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A Review of Bidirectional On-Board Chargers for Electric Vehicles

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ABSTRACT The fast development of electric vehicles (EVs) provides significant opportunities to further utilize clean energies in the automotive. On-board chargers (OBCs) are widely used in EVs because of their simple installation and low cost. Limited space in the vehicle and short charging time require an OBC to be power-dense and highly efficient. Moreover, the possibility for EVs to deliver power back to the grid has increased the interest in bidirectional power flow solutions in the automotive market. This paper presents a comprehensive overview and investigation on the state-of-the-art solutions of bidirectional OBCs. It reviews the current status, including architectures and configurations, smart operation modes, industry standards, major components, and commercially available products. A detailed overview of the promising topologies for bidirectional OBCs, including two-stage and single-stage structures, is provided. Future trends and challenges for topologies, wide bandgap technologies, thermal management, system integration, and wireless charging systems are also discussed in this paper.

INDEX TERMS Bidirectional on-board charger, DC/DC converter, electric vehicle, power factor correction converter, single-stage topology, wide bandgap devices.

I. INTRODUCTION

Electric vehicles (EVs) are highly attractive in the automotive industry because they use cleaner energy and can achieve superior performance compared to fossil-fueled vehicles [1]–[4]. Many countries, like the United States (US), Canada, China, India, and some European Union countries, have already established governmental incentive policies to support the development of EVs [5], [6]. For example, the US and Canada have announced the Zero Emission Vehicle policy, which provides economic support for selling ultra-low emission and zero-emission vehicles and improving the EV charging system in public places. China provides financial subsidies for energy-efficient EVs. India also sets a goal that only EV will be manufactured by 2030. As the largest automotive market of the European Union, Germany also provides a 10-year tax exemption and price subsidy of EVs. In order to respond to the increasing demand of EVs, it is, thus, critical to develop chargers and prepare global power infrastructure for the large incoming energy demand.

The on-board charger (OBC) provides the ability for EVs to be charged directly from the AC grid and is widely used in automotive industry for its convenience, especially compared to the high-cost and large-volume of off-board charging solutions [7]–[10]. Unidirectional OBCs are popular because of their simple hardware requirement and low battery degradation [11]. However, the current development of EVs has unveiled its potential as a mobile energy source. Indeed, bidirectional OBCs are able to achieve vehicle-to-grid (V2G) functionality by returning electrical energy back to the grid, which could be helpful during peak power demands [12], [13]. Moreover, bidirectional OBCs would allow EV owners to use their vehicles for other purposes like providing vehicle-to-home (V2H) or vehicle-to-load (V2L) power during grid outage or vehicle-to-vehicle (V2V) function in case of an emergency [14]–[16]. Although there are many challenges of the application of bidirectional OBCs [17], such as additional system cost and reliability burden, low power density and high weight, and complex smart grid architecture implementation [18], [19], it is widely believed that bidirectional OBCs will become the main charging solution in the future [20].

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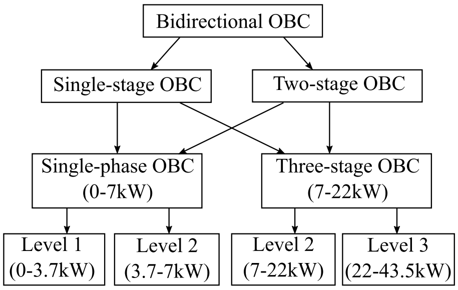


FIGURE 1. Bidirectional OBC classification.

Fig.1 shows the basic classification of bidirectional OBCs that includes single-stage OBCs and two-stage OBCs. Both OBCs are classified as single-phase OBCs from 0 to 7kW and three-phase OBCs from 7kW to 22kW. Charging time is inversely proportional to the power level. Due to the requirements for shorter charging times, higher-power bidirectional OBCs are expected in the future. Most single-phase topologies can achieve up to 7kW, while the high switches stress should be avoided. Three-phase OBC topology can achieve up to 22kW. The specific topology could be selected by their power rating according to the charging time needed. The power level of every topology will be emphasized in the following sections. In general, bidirectional OBCs are currently mainly used for level-2 AC charging with power levels from 3.7kW to 22kW. Level-1 OBC aims at low cost and low power rating which is not suitable for a bidirectional power flow. Level-3 AC charging, with power levels from 22kW to 43.5kW, minimizes charging time while the reverse power flow is mostly limited to 6.6kW to 12 kW, due to battery degradation and capacity [21], [22]. On the other hand, in order to meet global charging standards and to charge high voltage batteries, rated around 800V, wide input and output voltage ranges are required. Many manufacturers have shown their interest in developing bidirectional OBCs. For example, Nissan has developed V2H functionality for its 2013 Leaf model, and all the next-generation Leaf vehicles will be capable of V2G. In 2019, Tesla and Chinese EV brand, BYD Tang, have implemented V2L and V2V functions. Honda and BMW companies also developed bidirectional OBCs. In 2020, most OBCs are able to achieve 6kW to 10kW power levels, while some can reach up to 22kW like in the Renault Zoe. Moreover, the power density of the OBC is currently at 3.3kW/L, and the highest efficiency is estimated over 97%. Table 1 shows the US Drive OBC target for 2025 [23]. It shows that the specific power and power density of the OBC are expected to reach 4kW/kg and 4.6kW/L, respectively, while a peak efficiency of 98% should be achieved.

TABLE 1. The US Drive OBC targets.

OBC Target	PFC	DC/DC	OBC
Specific Power (kW/kg)	4	4	4
Power density (kW/L)	4.6	4.6	4.6
Efficiency (%)	>99	>98	98

Significant progress has been made in the research area of OBCs for EVs. Some excellent review papers have summarized the development of OBCs. A comprehensive topology survey of charging solutions of Plug-in EVs (PEVs), including on-board and off-board chargers, number of stages, power level, conductive and inductive charging technologies, and the semiconductor selection, is reviewed in [2]. However, it does not provide a detailed survey of OBCs. A detailed OBC review is introduced in [5], which includes promising topologies, two-stage and single-stage architectures, OBCs commercial examples from suppliers, and future trends. However, it mainly focuses on unidirectional OBCs. A comprehensive EV review introduces information such as battery chargers, electrical machines, and charging technologies in [24]. Nevertheless, it does not relate to current commercial examples of bidirectional OBCs. Many papers investigate integrated OBCs with electrical motor or contactless inductive charging technologies. However, they do not concentrate on the research and application of the bidirectional OBC [1], [13], [25], [26]. For bidirectional OBCs, some papers proposed advanced new two-stage or single-stage topologies, control strategy, and design optimization methods [16], [24], [27], which is summarized in the following section. However, the review about the research and commercial application of bidirectional OBCs has not been extensively reported in the literature yet. In summary, the following research gaps have been identified: 1) a comprehensive analysis for the current status of bidirectional OBCs, 2) an investigation of bidirectional OBC topologies combined with commercially available examples, 3) a systematic summary of the EV bidirectional OBCs trends and challenges.

Therefore, the proposed paper has the following contributions:

- Detailed analysis of the current status of bidirectional OBCs including commercial examples, two-stage and single-stage configurations, single-phase and three-phase structures, and industry standards [28], [29].
- Review of the promising bidirectional topologies based on the automotive industry sector.
- Summary of trends and challenges of bidirectional OBCs.

In section II, the current status of bidirectional OBCs, including architectures, configurations, smart operation modes, industry standards, components, and commercial examples, are summarized. Section III reviews the two-stage OBC, including power factor correction (PFC) topologies and DC/DC converters and their challenges. Section IV reviews single-stage OBC topologies. In section V, trends and challenges of bidirectional OBCs for EVs are discussed. Finally, the conclusions are presented in Section VI.

II. CURRENT STATUS OF BIDIRECTIONAL UNIVERSAL ON-BOARD CHARGER

This section reviews three main architectures and smart operating modes of bidirectional OBCs. The safety standard is summarized. The status of major components such as electromagnetic interference (EMI) filters switch devices, DC-link capacitors, transformers, and heat sinks are summarized. Finally, six commercial examples of key manufacturers are investigated.

A. ARCHITECTURES AND CONFIGURATIONS

The OBC is classified by two-stage and single-stage configurations, as shown in Fig. 2. For the two-stage OBC architecture, an active front-end AC/DC PFC converter and an active isolated DC/DC converter are necessary. The AC/DC PFC converter is used to provide a controllable DC voltage and meet the harmonic requirements of the grid. Isolated DC/DC converters provide galvanic isolation and regulate the power delivered to the battery. Most EVs use two-stage OBCs in the automotive industry [30]–[32]. On the other hand, single-stage configurations have emerged in OBC applications as the DC-link capacitor of the two-stage OBC is voluminous and has a limited lifetime. Indeed, single-stage removes the DC-link capacitor and is comprised of solely an isolated AC/DC converter, which can provide higher power density and reduce the hardware cost [33].

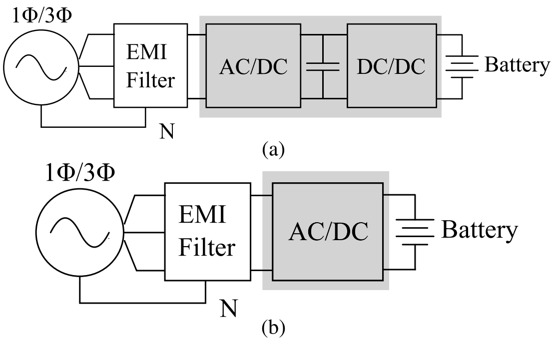


FIGURE 2. OBC configurations. (a) Two-stage architecture. (b) Single-stage architecture.

In recent years, the power range of bidirectional OBCs has significantly increased and includes several levels, such as 1.7kW, 6.6kW, 11kW, 22kW, and even 40kW. As three-phase OBC topology is preferred for power levels higher than 10kW, single-phase supply is often used in residential applications, while a three-phase supply is used in commercial and industrial facilities. However, EVs should have the capability to be charged at any location. Hence, OBC designs should be able to operate at full power capability with single- and three-phase supplies [34].

Three different architectures can be found in the literature and are shown in Fig. 3. A single-phase OBC architecture, as shown in Fig. 3(a), requires single-phase (L_1) AC current from the grid. The topology is widely used at power ratings of 3.3kW and 6.6kW because of simple structure [35], [36]. However, for single-phase OBCs, a large power pulsating at double-frequency would bring additional reliability issues. Conventional methods like employing a bulk DC capacitor would cause low power density, while connecting low-frequency pulsating current to the battery would impair the battery. Some advanced control methods were presented to reduce the output current distortion, but it causes high voltage stress and over modulation [37]. An active power filter could be used to store the energy, but it also requires more switches and passive components [38].

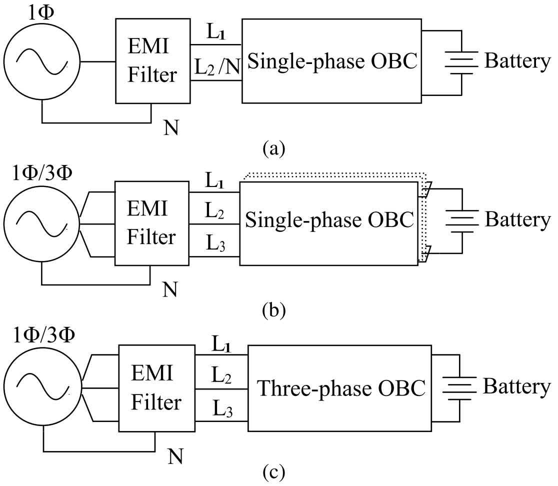


FIGURE 3. OBC power architectures. (a) Single-phase input architecture. (b) Modular single-phase input architecture. (c) Direct three-phase input architecture.

Three-phase topologies have emerged in the market to meet the high power demand, which can reach up to 40kW. There are two approaches in three-phase architectures, and both of them can operate in single- or three-phase modes. The first one, shown in Fig. 3(b), is a modular architecture composed of three single-phase OBC. The second one, shown in Fig. 3(c), illustrates a direct three-phase input architecture. It requires an active three-phase AC/DC PFC converter as the front-end, the output voltage of the front-end stage is higher in direct three-phase input architecture than others, and its DC/DC converter should be rated at around 700V. In some cases connecting DC/DC converters in series is a suitable alternative to reduce the voltage stress of the components on the primary side [39]. Compared to the direct three-phase structure, the modular single-phase architecture provides better reliability and power conversion efficiency [39]. Although this configuration needs more power transistors and sensors, it has lower current stress and filtering efforts. Therefore, it can use components with a lower current ratings [40], [41]. Some manufacturers, such as Current Ways, have proposed bidirectional OBC rated at 22kW with this configuration.

B. SMART OPERATION MODES OF BIDIRECTIONAL OBC

In addition to the fundamental mode grid-to-vehicle (G2V), other advanced modes like vehicle-to-everything (V2X) are promising as they can provide stable grid status and improve the power quality due to the communication between the EV and grid.

1) V2G MODE

V2G technology can enable the EV to supply power from the battery pack to the grid, which is the most popular functionality for bidirectional EVs. The V2G mode has lots of advantages. For example, it can balance the load by shaving peak and filling valley according to the grid demand [42]. Also, the V2G technology can provide frequency and voltage regulation, which balances the supply and demand for active power and reactive power, respectively [43], [44]. Moreover, the V2G mode can help to reduce the grid current harmonics. The battery chargers are treated as variable impedance and eliminate the harmonics issue through appropriate filtering methods [45].

Some novel topologies and control methods of bidirectional OBCs with V2G functionality have been developed. A downstream isolated DC/DC topology based on the PWM resonant converter is presented in [9], which can provide V2G mode by adding an extra circuit to increase the converter gain at discharging mode. A non-isolated interleaved buck-boost OBC topology is proposed in [21], and it provides a power quality control that reactive power operation is not harmful on the battery as the energy of the battery is not consumed. A segmented three-phase OBC integrated with the motor drive is proposed in [47], which can offer torque-less and simple control in V2G mode. Moreover, the controller presented in [44] can provide the functions of charging the vehicles and V2G reactive power compensation at the same time. An adaptive sliding current control is presented in [46] for dynamic current tracking, which fastens the convergence and provides control stability. Despite all its advantages, the V2G technology is still in early stage and has not been applied in the industry market yet due to the limitations of the battery capacity and grid infrastructure.

2) ANCILLARY MODES

Ancillary services of bidirectional EVs are also valuable for the power market. For example, the V2V technology can charge another EV when there is no charging station nearby [16], [48]. The V2H and V2L modes enable an EV to provide power to home-related devices during a power outage or to supply other loads without a grid connection respectively [49]. Home-to-vehicle (H2V) and Vehicle-for-grid (V4G) are presented in [50] for future smart homes. The H2V technique treats the EV current as a function of the main current in-home, aiming to avoid the overload and over current for the main breaker. A V4G mode can offer the grid support functionalities like active power regulation and reactive power compensation. There are a few V2X (V2V and V2L) technologies have been applied (i.e., BYD e6), but OEMs are unwilling to post their actual topology due to confidentiality.

Some bidirectional OBCs based on the V2X technology have been studied. A multifunctional single-phase V2V design and control is presented in [16]. The suggested design does not need the extra charging infrastructure, but the power level and efficiency are not mentioned. The DC/DC V2V charging proposed in [51] increases the charging efficiency by decreasing the number of power transfer stages, but it lacks experimental results. A single-stage OBC topology presented in [52] can achieve seamless V2G and V2H operations. However, it has high efficiency only at low power levels. A design of an amorphous high-frequency link for V2X is proposed in [53], and the charging and discharging modes are fully tested, but the efficiency is not mentioned. Since most V2X functions are not commercialized yet, and their research is at the early stages, most related research do not provide information like efficiency, power level, and power density.

Although these smart operation modes are beneficial to the power market, EV battery aging is still challenging. Frequently charging and discharging the battery causes severe battery degradation. Research shows that daily 2-hour frequency regulation would consume the battery capacity by 14.3%, and adding peak shaving would take up to 35.6% [42]. Therefore, a clear understanding on the economic benefits for EV owners is necessary to evaluate the risk of battery degradation. The ability to control and regulate the power grid locally could bring several long-term benefits to both EV owners and utilities companies.

C. STANDARDS

Due to the growing popularity of EVs, more and more operation and safety standards for OBCs are required. Firstly, it is necessary to ensure that the OBC operation in charging mode meets the power quality standard of the grid [27]. For example, the total harmonic distortion (THD) of currents should be less than 7% to comply with the Institute of Electrical and Electronics Engineers (IEEE) 519 requirements [54]. Many countries follow their own regulation about harmonics injection limit, such as the Society of Automotive Engineers (SAE) J2894 in the USA [55], International Electronical Commission (IEC) 61000 in Europe [56], and Guobiao (GB/T) 14549 in China [57]. Secondly, when the bidirectional OBC operates as a mobile energy source (e.g., V2L, V2V), it should obey the microgrid inverter standards, such as IEEE standard 1547 [58] and Underwriters Laboratories (UL) Standard 1741 [59]. Thirdly, there are some safety compliances, such as galvanic isolation standard with UL 2202 and IEC 60950 [60], the safety protection of onboard rechargeable energy storage systems (RESS) with International Organization for Standardization (ISO) 6469 [61] and IEC 61851 [56]. Finally, the OBC connector standards should be met with SAE Combo Charging System (CCS)1 SAE JI772 in the USA [62], IEC 62196 in Europe [63], and GuoBiao standard GB/T 20234 in China [57], respectively. Table 2 shows the classification and scope of common standards. More detailed information about OBC connectors can be found in [64].

D. MAJOR COMPONENTS

1) EMI FILTERS

The natural method to reduce the volume and weight of power conversion devices is by increasing the switching frequency to a value that is often a result of optimization techniques. However, higher frequencies increase the need for electromagnetic compatibility filters, which can take up to 30 % of the overall volume. This also demands more attention

TABLE 2. **OBC standards.**

Classification	Standards references	Scopes
Power quality standards	IEEE-519	Recommended practice and requirements for stable harmonics limitation of the voltage and current (THD<8%)
	SAE J2894	Power quality for plug-in electric vehicle chargers in US (THD<10%)
	IEC 61000	EMC requirements for power supplies in Europe (THD<8% for low and medium voltage)
	GB/T 14549	Harmonics standards for power supplies in China (THD<5% for low voltage)
V2G standards	IEEE 1547 UL 1741	Standards for interconnection between the grid and distributed energy resources. Compared to UL 1741, IEEE 1547 adds the test of the voltage unbalance, the saltation of the frequency and phase angle
Safety standards	UL 2202	Safety for EV OBC charging system supplied by a branch circuit of up to 600V for recharging the battery
	IEC 60950	Safety of technology equipment for a voltage rating lower than 600V
	ISO 6469	Safety for personal protection and EV storage system
OBC connector standards	CCS1 SAE JI772	North America standard: up to 240V AC and 16/80A AC
	IEC62196	European standard: up to 500V AC and 32A/63A AC
	GB/T 20234	Chinese standard: up to 440V AC and 32A AC

to EMI levels above 3MHz that are more challenging to attenuate. Discrete filters are often used to follow the standard IEC 61000-6-3:2006 to mitigate both common-mode (CM) and differential-mode (DM) noise. The DM noise is normally attenuated by shunt capacitors, or X-rated capacitors connected between the main lines combined with DM inductors, while CM noise is suppressed by Y-rated capacitors between line and ground along with the respective DM inductors. To further reduce the volume of such filters, active solutions are implemented to change the frequency response of wye-capacitors to increase the effective capacitance at higher frequencies, thus reducing the size of CM filter inductors [65]. The EMI characteristics can be analyzed before or after the prototype is built, depending on whether a predictive or non-predictive modeling technique is used. A combination of different modeling techniques can achieve satisfactory results that account for both DM and CM noise emission [66]. In some isolated solutions, the transformer windings are interleaved to reduce the AC resistance of the windings. This increases the stray capacitance between primary and secondary which are exposed to high dv/dt rates [67].

2) SWITCHING DEVICES

To reduce the volume of magnetic components and improve the performance of the converter, wide-bandgap (WBG) devices can be used at high switching frequency. More and more manufacturers use GaN or SiC devices with a 600V-1200V voltage rating for bidirectional OBCs. To save costs, some manufacturers combine WBG devices with Si devices. For example, Texas Instruments and Infineon applied GaN/SiC MOSFETs in high-frequency branch and Si MOSFETs in low-frequency branch of the totem-pole PFC, and applied GaN/SiC MOSFETs on the primary side and Si MOSFETs on the secondary side of the DAB converter [68]. In order to reduce the switching loss, all the diodes are fast body diodes. Some projects also choose fast IGBT to replace expensive SiC MOSFETs because of low tail current capability [69], [70].

3) DC-LINK CAPACITORS

In EV applications, a two-stage OBC connects the PFC converter and the DC/DC converter via a DC-link capacitor for energy buffering. It also serves as a filter that protect OBCs from voltage spikes, surges, and EMI. The DC-link capacitance is determined by the output voltage and power rating of PFC converter, capacitor holdup time, and the capacitor voltage during the holdup time. For DC-link capacitor, the performance such as high DC voltage rating, large capacitance, consistent performance over a wide temperature operating range, high root means square current capacity, low equivalent series resistance, and high mechanical ruggedness are the main requirements. In order to meet high voltage rating, ON Semiconductor uses two 450V rated electrolytic capacitors connected in series [71]. When the capacitance is too large to be reached by one capacitor, it is common to parallel multiple capacitors to form an array. Since the DC-link capacitors are exposed to twice the grid frequency, multiple capacitor technologies are applied.

4) TRANSFORMER

The transformer isolates the primary DC/AC side from the secondary AC/DC side to prevent the propagation of EMI noise, and protect against short circuits. In order to optimize the power density of the converter, custom-design transformers are preferred instead of off-the-shelf products. Different manufacturers design their transformers according to their specific transformer turns ratio, the resonant frequency of both primary and secondary sides, and the ratio of magnetizing inductance to resonance inductance. For popular CLLC and DAB converters, the transformer design is very critical. Planar transformers are preferable for high-frequency applications due to low AC winding loss, high power density, and excellent thermal dissipation. Planar magnetics can withstand extreme temperatures, vibrations, and other volatile environments that EV's may be subjected to.

5) HEAT SINK

The high switching frequency of high power-dense bidirectional OBCs results in potential thermal management challenges because of higher switching loss and eddy current loss [72]. For the 3.3kW or lower power OBCs, the heat can be easily dissipated by forced air convection using a fan. Most level-1 OBCs use an air-cooling method, which brings better flexibility to positioning the OBC inside the vehicle. However, bidirectional OBC that is widely used in level-2 produce higher power dissipation. Therefore, the thermal design has a more stringent requirement and liquid cooling is a widely used method. A proper liquid cold plate is necessary to cool the heat load of the OBC. The tube and channel types can be used in low-power density applications, and the extended fin type is more prevalent in high-power density applications [73]. The design of liquid cold plate is often customized to address the layout of heat load, pressure drop constraints, power density, and material compatibility with the rest of the cooling system [74]. Moreover, a suitable thermal interface material, which provides not only good thermal conductivity but also electric insulation, should be chosen to ensure efficient heat dissipation between the components and the heat sink [75]. The bidirectional OBC also needs to be mechanically integrated inside an enclosure, which has to be sealed to avoid environmental contamination [76]. Table 3 shows that ON Semiconductor and Texas Instruments use liquid cooling with aluminum enclosures.

E. COMMERCIAL EXAMPLES

Currently, more than ten manufacturers are active in the OBC market. Several key suppliers offer bidirectional OBC solutions. Six of these designs are shown in this paper due to their promising performance and the availability of details in the literature.

1) TEXAS INSTRUMENTS

A 6.6kW bidirectional OBC composed of a continuous-conduction-mode (CCM) totem-pole PFC and a resonant CLLC DC/DC converter was presented in [77]. Both converters use a digital controller. The interleaving architectures increases the power level and reduces the power loss at light load. Moreover, it also reduces the volume of the magnetic components and the heat sink. The input voltage can vary from 208V to 240V and the output voltage from 250V to 450V. Finally, the charger achieves a maximum efficiency of 97% utilizing Silicon Carbide (SiC) MOSFETs. Texas Instruments also developed a bidirectional 3.3kW PFC with Gallium Nitride (GaN) devices [78].

2) DELTA-Q

Delta-q developed a bidirectional 6.6kW OBC, which uses 650V GaN and 1200V SiC devices [79], [80]. The converter achieves an efficiency above 96% and has a power density of 2.26kW/L. The OBC topology includes a totem-pole bridgeless PFC converter that operates in critical conduction mode (CRM) and downstream CLLC resonant topology as the second-end stage. The efficiency of the whole system in reverse operation (i.e., V2G) can also achieve 96%, and the heat is removed with a liquid-cooled solution.

3) WOLFSPEED

Bidirectional 6.6kW OBC features Wolfspeed's C3MTM 1000V, 65mΩ SiC MOSFET, which comes in a TO-247-4 package. The OBC topology consists of a totem-pole PFC and an isolated CLLC DC/DC converter. The switching frequency of the CLLC converter varies from 150kHz to 300kHz with a variable DC-link voltage that can make the CLLC converter operates at resonance or close to the resonance frequency to optimize the overall efficiency. Moreover, MOSFETs are mounted vertically and magnetics are potted with a thermal compound inside the slots of the heat sink. By doing so, the thermal resistance from the heat sink to the system cooling baseplate can be reduced. The bidirectional OBC demonstrates a power density of 3.3kW/L and a peak efficiency exceeding 96.5% [81].

4) CURRENT WAYS

Current Ways offers a bidirectional 6.6kW OBC with SiC devices, which can be easily paralleled to achieve higher power of 13.2kW, 19.8kW, and 26.4kW. It consists of three-phase full-bridge PFC and dual active bridge (DAB) DC/DC converters. The input voltage ranges from 97V to 265V, and the output voltage from 250V to 425V. The OBC efficiency is around 96%, and a liquid cooling solution with a flow rate of 6 L/min is used. Current Ways also provides a 20kW modular SiC bidirectional OBC, which can achieve an efficiency higher than 97% and a power density of 3.3kW/L [82].

5) VALEO SIEMENS

Valeo Siemens developed a bidirectional 3.5kW OBC, which reaches an efficiency over 94% [83]. The input voltage of the totem-pole PFC varies from 85V to 275V, and the output voltage from 200V to 1000V. However, the information of the DC/DC converter is limited.

6) EATON

Eaton provides a bidirectional 3kW to 22kW OBC. The range of input voltage varies from 110V to 240V, and the output voltage is from 225V to 500V. It can achieve over 95% efficiency with the maximum charging rate, and a power density of 2kW/L [84]. It supports single-phase and three-phase AC supplies.

Table 3 shows a summary of main bidirectional OBCs posted online from these manufacturers. It can be seen that all OBCs use a two-stage structure because it can provide simple control strategies for different stages and implement galvanic isolation. All bidirectional topologies have a wide

TABLE 3. Examples of commercial bidirectional OBCs.

Manufacturer	PFC Topology	DC/DC Topology	Input Voltage (V)	Output Voltage (V)	Power (kW)	Efficiency (%)	Power Density (kW/L)	Switching Devices	Cooling Method
Texas Instruments	Totem pole	CLLC	208-240	250-450	6.6	97	-	SiC	-
Delta-q	Totem pole	CLLC	85-265	250-450	6.6	96	2.26	SiC/GaN	Liquid
Wolfspeed	Totem pole	CLLC	-	250-450	6.6	96.50	3.3	SiC	-
Current Ways	Three-phase full-bridge	DAB	97-265	250-425	6.6	96	3.3	SiC	Liquid
Valeo Siemens	Totem pole	Unknown	85-265	-	3.5	94	-	SiC	-
Eaton	Unknown	Unknown	110-240	225-500	22	>95	2	-	-

input-voltage range to address the global charging standards. The wide output-voltage range matches the current battery voltage requirements. Most manufacturers study the totem-pole PFC topology as the front-end stage and DAB or CLLC topologies as the back-end stage. However, these prototypes have only been developed for research and are not designed yet for a qualified production assembly. Due to confidentiality reasons, most EV companies are unwilling to share detailed topology information of their bidirectional OBCs. According to posted information, the single-phase full-bridge PFC or three-phase full-bridge PFC converters combined with active DAB or buck downstream converters have been installed on some bidirectional OBCs in the EV market. BYD adopts a three-phase full-bridge PFC converter and active buck converter in their bidirectional OBC. More bidirectional OBC topologies with higher efficiency and power density are being developed.

The power level of most bidirectional OBCs ranges from 3.3kW to 6.6kW in the current market. With the increase of battery capacity, a higher power level is needed. As of now, a few EVs are capable of charging at 22kW, such as Tesla Model X, Renault Zoe, and BMW ix3. BYD provides 40kW bidirectional charging with the model BYD E6. This power is supplied by a three-phase 380V AC charging station that is smaller and cheaper than a DC charging station. BYD E6 is widely used as a taxi vehicle in several cities in China. The reverse function can achieve low power V2V or V2L.

III. TWO-STAGE BIDIRECTIONAL OBC

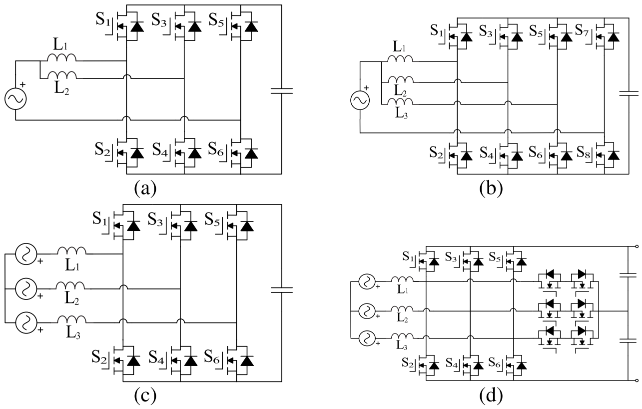
Most commercial OBCs used in the automotive market are two-stage architectures. This section reviews the most promising bidirectional PFC converters and DC/DC converter topologies. Challenges of two-stage bidirectional OBC will also be discussed.

A. PFC CONVERTERS

Single-phase PFC converters are the most widely studied in the OBC research. For example, single-phase bidirectional full-bridge converters, and their variants are popular but suffer high power losses [85]–[87]. A single-phase multilevel converters, such as three-level NPC [88], T-type [89] and six-level flying capacitor topology [90]–[94], enable device voltage stress reductions and power level increase. In addition to single-phase PFC topologies, a lot of research is being undertaken on three-phase bidirectional PFC converters like the full-bridge converter [95], NPC [93], T-type [96] and matrix converter [97]–[99]. Three-phase topologies can discharge power from the battery to the grid to achieve V2G. Single or three-phase topologies can achieve V2L technology. However, factors like cost and volume are limiting their adoption to the market. This paper focuses on the following most popular and promising bidirectional PFC converters topologies.

1) SINGLE-PHASE TOTEM-POLE PFC

Due to high conduction loss of conventional boost PFC converters, bridgeless interleaved totem-pole PFC are investigated [100]–[102]. Fig.4 (a) shows the topology, which includes two boost interleaved phases (L_1, S_1, S_2 and L_2, S_3, S_4). The switches in the same phase leg are complimentary and a deadtime is implemented to prevent short circuits. The synchronous rectification is achieved by an extra phase leg (S_5 and S_6). The second boost interleaved phase is driven with



(a) (b) (c) (d)

FIGURE 4. Bidirectional PFC topologies. (a) Totem pole PFC (two-phase boost interleaved). (b) Totem pole PFC (three-phase boost interleaved). (c) Three-phase full-bridge PFC. (d) Three-phase T-type PFC.

TABLE 4. Bidirectional PFC summary.

PFC		Modulation	Input Voltage (V)	Output Voltage (V)	Switching Frequency (kHz)	Power Level (kW)	Efficiency (%)	Power Density (kW/L)	Switching Devices	PF
Totem Pole	Two-phase	CCM	85-265	300-600	100	3.3	99.2	-	SiC	0.99
	Three-phase	CCM	85-265	400-600	100	6.6	98.86	-	SiC	>0.99
	Three-phase	CRM	85-265	390	450-1000	1.6	98.7	>15	GaN	>0.99
Three-phase full-bridge		Unknown	167-265	700	60-140	11	98.3	-	SiC	-
Three-phase T-type		Unknown	325	650	8	10	99	3.3	Si	-

a phase shift of 180 degrees, which increases the switching frequency by two. Some totem-pole converters add a third boost interleaved phase (L_3, S_5 and S_6) shown in Fig.4 (b), which increases the switching frequency by three times. Compared to conventional PFC topologies, the totem-pole PFC has a small CM current and input current ripple, and it can reduce the amount of components and improve the power density and efficiency. Two bridgeless boosts interleaved CCM totem-pole PFC with SiC, which uses dual closed-loop PWM control, has achieved up to 99.2% efficiency for a 3.3kW power level [102]. Texas Instruments implemented a three-phase interleaved control with phase shedding control and SiC technology [78]. The converter has achieved up to 98.86% efficiency at a 6.6kW power level. Three-phase interleaved operation with full digital control and GaN technology has been implemented and the converter achieves up to 98.86% efficiency at a 1.6kW power level [78]. Table 4 summarizes the information.

2) THREE-PHASE FULL-BRIDGE PFC

Three-phase PFC converters can provide a higher power level and further reduce the charging time [95]. The three-phase full-bridge converter, shown in Fig.4 (c), is one of the most popular bidirectional rectifiers because of easy control and structure. A bridgeless PFC with active MOSFET guarantees the bidirectional current path because of the body diode in each MOSFET. BYD EV has commercialized this topology as the front-end PFC converter of the bidirectional OBC. It can achieve V2G to supply power from the battery to the grid. It also can achieve V2V and V2L by bypassing one leg of this topology and treating the converter as an H-bridge inverter to charge other loads at 3.3 kW. ON Semiconductor also developed a three-phase full-bridge PFC stage, in [103]. It uses field-oriented control and SiC technology to achieve 98.3% efficiency and 11kW power level. However, the prototype presented in the paper is not optimized for high density or compactness.

3) THREE-PHASE T-TYPE CONVERTER

Three-phase three-level T-type converter is a potential PFC converter for bidirectional OBC applications. It has merits such as low conduction and switching loss, simple operation principle, and low switches stress. Compared to the NPC converter, it has a better reliability and less number of switches. The most popular three-phase PFC converter on the OBC market is the Vienna converter because it can achieve a higher efficiency than other conventional PFC topologies and has unidirectional power flow. However, it is unidirectional. On the other hand, the T-type converter uses six active MOSFETs instead of the diode bridge of the Vienna converter, to allow a bidirectional power flow. Fig.4 (d) shows the T-type topology. The prototype presented in [96] uses Si IGBT and full digital control, which has achieved 99% efficiency for a 10kW power level. If SiC or GaN MOSFETs are used in a T-type converter, it would achieve higher power density because of the possibility to increase the switching frequency. Therefore, the T-type converter is a good candidate for three-phase bidirectional PFC converter in the future OBC market [104].

Table 4 shows the comparison of the promising bidirectional PFC converters. Most commercial PFC converters have a wide input range to meet the global charging standards. WBG devices like SiC and GaN are widely used in OBC production by key manufacturers. All PFC converters can achieve an efficiency higher than 98%. However, most manufacturers do not share information on PFC power density. Currently, the main commercial bidirectional PFC stage is the totem-pole PFC topology. The three-phase full-bridge converter has been recently introduced in the industry as a commercial option for the PFC stage. Due to the demand for high-power and bidirectional OBCs, the T-type converter is also a commercial candidate for future PFC converters.

B. DC/DC CONVERTERS

Modular single-phase DC/DC converters are widely used in the OBC market and research area. In order to achieve bidirectional functionality, all the switches should be active bidirectional switches. A half-bridge LLC converter, as shown in Fig.5 (a), can achieve a 10kW bidirectional power flow with 96% efficiency when it is controlled with a variable switching frequency [105]–[107]. A variable DC-link voltage of the AC/DC converter can maximize the efficiency of second-end stage. To reduce the high current stress, a half-bridge LLC converter can be replaced by full-bridge LLC converters [108]. However, for the LLC converter, the voltage gain is less than one when it runs in reverse operation

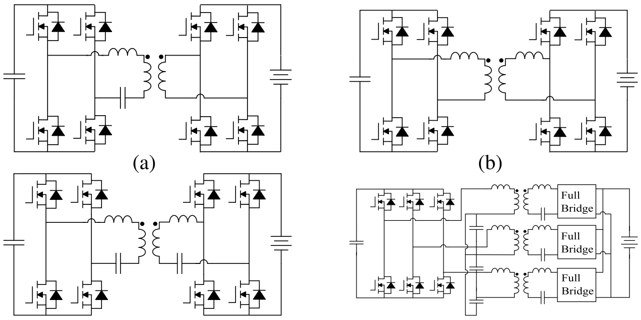
TABLE 5. Bidirectional DC/DC summary.

DC/DC Topology		Input Voltage (V)	Output Voltage (V)	Switching Frequency (kHz)	Power Density (kW/L)	Power Level (kW)	Efficiency (%)	Switching Devices
LLC	[108]	500-900	250-450	90-150	-	10	99	SiC
DAB	[119]	700-800	380-500	100	1.92	10	98.20	SiC
CLLC	[119]	380-600	280-450	300-700	-	6.6	98	SiC
	[81]	385-425	250-450	200	3.3	6.6	>96.5	SiC
	[124]	400-450	250-420	900-1250	9.21	3.3	>97	GaN
	[123]	550-840	250-450	500	7.93	6.6	97.80	SiC/GaN
Three-phase CLLC	[115]	800	400	500	9.46	12.5	>97.3	SiC/GaN

because of its asymmetrical structure. Therefore, the symmetrical phase-shifted DAB [109] or CLLC resonant converters [110]–[112] are more suitable for bidirectional DC/DC converters. Moreover, single-phase parallel dual DAB topologies [113], [114] and three-phase CLLC topologies [115], [116] have been studied. In the following paragraphs, the most popular and promising bidirectional DC/DC converters are presented.

1) PHASE-SHIFTED DAB

The phase-shifted DAB converter is one of the most popular bidirectional DC/DC converters in the OBC market [117], [118]. Fig.5 (b) shows the DAB converter. It has several advantages such as simple control and design, low device count, and competitive efficiency. Texas Instruments developed a bidirectional SiC DAB converter that achieves a 10kW power level and the peak efficiency of 98.2% [119]. Table 5 shows the detailed information.



(a) (b) (c) (d)

FIGURE 5. Bidirectional DC/DC topologies. (a) Single-phase LLC. (b) Single-phase phase-shifted DAB. (c) Single-phase CLLC. (d) Three-phase CLLC.

2) CLLC RESONANT CONVERTER

CLLC resonant converter adds two capacitors on each side of the transformer compared to the DAB converter, which is shown in Fig.5 (c) [120]–[122]. Compared to the DAB converter, the CLLC converter is controlled by a variable switching frequency and works with a much wider soft-switching region, especially at light load conditions. Although its control and design are more complicated, the CLLC resonant converter achieves higher efficiency. Many manufacturers have produced bidirectional CLLC resonant converters with SiC technology that can achieve a maximum efficiency of 98% and 6.6kW power rating, such as Texas Instruments and Wolfspeed. Some academic research groups also developed 3.3kW and 6.6kW CLLC resonant converter with GaN technology, feature a power density of 9.21kW/L [123], [124], as shown in Table 5.

3) THREE-PHASE CLLC

Three-phase CLLC converter, which is shown in Fig.5(d), is a candidate for DC/DC converters for OBCs due to its high power rating and high efficiency. This converter was designed for 12.5kW off-board charging using three CLLC converters connected in delta on the primary side and three full-bridge converters connected in parallel on the secondary side. By doing so, the current is equally shared among each resonant tank. High power density is achieved through planar magnetic transformer with a 500kHz switching frequency. The three-phase CLLC resonant prototypes using GaN and SiC technology have achieved an the efficiency above 97% and a power density up to 9.46kW/L [115].

Table 5 shows the summary of the promising bidirectional DC/DC converters. Most commercial DC/DC converters provide a wide output range to meet the wide battery charging standard. Generally, almost all DC/DC converters achieve an efficiency higher than 98%. Currently, the most common commercial bidirectional DC/DC converters are modular single-phase DAB and CLLC resonant converter, which can achieve a power level of 22kW by extending the single-phase to three-phase. However, with the adoption of three-phase PFC converters, three-phase CLLC resonant converters are promising candidates for future bidirectional OBCs.

C. CHALLENGES

Although bidirectional OBCs have lots of advantages, they use more active switch devices, which increases the cost, volume, and circuit reliability burden. In Table 1, for two-stage OBCs, it shows that PFC and DC/DC converters should achieve an efficiency higher than 99% and 98% respectively to meet the US Drive OBC targets. Table 4 shows that most commercial PFC converters are near 99% efficiency, but it is challenging to achieve a high power density at a high power rating. Table 5 shows similar results, most of the commercially available DC/DC converters achieve 98% efficiency at 6.6kW, but the power density is not satisfactory compared to the current targets. Other converters such as T-type PFC converter, CLLC converters with GaN devices, and three-phase CLLC converters, can achieve high power density, but are not commercially available due to their high cost. Therefore, the main goal for two-stage OBCs is to improve their power density while keeping a high efficiency and low cost.

A key limiting factor to high power density and reliability for PFC converter is the bulky DC-link capacitor. For resonant DC/DC converters, the wide range of input and output voltage cause low efficiency, because these converters only achieve the best efficiency when the switching frequency is the same as resonant frequency. A variable DC-link voltage of the PFC converter can mitigate this disadvantage, but the resonant tank needs to be carefully designed to cover that wide-voltage range [125], [126]. Moreover, compared to single controller of single-stage OBCs, some two-stage OBCs employ a separate controller for the PFC and DC/DC converters, respectively, which might be another reason for lower power density [39].

IV. SINGLE-STAGE BIDIRECTIONAL OBC

Single-stage OBCs combine the PFC converter with DC/DC converter without a bulky DC-link capacitor. Therefore, it has higher power density, lower cost, and higher reliability potential than the two-stage configuration. However, most single-stage OBCs focus on theoretical research without any practical application because of the low efficiency and the difficulty to simultaneously achieve PFC function and battery voltage regulation in a single conversion stage. For example, [127]–[129] and [130] have proposed some AC/DC topologies with GaN or SiC technology and achieved high power factor and full ZVS operation through different methods. However, [127], [128], and [130] lack efficiency information. [129] introduced two filter capacitors that decrease significantly the power density. [131] and [132] propose a high frequency isolation single-stage structure. It uses the interleaving technique based on both the three-state switching cell and the DAB concepts. It can achieve a high-power level, but it is challenging to implement in the OBC due to numerous components, high cost, and complexity in the control and design. To this day, there are only a few bidirectional single-stage OBCs used in the automobile industry. They are generally used in power levels up to 3kW for plug-in electric vehicle (PEV) or hybrid plug-in vehicles (HPEV) like the OBCs developed by BRUSA and Texas Instruments. Among all the research about high power-level bidirectional single-stage OBC topology, there are three promising topologies.

1) MODULAR THREE SINGLE-PHASE SINGLE-STAGE OBC

Fig.6 (a) demonstrates the single-phase converter, which consists of a full-bridge rectifier and an isolated DAB converter. The DC-link capacitance is 10μF, which is significantly smaller than a conventional DC-link capacitance in two-stage topologies. In this case, it is not treated as an energy-storaged capacitor, so this topology is considered a single-stage OBC solution. Since the front-end full-bridge is responsible for rectification, the back-end DAB needs to regulate the power factor and power delivery at the same time. Therefore, when the battery voltage is higher than the peak voltage of the grid, an additional phase shift is added on the secondary side to achieve ZVS function, which is called secondary side dual phase shift control method. When the battery voltage is lower than peak voltage of the grid, an extra phase shift is added on the primary side to obtain a square waveform in the secondary side, which is called primary side dual phase shift control method. In order to improve the performance of the converter at light load, a third triple-phase shift algorithm is applied to achieve ZVS at low power level. A single-phase 7.2kW topology with GaN technology was built in [41]. The duty cycle is always 50% in every mode. Three single-phase converters integrated into a single package and connected to the three-phase grid can achieve around 22kW with an efficiency higher than 97% and a power density of about 3.3 kW/L. The grid voltage range is from 80V to 260V, and the output voltage range varies from 200V to 450V. However, the high voltage stress of bidirectional switches, the relatively high cost of GaN devices, and complex control implementation, are some of the disadvantages of this topology.

2) DAB-BASED MATRIX CONVERTER

This topology is shown in Fig.6 (b). It removes the DC-link capacitor, which improves reliability and power density. This OBC topology has the following merits: 1) No switching loss because of full ZVS operation of all MOSFETs of the converter; 2) open-loop input PFC without load current sensor; and 3) simple closed-loop control due to the fact that the phase shift is proportional to the active power. The downside is that the bidirectional switch requirement doubles the switch count and gate driver demand, which increases cost. The performance of this matrix converter is similar to the traditional two-stage OBC topology. Since there are no switching losses, the switching frequency can be increased, leading to passive components with reduced volume. Therefore, this topology can be a promising solution for the OBC application because of its high power density and low system loss [133], [134].

3) THREE-PHASE T-TYPE MULTI-PORT CONVERTER

Fig.6 (c) shows a three-phase bidirectional AC/DC converter composed of a multi-port T-type topology with three AC ports and one active full-bridge with one DC port. The T-type converter connects the three-phase grid as the input signal.

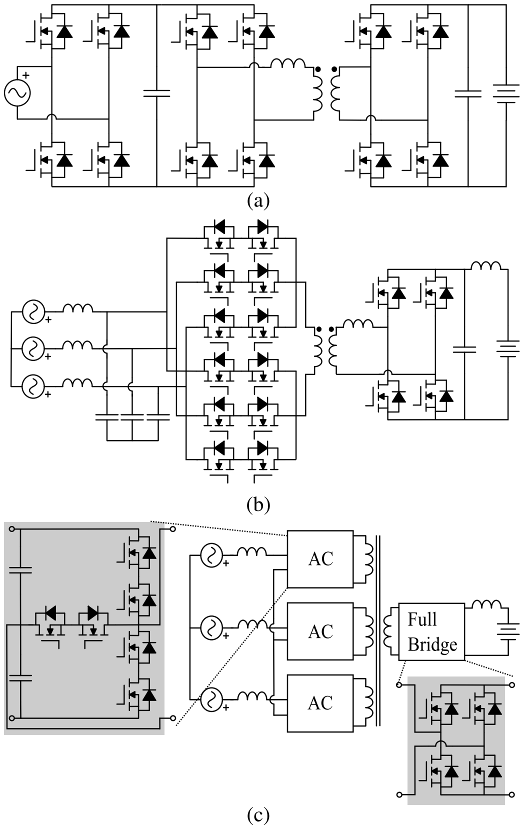


FIGURE 6. **Single-stage OBC Topology. (a) Modular three single-phase single-stage OBC. (b) DAB-based matrix converter. (c) Three-phase T-type multi-port converter.**

The frequency transformer has three windings on the primary side and one winding on the secondary side. For this topology, phase shift control is used, and ZVS operation is achievable for all MOSFETs. [135] achieves 96% efficiency and 2.5 kW/L power density for 11kW power rating. The positive aspect of this topology includes bidirectional power flow capability and small output capacitance due to ripple cancellation. However, the drawbacks includes high switch count, complicated single-phase implementation and control strategy.

Although single-stage OBCs can achieve high power density and improve the system reliability, there are also some disadvantages and challenges. Firstly, single-stage conversion suffers from large low-frequency output current ripple in single-phase applications, which has negative impact on the OBC operation. Secondly, due to power factor correction and rectification that need to be achieved in one converter, the control strategy is complicated, and the resonant frequency control will lower the conversion efficiency. Thirdly, all converter functionalities are performed by single conversion, so a sophisticated design and optimization within wide specifications needs to be considered. Therefore, most commercial single-stage OBCs are used in low power levels and unidirectional application [136], [137]. For example, the topology in [135] is applied in Brusa EV chargers and minimizes the volume of the filter capacitor at the power rating over 1 kW. Texas Instruments also developed a 1.5kW bidirectional single-stage OBC in HPEV or EV [137]. However, due to the requirement of shorter charging time and higher power density, high-power single-stage OBC will play an important role in the future.

V. FUTURE TRENDS AND CHALLENGES

To push the performance and adoption of OBCs, the main goals focus on low cost, high power density, high power level, and high efficiency. This section reviews the future research trends and potential challenges from the point of view of the topology, WBG devices, thermal design, system integration, and wireless charging system. Table 6 summarizes the future research trends and the drawbacks that need to be improved of bidirectional OBCs.

A. TOPOLOGY

It is expected that the majority of bidirectional OBCs will remain a two-stage structure within the next 10 years. Due to simple structures and controls, and high efficiency, further work is expected on single-phase totem-pole interleaved converter for front-end stage and resonant CLLC or DAB converters for DC/DC stage. As the power level requirement increases, a three-phase system is required where modular single-phase converters are a suitable option to achieve 22kW OBC. Three-phase full-bridge PFC is also a suitable option for bidirectional battery charging applications, in particular the three-level T-type converter, due to higher efficiency, although it has higher component number and higher complexity in control. Moreover, at high power levels, single-stage OBC converters would be preferred for bidirectional applications since they can achieve high power density and compactness, although they raise some challenges in terms of hardware design and achieving high efficiency [138]. Higher efficiency and better reliability could be achieved by an advanced control method and high-performance components.

B. WBG DEVICES

MOSFETs have been the predominant choice for bidirectional OBC converters compared to other switching devices because of its wide availability and its power capability. In fact, as SiC MOSFET devices have a blocking voltage of 600V to 1700V, they can easily deal with battery voltages from 200V to 800V in most EVs [139].

WBG devices, like SiC and GaN, provide many advantages over traditional Silicon (Si) devices [140]. For example, a WBG device has higher breakdown field that allows for optimized devices with thinner drift regions, which lowers the specific on-resistance. GaN has a lower on-resistance, which minimizes the volume and values of the passive components, while keeping the same current capability [141]. Though the SiC technology has good performance at high-temperature, the GaN technology seems more suitable for high-frequency applications. Moreover, as the maximum voltage rating of

TABLE 6. Future research trends.

Future work	Promising improvements	Drawbacks
Topology	a) Two-stage OBC: modular single-phase totem-pole PFC	1) Low power density; 2) Low reliability
	b) Two-stage OBC: three-phase PFC converter	1) Low power density; 2) Low reliability
	c) Single-stage OBC at a high power level	1) Low power level; 2) Low efficiency; 3) Complex design and optimization
WBG devices	SiC; GaN	1) High cost; 2) Complex gate driver design; 3) Complex EMI design
Thermal design	Integrated with OBC, motor, and DC/DC system	Need high heat transfer and compactness material
System Integration	OBC integrated with the traction inverter	1) Torque production; 2) No galvanic isolation
Wireless charging system	SWC, DWC, QWC	1) High cost; 2) Low efficiency; 2) Low power density

GaN semiconductors reaches up to 650V, these devices are becoming an attractive solution for OBCs [142].

The adoption of WBG devices by the OBC industry is constantly increasing and is a natural choice to achieve high compactness and high efficiency. Table 4 and Table 5 show several manufacturers that are currently using WBG devices for OBC application. Although WBG devices currently have a higher cost, it is expected that the price will decrease as the production rises [143], [144]. As an alternative solution, some companies, like Texas Instruments, combine SiC with Si technologies to reduce the cost while improving the overall performance [119]. However, new challenges regarding gate driver, PCB layout, dead time, and EMI design demand special attention.

C. THERMAL DESIGN

The high switching frequency and integrated power electronics devices cause significant thermal management challenges due to a more compact packaging and higher eddy current and skin effect losses of passive components. These eddy current losses induced in the magnetic components have a detrimental effect on the charger's performance and reliability. The future thermal design of OBCs will likely use high-end liquid cold plates integrated into the OBC enclosure along with intelligent interfaces with the vehicle liquid cooling system like motor and DC/DC system. Hence, the thermal management engineer will have to consider the vehicle thermal design comprehensively and very early to dissipate all the heat loads efficiently, including the OBC, inverter, and battery pack. Moreover, common heat sink manufacturing process like extrusion and casting have well known limitations for heat sink designs. On the other hand, additive manufacturing technology opens up an opportunity for nonconventional geometries that can achieve higher surface density and excellent heat exchange. Additionally, heat pipes are becoming an attractive solution for automotive cooling because of its high heat transfer, low thermal resistance and low cost [145].

D. SYSTEM INTEGRATION

To further increase the power density of the overall system, the OBC integration with the traction inverter is an alternative. Some production vehicles already include mechanical integration of the OBC with other vehicle power electronics modules such that they share a common housing, reducing cost and weight [6]. Beyond simple mechanical integration, there is potential to further increase the power density while simultaneously increasing the charging power capability by electrically integrating the OBC with the inverter at the topology level. This is often referred to as an integrated battery charger topology, and has received significant attention by the research community and some limited commercialization.

Integrated battery charger topologies generally repurpose some combination of the traction inverter, electric motor windings, and high voltage DC/DC converter if available, to achieve battery charging functionality from the AC grid. Since the traction inverter is inherently a bidirectional DC/AC converter, integrated battery charger topologies can often have bidirectional capabilities as well, depending on how the system is configured in charging mode. Topologies taking advantage of the conventional three-phase wye-connected machine found in EVs have been proposed, for both single-phase [146] and three-phase [147] solutions. Other topologies for multiphase [148], open ended winding [149], and switched reluctance machines [150] have also been proposed. Reviews of integrated battery charger topologies have also been conducted [151]–[153].

Common challenges with integrated battery charger topologies include torque production in the electric machine during the charging mode, and a lack of galvanic isolation between the AC grid and the vehicle. Torque production can be eliminated by restricting it to high frequency components with a zero average [146], phase transposition in the charging mode [148] or through flux cancellation with split winding machines [154]. Galvanic isolation is primarily required to prevent common mode currents from creating a shock hazard for the user [155]. Techniques for reducing these common mode currents have been presented [156]. Renault has included a 43kW non isolated integrated charger in the Zoe [148], demonstrating the commercial viability of these solutions.

E. WIRELESS CHARGING SYSTEMS

Conductive charging techniques for EVs bring challenges such as charging time, range anxiety, charging infrastructures, and queuing time at the charging station. On the other hand, the wireless power transfer (WPT) technique is a promising trend for EV charging, since it aims to address the issues above while bringing safety and convenience for the users. Many OEMs have started to research inductive power transfer (IPT) techniques for EVs. The BMW 530e PEV features wireless charging in California, US. Honda also presented its wireless V2G concept with wireless charging specialist WiTricity in 2019, which combines the WPT and bidirectional power transfer function. Moreover, SEA 2954 offers standard guidelines of WPT industry specifications [157]. WPT theory for EVs has been widely studied in the research field. Although WPT can be applied in both on-board and off-board chargers, this paper focuses on wireless charging of OBCs.

WPT is classified as static wireless charging (SWC), dynamic wireless charging (DWC), and quasi-dynamic wireless charging (QWC). SWC avoids the shock hazard of wires and metal and can be charged at a convenient location like home garages or parking lots. The control strategies like variable frequency and fixed frequency are presented to improve the operating efficiency in [157], [158]. Some structures and shapes of the coil are proposed in [157], [159] for better robustness, cost-effectiveness, and minimization of the stray magnetic field. DWC charges the EV with the specific charging lane, which can prolong the EV range and reduce the battery size. Many methods are proposed like road built-in pad [160], pad array-based coupling technique [161], and segmental track strategy [162]. However, due to high maintenance costs and complicated models, they are challenging to be applied in practice. The double couple method is presented in [163], but it fails because of high-frequency transmission. SWC and DWC are combined in [164], [165] and show promising results but are expected to also feature a high cost. QWC charges the EV when it stops for a short time, like at a traffic light, which combines the advantages of the SWC and DWC and also simplifies the complex implementation of the DWC [166].

WPT has many challenges to be overcome, such as relatively low efficiency and power density, high cost, and manufacturing complexity. Moreover, distant charging is also a challenge at a high power level.

F. CHALLENGES

Although there are clear benefits for the bidirectional OBC, it still brings the new challenge. Due to the increasing number of active components, it is challenging to maintain the system reliability of bidirectional OBCs. [167] presents a fault-tolerant system to improve reliability, but it adds additional models that cause more weight and cost. Some control methods are proposed to optimize the reliability, such as the switching function algorithm [168], the bi-objective algorithm based on efficiency and reliability [169], and the adaptive control method [170]. [171] offers a modular power converter to obtain reliable operations. The active thermal control method is also a valuable way to reduce failure [172].

Moreover, the development of bidirectional OBC also exposes challenges for the infrastructures in the related industry. Firstly, the bidirectional power flow needs to be compatible with advanced smart grid functionalities. Hence, updating the grid and infrastructures is a major concern. Secondly, although bidirectional OBC has some merits like peak shaving and frequency regulation for the grid, it has some potential impact on battery degradation because of frequent charging or discharging operations. Government or utilities need to provide additional motivation policies like financial incentives to encourage potential consumers to choose bidirectional power flow capable EV. On the other hand, safety monitoring and protection are required in the V2G and G2V modes. The smart grid should be robust and reliable to accept V2G.

VI. CONCLUSION

The capacity of the EV battery will increase in the future to deal with issues such as range anxiety, long charging time, and high financial pressure of off-board chargers. Facilitating a higher-power level, higher efficiency, and higher power density is the next step in the automotive industry.

This paper presents a detailed overview and future trends of bidirectional OBCs for EVs. The current status of bidirectional OBCs including architectures, smart operation modes, industry standards, components, and commercial examples has been reviewed. Two-stage and single-stage solutions have been investigated. Most high-power bidirectional OBCs for commercial applications use a two-stage configuration with a DC-link capacitor because of its simple structure and excellent performance. Front-end totem-pole PFC converter and downstream CLLC DC/DC converter are widely used. Three-phase PFC structure has also appeared in the industry. Single-stage OBCs without DC-link capacitors for high power levels may be attractive because of high power density. However, no commercial product has been developed to this day. In addition to industrial examples, this paper reviews key promising bidirectional OBC topologies. The future work of bidirectional OBCs is summarized from the viewpoints of topology, WBG devices, thermal design, system integration, and wireless charging system. Single-stage OBC is a new trend to achieve high power density. WBG devices are of interest to OBC manufacturers due to their superior performance. Moreover, it is expected that the cost of WBG devices will further decrease, which will help broaden their use in cost-competitive applications such as the automotive industry. Research areas like gate driver design and EMI design deserve attention. The thermal design of OBCs is also projected to integrate with the thermal design of other parts of EVs. Highly integrated OBC with other electrical components like the traction inverter or motor is also a trend to improve power density. Wireless charging system will keep the popular trend. Further work is ongoing to meet the expectations in terms of efficiency, power density, reliability, and cost of bidirectional OBCs.

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