost Type Rectifier

Because of its straightforward design, continuous input current, bidirectional operation, high output dc voltage, low current stress, fewer switches, straightforward control scheme, low THD, and high efficiency, the three-phase boost rectifier is ideally suited for the ac-dc power stage of the EV charger the circuit design of a three-phase six-switch boost rectifier (TPSSBR), which consists of three inductors connected in series with a three-phase input AC source and a total of six switches spread over the three legs. The input current's harmonic contents are decreased and the voltage is increased by using inductors. The top and bottom switches are switched in a complementary manner. A parallel TPSSBR system with each rectifier linked to the input and output sides without the need for an extra passive component [59]. This setup makes modular design and high-power operation possible. By using the zero-sequence current control approach, the circulating current produced by this system may be reduced. In general, the benefits of TPSSBR are supported by the assumption of an AC system with balanced inputs.

Harmonics show up at the dc-link voltage when the ac input voltage is not balanced [60]. A large capacitor, which makes the rectifier larger and degrades dynamic responsiveness, may be used to address this problem. Creating an active control technique is a further strategy to lower the dc-link voltage's harmonic components [61].

5. Multilevel Ac–Dc Converter

Researchers often use the multilevel converter (MLC) architecture, which generates alternating voltage levels from a number of lesser dc voltage levels. Because MLC can offer high power with greater efficiency and power density, it is a better option than alternative topologies for ac-dc power stages in EV fast and ultra-quick charging applications [62]. Three kinds of MLC.

may be distinguished based on the different designs that have been documented in the literature: 1) Flying Capacitor (FC), 2) Cascaded H-Bridge (CHB), and 3) Neutral Point Clamped (NPC) MLC. Using switches, capacitors, and voltage sources to create a staircase waveform at the output is the fundamental idea behind how an MLC converter works. Staircase multilevel PWM waveform to achieve low THD, smaller dv/dt and reduction of magnetic components to enable superior performance, reduced voltage transition between levels, low EMI, and less voltage stress on the switches in high voltage applications [63].

1. Cascaded H-Bridge Multilevel Ac–Dc Converter

It has been suggested to use a modular CHB multilevel ac-dc converter in a three-phase EV charging station layout. Because modularity and a high number of series and parallel connections of unit cells result in a large number of switching states, it is possible to take advantage of voltage balancing of cell capacitors and isolate malfunctioning cells without causing any operational difficulties [86]. The single-phase CHB is discussed as an ac-dc rectifier in the studies in [88] and [89]. A compensation technique that includes predictive current control has been used to increase the harmonic content of grid current within a single fundamental period because nonlinearities such as turn-on/turn-off delays and saturation voltage of the active switch distort unit cells, causing variations in the output voltage of CHB [88]. A modular MLC-based EV charging station is suggested in [90], with Fig. 5(a) displaying each submodule of the modular arrangement. Adapting to the high power and high voltage requirements for EV rapid charging is made possible by many submodules linked in series. Sinusoidal pulse width modulation (SPWM) and SVPWM are the most widely used modulation algorithms among those created for MLC [91].

6. LLC Resonant Converter

The LLC dc-dc converter, seen in Fig. 6(a), has been frequently used as the dc-dc power stage of EV chargers in recent years because to its many benefits over alternative resonant topologies. The main benefits include: 1) the capacity to regulate output voltage under low load conditions; 2) ZVS throughout a broad output voltage range; 3) the ability to switch the rectifier diodes using ZCS, which reduces diode recovery losses; and 4) the use of a single capacitor as an output filter. The converter switching frequency is changed to control the output voltage. Resonant tank gain, switching bridge gain, and transformer turns ratio all affect the converter's gain. Depending on the relative values of the switching frequency (fs) and resonant frequency (fr), an LLC converter may operate in three different modes. The converter is operating in its most optimal mode when the resonant tank has unity gain during resonant frequency operation (fs = fr). In order for the converter to function at the resonant frequency at nominal input and output voltage, the transformer turns ratio is thus built in this manner.

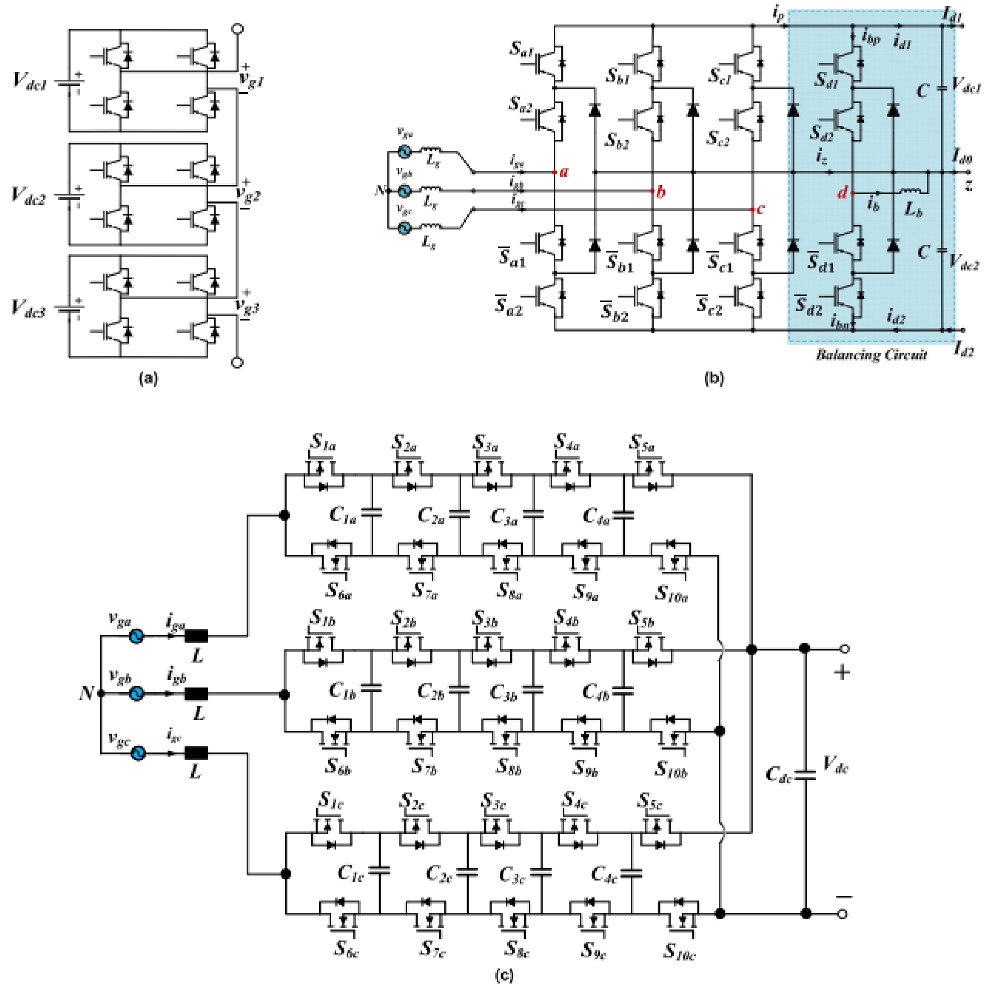

Fig 8 Circuit schematics of multilevel converter for AC-DC power stage: (a) Cascaded H-bridge (CHB) rectifier. (b) Three-phase neutral point clamped (NPC) rectifier with voltage balancing circuit in bipolar dc bus structure. (c) Three-phase 6-level flying capacitor multilevel ac-dc converter [64].

Table 3 Summary of Recent Works

Author(s) & Year	**Title / Focus**	**Key Contributions**
[65] (2019)	Review of DC-DC converter topologies for BEVs and PHEVs	Identified Multidevice Interleaved DC-DC Converter (MDIBC) as best for high-power EVs.
[66] (2017)	Soft-switched DC-DC converter for cloud computing and other applications	Introduced modeling for optimizing efficiency in soft-switched converters.
[67] (2023)	EV Fast-Charging System Architecture and Future Trends	Discussed converter topologies and control techniques for high-power fast charging.
[68] (2022)	Review of off-board chargers for EVs focusing on multiport chargers integrating renewable energy	Detailed topologies and control methods for off-board chargers, including integrating solar and energy storage.
[69] (2023)	Challenges of integrating EVs with the power grid	Reviewed charging systems, converter topologies, and grid challenges, focusing on grid support.
[70] (2023)	Power converter for EV battery charging from solar energy sources	Proposed improved Z-source DC-DC converter for solar charging using advanced control.
[71] (2021)	Review of extreme fast charging (XFC) converters for EVs	Evaluated Solid-State Transformer (SST) based converter performance for fast charging stations.
[72] (2020)	Power converter developments for EV charging solutions	Explored resonant and other DC-DC converter advantages and challenges in EV charging.
[73] (2024)	Efficiency of DC fast chargers using MATLAB simulation	Examined DC fast charger efficiency using interleaved and phase-shifted converter topologies.
[74] (2022)	Impact of renewable energy integration on EV charging infrastructure	Reviewed bidirectional converters for PV-EV charging, considering efficiency and power.
[75] (2019)	Modified PSFB DC/DC converter for on-board EV chargers	Proposed modified converter with improved performance for EV charging.
[76] (2021)	HR-LLC-PSFB converter for soft-switching in EV charging	Introduced a hybrid resonant converter for achieving soft-switching in EV chargers.
[77] (2023)	Simultaneous charging of multiple EVs using isolated DC-DC converters	Reviewed isolated converters for simultaneous charging of multiple EVs with different battery voltages.
[78] (2023)	Reconfigurable charger for next-gen EV battery packs	Proposed a new charger design to handle various voltage levels in future EV battery packs.

Resonant Converter Topologies

The semiconductor losses are one of the primary selection factors for DC-DC converters. Conduction and switching losses are two types of semiconductor losses. Turn-off switching losses happen when there is non-zero current flowing through the switch during turn-off, and turn-on switching losses happen when there is a voltage across the switch during turn-on. At zero voltage across the switch, ZVS is switching [79]. Switching at zero current via the switch is known as zero current switching (ZCS). Resonant converters are those that have a resonant tank (inductors and capacitors) that permits ZVS and/or ZCS. Owing to the wide variety of resonant converters, the literature offers a variety of categorisation grounds, including the number of resonant tank components, resonant tank layout, and modes of resonance [80].

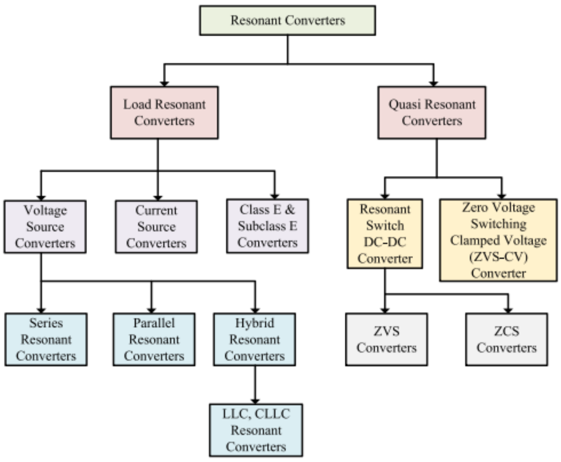

Fig 9 Resonant converter classification [81].

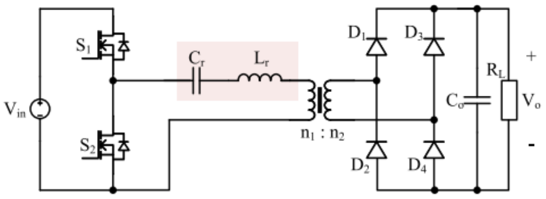

Fig 10 Half bridge series resonant converter [82].

The resonant tank in quasi-resonant converters, also known as resonant switch converters, controls the voltage and current waveforms' shape to produce ZVS and/or ZCS. These converters have both resonant and non-resonant working durations within a single switching period. Moreover, galvanic isolation between the two bridges allows the DC-DC resonant converters to be categorised as either isolated or non-isolated converters. This study will concentrate on DC-DC isolated voltage source resonant converters, which are widely used in electric vehicle applications [83].

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