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Design and Implementation of Inductive Coupling Power Transfer Device Based on Structural Parameters Analysis

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Abstract

With the rapid development of power electronics technology, the applications of inductively coupled power transfer make the wireless power transmission reality. In order to explore the practical application in the field of ICPT, we analysis the core component of a loosely coupled transformer of ICPT and design it. We make a model and simulate the core magnetic field distribution of the loosely coupled transformer with ANSYS and we select the appropriate core structure. We produce loosely coupled transformer through the analysis of loosely coupled transformer performance parameters affecting factors. Research on the basis of loosely coupled transformer, we build ICPT experimental device and we also analysis the transmission efficiency by the gap of the system with actual measurement.

Keywords: *ICPT, ANSYS, loosely coupled transformer*

1. Introduction

ICPT technology is a new kind of power transmission technology which based on Faraday electromagnetic induction principle, and it can solve the problem of mobile devices wireless and flexible power supply. This technology is safer, more reliable and flexible than traditional technology. And broader application prospects than traditional power transmission technology. The system of new kind of non-contact power supply make comprehensive using of some new technologies, such as electromagnetic induction coupling technology, high frequency transformation technology and power electronic technology. The electricity transmit from power supply side to one or more loads through air gap with loosely coupled transformer that primary and secondary side can be separated, thus making non-contact transmission of electrical energy become securely, efficiently, reliably and flexibly, overcoming unsafe factors existing in the traditional power transmission, such as exposed conductors, contact fire, electric shock and short circuit.

In the 1990s, professor John T. Boys as a leader in a team at the Auckland University in New Zealand took the lead in putting forward. Professor Sun Yue, in Institute of Automation, Chongqing University, guided inductively coupled power transfer technology research team to track and research "Inductively coupled power access technology" related basic theory and practical technology at home and abroad closely in 2001, completed the first set of power level which achieve 1kW in 2006, the first set of power level which reach 10kW and efficiency is about 75% of inductively coupled power transfer system in August in 2010. In addition, other universities at home and abroad also carried on the research which related to ICPT.

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Based on background of the above research, this design take advantage of ICPT technology principle and it combine with finite element analysis to discuss how to design and develop loosely coupled transformer in ICPT. By calculating the core parameters about loosely coupled transformer and manufacturing an ICPT experiment device which has reasonable structure through the analysis of the loosely coupled transformer model. To analyze this kind of structure, and actual measure to ensure the influence between primary and secondary side air gap and transmission efficiency.

2. Structure of the Induction Coupling Power Transmission Device

Inductively cpoupled power transfer technology is a new kind of technology that give energy to load in electromagnetic coupling non-contact way, and transmit electrical energy by non-contact way through "electric - magnetic - electric" method of transformation. After high frequency inverter link, the input direct current switch to high frequency alternating current, and achieve goals that transmit energy to the secondary side via loosely coupled transformer induction coupling. Putting compensation circuit in the primary and secondary edge of loosely coupled transformer, due to the magnetic circuit structure of the loosely coupled transformer have larger gap, two coils coupling have low coefficient and large leakage inductance. The transmission capacity of ICPT system is limited. In order to improve it, compensation should be carried out on the coils. Compensation capacitor is increased in the circuit to improve the power factor, so as to enhance transmission capability. High frequency inverter circuit mainly provides high frequency adjustable power supply to loosely coupled transformer primary side. The frequency is higher, and the induced voltage of loosely coupled transformer secondary edge increase accordingly. In this way, it can improve the transmission efficiency. Treating 24V direct current as input and adopting IPPF260N type of MOSFET as switching element transform direct current to high frequency alternating current. To use full bridge topological structure transfer power supply in order to enhance transmission ability. Overall system block diagram of ICPT is shown in Figure 1.

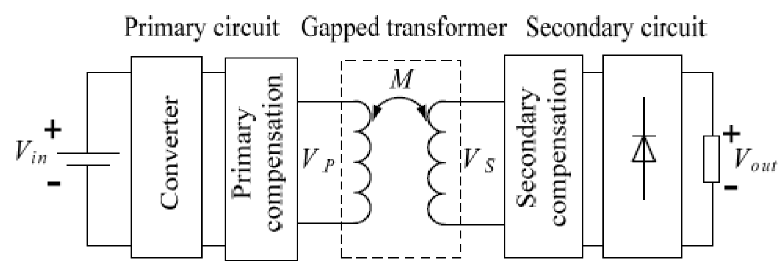


Figure 1. Database Contexts

3. Loosely Coupled Transformer Model Analysis

Loosely coupled transformer model of the system is the major factor to determine the transmission capacity ICPT. The core coil structure and materials, the gap of loosely coupled transformer have impact on the parameters. Therefore, the analysis of the characteristics of loosely coupled transformer has two-pronged approach, magnetic and circuit model to explore core coil structure of the system's transmission performance.

3.1. Reluctance Model

Using the loosely coupled transformer inductance parameters to analysis reluctance modeling is an effective method to analysis the electromagnetic properties. Through the analysis of the loosely coupled the transformer structure in the magnetic flux distribution, establish a equivalent magnetic circuit include reluctance. Re-establish its transformation through the equivalent circuit model to analyze the inductance parameter.

Fpield is produced by the current in the two coils co-excitations. Or it can be said that it's the magnetic field superimposed result of the primary current and the secondary current excitation. According to the principle of electromagnetic induction, the magnetic field of secondary excitation has hindered effect to the primary coil magnetic field changes of incentives. Therefore, when the primary i_s and secondary current i_p flow through each coil, they produce the corresponding magnetomotive force in the electromagnetic coupling magnetic circuit. And there is a certain balance between magnetomotive force of excitation current.

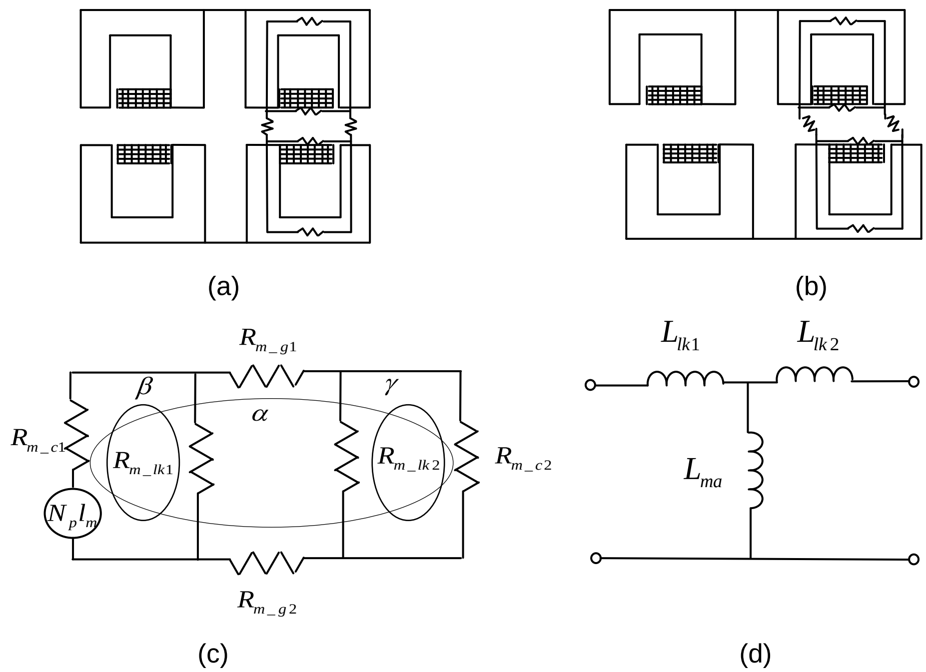


Figure 2. Reluctance Model of Loosely Coupled Transformer

Seen in the primary coil excitation current decision coupler in the total magnetic MMFs. Figure 2(c) is under the action of the excitation force of the equivalent magnetic circuit coupling. According to the structure of the core and the structure of the gap, the size difference, reluctance can be divided into the following categories:

$R_{m\text{-}c1}$ is primary side core reluctance, $R_{m\text{-}c2}$ is secondary side core reluctance; $R_{m\text{-}g1}$ is gap reluctance within the core; $R_{m\text{-}g2}$ is core outer gap reluctance; $R_{m\text{-}lk1}$ is primary leakage magnetic resistance; $R_{m\text{-}lk2}$ is secondary leakage magnetic resistance;

Figure 2(a) a reasonable simplified tank type magnetic core magnetic circuit. It reflects the electromagnetic coupling between the two coils magnetic coupling relationship and the relationship between magnetic flux leakage and magnetic circuit.

Under the action of the exciting momentum Figure 2(c) is under the action of the exciting momentum coupler equivalent magnetic circuit.

Figure 2(c) shows the magnetic coupling that can be divided into three sub-circuits, namely, α, β, and γ. Combining (a) shows the structure of the coupler, α of the magnetic flux through the circuit closed after two cores, the total excitation magnetic circuit reluctance that is:

$$R_{m\_a} = R_{m\_c1} + R_{m\_c2} + R_{m\_g1} + R_{m\_g2} \tag{1}$$

According to the electromagnetic field of related knowledge derived excitation inductance:

$$L_m = N_P \frac{\phi_m}{i_m} = \frac{{N_P}^2}{R_{m\_a}} = {N_P}^2 \mu_0 A_\varepsilon \frac{1/2}{l_c/\mu_{rc} + l_g} \tag{2}$$

$\mu_0=4\pi\times10^{-7}$H/m is the vacuum magnetic permeability, A_e and l_c is the average magnetic path length of the core, l_g is gap length of the coupler cores, μ_{rc} is the relative magnetic permeability core material. Magnetizing inductance length L_m determines the magnetizing inductance. As Figure 2(d) shows, excitation circuit model derived from the reluctance model. It reveals the essential characteristics of the electromagnetic coupling On CLPT system characteristics analysis, research mutual inductance between the primary and secondary coupling and to explore mutual inductance coupling, inductance, coupling coefficient and other parameters on the impact of power transmission. Therefore, be in the excitation circuit model is established based on mutual inductance circuit model.

3.2. Mutual Model

Loosely coupled transformer mutual inductance circuit model is shown in Figure 3, in which L_P、L_S is the self-inductance of primary coil and the secondary coil, M is the mutual inductance between two coils, R_L is the load resistance. It's different with excitation circuit models, mutual model does not distinguish between magnetizing inductance and leakage inductance .And induced voltage is represented by the mutual inductance M. The coupling between the two coils with the coupling use the coefficient k to express. There's only the primary current i_P and the secondary current i_S in the current model. It's closer to the physical structure of the coupler. So, the mutual inductance has more advantage than excitation model for the electrical characteristics of the system.

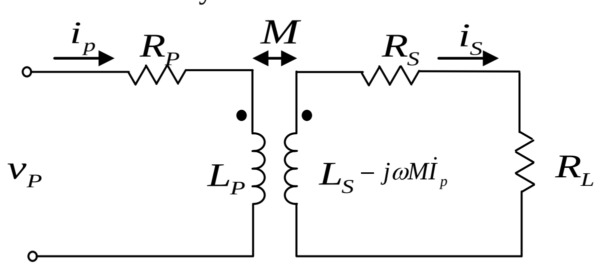


Figure 3. Mutual Inductance Model Diagram

When the input angular frequency ω of electromagnetic coupling's primary coil with sinusoidal AC voltage, the coil inductance and resistance will impedance to the input voltage generator. And mutual inductance M will induced electromotive force on the primary side and the secondary side at the same time, which is $-j\omega M\dot{I}_S$ and $-j\omega M\dot{I}_p$.And I_P and I_S are the current I_P, I_S expression vector of primary coil and the secondary coil.

Therefore, the relationship between voltage and current as a vector in the mutual inductance circuit model as Figure 3

$$\dot{V}_p = j\omega L_p \dot{I}_p + R_p \dot{I}_p - j\omega M \dot{I}_s \tag{3}$$

$$j\omega M \dot{I}_p = j\omega L_S \dot{I}_S + R_S \dot{I}_S + R_L \dot{I}_S \tag{4}$$

Equation (3) and equation (4) are electromagnetic coupling sides of the voltage balance equations.

4. Loosely Coupled Transformer Design

4.1. The Selection of the Loosely Coupled Transformer Core and Material

It has a variety of choices to choose the core of loosely coupled transformer. We take the EE-type and EC-type for example to describe the selection criteria of the loosely coupled transformer core. We take the loosely coupled transformer with EE42 and EC42 core model and PC40 ferrite materials for study. The dimensions of EE42 are l=2.1cm, e=1.45cm, h=4.2cm, a=0.6cm, d=0.91cm, p=1.18cm, c=1.55cm, b=0.55cm. The model of EC42 is similar to the EE42, but the middle is cylindrical. And the diameter is 1.45cm, the other size is same to EE42. Figure 4 is the diagram of the two cores' three-dimensional model.

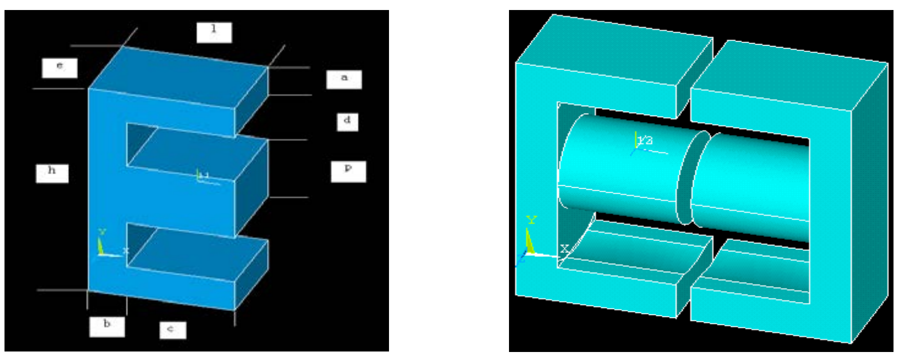
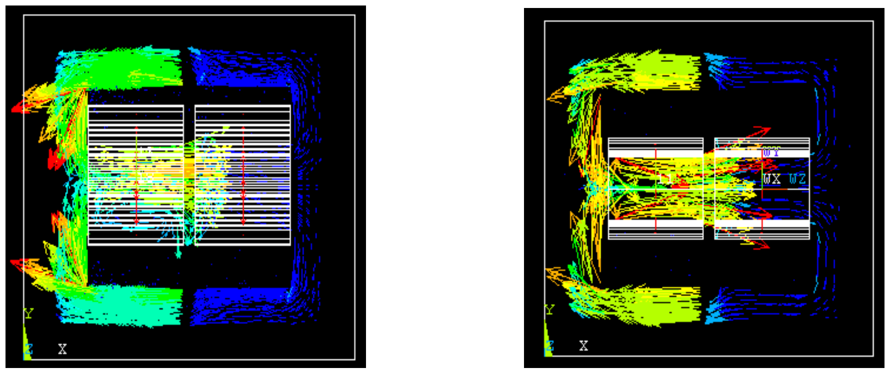


Figure 4. EC42 Core and EE42 Core Three-dimensional Model Diagram Mutual Inductance Model Diagram

We get the magnetic flux density vector with ANSYS modeling and simulation as Figure 5. As can be seen from the Figure, the magnetic flux density vector lines of EC42 are significantly more concentrate than EE42. The comparison results of numerical shows that the flux density of EC42 has the higher transmission efficiency than EE42.

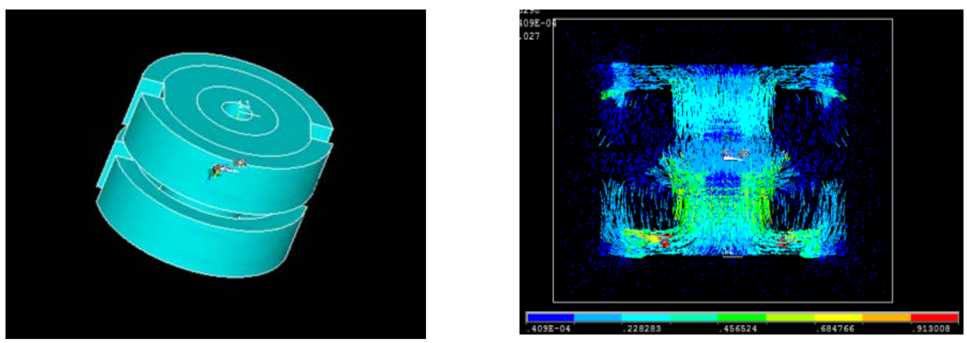
We choose the tank-shaped core in the design, Figure 6(a) is the dimensional model diagram with ANSYS simulation. Figure 6(b) is magnetic lux density map with it. As can be seen as Figure, the cans core has less magnetic flux leakage compared with EE-type and EC-type. Because it has good electromagnetic shielding characteristics to reduce electromagnetic interference from outside. And two coils can be obtained a high coupling coefficient.

We analysis of various alloy what can be core material. And take the current conditions and economic into account, the paper chooses commonly used and affordable ferrite core. And it also select TDK PC40-P48/30 ferrite pot core.



(a). EE42 Core Front View (b). Ee42 Core Front View

Figure 5. The Diagram of EC42 Core and EE42 Core Flux Density



(a). Three-dimensional Model Diagram of Pot Core (b). Core Flux Density Diagram of Pot Core

Figure 6. Pot-Shaped Core ANSYS Simulation Diagram

4.2. Coil Parameter

4.2.1. Coil Distribution Effect on the Parameter: The distribution of the coil is mainly determined by the coil cross-sectional area and window area of the core. In the case of the coil can not completely fill the core window, it can have a different layout of the form as Figure 7. Each layout in the diagram uses the same number of turns, so the coil window represents the same proportion core window. In order to facilitate to comparison and reduce the workload experiments, we assume that each layout select the coil with 1mm diameter and turns ratio of 30:30. And the core gap is 4mm.

Table 1 list the inductance, mutual inductance, coupling coefficient and other parameters simulation results of loosely coupled transformer under the condition of three layout of the coil. Because the same two coil turns and fully symmetric in the structure, the inductance theoretical value of two coils are same. So the table lists only the primary winding's inductance value. In addition, this paper takes actual measurement of the parameters of three layout of the structure. We measure the actual coupler with the measurement method of multifunction inductance measuring instrument. The result is shown in Table 1. As can be seen from it, different coil layout will produce different effects for the electromagnetic coupling parameters. Therefore, more satisfactory efficiency can be achieved for the particular situation in the application. This article uses the layout of three structures with high coupling coefficient.

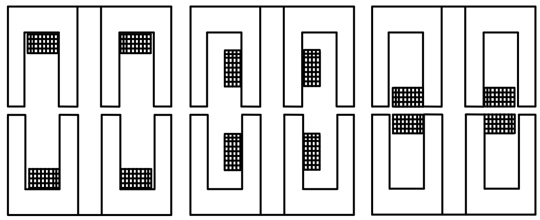


Figure 7. Different Layouts Loosely Coupled Transformer Coil Structure

Table 1. The Simulation Results of the Loosely Coupled Transformer

Parameter	First layout		Second layout		Third layout	
	simulation value	measured value	simulation value	measured value	simulation value	measured value
L_p/μH	233.6	229.7	204.1	202.8	176.0	173.4
M/μH	150.4	141.0	148.3	141.5	152.6	145.3
k	0.643	0.614	0.727	0.698	0.867	0.838

4.2.2. Clearance on Parameters of the Core

Loosely coupled transformer primary and secondary windings are connected to the power supply side and load side, Two cores are separated in the normal session. So Core gap is an inevitable part of a loosely coupled transformer, also affecting the performance of the coupler is one of the main factors. From the formula 2 and reluctance model of loosely coupled transformer, we can see that the permeability is much smaller than ferrite core at the gap. Even a small gap can cause a lot of reluctance, results in a serious decline in the magnetizing inductance. In the circuit, the leakage flux form leakage inductance of the coil and it becomes major obstacle of a power transmission process. With the gap increases, inductance and mutual inductance decline by a negative exponential. Figure 8(Horizontal axis represents the core gap, *mm*. Vertical axis represents inductance, *mH*) is electromagnetic coupler inductance, mutual inductance increases with the change of the magnetic core gap. With the increase of the gap, inductance and mutual inductance are decline of a negative exponential. This indicates that electromagnetic coupling inductance value is more sensitive to changes in the gap at the smaller gap of the core.
Coupling coefficient is:

$$k = \frac{\phi_m}{\phi_m + \phi_{1k}} = \frac{R_{m\_1k}}{R_{m\_1k} + R_{m\_g}} \tag{5}$$

The analysis of loosely coupled transformer model shows that drain reluctance R_{m_lk} is much more stable than the reluctance R_{m_g} in a certain gap. Therefore, the coupling coefficient k is determined by the gap reluctance R_{m_g} in the formula 5. The gap reluctance becomes smaller when the gap becomes smaller. And the magnetic flux through the leakage reluctance is small, the coupling of two coils is high and k is approaching 1. When the gap is large, the magnetic flux passing through the gap reluctance reduces. The degree coupling of two coils reduce and k also decreases.

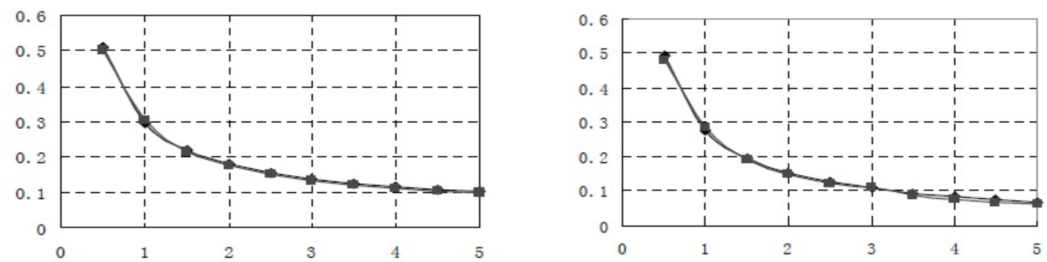


Figure 8. Parameters of Loosely Coupled Transformer Curve with Air Gap

4.2.3. The Calculation of Coil Parameter: Parameters of the electromagnetic coupler are determined primarily by the structure magnetoresistive. And the reluctance relate to the permeability of the magnetic circuit, the equivalent cross-sectional area and the equivalent length. From the above analysis, we know that when the core gap changes, magnetic circuit's reluctance changes accordingly. And coupling parameters are also changes. Therefore, the parameters of coupler's inductance and mutual can be calculated as follows.

$$
\begin{aligned}
L_p &= N_p^2 \frac{R_c + R_r}{(R_c + R_r)^2 - R_r^2 k_r^2} \approx N_p^2 \frac{1}{2R_c - (1-k_r^2)R_r} \\
M_{12} &= -N_p N_S \frac{k_r R_r}{(R_c + R_r)^2 - R_r^2 k_r^2} \approx -N_p N_S \frac{k_r}{2R_c + (1-k_r^2)R_r} \\
M_{21} &= -N_p N_S \frac{k_r R_r}{(R_c + R_r)^2 - R_r^2 k_r^2} \approx -N_p N_S \frac{k_r}{2R_c + (1-k_r^2)R_r} \\
L_S &= N_S^2 \frac{R_c + R_r}{(R_c + R_r)^2 - R_r^2 k_r^2} \approx N_S^2 \frac{1}{2R_c - (1-k_r^2)R_r}
\end{aligned} \tag{6}
$$

In equivalent magnetic circuit of the coupler, each of the magnetoresistance can be calculated:

$$
\begin{aligned}
R_c &= \frac{c}{2\mu_0 \mu_r} \\
R_g &= \frac{l_g}{A_e \mu_0} \\
R_{lk} &= \frac{a}{2\mu_0 \pi t} \ln\left(\frac{r_3}{r_2}\right)
\end{aligned} \tag{7}
$$

Among:

$$A_e = \pi \frac{(r_2^{\ 2} - r_1^{\ 2})(r_4^{\ 2} - r_3^{\ 2})}{(r_2^{\ 2} - r_1^{\ 2}) + (r_4^{\ 2} - r_3^{\ 2})} \tag{8}$$

A_e is equivalent cross-sectional area of the core and c is core constant (mm^{-1}). And a is correction factor of the core (dimensionless), t is the depth of the coil embedded in the core. r_1, r_2, r_3, r_4 are the radius of the cross section of the core as shown in Figure 9. r_1=2.91mm, r_2=9.75mm, r_3=20.72mm, r_4=24.00mm. When the relative permeability of the material under the same condition, the increasing core gap will weak impact of the parameter by core reluctance. It can be approximate considered that the parameters of coupler are determined by the gap reluctance and leakage reluctance.

$$R_r = \frac{1}{2} R_{lk} \left(2 - \frac{abA_e}{\pi l_g t + abA_e} \right)$$

$$k_r = \frac{abA_e}{2\pi l_g t + abA_e} \tag{9}$$

It can be seen from formula (7) that the core of high relative magnetic permeability of the core is only affected reluctance R_c. Therefore, formula (6) can express in the core reluctance coupler by the parameters of the core material.

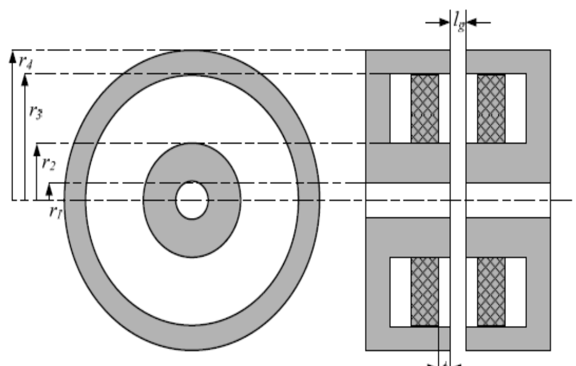


Figure 9. Core Cross-sectional Dimension

We can get the number of coil turns through the above parameters for the specific method of the coil and the analysis of loosely coupled transformer model. We can also get loosely coupled transformer at different air gap and coils by calculating. The turns number of loosely coupled transformer's primary side is 100 .number of turns is 120 turn coil secondary side. Specific parameters by comparing with ANSYS simulation software and actual measurement can be concluded that Ls is 0.6631 H, L_p is 0.8542 H, M for 0.5139 H, transmission frequency to 15 KHZ, gap is 10 mm.

5. Commissioning Results

On the overall test of ICPT experimental device, we select a different air gap distance with different input frequencies to make a test of the non-contact power feeding device. The input DC voltage is 24V, and it connects the primary side of loosely transformer after the increased frequency by frequency inverter. Because of the switching loss and it has a voltage loss, cause the input loosely coupled transformer primary voltage is less than 24V. We get many groups of data through the overall test. Due to the limited space, it can not be posted one by one. We only give experimental data measured of different air gap distance at the same input frequency with 15kHz here. Because the secondary current can be measured, the ratio of turns is known and power transmission efficiency can be calculated through primary and secondary voltage as the following Table 2.

Table 2. The Experimental Data Sheet with Different Air Gap and the Same Frequency

Air gap distance (mm)	Primary voltage (V)	Secondary voltage (V)	Transmission efficiency (%)
4	22.1	16.8	76.02
5	22.0	16.4	74.51
6	21.8	15.7	72.12
7	22.0	14.9	68.40
8	21.8	14.1	64.09
9	21.9	13.4	60.91
10	22.0	12.5	57.34

6. Conclusion

The paper analyzes the structure parameters of loosely coupled transformer which is the ICPT experimental apparatus's core member. Compared to determine the core of loosely coupled transformer through simulation and calculating the parameters of loosely coupled transformer to complete the production of ICPT experimental device as Figure 11. By testing the experiments apparatus of ICPT, we can derive the affect of efficiency from primary and secondary air gap on loosely coupled transformer. And it lay the research foundation for high-power ICPT in the future.

Figure 9. Experimental Setup

Acknowledgements

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