# Overview of Wireless Charging Technologies for Electric Vehicles

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## Abstract
*This paper gives an overview of current wireless charging technologies on electric vehicles (EVs) charging. In general, the near-field technologies are preferred over far-field ones. Inductive power transfer and strongly coupled magnetic resonance technologies are chosen for detailed review. Furthermore, special issues related to EV applications are also discussed, namely efficient power supply, misalignment tolerance, multiple pick-up control, simultaneous power and data transmission and shielding methods.*

## Keywords
*electric vehicle, wireless charging, wireless power transfer, inductive power transfer, coupled magnetic resonance*

## 1. INTRODUCTION
The commercial market of electric vehicles (EVs) has begun to grow. The existing conductive charging method requires high power charging devices or charging stations to recharge the vehicle within a short time [Liu et al., 2013]. Incompatible plugs receptacles also cause additional inconvenience between different EV models. As for the wireless charging technologies, different EV models can share their charging infrastructure if the same wireless power transfer (WPT) technology is adopted. In longer term, dynamic road charging technology will enable users to charge the EV battery while driving, as shown in Figure 1. This brings about much reduced battery size, extended driving range and reduced vehicle price, and further stimulates the EV market.

Far-filed and near-field are the two main categories for WPT technologies. The far-field technologies use microwave radiation or laser as energy carrier. They are capable to transfer high power over long distances. But a direct line-of-sight transmission path and complicated tracking strategies are required [Shinohara, 2013].

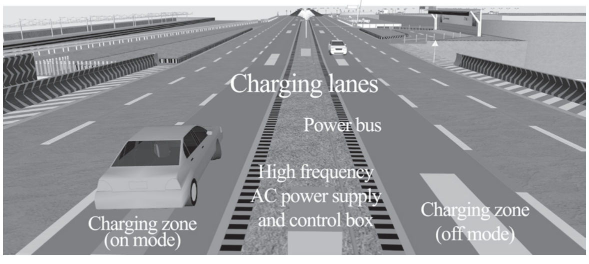


**Fig. 1** Move-and-charge EV system

Moreover, the EMC requirements are more stringent as the frequency of operation increases. So the antennas should be large enough to satisfy the power density limits, which is impractical for EV WPT applications. For these reasons, far-field WPT technologies are by far mostly used in space and military applications, such as solar power satellite [Jaffe and McSpadden, 2013].

For the near-filed WPT technologies, both electric-field and magnetic-field are used for energy transmission. By using electric-field, energy transmission is unaffected by metal barriers, and also causes lower EMI than the magnetic-field counterpart. However, the permittivity of air is intrinsically small, which results inadequate coupling capacitance [Liu, 2011]. Special dielectric materials can help to enhance coupling. However, it is still quite sensitive to the air gap length and displacement of coupling plates [Theodoridis, 2012]. The near-field magnetic-field based WPT technologies have made many achievements in both short-range and mid-range applications [Suzuki et al., 2011; Liu et al., 2014]. Early short-range EV application employs pairs of ferrite cores to achieve strong coupling. The charging power can transfer tens of kilowatts, but the air gap is limited to several centimeters and the vehicle movement is highly restricted [Covic and Boys, 2013]. Later researches use resonance to extend the air gap length and modified core/winding arrangements to accommodate large lateral misalignment. The air gap can reach tens of centimeters, which is governed by the dimensions of transmitting coil

[Wang et al., 2005]. Mid-range applications by eliminating the ferrite cores extend transmitting distance to the order of the coil diameter or even several times of the coil size. By using magnetic resonance and multi-coil configuration, the resistance of the coils is further reduced and the transmitting distance is extended to several meters with a power level up to hundreds of watts [Kurs et al., 2007].

This paper mainly focuses on the magnetic-field based near-field short-range and mid-range WPT technologies, which are most promising for EV wireless charging applications. The inductive power transfer (IPT) and strongly coupled magnetic resonance are introduced with a summary on their state-of-the-art applications. Key issues and technologies for EV wireless charging are specially chosen and discussed, namely power converter design, mis-alignment tolerance, adaptive control strategies, and EMI issues.

## 2. WIRELESS POWER TRANSFER

### *2.1 Inductive power transfer*

The typical arrangement of IPT system is shown in Figure 2. An inverter converts the DC power into high frequency AC current or voltage. The operating frequency varies from tens of kilohertz to several megahertz. The key element is a pair of magnetically coupled coils. In order to enhance the mutual inductance, ferrite cores are used in one or both sides of the coils. Litz wires are frequently used to lower the parasitic resistance and therefore high Q-factor. The litz coil consists of many individually insulated thin conductor stands wounded in a particular patterns to reduce both the skin and proximity effects. However, for frequency higher than 1 MHz, (e.g. 13.56 MHz) litz wires are less effective and rarely used. Copper conductor or hollow copper tube could be alternative solutions [Karalis et al., 2008].

Compensation capacitances are added on both primary and secondary sides, either in series or in parallel. The purpose of compensation networks is to maximize the load power and meanwhile minimize the reactive power of the primary inverter. The series-series topology is theoretically optimal because the value of primary compensation capacitor is independent from mutual inductance and the load conditions [Ko and Jiang, 2013]. For the series-parallel topology, the value of primary compensation capacitor is independent with mutual inductance but varies with load. The parallel compensation is more suitable when current source characteristic at the secondary end is required or a large primary current is preferred. Fixed or adjustable passive capacitors are usually used in most applications. Active capacitance control is also theoretically achievable using switch-mode power converters, which offer much more freedom of operation.

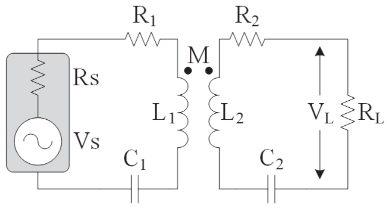


**Fig. 3** Schematic of series compensated inductive power transfer system

The simplified equivalent circuit of series-series compensated IPT system is shown in Figure 3. $M$ denotes the mutual inductance between primary and secondary coils. Model elements include self-inductance of coupled coils $L_1$ and $L_2$, lumped compensation capacitors $C_1$ and $C_2$, parasitic AC resistance of coils and capacitors $R_1$ and $R_2$, the internal resistance of AC voltage supply $R_S$, and the load $R_L$, which is assumpted purely resistive to simplify the analysis. The operation at resonant frequency $\omega_0$ can be described by (1) to (6),

$$V_S = (R_S + R_1)\, I_1 - j\omega_0 M I_2 \tag{1}$$

$$V_L = j\omega_0 M I_1 - R_2 I_2 \tag{2}$$

$$P_L = \frac{\omega_0{}^2 M^2 V_1{}^2 R_L}{[(R_S + R_1)(R_L + R_2) + \omega_0{}^2 M^2]^2} \tag{3}$$

$$\eta = \frac{\omega_0{}^2 M^2 R_L}{(R_S + R_1)(R_L + R_2)^2 + \omega_0{}^2 M^2 (R_L + R_2)} \tag{4}$$

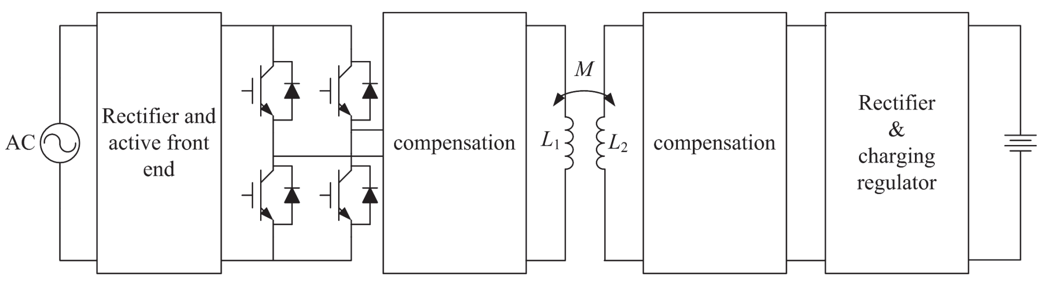


**Fig. 2** Typical IPT EV charging system

$$R_{L,\ \mathrm{max\ power}} = R_2 + \frac{\omega_0^2 M^2}{R_1} \quad (5)$$

$$R_{L,\ \mathrm{max\ efficiency}} = \sqrt{R_2^{\,2} + \frac{\omega_0^2 M^2 R_2}{R_1}} \quad (6)$$

In equations (3) and (4), the transferred power and efficiency are functions of load and mutual inductances. For EV application, the load is defined by the battery's depth-of-discharge and the charging speed, and the mutual inductance is directly related to the relative position between on-board pickup coil and fixed transmitting coil. The first problem is both the load and mutual inductance are ever changing because EVs cannot be always perfectly parked or they are moving during power transfer. Another problem is that for a certain conditions, the load power and efficiency cannot achieve maximum point at the same time, as shown by equations (5) and (6). Therefore, the challenge for IPT wireless charging is the implementation of suitable control strategies, such as load matching and variable frequency control to regulate the load power while maintaining high transmission efficiency.

### *2.2 Strongly coupled magnetic resonance*

The strongly coupled magnetic resonance technologies are characterized by special multiple coils and loops combination arrangement, as shown in Figure 4. By using two loops and two coils, the internal resistance of voltage source $R_S$ and the load resistance $R_L$ are excluded from the *RLC* resonators, which results a much higher Q-factor than conventional two coils

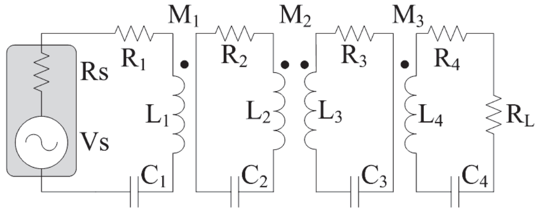


**Fig. 4** Schematic of strongly coupled magnetic resonance system

resonators. With the same coupling coefficient, more energy could be transferred to the load [Cannon et al., 2009]. Additionally, the lumped resonant capacitors are replaced by coil parasitic capacitance ($C_2$ and $C_3$) which results an even higher Q-factor. The system operating frequency is normally fixed and equal to the self-resonant frequency of the coil. This frequency is defined by geometric layout of the coils and can be up to several megahertz.

For practical EV applications, lumped compensation capacitors are still preferred in order to simplify the coil construction and lower the operating frequency to kilohertz range.

### *2.3 Current wireless EV charging projects*

Integrating wireless charging technologies with EV applications are being demonstrated in both industrial and academic fields. Major achievements have been made in the last two decades, and are summarized in Table 1. The University of Auckland made an early exploration on high power IPT charging. Although the air gap was limited to several centimeters the power transfer reached tens of kilowatts [Covic and

**Table 1** Summary of existing wireless EV charging projects

| Institute / corporation | Year of Installation | Vehicle Type | Power | Air Gap | Efficiency |
|---|---|---|---|---|---|
| The University of Auckland | 1997 | 5 Golf buses | 20 kW | 50 mm | 90-91 % |
| | 2002-2003 | 8-23 mini buses | 60 kW | 30 mm | – |
| | 2010 | Private vehicles | 3 kW | 180 mm | 85 % |
| Oak Ridge National Laboratory (ORNL) | 2010 | – | 4.2 kW | 254 mm | 92 % (coil-to-coil) |
| | 2012 | – | 7.7 kW | 200 mm | 93 % (coil-to-coil) |
| | 2012 | GEM EV | 2 kW | 75 mm | 91 % (coil-to-coil) |
| Korea Advanced Institute of Science and Technology (KAIST) | 2009 | Golf Bus | 3 kW | 10 mm | 80 % |
| | | Bus | 6 kW | 170 mm | 72 % |
| | | SUV | 17 kW | 170 mm | 71 % |
| | 2010 | Tram | 62 kW | 130 mm | 74 % |
| | 2012 | Bus | 100 kW | 200 mm | 75 % |
| MIT WiTricity | 2010 | Private vehicles | 3.3 kW | 180 mm | 90 % |

Boys, 2010]. Their recent research has been aiming at extending vertical distance and adapting horizontal offsets, such as the single-sided flux magnetic coupler (DD-DDQ) system [Budhia et al., 2013]. ORNL focused on the high efficiency lumped coil design and successfully implemented it into a 72 V lead-acid battery powered EV [Miller, 2012]. KAIST has made great achievement on dynamic wireless charging in the last few years, which is called on-line electric vehicles (OLEV) [Jung et al., 2013]. The OLEV project was launched in 2009. In the same year, three generations of prototypes were reported with power ranges from 3 to 17 kW [Lee et al., 2010]. The first demonstration, a 2.2 km tram loop, was installed in 2010. This 62 kW wireless powered tram equipped with a battery module of 40 % smaller than normal battery-powered trams. In 2012, an OLEV bus system was demonstrated which was capable to transfer 100 kW (5 sets of 20 kW pick-up coils) through a 20cm air gap with average efficiency of 75 %. [Jim et al., 2013]. KAIST is ready to apply its OLEV technology on a high-speed high-power railway (over 300 km/h, 180 kW) at the end of 2013 [Ahn et al., 2013]. MIT (WiTricity) employed the strongly coupled magnetic resonance technology and implemented a commercially available 3.3 kW charging kit for market EV models.

## 3. EFFICIENT POWER CONVERTER

For the IPT applications operating under 1 MHz, LCL resonant converter is widely adopted [Wang et al., 2004], as shown in Figure 5. The inductance $L_0$ can be a lumped inductor or the secondary winding of high frequency isolation transformer. The LCL resonant converter has the following merits. Firstly, the constant voltage from H-bridge results constant current in the primary coil which is independent of load conditions. And this current can be easily controlled by adjusting the duty cycle of the bridge. Secondly, the H-bridge only support the real power dissipated by the load and parasitic resistances, while high resonant current in the primary coil is supported by compensation capacitor $C_1$ [Kissin et al., 2009].

Different types of RF amplifiers are used for operating frequency over megahertz range. Class E amplifier has the simplest one-switch architecture and offers high output power. Class D is an alternative solution. With

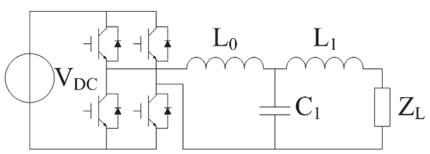


**Fig. 5** Typical schematics of LCL resonant converter for IPT

half-bridge or full-bridge topologies, the VA rating of power switches can be lower than Class E amplifier. However, the efficiency of the Class D amplifier is related to the reflected loaded Q. So there may be a notable drop when the transmission distance increases [Garnica et al., 2013].

## 4. MISALLIGNMENT TOLERANCE

### *4.1 Optimal ferrite core structure design*

For on-road wireless charged EVs, the track-shaped primary coil structure is usually adopted. This created constrains on lateral movement of the EV. The basic concept in optimal ferrite core design is straightforward: to maximize the effective magnetic flux through pickup coil and minimize the leakage flux. A pair of common E-shape ferrite cores are shown in Figure 6. For the air gap shown, increasing the pole width is an effective way to decrease the air reluctances, and therefore increase useful effective flux. On the contrary, increasing distance between poles will relief the magnetic field distortion when misalignment occurs, giving a better tolerance of lateral offset. But it will also increasing leakage flux within poles [Shin et al., 2014]. Therefore, optimal consideration should be taken when choosing the pole width.

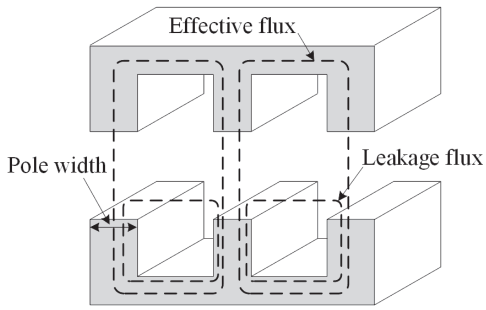


**Fig. 6** Typical pair of E-shape ferrite cores

### *4.2 DD-DDQ pad system*

Alignment tolerance is also an important issue in stationary EV charging application. One of the solutions is to adjust the configuration of the ferrite cores and coil windings. A new polarized coupler topology called DD-DDQ system is proposed to offer five times larger charging zone than traditional circular pad without increasing the materials [Budhia et al., 2013]. Inside the transmitting pad, two D-shaped coils are placed side by side above a set of ferrite bars, rather than wounding around these ferrites. As a result, the magnetic flux path travels only into the side of receiving coil and the unwanted rear flux path is cancelled. Inside the receiving pad, a pair of orthogonal quadrature (Q) ferrite cores is added to the existing DD structure, enabling capture of magnetic flux from both horizontal and vertical directions.

### *4.3 Range adaption control of strongly coupled magnetic resonance*

For the strongly coupled magnetic resonance, the transmission efficiency drops quickly when distance or orientation between coupled resonators deviates from its normal position. For wireless EVs charging, the relative position between resonators could hardly be stable. So, adaptive control is essential [Sample et al., 2011].

The highest possible efficiency is occurred when source/load impedance matches with coil impedances. The impedance adjusting can be realized by real-time tuning the operating frequency, or by keeping a fixed operating frequency but using impedance matching networks between coils and source, and between coils and load. Either frequency tuning or impedance matching is effective in the over-coupled regime. Otherwise, the mutual inductance is too weak to support high efficient transmission [Sample et al., 2013].

## 5. MULTIPLE PICK-UP CONTROL

For on-road wireless EV charging, there is a situation when more than one vehicle connects onto the same power transmitter. Each secondary coil has magnetic coupling with the primary coil but demands for independent power control. The system will become unstable when too many light loaded secondary pick-ups are connected. Therefore, decoupling control is proposed to solve this problem and meanwhile offers a possible way to regulate secondary power [Covic and Boys, 2013].

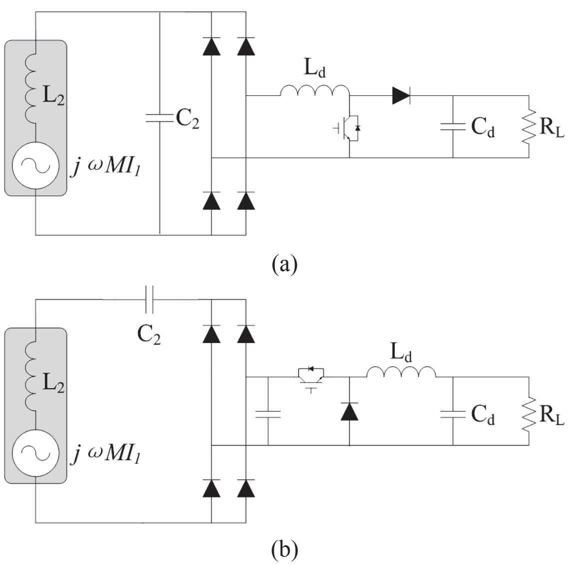


**Fig. 7** Decoupling regulator. (a) parallel compensated secondary, (b) series compensated secondary

The key concept of decoupling control is to short-circuit the light loaded pick-ups. This is equivalent to removing unwanted pick-ups from primary transmitter and adding a small amount of reactive power in the primary supply. For a parallel compensated topology, a boost converter is added before the load, and similarly, a buck converter is added for the series compensated topology, as shown in Figure 7 [Keeling et al., 2010].

However, this method assumes that all pick-ups are operating at the tuned frequency and the mutual inductance between every primary and secondary coil keeps constant. This might be a reasonable assumption for monorail system. But for other configuration (e.g. lumped pad system), more effective method should be explored since mutual inductance changes with pad positions.

## 6. CONCURRENT DATA TRANSMISSION

Normally, when primary side control is adopted, the information of secondary side conditions should be sent back to the primary side, using wireless communication. However this will increase the overall system cost. Recent studies reveals that concurrent data transmission with power will offer better solutions.

Figure 8 shows the basic principle of capacitive amplitude modulation. The modulation capacitors $C_{m1}$ and

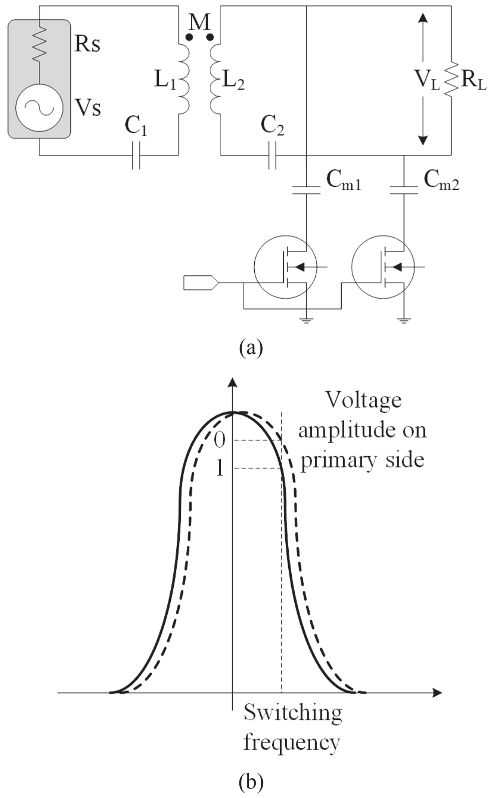


**Fig. 8** Capacitive amplitude modulation. (a) schematics, (b) amplitude modulation

$C_{m2}$ are periodically added to the load, changing the network impedance characteristics. This change will result in the change of primary voltage. The change of primary voltage is then demodulated and converted to corresponding data. The format of the data package can be found in wireless power transfer standard Qi [Johns, 2011].

## 7. EMI SHIELDING AND SAFETY ISSUES

The alternating current through the coupled coils generate unwanted electromagnetic fields. As the unwanted EMI brings up safety issues, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) suggests that the acceptable human exposure to electromagnetic field should be less than 6.25 μT at frequency 0.8-150 kHz [ICNIRP, 1998].

Coreless hollow winding coils have better misalignment tolerant performance but with severe EMI into the space [Qiu et al., 2014]. By using ferrite material as flux guide, the unwanted leakage flux is contained, resulting less EMI. Using metallic plate as shielding between human and coils is a common method to control the EMI level inside an EV. It is worth noting that directly placing metal object near coils will decrease the self and mutual inductances, thus hinder the power transfer [Geselowitz et al., 1992]. When ferrite materials are placed between the coil and metallic shielding, this effect can be minimized.

Using reactive conducting coils to create reverse EMI is proved to be anther effective counter-measure [Kim et al., 2013]. In a 5 x 20 kW wireless charging prototype, ten parallel compensated reactive coils are placed alongside with the receiving coils. Each resonating coil is parallel compensated with controlled capacitor array. The EMI levels measured at strategic points are feed to the controller. By choosing a suitable resonating capacitance, the EMI can be minimized.

## CONCLUSION

In this paper, various WPT technologies are introduced and compared in the perspective of EV wireless charging applications. The principles of inductive power transfer and strongly coupled magnetic resonance are discussed, focusing on maximum power transfer and maximum efficiency. A summary has been made on current wireless EV charging achievements. Other core issues in EV wireless charging are specially chosen and discussed. Latest solutions for every issue is being discussed.

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