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A Comprehensive State-of-the-Art Review of Wired/Wireless Charging Technologies for Battery Electric Vehicles: Classification/Common Topologies/Future Research Issues

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ABSTRACT The increasing emissions created by the large-scaled number of automobiles around the world pose severe threats to modern life by causing global warming issues and deteriorating air quality. These serious issues stimulate the essential demand for cleaner, safer, and more efficient vehicles, such as battery electric vehicles (BEVs). Unlike other studies on the charging technologies of BEVs, this paper gives a comprehensive state-of-the-art review on the charging technologies available for BEVs: wired charging and wireless charging technologies. First, the wired charging technologies are systematically classified into AC charging (indirect charging) and DC charging (direct charging) methods based on how the BEVs batteries are fed from the grid. Next, the configurations and commonly used topologies of wireless charging technologies for BEVs are thoroughly discussed. The leading institutes/companies driving advancements in both technologies are also acknowledged. Finally, this paper extensively highlights the recent and future research trends along with the industrial applications.

INDEX TERMS AC charging, battery electric vehicles (BEVs), DC charging, off-board charger, on-board charger (OBC), wired charging, wireless charging.

I. INTRODUCTION

The increasing number of automobiles, e.g., motorcycles, cars, trucks, buses, etc., powered by fossil fuels is the main contributor to environmental pollution, which deteriorates air quality and causes global warming pollution by releasing harmful air pollutants (e.g., sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), etc., [1]–[3]). These gases not only threaten the environment, but also have detrimental effects on almost every organ system in the human body [4]–[6].

The above-stated environmental problems have raised concerns from researchers and governments, who have responded by placing substantial emphasis on overcoming the reliance on fossil fuels by replacing them with clean solutions; electric vehicles (EVs) represent an example of this [7]–[9]. Over the past few decades, EVs have gradually attracted increasing attention due to their promising features such as free-pollutant gases, no greenhouse gas emissions, and high efficiency [3], [5], [10].

Recently, several studies have achieved significant and positive advancements in the utilization of EVs, specifically in terms of reducing the higher fuel prices, increasing the energy-saving capability, and meeting the essential needs for green sources of transportation along with substantially improved fuel economy and reduced emissions [4], [5]. For instance, battery electric vehicles (BEVs) have experienced remarkable growth in market share since 2014. The batteries and corresponding charging systems used in these particular BEVs play a key role in their efficiency and price. Thus, some companies are conducting more intensive research into charging technologies for BEVs to maintain their growth rates through the coming years [11].

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Currently, BEVs are attracting increasing attention every day due to their promising achievements, mentioned above. However, further improvements to their charging systems have proved challenging since multiple factors need to be taken into account when studying these systems, such as an optimized structure design with fewer components, safety measures, high efficiency, fast charging, etc. These charging technologies can be subdivided into two different technologies: wired charging technologies (contact charging) [12]–[43] and wireless charging technologies (contactless charging) [44]–[89]. First, wired charging technologies require a direct connection between the EV and the charging system via cables to achieve charging, and these can be further divided into AC charging technologies [12]–[25] and DC charging technologies [26]–[43]. AC charging technologies do not directly charge the battery EVs (BEVs), but instead charge the battery via the on-board charger (OBC) that feeds the battery. In these technologies, the conversion unit (i.e., that converting AC into DC) is placed inside the vehicle, which increases the weight of the overall system. They are commonly charged in either single-phase (1ϕ) on-board (OB) slow charging [12]–[15] or three-phase (3ϕ) OB fast charging systems [16]–[25]. Unlike AC charging technologies, DC charging technologies [26]–[43] can directly charge the battery, thus offering a fast charging capability, and these can be further divided into two groups: off-board fast charging [26]–[35] and off-board rapid charging systems [36]–[43]. Such technologies can achieve an overall reduced size and weight of the driving system in the vehicle, because the conversion unit is separate from the vehicle [30], [31]. However, they offer no flexibility to allow the battery to be charged at different places, and the installation of their battery management system (BMS) is more costly. Despite the remarkable and promising achievements that have been achieved in wired charging technologies, their inflexibility that limits where they can charge is one of their main drawbacks. In addition, the BMS should be considered in terms of safety and reliability demand, both of which are difficult tasks [35], [37].

Next, wireless charging technologies [44]–[89] can be classified into three groups: near-field charging technologies [44]–[65], medium-field charging technologies [66]–[70], and far-field charging technologies [71]–[89]. The first two charging technologies (i.e., near-field charging [45]–[65] and medium-field charging (also referred to as mechanical charging) [66]–[70]) are the most dominant and currently used charging technologies for BEVs. The demand for wireless charging technologies is currently increasing each day. Wireless charging technologies are less costly than wired charging technologies and require no direct connection with the batteries of EVs. Instead, they can wirelessly charge the batteries by converting the grid-frequency AC (50/60 Hz) into a high-frequency AC (up to 600 kHz) that is then transmitted via a transmitter pad and received by a receiver pad attached to the BEV being charged [45]–[60]. Meanwhile, far-field charging technologies [71]–[89] are considered to be the future charging method for EVs. However, one of the major drawbacks of wireless charging technologies is that they can easily get out of control if the connection between the transmitter and the receiver is lost.

This paper comprehensively presents a state-of-the-art review on charging technologies for BEVs, namely, wired charging technologies and wireless charging technologies. First, wired charging technology is subdivided into AC charging (indirect charging) via OBC and DC charging (direct charging) via an off-board charger; their commonly adopted topologies are also presented. Next, wireless charging technologies currently used for BEVs are discussed in detail. This paper also highlights the leading companies in both technologies. Finally, it extensively investigates the future research trends of these technologies along with their industrial applications.

The rest of this article is arranged as follows. Section II presents the classification of wired/wireless charging technologies. Section III discusses the recent technologies in the wired charging technologies along with the leading companies in on-board and off-board charging for BEVs. Section IV highlights the wireless charging technologies for BEVs along with their available topologies. Finally, the future research issues associated with wired/wireless technologies are discussed in Section V, and concluding observations are given in Section VI.

II. CLASSIFICATION OF WIRED AND WIRELESS CHARGING TECHNOLOGIES

This section presents the classification of wired and wireless charging technologies for BEVs. Fig. 1 shows the overall classification for both charging technologies, which occurs in a systematic manner.

As illustrated in this figure, the wired charging technology can be achieved through two methods: AC charging (i.e., 1ϕ OB slow charging [12]–[15] and 3ϕ OB fast charging [16]–[25]) and DC charging (i.e., off-board fast charging [26]–[35] and off-board rapid charging [36]–[43]).

The AC charging method generally feeds the OBC, where the AC is converted into regulated DC. It should be noted that the OBC not only takes over the responsibility for the AC to DC conversion, but it also improves the quality of the regulated current (i.e., less ripples, reduced switching loss, and reduced electromagnetic interference (EMI)) [12], [16]. In addition, AC charging technologies are mainly used in low power and slow charging BEVs with power levels and charging times below 20 kW and 2 $\sim$ 6 h, respectively. Next, to overcome the limitations of AC charging methods, DC charging methods (i.e., off-board fast charging and off-board rapid charging) have been developed such that they can charge a high-capacity battery within a short time under 1 h. Fig. 2 shows the overall charging system for BEVs using wired/wireless charging technologies. As shown in this figure, the OBC is basically equipped inside the BEV, and it consists of a full-bridge rectifier, a power factor cor-

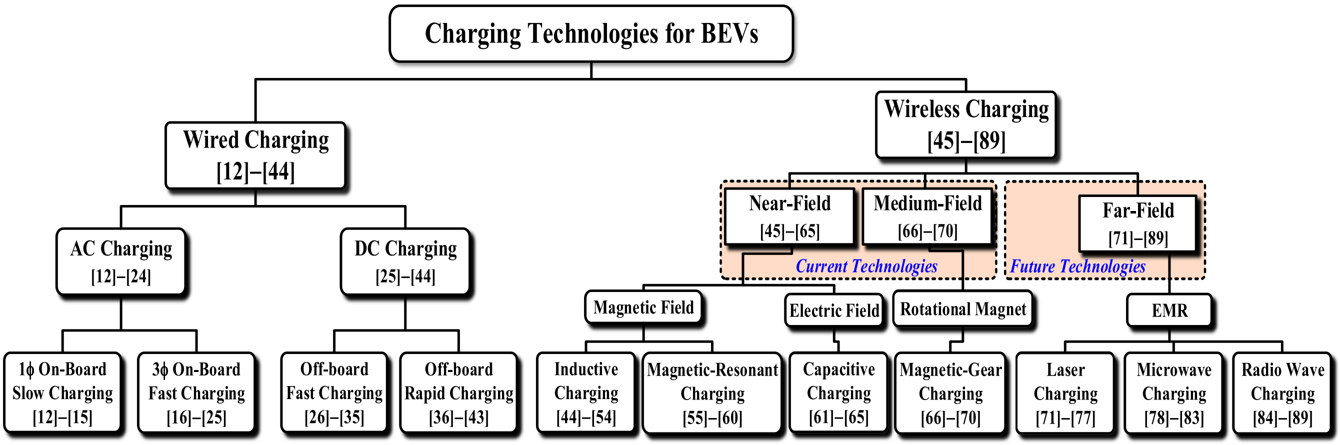

FIGURE 1. Overall charging system for BEVs using wired/wireless.

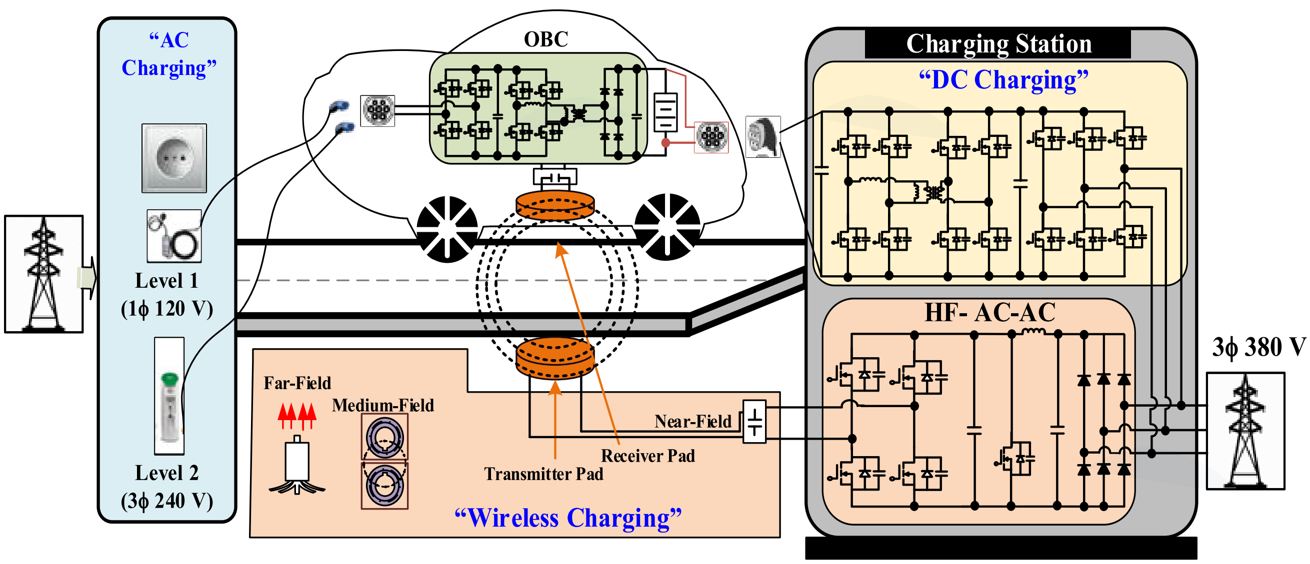

FIGURE 2. Overall charging system for BEVs using wired/wireless charging technologies [14], [20], [30], [40], [50], [55], [67], [71], [78], [84].

rection (PFC) circuit, and a chopper such as a dual-active bridge (DAB), through which it indirectly charges the battery. Unlike the OBC, the off-board charger is located outside the BEV (i.e., installed at a charging station), which directly feeds the battery.

On the other hand, the limitations of wired charging technologies (e.g., the need for charging cables, maintenance requirement, and safety concerns) have spurred research into wireless charging technologies. In these types of technologies, the BEV has to park in a spot above the charging system where it can receive the high-frequency charging current [44], [45].

The available wireless charging technologies are near-field charging (i.e., inductive charging [44]–[54], magnetic-resonant charging [55]–[60], and capacitive charging [61]–[65]) and medium-field charging (i.e., magnetic-gear charging) [66], [70]. However, far-field charging technologies (i.e., laser charging [71]–[77], microwave charging [78]–[83], and radio wave charging [84]–[89]) are still the subject of extensive research and are expected to represent the future trend in wireless charging technologies

III. WIRED CHARGING TECHNOLOGIES FOR EVS

This section extensively discusses the classifications of wired charging technologies for BEVs. As shown in Fig. 1, the wired-based technologies are categorized based on the input voltage type supplied to the BEV's inlets; i.e., AC-charging technologies [12]–[25] and DC-charging technologies [26]–[44]. The former set is subdivided into two groups: 1ϕ OB slow charging technologies [12]–[15] and 3ϕ OB fast charging technologies [16]–[25]. The latter set is classified into two groups: off-board fast charging technologies [26]–[35] and off-board rapid charging technologies [36]–[43].

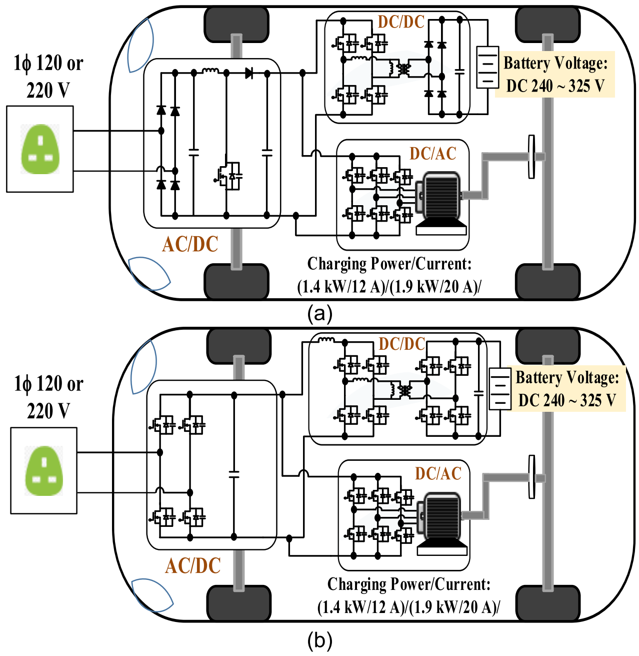

FIGURE 3. **1ϕ on-board slow charging topologies [12]–[15]. (a) Unidirectional topology. (b) Bidirectional topology.**

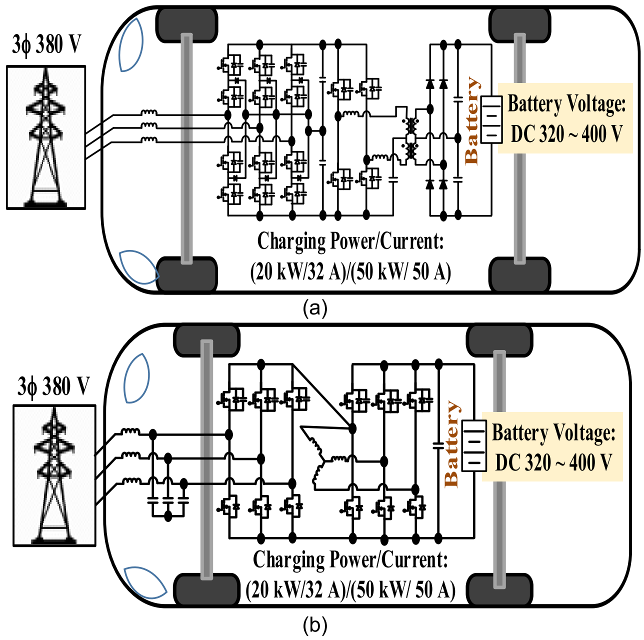

FIGURE 4. **3ϕ on-board fast charging topologies [16]–[25]. (a) Unidirectional topology. (b) Bidirectional topology.**

A. AC CHARGING

As discussed previously, AC charging indirectly charges the battery via the OBC, which can be classified into two groups: 1ϕ OB slow charging [12]–[15] and 3ϕ OB fast charging [16]–[25].

1) 1ϕ ON-BOARD SLOW CHARGING

1ϕ OB slow charging typically requires multi-stage conversions (i.e., AC-DC and DC-DC), which inherently leads to low-voltage ripples and a relatively high power rating [12]–[15]. Thus, it is widely used as an OBC inside BEVs such as for level 1 AC charging (i.e., input voltage: 1ϕ 120 or 220 V, charging power: below 2 kW, and battery voltage (V_B): DC 240 $\sim$ 325 V) in a number of BEV models on the market (e.g., Tesla Model 3, Toyota RAV4, etc.).

A simplified two-stage 1ϕ OBC of BEVs is depicted in Fig. 3. The battery charging is achieved as follows: First, the grid voltage is rectified to feed the power factor correction (PFC) circuit via an AC/DC converter. Then, the output voltage of the PFC circuit is fed to the intermediate DC-link bus, which is in turn transformed to a controlled DC output voltage by means of an isolated DC/DC converter (e.g., full-bridge (FB), flyback, etc.) thereby achieving effective and safe battery charging. Note that the galvanic isolation is acquired at the DC-DC stage by using a galvanic transformer [12]–[15]. They can be configured according to the power flow into two groups: unidirectional and bidirectional chargers, shown in Fig. 3(a) and (b), respectively. The unidirectional charger facilitates a utility grid delivering power to a heavy load, i.e., multiple BEVs at once [12]–[13]. One of the main benefits of a unidirectional active front-end rectifier is its capability of supplying power without discharging the battery by controlling the phase angle of the supply current. Thus, to achieve high penetration of BEVs and active control of charging current, a unidirectional charger presents a practical solution.

Unlike the unidirectional charger, the bidirectional charger can be used in both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) technologies [14], [15]. However, there are still some challenges with this charger; for one, the frequent charging and discharging reduce the lifetime of the battery and increase the cost of the charging system. Thus, these issues should be considered when using a bidirectional battery charger. This type of charging technology also involves extensive anti-islanding protection and safety measures [12]–[15]. Fig. 3 shows one of the most common 1ϕ OB slow charging technologies, i.e., level 1 with an output power of about 2 kW and a charging time that can reach up to 6 h or more.

2) 3ϕ ON-BOARD FAST CHARGING

Compared to the 1ϕ OB slow charging technologies, the 3ϕ OB fast charging technologies [16]–[25] can provide a faster charging capability because of their medium power rating (about 20 kW); i.e., they can charge the battery up to 80% within a charging time ranging between 2 $\sim$ 3.5 h.

Consequently, they can be used for an OBC inside BEVs such as level 3 (i.e., input voltage: 3ϕ 280 $\sim$ 420 V, charging power: up to 50 kW, and battery voltage (VB): DC 320 $\sim$ 400 V) in the following BEV models (e.g., Smart FortWo ED, Tesla Model 3, Toyota RAV4, etc.). Dual-active-bridge (DAB) topologies are the most commonly used for these charging technologies. Fig. 4 illustrates the prevailing 3ϕ OB fast charging technologies. This approach is more practical for almost all BEVs in the market due to its easy application.

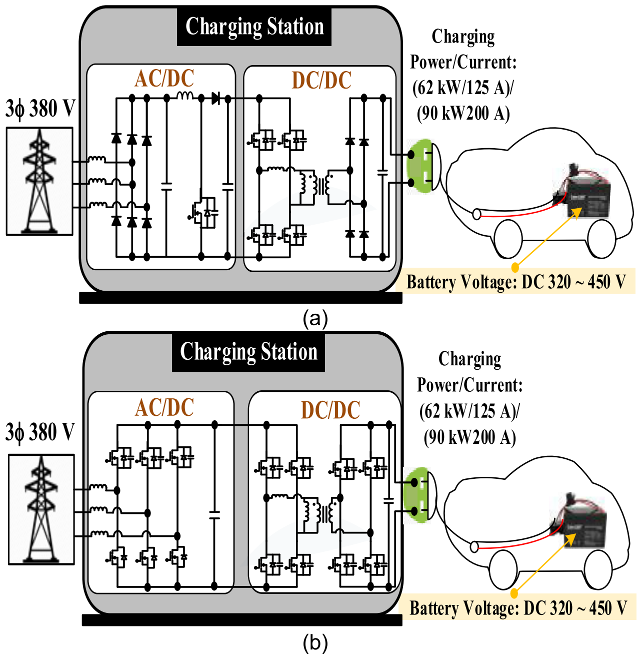

FIGURE 5. **3ϕ off-board fast charging topologies [26]–[35]. (a) Unidirectional topology. (b) Bidirectional topology.**

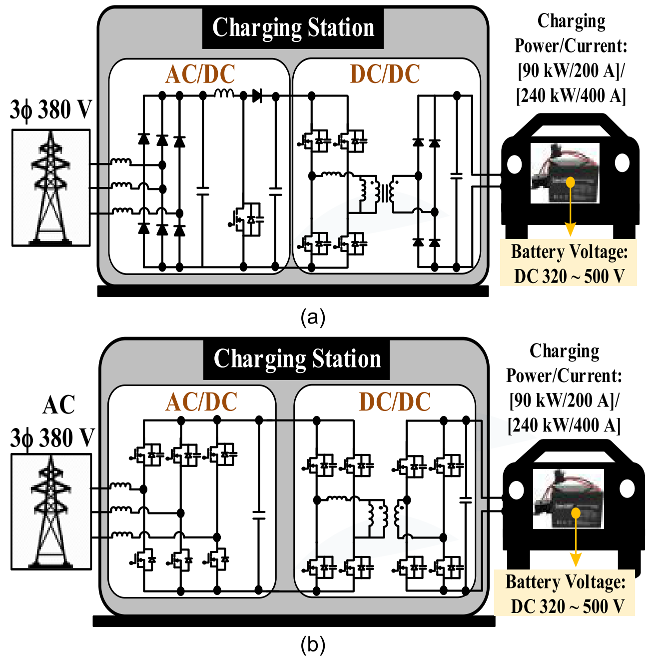

FIGURE 6. **3ϕ off-board rapid charging topologies [36]–[43]. (a) Unidirectional topology. (b) Bidirectional topology.**

B. DC CHARGING

The DC charging technologies for BEVs are discussed below. They can be classified into two groups: off-board fast charging [26]–[35] and off-board rapid charging [36]–[43].

1) OFF-BOARD FAST CHARGING

The presence of the rectifying unit in the charging station enables these technologies to directly charge a BEV's battery. As a result, they can achieve an overall reduced size and weight of the driving system [26]–[35]. DAB topologies are the most common for these specific charging technologies.

These types of charging technologies are particularly known for their fast charging (specifically, for their charging time below 1 h). Recently, reputable companies such as Tesla, BMW, Nissan, and Hyundai have begun to offer fast DC charging stations that are capable of charging batteries within 1 h. Fig. 5 shows the off-board fast charging technologies that mainly feed the battery with a 3ϕ power source using a power level ranging between 20 $\sim$ 120 kW, charging time less than 1 h, and battery voltage of DC 320 $\sim$ 450 V [26]–[30].

2) OFF-BOARD RAPID CHARGING

An extended form of fast charging technologies can be found in the so-called rapid charging technologies, which use more power and charging current [36]–[43].

In these charging approaches, the charging time is faster, such that the battery of BEVs with DC 320 $\sim$ 500 V can be charged up to 80% within 15 min. One of the most well-known rapid chargers, which is manufactured by Tesla, is fed by DC 480 V and 250 kW. As of March 2020, Tesla successfully operated around 16,013 superchargers at 1,826 charging stations worldwide for different BEV models such as Model S, 3, X, and Y [36]–[39].

As an example, Model S has a charging current of 80 A, then the battery requires about 20, 40, and 75 min to be charged up to 50%, 80%, and 100%, respectively, as for 85 kWh. Fig. 6 shows the rapid charging topology whereby the battery is charged by a high power DC current that can reach 400 A. Two off-board configurations are presented in the figure: a 3ϕ unidirectional and 3ϕ bidirectional topology.

Table 1 summarizes the wired charging technologies along with some important factors such as the supported BEV models, battery capacity, charger location, charging time, power level, and interface for battery charging, as well as some other relevant remarks.

IV. WIRELESS CHARGING TECHNOLOGIES FOR EVS

This section thoroughly discusses the classifications of wireless charging technologies for BEVs. Beyond wired charging technologies, wireless charging technologies are recently attracting substantial attention due to their advantages, which are discussed below. Wireless charging technologies can be subdivided into three groups according to the transmitted distance: near-field charging technologies [44]–[65], medium-field charging technologies [66]–[70], and far-field charging technologies [71]–[89].

A. NEAR-FIELD CHARGING TECHNOLOGIES

The near-field charging technologies for BEVs include inductive charging [44]–[54], magnetic-resonant charging [55]–[60], and capacitive charging [61]–[65], which are described in detail below.

TABLE 1. Summary of the most common wired charging technologies along with the leading companies.

BEV Model/ Country	Battery		Charging Criteria							
	Type	DC Voltage [V]/ Capacity [kWh]	Type	Charging Time	Charging Current [A]	Power Level [kW]	Interface	Charging Speed Rate	Type of Connector
Smart FortWo ED/ France	Li-ion Polymer	(280~380)/17.6	①	8.45 h with 2.3 kW	10	2.3 ~ 7	⑤ and ⑥	Slow and fast	-
			②	7.30 h with 4.6 kW	30				
			③	-	-				
			④	-	-				
Hyundia IoniqEV/ South Korea	Li-ion Polymer	(240~360)/28	①	13 h with 3 kW	-	3 ~ 50	⑤ and ⑥	Slow and fast	-
			②	5.5 h with 7 kW	30				
			③	5.5 h with 22 kW	-				
			④	40 min with 50 kW	-				
Mitsubihi iMiEV/ Japan	Li-ion	(~360)/16	①	3 h with 3.7 kW		2 ~ 24	⑤ and ⑥	Slow and fast	TEPCO/ JARI SAE J1772
			②	2 h with 7.4 kW	32				
			③	1 h with 24 kW	-				
			④						
Kia Soul EV/ South Korea	Li-ion Polymer	(230~350)/30	①	11 h with 2.3 kW	10	2 ~ 100	⑤ and ⑥	Slow and fast	-
			②	5 h with 6.6 kW	30				
			③	50 min with 50 kW	125				
			④	-					
Tesla Model 3/ US	Li-ion	(230~350)/75	①	20 h with 3 kW	-	3 ~ 120	⑤ and ⑥	Slow and fast	SAEJ 1772
			②	8.5 h with 7 kW	-				
			③	55 min with 50 kW	100				
			④	20 min with 120 kW	300				
Tesla Model S/ US	Li-ion	(~500)/100	①	15 h with 7 kW	-	3.7 ~ 150	⑥	Fast	SAEJ 1772
			②	55 h with 22 kW	32				
			③	80 min with 50 kW	-				
			④	10 min with 240 kW	400				
BMW i3/ German	Li-ion	(~352)/33	①	6 h with 7.4 kW	-	3 ~ 50	⑥	Fast	-
			②	3 h with 11 kW	-				
			③	45 min with 50 kW	-				
			④	-					
Nissan Leaf/ Japan	Li-ion	(~360)/40	①	6 h with 7.4 kW	16	3 ~ 100	⑥	Fast	SAEJ 1772
			②	3 h with 22 kW	32				
			③	40 min with 100 kW	-				
			④		-				
Toyota RAV4/ Japan	NiMH	(230~386)/41.8	①	14 h with 3 kW	-	3 ~ 50	⑤ and ⑥	Slow and fast	SAE J1772
			②	6 h with 7 kW	25				
			③	50 min with 50 kW	125				
			④	-	-				

Note that "①", "②", "③", and "④" respectively represent "1ϕ OB slow charging", "3ϕ OB fast charging", "3ϕ off-board fast charging", and "3ϕ off-board rapid charging", while "⑤" and "⑥" represent "any convenient outlet" and "BEV supply equipment", respectively.

1) INDUCTIVE CHARGING

Inductive charging [44]–[54] is one of the recent cost-saving near-field charging technologies for modern transportation wherein power is transferred in the form of an electromagnetic field from a transmitter pad to a receiver pad, as shown in Fig. 7. In these systems, achieving a maximized power transfer with high efficiency is one of the essential considerations during both the design stage and operation. In addition, to attain a long lifetime of the battery, it is very important to regulate the EV power bus voltage [45]–[50]. This can be achieved by simultaneously regulating the switching frequency and conversion ratio of the primary-side converter (i.e., high-frequency (HF) AC-AC converter at the transmitter pad) and the secondary-side converter (e.g., full-bridge, dual-active bridge DC-DC converter, etc., at the receiver pad).

The design of a suitable power pad is considered among the most critical phases in the fabrication of a reliable and

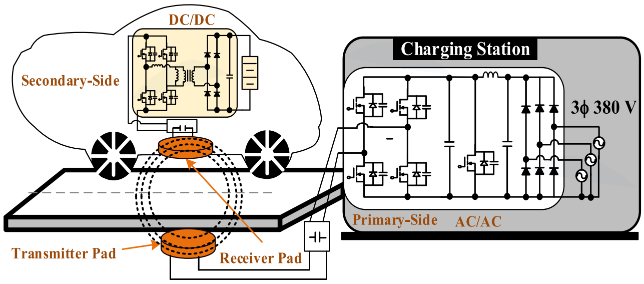

FIGURE 7. Inductive charging topology for BEV [44]–[54].

efficient wireless power transfer (WPT) system for charging the batteries of BEVs. Although WPT systems have come to be used in many BEV applications, there are still a number of challenges involved with such systems, such as the designs of the power pad and the coil [45]–[47], electromagnetic field protection [48]–[50], HF power converters [51]–[54], metal object detection, etc. These kinds of charging technologies have a power transfer capability set between 3 ∼ 60 kW for a short distance of 4 ∼ 10 cm, respectively, with a maximum efficiency of 90% for the distance of 4 cm.

2) MAGNETIC-RESONANT (MR) CHARGING

In contrast to inductive charging, MR charging [55]−[60] shown in Fig. 8, is very effective because the resonant frequency can be magnified by adding compensation capacitors, thereby resulting in a long transmission distance capability (i.e., 1 ∼ 5 m). The range of the power delivery achieved by MR charging can reach up to 100 kW [55]–[60].

These forms of charging technologies can be implemented in four phases as follows: phase 1, simple residential systems; phase 2, parking areas; phase 3, on-street parking; and phase 4, dynamic charging systems (future technology for highways) [55], [56]. While phase 1 appears to be widespread in residential BEVs, phases 2 through 4 require government support. For instance, the UK dedicates 40 million pounds to research into MR-based charging technology [57], [58], which includes investigating wireless charging solutions for streets, commercial vehicles such as ride-sharing vehicles, delivering vehicles, etc. Further, the Oak-Ridge national laboratory has recently demonstrated an MR-based wireless charging system with an output of 120 kW, which is equivalent to that of a Tesla supercharger. It can transfer a high power (i.e., 100 kW) over a medium range (i.e., 1 m) with a high efficiency of 90%. Qualcomm also constructed a 100-meter test-track in France, which is embedded with a 20 kW wireless charging system. Therefore, MR charging has attracted more interest than inductive charging because of its promising features, which were mentioned earlier.

3) CAPACITIVE CHARGING

Unlike the inductive and MR charging technologies, capacitive charging [61]–[65] can be generated by means of the electric field, where two metallic plates are integrated

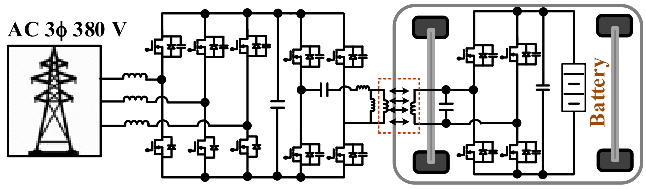

FIGURE 8. Magnetic-resonant charging topology for BEV [55]–[60].

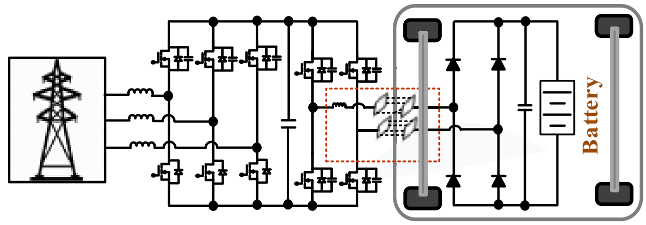

FIGURE 9. Capacitive charging topology for BEV [61]–[65].

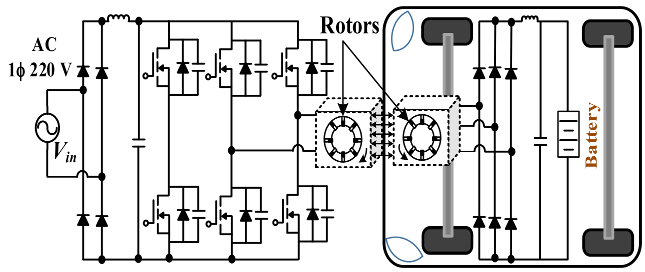

FIGURE 10. Medium-field charging topology for BEV [66]–[70].

with both the transmitter and receiver pads that can be connected to the power source or load in the manner shown in Fig. 9.

These two plates act like two capacitors in parallel connection, so an electric field can be generated between them, resulting in the induction of electrical current in the receiver pad [60]–[65]. This induced current is equivalent to the rate of change of the electric field between the transmitter and receiver pads. Thus, power converters such as resonant-based converters can be utilized to increase the rate of the electric field by elevating the frequency provided by the utility grid. Their power transfer capability, distance, and maximum efficiency can reach up to 7 kW, 12 cm, and 80%, respectively.

B. MEDIUM-FIELD CHARGING TECHNOLOGIES

The principle of medium-field charging technologies (i.e., magnetic gear-based charging technology) makes use of mechanical force as a main energy-carrying medium. They can be implemented in charging applications with a low power range of 1.5 ∼ 3 kW [66]–[70]. Fig. 10 shows the magnetic-gear charging system for BEVs.

As shown in the figure, the working principle of this charging technology depends on the mechanical interaction between two synchronized permanent magnets (PMs), which are placed side by side [66]–[70]. They can transfer a power of 3 kW over a medium range (i.e., 15 cm). As of late 2009,

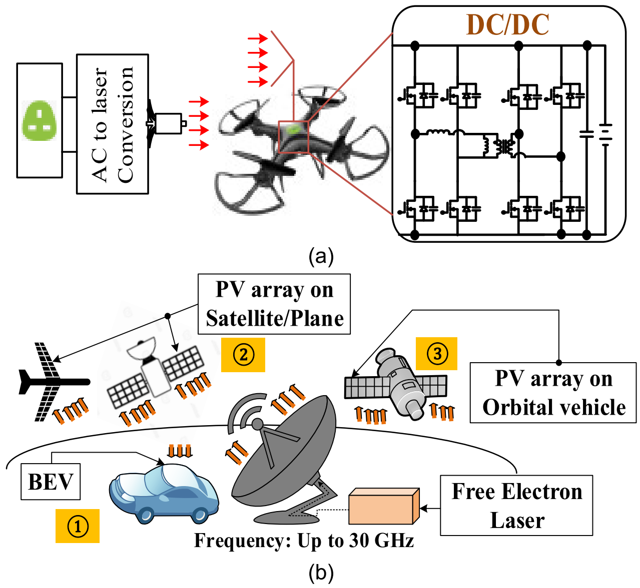

FIGURE 11. Wireless charging topology via laser [71]–[77]. (a) Laser charging for BEV. (b) Future technology of laser charging for satellite and orbital vehicles.

a number of well-documented reports had presented magnetic gear-based charging prototypes that could transfer 1.6 kW over 5 cm with 81% efficiency [70].

C. FAR-FIELD CHARGING TECHNOLOGIES

This subsection discusses the far-field charging technologies for BEVs, which use electromagnetic radiation (EMR) such as laser charging [71]–[77], microwave charging [78]–[83], and radio wave charging [84]–[89].

1) LASER CHARGING

Laser power transfer [71]–[77] has been used for charging purposes in relatively few practical applications (e.g., drones, orbital vehicles, autonomous rover, etc.) over the past several years.

For this type of charging technology, the energy is transmitted via a resonating beam with a frequency that can reach up to 3.59×10^{14} Hz, which is generated from a distributed laser charging (DLC) transmitter and then received by a DLC receiver [71], [72]. As shown in Fig. 11(a), the received beam is then fed to a DC/DC power converter to control the output voltage for battery charging purposes. As reported in [73], JAXA institute is developing a laser-based system that is capable of transferring a power of 10 MW over a distance of up to 10 km, with a maximum efficiency of 37%. Nevertheless, to sustain stable charging with a good charging capability, the charging connection should be taken into consideration, because losing the communication between the transmitter and receiver pads leads to no charging [75], [76]. Fig. 11(b) shows one of the future technologies of wireless charging via laser (e.g., for BEVs (①), solar power planetary/satellite applications (②), orbital vehicles (③), etc.).

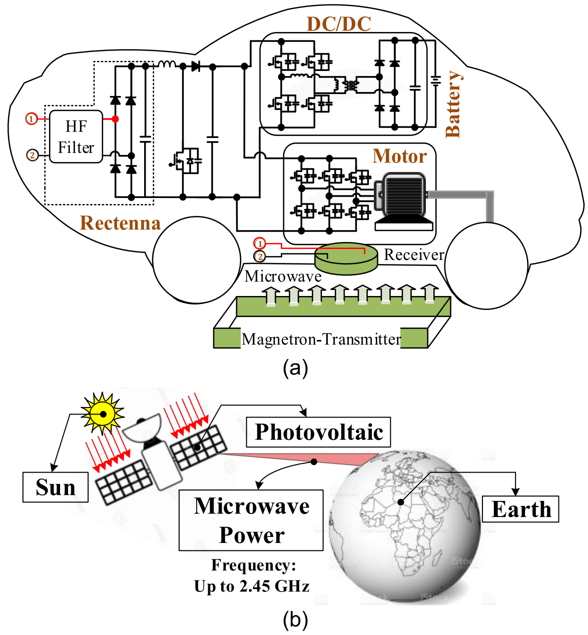

FIGURE 12. Wireless charging topology via microwave [78]–[83]. (a) Microwave charging for BEV. (b) Future technology of microwave charging for a satellite vehicle.

2) MICROWAVE CHARGING

Microwave charging technologies have been tested in applications involving the delivery of power over a far distance (i.e., a hundred km) such as platforms based on balloons, helicopters, experimental airplanes, experimental cars, etc. [78]–[83].

In 1975, an experiment by the US Jet Propulsion Laboratory achieved the maximum amount of transmitted energy. Specifically, a power of 30 kW was enclosed from a parabolic dish with a diameter of 26 m to a rectenna (i.e., rectifying antenna) 1.54 km away with 85% efficiency [79], [80]; the second attempt was tested by N. Kaya, wherein two objects situated in space successfully achieved energy transmission. Then, the first wirelessly powered airplane was launched in Canada in 1987 by a ground-based microwave emitter [81].

Fig. 12(a) depicts an EV system powered up using microwaves that are generated by Magnetron with a maximum frequency of 2.45 GHz. As documented in [82], for such applications, the corresponding power, distance, and maximum efficiency are set as 10 kW, 5 m, and 80%, respectively. However, this technology is not yet widely applicable to BEVs. The drawback of this type of charging technology is that the loss of communication between the transmitter pad and receiver pad cuts off the charging process [81], [82]. They also require large antennas, direct line-of-sight transmission paths, and complex tracking mechanisms. In the future, wireless charging via microwaves could be used for applications such as EVs and orbital vehicles, as shown in Fig. 12(b).

TABLE 2. Summary of the most common wireless charging technologies along with leading companies.

Leading Corporation/ Country	Technology Level	Charging Criteria						
		Field Range	Type	Energy Carrying Medium	Power Level [kW]	Distance Range	Maximum Efficiency [%]	Maximum Frequency
Conductix-Wampfler/Italy	Public Demonstration (Stationary)	Near-Field	Inductive	EMF	60	①		
Qualcomm Halo/UK	Public Demonstration (Stationary)/Prototype Kit (Dynamic)		Magnetic Resonant		7	②	-	20 kHz
ORNL/US	Prototype (Stationary/Dynamic)		Capacitive	Electric Field	2 ~ 7.7	③	92	20 kHz
KAIST/South Korea	Public Demonstration (Stationary)/ Prototype (Dynamic)		Magnetic Resonant	EMF	3 ~ 100	②	85	20 kHz
MIT WiTricity & Delphi/US	Commercial Kit (Stationary)		Inductive		3.3	①	90	145 kHz
UM Dearborn/US	-		Magnetic Resonant		-	②	-	80 kHz
Evatran/US	Commercial Product (Dynamic)		Magnetic Resonant		3.3		90	-
Columbia University/ Columbia	-	Medium-Field	Mechanical	Mechanical Force	1 ~ 3	④		
JAXA/Japan	Prototype (Stationary)	Far-Field	Laser	EMF	-	⑤	37	7.5 GHz
Kyoto/ Japan	Prototype (Stationary)		Microwave		10 ~ 30		-	2.45 GHz
Tesla/USA	Prototype (Stationary)		Radio wave		-		-	30 GHz

Note that "①", "②", "③", "④", and "⑤" represent "90% power efficiency within 4 cm", "90% power efficiency at 1 m and 40% at 2 m", "10 ~ 13 cm", "5 ~ 15 cm", and "37% power efficiency at 10 km", respectively.

3) RADIO WAVE CHARGING

Another type of far-field charging technology is radio wave charging [84]–[89], which is based on electromagnetic field (EMF) propagation. For this type of charging technology, the power transferred from the transmitter can be captured by a rectenna that includes a high frequency (HF) filter (i.e., which only allows high frequency (up to 30 GHz) components to pass), a rectifier (i.e., which is used to rectify the HF sine wave), and a low frequency (LF) filter (i.e., which only allows low frequency components to pass). As shown in Fig. 13, the rectifier feeds a chopper DC to provide the battery with the desired DC voltage and charging current. Unlike laser and microwave charging technologies, the efficiency of radio wave charging is too low at this point, and it therefore requires intensive research to have the ability to meet the desired power efficiency for BEV charging. In addition, for a radio wave charging system to maintain good charging capability, an operator has to ensure that the charging connection is not interrupted because any loss in connection results in no charging [85], [86].

Table 2 summarizes the most significant characteristics of various wireless charging technologies, e.g., the BEV model, project type, energy-carrying medium, power level, distance range, maximum efficiency, and frequency.

V. FUTURE RESEARCH ISSUES FOR CHARGING TECHNOLOGIES FOR BEVS

This section discusses the possible future research issues for wired and wireless charging technologies for BEVs.

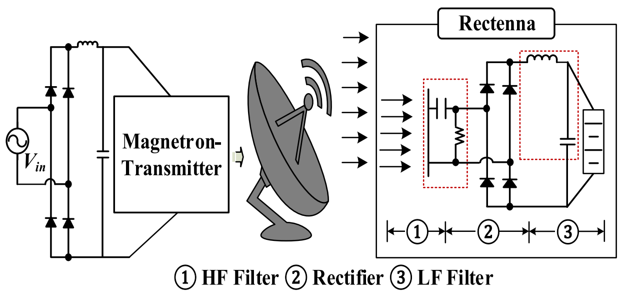

FIGURE 13. Wireless charging topology via radio wave for energy harvesting purpose [84]–[89].

A. ISSUES FOR WIRED CHARGING

There are a number of ongoing studies on wired charging technologies for BEVs, which are highlighted below:

1) UNIFICATION OF INLETS/PLUGS/CHARGING TYPES/COMMUNICATION STANDARDS/SAFETY STANDARDS

The unification of inlets/charging types/communication standards is vital to ensuring more effective charging to promote a market that is sustainable, safe, and globally accepted. For each charging level, the unification of inlets (e.g., SAE J1772, IEC 62196-1, IEC 62196-2, etc.), plugs (e.g., SAE-Combo, CHAdeMO, etc.), charging types (i.e., Types 1, 2, 3), communication standards (e.g., SAE J2931/1, SAE J2931/2, SAE J2931/3, etc.), and safety standards (e.g., IEC 60529, IEC 60364-7-722, ISO 6469-3, etc.) should be taken into account [90]–[92], as listed in Table 3. This refers to the physical connection between BEV and charging stations. For

TABLE 3. Unified items for wired charging technology.

Unified Items	Descriptions
Inlets	SAE J1772, IEC 62196-1, IEC 62196-2, IEC 62196-3, GBT20234-2, GBT20234-3
Plugs	SAECombo, CHAdeMO
Charging Types	IEC 62196-2 Type 1, IEC 62196-2 Type 2, IEC 62196-2 Type 3
Communication Standards	SAE J2931/1, SAE J2931/2, SAE J2931/3, SAE J2931/4, SAE J2931/5, SAE J2931/6, SAE J2931/7, etc.
Safety Standards	IEC 60529, IEC 60364-7-722, ISO 6469-3, ISO 17409, SAE J1766, SAE J2344, SAE J2929, SAE J2578, etc.

example, the most dominant and accepted charging types are based on the Society of Automotive Engineers (SAE) and International Electrotechnical Commission (IEC) unification standards. As shown in Table 3, the three commonly used charging types are: Type 1 (i.e., 1ϕ vehicle couplers that do not exceed 250 V, 32 A), type 2 (i.e., 1ϕ or 3ϕ vehicle couplers that do not exceed 480 V, 63 A (3ϕ) or 70 A (1ϕ)), and type 3 (i.e., 3ϕ vehicle couplers that do not exceed 480 V, 63 A with two pilots), as suggested by SAE, IEC, Combo, CHAdeMO [91], [92].

These three charging types have been adopted by several companies, such as Tesla, BMW, etc. The above discussed unification is of great interest, as it may improve the universality of BEVs and make them globally widespread regardless of the manufacturer.

2) RELIABLE CHARGING TECHNOLOGIES

The development and maintenance of a reliable infrastructure are one of the most essential and important factors in improving wired charging technologies for BEVs by properly managing the charging of BEVs and employing reduced cost elements (i.e., improving the structure of the charging system through the use of simple topologies with a reduced number of power control switches) [93], [94]. Thus, there is an ongoing effort to develop efficient charging systems to improve the reliability of BEVs (e.g., longer battery lifetimes, reduced maintenance requirements, etc.). In fact, a variety of investigations have been conducted in this field, and these have considered certain factors, including the following. First, for a better and reliable charging process, some important data (e.g., capturing shared stops, daily operation hours) has to be considered for the operating time. In addition, information regarding landmarked areas, lacking energy grid capability, and respective bus stops should be obtained to achieve a better charging capability [93]. Second, data on battery specifications and charging power are also very important [94]. For instance, the energy at charging stations depends heavily on a number of factors, i.e., the time determined by operational planning, available charging infrastructure (i.e. charging power and grid power), and state of charge (SOC)/type of battery [15], [24]. Thus, to lessen the maintenance demand and achieve a battery with a longer lifetime, the proper management of daily operation hours and the effective identification of landmarked areas should be seriously considered.

3) SMART CHARGING TECHNOLOGY

The massive increase in the number of EVs on the road (i.e., 120 million EVs expected by 2030) has stimulated the demand for smart charging facilities and energy networks to improve the wired charging infrastructure by handling the overloading applied on the grid, particularly during the evening, at which time the majority of EVs are typically plugged in [95], [96]. Smart charging technologies (e.g., scheduled charging, customer choice products (CCPs) that facilitate different electricity pricing for BEV charging, etc.) are highly demanded to enable the enhancement of wired charging technologies by monitoring the shared data connection between BEVs and charging stations. For example, the owner of a charging station can optimize the energy consumption and effectively manage the overload applied on the grid to remotely monitor and restrict the use of their BEV systems [95]. Ultimately, proper monitoring between BEVs and the charging station is a key factor in achieving better smart charging.

4) ADVANCED BMS

To ensure the improved efficiency of wired charging technologies along with the safe utilization of electrical energy stored inside Li-ion batteries from the initial usage until the completion of the electrochemical system, the use of an advanced battery management system (BMS) is critical [12]–[15]. For instance, the BMS enables the capability of setting the allowable charging/discharging current (i.e., charge maximal intensity (CMI) and discharge maximal intensity (DMI)) to safely absorb or supply to the BMS at different states-of-charge (SOC) and temperatures (T). There are various conventional BMS (e.g., cell balancing, overcharge/discharge protection, CMI, and DMI) that function based on the information of the current intensity, i.e., the current that can be safely provided to/extracted from the battery system at any time [97], [98]. On the other hand, to guarantee an improved charging for BEV, the current intensity can be properly identified by some recently reported advanced estimated methods that do not require the use of some current sensors, which add to the cost of the overall BEV systems. Some of these advanced BMS techniques are the SOC-based methods [97], [98], whereby the current intensity can be effectively estimated based on some model parameters, e.g., neural network-based SOC, Kalman filter-based SOC, etc. Finally, the estimation-based BMS methods should be further improved to address other issues such as inter-turn faults, self-commissioning, etc.

B. ISSUES FOR WIRELESS CHARGING

The common power source for wireless BEVs (e.g., 3 $\sim$ 11 kW, 11 $\sim$ 50 kW, and $>$ 50 kW) can be installed at homes, commercials, distribution channels (e.g., original equipment manufacturers (OEMs) and aftermarket distributors), etc. The global wireless charging market for EVs has experienced tangible growth over the past several years, and it is expected to grow up to $701.38 million by 2030. The most reputable companies for wireless BEVs are Qualcomm Inc., Continental AG, Witricity Corporation, Powermat Technologies Ltd., Elix Wireless, etc. There are many possible research issues related to wireless charging technologies for BEVs, which are discussed in the following.

1) HIGH POWER LEVEL TRANSFER CAPABILITY

For BEV charging using wireless charging technologies, the power transfer capability is limited to a certain kilowatt value (about 30 kW). Thus, to overcome this constraint, several studies have attempted to boost the power level transfer capability by strengthening the magnetic field coupling between the transmitting and receiving coils. Applications such as marine vehicles and ships require higher power charging capabilities than public transportation systems like buses, cars, and trams. Over the past few decades, inductive wireless charging [99]–[101] has effectively allowed for safe and fully automated operations with better battery charging times.

For instance, established wireless systems to charge the batteries of ships have been developed to enable charging when they remain in a harbor for a period of a few hours or more [99], [100]. In the last couple of years, outstanding industrial development attempts, e.g., those by Conductix-Wampler (later IPT Technology in Italy), Bombardier Primove, KAIST in South Korea, etc., have shown an improved wireless power transfer capability reaching up to about 200 kW [101]. According to the production at KAIST, the Korea Railroad Research Institute has designed a system powered by a 1 MW transmitter along with the parallel operation of various receiver units in the 200 kW range to obtain a total power transfer capacity of 820 kW [99]–[101]. To this end, to ensure a high power transfer capability, intensive research is still needed to find new ideas that can achieve better magnetic field coupling between the transmitting and receiving coils.

2) LONG DISTANCE CHARGING CAPABILITY WITH SAFETY CONCERNS

Over the past years, wireless charging for BEVs had been bounded by only a short distance (few centimeters), as it was mainly achieved through near-field charging technologies [12]–[44]. To extend the charging distance capability for BEVs, far-field charging technologies should be further developed for improved efficiency to eventually be adopted globally.

However, wireless charging with high power should take certain safety measures into consideration, e.g., protecting human bodies from radiation exposure. Recently, a company named LaserMotive successfully beamed a 17.5-pound drone and kept it airborne for at least 48 h (i.e., about 46 h longer than a conventional drone), and that research is ongoing with the aim of expanding to applications for fighter jets [102], [103]. However, these far-field charging technologies cannot achieve maximum power utility. For example, laser charging can only transfer about 20 $\sim$ 25% of the electricity it takes from its ground source [55], [56]. To deal with the above issues, an effective design should be included at the transmitter side to guarantee a strong wave and proper utilization of the power utility [102].

3) OPTIMIZED STATIC/DYNAMIC WIRELESS CHARGIN

Despite the widespread distribution of static wireless charging (SWC) technology for BEVs over the last several years, it can only occur when the BEV is on the spotting points at charging stations or street parking, etc. Thus, a solution to improve SWC-based methods can be acquired through the further development of dynamic wireless charging (DWC).

Unlike SWC, DWC allows for charging while the BEVs are moving [104], [105]. Recent advances in SWC (i.e., utilizing optimized designs of the primary/secondary pads with advanced power converters and circuits) can effectively solve the problems related to wired-based charging systems by overcoming any safety issues such as trip hazards and risks of electric shock. Unlike SWC, DWC occurs while the BEVs are being driven over charging pads that are positioned under the roadbed [105]. Thus, they are the only promising technologies for future roadway-powered/in-motion EV systems. This is achieved by embedding advanced transmitter pads into the road-concrete at a certain distance from the surface with a high voltage/high frequency AC source. The receiver pads are mounted underneath the BEVs to be charged, similar to those for SWC systems. Ultimately, to effectively overcome the drawbacks of SWC, DWC should be made available in a wide range of locations in the near future.

VI. CONCLUSION

The substantial emission pollution from the enormous number of vehicles around the world is seriously threatening modern life through consequences such as rising global warming, declining air quality, and depleting oil supplies. These serious issues have generated vital demand for safer, healthier, and more reliable BEVs. Unlike other research articles on charging technologies for BEVs, this review paper discussed in detail the currently appealing and available charging technologies for BEVs; namely, wired charging technologies and wireless charging technologies. Wired charging systems were further divided into AC and DC charging methods depending on the way in which the EV battery is connected to the utility grid. Afterward, the classifications of wireless charging technologies for BEVs were thoroughly investigated along with their commonly employed topologies. Finally, future research issues were discussed along with the expected industrial applications of these technologies.

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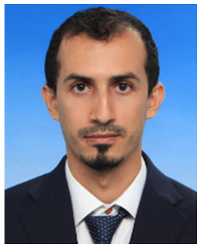

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