Power Electronics for EV Charging Stations

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This paper proposes a design for the Bidirectional electric vehicle charger which is capable of doing both the Grid to Vehicle and Vehicle to Grid power transfer, and the interaction will be made through an automatic smart energy management system(EMS). A simple power electronics topology is used. The user can adjust the output of this charger by using the control signal provided by the controller. The simulation result obtained shows that it has an interaction between the charger and an Energy Management System(EMS) in a residence

Abstract

The enormous number of automobiles across the world has caused a significant increase in emissions of greenhouse gases, which pose a grave and mounting threat to modern life by escalating global warming and polluting air quality. These adverse effects of climate change have motivated the automotive sector to reform and have pushed the drive towards the transformation to fully electric. Charging time has been identified as one of the key barriers in large-scale applications of Electric Vehicles (EVs). In addition, various challenges are associated with the formulation of a safe charging scheme, which is concerned with appropriate charging converter architecture, with the aim of ensuring a safe charging protocol within a range of 5–10 min. This paper provides a systematic review of thharging technologies and their impacts on battery systems, including charger converter design and associated limitations. Furthermore, the knowledge gap and research directions are provided with regard to the challenges associated with the charger converter architecture design at the systems level.

Keywords:

electric vehicle; fast-charging techniques; fast-charging converter; battery; energy storage

1. Introduction

Recently, Electric Vehicles (EVs) have gained popularity over traditional fossil fuel-based automobiles, which cause environmental pollution by releasing greenhouse gas emissions (GHG) [1,2,3,4]. EVs not only curtail carbon emissions but also reduce the burden of fossil fuel dependency [5]. Key bottlenecks in enabling larger EV adoption include the high cost due to batteries, range anxiety due to reduced battery capacity and speed, high charging time, and lack of sufficient charging infrastructures [6,7,8]. To meet the challenge of time, it is possible to develop highly efficient, reliable, and compact EVs by enabling game-changing battery charging technologies with the aim of reducing charging time and enhancing battery capacity [9,10,11]. It is expected that EV penetration by 2030 will be approximately 30% of all vehicles sold that will be either electric-powered or hybrid [12]. China, the US, and Europe are, so far, the biggest EV exporters worldwide, and the sales volume of EVs increased at a rate of 94% between 2011 and 2015. The Li-ion battery itself accounts for 40% of the total production cost of EVs. Prices of Li-ion batteries were reduced from $600 per kWh in 2012 to $250 per KWh in 2017 [13]. The recent target is set to push the price drop further to $100 per KWh by 2024. EVs have become a hot topic of research since 1990, therefore it is important to understand the development trend and technological barriers.

Charging time is the key bottleneck, particularly for Battery Electric Vehicles (BEVs), where it ranges from 2 to 6 h [14]. Three classifications have been made by the U.S. Department of Energy based on charging EV power capacity. The first includes charging EVs at less than 5 kW [9,15,16], the second covers the fast-charging power range between 5 and 50

kW, and the last one denotes a charging power range greater than 50 kW [17]. The first two are referred to as on-board chargers that are integrated into the vehicle, while the third one is referred to as an off-board charger, which is basically equivalent to a fuel station [18]. The reduction in the size of the off-board charger is the future focus of research. Still, the on-board charger can charge the battery on a domestic load. However, the mileage capacity is restricted to 240–300 Wh/mi [19]. Thus, if the vehicle is needed to make an extra trip urgently outside the daily drive, it would require fast-charging solutions.

EV charging systems can be categorized into three groups based on the power levels, as shown in **Table 1**. Usually, the chargers with a power level below 3.3 kW (1-phase) are termed slow chargers or Level 1 chargers with 120Vac outlet, which can be integrated in-to the vehicle power train (on-board charger) or can be installed as a convenience outlet at home (wall-charging outlet). The charging time for Level 1 charger is higher which is 4–11 h for 1.4 kW (for PHEV battery of 5–15 kWh capacity) and 11–36 h for 1.9 kW (for EV battery of 16–50 kWh capacity). Level 2 chargers can charge EV batteries with a power of up to 22 kW for both 1-phase and 3-phase with 240Vac (US standard) and 400Vac (EU standard) [20]. Similar to Level 1 chargers, they can either be part of the vehicle or part of the dedicated Electric Vehicle Supply Equipment (EVSE) outside the vehicle. Three types of charging time scenarios are available for Level-2 charger such as 1–4 h for 4 kW with PHEV battery capacity of 5–15 kWh, 2–6 h for 8 kW with EV battery capacity of 16–30 kWh and 2–3 h for 19.2 kW with EV capacity of 3–50 kWh [20]. On the other hand, Level-3 chargers have power levels up to 200 kW and they are always outside the vehicle as a part of EVSE. Level-3 charger has both ac and dc power facilities with voltage outlets of (208–240) Vac and (200–600) Vdc. It is mostly applicable in commercial area analogous to a filling station. It is termed as fast charging prototype due to its less charging time which is 0.4–1 h for 50 kW prototype and 0.2–0.5 h for greater than 90 kW prototype. The battery capacity of the dedicated EVs ranges from 20–50 kWh [20]. All three types of chargers convert AC grid voltage to suitable DC voltage to charge the battery. The power levels determine how fast the battery will be fully charged from a specified state-of-charge (SOC) level [21].

Table 1. Charging characteristics and required infrastructure of some manufactured PHEVs and EVs (data collected from [14,15,16]).

The charging characteristics and required infrastructure of some of the commercially available Plug-in electric vehicles (PEVs) and EVs are shown in **Table 1**. Most of the vehicles have either a Level 1 or Level 2 charger as a part of their vehicle power train (on-board chargers). However, Level 3 fast charging is the quickest option to charge any EV battery if the required connector is available in the vehicle.

A U.S. Department of Energy report in 2008 [22] pointed out that charging location is critical for building future EV mobility and classified the locations for EV charging into three groups: (i) Residential garage charging (Level 1 and Level 2), (ii) apartment complex charging (Level 1 and Level 2), and (iii) commercial facility charging (Level 2 and Level 3). For both the home and apartment scenarios, it is assumed that a majority of the charging will be performed at night. For commercial facilities, it is assumed that charging is primarily performed during normal business hours.

Several review papers on charging technologies of EVs can be found in the literature based on a number of factors [23,24]. In [25], a comprehensive review of EV charging station infrastructure, standards of charging cables, cords, and connectors, the impact of semiconductors devices used in converters on charger performance and cost, and the integration of a charging system with the microgrid for better energy management systems have been analyzed. The technologies related to EVs, EV charging systems, and optimization strategies to obtain the available output have been represented in another review [26]. An overview of the recent EV market, standards related to charging, grid integration and safety, charging infrastructure, and effects of EV penetration are discussed in [24]. An overview of the diverse kinds of EVs that are commercially available and associated with energy storage systems (ESS), as well as a detailed review of public and residential power outlets, EV charging cords, and charging stands based on various power levels, was discussed in [27]. The negative impact of EV charging on the utility grid and the safety code associated with EV charging systems has also been analyzed. A converter is an integral part of the EV charging system [28]. In [29], a review of converter architectures, international standards, and EV charger manufacturers was analyzed. The architecture of the converter topologies and the reliability associated with these topologies are considered to be important factors to evaluate the effectiveness of these converter topologies, which were not considered in the aforementioned studies.

Different factors have to be considered to design the converter topologies of EV chargers, such as the efficiency, power factor, isolation, harmonic contents, filter, and switching components [30,31,32,33], which have been highlighted in this paper for both DC-DC and AC-DC converters. The reliability of electronic components associated with EV converter technology ensures the reliable performance of the entire system [34,35]. Reliability assessment of the power electronics converter from manufacturer, seller, and customer standpoints is crucial to verify the reliable operation of the EVs in all environmental conditions [36,37]. Adaptation of safe and reliable charging methods ensures a long lifetime and better performance of EV batteries by limiting the temperature [38]. The development of the fast-charging converter accelerates the revolution toward sustainable transportation through EVs [39,40]. Therefore, different charging methods and charging strategies are important factors in evaluating the total performance of the EV. EV technologies are facing various challenges such as slow charging, isolation, power loss due to converter structure, power electronic component reliability, and thermal condition of EV batteries [41]. Vehicle to Grid (V2G) is not only a promising solution to cope with a large number of EVs considering all the aspects of charging and discharging EVs but also a possible way to boost economic growth [42,43]. Clearly, the need to develop reliable and fast chargers is not only important to remove the range barrier, but also to improve the robustness of the EV in the energy transfer context. Therefore, the specific goal of this review is to provide a detailed overview of the current development of the charging converter architecture and converter reliability, highlighting the challenges and potential solutions related to EV charging.

The review started by collecting the latest journal papers from major databases such as Scopus and the Web of Science with keywords including EV Charging, EV Charger Converter, EV charger/converter reliability, Thermal challenges in EV charging, and Vehicle to Grid. One hundred and forty papers were selected for this review with particular focus given to the key topics related to EV converter topology and reliability and EV charging. This paper first reviews and presents available converter topologies of both AC-DC and DC-DC converters for charging architectures. An overview of the reliability analysis of EVs and EV converters with diverse reliability assessment methods to ensure reliable converter performance and future trends related to EV converter topologies have been discussed. Various EV charging methods and strategies are presented, highlighting the charging challenges, thermal challenges of the battery, and V2G as potential solutions. Finally, insights into the fundamental charging protocol and guidelines for new research directions are provided.

2. EV Converter Topology

The EV charger usually creates a non-linear load in the power system, which causes problems such as weak power factor and excessive total harmonic distortion in the network. A well-designed battery charger aims not only to safely charge the battery pack with high efficiency but also to meet international standards such as IEEE 1547 [44]. Therefore, all EV chargers need a power factor correction (PFC) stage, an isolation stage, and filtering components. Several power electronics converter topologies are proposed in the literature to achieve these. The 6.6 kW prototype proposed by Lee et al. [45] used a single-phase PMW rectifier in the first stage and a full bridge resonant converter in the second stage. The rated efficiency in both charging and discharging modes was approximately 93%, but the power density was poor (less than 1 kW/L). The prototype used Silicon (Si) super-junction MOSFETs in the power stage. A three-phase 10 kW prototype based on a three-phase active rectifier and a dual active bridge converter proposed by Zeljkovic et al. [46] (Infineon) showed approximately 91% efficiency for the worst battery charging condition (195 V), with the topology presented in **Figure 1**. The prototype mostly used Si devices except for the high-voltage section of the dual active bridge (DAB) where Silicon Carbide (SiC) JFETs (Junction Field-Effect Transistors) were used.
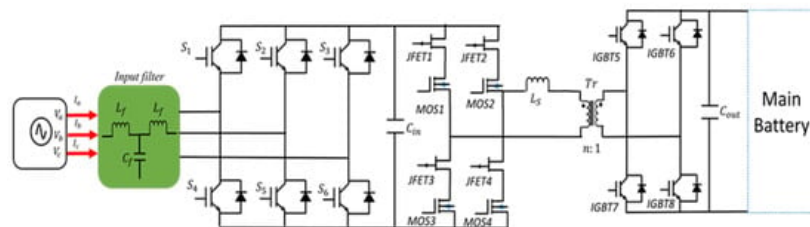

Figure 1. Three-phase on-board charger topology based on active rectifier and single DAB.

2.1. Development Trend of DC-DC Converter

In [28], the DAB topology with the series-resonant converter (SRC) topology and two-stage series-resonant converter topology were compared for the DC-DC stage of the charger. It was found that the two-stage SRC was more efficient compared to the DAB topology. However, the analysis was shown for a 12 V battery charger (auxiliary charger) rather

than the main battery charger of the vehicle. SRC and two-stage SRC topologies are shown in **Figure 2** and **Figure 3**, respectively [47].
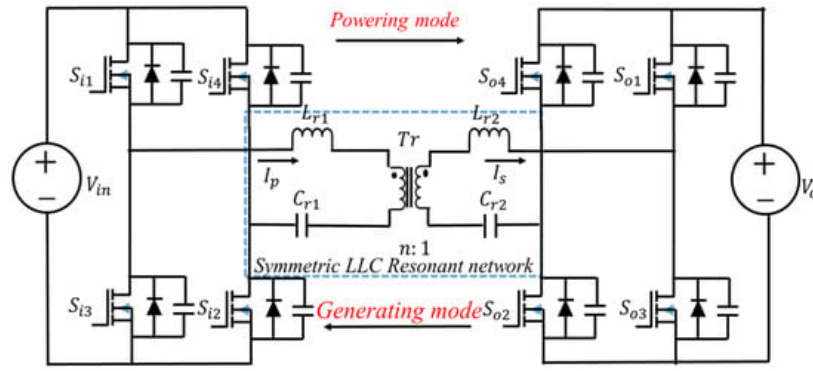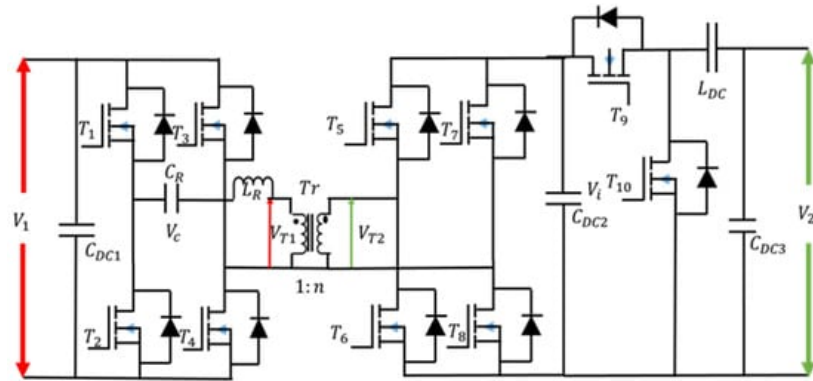

Figure 2. SRC DC-DC converter topology.

Figure 3. Two-stage SRC topology.

A modified DAB converter topology for an EV charger was proposed in [48], which uses a turned L-C-L network to improve the efficiency of the converter by reducing the reactive currents in the active bridges. Although the topology reduces the capacitor requirements of traditional DAB topology, the additional L-C-L filter could increase the overall volume of the converter.

Several advanced modulation strategies have been proposed to reduce the reactive current in the active bridges such as pulse-width modulation (PWM) with phase shift [49,50,51,52] and triangular and trapezoidal modulation [53,54]. These advanced modulation schemes also extend the Zero-Voltage Switching (ZVS) range and increase the low-power efficiency of the DAB topology. Reactive currents can also be reduced by combining the phase-shift modulation with equal PWM in corresponding bridge switches [55]. A composite modulation scheme was proposed in [56] for advanced independent PWM control of individual switching devices, as well as phase-shift, which improves the low-power efficiency of the topology significantly. This is due to the reduced root mean square (RMS) current in each switching device. However, the control algorithm is complex and needs to change the modulation strategy at different load conditions.

The authors in [57,58] proposed the CLLC-based SRC topology for EV charging applications. However, it is clear from their research that the CLLC resonant network design in the SRC converter is much more complicated than the DAB converter design. Furthermore, the voltage gain is very sensitive to various parameters, such as the secondary transformer voltage, load condition, inductance of the inductors, and capacitance of the capacitors in the CLLC network. Compared to the DAB topology, the voltage gain equation in CLLC SRC is much more complicated. To design the parameters in CLLC SRC, all the variations in different parameters should be considered. Even for charging mode and discharging mode operations of the EV charger, the topology might require different CLLC parameters to optimize the performance, which significantly complicates the design procedure.

Another critical issue with CLLC SRC is that the control complexity is greatly increased when compared with the DAB topology. **Table 2** represents a comparison of various topologies utilized in the DC-DC stage of EV converter topologies for different types of EV chargers.

The dual active half-bridge (DAHB) converter is another promising DC-DC topology for EV fast chargers, which is presented in **Figure 4** [59]. Although this topology has a smaller number of semiconductor switches than the DAB topology, maintaining the closed-loop control stability is very challenging in this topology due to the low-frequency

resonance issues. The ZVS range with traditional phase-shift modulation is very limited as well. An advanced asymmetrical modulation strategy is needed to resolve the stability issues and extend the ZVS range.

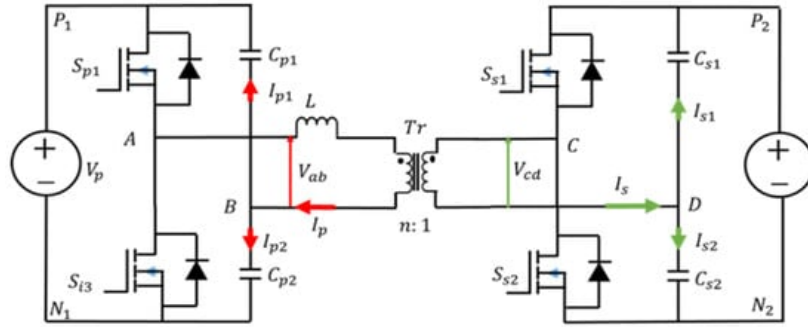**Table 2.** Comparisons of various topologies for DC-DC stages.

Figure 4. DAHB converter topology.

2.2. Development Trend of AC-DC Converter

Although three-phase diode rectifier [20] (unidirectional topology) and 2-level active PWM rectifier [46] are the two most popular topologies for the AC-DC stage, several other topologies have been found in the literature, which reduces the filtering requirements at the PFC stage of the EV charger. For example, [62,63] proposed a three-level neutral-point clamped (NPC) phase-leg-based AC-DC converter topology, which is presented in **Figure 5**. Because of the three-level operation and the PWM modulation strategy, the topology can reduce the input filter size. Although the voltage rating of each semiconductor device is reduced, the number of semiconductor devices is doubled compared to the two-level active rectifier, which can reduce the power density of chargers greater than 10 kW.
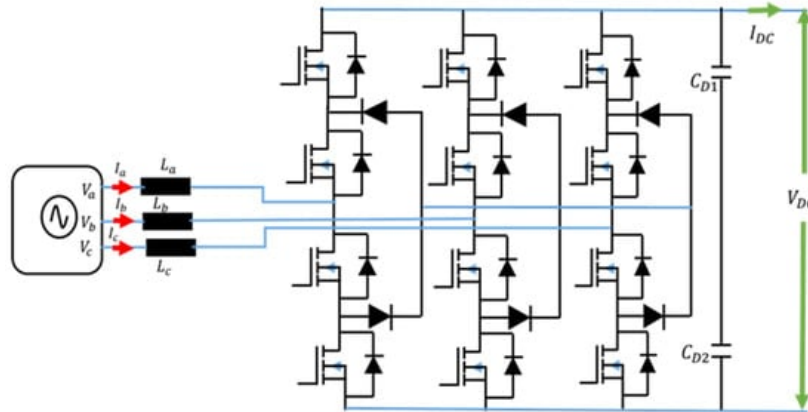

Figure 5. Three-level NPC boost AC-DC converter topology.

A three-level T-NPC PWM boost rectifier-based charger topology was proposed in [64]. The 11 kW charger achieved an impressive 95.6% peak efficiency and 2.5 kW /liter power density by employing a multi-port design approach and a novel phase-shift PEM modulation strategy. Again, the number of semiconductor devices, three times that of the two-level rectifier, is the main issue in this topology.

Krishnamoorthy et al. [65] proposed a matrix converter (AC to AC) for EV fast-charging applications, which does not require the traditional AC/DC/DC structure. The topology is presented in **Figure 6**. The front-end matrix converter converts the three-phase 50/60 Hz AC voltage to single-phase high-frequency AC voltage. The high-frequency transformer creates the galvanic isolation and the PWM rectifier rectifies the high-frequency AC voltage to DC voltage suitable for the battery. This topology ensures single-stage power conversion and removes the DC link capacitor at the output of the conventional AC-DC stage. Therefore, matrix converters usually achieve higher power density when compared to traditional two-stage solutions [66,67].
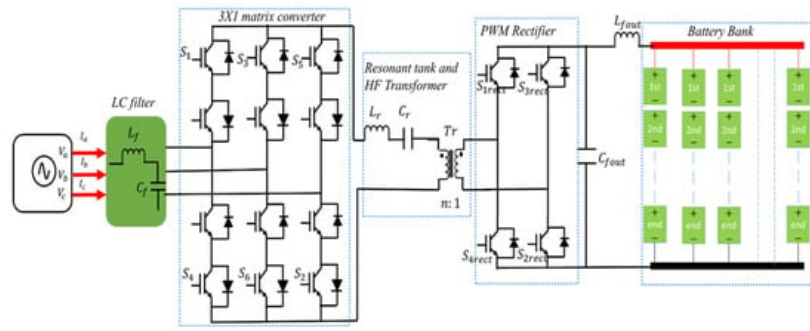
Figure 6. Matrix converter topology with resonant tank and HF transformer for EV charger.

The authors in [68] proposed an advanced modulation strategy to compensate for the reactive power drawn by the input filter, which reduces the input current distortion and ensures very low total harmonic distortion (THD) for the input current. The controller achieves good dynamic performance in both the charging and discharging modes of the EV battery. However, the matrix converter has twice the number of semiconductor devices compared to the two-level PWM rectifier, which could reduce the power density of the charger. **Table 3** represents a comparison of various topologies discussed in this paper for the AC-DC stage of EV converter topologies for different types of EV chargers.

Table 3. Comparisons of various topologies for the AC-DC stages.

3. EV Converter Reliability

Every electronic system is developed with individual parts or components. Therefore, if any single part fails then it may affect the entire system. From the manufacturing point of view, it is important to ensure high-quality products are delivered to the customers. They should also ensure that the product will perform consistently under various operating conditions. The key driving factors for reliability issues are the massive adoption of electronic systems and their increasing complexity. In addition, customers are expecting high reliability from their desired product. For example, in modern electric drives, power electronics converters with associated components together work as a power processor mainly for charging the batteries and delivering power to another auxiliary load. Trends of the power converter are shifting toward becoming small in size, compact, efficient, and power dense. They have been popular in EVs due to their ease of control and flexibility in scaling. However, the poor reliability of these devices is an issue, and they fail frequently; therefore, to ensure the reliability of this product, this important issue needs to be considered [69].

The extreme use of fossil fuels in the transport sector has contributed to environmental pollution over the past decades. The automotive industry has introduced a new concept for vehicles by replacing fossil fuels with electricity, as the driving force in electric vehicles (Evs) [70]. Thus, Evs appear to be the best alternative to traditional vehicles. Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Battery Electric Vehicles (BEVs) are the three major Evs that exist in the current market. Automotive manufacturers are conducting research on designing and manufacturing Evs, whereas charging stations are increasing to feed the Evs.

Reliability assessment plays an important role in maintaining the operation of Evs' components, mainly the power electronics converter. Reliability assessment is a critical issue for Evs, and various perspectives of reliability are required to be considered:

I. The customer's standpoint.

II. The manufacturer's standpoint.

III.The seller's standpoint.

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