Electromagnetic Mutual Inductance Coupling Model of Wireless Power Transfer in Oil-gas downhole

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Abstract. According to the wireless power transfer system (WPT) in oil-gas downhole, the structure of the WPT device suitable for the simultaneous existence of oil-water medium in high-temperature and high-pressure environment is put forward by using the principle of electromagnetic induction. Through the analysis of magnetic circuit, the electromagnetic mutual inductance coupling model is established, and the main factors affecting the transmission efficiency are obtained. Based on the model, the system is simulated and verified by experiments, in order to further improve the efficiency of power transfer system.

1. Introduction

WPT technology based on electromagnetic induction coupling principle has gradually matured, and has been rapidly developed and widely applied with the advantages of flexibility, safety and reliability, such as wireless charging for electric vehicles, power supply for Maglev trains. It effectively solves the problems and defects existing in traditional power supply methods for mobile devices and in some special occasions.

Ref. [2] establishes the model of ground electromagnetic resonance WPT system and analyses the main factors affecting the transfer efficiency. Ref. [3] establishes a high-precision simplified model of ground WPT system. Ref. [4] establishes an accurate model of ground WPT system and analyses influence of coil resistance on power transfer efficiency.

However, the design of downhole WPT in oil-gas downhole is more complicated than that of ground WPT, and there is a special problem. Considering the need to withstand high-temperature and high-pressure and the need of shock protection in underground operation and ground operation, the device must be encapsulated in a metal protective cylinder. There must also be a large overflow space, that is, there is a large wireless transfer distance requirements. Because of the complexity underground environment, the research of this system is one of the difficult problems to be solved in this field.
In view of the complexity of the downhole environment, a kind of mutually-sleeved mechanical structure is proposed, and the electromagnetic mutual inductance coupling model considering the characteristics of oil-water medium and the material of the working cylinder is established. Based on the model, the system is simulated and analyzed, and the results are basically consistent with the experimental data obtained from the WPT system.

2. Structure of downhole WPT device for oil-gas

Based on the structure principle of conventional electromagnetic induction loosely coupled transformer, considering the influence of underground oil, gas and water medium, high temperature and high pressure working environment, a kind of mutual mechanical structure radio energy transmission device is designed. The schematic diagram of the principle structure is shown in Figure 1.

The working principle of the device is as follows: the direct current provided by the battery pack is converted into alternating current through the inverter circuit, which supplies the transmitting coil of the device with a constantly changing alternating magnetic field. When the coils of the transmitting part and the receiving part are coupled, the induced electromotive force is generated. In order to improve the efficiency of power transmission, super capacitor energy storage device is added. The rectifying device converts the alternating current induced by the receiving coil into direct current, and then transmits the electric energy to the load to complete the transmission of radio energy.

3. Modeling and analysis of WPT system

The equivalent circuit of electromagnetic mutual inductance model is established, as shown in Figure 2.

The KVL loop equations of the model are as follows:

\[
\begin{align*}
\dot{U}_p &= (R_p + j\omega L_p)\dot{I}_p - j\omega M\dot{I}_s \\
\dot{U}_s &= -(R_s + j\omega L_s)\dot{I}_s + j\omega M\dot{I}_p
\end{align*}
\]

By compensating the inductors in series and eliminating the complex factor, the input and output voltage of the primary and secondary sides are obtained respectively.

It is further concluded that the transfer efficiency of the system is as follows:

\[
\eta = \frac{P_s}{P_p} = \frac{(wM)^2 R}{[R_p (R_s + R) + (wM)^2][R_s + R]} \tag{2}
\]
In order to simplify the analysis, the improved mutual inductance model considering the characteristics of metal protective cylinder is transformed into the equivalent two-port network model, as shown in Figure 3.

Figure 3. Equivalent dual-port network model considering the characteristics of metal protective cylinders

In the Fig.3, $L_p$ and $L_s$ are self-inductance of primary and secondary windings; $R_p$ and $R_s$ are internal resistance of primary and secondary windings; $M$ is mutual inductance between primary and secondary windings; $C_e$ is distributed capacitance between primary and secondary windings. Among them, $W_1$ is a loosely coupled transformer dual-port network and $W_2$ is a distributed capacitor dual-port network.

Impedance parameter matrix $Z$ of loosely coupled transformer dual-port network $W_1$ is

$$Z = \begin{bmatrix} Z_p & Z_M \\ Z_M & Z_s \end{bmatrix} = \begin{bmatrix} R_p + j\omega L_p & j\omega M \\ j\omega M & R_s + j\omega L_s \end{bmatrix}$$

(3)

The transfer parameter matrix $T$ of distributed capacitance dual-port network $W_2$ can be expressed as

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} 1 & \frac{2}{j\omega C_e} \\ 0 & 1 \end{bmatrix}$$

(4)

The total admittance matrix $Y_T$ of parallel dual-port network can be expressed as

$$Y_T = \begin{bmatrix} \frac{R_s + j\omega L_s}{\Delta Z} + \frac{j\omega C_e}{2} & -\left(\frac{j\omega M + j\omega C_e}{2}\right) \\ -\left(\frac{j\omega M + j\omega C_e}{2}\right) & \frac{R_p + j\omega L_p}{\Delta Z} + \frac{j\omega C_e}{2} \end{bmatrix}$$

(5)

The total admittance matrix of parallel dual-port network is transformed into transfer parameter matrix, which can be expressed as

$$T_T = \begin{bmatrix} T'_{11} & T'_{12} \\ T'_{21} & T'_{22} \end{bmatrix} = \begin{bmatrix} \frac{2(R_p + j\omega L_p) + j\omega C_e\Delta Z}{2j\omega M + j\omega C_e\Delta Z} & \frac{2\Delta Z}{2j\omega M + j\omega C_e\Delta Z} \\ \frac{4(R_p + j\omega L_p) + 2j\omega C_e\Delta Z(R_p + R_s + j\omega L_p + j\omega L_s) + 2\omega^2 MC_e\Delta Z}{2j\omega M + j\omega C_e\Delta Z} & \frac{2(R_s + j\omega L_s) + j\omega C_e\Delta Z}{2j\omega M + j\omega C_e\Delta Z} \end{bmatrix}$$

(6)

The transfer parameter equation of the improved mutual inductance model considering the characteristics of metal protective cylinder is as follows:
\[
\begin{align*}
U_p &= T'_{11}U_s + T'_{12}I_s \\
I_p &= T'_{21}U_s + T'_{22}I_s
\end{align*}
\] (7)

If the load is, the total input impedance of the system is

\[
Z_{\text{TOTAL}} = \frac{U_p}{I_p}
\] (8)

According to the electromagnetic mutual inductance coupling model of downhole WPT system, the total input impedance of the system is mainly related to the system internal resistance, primary and secondary mutual inductance, working frequency and load resistance, which is basically consistent with the main factors affecting transfer efficiency.

4. Simulation and experimental analysis

4.1. Simulation

The finite element analysis model is established by using COMSOL multiphysics multi physical field software. The two-dimensional axisymmetric finite element model is selected to solve the model. The magnetic flux density model of the magnetic field is obtained by simulation, as shown in Fig. 4.

![Figure 4. Flux density modes of magnetic fields](image)

Fig. 5 shows the voltage and current waveforms at both ends of the transmitting coil and the receiving coil. The simulation results show that the receiving coil can generate inductive electromotive force and inductive current, which shows that the WPT device designed in this paper can realize the wireless transfer of electric power.
4.2. Experimental results

In order to verify the simulation results, the functional principle prototype of the WPT device is made after selecting the appropriate metal shell material, as shown in Figure 6.

![Physical diagram of WPT device](image)

It can be seen from the simulation that the induction electromotive force is very small. In order to improve the efficiency of power transfer, a supercapacitor power storage device is added to the device. In the experiment, the transfer medium is oil-water mixture, and the load is 5W LED lamp. When the transmitting coil is fully coupled with the receiving coil, the LED can be lit, which verifies the rationality of the design of downhole WPT system for oil and gas. After the system is stable, a set of test data is shown in Table 1.

| load             | Transmitter coil voltage (V) | Receiving coil voltage (V) | transmitter coil current (mA) | Receiving coil current (mA) |
|------------------|------------------------------|---------------------------|-------------------------------|----------------------------|
| no load          | 16.0                         | 12.6                      | —                             | —                          |
| LED (100Ω)       | 15.7                         | 6.2                       | 220                            | 20.0                       |

Table 1 shows that the inductive voltage and current of the receiving coil vary with the load. After testing and calculation, the power transfer efficiency of the device is 27.2%, and the transfer distance is 25 cm. The experimental data are basically the same as the simulation results. The correctness of the electromagnetic mutual inductance coupling model of the downhole WPT device for oil-gas is verified.

5. Conclusion

On the basis of theoretical analysis and simulation study of WPT in oil-gas downhole, this paper establishes an electromagnetic mutual inductance coupling model considering the characteristics of oil-water medium and metal protective cylinder. Based on this model, the system is simulated and studied. The results applied to the WPT system in oil-gas downhole are verified. The electromagnetic mutual inductance coupling model of downhole WPT system for oil-gas is established, which fills the gap in this field and provides an effective modeling method for in-depth study of WPT in all directions.
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