RESEARCH ON WIRELESS POWER TRANSMISSION CHARACTERISTICS OF THE TORQUE TELEMETRY SYSTEM UNDER THE INFLUENCE OF ROLLING MILL DRIVE SHAFT

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In this paper a wireless torque telemetry system of rolling mills is studied, in order to underline the influence of the transmission shaft on the power transmission efficiency. For this, numerical simulation and experiments have been performed. Aiming that the metal medium passes through the primary and secondary coils of the wireless transmission system, the power and its transmission efficiency are reduced. The results show that the ferromagnetic medium passing through the primary and secondary coils reduces the inductance of the primary and secondary coils and generate eddy current losses inside the medium, resulting in a system transmission efficiency drop of 11%.

Keywords: Wireless power transmission, Ferromagnetic metallic medium, Inductance change, Eddy-current loss, Transfer efficiency, Transmission power

1. Introduction

Torque parameter is an important parameter to master the working condition of rolling mill equipment, and the torque telemetry system is an important method to measure the torque parameter. In order to realize the rolling mill torque telemetry system to grasp the change of the output torque of the transmission shaft online for a long time in real time. At present, the commonly used domestic torque telemetry system mostly adopts the mode of high-frequency induction power supply for the wireless transmission of electric energy to ensure the long-term stability of online monitoring purposes[1]. Wireless power transmission technology has become a hot topic of research and analysis by domestic and foreign scholars in recent years due to its advantages of safety, convenience, reliability and flexibility that traditional power transmission cannot match.

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Wireless power transmission can be divided into three basic forms: (1)Magnetically-coupled Inductive wireless power transfer, (MCIWPT) (2)Magnetically-coupled resonant wireless power transfer, (MCRWPT) (3)Microwave wireless power transfer, (MWPT)[2, 3]. Different forms of WPT technologies have different characteristics. MCIWPT has the characteristics of large transmission power and high efficiency. The maximum power can be more than several kW, and the maximum transmission efficiency can be more than 90%.The transmission distance of MCRWPT can range from tens of cm to several meters, the transmission power can range from dozens of W to several kW, and the transmission power can be more than 40% to 90%.The transmission distance of MWPT is relatively long, which can reach km level, and the transmission power can be from mW to MW level, but the transmission efficiency is very low, generally about 10% [4,5]. At present, MCIWPT and MCRWPT have better application and development prospects. Although MCRWPT technology has made great progress, there are still many problems to be solved due to insufficient theoretical research and lack of extensive application [6]. MCIWPT technology has become increasingly mature and has been widely used in commercial and engineering applications.

There have been many researches on the establishment of power characteristics and transmission efficiency of the power transmission principle model in the process of WPT. The references [7] analyzed the energy loss caused by eddy current in the chassis of electric vehicles in the process of wireless charging through simulation and experiment, and concluded that the total loss of the system could be minimized by adding a divergent magnet structure. The mathematical model of eddy current loss in the medium is established in [8], and the analytical expression of eddy current loss is derived. Through the comparison of experiment and simulation, it is concluded that wrapping the permalloy layer around the primary coil can effectively reduce the eddy current loss of the system. The references [9] obtained through experimental and simulation analysis that ferromagnetic materials had an impact on coil inductance and coupling coefficient of resonant WPT system, which caused the original system to deviate from the original resonant frequency and led to a decrease in transmission efficiency. Through theoretical analysis and experimental means, in [10] shows that the changes in the transmission performance of the magnetic resonance coupling system under the influence of non-magnetic metals are caused by the changes in the total equivalent impedance and the equivalent load impedance of the system caused by eddy current parameters. The references [11] achieves high quality factor and relatively uniform magnetic field distribution by connecting a small coil in series in the transmitting coil. The proposed asymmetric coil improves the efficiency and degree of freedom in the aspect of position change. At the transmission distance of 50mm and 300mm, the transmission efficiency is 96%

and 39%, respectively. A new type of magnetic resonance structure is proposed in [12], which can improve the magnetic field and increase mutual inductance by reducing the demagnetization coefficient of ferrite core coil, so as to improve the transmission efficiency and power.

However, in view of the existing external ferromagnetic metal media on WPT can affect the system transmission characteristics study also insufficient. In this paper, the influence of MCIWPT technology on power transmission efficiency and power under the influence of rolling mill drive shaft in the application process of rolling mill torque telemetry system is analyzed theoretically and studied experimentally. The influence of ferromagnetic materials on the inductance change of primary and secondary coils and the power of eddy current loss of MCIWPT system are simulated and analyzed, and the theoretical and simulation results are verified by experiments, providing scientific theoretical guidance for the application of MCIWPT technology in practical engineering. It is worth mentioning that in my other paper: Applications of magnetic coupling resonant wireless power supply in torque online telemetric rolling mill system, I studied the application characteristics of magnetic coupling resonance wireless power transmission in the torque telemetering system of rolling mill.

2. System modeling and theoretical analysis

System modeling. The model of the magnetic coupling induction power supply system studied in this paper is shown in Fig. 1. The primary side coil is made of aluminum ring, the secondary side coil is made of copper-clad PCB board, and the mill drive shaft is generally made of cast iron. The inner and outer rings are placed concentrically, there is about 10mm clearance between them. The mill drive shaft is passed through the center of the coil. The copper-clad PCB board is riveted on the special inner ring and bolted on the drive shaft to rotate along with the shaft. The outer ring is fixed through the bracket to keep the static state.

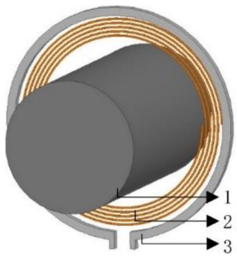
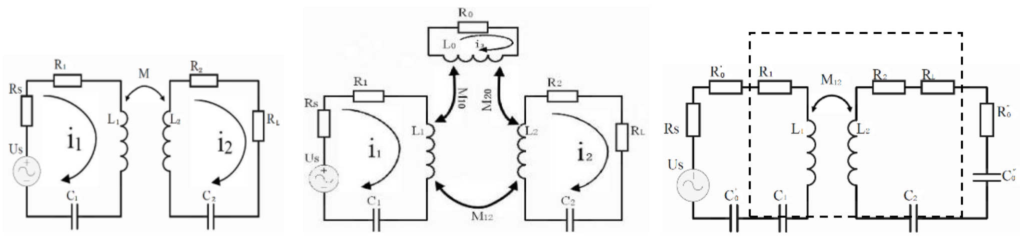


Fig.1 Torque Telemetry System MCIWPT Model

1. Drive shaft-made of cast iron 2. Secondary coil-copper clad PCB 3. Primary coil-made of aluminium

MCIWPT technology is based on Faraday electromagnetic induction principle to realize the wireless transmission of electric energy, the outer ring as the drive coil to produce high frequency induction magnetic field, the inner ring coil through magnetic field coupling to achieve wireless transmission of electric energy. In the absence of transmission shaft, the inner and outer rings use air as magnetic medium for energy exchange. The drive shaft is ferromagnetic medium in the primary secondary coil magnetic field transmission channel, the magnetic medium can not only enhance the magnetic field intensity of the induced magnetic field, but also change the inductance of the primary coil, thus changing the coupling coefficient of the primary auxiliary coil of the system. On the other hand, eddy current will be generated on the surface of the medium due to eddy current effect, and part of the power of the system will be lost in the form of eddy current loss, reducing the transmission efficiency of the system.

Theoretical analysis. According to the mutual inductance circuit model and Loose model of eddy current loose-coupling transformer, the equivalent circuit model of MCIWPT system and the equivalent circuit model under the influence of ferromagnetic metal medium are established respectively. Due to the influence of ferromagnetic metal medium, high-frequency magnetic field will generate eddy current and eddy current magnetic field in ferromagnetic medium. The eddy current loss under the influence of ferromagnetic medium is equivalent to the loss generated by resistance, and the effect of eddy current magnetic field on resonant magnetic field is equivalent to the magnetic field generated by inductance. The equivalent model of circuit is shown in Fig. 2[10].



(a) (b) (c)

Fig.2 (a)equivalent circuit model (b)The equivalent circuit model under the influence of ferromagnetic metal medium (c)The equivalent calculation model under the influence of ferromagnetic metal medium.

As shown in Fig.2 (a) and (b), the influence of the main difference is that the existence of a ferromagnetic metal medium, R_0 and L_0 represent the eddy current effect and eddy current magnetic field of the equivalent resistance and inductance value, the U_S and the R_S on behalf of the high frequency power supply and power resistance, R_1 and R_2 represent the emission circuit and receiving circuit equivalent resistance, R_L on behalf of the load resistance,L_1 and L_2 represent the primary coil and deputy coil inductance, C_1 and C_2 respectively represent the primary coil and secondary coil resonant capacitance, M_{12}、M_{10}、M_{20} represent the primary secondary coil mutual inductance and mutual inductance coil and ferromagnetic medium mutual inductance. The effect of eddy current circuit on resonant coil in its magnetic field is mainly the increase in the real part of circuit impedance and the decrease in the virtual part. Therefore, the circuit calculation model of the effect of eddy current on resonant circuit under the influence of ferromagnetic metal medium can be equivalent to Fig.2(c)[12]. Fig.2(c) shows the primary resonant coil circuit in the dotted box, $R_0^{'}$ and $R_0^{''}$ respectively represents the real part of the increase in the equivalent circuit impedance of the eddy current circuit, the reduced part of the virtual part of the equivalent circuit is equivalent to capacitance $C_0^{'}$ and $C_0^{''}$.

According to references [13], equivalent resistance and equivalent capacitance are respectively:

$$R_0^{'} = \frac{R_0(\omega M_{10})^2}{R_0^2 + (\omega L_0)^2}, \quad R_0^{''} = \frac{R_0(\omega M_{20})^2}{R_0^2 + (\omega L_0)^2}, \quad C_0^{'} = \frac{R_0^2 + (\omega L_0)^2}{\omega^2 L_0 (\omega M_{10})^2}, \quad C_0^{''} = \frac{R_0^2 + (\omega L_0)^2}{\omega^2 L_0 (\omega M_{20})^2}.$$

From KVL, the circuit voltage equation can be listed for Fig.2(c) :

$$\begin{bmatrix} R_1^{'} + jX_1 & -j\omega M_{12} \\ -j\omega M_{12} & R_2^{'} + jX_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} U_S \\ 0 \end{bmatrix}$$

In equation (1), $R_1^{'} = R_S + R_1 + R_0^{'}$, $X_1 = \omega L_1 + \frac{1}{\omega C_1} + \frac{1}{\omega C_0^{'}}$, $R_2^{'} = R_L + R_2 + R_2^{''}$.

Solving equation (1), the circuit current can be obtained:

$$i_1 = \frac{R_2^{'} + jX_2}{(R_1^{'} + jX_1)(R_2^{'} + jX_2) - (j\omega M_{12})^2} U_S$$

$$i_2 = \frac{j\omega M_{12}}{(R_1^{'} + jX_1)(R_2^{'} + jX_2) - (j\omega M_{12})^2} U_S$$

The load absorption power can be denoted as:

$$P_o = i_2^2 R_L$$

Transmission efficiency can be expressed as:

$$\eta = \frac{i_2^2 R_L}{i_1^2 R_1^{'}}$$

The schematic diagram of the eddy current loop generated by the coil in ferromagnetic metal medium is shown in Fig.3, Where r_i and r_0 are the inner and outer radii of the eddy current formation range, h is the depth of the eddy current, and a vortex cell with thickness of dr is selected, the resistance of this vortex cell can be expressed $R = \rho \frac{l}{S} = \rho \frac{2\pi r}{hdr}$, then the loss power of this vortex cell can be approximately expressed as:

$$dP = \frac{E^2 h}{2\rho\pi r} dr$$

In the equation, E is the effective value of the induced electromotive force of the eddy current loop, and the induced electromotive force is:

$$e = \frac{-d\varphi}{dt} = -\pi r^2 \cdot \frac{dB}{dt} = -\pi r^2 \cdot B_m \omega \cos(\omega t)$$

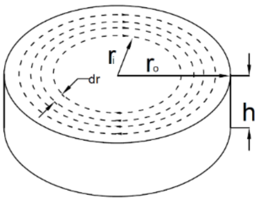


Fig.3 Schematic diagram of eddy current circuit in ferromagnetic metal medium

According to equation (6) and (7), the eddy current loss power is：

$$P_{loss} = \int_{r_i}^{r_0} dP = \frac{\pi \cdot \omega^2 B_m^2 h}{16\rho}\left(r_0^4 - r_i^4\right)$$

It can be known that the power of eddy current loss can be obtained by solving the magnetic induction intensity B near the ferromagnetic metal medium or the current density J within the medium and the range of eddy current formation.

3.Simulation analysis of energy transmission characteristics

In this paper, the MAXWELL 3D electromagnetic simulation module in ANSYS finite element analysis software was used to conduct the simulation analysis of eddy current field characteristics. The simulation model is shown in Fig.1, and the modeling parameters are shown in table 1.

Table 1

Modeling parameter

Parameter		Value
Metallic media	materials	Cast iron
	D/mm	300
	h/mm	400
Primary coil	materials	Aluminum
	D/mm	420
	turns	1
Secondary coil	materials	Copper
	D/mm	334
	turns	9

Distance between primary and secondary coil *d/mm*	12
Distance between medium and secondary coil *d/mm*	17
Distance between medium and primary coil *d/mm*	70
Excitation frequency *f/kHz*	50-300

Fig.4 shows the distribution of magnetic induction lines around the primary secondary coil. It can be seen from the Fig.4 that the magnetic field is concentrated around the primary secondary coil, the magnetic induction is concentrated between 1.01mT and 5.41mT, and the magnetic induction in the z-axis direction of the coil is around 5.41mT. The Fig.5 shows the distribution of magnetic induction lines around the coil when the ferromagnetic metal medium passes through the coil center. As the magnetic medium changes, the permeability increases and the magnetic induction around the coil increases obviously. The magnetic induction around the coil is concentrated from 1.16mT to 6.97mT. When an axis passes through the coil, the magnetic induction in the z-axis direction reaches its maximum around 6.96mT. The magnetic induction passing through the medium causes eddy current phenomenon in the ferromagnetic metal medium, which causes eddy current loss in the system and reduces the transmission efficiency of the system.

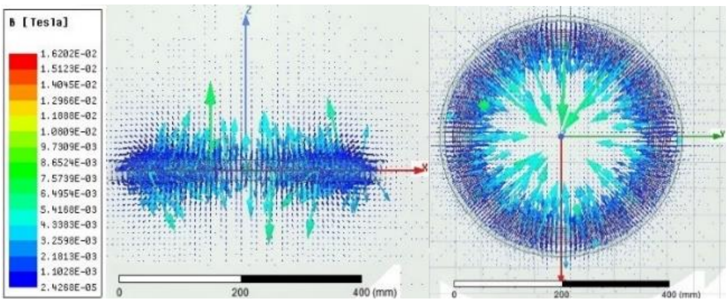


Fig.4 Primary secondary coil magnetic field distribution diagram

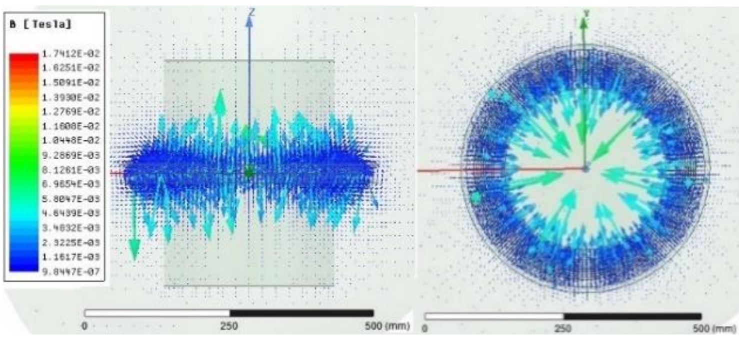
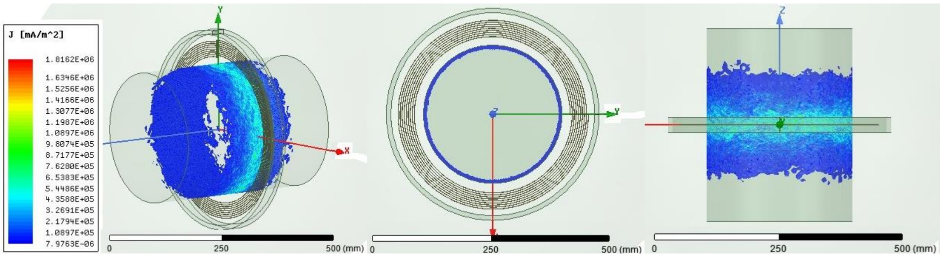


Fig.5 Magnetic field profile of a ferromagnetic metallic medium passing through the primary secondary coil

As shown in Fig.6 for the system to produce the eddy current in the ferromagnetic metal medium, the distribution of current density *J* can be seen by the strakes vortex mainly distributed in the secondary coil around, you can see by the vertical eddy current are mainly distributed in near the surface of the medium. The biggest media center part of the current density of basic is zero, from right view can be seen that the eddy current in the secondary coil as the center, to gradually decrease. It can be seen that the eddy current in the metal medium is obvious and shows significant skin effect under the high frequency magnetic field.

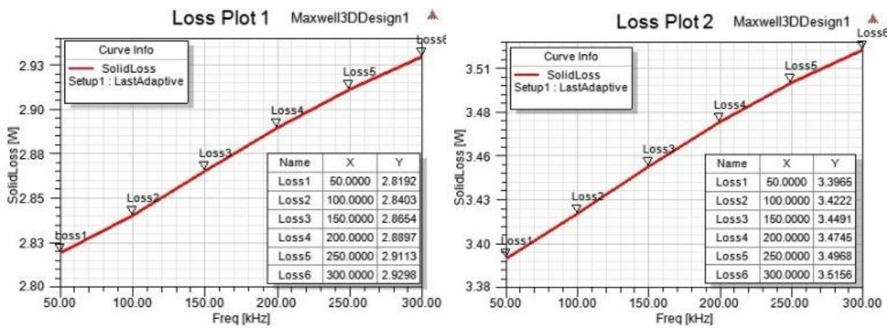
The losses generated in the power transmission process when the operating frequency of the system is from 50kHz to 300kHz are shown in Fig.7. The eddy current losses under the influence of the metal medium can be obtained by comparing the power losses of the system with and without ferromagnetic metal medium.



(a) (b) (c)

Fig.6 Eddy current density distribution in ferromagnetic metal medium(a)Side view(b)Plan view(c) Right view

It can be seen from Fig.7a) that the total energy loss of the system is 2.93W when there is no ferromagnetic medium passing through at the operating frequency of 300kHz, Fig.7b) shows that the total energy loss of the system is 3.52W when there is medium passing through at the operating frequency of 300kHz.



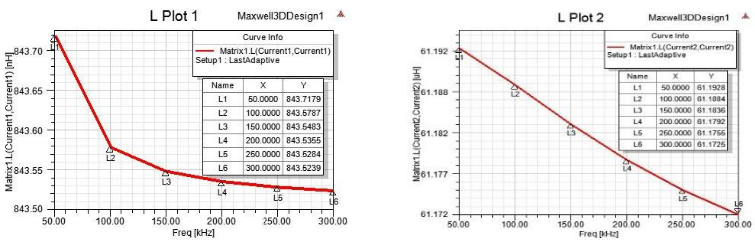
(a) (b)

Fig.7 (a)System energy loss diagram in the absence of medium (b)The energy loss of the system as the medium passes through

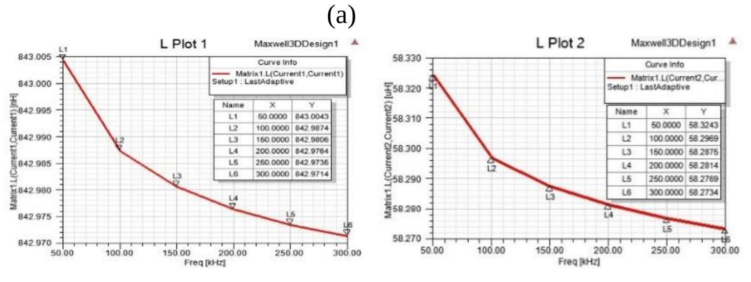
Therefore, the eddy current loss of the system under the influence of ferromagnetic metal medium at the operating frequency of 300kHz is 0.59W. The eddy current loss can be calculated to reduce the transmission efficiency of the system by 8.42%.

When the operating frequency changes from 50kHz to 300kHz and ferromagnetic metal medium passes through, the comparison of the inductance changes of the primary secondary coil in MICWPT system is shown in Fig.8, where L Plot1 is the inductance change trend of the primary coil and L Plot2 is the inductance change trend of the secondary coil. It can be seen from the diagram as a medium through the secondary coil inductance has obvious decrease, due to the secondary coil is closer to the medium, secondary coil inductance is significant, when the working frequency of 300 kHz secondary coil inductance reduced 2.9 μH, the primary inductance is reduced 0.55 nH. It can be seen from the Fig.8 that the coil self-inductance has little influence on the change of working frequency.

It can be seen from the above simulation results that when ferromagnetic metal medium passes through the primary and secondary coils, the influence on the transmission efficiency of MICWPT system is mainly manifested as the decrease of inductance and the increase of energy consumption caused by eddy current effect, which is basically consistent with the theoretical analysis results.



(a)



(b)

Fig.8 (a)Variation diagram of the primary secondary coil inductance in the absence of medium(b)The primary secondary coil inductance variation diagram with the medium

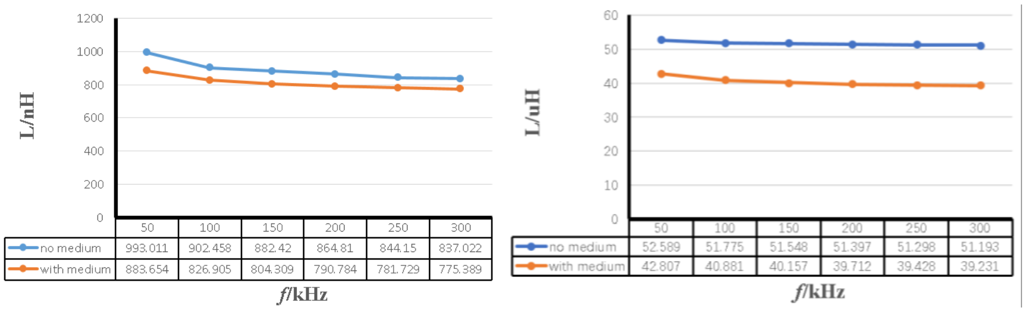
The decrease of inductance causes the change of resonance state of the system, which leads to the decrease of transmission efficiency and transmission power.

3. Experimental verification and result analysis

In order to verify the correctness of theoretical simulation analysis, relevant experimental platform was built according to the simulation model for verification, as shown in Fig.9. The experimental system parameters are consistent with the simulation parameters in table 1, and the remaining parameters are as follows. The resonant compensation capacitors of the primary secondary coil are respectively C_1=13μF, C_2=0.2μF, The working frequency f=300kHz. Input power P_{in}=12W.

Fig.9 Experimental platform for WPT system

The LCR bridge table is used to measure the variation of the inductance parameters of the original secondary coil when ferromagnetic metal medium passes through at 50-300kHz working frequency, as shown in Fig.10.



a) b)

Fig.10 a) Primary inductance change b) Secondary coil inductance change

It can be seen from the Fig.10 that the inductance of the original secondary coil changes significantly with or without medium. When the metal passes directly through the coil, the inductance of the original secondary coil decreases obviously. Since the secondary coil is closer to the metal medium, the reduction of the secondary coil is larger. When the working frequency is 300kHz, the inductance reduction is compared and analyzed, as shown in table 2. The comparison results show that the primary coil decreases by 0.06 μH and the secondary coil decreases by 11.96 μH when ferromagnetic medium passes through the primary secondary coil.

Table 2

Experiment Parameter

Parameters	No medium	With medium	Difference value
Primary inductance (L_1/μH)	0.83	0.77	0.06
Secondary inductance (L_2/μH)	51.19	39.23	11.96

The large difference between the inductance change result and the simulation result is caused by some errors between the measured environment, the physical object, the simulation model and the test instrument. But there's another important reason. The permeability of cast iron is between 200 and 400. With the increase of frequency, the flux density of cast iron reaches saturation and no longer increases, which leads to the increase of exciting current and eddy current phenomenon, which makes the cast iron hot. With the increase of frequency, the flux density of cast iron will not change, and the exciting current will continue to increase. According to equation $L=\frac{d\psi}{dI}$, it can be seen that the inductance of the coil continues to decrease. However, the saturation flux density is not considered in the simulation results, which leads to the difference between the simulation results and the experimental results.

At the working frequency f=300kHz, the load power of the system measured separately is shown in Tab 3.

Table 3

Measured power parameters

Parameters	No medium	With medium	Difference value
Load power (P_{load}/W)	6.99	5.67	1.32
Transfer efficiency (η/%)	58.25	47.25	11.00

According to the measured results, when the ferromagnetic metal medium passes through the original secondary coil, the load power drops by 1.32W and the transmission efficiency of the system drops by 11%, which is basically consistent with the simulation results.

The experimental results show that the ferromagnetic metal medium in the WPT system make the original secondary coil self-induction is reduced, the intensity of magnetic field changes, inductance change led to the decrease of the system resonance frequency shifts the system transmission efficiency, internal ferromagnetism metal caused by eddy current effect produce eddy current loss reduce transmission power led to the decrease of the system transmission efficiency of the experimental results and simulation results are basically identical.

4. Conclusions

Aiming at the WPT application of on-line telemetry system of rolling mill torque, the following conclusions are drawn through theoretical simulation analysis and experimental verification. (1) When the ferromagnetic metal medium passes through the coil of MCIWPT system, the self-inductance of the coil decreases obviously, and the closer it is to the medium, the more obvious the change will be. (2) The existence of ferromagnetic metal medium changes the magnetic field distribution of the system, and the magnetic field generated by the system leads to obvious eddy current phenomenon in the medium. (3) The eddy current loss measured in the experiment increases the total energy loss of the system by 1.32W, and the system transmission efficiency decreases by 11%, which is basically consistent with the simulation results. (4) The transmission power of the system is reduced when ferromagnetic metal medium passes through the transmission channel. The fundamental reason for the decrease of transmission efficiency is that the inductance of the system decreases due to the change of magnetic field distribution, which leads to the deviation of resonant working frequency and the increase of eddy current loss due to eddy current effect.

The conclusion of this paper provides a theoretical reference for the application of radio energy transmission technology in ferromagnetic metal environment and provides a theoretical basis for the application of WPT technology in engineering practice. How to restrain the influence factors of ferromagnetic metal medium on WPT characteristics is the direction of further research in the following work.

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