A wireless transmission coupling structure with low electromagnetic force disturbance and stable coupling coefficient

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Abstract: In the inductive wireless power transmission, electromagnetic force, which between the primary part and the secondary part, may cause the non-contact free motion and cause bad side effects on transmission. In order to calculate the force, magnetic vector potentials differential equations, based on linear array, are built, and the expression of the electromagnetic force is produced by solving this equation system.

1. Introduction

As a developing technique, wireless power transfer has been widely utilized in an increasing number of areas, due to its advantages in convince and safety[1][2]. In WPT, electric energy is transferred by using near-field electromagnetic induction rather than connecting electrical circuit directly. In this technology, power is transferred between two coils which are non-contact but coupled. Electrical circuit, which is based on coupling, is set to transfer power more conveniently.

In WPT, electrical circuit and coupling coefficient must be matched, only in this way can coupling module get high capacity and high efficiency[3][4]. Coupling coefficient irregularly fluctuates under the influence of changing position between primary coils and secondary coils. In some applications, considering the requirement of high-power transmission, the size and frequency of the current can be very large. The high electromagnetic force, which results from large current, can cause the non-contact free motion between the primary part and the secondary part. Sometimes, coupling coefficient may be affected by the free motion of coupling module. That will have bad side effects on transmission and reduce efficiency.

To avoid this situation, there are a few ways to keep coupling coefficient stable. Using a special structure so that coupling coefficient won’t change drastically as motion appears. Decreasing the electromagnetic force can be a useful way.

In this WPT system, the coupling part are made of two cores and two coaxial coils with many turns.
This type of coils has a clear force of its own. There is compression force in its axial direction and expansion force in its horizontal direction[5][6]. But when two coils couple, the electromagnetic force becomes difficult to analyse as a result of the superposition of magnetic field.

2. Analysis

2.1 Circuitry system

A basic composition of induction wireless power transmission system is shown in the figure 1, which mainly includes primary part, secondary part and magnetic field coupling link. The DC input power is transformed into high-frequency alternating current through the inverter. The alternating current signal generates alternating magnetic field through the couple coil, and the receiving coil generates current under the influence of the alternating magnetic field. The receiving coil can generate a large amount of alternating current, which is converted into DC by rectification and then output for the load.

![Figure 1. transmission structure](image)

The function of the high-frequency inverter in primary part is to convert DC into high-frequency AC, and then provide AC to the primary transmitting coil. The inverter circuit of the transmission system described in this paper adopts full bridge pulse-width modulation circuit. This kind of circuit, because its easier adjustment and advantages in high-power transmission, is widely used in wireless power transmission. The function of conversion circuit in secondary part is to convert the AC signal which is received by the coupling structure into DC power for the load. Magnetic coupling part is the core part of the whole system. The condition of coupler has great influence on the power transmission capacity and efficiency in a induction coupled wireless power transmission system. The coupling characteristics of the coupler mainly include inductance of primary and secondary sides, mutual inductance, coupling coefficient, equivalent series reactance of primary and secondary sides and leakage inductance of primary and secondary sides. In the same coupler, the mutual inductance and coupling coefficient can be characterized by each other, the variation rules of leakage inductance in primary side and secondary side are the same. As a result, the parameter dimension can be reduced without affecting the analysis integrity.

The induction coupling structure described in this paper can be regarded as a loose coupling transformer with special structure, which includes two structural parts, the primary and secondary of the coupling transformer. The material of primary part and secondary part is the same, and the structure of them is symmetrical. From the outside to the inside, the whole structure can be divide into insulation layer, transmitting core, transmitting coil, receiving coil, receiving magnetic core and insulating layer.

The insulation potting is matched by the structure wall which is seal and waterproof, and the potting is used to support and protect the magnetic core and winding coils. The primary winding is used to convert electric energy into alternating magnetic field, and the secondary winding is used to couple alternating magnetic field and convert it into electric energy. The magnetic core is used to concentrate and guide more magnetic lines of flux across the primary and secondary winding, so as to improve the coupling coefficient and improve the power transfer efficiency. The structure wall is made of aluminum alloy material, which is used for magnetic separation, to avoid the leakage of magnetic force line to the periphery of the structure and affecting the operation of other circuits and components. In the meantime, the radiating loss can be reduced by the electromagnetic shielding and the transmission efficiency can be improved.
Generally, capacitance compensation is usually applied to the primary and secondary coils of the system to make the system work in resonance state so as to increase the transmission capacity of the system. The coupling module circuit matching is determined by the operation frequency of the primary circuit. The resonance compensation of the primary side and secondary side is designed according to the coupling of the magnetic field. Only when the circuit and coupling module exactly match, can the whole transmission device carry out high-power and high-efficiency energy transmission.

The magnetic field coupling structure of inductive wireless transmission can be described by two coupled inductors. Taking the direction which is shown in the figure as the reference direction, the coupling electrical relationship of the coupling conduction can be expressed as (1).

\[
\begin{align*}
\frac{du_1}{dt} &= L_p \frac{di_1}{dt} + M \frac{di_2}{dt} \\
\frac{du_2}{dt} &= L_s \frac{di_2}{dt} + M \frac{di_1}{dt}
\end{align*}
\]

Where \(L_p\) is the inductance of primary side and \(L_s\) is the inductance of secondary side. \(M\) is mutual inductance.

2.2 Electromagnetic

In the discussion of magnetic field, circular current is the simplest and most basic current distribution. In many other applications, magnetic field calculations of current distribution are based on the magnetic field distribution of circular current. The magnetic field of circular current is resolvable based on Biot-Savart law. When there is a point X in the same plane of circular current, the magnetic induction B in the circular current is defined as follows:

\[
\frac{dB}{dI} = \frac{\mu dI}{4\pi} \frac{\sin \lambda}{r^2}
\]

Where \(I\) and \(l\) are the size and path of current element, \(r\) are the distance between current element and point X, \(\lambda\) is the included angle of current element and the line between current element and point X. When the radius of circular current is R, \(\beta\) is the included angle of current element and the centre, \(r^2 = R^2 + x^2 - 2Rx\cos\beta, \sin \lambda = \cos(\frac{\pi}{2} - \lambda) = \frac{R-x\cos\beta}{r}\), the magnetic induction B can be present as:

\[
B = \frac{\mu I R}{4\pi} \int_0^{2\pi} \frac{2\pi(R-x\cos\beta)}{(R^2 + x^2 - R\cos\beta)^{\frac{3}{2}}} d\beta
\]
2.3 The electromagnetic and electromagnetic force in solenoid

In this WPT system, the solenoid can be regarded as a spiral coil uniformly wound around a long cylindrical surface. In the meantime, as a result of the superposition of current, the current through the wire can be divided into two parts, axial current and annular current. When the current is distribution, the surface current density can be expressed as $j = \frac{dI}{dS}$, where the $I$ is current and $S$ is section of conductor. Axial surface current density can be expressed as $j_\theta = \frac{j \sin \theta}{d}$, and annular surface current density can be expressed as $j_\varphi = \frac{j \cos \theta}{d}$, where $D$ is the diameter of solenoid and $d$ is the diameter of conductor.

The section of conductor can be divided into two parts, axial part $dS_\theta = dS \sin \theta$, and annular part $dS_\varphi = dS \cos \theta$. The axial current can be calculated by $I_\theta = I \sin^2 \theta$ and the annular current can be calculated by $I_\varphi = I \cos^2 \theta$.

At X point, the magnetic field caused by axial current can be expressed as
$$B = \int_0^{2\pi} \frac{(R \cos \beta - x)}{R^2 + x^2 + 2Rx \cos \beta} \cdot \left( \frac{\sqrt{R^2 + x^2 - 2Rx \cos \beta}}{\sqrt{R^2 + x^2 + 2Rx \cos \beta} + \sqrt{h^2 + x^2 + 2Rx \cos \beta}} \right) \cdot \frac{l_z}{2\pi R} \, d\beta$$  \hspace{1cm} (4)

Where \( x \) is distance from center to point \( X \).

The magnetic field caused by annular current can be expressed as (5). Where \( l \) is the radius vector of circular current. The vector from point \( X \) to current element \( r \) can be expressed as (6). So the magnetic in the solenoid can be expressed as (7). Where \( B_\sigma \) is the magnetic in axial direction and \( B_\tau \) is the magnetic in tangential direction.

$$dB_\sigma = \frac{\mu l_z dl \times r}{4\pi^2 r^3}$$ \hspace{1cm} (5)

$$r = l - x + h z$$ \hspace{1cm} (6)

$$\begin{cases}
  dB_\sigma = \frac{\mu l_z dl \times (l-x)}{4\pi^2 r^3} \\
  dB_\tau = \frac{\mu l_z dl \times h z}{4\pi^2 r^3}
\end{cases}$$ \hspace{1cm} (7)

In a tightly and evenly wound cylindrical solenoid, the axial current can be generally ignored. So \( B_\sigma \) and \( B_\tau \) can be transformed and expressed as (8).

$$\begin{cases}
  B_\sigma = \frac{\mu l_z}{4\pi^2} \int_{-h}^h \int_{-\beta}^{2\pi} R(R - x \cos \beta) \, d\beta \, dz \\
  B_\tau = \frac{\mu l_z}{4\pi^2} \int_{-h}^h \int_{-\beta}^{2\pi} \frac{R z}{(z^2 + R^2 + x^2 - 2Rx \cos \beta)^2} \, d\beta \, dz
\end{cases}$$ \hspace{1cm} (8)

Because the magnetic field is central symmetrical in the same shaft section, and the sum of upper limit and lower limit of \( z \) is constant. It is easy to find that \( B_\sigma \) is axial symmetry and \( B_\tau \) is central symmetrical.

In magnetism, the level of material magnetized can be expressed by magnetization \( M \). The magnetization surface current can be represented as \( \delta_\sigma = n \times M \) and the magnetization volume current can be represented as \( \delta_\tau = \nabla \times M \). Magnetic forces under magnetization can be expressed as (9). If the material is isotropic, it can be transformed as (10). Then it can be calculated by integral transformation as (11).

$$F = \iiint \delta_\times B dv + \iiint \delta_\tau \times B dS$$  \hspace{1cm} (9)

$$F = \iiint (\nabla \times M) \times B dv$$  \hspace{1cm} (10)

$$F = \frac{1}{2} \iiint \nabla M \times B dv = \frac{1}{2} \iiint M \cdot B dS$$  \hspace{1cm} (11)

The structure in this paper is as shown in the figure 5, the magnetic induction of a single point in it can be expressed as (12). It can be transformed as (13) by mathematical transformation. Where \( S \) is the interaction surface between magnetic field and magnetic core. The integral surfaces of \( B_1 \) and \( B_2 \) are the upper and lower planes of the cylinder and they are perpendicular to magnetic induction line. The integral surfaces of \( B_3 \) and \( B_4 \) are tangent to magnetic induction line. So the expression can be simplified to (14). The receiving magnetic core is only under the influence of electromagnetic force on the upper and lower surfaces. So the electromagnetic force of structure is equal to zero when it is working in normal condition.
Figure 5. the structure of coupling

Figure 6. decomposition of current in the structure of this paper

\[
\begin{align*}
B_{1\sigma} &= \frac{\mu_0 I_1}{4\pi} \int_{R_1}^{R_2} \int_{0}^{2\pi} \int_{-h}^{0} \frac{R_1 (R_1 - x \cos \beta)}{\left( z^2 + R_1^2 + x^2 - 2R_1 x \cos \beta \right)^{3/2}} \, dx \, d\beta \, dz \\
B_{1z} &= \frac{\mu_0 I_1}{4\pi} \int_{R_1}^{R_2} \int_{0}^{2\pi} \int_{-h}^{0} \frac{R_1 z}{\left( z^2 + R_1^2 + x^2 - 2R_1 x \cos \beta \right)^{3/2}} \, dx \, d\beta \, dz \\
B_{2\sigma} &= \frac{\mu_0 I_2}{4\pi} \int_{R_1}^{R_2} \int_{0}^{2\pi} \int_{-h}^{0} \frac{R_2 (R_2 - x \cos \beta)}{\left( z^2 + R_2^2 + x^2 - 2R_2 x \cos \beta \right)^{3/2}} \, dx \, d\beta \, dz \\
B_{2z} &= \frac{\mu_0 I_2}{4\pi} \int_{R_1}^{R_2} \int_{0}^{2\pi} \int_{-h}^{0} \frac{R_2 z}{\left( z^2 + R_2^2 + x^2 - 2R_2 x \cos \beta \right)^{3/2}} \, dx \, d\beta \, dz \\
F &= \iiint_{\Omega} \nabla \cdot \mathbf{B} = -\int_{S} \mathbf{M} \cdot d\mathbf{S} \\
F &= -\frac{\mu_0}{\mu_{r}} \int_{S} (B_{1\sigma} + B_{2\sigma}) \, dS
\end{align*}
\]

3. Simulation
To test the hypothesis, electromagnetic model, which is based on Ansoft, is used to discover how coupling coefficient and electromagnetic force change under the structure of this paper. The displacement range of the secondary coil move along the axial direction is set as - 5mm ~ + 5mm, and
it moves along with a step of 1 mm. At the same time, the displacement range of 0 ~ 5mm away from the central axis is set, and the simulation is carried out with 0.5 mm as the step.

![Figure 7. Changes of coupling coefficient and electromagnetic force when the position change](image)

Simulation result indicates that the coupling coefficient change less as position varies. And the electromagnetic force has small effect under this kind of structure.

4. Conclusion
This paper introduces a wireless power transmission system, which is less affected by displacement change and electromagnetic force. With the popularization of wireless transmission, it has wide application prospect and vast research potential.

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