

Technical Development of Electro Magnetic Compatibility for Plug-in Hybrid Vehicle / Electric Vehicle Using Wireless Power Transfer System

Akira Mori
Toyota Motor Corporation

ABSTRACT

In 2007, researchers at the Massachusetts Institute of Technology successfully completed a Wireless Power Transfer (WPT) experiment. Ever since, interest in WPT has been growing. At Toyota, we have been developing the underlying technology of a WPT system. Simultaneously we have been working with regulatory committees to create a standard for WPT. In particular, there are concerns that WPT's radiated emissions could cause harm to humans and the neighboring electronic equipment. There are many challenges that need to be overcome, but a key concern is understanding WPT's electromagnetic compatibility (EMI: Electro-Magnetic Interference and EMF: Electro-Magnetic Field). In this paper, we show the technical issues, the evaluation method, and the development status of EMI and EMF on PHVs/EVs when using WPT.

- For Electromagnetic interference (EMI) performance, we investigated both an open area test site and an electromagnetic anechoic chamber as evaluation environments. Through these tests, we found that we could evaluate the fundamental frequency of WPT's radiated emissions at an open area test site. In addition, we found that we could evaluate the harmonics of WPT in an electromagnetic anechoic chamber.
- We developed some countermeasure materials made of different magnetized materials to reduce the fundamental frequency's radiated emissions. As a result, we confirmed that higher magnetic permeability materials have larger effects to reduce the fundamental frequency's radiated emissions.
- To address EMF concerns, we investigated the possibility that the human body and active implantable medical devices were affected by the radiated emissions of WPT. We introduced an evaluation method to investigate these claims using a torso phantom. Our results found no adverse effects to the human body or active implantable medical devices (AIMD) and that users can use WPT safely.

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1. INTRODUCTION

In 2007, researchers at the Massachusetts Institute of Technology successfully completed a Wireless Power Transfer (WPT) experiment of a 60W bulb at 2m [1]. Ever since, interest in WPT has been growing. By using WPT, an electrical device does not need to use cables for power because the electricity is delivered through the air to the device. In 2008, the Wireless Power Consortium (WPC [2]) was established to institute a global standard for inductive charging technology. In 2010, the "Qi" standard for low power (maximum power 5W) was instituted. Several companies moved to commercialize the Qi technology, particularly for cell phones. Other research and development applications on WPT focused on the use of high power (kW) which could be supplied to a vehicle using electricity (PHVs/EVs). In February 2014, we held a demonstration of its WPT technology in Toyota City. We hope to contribute to the technological development of WPT for PHVs/EVs and to the realization of a comfortable smart mobile society with low carbon dioxide emissions.



Fig. 1. Image of WPT

2. POWER TRANSFER METHOD AND COIL CONFIGURATION

2.1. Power Transfer Method

The following two power transfer methods were considered.

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Inductive Method

The inductive method of transfer power occurs by transferring power between the Primary (transmission side) and Secondary (receiver side) coils. This works if the transmission distance between the coils is short (about 10 cm) and the permissible range of misalignment between the coils is narrow. This logic is consistent even when increasing the size of the coils. Therefore, there are applications for large vehicles (e.g. EV busses) and there have in fact been successful experiments in various countries to supply 10 kW of power. Recently, some researchers are trying to use the inductive method of WPT but there are problems of misalignment and miniaturization [4] [5].

Resonance Method

Another method of transferring power is the resonance method. The resonance method transfers power by a resonance of the primary and secondary coils. As shown in Fig.2, the resonant circuit consists of connecting capacitors to each coil in series. L is the inductance of the coil, C is the tuning capacitance, k is the coupling factor, and r is the equivalent series resistance caused by copper loss, iron loss, and other losses. The Q-factor, the sharpness of the resonance, of the circuit in Fig.2 is given by $Q = \omega L / r$. A lot of research focuses on the resonance method for WPT systems for PHVs/EVs because the distance between coils is longer (several 10 cm in the resonance method) and the permissible range of a misalignment between the coils is larger than that of the inductive method. Therefore, we used the resonance method for our WPT demonstration.

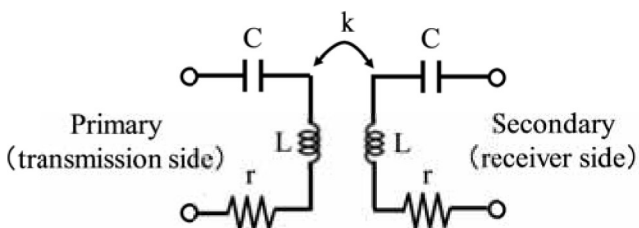


Fig. 2. An example of resonance method

2.2. Coil Configuration

We show the characteristics of the following two shapes of coils in WPT for PHVs/EVs.

Spiral Coil (Circular)

The structure of a Spiral-shaped coil is shown in Fig.3. The dimensions necessary for the core is given by $4a+2b$ where a is the width of the core and b is the width of the coil. This equation is mainly used with a high coupling factor because there is no magnetic flux behind the core. However, it has some problems. As shown in Fig.4, the upward magnetic flux generated by the primary (transmission side) penetrates into the secondary (receiver side) for an aligned coil (a). For a misaligned coil (b), we have positions where power is not supplied to the secondary because the upward and downward magnetic fluxes penetrating into the secondary cancel out each other. Therefore, we need to increase the size of the coils to

expand the permissible range of misalignment [4]. The research for wide fields from mobile device to PHVs/EVs is carried out.

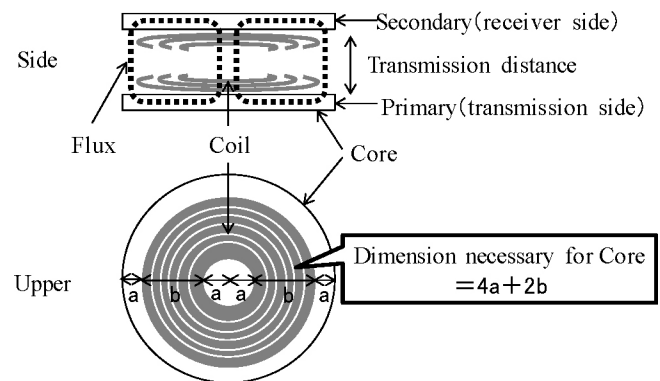


Fig. 3. An example of circular coil [4]

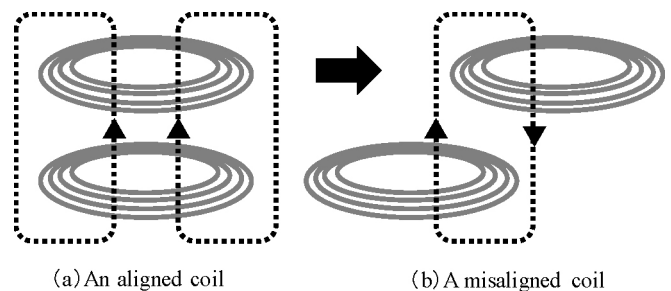


Fig. 4. An example of a misaligned circular coil [4]

Solenoid Coil (Polarized)

The Solenoid coil shape is shown in Fig.5. In the case that the distance between the coils for a spiral coil is the same as a solenoid coil, the coils of a solenoid can be downsized because the dimension necessary for the core of a solenoid coil is half the size as a spiral coil (shown in Fig.3 and Fig.5 the dimension necessary for a spiral core is $4a+2b$ in a Spiral coil and $2a+b$ for a solenoid coil.) [4]. The difference of the coupling factor is small when misalignment happens. Therefore, the permissible range of misalignment is wide for a solenoid coil. With this advantage, there are many applications for power transfer research for wide-ranging fields from mobile device to PHVs/EVs.

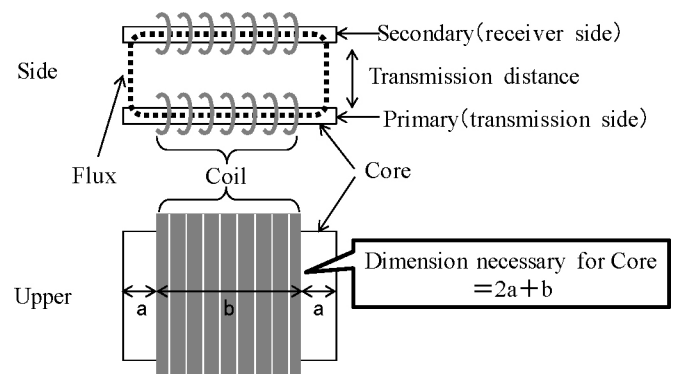


Fig. 5. An example of a Polarized coil [4]

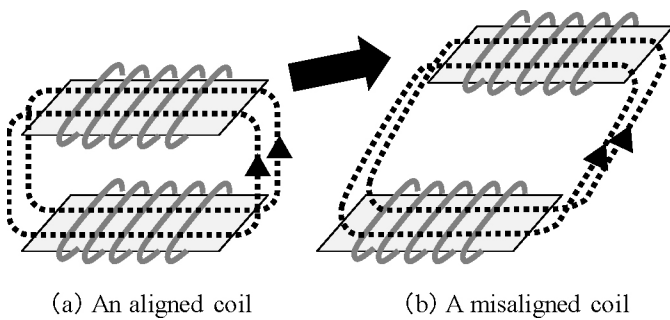


Fig. 6. An example of misaligned polarized coil [4]

3. WPT SYSTEM FOR PHVS/EVS

A diagram for our WPT system for PHVs/EVs is shown in Fig. 7. First, AC 200 V of commercial power is converted into a high frequency signal of 85 kHz at the WPT stand. Then the power is transferred from the primary to the secondary coils wirelessly. Finally, the power is supplied to the HV battery after the power is rectified at the WPT unit in the vehicle. The vehicle is connected to the stand by wireless communication and the status of the power transfer is monitored from beginning to end. With constant communication between the vehicle and WPT stand, the safety operation of power transfer can be monitored. The basic specification of our WPT demonstration vehicle is shown in Table. 1.

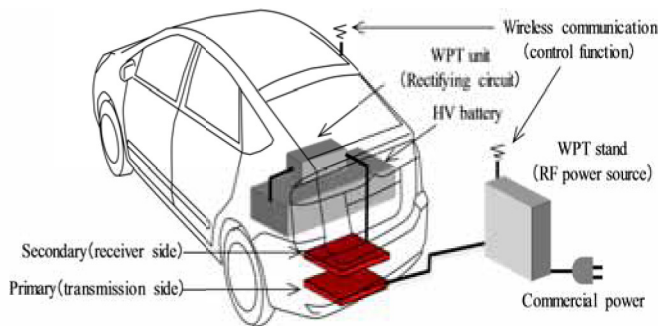


Fig. 7. Diagram of WPT system for PHVs/EVs

Table 1. Basic specification of our WPT demonstration vehicle

Item	Spec.
Wireless power transmission method	Resonance method
Power transfer frequency	85kHz
Input voltage	AC200V
Transmission power	2kW
Charging time	About 90 minutes

4. ACTIVITY FOR PRACTICAL REALIZATION AND INSTITUTIONALIZATION

We have been working to improve the technology of the WPT system in every way (making smaller, lighter, improving the flexibility of the power transfer range, higher efficiency, reducing cost, etc.). In

addition, we have also been working on establishing the regulatory environment for WPT. In Japan, a Broadband Wireless Forum (BWF [6]) was established in 2009 to unite industry, government, and academia in promoting wireless technology and the environment. Particularly for WPT, there is a concern that humans and neighboring electronic equipment can be hurt by radiated emissions. There are many challenges that need to be overcome to achieve electromagnetic compatibility (EMI: Electro-Magnetic Interference and EMF: Electro-Magnetic Field). We think that these next two items are necessary for the growth of WPT:

- I. The establishment of a WPT radiated emission limit.
- II. The international harmonization of WPT's frequency.

There is no regulation or category for WPT in Japanese Radio Law; therefore, the commission of Ministry of Internal Affairs and Communications of Japan (JP-MIC) created a working group in June, 2013 [7]. This working group has been working on WPT regulation since that time. In Europe and America, similar standardization is being developed by the International Electro-technical Commission (IEC) and the Society of Automotive Engineers (SAE) [8] [9].

5. METHODS OF EVALUATING RADIATED EMISSION AND TEST RESULTS

In order to develop the maximum WPT radiated emission limit, it is necessary to evaluate quantitatively the electromagnetic emissions radiated by a WPT system. Thus, it is necessary to evaluate the characteristics of the frequencies that WPT uses for power transfer (fundamental frequency) and unnecessary spurious waves (harmonic frequencies). For the fundamental frequency, we thought that detailed analysis was needed because the propagation characteristics (fundamental attenuation characteristics) are changed by how the coil is configured. Therefore we planned an experiment using our WPT prototype in cooperation with JP-MIC from 2013 through 2014 to investigate [7].

The emission measurement method for WPT is shown in Fig. 8. The radiated emissions propagated through the air from the WPT system were evaluated by the measurement antenna. The conducted emissions which are coupled through the commercial power supply were evaluated by the measurement receiver. The measurement equipment (antenna, receiver and artificial mains network) and the measurement condition (antenna position and ground condition) which we used in our experiments are based on CISPR standards. In an open area test site (OATS), it is difficult to measure the harmonics of WPT because the background noise is easily affected by foreign waves such as radio broadcasts. However, we think that the OATS is suitable for the measurement of fundamental attenuation characteristics because an OATS can allow measured distances up to 30 m from the measurement antenna. Conversely, harmonics can be measured in the anechoic chamber because there is no influence from foreign waves. The standard distance between the antenna and the equipment under test (EUT) is often defined as 10m or 3m in an anechoic chamber. Therefore, we used the OATS for measuring fundamental attenuation characteristics and we used an anechoic