Optimal Design of the Coupled Structure of Undersea Contactless Power Transmission System

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Abstract. In order to achieve more efficient and effective transferred power, the coupled structure of an undersea power transmission (CPT) system was carefully designed. The coupling magnetic field was analyzed by FEM simulation to reveal the transferring nature of two coupled windings. Simulation and prototype measurement were compared to demonstrate that the optimal winding layout has higher coupling coefficient. Furthermore, high frequency current in windings was also being considered in the optimization to calculate power loss. In this calculation, alternating current resistance was serious discussed because it plays a more important role in power loss than direct current resistance in windings does. Optimizing methods mentioned in this paper are very useful in system design to obtain a capable coupled structure, especially those works in undersea environment.

Introduction

As ocean explorations practiced deeply in recent decades, undersea electric equipment's have been used more and more widely. Meanwhile, it is obvious that transferring electric power to these equipment's is extraordinary difficult. Seawater surrounding power interfaces will damage electric circuits when electric leakage occurred. Mechanical sealing is usually expensive and difficult to operate, and has a short life [1]. By comparison, the contactless power transmission (CPT) method has many inherent advantages, such as simple docking, without wearing, little operating force, being immune from electric shock and leakage, and so on[2,3].

A CPT system works based on Faraday theory about electromagnetic induction. Inductive linkage between two separated parts with respective cores and windings is the only way for electric energy being transferred from power source to equipment's. But this structure results in two critical problems, low efficiency and low power, because the inductive windings have high leakage inductance and low coupling coefficient with an inevitable gap between cores. On the other hand, when the essential high frequency current up to about hundreds of kHz is occurred in windings, alternating current (AC) resistances which cause high power loss will rise much larger than direct current (DC) resistances. So a significant work on a CPT system design is optimizing its coupled structure to improve coupling coefficient and reduce power loss.

This paper analyzed magnetic field in the coupled structure and its vicinity by FEM software, in order to disclose the power transferring way. Three models with different windings layouts were used in the analysis to make clear what effect the windings have on the coupled magnetic field. Electric parameters of these structures were calculated based on data from the software, comparing with those measured from prototypes. Another considered object of the designed structure was the winding resistance which is related not only with its total length but also with the current frequency because of the skin effect when the frequency is very high.

Coupling Magnetic field in the Structure

A CPT system worked based on electromagnetic induction between two windings, transferring electric energy from primary side to secondary side by the alternating magnetic field generated by the primary winding. Cores in both sides are used to mount windings and concentrate magnetic flux.

However the two sides should be separated in non-powering periods, so the gap between cores is inevitable. The cores are made of soft magnetic material which has much higher permeability comparing to seawater. Therefore the magnetic reluctance of gap is much larger than that of cores [4]. The magnetic circuit comprised of cores and gap cannot concentrate all of magnetic flux some of which does not pass through the secondary winding and became leakage flux, as shown in Fig.1. Other flux through the secondary winding is called mutual flux. More leakage flux causes more power loss and lower capability of power transmission. In the other words, the leakage flux is power barrier, and the mutual flux is power way. The power transferring capability of the structure can be indicated by a parameter called coupling coefficient which represent the ratio of mutual flux to total flux.

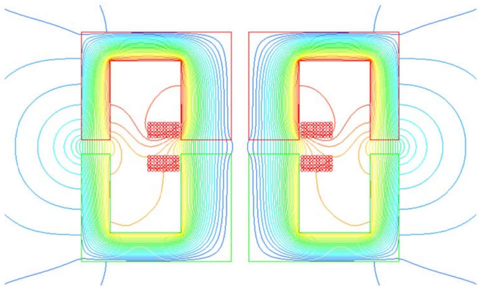


Fig. 1 Distribution of flux lines in the EM coupler

In a corresponding electric model of the magnetic circuit as shown in Fig.2 (a), the leakage flux and mutual flux were converted to leakage inductance L_{k1}, L_{k2}, and exciting inductance L_m. Fig.2 (b) illustrated another electric model of the structure which is more often used to calculate its coupling coefficient. In this model, parameters such as primary inductance L_P, secondary inductance L_S and mutual inductance M can be directly measured or deduced. The coupling coefficient k of the two windings is given by

$$k = \frac{M}{\sqrt{L_P L_S}} \tag{1}$$

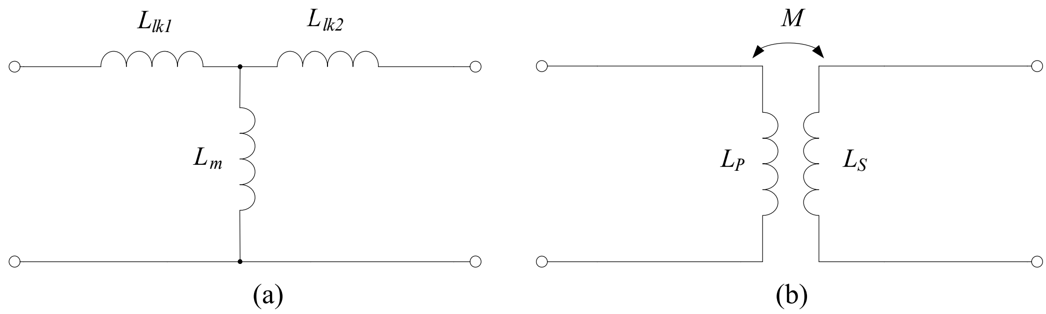
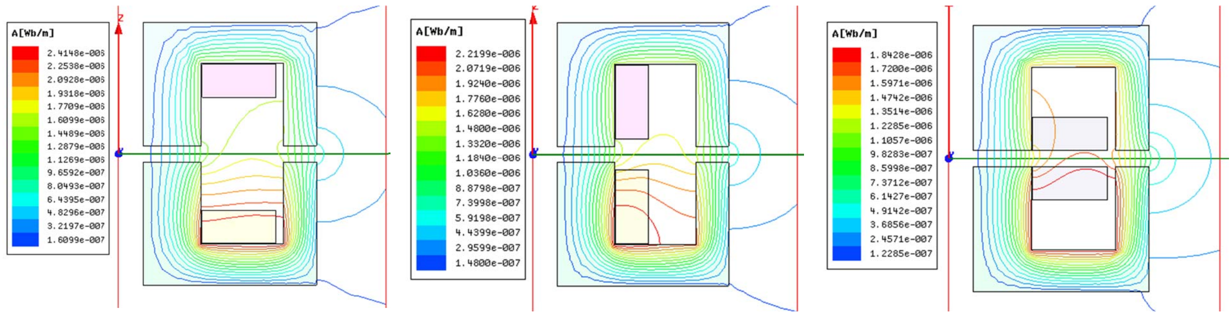


Fig.2 Electric model of the coupling structure

As mentioned above, this equation can also express how much magnetic flux generated by primary winding pass through the secondary winding, as shown in Fig.1. It is obvious that the coupling coefficient is mainly associated with the distribution of magnetic flux. If cores are determined, the windings layout and the gap between cores are main affecting factors.

By using the FEM software a soft Maxwell, three different winding layouts with the same pot cores and gap were analyzed, and their magnetic fields were illustrated in Fig. 3. This figure revealed that layout (c) had the better coupling than (a) and (b) for the adjacent windings ensured most flux from primary winding can be captured by secondary winding. To demonstrate the simulations, Table 1 provided comparison of the simulated results and measurements of three structure prototypes which have the same core dimensions and material, and the same winding turns and layouts with models in Fig.3. It was evident from data in Table 1 that the coupling coefficient of layout (c) is much higher than those in the others, although inductances of windings are somewhat smaller. The coupling coefficient is the dominant factor effect on a CPT system, playing a more important role than self-inductances L_P and L_S. Therefore, layout (c) in Fig.3 is the optimized approach to design the coupling structure for the system.



(a) (b) (c)

Fig. 3 Magnetic flux distribution in coupling structures with different winding layoputs

Table 1 Parameters of different winding layouts

Parametes	Layout (a)		Layout (b)		Layout (c)	
	Simulation	Measurement	Simulation	Measurement	Simulation	Measurement
Lp/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

Effective resistance of windings

High frequency current in windings will produce high frequency magnetic field around windings, and disturb the current density. As a result, resistances in windings have two compositions- direct-current (DC) resistance R_{dc} and alternating-current (AC) resistance R_{ac}. R_{dc} is determined by conductor's material and diameter, conforming to Ohm's law. R_{ac} is caused by the no uniform current density in windings, associating with current frequency. To calculate the effective resistance R_{eff} comprising of R_{dc} and R_{ac}, some factors should be taken into account, such as winding layers, skin effect and proximity effect of wires [5-7]. The following equations were always be used in high frequency transformers,

$$R_{eff} = R_{dc} + \frac{\Psi}{3} \cdot \Delta^4 \cdot R_{dc} \cdot \left[\frac{I'_{rms}}{\omega I_{rms}} \right]^2 \tag{2}$$

$$\Psi = \frac{5 \cdot p^2 - 1}{15} \tag{3}$$

$$\Delta = \frac{d}{\delta_0} \tag{4}$$

Where, p is the layer number of the wire in radial direction, δ_0 is penetration depth of current, I_{rms} is RMS current in windings, I'_{rms} is RMS of the current derivative, ω is the angle frequency of currents, d is the wire diameter. If the current is sinusidal, equetion (2) can be simplified as:

$$R_{eff} = R_{dc}(1 + \frac{\Psi}{3} \cdot \Delta^4) \tag{5}$$

This equation shows that more wire layers and more higher current frequency results in more biger AC resistance R_{ac} and more power losses in windings. On the other hand, decreasing the wire diameter d can reduce Δat the same frequency. So a useful method to optimze windings is fabricating windings with Litz wire instead of solid wire. In this paper, an example was used to calculate a winding's AC resistance with 30-turns and 20mm inner diameter accoding to a P48 type pot core. The winding shape was shown in Fig.4, where a:b is equal to 5:6. In this case, four kinds of wires were compared including one solid wire with 1mm diameter and three Litz wires with 0.35mm, 0.2mm and

0.1mm respetively. Table2 shows structure parameters and DC resistance of these windings. These windings have almost same inductance and DC resistance.

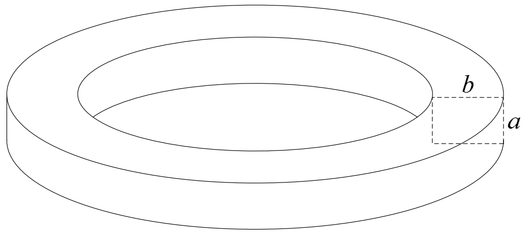


Figure 4 The configuration of the fabricated winding (N=30)

Table 2 The structual parameters of the windings with different wires

Wire diameter d/mm	Strand number of wire N0	Wire conduct area A/mm2	Strand layers p	DC resistance Rdc/Ω
1	1	0.785	6	0.1077
0.35	8	0.770	17	0.1042
0.2	25	0.785	30	0.1085
0.1	100	0.785	60	0.1085

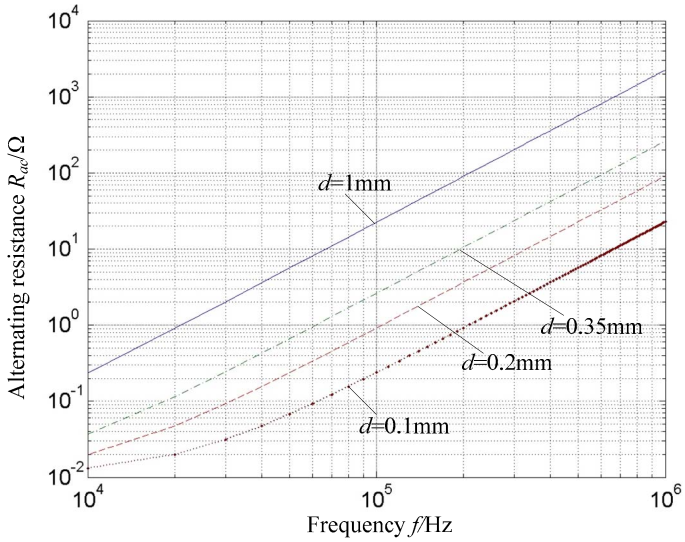


Fig.5 Comparison of the AC resistance of windings with different conduct wires (N=30)

The calculated results were shown in Fig.5. It is clear that higher frequency results in higher AC resistance, and the resistance rises exponentially with frequency increasing. For expamle, if the frequency increases from 10 kHz to 500 kHz, the AC resistance of 1mm solid wire winding changed from 0.236Ω to 561.8Ω, rising more than 2300 times. On the other hand, Litz wire works very effective seen from Fig.5. For example, the winding with 0.1 mm-strand wires has only 5.7Ω AC resistance at 500 kHz, much smaller than the 1 mm solid one. It can be summarized from above analysis that the windings should be made of Litz wire, and the strand diameter should not larger than penetration depth of current based on the current frequency to avoid too much power loss in the winding.

Summary

Undersea power transmission is difficult because the surrounding seawater is very dangerous for the power interface. The CPT system is a reliable alternative to general conduct interface. This paper provided optimal designing method for the coupled structure used in a CPT system. By using FEM simulation and prototype measurement, the optimal winding structure and layout with high coupling coefficient were demonstrated. Moreover, high frequency current was taken into account to analyze power loss in windings. As a conclusion, the winding should be better made of Litz wire to reduce AC resistance. Furthermore, the current frequency should be balance with wire dimensions.

Acknowledgements

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