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# Experimental analysis and simulation calculation of the inductances of loosely coupled transformer

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**Abstract:** The experimental design of iron-core wireless power transmission system is designed, and an experimental model of loosely coupled transformer is built. Measuring the air gap on both sides of the transformer 15mm inductor under the parameters. The feasibility and feasibility of using the finite element method to calculate the coil inductance parameters of the loosely coupled transformer are analyzed. The system was modeled by ANSYS, and the magnetic field was calculated by finite element method, and the inductance parameters were calculated. The finite element method is used to calculate the inductive parameters of the loosely coupled transformer, and the basis for the accurate compensation of the capacitance of the wireless power transmission system is established.

## 1. Introduction

With the electric power industry fast going, Traditional Finite power transmission system industry cannot satisfy people's needs. Therefore Wireless Power Transmission (WPT) and charging technology is born at the right time. In recent years, with the further research of Wireless Power Transmission, we found that there are many achievements already have positive influence on our life, for example, music player、mobile phone、 compute、electro bile etc.[1-3] WPT are praised as the top 10 research direction by Technology Review American.

Loosely coupled transformer, as the core of the core type radio, can transmit system device, its structure is between traditional tight coupling between the transformer and signal transmitting, receiving device. Using the electromagnetic coupling relationship, while working under power frequency or high frequency power transmission through a medium distance. Studies have shown that the loosely coupled transformer coupling coefficient is low, the energy transfer efficiency is not high [3], this has to do with high transmission efficiency of traditional transformer gap is bigger, therefore, improve the energy efficiency of WPT system is the key to the research question [4]. To this end, on the one hand, the domestic containing core type can radio frequency to high frequency transmission system of research, this inevitably in the system of rectifier and inverter for additional investment, with the radiation will be to produce a great impact on the environment and human health; Capacitance compensation, on the other hand, can effectively improve the efficiency of radio transmission system, this method has the advantage of small investment, easy to use, but the key is that can accurately determine the inductance parameters of the system.

In this essay, based on the radio energy transmission system theory, analysing the core type radio energy transmission system. Using finite element method to calculate loosely coupled transformer magnetic field to get the inductance parameters of the loosely coupled transformer. At the same time, design the experiment to measure the inductance parameters of the loosely coupled transformer. Based on the experimental data, the accuracy of the inductance calculation of the finite element method is analysed, which lays the foundation for further study of the capacitive compensation.

## 2. Principle

Loose-coupling transformer is the core part of iron core wireless power transmission system. Familiar to the traditional tightly coupled transformer, the working principle is Faraday's law of electromagnetic induction. The alternating magnetic field generated by the excitation side coil is coupled with the load coil through the core and air gap to realize the transmission of energy on the excitation side and the load side of the transformer.

Set the internal resistance of the voltage source r, line side resistance of the excitation side Rl1, load side line resistance of R12, loosely coupled transformer coil resistance on both sides were RT1, RT2, load ZL. L1, L2 are loosely coupled transformer equivalent inductance on both sides of the coil, M is equivalent mutual inductance. The excitation side resistance and the load side resistance are equivalent to a resistance, namely: R1=r+RT1+Rl1, R2=RT2+Rl2.

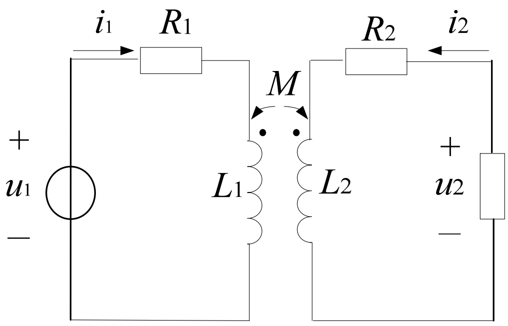



**Figure.1** Schematic diagram of wireless power transmission system

As is shown in figure 1, according to the Kirchhoff voltage law, available wireless power transmission system basic equation:

$$\begin{cases} \dot{U}_1 = (R_1 + j\omega L_1)\dot{I}_1 - j\omega M_{12}\dot{I}_2 \\ 0 = (R_2 + Z_L + j\omega L_2)\dot{I}_2 - j\omega M_{12}\dot{I}_1 \end{cases} \tag{1}$$

In the formula, the output voltage of the AC voltage source is U1, and the current on both sides of the loosely coupled transformer is I1 and I2 respectively.

Because of the loosely coupled transformer and the traditional transformer are significant differences between the excitation side and the load side, there is a large air gap, large reluctance, coupling coefficient is small, low transmission efficiency, improve the energy transfer efficiency of the feasible method is compensated by the capacitor [5], and the crux of the problem is how to determine the transformer inductance parameters, that is, to determine the L1,L2, M12.

## 3. Inductance Parameters Determination

As shown in Fig. 2, the "E-E" type loosely coupled transformer transmission system is adopted in the experiment. Both sides of the windings are made of enameled coil of the same parameters. Both sides of the coil are fixed in the coaxial position. Excitation side of the magnetic field can be transmitted to the maximum load side of the coil, and coupling rate is the highest.

**Figure.2** Loosely coupled transformer

The voltage U1, current I1, resistance R1, no-load side voltage U2 and resistance R2 are determined by measuring the loosely coupled transformer. The excitation side self-inductance is:

$$L_1 = \frac{X_1}{2\pi \mathrm{f}} = \frac{\sqrt{\left(\frac{U_1}{I_1}\right)^2 - R_1^2}}{2\pi \mathrm{f}} \tag{2}$$

As the no-load side voltage U2=ωM12I1, available on both sides of the mutual inductance:

$$M_{12} = \frac{U_2}{\omega I_1} = \frac{U_2}{2\pi f I_1} \tag{3}$$

Non-contact power transmission system experiment by the adjustable voltage source, the loose coupling transformer, load and measuring instruments and other components. Loosely coupling transformer parameters are shown in Table 1.

**Table.1** Loose coupling transformer parameters

| Transformer parameters | Rating | Measurements |
|---|---|---|
| Frequency / Hz | 50 | – |
| Rated Capacity / VA | 500 | – |
| Rated voltage / V | 220/ 220 | – |
| Core size / mm | – | 118×114×22 |
| Number of primary/secondary turns | 910/910 | – |
| Primary winding DC resistance /Ω | – | 14.4 |
| Secondary winding DC resistance /Ω | – | 14.3 |

## 4. Inductance calculation principle of finite element method

### *4.1 Magnetic field calculation*

Edge finite element method using vector magnetic potential A, according to Maxwell available nonlinear magnetic field equation:

$$\nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{A} = \boldsymbol{J} \tag{4}$$

Where μ is the magnetic permeability of the permeable material; J is the current density, which needs to be obtained by actual measurement and calculation.
The edge interpolation function is:

$$\boldsymbol{A} = \sum_{n=1}^{n_n} \boldsymbol{M}_n (x, y, z) A_n \tag{5}$$

Where {Mn, n=1, 2, …, nn} is the general term number of the basis function sequence, nn is the total number of items (the total number of edges ).
Applying Green's theorem, we obtain the Galerkin weighted residual equation:

$$\iiint_V \frac{1}{\mu} (\nabla \times \boldsymbol{M}_m) \cdot (\nabla \times \boldsymbol{M}_n) A_n \, \mathrm{d}V = \iiint_V \boldsymbol{M}_m \cdot \boldsymbol{J} \mathrm{d}V \tag{6}$$

Where Mm is the basis function sequence and the weight function is the same as the basis function. If the current I is known, the weighting function is substituted into the above equation. For all weight functions, the weighted residual equation is discretized to form an algebraic equation, and A is calculated for all nodes or edges. B,H and so on.

### *4.2 Inductance calculation principle*

According to the idea of energy perturbation, when the coil current increase ΔIp, (0 ≤Δ≤1, 1≤p ≤2), resulting in flux Ψ, by Faraday's law of electromagnetic induction, port voltage required to impose increments ΔU = d (Δψ) / Dt, to counteract the induced electromotive force in the coil. The energy increment provided by the external power source is dW=ΔUΔIdt=ΔId(Δψ). If the coil current increment is ΔI, the magnetic field energy increment is associated with the dynamic inductance and the excitation current,

$$\Delta w = \frac{1}{2} L_{\mathrm{D}pq} \Delta I_p \Delta I_q, (p, q = 1, 2) \tag{7}$$

On the other hand, at each moment of time domain calculation, the nonlinear magnetic field is solved according to the steady-state field. At this time, the local energy is calculated by local linearization method, as shown in Fig.2.

The amount of field change caused by the current increment ΔI is ΔH, ΔB, and the calculated energy increment is:

$$\Delta W = \frac{1}{2} \int_{\Omega} \Delta \boldsymbol{B} \cdot \Delta \boldsymbol{H} \mathrm{d}\Omega \tag{8}$$

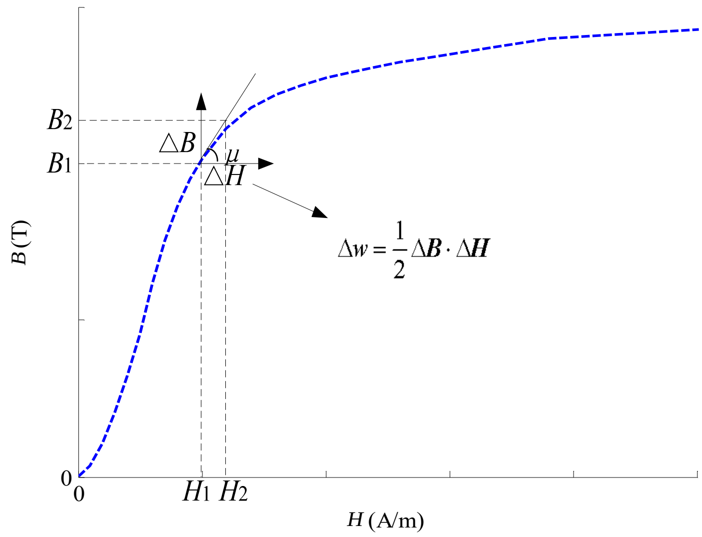



**Figure 3** Inductance calculation principle

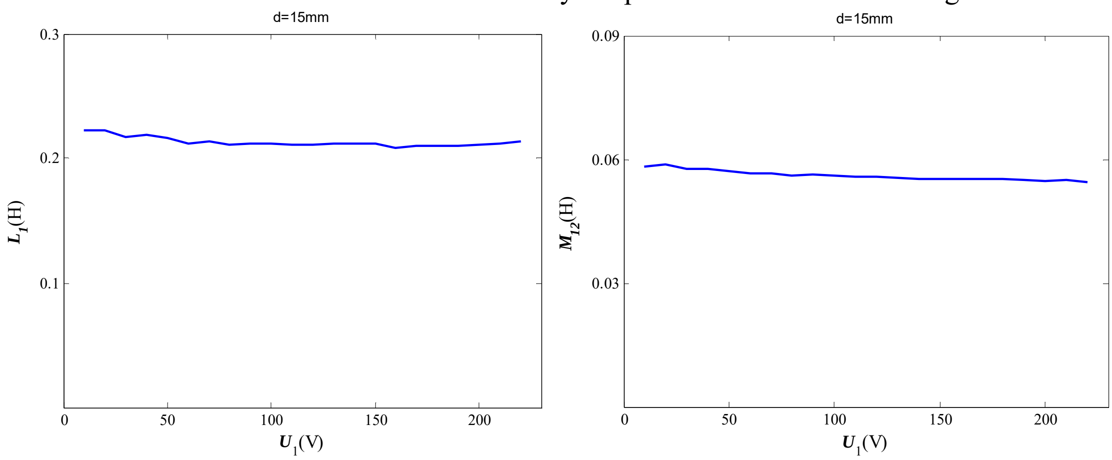
(7) and (8) are equal to calculate the dynamic inductance parameters, that is, from the ΔI1, ΔI2 calculated self-inductance parameters L1, L2, and then solve for M12.

In the traditional experiment, the measured inductance is static inductance, while ANSYS calculates the dynamic inductance based on the magnetic field finite element calculation, and the dynamic inductance is approximately equal to the static inductance in linear or approximate linear condition. In linear conditions, ANSYS can accurately calculate the static coil inductance parameters.

## 5. Calculation and analysis

### *5.1 Analysis of experimental results*

Take the gap width of 15mm as an example, through the experimental method to measure the excitation voltage from 0V to 220V inductor parameter values. Figure 4 (a), (b) shows the self-inductance and mutual inductance of the loosely coupled transformer with voltage.




(a) Self-inductance L1 (b) Mutual inductance $M_{12}$

**Figure.4** The experimental value of inductance parameter when air gap is 15mm

There is a large gap thickness of the loosely coupled transformer, the larger the magnetic reluctance. Compared with traditional close-coupled transformers, the magnetic properties of ferromagnetic materials significantly reduce the overall excitation of the transformer, the overall excitation characteristics tend to linear. Self-inductance and mutual inductance with the voltage increase remained unchanged, with an average of 0.213H, 0.0561H.

*5.2 Finite element method*

The experimental model was modeled by ANSYS software, and the magnetic field was calculated for the loosely coupled transformer with an air gap of 15mm. Figure 5 for the magnetic field obtained after the magnetic induction B diagram.

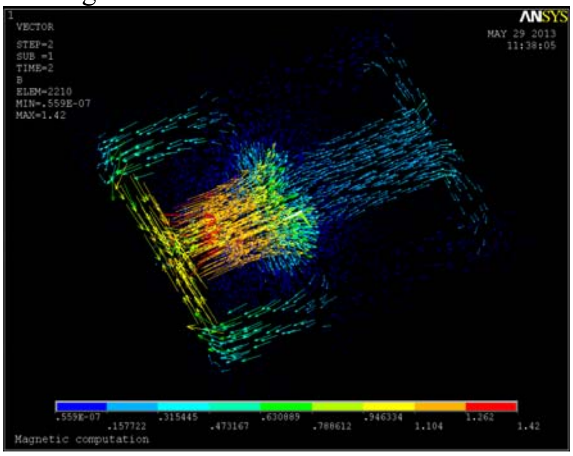
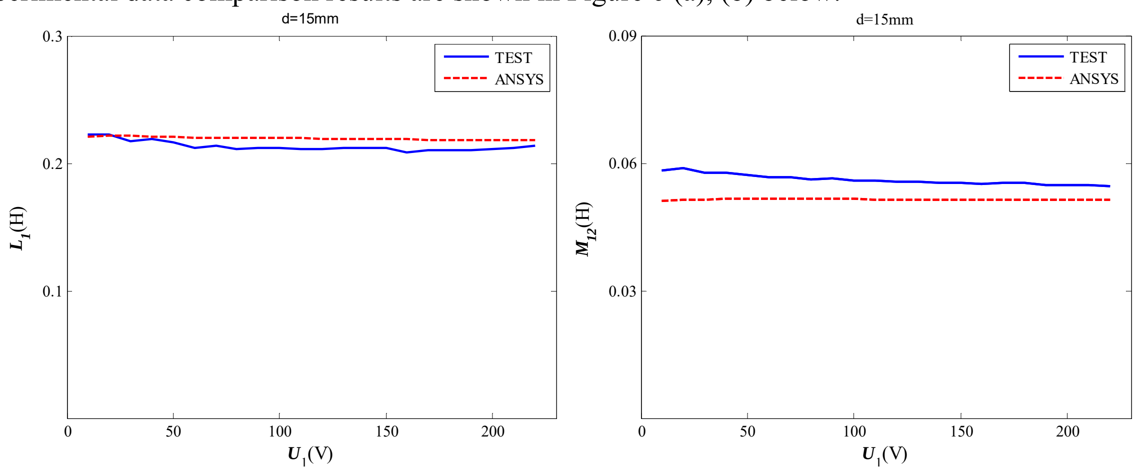



**Figure.5** Vector illustration *B*

Using the macro command lmatrix can be calculated coil inductance L, mutual inductance M12 value, the use of different voltage nodes of the current value, can be calculated from 0V to 220V voltage self-inductance, mutual inductance at each point value. ANSYS simulation results and experimental data comparison results are shown in Figure 6 (a), (b) below.




(a) Self-inductance L1 (b) Mutual inductance $M_{12}$

**Figure.6** Simulation of Inductance Parameters and Experimental Comparison for Air Gap

It can be seen from Figure 6, ANSYS simulation results and experimental data are basically the same. M12 relative to the experimental data is slightly smaller, which is due to the existence of large air gap energy loss caused by the reason.

**Table 2.** The gap is 15mm when the self-inductance *L* and mutual inductance $M_{12}$ of the mean and error

| Inductor value | Experimental results | ANSYS calculations | ANSYS Calculation error ε1 |
|---|---|---|---|
| L(H) | 0.213 | 0.22 | 3.04% |
| M (H) | 0.0561 | 0.0515 | 8.18% |

Self-inductance L and mutual inductance M12 results of mean and average error shown in Table 2, ANSYS calculated inductance parameters consistent with the experimental data, the error is small, proved by finite element method to calculate the magnetic field inductance parameters of the feasibility and correctness of the method.

## 6. Conclusions

In this paper, the inductance parameters of the loosely coupled transformer in the wireless power system are analyzed and simulated, the conclusions are as follows:

1）The magnetic field is solved by ANSYS, that is, the magnetic field of the loosely coupled transformer is simulated by finite element method, and the inductance parameters are obtained. In view of the existence of large air-gap looseness transformer, the air magnetic-resistance is big, the non-linear effect of the ferromagnetic material is small, the nonlinear effect is small in the transformer excitation characteristic, the transformer can be considered to work in the linear area and the inductance parameter of the loosely coupled transformer remains constant. Theoretically, the ANSYS finite element method can be used to calculate the inductance of the loosely coupled transformer.

2）Based on the experimental data, the results of the finite element method are compared and analyzed. The results show that the inductance of the transformer is constant with the voltage increasing, and the mean error of ANSYS is less than 10%. The feasibility of using ANSYS to calculate the inductance parameters of the loosely coupled transformer in the wireless power transmission system is verified by experiments.

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