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Magnetic Coupling Performance Analysis and Simulation of ICPT Landing-type Pickup Mechanism

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Magnetic energy conversion mechanism simulation model of contactless energy transmission system has been set up based on Maxwell 3D simulation environment. According to the model, the influence of primary and secondary- side coil position of loosely coupled transformer on contactless power transmission system and the influence of primary and secondary- sided coil position on the system apparent power, transmission power and system transmission efficiency have been analyzed with utilization of experimental and ANSYS finite element simulation software. Feasibility of the above simulation calculation has been verified through experiments. Simulation and experimental results show that mutual inductance coupling is affected by the above factors, providing a theoretical basis and guidance for design of landing- type scaffolding pickup coils.

1. Introduction

Inductively Coupled Power Transfer ICPT (Inductively Coupled Power Transfer) is defined as power transfer in the form of wireless by space magnetic field from the primary side coil to vice side coil also called pick-up mechanism. The existence of air magnetic circuit of the magnetic coupling mechanism result in larger leakage inductance of the system. Bigger air gap between pick-up coil and transmitting terminal leads to lower coupling coefficient, larger size of the coupling mechanism and higher costs. In order to improve power transmission efficiency, The following measures can be taken: 1) High frequency alternating current is injected into launching terminal; 2) The resonance compensation is taken between launching terminal and pick-up terminal; 3) Shorten the distance between pick-up mechanism and the transmitting coil, to improve the coupling coefficient (Wang, 2014; Qin, 2010; Su, 2013). Traditionally, the larger distance between fixed pick-up coil used in electric car and the transmitting rail (20 ~ 30 cm) leads to the lower coupling coefficient, the larger size of the coupling mechanism and the higher cost. For this, through the use of landing-type scaffolding coil, as shown in figure 1, minimize air gap of coupling mechanism is to improve mutual inductance and magnetic coupling transmission efficiency (Dong, 2016).

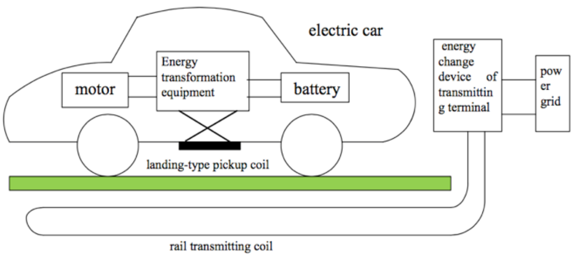

Figure 1: Wireless charging schematic diagram of landing- type scaffolding pick-up coil

2. System Main Circuit

The system main circuit of Wireless power-supply electric vehicle consists of the following three parts: electric energy conversion device in transmitting terminal, electromagnetic coupling mechanism, electric energy conversion device of vehicle side. The transmitting terminal by rectification, filtering, voltage stabilization, high-frequency inverter converts Power-frequency AC into high-frequency AC send it into electromagnetic coupling mechanism, the circuit structure is shown in figure 2. In the circuit model, capacitors work as compensation of the original coil and deputy coil.

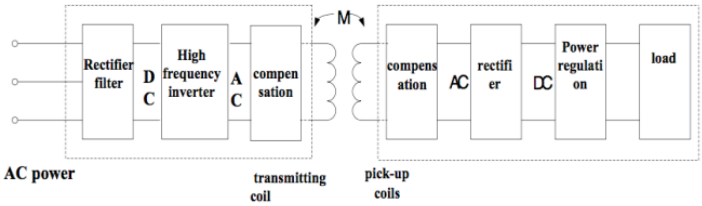

Figure 2: Power transmission system main circuit structure diagram

Because the original side compensation capacitor is neither affected by the coils coupling coefficient, nor by vice edge quality factor Q, and reflection impedance of vice side of series compensation topology structure on the former side appears pure resistance, and the influence of the load variation on the former is relatively small and make it work in resonant state, finally this improve power transmission capacity of the system, reduce the input volt-ampere rating. Therefore, the original edge series compensation topology structure as shown in figure 3 is employed to realize the high-power electric power transmission.

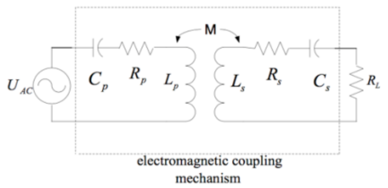

Figure 3: SS topology structure diagram

3. The relation between mutual inductance coefficient and the relative position of the original coil and vice coil

Design experiment circuit as shown in figure 4 to simulate magnetic coupling mechanism of ICPT system, the system working frequency and the input voltage is set to a fixed value, actually they can be controlled by feedback. The formula estimating Exciting current is $V_{ac} \cdot I_p \approx \sqrt{(P_L^2 + (QP_L)^2)}$, value of Q is 3 to 6 (He, 2007). By Open circuit voltage method (Liu et al., 2012) mutual inductance is measured, $M = \frac{U_o}{\omega I_1}$, ($U_o$- open circuit voltage and I_1-no-load current) two coil parameters are shown in table 1.The loose coupling transformer employs EI-type, the vertical motion of E type iron core coil imitates drop of stents, level motion simulates mobile location. By ANSYS the inductance value is calculated of the former and vice

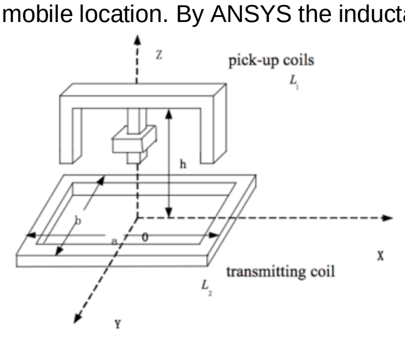

Figure 4: Schematic diagram of pickup coil and transmitter

Assume that loop L1 and loop L2 carry steady current I1 and I2 respectively, model of different thickness of air gap of loosely coupled transformer are set up. Calculate mutual inductance values of 4 set of magnetic coupling mechanism, the longitudinal distances of which are 4 cm, 9 cm, 12 cm, 15 cm, 18 cm respectively, and then horizontally move 2 cm, 6 cm, 8 cm, 10 cm with longitudinal distances fixed.

Table 1: Parameters of transmitter coil and pickup coil for experiment

Coil	Size (cm)	Iron core	Number of turns	Self- Inductance (μH)	Nominal voltage
Transmitting coil	100×200	be	5	80	220V
pick-up coils	120×90×20	be	10	65	220V

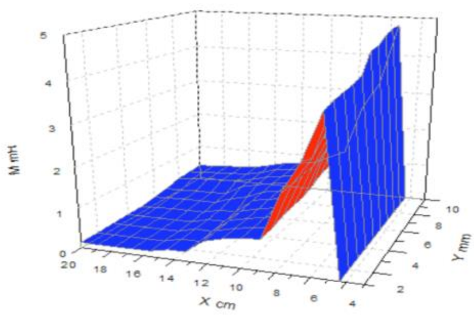

Figure 5: Variation curves of mutual inductance M changing along with primary and secondary side distance X and lateral motion Y

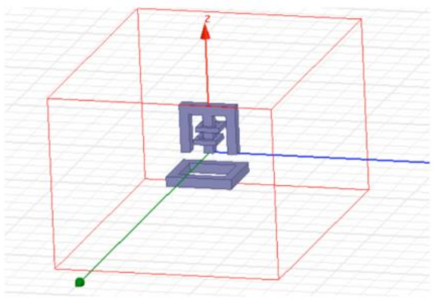

Figure 6: Maxwell magnetic coupling simulation

The figure 5 shows that with the increase of air gap distance X the mutual inductance parameter and coupling degree decay quickly, significantly reduce, so the inductance parameters are greatly influenced by gap thickness.
The mutual inductance between two adjacent circuit is determined by the circuit size, shape and relative position (Liu et al., 2012) in magnetic simulation environment of Maxwell's 3D (Hoang et al., 2012) mutual inductance simulation of contactless power transmission system, magnetic energy conversion mechanism, is done as shown in figure 6, model sizes are shown in table 2.

Table 2: Parameters of transmitting coil and receiving coil for simulation

Coil size	Coil material self-inductance Exciting current height
Transmitting coil	copper40mH 100A 80mm
Receiving coil	copper 20mH 20A 10mm

The loose-coupled transformer model a transmitting coil and pick-up coil is set up as follows:
Figure 8 shows that when the air gap is not very big, with the increase of air gap, the coupling coefficient reduced greatly; when the air gap increases to a certain degree, the extent of coupling coefficient decreases slowly; when the I type iron leave away coupling coefficient decreased to minimum value 0.55. The results of simulation and experimental results are consistent.

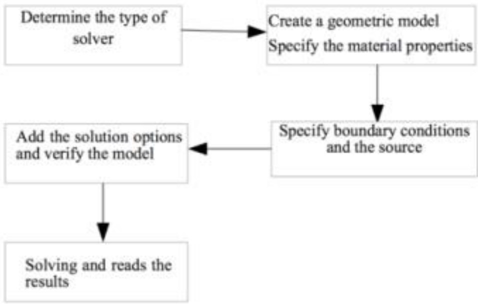

Figure 7: Steps and process to build a simulation model

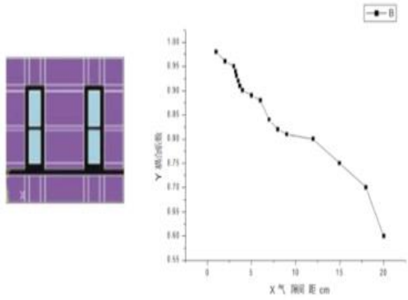

Figure 8: Simulation results

4. The relation between inductance parameters and the transmission efficiency of the system

Non-contact transformer coupling tightness can be described by the mutual inductance value and the coupling coefficient, the model is shown in figure 3, R_p and R_s stand for behalf transmitting coil and receiving coil resistance, M is the mutual inductance between the two coils, U_{AC} is the equivalent ac power on the transmitting coil, and R_L is the equivalent load impedance.

$$\dot{U}_{AC}=\dot{I}_p R_p+\dot{I}_p j(\omega L_p-\frac{1}{\omega C_p})-\dot{I}_s j\omega M \tag{1}$$

$\dot{I}_P j\omega M=\dot{I}_S R_S+\dot{I}_S j\left(\omega L_S-\frac{1}{\omega C_S}\right)+\dot{I}_S R_L$ Transformer is in a resonant state, the resonant frequency is:

$$\omega=\omega_0=\frac{1}{\sqrt{L_p C_p}}=\frac{1}{\sqrt{L_s C_s}}$$

$$\dot{I}_P=\frac{(R_s+R_L)\dot{U}_{AC}}{(R_s+R_L)R_P+\omega^2 M^2} \quad \dot{I}_s=\frac{j\omega M\dot{U}_{AC}}{(R_s+R_L)R_P+\omega^2 M^2} \tag{2}$$

The resonant reflecting impedance and the transmission efficiency of the system are:

$$R_r=\frac{(\omega_0 M)^2}{R_s+R_L} \quad \eta=\frac{P_2}{P_1}=\frac{\omega_0{}^2 M^2 R_L}{R_p(R_L+R_s)^2+\omega_0{}^2 M^2(R_L+R_S)} \tag{3}$$

System of transmission efficiency η and system parameters ω_0, R_L, R_P, R_S and the mutual inductance M, M is proportional to the working frequency and the load resistance and inversely proportional to the transmitting coil resistance and receiving coil resistance.
Entering the following parameters: the working frequency $f_0=40kHz$, load resistance $R_L=3\Omega$, the original side coil resistance $R_P=0.25\Omega$, vice side of coil resistance $R_S=1\Omega$, mutual inductance $\mathrm{M}=20\mu\mathrm{H}$ into formula (3), the results are shown in figure 7.

5. The relationship between inductance parameters and apparent power

Because of existence of air gap in ICPT system, larger primary power capacity is needed for power transmission, primary apparent power become important parameters.
Without considering winding resistance and core loss, and load power output is constant, $I_S=\sqrt{\frac{P_L}{R_L}}$ according to the formula (1), the original voltage and current are:

$$U_{AC}=\sqrt{\frac{P_L}{R_L}}\sqrt{(\frac{L_P R_L}{M})^2+\omega(\frac{L_P L_S}{M}-M)^2} \quad I_P=\sqrt{\frac{P_L}{R_L}}\cdot\frac{\sqrt{R_L^2+\omega^2 L_S^2}}{\omega M} \tag{4}$$

Get the original winding apparent power:

$$\begin{aligned} S_P &= U_{AC} I_P \\ &= \frac{P_L}{M^2 R_L}\sqrt{\frac{L_P^2 R_L^4}{\omega^2}+\omega^2 L_S^2(L_P L_S-M^2)^2+(L_P L_S-M^2)^2 R_L^2+L_P^2 L_S^2 R_L^2} \end{aligned} \tag{5}$$

In the case of resonance frequency operation, system input power is minimum:

$$S_{P\min} = \frac{P_L(2L_P L_s - M^2)}{M^2} = \frac{P_L(2-k^2)}{k^2} = P_L(\frac{2}{k^2}-1) \quad (6)$$

The apparent power of original coil is only related to coupling coefficient k and the output power P_L. If the coupling coefficient and the output power are constant, the minimum input apparent input power is determined. When the coupling coefficient increases, the system input apparent power decreases (Kacprzak et al., 2005; Mecke and Rathge, 2004).

Apparent power increasing rate Δ is deduced by formula (5):

$$\Delta = \frac{S_P - S_{P\min}}{S_{P\min}} = \frac{\sqrt{(1-k)^2 R_L^2/(\omega L_S\sqrt{1-k^2})^2 + (1-k^2) + 1 + (1-k^2)(\omega L_S\sqrt{1-k^2})^2/R_L^2}}{2-k^2} - 1$$

Table 3: The influence of coupling coefficient on apparent power

Apparent power increasing rate Δ	1	2	2.5	3	3.5
coupling coefficient	0.25	0.5	0.6	0.7	0.8

Table 3 indicates that under the condition of the same voltage input, with the increase of the coupling coefficient apparent power decreases.

6. The relationship between inductance parameters and transmission power

Position change of original and vice coils leads to change of mutual inductance, according to the formula (4), the change of mutual inductance causes reflecting impedance changes vice side, and influences ICPT system resonant frequency and the excitation current, and affects the transmission power of the system (Chen, 2014). As shown in figure 3, vice side current is as shown in formula (8):

$$\dot{I}_S = \frac{j\omega M U_{OC}}{[j\omega L_S + 1/j\omega C_S + R_S + R_L][j\omega L_P + 1/j\omega C_P + R_P + \omega^2 M^2/(R_S + R_L)]} \quad (7)$$

When the ICPT system works in the natural frequency of resonance system, vice side are in resonant state completely, the vice current amplitude is simplified, transmission power is equal to:

$$P_O = \frac{R_L \omega_0^2 M^2 U_{OC}^2}{[(R_S + R_L)R_P + \omega_0^2 M^2]^2} \quad I_S = \frac{\omega_0 M U_{OC}}{(R_S + R_L)R_P + \omega_0^2 M^2}$$

Let $f_0 = 40kHz$, load resistance $R_L = 3\Omega$ the original side coil resistance $R_P = 0.25\Omega$, vice side of coil resistance $R_S = 1\Omega$, mutual inductance M=5,10,15,20,25,30,35,40,45 μH, contactless power transmission system is shown in the curve of the relationship between transmission power η% and the mutual inductance.

7. Conclusion

1) In SS topology, the presence of air gap of primary coil and secondary coil leads to small mutual inductance coefficient, through the design of the movable scaffold, the electromagnetic coupling mechanism to a certain extent solves the problem about the worse performance of small mutual inductance.

When the car passes through the transmission rail coil, pick-up coil downs to below 9 cm off the ground, the purpose is to achieve of reducing coupling mechanism air gap and optimizing coupling performance and increase mutual inductance, system apparent power will be reduced so as to improve the system transmission power and the transmission efficiency and the stability of the output power.

2) Through analysis of the simulation results compared with the actual values, it is known that by the key parameters simulation results of ANSYS software to non-contact electromagnetic coupling transformer conform better with the actually measured values. By ANSYS software it is easy to realize the change of the transformer model geometry size and parameters, and find out the effect of key parameters of the non-contact electromagnetic coupling transformer on its transmission efficiency: Air gap applies the greatest influence on the transmission efficiency, which is also the most comprehensive (affecting the transformer magnetic flux leakage and coupling coefficient). For ICPT system of wireless-charging electric vehicles, the high frequency

resonance and other measures can increase the output power and transmission efficiency of system, and can also the use of landing-type scaffold to adjust the distance between the original and deputy coil enhance practicability and economy of contactless power transmission system.

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