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Study on the Electric Vehicle Wireless Power Supply Technology and System Based on ICPT

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Abstract

The electric vehicle power supply technology based on wireless power transfer (EVPS-WPT) has several advantages over conventional energy transmission using wires and connectors, such as flexibility, convenience, safety, reliability and all-weather operation, etc. The development of EVPS-WPT will certainly promote the popularization and industrialization of EVs. The fundamental structure of electric vehicle wireless power supply system based on ICPT (EVPS-ICPT) is described firstly in this paper. A supposed dynamic battery charging system for electric vehicles based on ICPT (EVC-ICPT-D) is proposed to explain some concepts more clearly. The main circuit topology of EVPS-ICPT system is also discussed and selected. As the focus of this paper, the key techniques for EVPS-ICPT system are discussed and analyzed in the round.

Keywords: Electric Vehicles, wireless power supply, dynamic battery charging system

1   Introduction

Electric vehicles (EVs) are becoming more and more favorable in the whole world because of the energy conservation and environment protection. Many automobile manufacturers have launched their own EVs and a number of governments are introducing related policies to promote the development of EVs [1-3]. Nevertheless, there are various factors such as the terrible mileage range, inconvenient charging still restricting the popularization and promotion of EVs. Owing to the rapid development of inductively coupled power transfer (ICPT) technology, the electric vehicle wireless power supply (EVPS-WPT) is feasible and expected. The EVPS-WPT system has many advantages over conventional energy transmission using wires and connectors, such as the ability of charging for a moving EVs, flexibility-convenience and safety-reliability and so on.

Several studies on ICPT technology and system applied to electric vehicle battery charge have been carried out. In [4], a kind of electric vehicle battery charge system based on ICPT is proposed. In [5], the steps to follow in the optimized design of an electric vehicle ICPT system are shown, and the theoretical results are validated on a 2-kw prototype with a 15-cm air gap between coils. In [6], a novel contactless inductive charging system with its circuit topology for electric vehicles is proposed, and the equivalent models for the primary and secondary circuits are built based on the theory of mutual induction. The relationships between the power transmitted from system to load and circuit parameters are obtained, and the charging power control circuit is designed. In [7], a general design approach is proposed that includes the magnetic coupling effect in the primary resonance design for the commonly used resonant topologies. A design example for contactless electric vehicles battery charging

using a variable-frequency controller is proposed and verified. However, these studies are carried out for a parked electric vehicle and do not include a comprehen-sive consideration. This paper focuses on how to supply power or charge the batteries contactlessly for a moving electric vehicle and discusses the key techniques for the EVPS-ICPT system roundly.

2 The EVPS-ICPT Technology

In this section, the fundamental structure of power supply system based on inductively coupled power transfer for electric vehicle (EVPS-ICPT) will be introduced firstly. And then, a supposed dynamic power supply system based on inductively coupled power transfer for electric vehicles (EVPS-ICPT-D) will be proposed. The four basic resonant topologies of ICPT system and a typical main circuit based on SP topology for EVPS-ICPT will also be described.

2.1 The EVPS-ICPT System

The electric vehicle wireless power supply technology mainly employs inductive coupling, magnetic resonance and microwave in the place of wires and connectors to transmit electric energy. Fig.1 shows the fundamental structure of EVPS-ICPT system [7]. Power convertor takes power from a conventional single-phase or three-phase power supply to generate a high frequency current in the primary energy emission unit (underground track or coil array), around which high frequency magnetic field is formed. In the pick-up unit, which is located in the high frequency magnetic field, high frequency current is induced and conditioned to produce stable supply to battery charging.
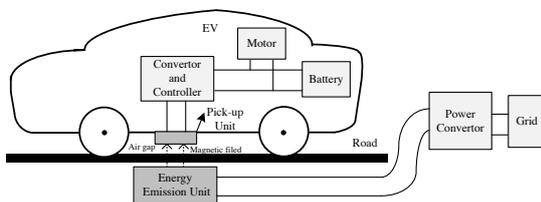
Figure 1: Structure of EVPS-ICPT system

A supposed EVC-ICPT-D system is proposed in this paper, as shown in Fig.2. To forbid unauthorized EVs entering the charging lane, a rail fence is built between the charging lane and the normal lane. At the entry to charging lane, a RF reader is installed to collect information of EVs, which will enter into the charging lane, and transmit it back to management system. The

whole charging lane is segmented into several charging section, labeled as $EVCS_1 \sim EVCS_n$, and each section owns independent primary underground and side track or coil arrays. This is not only good for charging energy measure but also reducing watt level of single power supply device. Moreover, the copper mass is reduced enormously, as system only supplies power for these charging sections, in which electric vehicles are being charged. What's more, an intelligent admittance mechanism is built to insure that every EV in the system is identifiable and the system is never overload.
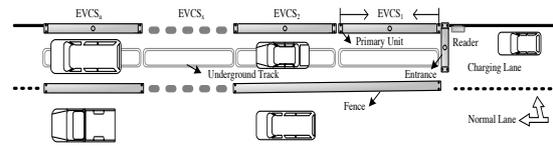
Figure 2: A supposed EVC-ICPT-D system

2.2 Main Circuit

The circuit block diagram of EVPS-ICPT system is shown in Fig.3. The primary is comprised of soft startup circuit, rectifier, filter, high frequency inverter, primary compensation, emission unit and protective circuit. The secondary consists of pick-up unit, secondary compensation, rectifier, filter, power regulator and protective circuit.
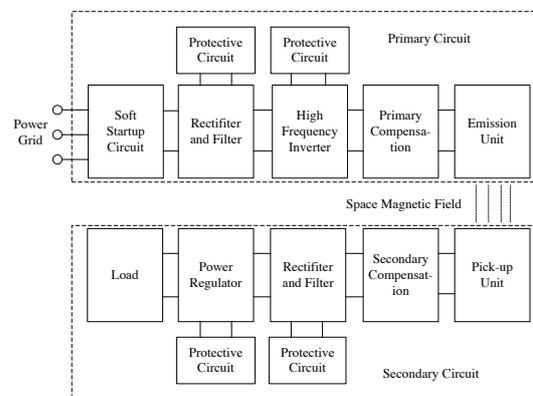
Figure 3: The circuit block diagram of EVPS-ICPT system

Four basic resonant topologies of ICPT system labeled as SS, SP, PS, PP is shown in Fig.4, where the first S or P stands for series or parallel compensation of the primary winding and the second S or P stands for series or parallel compensation of the secondary winding. Here, the "C_P", "L_P", "C_S", "L_S" and "R_L" stands for primary compensation capacitor, primary inductor, secondary compensation capacitor, secondary inductor and load, respectively.
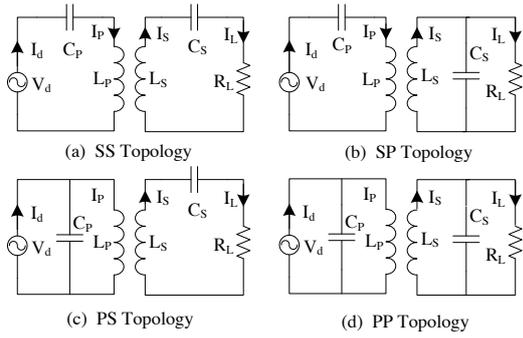
Figure 4: Four basic resonant topologies

Since the series-compensated secondary reflects no reactance at the nominal resonant frequency, the primary inductance can be tuned out independent of either the magnetic coupling or the load by a series-connected capacitance in the primary network. As the parallel-compensated secondary reflects a load-independent capacitive reactance at the nominal resonant frequency, series tuning in the primary is dependent on the magnetic coupling but not the load. Because the reflected impedance contains a real component representing the load, parallel tuning in the primary becomes dependent on both the magnetic coupling and the load [7]. What's more, SS and SP compensation are more advantageous for high-power transmission. At low-power levels, where wire section is not a relevant parameter, PS and PP compensations make possible working at a larger distance with the same operating frequency [5]. Theoretically, SS is the best topology, as the primary capacitance is then independent of either the magnetic coupling or the load and is viable for high-power transmission. Considering capacitor requirements, however, parallel compensation implies lower voltages and higher currents than series compensation, and requires lower operating frequency. That is due to the fact that the higher the required current, the lower the operating frequency. Therefore, SP topology is also widely used for EVPS-ICPT application. A typical main circuit based on SP topology for EVPS-ICPT is shown in Fig.5.

EVPS-ICPT system is a loosely coupling system, as there is a large air gap between the power emission unit and the secondary pick-up unit. Using the mutual coupling inductance theory to analyze it is suitable. The equivalent circuit of SP topology is shown in Fig.6, where I_P, Z_r, U_{oc} and R_{eq} stand for primary winding current, secondary reflected impedance, induced voltage in the secondary winding and equivalent resistance of the load, respectively.
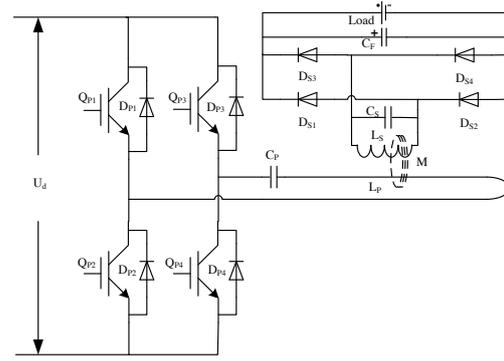
Figure 5: A typical SP topology
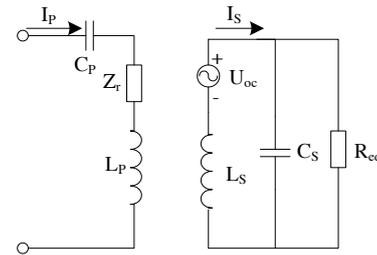
Figure 6: The equivalent circuit of SP topology

The induced voltage in the secondary winding can be figured out by

$$U_{OC} = jwMI_P \qquad (1)$$

where w is the operational frequency and M is the mutual inductance.

The reflected impedance from the secondary circuit to the primary circuit is given by

$$Z_r = w^2 M^2 / Z_S \qquad (2)$$

where Z_S is the impedance of the secondary network.

The power transferred from the primary to the secondary is given by

$$P = (\operatorname{Re} Z_r)I_P^2 \qquad (3)$$

where the operator "Re" represents the real part of corresponding variable [6-7].

Equation (1) to (3) implies that the transferred power of the system depends on I_P, w, M and so on.

3   Key Techniques

The EVPS-ICPT is a large scale, multi-parameter, multi-object, multiple steady-state [8] and greatly complex system. In this chapter, some key techniques for EVPS-ICPT such as hybrid real-time transmission of power and signal, directive transmission of magnetic field, bidirectional transfer of power based on ICPT technology and so on are discussed and analyzed.

3.1 Load Identification and Admittance Mechanism

3.1.1 Load Identification

The EVPS-ICPT is a random system, as the number of EVs and the required watt level of each single EV are unpredictable. For the ICPT system, it has been known that load variation leads to the change of reflected impedance and primary network parameters, which will destroy the normal operating. Therefore, the EVPS-ICPT system must be able to identify the load and adjust parameters of primary network to keep operating steadily. Considering the slip road track of the primary circuit and the phase angle change between the front of the sub-network rectifier circuit current and the voltage, different circuit models were employed to analyze the nature and size of the load for the two types of anti-perceptual situations. An algorithm [9], which is given by equation (4) to (6), was derived to calculate the load with primary circuit parameters.

$$Z_{eq} = V_{eq}(\cos\theta_{eq} + j\sin\theta_{eq})/I_{eq} \qquad (4)$$

$$R_L = \frac{8\cdot[I_P\omega^2 M^2 - Z_{Ls}(a_2 - I_P a_2)]}{\pi^2\cdot[a_1 - I_P a_3 + Z_{Cs}Z_{Ls}(a_1 - I_P a_2)]}, $$
$$a_1 = V_P(\cos\theta + j\sin\theta) $$
$$a_2 = Z_{L_P} + R_P $$
$$a_3 = Z_{L_P} + R_P + Z_{C_S}\omega^2 M^2 \qquad (5)$$

$$Z_{eq} = \frac{8\cdot[b_1 - Z_{Ls}(\omega)(b_1 - b_2)]}{\pi^2\cdot[b_1 - b_2 - Z_{Ls}(\omega)(b_1 - b_2)]} - Z_{Ls}(\omega) $$
$$b_1 = V_P \cdot e^{j\theta(\omega)} $$
$$b_2 = I_P(\omega)[Z_{L_P}(\omega) + R_P] $$
$$b_3 = I_P(\omega)[Z_{L_P}(\omega) + R_P + Z_{C_S}(\omega)\omega^2 M^2] \qquad (6)$$

Where V_{eq}, I_{eq} and θ_{eq} stand for voltage and current of secondary circuit after compensation, and phase difference between the voltage and current, respectively. Here, equation (4) is used to identify whether the load is purely resistive or not. If the result only contains real part, then the load is purely resistive, and it can be calculated out by equation (5). If not, then it is resistive and inductive, and it can be calculated out by equation (6).

3.1.2 Admittance Mechanism

An admittance mechanism should be built to manage the electric vehicles that will enter into EVPS-ICPT system effectively. It is responsible for identifying the EVs that is going to enter the

system to pick up energy, preventing unauthorized EVs to access the system and avoiding the system overload. As shown in Fig.7, if the system is not overload, an EV is not permitted to access into the EVPS-ICPT area until it is identified.
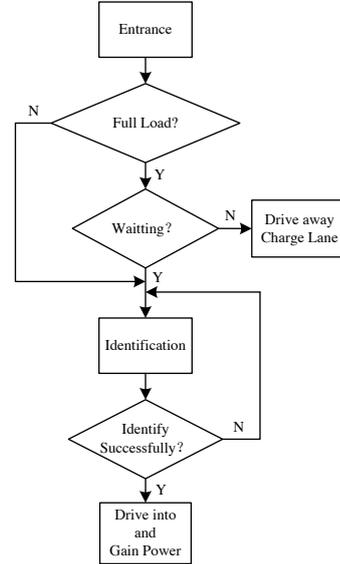
Figure 7: The flow chart of admittance mechanism

3.2 Hybrid Transmission of Power and Signal

In the EVPS-ICPT system, the electric vehicle should communicate with management system unavoidably. For example, the electric vehicle is allowed to access dynamic charging system until it receive confirmation and permission message from the management system, at the same time, the battery type and charging power will be informed to it. Hybrid real-time wireless transmission technique of energy and signal has three advantages: no need for additional communication equipment; no restriction by the density of communication equipment; and convenient interoperate message between electric vehicles and management system. However, in the inductively coupling power transfer system, energy is transmitted by a loosely coupling air passage, which makes signal transmission effectively difficult.

At present, there are three methods for the wireless synchronous transmission of energy and signal [10]: ①A pair of signal transmission coil is added to the energy transmission electromagnetic coupling mechanism. This method needs a pair of additional signal transmission coil, which makes the system design more complex. ②Modulating signal is loaded to the electric energy sending coil and transmitted with electric energy

simultaneously. Electric energy is received by electric energy pick-up coil, at the same time, the signal carrier is abstracted by filter and other method, and then it is reduced to corrected signal after demodulation. In this method, signal is easily interfered by high frequency inverter and the system is more complex because of some added units. ③Signal is modulated on the frequency of inverter and transmitted simultaneously with electric energy by changing the frequency of inverter. In this method, inverter can only work on the condition of hard switching, and the signal transmission speed is limited by the operating frequency of inverter.

In order to overcome the drawbacks of these methods, a signal transmission method based on energy modulation has been proposed, as shown in the Fig.8.
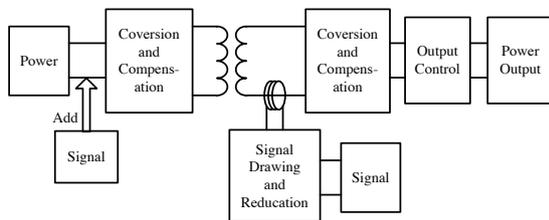
Figure 8: The ICPT system block diagram for hybrid real-time transmission of energy and signal

Power is injected to the system according to the signal transmitted, forming the integrated energy and information flow in the coupling windings. The receiver of system receives the power, and extracts the characteristics of the signal and recovers the signal at the same time. This method is simple to operate with low cost and high reliability.

3.3 Contactless Power Bidirectional Push

In the system of electric vehicle and power grid, electric vehicle can not only be used as a load for getting energy from power grid, but also be used as a distributed energy-storing device, which can be charged at the off-peak period of power grid, and feeds back extra energy to power grid during peak demand period (V2G，Vehicle to Grid). It can relieve the pressure of power grid, and decrease the peak-valley difference. It can make the power supply system more stable and reliable by adjusting supply and demand balance. What's more, the electric vehicle can feed back residual energy to the power grid when battery maintaining. It is not only good for saving energy but also for prolonging the life of batteries. In this

way, the relationship between electric vehicle and power grid is not just the relationship between load and energy source: when electric vehicle is being charged, it is a load, and power grid is an energy source; when electric vehicle is feeding back residual energy to the power grid, conversely, it is an energy source, and power grid is a load. To solve the problem of reliable, free and convenient energy exchange between electric vehicles and power grid, a contactless bidirectional push mode based on ICPT has been proposed, as shown in Fig.9.
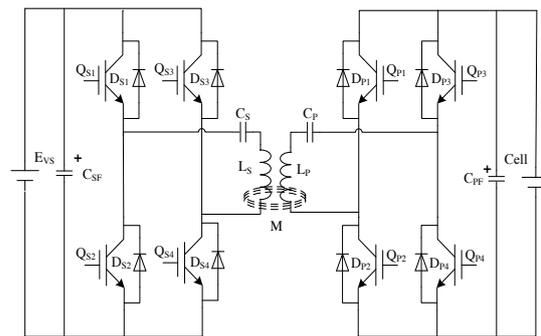
Figure 9: A contactless bidirectional push circuit topology

In this mode, the ports of energy emission and receiving are symmetrical structurally. It can work in both magnetic field exciting mode and magnetic field receiving mode. It can meet the requirements of power bidirectional transfer. This technology has only realized in the transmission of small power, but further studies are needed for the bidirectional transmission of high power.

3.4 Proportional Magnetic Field Extension Technology

Owing to the large air gap between the primary and secondary, the transmission efficiency of ICPT system is lower compared to the conventional power transmission using wires and connectors. The coupling coefficient is descending with the increasing of distance exponentially, and the transmission efficiency is reducing obviously as well. Therefore, a key point for EVPS-ICPT system is how to realize the directed transmission of magnetic field, and how to strengthen the coupling ability of the primary and secondary, which results in improved system transmission efficiency.

As the magnetic line of force is closed and nonintersecting, a magnetic and electric coil array distributed like a concave mirror has been proposed to realize the gather of magnetic field.

Its profile map is shown in Fig.10(a), where M_0, the main magnetic field generating pole, is in the center, and M_{na} and M_{nb}, the auxiliary magnetic poles, are distributed around. The magnetic field produced by auxiliary magnetic poles can increase the magnetic field of the whole space; what's more, it can gather magnetic field produced by the main pole intensively. And the 2D static magnetic field distribution simulated with Maxwell is shown in Fig.10(b). This method can realize the equilibrium distribution of the magnetic field in certain ranges that strengthen the ability of magnetic field transmission in a certain direction.
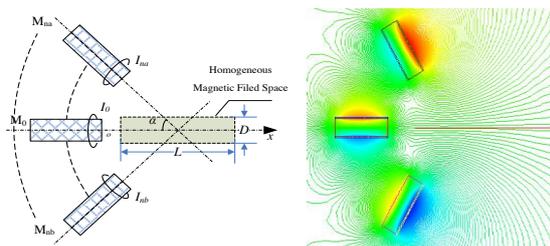
(a) The profile map   (b) Maxwell simulation result
Figure 10: The directed transmission of magnetic field

3.5   The Optimal Layout Design of Emission Unit

The EVPS-ICPT system is mainly used for energy supply to electric vehicle dynamically. The scale of power supply area is related to the charging speed, recharged volume of battery energy and running speed of vehicle and so on. Supposing it takes 30 minutes to make over 80% power for battery, the length of 6KM in charging area is needed for an electric vehicle with speed of 60KM/h to supply dynamically 30% of the battery capacity. If the overall style primary track is designed for this long charging area, the energy loss is huge, and it has a critical power requirement for every single electrical energy transducer. To avoid these problems, energy emission unit of primary side can take the form of coil array (Fig.11(a)), and the form of segmented track (Fig.11(b)).

(a) Coil array   (b) Segmented track
Figure 11: The layout of energy emission unit

Optimal design should be made to the structure and layout of energy emission unit, as the transmission efficiency of whole charging system, the first investment cost, operating cost and operating management are decided by it directly.

The layout design of energy emission unit is a large scale, multi-constraints and nonlinear combinatory optimization problem. The genetic algorithm (GA) [11-12], evolution algorithm (EA) [13], ant colony (AC) [14], Tabu search algorithm [15], neural network [16], particle swarm algorithm and so on can be used for analysis.

3.6   Optimal Design for Pick-up Unit

3.6.1   Design for Multiple Pick-up Unit Combination

Optimal design for pick-up unit is needed to increase the pick-up efficiency, and reduce the weight of pick-up unit simultaneously at all possible. It contains the shape of pick-up unit, the number of pick-up units, and the connected mode between pick-up units etc. Pick-up unit can take many kinds of structures, like E-shaped, U-shaped, square-shaped, disk-shaped [17] and so on. The deep theoretical analysis and experimental verification are needed to decide which structure is best for the EVPS-ICPT system. And multiple pick-up units can increase energy pick-up ability adequately. The pick-up units can be combined as the following forms: first rectification, and then parallel connection; first parallel connection, and then rectification; first rectification, and then series connection; first series connection, and then rectification. The combining forms of 2 pick-up units are shown in the Fig.12 [18].

(a) rectification-series   (b) rectification-parallel

(c) parallel-rectification   (d) series-rectification
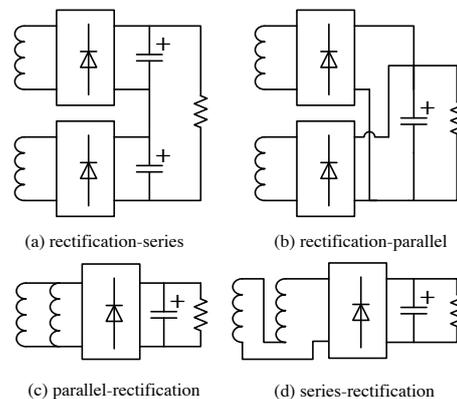
Figure 12: The combining forms of 2 pick-up units

In the mode of first series connection and then rectification, when the coupling factor of some pick-up units is low, the reaction electric potential to be excited is low as well. It is just like a large inductance series-wound in the current, and the phase of every inductive voltage may not be same, which is disadvantageous for the continuous work of whole pick-up unit. In the mode of first parallel connection and then rectification, when the

coupling factor of some pick-up units is low, the pick-up inductance with a higher coupling factor will be short-circuited and decoupled, which will prevent the whole pick-up unit from working. In the mode of first rectification and then parallel connection, it can export a regulated voltage, but the utilization factor of pick-up coil is low, because only one pick-up coil supplies power at a time. In the mode of first rectification and then series connection, the utilization factor of pick-up coil is high, because the inductive energy of every pick-up coil can be used at a time, but the fluctuation of output voltage is serious. Thus, a further study is needed to make pick-up unit work stably and efficiently.

3.6.2 Self-adapting Adjusting of Pick-up Unit

In the EVPS-ICPT system, the pick-up unit should get as close as possible to the energy emission unit, which can insure the energy pick-up is adequate and the transmission efficiency of system is high. However, in order to maintain the constant close distance energy pick-up, the pick-up unit should adjust its position automatically, including vertical position and horizontal position, to adapt road condition, position variation of energy emission unit and vehicle. The pick-up unit should be able to detect the position of energy emission unit in real-time, and adjust its position automatically to insure the energy pick-up reliably and safely (Fig.13).
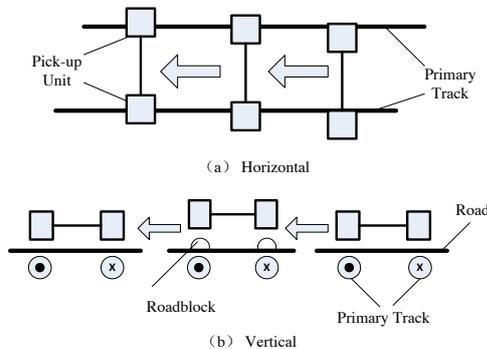
Figure 13: Self-adapting tuning techniques of pick-up unit

3.7 Magnetic Shielding Technology

As a metal conductor, magnetic field cutting will form in vehicle during dynamic charging process, and then induce the eddy-current effect. So how to use magnetic shielding technology to avoid or decrease eddy-current, and guarantee the security of both passengers and vehicle itself, is a crucial problem for EVPS-ICPT system. There are two

way for resolving the problem of magnetic shielding: ① Controlling magnetic field, let it attenuates to a low level before arrives to electric vehicle chassis, in this case, the induced eddy-current effect is not enough to harm electric vehicle and passengers. This mode is called as initiative mode in the paper. ②Weakly magnetic chassis material is used, and electric vehicle chassis structure is changed to realize magnetic shielding. This mode is called as passive mode in the paper.

4   The Demonstrated System

A 400 watts demonstration system of inductively coupled power supply for electric vehicle shown in Fig.14 is designed to validate the theoretical analysis.

Figure 14: Demonstrated electric vehicle wireless power supply system

PP compensation was selected because of it is the topology that requires lower operating frequency (the lower the required current, the higher the operating frequency) and controlled easily. The primary track is fixed under a red carpet and two secondary windings (first parallel connection and then rectification) are installed on the electric vehicle chassis. The total efficiency of system is 40% approximately with a large air gap of 30mm.

5   Conclusion

Electric vehicle wireless power supply system can supply energy or charge batteries for the electric vehicles, regardless of whether they are parked or on the move. It will certainly be an important research area on electric vehicles. This paper describes the fundamental structure of electric vehicle wireless power supply system, analyzes the basic resonant topologies based on ICPT and proposes a supposed electric vehicle dynamic battery charging system. As the key point of this

paper, the related key techniques for electric vehicle wireless power supply system are discussed and analyzed. At the same time, some possible ways to solve these difficult problems are proposed.

Acknowledgments

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