

A 13.56 MHz Antenna Design with the Efficiency Improvement for the Wireless Power Transfer System

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Abstract

Wireless power transfer is the most convenient solution for the electric device charging. However, it still keeps a disadvantage such as the transfer distance is short which is the most difficult to eliminate. Moreover, the relative position of the transmitter and the receiver depends on the movement of the electric vehicles in the dynamic wireless charging. Therefore the average efficiency is low in the charging area when the electric vehicle runs away from the optimized position of the transfer system. In this paper, a 13.56MHz antenna is designed by the finite element analysis. At the highest efficiency, the transfer distance is 55 cm. Otherwise, the solution to improve efficiency due to the variation of the charging position is proposed. The coupling system is strongly coupled magnetic resonance technology. The impedance is dynamically matched in the transmitter to improve the transfer efficiency. In the simulation, the 91.2% highest efficiency at 55 cm is obtained and it is improved maximum of 56.4% within 55 cm transfer distance and 40 cm misalignment with the proposed solution. The experimental system can improve efficiency depending on the position of receiver and lookup data.

Keywords: Wireless Power Transfer, Coupling System, Magnetic Resonance, 13.56 MHz Antenna, Efficiency Improvement.

I. INTRODUCTION

In the present, energy and environment are concerned. In daily life and production, transport is very important. It also consumes a lot of energy. Gasoline and oil are used in common. They have high energy density but they are limited. Moreover, the emissions are the major issues when fossil energy is used. Hence, the electrification for transportation has been carrying out for many years. A train can get electric power easily because it runs on a fixed rail. It is not easy for electric vehicles (EV) to get power similarly. Therefore, the EV has to equip a large and heavy battery pack. It is very necessary for a long trip. And people have to connect the vehicle to the power source for a long time to charge the battery. It is not convenient. The proposed solution is wireless dynamic charging. With the wireless power transfer (WPT) technology, the vehicle can increase the moving distance and reduce battery capacity. When the WPT is used in EV, there are three popular technologies: capacitive power transfer (CPT), inductive power transfer (IPT), and magnetic resonant coupling (MRC). The frequency of MRC is usually less than 100 kHz and using ferrite core. It is similar to inductive power transfer (IPT) because of using non-radioactive and near-field

electromagnetic. The tens kW power can be transferred with above 80% efficiency. However, the effective operation is under 200 mm transfer distance [1]-[8].

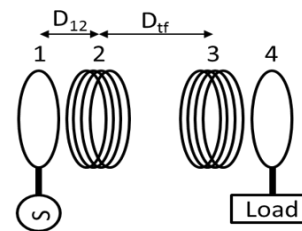


Fig.1. The antenna with SCMR structure

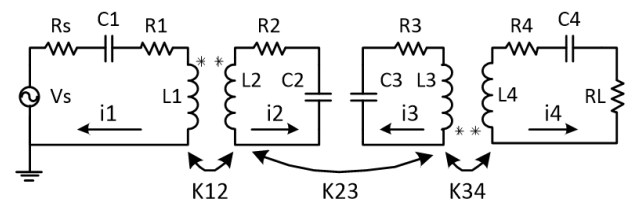


Fig.2. The equivalent circuit

In 2007 and 2008, the research team from MIT reported WPT theory based on optics and photonic crystal theories, explaining it as a phenomenon caused by near-field evanescent waves [9], [10]. The technology is named as strongly coupled magnetic resonance (SCMR) [11]-[16]. In the MIT group's publication, they transfer 60W over 2 meters. The highest efficiency is obtained at the resonance frequency which is about 10MHz. This technology not only transfers power over a long distance but also eliminates a discrete capacitor in the resonant system. This is the most important because the capacitor has to operate at a very high voltage. Therefore, we chose the SCMR technology for EV dynamic wireless charging in this research. The WPT system includes the rectifier, the high-frequency converter, the coupling system, and the load voltage converter. The coupling system makes the power transfer system become wirelessly. Therefore, it is an important part of the WPT system. It also determines the transfer distance and efficiency of the system. There are four coils in the SCMR (Fig.1). They are divided into the power side and load side: the coil 1 and coil 4 are the rings coil 1, 4. And the coil 2 and coil 3 are the resonant coil. The resonance circuit of the system includes the capacitance between coils, the parasitic capacitance inside the coils, and the inductance of coils. Fig.2 shows the equivalent circuit of SCMR [17]. V_{in} and R_s are the internal parameters of the power source. R_1 and L_1 , R_2 and L_2 , R_3 and L_3 , R_4 and L_4 are the internal resistor and inductance of transmitting ring, transmitting coil, receiving coil, and receiving ring,

respectively. The internal and parasitic capacitance of the transmitting coil and the receiving coil is C_3 and C_4 , respectively. The main mutual inductance is M_{12} , M_{23} , and M_{34} . The quality factor Q_i represents the quality of the coil. The resonance occurs between coils if their resonance frequency is matching each other.

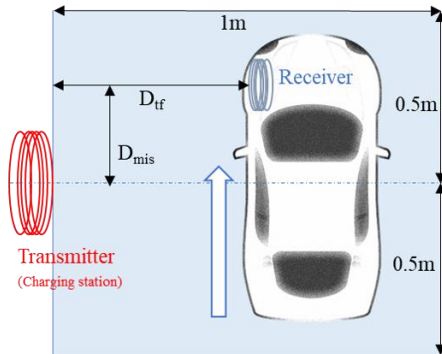


Fig.3. The dynamic wireless charging system

Table 1. The parameters of the antenna model

Name	Initial	Optimized	Description
D_{tf}	550 mm	550 mm	The transfer distance
D_{mis}	0 mm	0 mm	The misalignment
D_{12}	65 mm	120 mm	Distance between ring coil and resonant coil
D_{res}	350 mm	400 mm	Diameter of resonant coil
D_{ring}	300 mm	350 mm	Diameter of ring coil
D_w	1.6 mm	3.2 mm	Diameter of copper wire
p	15 mm	20 mm	Pitch of resonant coil
N_t	5	5.18	Number of turns of resonant coil
F_{res}	13.47 MHz	13.56 MHz	Resonant Frequency
$ S_{21} $	60.9%	95.5%	The transmission S_{21}
Eff	36%	91%	The highest efficiency

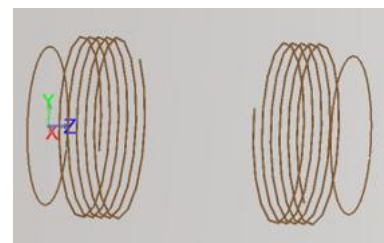
Our research focuses on the wireless dynamic charging system which is shown in Fig.3. The transmitter is located next to the road and the receiver is set inside the vehicle. The moving of the EV makes the variation of the position of the receiver. By the phenomenon of the MRC, the resonant frequency is split and the efficiency at the operating frequency is reduced [11], [18], [19]. The researchers tried to obtain high efficiency by adjusting the operating frequency to an efficient point [11]. However, the ISM band limits the operating frequency of the system in the industrial, scientific, and medical applications. The MHz range is limited in 6.78 ± 0.015 MHz, 13.56 ± 0.007 MHz, 27.12 ± 0.163 MHz. Therefore, some variable LC circuits are added as the impedance matching circuits. It keeps

the efficiency at operating frequency [18]. In the high power application, this solution is difficult in applying because of the power loss on the additional devices. Fortunately, the SCMR's structure has more freedom of parameter variations. Especially, the coupling coefficient K_{12} and K_{34} can be changed physically. In this paper, the proposed solution improves the efficiency of the coupling system (maximum 56.4%) with the variation of the receiving position. It's confirmed by the simulation results. Moreover, the experiment with the matching system can adjust K_{12} as lookup data to archive the highest efficiency according to the position of the receiver.

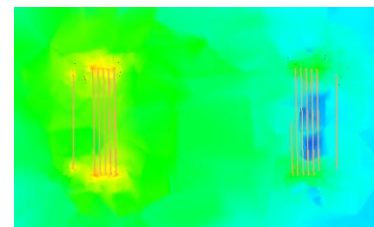
II. DESIGN OF A 13.56 MHZ ANTENNA

After the Coupled Mode Theory (CMT) of electromagnetism is introduced in the early 1950s, the theory undergoes a lot of development. The current theory is suitable for analyzing the energy exchange process between two resonators. However, the CMT concepts are still obscure. Another method to model a wireless power transmission scheme is by the equivalent circuit theory and the parameter of the scheme can be analyzed using the two-port network theory with scattering parameters (s-parameters). The antenna also can be analyzed by the S-parameter method. The source-side port is P_1 and the load-side is P_2 . The transmission S_{21} is analyzed by finite element analysis (FEA) in simulation or is measured by the vector network analyzer (VNA). The efficiency η of the coupling system is defined by (1).

$$\eta = |S_{21}|^2 \quad (1)$$



(a) The 3D model of the Antenna.



(b) The Visualization of the simulation.

Fig.4. Finite Element Model of the Antenna

To achieve the resonant frequency and high-efficiency design of the antenna, we investigate the effect of mechanical parameters by simulation. In this case, the 3D model of the coupling system is built and EMpro software is used to get the FEA simulation result. This software supports generating the s-

parameter result directly which is shown in Fig.5. The 3D model is shown in Fig.4. The initial parameters of the design are listed in Table 1. The highest point of $|S_{21}|$ shows the resonant frequency and efficiency which is calculated by (1). After optimization, the 13.56 MHz antenna with high efficiency is confirmed. The parameters are list in Table 1. The s-parameters results are shown in Fig. 5. The highest efficiency is calculated from (1) and the results are 36% and 91% for the initial and optimized model, respectively.

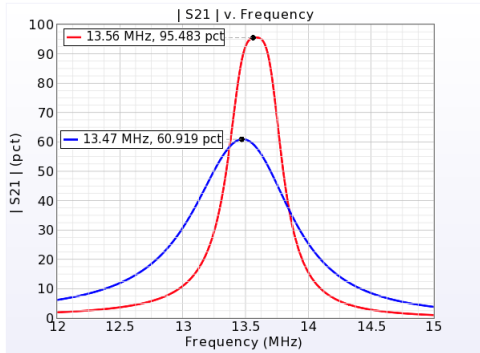
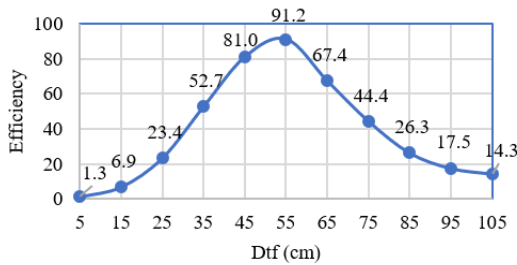


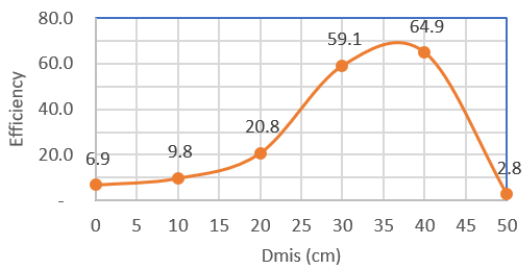
Fig.5. The s-parameters results in simulation

III. DYNAMIC CHARGING SYSTEM

III.I The Problem Analysis



(a) The efficiency depends on D_{tf} when $D_{mis}=0\text{cm}$



(b) The efficiency depends on D_{mis} when $D_{tf}=15\text{cm}$

Fig.6. The efficiency depends on D_{tf} and D_{mis}

The typical model of the four-coil power transfer system is shown in Fig.1. The detail already is described in section 1. To clearly explain the issue of the dynamic charging system, the represented circuit is shown in Fig. 2. Normally, the AC power supply can be either a power amplifier or a vector network analyzer (VNA) which is useful to measure a transmission and

reflection ratio of the system. Therefore, the value of R_S and R_L is 50Ω . The circuit model offers a convenient way to analyze the system's characteristics. By choosing the currents in each circuit as in Fig. 2 and applying circuit Kirchhoff's Voltage Law to the system, a relationship between currents and voltages can be captured as (2).

$$\begin{bmatrix} V_S \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & j\omega M_{12} & 0 & 0 \\ j\omega M_{12} & Z_2 & -j\omega M_{23} & 0 \\ 0 & -j\omega M_{23} & Z_3 & j\omega M_{34} \\ 0 & 0 & j\omega M_{34} & Z_4 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} \quad (2)$$

The Z_i (with $i=1\sim 4$) are indicated as:

$$Z_1 = R_S + R_1 + j(\omega L_1 - \frac{1}{\omega C_1})$$

$$Z_2 = R_2 + j(\omega L_2 - \frac{1}{\omega C_2})$$

$$Z_3 = R_3 + j(\omega L_3 - \frac{1}{\omega C_3})$$

$$Z_4 = R_L + R_4 + j(\omega L_4 - \frac{1}{\omega C_4})$$

It is seen that the voltage across the load is equal to $V_L = -i_4 R_L$ and the relationship between the voltages of the source and load is given as V_L/V_S . The s-parameter is a suitable candidate to analyze a figure of merit of this system. S_{21} is determining of power transfer efficiency which is given by $|S_{21}|^2$. The parameter of S_{21} is calculated by (3) [11].

$$S_{21} = 2 \frac{V_L}{V_S} \sqrt{\frac{R_S}{R_L}} \quad (3)$$

$$S_{21} = \frac{j2\omega K_{12}K_{23}K_{34}L_2L_3\sqrt{L_1L_4R_S R_L}}{Z_1Z_2Z_3Z_4 + K_{12}^2L_1L_2Z_3Z_4\omega^2 + K_{23}^2L_2L_3Z_1Z_4\omega^2 + K_{34}^2L_3L_4Z_1Z_2\omega^2 + K_{12}^2K_{34}^2L_1L_2L_3L_4\omega^4} \quad (4)$$

The quality factor which appreciates how well the resonator can oscillate is defined as:

$$Q_i = \frac{1}{R_i} \sqrt{\frac{L_i}{C_i}} = \frac{\omega_i L_i}{R_i} \Leftrightarrow \omega_i L_i = R_i Q_i; \quad i = 1 \sim 4 \quad (5)$$

When the resonance takes place:

$$\omega_i = \omega_0$$

$$Z_1 = R_S + R_1 \approx R_S$$

$$Z_2 = R_2$$

$$Z_3 = R_3$$

$$Z_4 = R_L + R_4 \approx R_L$$

$$|S_{21}| = \frac{2K_{12}K_{23}K_{34}Q_2Q_3\sqrt{Q_1Q_4}}{1 + K_{12}^2Q_1Q_2 + K_{23}^2Q_2Q_3K_{34}^2Q_3Q_4 + K_{12}^2K_{34}^2Q_1Q_2Q_3Q_4} \quad (6)$$

The variation of $|S_{21}|$ is similar to the line in depends on the Fig.6. It depends on the variation of K_{23} . With the variation of K_{23} in the dynamic wireless charging system, $|S_{21}|$ or efficiency η is maximum when:

$$\frac{d|S_{21}|}{dK_{23}} = 0 \quad (7)$$

$$\Leftrightarrow K_{23}^* = \sqrt{\frac{(1 + K_{12}Q_1Q_2)(1 + K_{34}^2)Q_3Q_4}{Q_2Q_3}} \quad (8)$$

$$|S_{21}|_{max} = \frac{K_{12}K_{34}Q_1Q_4R_L}{K_{23}^*\sqrt{L_1L_4}\omega_0}$$

By the common way, the electric vehicle is charged by the transmitting system which is constructed under the ground or street [20]-[25]. It makes the difficulty in construction and maintenance. Therefore, we propose to put the transmitter next to the road and charge the EV from the roadside. The charging system power the EV continuously when it runs into the coverage area. The transmitters are put next to each other belong to the charging line. The coverage area of each transmitter is about 1 m distance and 0.5 m misalignment (Fig. 3).

Firstly, we investigate the distributions of the efficiency of the coupling system by FEA. At 13.56 MHz, the efficiency is high at an only constant distance and no misalignment condition (Fig. 6). Fig. 6(a) is the efficiency of the coupling system at the misalignment distance $D_{mis} = 0$. The efficiency reaches 91.2% at $D_{tr}=55$ cm. Fig. 6(b) shows the efficiency at $D_{tr}=5$ cm. The maximum efficiency is 90.5% at 35 cm of misalignment. The distribution of efficiency in the charging area is shown in more detail in the next section. Therefore, the average receiving power of EV is not high. The reason for this phenomenon is explained by equations (6) to (8).

III.I The Proposed Solution

At certain transfer position, the coupling coefficient K_{23} is constant. The efficiency η or $|S_{21}|$ is depended on the coupling coefficients K_{12} and K_{34} . Because of the proposed system, it is difficult to transform the receiver parameters. Our proposed solution to improve efficiency is changing the K_{12} . The maximum of $|S_{21}|$ is obtained when:

$$\frac{d|S_{21}|}{dK_{12}} = 0 \Leftrightarrow K_{12}^* = \sqrt{\frac{1 + K_{23}^2Q_2Q_3 + K_{34}^2Q_3Q_4}{Q_1Q_2 + K_{34}^2Q_1Q_2Q_3Q_4}} \quad (9)$$

Moreover, the coupling coefficient between coils is calculated as:

$$K_{ij} = \frac{M_{ij}}{\sqrt{L_jL_j}}; \quad i, j = 1 \sim 4 \quad (10)$$

An approximation of the mutual inductance given as (11) [10]:

$$M_{ij} = \pi\mu_0(r_i r_j)^2 \frac{N_i N_j}{2D_{ij}^3} \quad (11)$$

$$K_{ij} \sim \frac{1}{D_{ij}^3} \quad (12)$$

With equations (10) to (12), the variation of the D_{12} and D_{23} can be represented to the variation of K_{12} and K_{23} . The variation of the mutual inductance or coupling coefficient K_{23} between the transmitting side and receiving side when the relative position is changed. The dependence of the coupling coefficient on the receiving position is shown in Fig.7.

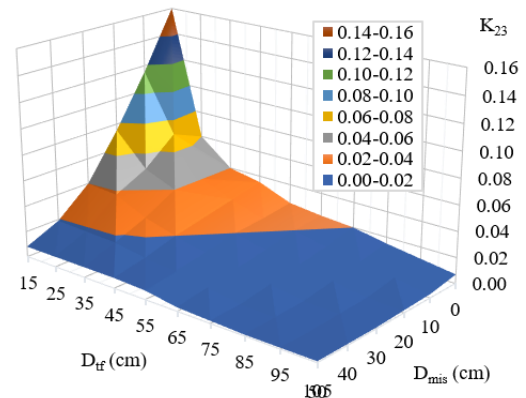


Fig.7. The dependence of K_{23} to D_{tr} and D_{mis}

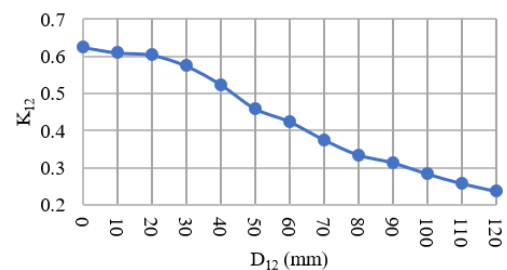
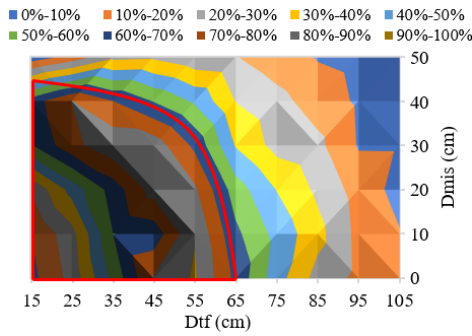


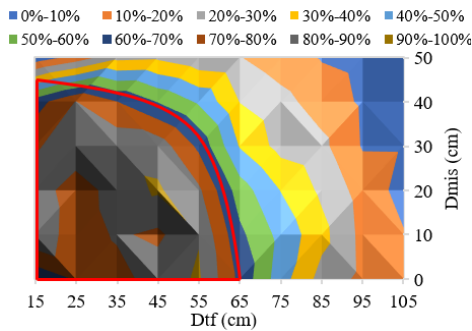
Fig.8. The dependence of K_{12} to D_{12}

The efficiency of the coupling system can be calculated from the s-parameter and the parameters of the system. It does not only depend on the K_{23} but also depends on K_{12} and K_{34} . Therefore, the efficiency can be improved by changing K_{12} and K_{34} when K_{23} is changed. By the way, the K_{12} and K_{34} depend on the distance of the link coil and a resonant coil (Fig. 8). In this system, the changing of K_{34} is difficult because the receiver is in the EV. So we propose changing the D_{12} which is the distance between the link coil and the resonant coil of the transmitting side to improve the efficiency of the charging area.

IV. SIMULATION AND EXPERIMENTAL RESULTS



(a) Without improvement



(b) With improvement

Fig.9. The efficiency of antenna in simulation

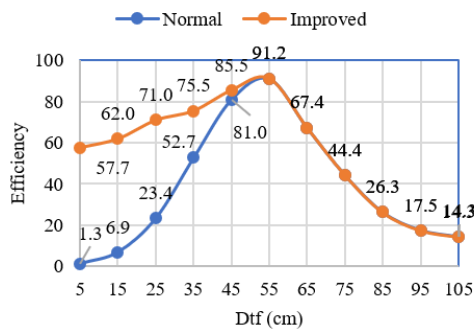


Fig.10. The efficiency of the antenna with and without improvement

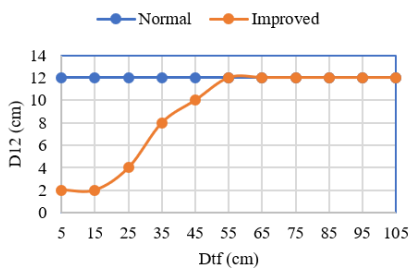


Fig.11. The variation of D_{12} to improve efficiency

The proposed coupling system is designed and verified by the FEA simulation - EMpro software. The parameters of the coils are listed in Table 1. The transfer distance is changed from 15 cm to 105 cm while the misalignment is changed from 0 cm to 50 cm with a 10 cm changing step. The simulation results of the efficiency of the coupling system are shown in Fig. 9. Fig. 9(a) shows the efficiency map of the coupling system when the D_{12} is constant. Fig. 9(b) shows the efficiency map of the coupling system when the proposed solution is applied. In the dark gray area, the efficiency is higher than 80%. The efficiency is distributed as the curve which has the center at the left bottom corner.

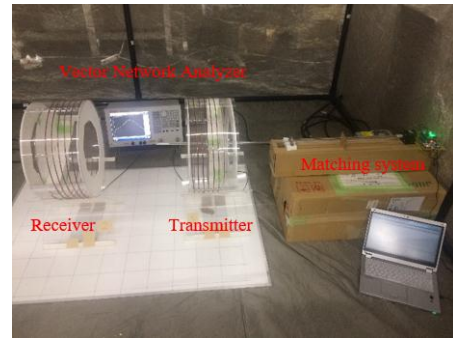
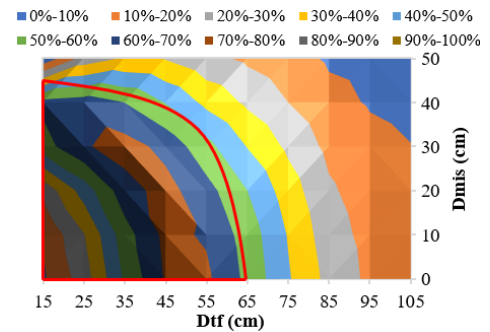
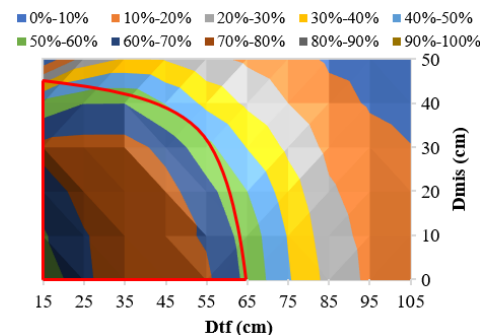


Fig.12. The experiment system



(a) Without improvement



(b) With improvement

Fig.13. The efficiency of the antenna in experiment

When the D_{12} is constant, the high-efficiency area is in the middle area and it is small. The efficiency decreases when the transfer distance or misalignment move out of the middle area. With the proposed solution, the efficiency is increased in the

red line border area which has 65 cm and 40 cm of D_{tf} and D_{mis} , respectively. In other areas, efficiency cannot be improved. Finally, the average transfer efficiency is increased. Fig. 10 shows more detail about the improved efficiency at $D_{mis}=0$ cm. The maximum increased efficiency is 56.4%. The D_{12} is changed due to the proposed solution. The variation of D_{12} is shown in Fig.11.

To verify the proposed solution, a prototype experimental system is constructed as shown in Fig.12. The position of the receiver is collected by a microcomputer. Depend on the lookup data of D_{12} to obtain the highest efficiency, then the matching system adjusts the position of the powered coil in the transmitter to improve the transfer efficiency. The efficiency map in the experiment is shown in Fig.13. In comparison with simulation results, the distribution of charging efficiency is similar.

V. CONCLUSIONS

This paper presents the efficiency improvement method of the wireless dynamic charging antenna at 13.56 MHz. The advantage of the method is ignorable the applying discrete inductance or capacitance into the system. Additionally, the efficiency is improved at the multi-position of load side which is implemented in EV. The solution is demonstrated by the FEA and experiment. The limitation of improving the area is closed to the design point. In the future, the designed point will be 1m. Therefore, an improved area of efficiency will be expanded. The experiment also can be upgraded to automatically matching the system impedance to achieve high efficiency.

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