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Overview of wireless power transfer technologies for electric vehicle battery charging

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Abstract: In this study, a comprehensive review of existing technological solutions for wireless power transfer used in electric vehicle battery chargers is given. The concept of each solution is thoroughly reviewed and the feasibility is evaluated considering the present limitations in power electronics technology, cost and consumer acceptance. In addition, the challenges and advantages of each technology are discussed. Finally, a thorough comparison is made and a proposed mixed conductive/wireless charging system solution is suggested to solve the inherent existing problems.

1 Introduction

Recent attention to transportation electrification and the rise in electric vehicle (EV) deployment have led researchers to investigate several aspects of EV and charging technologies including advanced battery technologies, electric drives, on-board charging systems, and off-board level 3/fast-charge systems. On-board chargers are burdened by the need for a cable and plug charger, galvanic isolation of the on-board electronics, the size and weight of the charger, and safety and issues with operating in rain and snow. Wireless power transfer (WPT) is an approach that provides a means to address these problems and offers the consumers a seamless and convenient alternative to charging conductively. In addition, it provides an inherent electrical isolation and reduces on-board charging cost, weight and volume.

Recent active program announcements in the area of WPT chargers, are truly showing the significance of WPT chargers in acceptance and emergence of EVs. Active companies and groups include:

- Tier 1 automotive suppliers including Delphi, Magna, Maxwell and Panasonic;
- Government organisations and RD centres such as Phillips Research Europe, Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), Energy Dynamics Laboratory (EDL), Idaho National Laboratory (INL), US DOE, US DOT;
- Universities including the University of Tennessee, the University of Wisconsin-Madison, the University of British Columbia, the Korea Advanced Institute of Science and Technology (KAIST), and Utah State University;
- Auto OEMs, including, GM, Audi, BMW, Chrysler, Daimler, Ford, Mitsubishi, Honda and Toyota.

Present day active WPT suppliers include: WiTricity, Evatran, Conductix-Wampfler, LG, HaloIPT (Qualcomm) and Momentum Dynamics. In total, there is a wide array of research activities in the area of WPT. Accordingly, there is a need to categorising these technologies, in greater breadth and detail than provided in [1]. Recent comprehensive survey papers [2, 3] on chargers and charging infrastructures for plug-in hybrid EVs (PHEVs) and EVs have reviewed the existing solutions for inductive chargers as well. However, these works provide very little technical detail for each solution, including an evaluation of their feasibility considering the present limitations in power electronics technology, cost and consumer acceptance.

A typical closed-loop inductive WPT charging system is illustrated in Fig. 1 [4, 5]. The basic principle of inductive WPT charging is that the two halves of the inductive coupling interface consist of the primary and secondary of a two-part transformer. The charger converts the low frequency AC utility power to high frequency AC power in the power conversion stage. The secondary side wirelessly receives high frequency AC from the charger, which is converted to DC by a rectifier, which then supplies the battery pack.

The following sub-sections reviews the coupling theory used in WPT, and winding structures in the same systems.

1.1 Coupling theory

A two-part transformer behaves like mutual-inductively coupled, or magnetically coupled inductors configured such that change in current flow through one winding induces a voltage across the ends of the other winding through electromagnetic induction, as shown in Fig. 2.

The inductive coupling between two conductors is given by the following equations

$$v_1 = L_1 \frac{\mathrm{d}i_1}{\mathrm{d}t} + M \frac{\mathrm{d}i_2}{\mathrm{d}t} \quad (1)$$

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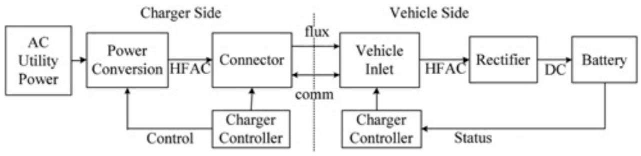

Fig. 1 *Typical closed-loop WPT charging systems [2, 3]*

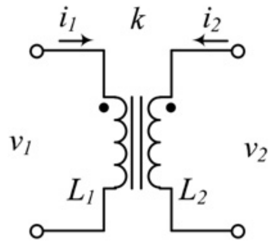

Fig. 2 *Coupled inductor circuit symbol*

$$v_2 = L_2 \frac{\mathrm{d}i_2}{\mathrm{d}t} + M \frac{\mathrm{d}i_1}{\mathrm{d}t} \tag{2}$$

In (1) and (2), M denotes the mutual inductance, as given by (3), where k is the coupling coefficient of the windings, or the quality of the magnetic circuit

$$M = k\sqrt{L_1 L_2} \tag{3}$$

For a current I_1 in L_1, the open circuit voltage induced in L_2 is given by the following equation

$$V_{\mathrm{OC}} = \omega M I_1 \tag{4}$$

With a short circuit on the right-hand side, the current is given by the following equation

$$I_{\mathrm{SC}} = \frac{V_{\mathrm{OC}}}{\omega L_1} = I_1 \frac{M}{L_2} \tag{5}$$

When the system is tuned at the operating frequency with a capacitor, the available power is $V_{\mathrm{OC}} I_{\mathrm{SC}}$ multiplied by the circuit tuning resonant factor Q, and given by (6), where Q is given by (7) [6]

$$P = \omega \frac{M^2}{L_2} I_1^2 Q = \omega L_1 I_1 I_1 \frac{M^2}{L_1 L_2} Q = V_1 I_1 k^2 Q \tag{6}$$

$$Q = \frac{\omega L}{R_L} \tag{7}$$

In (5), the first two terms are the input voltage and current, the third term is the magnetic coupling factor and the final term is the secondary circuit Q. The power that an inductive WPT system can produce is therefore dependent on the input voltage–ampere product (VA) to the primary pad, the quality of the magnetic circuit (k), and the quality of the secondary electric circuit (Q).

1.2 Winding structures

Owing to the absence of metal–metal contact in an inductive WPT charger, the shape, size and location of the magnetic core material and windings play a crucial role in an efficient

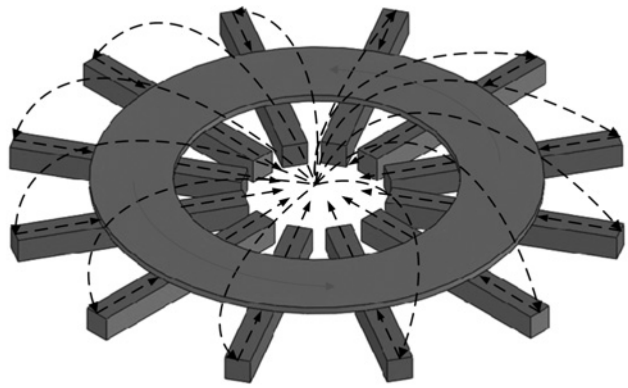

Fig. 3 *Circular-coil with flux lines [6]*

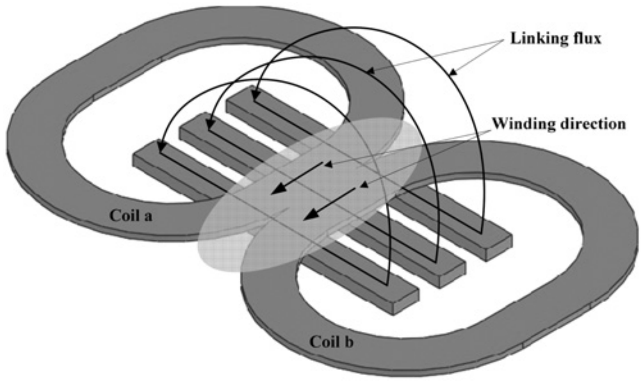

Fig. 4 *Polarised coupling system (double D) [6]*

power transfer. New magnetic circuits for coupling on-vehicle pads to ground based pads at higher efficiency over a wider range of misalignment have improved significantly. New polarised pads have evolved and exhibit superior performance when compared to earlier round pad constructs [6]. The performance of the prevailing circular-type pads has now been surpassed – for pads of identical area and materials the new pad combinations give twice the power delivery over three times the operational area, at higher efficiency than circular pads. Fig. 3 illustrates a conceptual drawing of a circular-coil with flux lines.

Fig. 4 illustrates a polarised coupling system (Double D). Subsequent innovation in the windings of the Double D (DD) pads resulted in an additional independent (Quadrature) coil being added, whereas using the same magnetic components.

In the following sections, the present state of the art technologies in WPT are reviewed, compared, and the challenges facing the power conversion systems of the charger are noted.

2 Inductive WPT

Inductive power transfer (IPT) has been used successfully in several EV systems [4], such as the GM EV1. The charging paddle (the primary coil) of the Magne charge inductively coupled charger was sealed in epoxy as was the secondary. The paddle inserted into the centre of the secondary coil permitted charging of the EV1 without any contacts or connectors at either 6.6 kW or at 50 kW. As it depicts in Fig. 5, this system is connector-less, but not wireless.

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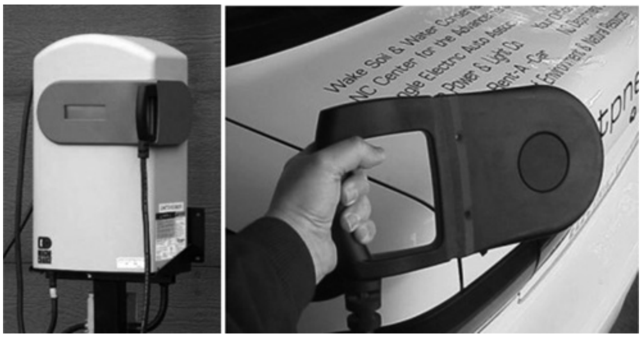

Fig. 5 *Small paddle inductive station (Left), and the paddle (Right)*

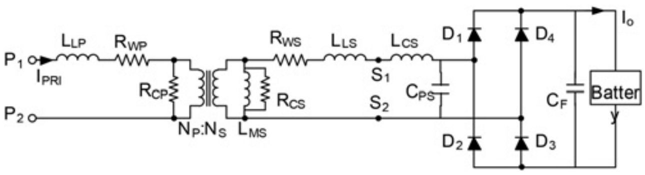

Fig. 6 *Inductive interface (paddle) equivalent circuit*

The equivalent circuit parameters at the charge coupling interface for an IPT charger are shown in Fig. 6.

An universal IPT system using 10 kVA coaxial winding transformer for a 6.6 kW, 77 kHz, 200/400 V EV charger is presented in [7]. One of the most significant benefits of utilising a coaxial winding transformer is the ability to relocate all transformer core material off-board, thereby minimising the sensitivity of on-board EV components to flux density and frequency. Utilisation of a coaxial winding transformer makes it feasible to implement a single loop, which can operate over wide frequency range and the ability to scale up to meet wide variety of power requirements. An ultra-compact 100 W to 120 kW IPT EV charging system detailing the tradeoffs in designing the transformer for the IPT system is presented in [8]. Core design specific issues primarily concern the impact of nonlinear flux distribution, which results in geometric effects (denser flux around inside corners), eddy current losses and electromagnetic interference. The aforementioned losses are greatly influenced by the core size, increasing when the transformer is scaled up. Symmetrically dividing the secondary winding and assembling the core in a piecewise manner using ferrite materials are reported as possible solutions [8].

3 Capacitive WPT

Wireless capacitive power transfer (CPT) technology has been proposed recently as an alternate contactless power transfer solution [9–12]. As illustrated in Fig. 7, the CPT interface is constructed around a pair of coupling capacitors. The remainder of the power conversion system, including the inverter and rectifier structures remains the same.

Since magnetics do not scale down as desired with decreasing power, at some power level, the cost and size of the galvanic isolation components can be minimised with a capacitive interface. Therefore the most significant advantage of CPT is its cost and size at lower power levels. However, in high power applications, it is not a preferred solution. For this reason most existing CPT solutions are

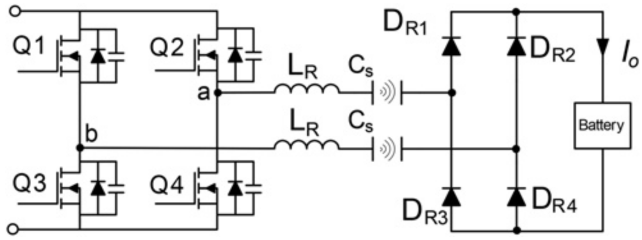

Fig. 7 *Typical schematic of a series resonant converter circuit constructed around the coupling capacitor [9–12]*

focused on low power applications and portable electronic devices, such as wireless tooth brush chargers, or wireless cellular phone chargers where the power transfer interface is implemented with capacitive coupled matrix pads.

The application of printing and MEMS technology [13] in CPT shows promise for advancement and acceptance of these technologies in consumer electronics applications.

4 Low frequency permanent magnet coupling power transfer (PMPT)

Low frequency PMPT combines known elements of magnetic gears and synchronous permanent magnet electric machines [14, 15]. There are two main physical components, a transmitter and a receiver, as shown in Fig. 8.

4.1 PMPT transmitter

A rotating cylindrical, permanently magnetised rotor is driven either by an external, self-contained motor or more directly, by means of static windings that are positioned around the circumference of the rotor itself, separated by an air-gap and located either outside of the rotor, or inside if the rotor is hollow.

4.2 PMPT receiver

A similar rotor on the vehicle is positioned within 150 mm and parallel to the utility-side installation during charging. Owing to the coupling of the magnetic fields of the two rotors, the vehicle rotor will tend to rotate at the same speed as the utility-side rotor. This is the magnetic gear effect.

The prototype system uses an externally driven rotor for the transmitter, as shown in Fig. 9. The proposal for a production transmitter is to have a directly driven rotor, using externally mounted air-cored windings as the energy transfer mechanism. The prototype system efficiency is quoted as 81% [14], which is the product of 90% (±2%) efficiency

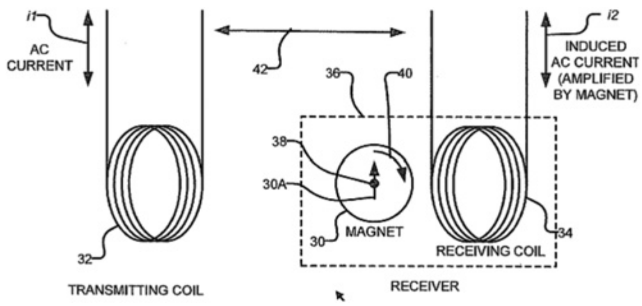

Fig. 8 *Use of a rotating magnet to enhance inductive power transfer between two coils [14, 15]*

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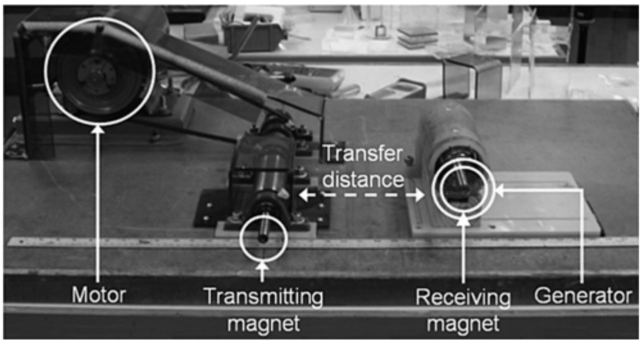

Fig. 9 *Photograph of the kW scale low frequency PMPT prototype [14, 15]*

for the transmitter and receiver stages. It is believed that the current prototype system has significant opportunities for improvement in terms of both component optimisation and system architecture. However, because of the mechanical components used in the transmitter and receiver, this technology may have issues with noise, vibration, and harshness (NVH) and lifetime.

5 Resonant inductive power transfer (RIPT)

RIPT is the most popular current WPT technology [16, 17]. It was pioneered by Nikola Tesla and has recently become popular again, enabled by modern electronic components. This technique uses two or more tuned resonant tanks resonating at the same frequency [18].

A typical schematic of a RIPT system is illustrated in Fig. 10. The receiver and transmitter contain resonant capacitors, C_p and C_s. Various resonant compensation topologies are proposed in [19]. As noted in [18] the primary functions of the resonant circuits include:

- Maximising the transferred power;
- Optimising the transmission efficiency;
- Controlling the transmitted power by frequency variation;
- Creating a certain source characteristic (current or voltage source);
- Compensating variation of the magnetic coupling;
- Compensating the magnetising current in the transmitter coil to reduce generator losses;
- Matching the transmitter coil impedance to the generator;
- Suppressing higher harmonics from the generator.

Efficient resonant magnetic power coupling can be achieved at distances up to ~40 cm. RIPT systems have several advantages over IPT including increased range, reduced EMI, higher frequency operation, resonant switching of the inverter and receiver rectification circuitry and higher efficiency. However, the main advantage of this concept is that the operating frequency is in kHz range, which can be supported by current state of the art power electronics technologies.

A RIPT lab prototype was built and tested in [20]. A maximum power transferred of 4.2 kW was reported at 92% efficiency. This unit did not have a front end AC–DC power factor correction (PFC) circuit. When multiplied by the PFC and power supply efficiencies, the overall efficiency is expected to be approximately 85%.

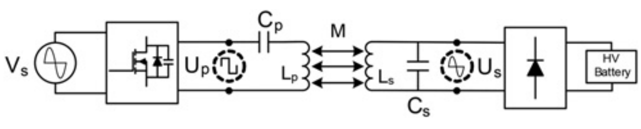

Fig. 10 *Simplified typical schematic of a resonant inductive charger*

6 Roadway/online power transfer

The application of RIPT technology in public transit systems has been proposed in [21–31]. An online wireless power transfer system (OLPT) is illustrated in Fig. 11. The concept is similar to RIPT, however a lower resonant frequency is used and the technology has the potential for application at high power levels. Technologically, the primary coil is spread out over an area on the roadway and the power transfer happens at multiple locations within this area. Typically, the combination of the input side of the resonant converter along with the distributed primary windings is called the track and is on the road, and the secondary is called as the pickup coil, which is in the vehicle. The system is supplied by a three phase AC system, or high voltage DC system. Considering both the short range of EVs and the associated cost of infrastructure, the feasibility of these charging systems might be unfavourable. However, one benefit is that due to frequent and convenient charging, vehicles can be built with a minimal battery capacity (about 20% compared to that of the conventional battery-powered EVs), which can consequently minimise the weight and the price of the vehicle [29].

A charger with narrow rail width, 10 cm, and large air-gap, up to 20 cm, was proposed in [27]. An efficiency of 74% was reported at 27 kW output power for a three-phase supply input of 440 V, and 20 kHz switching frequency.

7 Resonant antennae power transfer (RAPT)

RAPT, also pioneered and patented by Nikola Tesla, has recently been studied by MIT and Intel. RAPT uses two, or more resonant antennae tuned to the same frequency. The resonant capacitances and inductances are integrated into the antennae. These systems often have large WPT coils (antennae), often helical with controlled separation between the turns to obtain a distributed and integrated, resonant capacitance. Acceptably, efficient power transfer is possible at distances up to approximately 10 m [32–35].

An equivalent circuit diagram for a series–parallel resonant wireless transfer system is illustrated in Fig. 12. The concept is similar to RIPT, but the impedance match frequencies are in the MHz range. Ignoring EMI/EMC concerns, basic limits on human exposure to radio frequency (RF) radiation are exceeded by most of these systems and difficult to shield

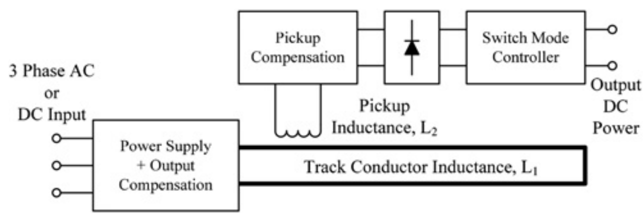

Fig. 11 *Typical OLPT system [21–31]*

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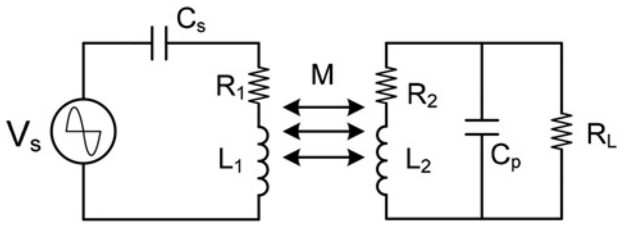

Fig. 12 *Series–parallel resonant wireless transfer system*

without hampering performance and range. Furthermore, generating a high frequency power signal in the MHz range is a significant power electronics challenge and not efficiently and cost effectively feasible with today's technology.

8 Commercially available systems

Thus far, there are only a handful of wireless charger systems available. These systems are only in pre-commercial trials and none of them are in mass production. WiTricity Corp. is active and has collaborative ties with Delphi Electronics, Mitsubishi Motors Corporation, Audi and Toyota Motor Corporation. Plugless power (manufactured by Evatran) is another active player in collaboration with Nissan and GM to support the Nissan Leaf and Chevy volt products. Mercedes Daimler and Conductix-Wampfler have a wireless charging research project. Finally, Qualcomm Inc. (acquired HaloIPT) has announced a wireless EV charging trial in collaboration with the UK Government, and Transport for London.

9 Challenges

The most significant drawback of all WPT systems is the low efficiency of the energy transferred. Most losses happen during the transfer from coil to coil. In addition, the installation cost of WPT charging systems will be higher than plug-in charging methods because of many factors, including but not limited to increased infrastructure, goods and safety/shielding requirements. Therefore WPT is likely to be disadvantageous to EV owners from a cost perspective.

Another significant concern with these technologies are health hazards and basic limits on human exposure to RF radiation. In Canada, these limits are set by Canadian Safety Code 6 [36]. In the USA, many follow the IEEE C95.1 standard [37], and in Europe users are required to meet the strictest of these standards set by the International Commission on Non-Ionising Radiation Protection (ICNIRP) [38]. In Australia the Australian Radiation Protection And Nuclear Safety Agency (ARPANSA) places limits on RF exposure [39].

In addition to RF limits, wireless chargers are required to comply with magnetic field exposure standards, primarily recommended by the International Committee on Non-Ionising Radiation Protection (ICNIRP). ICNIRP establishes regulations on human exposure to time varying electromagnetic fields. ICNIRP standards require that the human body should not be exposed to average flux densities greater than 6.25 μT for switching frequencies in the range of 0.8–150 kHz. Using the ICNIRP guidelines, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) established detailed guidelines on calculating the average flux density. ARPANSA conformance requires that the human body should not be exposed to flux densities greater than 6.1 μT in the frequency range of 10–150 kHz.

10 Comparison and proposed solution

10.1 WPT comparison

A comparison of the WPT technologies previously discussed is presented in Table 1. IPC is a mature and proven technology. Its only drawback is that it is only a contactless solution, and not a wireless solution. In spite of being around for many years, it did not emerge as a viable answer to the EV market. One reason may be because of low acceptance rate of EVs in the early 2000s because of many factors, including the relatively low price of oil.

CPT has gained popularity in low power applications because of the poor scaling properties of magnetics at lower power levels. The cost and size of the galvanic isolation components is minimised with a capacitive, rather than inductive interface. Therefore the most significant advantage of CPT is its cost and size at lower power levels. However, in high power applications, including EV charging, it is not a suitable charging method.

PMPT technology operates at the supply line frequency, therefore the inherent high frequency problems with other wireless technologies do not exist. However, there are additional concerns with NVH and life, because of the

Table 1 Comparison of wireless charger technologies

Technology	Performance			Cost	Size/volume	Complexity of system	Suggested power level
	Efficiency	EMI	frequency				
inductive power transfer (IPT)	medium	medium	10–50 kHz	Medium	Medium	medium	medium/high
capacitive power transfer (CPT)	low	medium	100–500 kHz	Low	Low	medium	low
permanent magnet coupling power transfer (PMPT)	low	high	100–500 Hz	High	High	high	medium/low
resonant inductive power transfer (RIPT)	medium	low	1–20 MHz	Medium	Medium	medium	medium/low
on-line inductive power transfer (OLPT)	medium	medium	10–50 kHz	High	High	medium	high
resonant antennae power transfer (RAPT)	medium	medium	100–500 kHz	Medium	Medium	medium	medium/low

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mechanical components used in the transmitter and receiver, as well as cost and size of this technology.

RIPT and OLPT are likely the most promising technologies among the solutions discussed for EV charging applications. However, the feasibility of these chargers might be unfavourable considering both the short range of EVs and the associated cost of infrastructure.

RAPT is conceptually similar to RIPT but the resonant frequency is in the MHz range, which is up to 100 times as high as RIPT. This can result in problems with human exposure to RF radiation, where limits are easily exceeded by most of these systems. Shielding this radiation is difficult without hampering performance and range. Also generating a high efficiency high frequency power signal in the MHz range is presently a nearly impossible power electronics challenge.

10.2 Proposed EV charging solution

A pure EV needs sufficient battery storage on-board to maintain its driving range. Currently, the common lithium ion battery chemistry is estimated to cost around $ 700 per kWh. Consequently, the price of EVs is often nearly twice that of comparable internal combustion engine (ICE) vehicles, with the EV batteries comprising approximately half the EV cost [40]. Furthermore, the typical charging time is very long, typically overnight, and it is very difficult to 'refuel' or recharge it quickly like a standard ICE vehicle without compromising battery life. Conversely, the feasibility of WPT chargers considering both the short range of EVs and the associated cost of infrastructure might be unfavourable, but if the vehicle energy storage and charging system is appropriately designed, a vehicle with a reduced battery capacity (e.g. about 20% compared to that of the conventional battery-powered EVs) could be developed. Clearly, this solution would minimise the weight and the price of the vehicle. The proposed solution uses a combination of fast chargers, on-board chargers and wireless chargers, depending on the vehicle size and its application.

The proposed future integrated wireless/on-board/fast charger solution for small passenger vehicles is illustrated in Fig. 13. Since the battery pack can be smaller, only a 1.6 kW on-board (an integrated conductive/inductive) charger needs to be used to complete the charge cycle. The bulk charging can be done through the use of fast off-board DC charging stations. The wireless battery charger can be a stationary small charger installed in a home garage.

For large vehicles, including public transit vehicles, the proposed future integrated wireless/fast charger solution is illustrated in Fig. 14. The bulk charging can be done using fast off-board DC charging stations. For these applications,

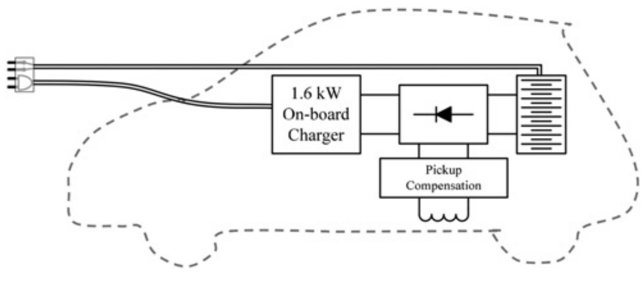

Fig. 13 *Future viable integrated wireless/on-board/fast charger solution for small vehicles*

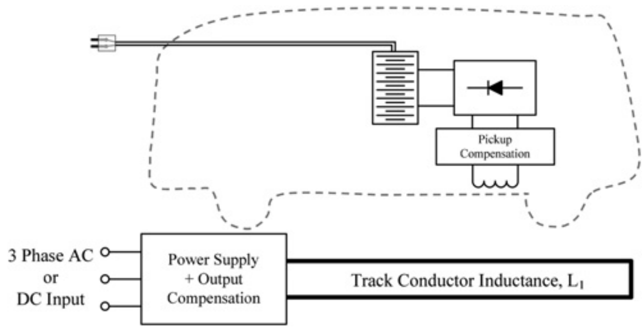

Fig. 14 *Future viable integrated wireless/fast charger solution for public transit vehicles*

there is no need for low power on-board charging. The wireless battery charger can be used for finishing the charge cycle whereas the vehicle is moving. The wireless battery charger can be an OLPT installed close to bus stops and/or traffic lights.

11 Conclusions

A review of existing technological solutions for WPT used in EV battery chargers has been presented. A conceptual review of WPT theory along with winding structure was performed. Several existing technological solutions, including IPT, CPT, PMPT, RIPT, OLPT and RAPT were discussed in detail and their feasibilities were evaluated considering the existing limitation in power electronics technology, cost and consumer acceptance. In addition, the challenges and advantages of each proposed technology were discussed. A detailed evaluation of health hazards and basic limits on human exposure to RF radiation were given. Moreover, finally a thorough comparison of these technological solutions was made, considering performance, cost, size/volume, complexity of the system and suggested power levels. Two system level integrated wireless/on-board and fast charging solutions for small passenger vehicles and large public transit vehicles were suggested to solve the inherent existing problems.

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