Dynamic Wireless Power Charging

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ABSTRACT: Recent days, the demand for wireless power transfer system is highly growing since it is more convenient, reliable and safer solution for electric vehicle (EV) consumers. The basic concept behind Dynamic Wireless Power Transfer (DWPT) is magnetic resonance. Two resonant objects of same resonant frequency tends to exchange energy efficiently, while dissipating relatively little energy in extraneous off resonant objects. Battery technology is no longer relevant in the mass market penetration of EVs so we are moving towards Dynamic Charging. This project works on the concept of Inductive power Transfer (IPT). Thus, it is hoped that this project push forward the further development of WPT as well as the expansion of EV.

Keywords: magnetic coupler, power converters, compensation network

1 Introduction

Wireless power transmission is not a new technology. N. Tesla introduces his wireless work in the US patent in 1914. Some researchers continue their works on power delivery. The major disadvantages of existing wireless power transmissions are low efficiency, typical < 40 %, low power density as 0.004 W/cm2 not considering biological effects, large and heavy equipment and only low amount of power transmissible. Therefore, this project proposes the wireless energy transfer by resonance coupling with the high power density to achieve a smaller size together with high efficiency. For energy, environment, and many other reasons, the electrification for transportation has been carrying out for many years but not in the case of electric vehicles. The wireless power transfer (WPT) technology, which can eliminate all the charging troublesome, is desirable by the EV owners.

By wirelessly transferring energy to the EV, the charging becomes the easiest task. The percentage of loss of power during transmission and distribution is approximated as 26%. The main reason for power loss during transmission and distribution is the resistance of wires used for grid. The efficiency of power transmission can be improved to certain level by using high strength composite over head conductors and underground cables that use high temperature super conductor. But, the transmission is still inefficient. For a stationary WPT system, the drivers just need to park their car and leave. For a dynamic WPT system, which means the EV could be powered while driving; the EV is possible to run forever without a stop. Also, the battery capacity of EVs with wireless charging could be reduced to 20% or less compared to EVs with conductive charging. In an EV, the battery is not so easy to design because of the following requirements: high energy density, high density, affordable cost, long cycle life time, good safety, and reliability, should be met simultaneously. Lithium-ion batteries are recognized as the most competitive solution to EV be used electric vehicle. The size and cost of the battery in dynamic wireless power charging plays a key role. Considering the vehicle initial investment, maintenance, and energy cost, the owning of a battery electric vehicle will make the consumer spend an extra 1000$/year on average compared with a gasoline-powered vehicle.
Besides the cost issue, the long charging time of EV batteries also makes the EV not acceptable to many drivers. For a single charge, it takes about one half-hour to several hours depending on the power level of the attached charger, which is many times longer than the gasoline refuelling process. The EVs cannot get ready immediately if they have run out of battery energy. To overcome this, what the owners would most likely do is to find any possible opportunity to plug-in and charge the battery. It really brings some trouble as people may forget to plug-in and find themselves out of battery energy later on. The charging cables on the floor may bring tripping hazards. Leakage from cracked old cable, in particular in cold zones, can bring additional hazardous conditions to the owner. Also, people may have to brave the wind, rain, ice, or snow to plug in with the risk of an electric shock.

The dynamic power transfer can be done using various transmitting technologies. The most widely used technologies are RF based wireless transfer, microwave based wireless transmission, capacitive coupling, laser, Inductive power Transfer (IPT) etc. The RF based wireless transfer involves high frequency in the range of MHz. Uncontrolled RF radiations affect the metabolism of living organisms significantly. In capacitive coupling, the conjugate of inductive coupling, energy is transmitted by electric fields between electrodes such as metal plates. Capacitive coupling has only been used practically in a few low power applications, because the very high voltages on the electrodes required to transmit significant power can be hazardous, and can cause unpleasant side effects such as noxious ozone production. Microwave power transfer is a far field technique where the power is transferred at microwave range. Then a rectenna is used to convert microwaves to electricity and it is mostly used in space stations. Inductive coupling is the oldest and most widely used wireless power technology and virtually the only one so far which is used in commercial products. It is used in inductive charging stands for cordless appliances used in wet environments such as electric toothbrushes and shavers, to reduce the risk of electric shock. By introducing the latest achievements in the WPT area, we hope the WPT in EV applications could gain a widespread acceptance in both theoretical and practical terms.

2. Fundamentals

The dc power from battery is converted to a high-frequency ac by a inverter to drive the transmitting coil through a compensation network. Considering the insulation failure of the primary side coil, a high-frequency isolated transformer may be inserted between the dc-ac inverter and primary side coil for extra safety and protection. The high-frequency current in the transmitting coil generates an alternating magnetic field, which induces an ac voltage on the receiving coil. By resonating with the secondary compensation network, the transferred power and efficiency are significantly improved. At last, the ac power is rectified to charge the battery. In inductive coupling power is transferred between coils of wire by a magnetic field. The transmitter and receiver coils together form a transformer. An alternating current (AC) through the transmitter coil (L1) creates an oscillating magnetic field (B) by law. The magnetic field passes through the receiving coil (L2), where it induces an alternating EMF (voltage) by Faraday’s law of induction, which creates an alternating current in the receiver. The induced alternating current may either drive the load directly, or be rectified to direct current (DC) by a rectifier in the receiver, which drives the load.

A wireless EV charger consists of the following main parts:

- The detached (or separated, loosely coupled) transmitting and receiving coils. Usually, the coils are built with ferrite and shielding structure, in the later sections, the term magnetic coupler is used to represent the entirety, including coil, ferrite, and shielding;
- The compensation network;
- The power electronics converters.
For stationary EV wireless charging, the coupling between the two coils is usually around 0.2. If both the sending and receiving coils have a quality factor of 300, the theoretical maximum power transfer efficiency is about 96.7%.

A typical wireless EV charging system is shown in Fig. 1.

### 3. Magnetic Coupler

To transfer power wirelessly, there are at least two magnetic couplers in a WPT system. One is at the sending side, named primary coupler. The other is at the receiving side, named pickup coupler. Depending on the application scenarios, the magnetic coupler in a WPT for an EV could be either a pad or a track form. For higher efficiency, it is important to have high coupling coefficient $k$ and quality factor $Q$. Generally, for a given structure, the larger the size to gap ratio of the coupler is, the higher the $k$ is; the thicker the wire and the larger the ferrite section area is, the higher the $Q$ is. By increasing the dimensions and materials, higher efficiency can be achieved. But this is not a good engineering approach. It is preferred to have higher $k$ and $Q$ with the minimum dimensions and cost. Since $Q = \omega L / R$, high frequency is usually adopted to increase the value of $Q$.

The researchers at Massachusetts Institute of Technology (MIT) used a frequency at around 10 MHz and the coil $Q$ value reached nearly 1000. In high power EV WPT applications, the frequency is also increased to have these benefits. In Bolger's early design, the frequency is only 180 Hz. A few years later, a 400 Hz frequency EV WPT system was designed by System Control Technology. Neither 180 Hz nor 400 Hz is high enough for a loosely coupled system. Huge couplers were employed in the two designs. Modern WPT system uses at least 10 kHz frequency. As the technical progress of power electronics, 100 kHz could be achieved at high power level. The Wi Tricity Company with the technology from MIT adopts 145 kHz in their design. In the recent researches and applications, the frequency adopted in an EV WPT system is between 20 and 150 kHz to balance the efficiency and cost. At this frequency, to reduce the ac loss of copper coils, Litz wire is usually adopted.

The flux path height of a circular pad is about one-fourth of the pad's diameter. With all the efforts, at 200 mm gap, the coupling between the primary and secondary pads could achieve 0.15–0.3 with an acceptable size for an EV. At this coupling level, efficiency above 90% could possibly be achieved. The dynamic charging, also called the OLEVAs or roadway powered electric vehicles, is a way to charge the EV while driving. It is believed that the dynamic charging can solve the EVs' range anxiety, which is the main reason limits the market penetration of EVs. In a dynamic charging system, the magnetic components are composed of a primary side magnetic coupler, which is usually buried under the road, and a secondary side pickup coil, which is mounted under an EV chassis. There
are mainly two kinds of primary magnetic coupler in the dynamic charging. The first kind is a long track coupler.

When an EV with a Top view of W-shape and I-shape track configuration. Pickup coil is running along with the track, continues power can be transferred. The track can be as simple as just two wires or an adoption of ferrites with U-type or W-type to increase the coupling and power transfer distance. Further, a narrow-width track design with an I-type ferrite was proposed by KAIST. For W-type configuration, the distribution area of the ferrite W determines the power transfer distance, as well as the lateral displacement. The total width of W-type should be about four times the gap between the track and the pickup coil. For I-type configuration, the magnetic pole alternates along with the road. The pole distance W1 is optimized to achieve better coupling at the required distance. The width of pickup coil W2 is designed to meet the lateral misalignment requirement. The relation between track width and transfer distance is decoupled and the track can be built at a very narrow form. The width for U-type and W-type is 140 and 80 cm, respectively. For I-type, it could be reduced to only 10 cm with a similar power transfer distance and misalignment capacity. 35 kW power was transferred at a 200 mm gap and 240 mm displacement using the I-type configuration. With the narrowed design, the construction cost could be reduced. Also, the track is far away from the road side, the electromagnetic field strength exposed to pedestrians can also be reduced.

The problem of the track design is that the pickup coil only covers a small portion of the track, which makes the coupling coefficient very small. The poor coupling brings efficiency and electromagnetic interference (EMI) issues. To reduce the EMI issue, the track is built by segments with a single power converter and a set of switches to power the track. The excitation of each segment can be controlled by the switches’ ON-OFF state. The electromagnetic field above the inactive segments is reduced significantly. However, there is always a high-frequency current flowing through the common supply cables, which lowers the system efficiency. The published systems efficiency is about 70%-80%, which is much lower than the efficiency achieved in the stationary charging. When each segment is short enough, the track becomes like a pad in the stationary charging, which is the other kind of the primary magnetic coupler. Each pad can be driven by an independent power converter. Thus, the primary pads can be selectively excited without a high-frequency common current. Also, the energized primary pad is covered by the vehicle. The electromagnetic field is shielded to have a minimum impact to the surrounding environment.

4. Compensation Network

In a WPT system, the pads are loosely coupled with a large leakage inductance. From the analysis, it is required to use a compensation network to reduce the VA rating in the coil and power supply. In early inductive charging designs, the compensation is set on primary or
secondary side only. When the coupling coefficient is reduced to less than 0.3 in the EV WPT, compensation at both the primary and secondary side is recommended to have a more flexible and advanced characteristics. To compensate a leakage inductance, the simplest way is to add a capacitor at each side.

Depending on how the capacitors are connected to the coils, there are four basic compensation topologies, which are series-series (SS), series-parallel (SP), parallel-parallel (PP), and parallel-series (PS). If the primary is series compensated, a voltage source converter could be connected directly to the coil. If the primary is parallel compensated, usually an inductor is inserted to change the converter to a current source. However, not all the design has a constant primary side current, and different output characteristics can exist for a series or parallel compensation at the secondary side. According to our analysis, we are using an RC low pass filter as our compensation network.

5. Power Converters

In a WPT system, the function of the primary side power electronics converter is to generate a high-frequency in the sending coil. To increase the switching frequency and efficiency, usually a resonant topology is adopted. At the secondary side, a rectifier is adopted to convert the high-frequency ac current to dc current. Depending on whether a secondary side control is needed, an additional converter may be employed. The primary side converter may be a voltage or a current source converter. Many different control methods were proposed to control the transferred power. Depending on where the control action is applied, the control method could be classified as primary side control, secondary side control, and dual-side control. In most cases, the primary side and dual-side control is only suitable for power transfer from one primary pad to one pickup pad. The secondary side control could be used in the scenario where multiple pickup pads are powered from one primary pad or track. The control at the primary side can be realized by changing the frequency, duty cycle and the phase between the two legs.

6. Conclusion

This paper presented a review of wireless charging of electric vehicles. It is clear that vehicle electrification is unavoidable because of environment and energy related issues. Wireless charging will provide many benefits as compared with wired charging. In particular, when the roads are electrified with wireless charging capability, it will provide the foundation for mass market penetration for EV regardless of battery technology. With technology development, wireless charging of EV can be brought to fruition. Further studies in topology, control,
inverter design, and human safety are still needed in the near term.

References


