ISSN: 2688-8645

Structural Optimization Design of Rotary Loose Coupler

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Abstract

The loose coupling transformer, the core component of the rotary wireless excitation system, has a large leakage inductance due to the existence of a large gap, and the coupling coefficient cannot be effectively improved, thus limiting the improvement of the system efficiency. In order to solve this problem, firstly, the equivalent modeling and leakage inductance analysis of the rotary loosely coupled transformer are carried out, and the improved design is carried out according to the defects of common windings, and an improved shaft rotary coupler is proposed. The feasibility of this optimized structure was determined using Ansys/Maxwell simulation analysis software. The S-S resonance compensation scheme is designed, and the co-simulation with Simplorer and Maxwell is used to compare the coupling coefficient and transmission efficiency of the loosely coupled transformer before and after the improvement under the condition of large air gap, and the rationality of the proposed scheme is verified.

Keywords

Rotary Wireless Excitation System; Loosely Coupled Transformer; Winding Optimization.

1. Background

The wireless power transfer mainly relies on the mutual inductance between the primary coil and the secondary coil, and the existence of leakage inductance will adversely affect the transmission of active power. Due to the existence of an air gap between the primary and secondary coils of the loosely coupled transformer, the coupling coefficient between the coils is reduced, resulting in an increase in the leakage inductance of the entire system and a decrease in the mutual inductance, which in turn affects the transmission efficiency of the system. Therefore, in order to compensate the leakage inductance, weaken or offset the reactive power, and improve the efficiency of the system, it is necessary to design the compensation network reasonably.

In this paper, an improved shaft-type rotary coupler is proposed by analyzing the structure of the coupler windings. Ansys/Maxwell simulation analysis software was used to compare and analyze the advantages and disadvantages of this structure and the planar winding structure leakage flux and magnetic flux density. The S-S resonance compensation circuit is selected to formulate the design scheme of the wireless excitation power supply. Using Simplorer and Maxwell to carry out co-simulation, the coupling coefficient and transmission efficiency of the loosely coupled transformer before and after the improvement are compared under the condition of large air gap, and the rationality of the proposed scheme is verified.

2. The Basic Structure of the Rotary Wireless Power Transmission System

Like common transformers, rotary couplers are based on electromagnetic induction for energy transmission. The electromagnetic induction transmission system is mainly divided into six parts: DC power supply, inverter, coupler, rectifier filter, voltage stabilizer and load . The power supply is the energy source of the wireless power transmission system. The inverter must be designed to match the coupler coil to ensure that it can drive the coupler and improve the transmission efficiency. It generally includes soft switching circuits and hard switching circuits; rotary couplers are generally It consists of two coils, with a certain air gap in the middle, and the coupling coefficient generally does not exceed 0.9. This type of coupler is also called a loose coupler. The DC power supply is converted into a high-frequency power supply after passing through the inverter. The high-frequency power supply enters the transmitting coil of the coupler to generate a high-frequency changing magnetic field. The receiving coil of the coupler is located in the magnetic field, and the corresponding high-frequency power supply is induced. After the rectifier filter, the The high-frequency power supply is converted into a DC power supply, which is regulated to supply power to the load to complete energy transmission[3].

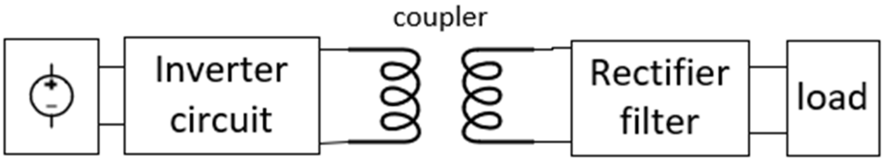


Figure 1. Rotary Coupler Power Transmission System

3. Characteristic Analysis of Rotary Coupler

The path through which the magnetic flux flows is called the magnetic circuit. The transmission capacity of the magnetic flux is represented by the magnetoresistance, and the relationship between the magnetoresistance and its external structure is reflected by the magnetoresistance model[4]. For the electromagnetic characteristics and structural optimization of the rotary coupler, the relevant data analysis can be carried out according to the method of magnetoresistance modeling.

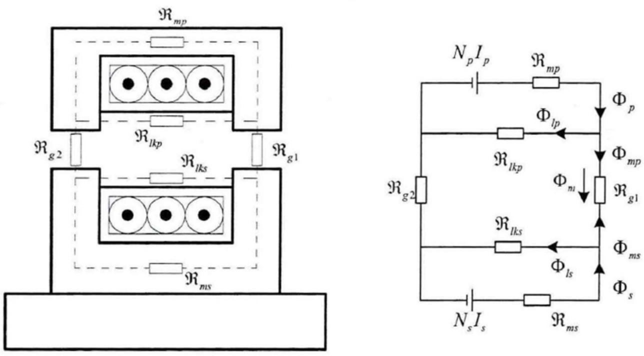


Figure 2. Magnetic circuit model of rotary coupler

According to Ohm's law of magnetic circuit, it can be known that the calculation formula of magnetoresistance is:

$$R_i = \frac{1}{\mu_0 \mu_r A} \tag{1}$$

$$L_{lk1} = \frac{N_1^2}{R_{1k}} = \frac{N_1^2 \mu_0 A_{lk1}}{l_{lk1}} \tag{2}$$

$$L_{lk2} = \frac{N_2^2}{R_{1k}} = \frac{N_2^2 \mu_0 A_{lk2}}{l_{lk2}} \tag{3}$$

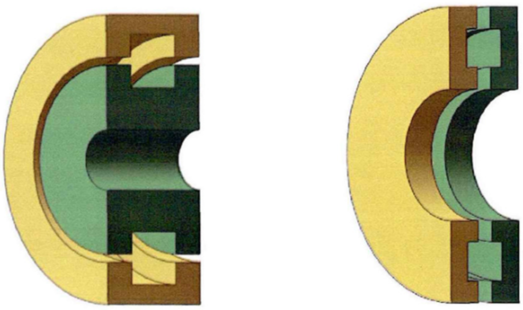
$$R_m \approx R_{g1} + R_{g2} \tag{4}$$

In the formula, R_i is the magnetic resistance; R_m is the total magnetic resistance; the subscript lk is the winding; the subscript g is the air gap; l is the average length; μ_r is the relative permeability; μ_0 is the vacuum permeability; A is the cross-sectional area of the magnetic core ; N_1 is the number of turns of the primary winding; N_2 is the number of turns of the secondary winding; L_{lk1} is the leakage inductance of the primary winding; L_{lk2} is the leakage inductance of the secondary winding.

4. Optimal Design of Rotary Coupler Structure

4.1. Shaft and Planar Winding Structures

The rotary coupler can be divided into a shaft coupler and a planar coupler according to the difference of the magnetic core and the winding. The structure is shown in Figure 3. The secondary side of the transformer of both structures is embedded on the rotating shaft, the primary side remains stationary and is connected to an external power source or load, and the secondary side keeps rotating, which can be used as a rotating load or rotating power source on the primary side[4]. The shaft coupler consists of a primary core with a larger diameter and a secondary core with a smaller diameter, the two cores are coaxial and the secondary core is placed inside the primary core; planar coupling In the device, the two cores are placed face to face with equal diameters.



(a) shaft coupler (b) Planar Coupler

Figure 3. Rotary Coupler Structure

In this paper, ANSYS MAXWELL is used to simulate and analyze the two coupler structures. It should be noted that in actual engineering, the coupler has a wider range of activities in the axial distance. Therefore, in the simulation, the primary side and secondary side coils of the coupler are recorded[5]. The position when there is a 15mm axial offset is the axial distance zero point.

Figure 4. Schematic diagram of the shaft coupler coil offset 0mm

Figure 5. Schematic diagram of the shaft coupler coil offset 5mm

The simulation results are shown in Figure 6 and Figure 7:

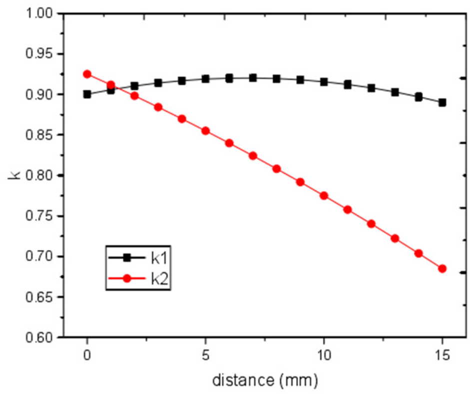


Figure 6. Simulation comparison of coupling coefficient between shaft coupler (k1) and planar coupler (k2)

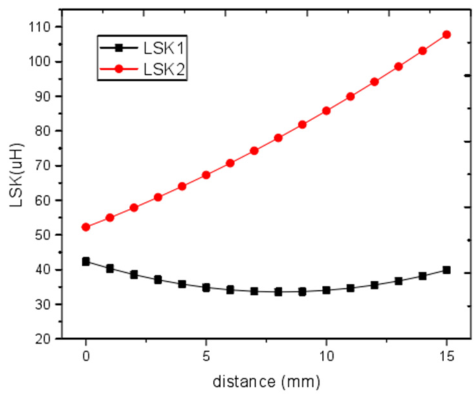


Figure 7. Comparison of leakage inductance simulation of shaft coupler (LSK1) and planar coupler (LSK2)

4.2. Improved Magnetic Core Structure

When the rotary coupler transmits energy, it is in a state of high-speed rotation. There is a certain air gap between the primary side magnetic core and the secondary side magnetic core. Due to the existence of the air gap, the magnetic circuit cannot be completely closed, and the magnetic induction intensity of the magnetic core becomes smaller, the coupling coefficient

ISSN: 2688-8645

becomes smaller, and the energy transfer efficiency is lower. In this paper, some improvements have been made on the structure of the original magnetic core, and the influence of the air gap on the coupling coefficient is reduced without affecting the motion of the rotary coupler.

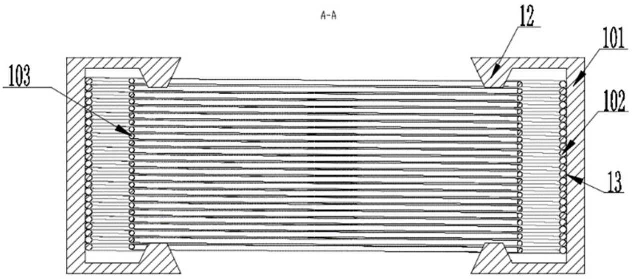


Figure 8. Improved core structure

Figure 8 shows the improved iron core structure. The top and bottom of the magnetic core are concave, which can increase the magnetic flux of the coupler, increase the coupling coefficient, and improve the energy transfer efficiency.

4.3. Parameter Simulation Analysis of Shaft Coupler

When using ANSYS MAXWELL to divide the rotary coupler model, because the coupler is axisymmetric and the size of the model is relatively standard, it is divided manually. Since the primary side of the rotary coupler is rotating, the meshing of the primary side of the rotary coupler is denser than that of the secondary side. Figure 9 shows the split part of the coil, and Figure 10 shows the split part of the magnetic core.

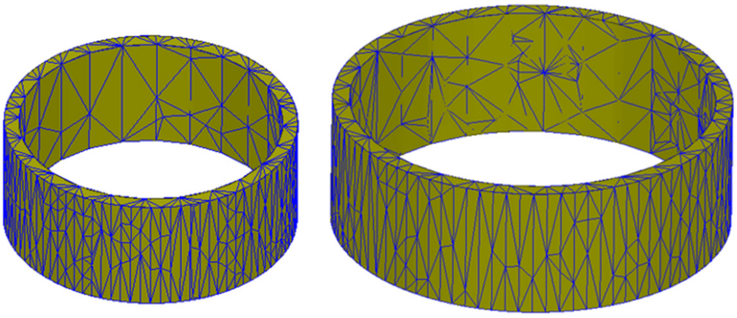


Figure 9. Coil meshing

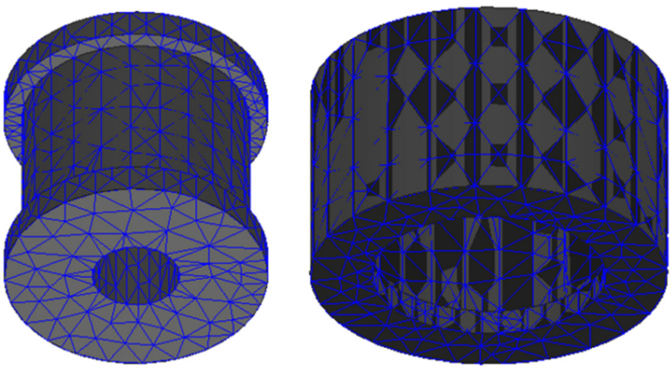
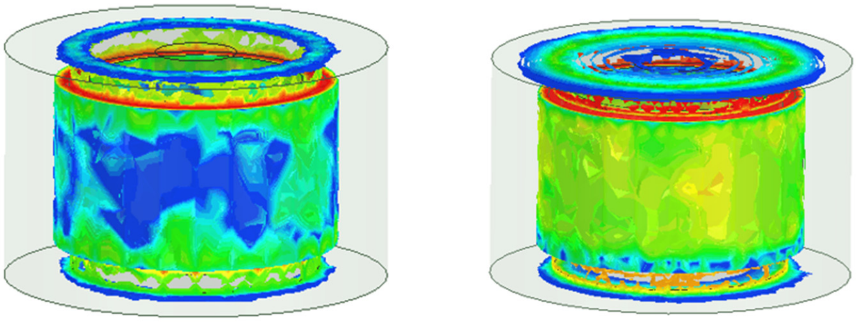


Figure 10. Core meshing

The physical quantity used to describe the strength and direction of the magnetic field is the magnetic density. According to the modeling analysis of the multi-strand enameled stranded wire winding, the primary side and secondary side windings of the rotary coupler are designed to work under 2mm, 4mm and offset state respectively. When the loosely coupled transformer is relatively static, ANSYS MAXWELL electromagnetic field simulation analysis is carried out for different air gaps, and the simulation results of the magnetic density cloud diagram are shown in Figure 11 below:

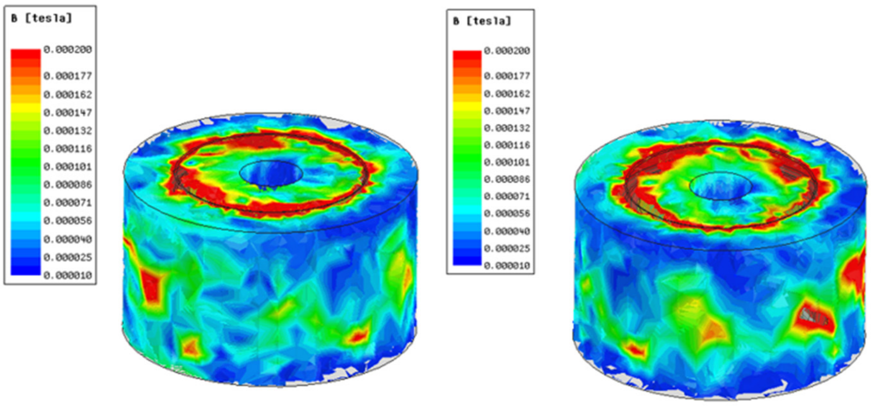


(a) 2mm offset (b) 4mm offset

Figure 11. Simulation diagram of magnetic density with different offset degrees

According to the analysis of the above figure, in a relatively static state, when the offset is 2mm, 4mm, the loosely coupled transformers all work in the linear region of the magnetic characteristic curve, and there is no phenomenon of magnetic flux saturation. The model constitutes a 3D loop of a magnetic field whose flux density decreases with increasing offset.

Under the condition of an air gap of 2mm, the magnetic density simulation of the loosely coupled transformer in the state of relative rotation is carried out, and the simulation is carried out when it is relatively static and when the rotation speed is 1500r/min. The simulation results are shown in Figure 12.



(a) Stationary state (b) 1500r/min state

Figure 12. Simulation diagram of magnetic density at different rotational speeds

It can be seen from Fig. 13 that the magnetic field distribution during rotation is basically the same as that at rest, which verifies the characteristic that the magnetic field distribution of the rotary coupler is not affected by the primary side rotation.

5. Conclusion

Aiming at the problem that the coupling coefficient of the loosely coupled transformer in the rotary wireless excitation system is low and the transmission efficiency is affected under the condition of large air gap, the anti-offset simulation experiment of the shaft and plane couplers is carried out by analyzing the parameters of the rotary coupler model. , under the same offset

ISSN: 2688-8645

condition, with the increase of the offset distance, the planar coupler has a large variation range of the coupling coefficient and low transmission efficiency, and the axial coupler has more advantages in anti-offset. In this paper, the magnetic core of the rotary coupler is improved, which can improve the coupling coefficient of the rotary coupler to a certain extent. The Maxwell 3D simulation model of the shaft-type rotary coupler is established to analyze the influence of parameters such as magnetic flux density, magnetic flux leakage and air gap on the coupling coefficient in the rotary loosely coupled transformer. Design the S-S resonance compensation scheme to further reduce the influence of leakage flux. Co-simulation with Simplorer and Maxwell is used to verify the feasibility of the shaft-type rotary coupler scheme.

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