

Research on Efficiency Optimization of Rail Transit Wireless Power Transmission System Based on Electromagnetic Detection

Yunzhi Lin^{1, *} and Yixiong Lai²

Abstract—In the installation of a dynamic wireless power transmission system of rail transit, the distance change among coils causes large power loss under high power conditions. Due to the limitation of detection surface and Doppler effect as well as other deficiencies, the traditional ranging methods cannot be adapted to fast, continuous, and large-area dynamic ranging in the wireless power transmission of rail transit. Therefore, the paper proposes a single coil dynamic wireless power efficiency optimization method based on electromagnetic induction for the first time. The distance between the transmitter and receiver is taken as the intermediate quantity, and the relationship between the detection coil amplitude and the wireless power transmission efficiency is constructed. Firstly, based on electromagnetic field theory, a quantitative relationship among the detection coil amplitude, wireless power transmission efficiency, and coil distance is established. Then detection experimental platform is designed. Finally, relevant experiments are accomplished through the established experimental platform. The experimental results show that for the area with low power transmission efficiency on the whole dynamic wireless power transmission line, relevant ranging data can be obtained by detecting the amplitude.

1. INTRODUCTION

Wireless power transmission technology, hereafter referred to WPT, converts municipal electricity into high frequency AC through a converter, so that the transmitting coil on the ground generates alternating magnetic field with a specific frequency. The magnetic field is coupled to the receiving coil, and the alternating current is induced therein, which realizes WPT. The technology has gained rapid development in recent ten years. In electrified transportation, the wireless charging technology of rail transit has initially entered the practical stage.

For a dynamic WPT system, transmission efficiency is an important index and is of vital significance for a high power system. The distance between transmitter and receiver is an important factor for system efficiency, but in the installation of transmitting coils, the change of roadbed, the difference of construction quality and the thermal expansion and contraction of materials will lead to the inconsistency of transmission distance between different locations on the whole line, thus it will affect the overall efficiency. Fig. 1 presents a typical dynamic wireless power supply system for rail transit.

At present, the main ranging methods suitable for engineering field include laser ranging, ultrasonic ranging, and electromagnetic testing.

Laser ranging [1,2] refers to moving a laser beam from the initial position to the target and reflecting it back from the target. It is a method to determine the measurement distance based on the measurement time of the round trip of the emitted laser. Laser ranging plays an important role in military applications, engineering construction, science and technology, shipbuilding, as well as other

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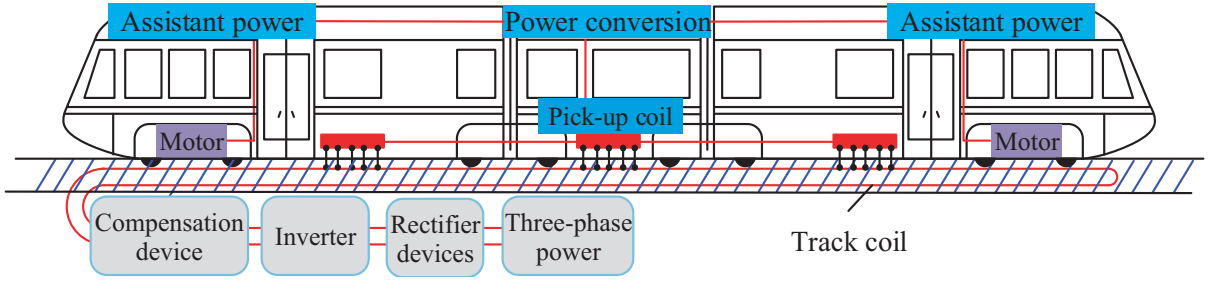


Figure 1. Typical dynamic wireless power supply system for rail transit.

fields. Ultrasound ranging [3,4] emits a certain frequency of ultrasound. When the acoustic wave encounters obstacles, it will produce reflected echo to compare the reflected echo with the emitted acoustic wave and measure the time difference. Then the distance is calculated according to the speed of the ultrasonic wave propagating in the medium. Electromagnetic ranging [5–8] emits electromagnetic waves modulated by alternating current from one end of the line and returns from the other end. The phase difference between the transmitted wave and the echo is measured by a phase discriminator, and the distance can be calculated according to the measured phase difference.

Laser ranging is not applicable in large area plane detection and dynamic detection, and it is greatly affected by rain and fog weather. Doppler effect exists in the detection of fast and dynamic moving targets by ultrasonic ranging method, which will result in larger detection errors. Therefore, based on the method of electromagnetic detection, the paper proposes to optimize the transmission efficiency of the system according to the amplitude, so as to adjust the distance between the receiving end and transmitting orbit. According to different transmission distances of the system, the efficiency of the system will change, and then the amplitude of the detection coil will change, so that the system efficiency of the whole line can be optimized. The proposal exerts an important guiding significance on the application of dynamic WPT system of rail transit.

2. WORKING PRINCIPLE OF DETECTION SYSTEM

2.1. System Efficiency

Figure 2(a) is the theoretical principle of WPT system. The factors affecting the transmission efficiency of the system in WPT include the distance between coils, the radius of coils, the number of turns between coils, and the frequency of the system. When transmitting and receiving coils share the same structure parameters and the same frequency, the influence of coil distance on transmission efficiency is mainly considered. The theoretical formulas under the SS-type topology are as follows [9–12].

When the structures of transmitting coil and receiving coils are the same, $R_p = R_s = R$. The

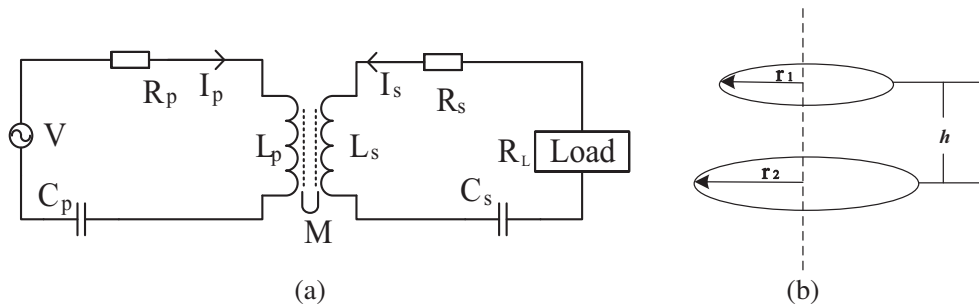


Figure 2. Theoretical principle.

transmission efficiency η of the system is expressed [13–16] as by formula (1).

$$\eta = \frac{1}{\left(1 + \left(\frac{R + R_L}{\omega M}\right)^2\right) \frac{R}{R_L} + \frac{R}{R_L}} \quad (1)$$

As shown in Fig. 2(b), the spacing between the two coaxial circular coils with radii of r_1 and r_2 respectively is d . We denote $K = r_1/r_2$, which is called the relative size, and denote $j = d/r_1$, which is called the relative distance. Since the mutual inductance $M_{12} = M_{21}$, the calculation of the mutual inductance (M) is proven by the Biot-Savart law to be formula (2):

$$M = \frac{\mu_0 r_1}{2} \int_0^k \int_0^{2\pi} \frac{x(1 - x \sin \theta)}{(x^2 - 2x \sin \theta + 1 + j^2)^{3/2}} d\theta dx = \frac{\mu_0 r_1}{2} I_0 \quad (2)$$

where in engineering design, K is controlled between 0 and 0.3. At this time, two terms $x \sin \theta$ and x^2 in formula (2) are omitted, easily resulting in the expression of mutual inductance as follows:

$$M = \frac{\mu_0 r_1}{2} I \approx \frac{\mu_0}{2} \frac{\pi r_1^2 r_2^2}{2(h^2 + r_1^2)^{3/2}} \quad (3)$$

In formula (3), μ_0 is the vacuum permeability; n is the turn number of coils; r_1 is the radius of detecting coils; r_2 is the radius of excitation coils; h is the distance between coils.

2.2. Principle of Electromagnetic Detection

The detection schematic given in Fig. 3 adopts a coil detection structure with single excitation and single reception. When sinusoidal alternating current is introduced into the excitation coil, alternating magnetic field is produced in space. The receiving coil can detect the changed electrical signals in space. However, due to different positions of the two coils, different electromotive forces are generated. According to the relationship between coil position and system efficiency in formula (1), the change of system efficiency is reflected by the amplitude, and the transmission efficiency of the system is tracked.

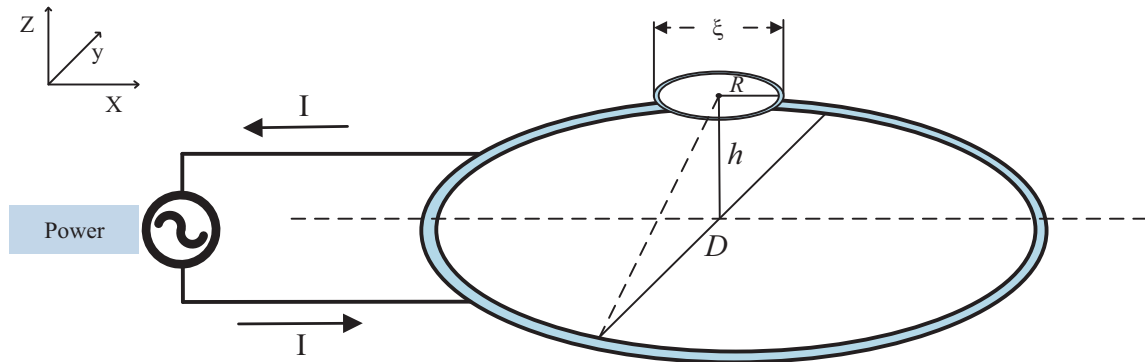


Figure 3. System structure diagram.

According to the principle of electromagnetic induction, when the flux in the conductor changes with time, the corresponding electromotive force will be generated in the circuit of the inductive conductor [17–20], and the following formula holds:

$$E = -\frac{d\varphi}{dt} = -N \cdot \frac{d}{dt} \oint_s \vec{B} \cdot d\vec{S} \quad (4)$$

where N is the number of turns of the coil, φ the magnetic flux through the surface S , and E the induction electromotive force.

In a constant magnetic field in space, the current in the transmitting coil is simplified to line current. According to Biot-Savart Law, the magnetic induction intensity of the transmitting line can be expressed as:

$$B = \frac{\mu_0}{4\pi} \int_{\Gamma'} \frac{Id\mathbf{l}' \times \mathbf{e}_R}{|r - r'|^2} \quad (5)$$

where $|r - r'|$ represents the distance between the field point and the original point, Γ' the closed loop of the transmitting coil, and $\mathbf{e}_R$ the unit vector from the source point to the field point. Simplified results are as follows:

$$B = \frac{\mu_0 I}{2\pi |r - r'|} \quad (6)$$

In the formula, I is a current excitation signal, and the electromotive force in the coil is expressed as:

$$E = -i\omega BS = -i\omega \int_s \frac{\mu_0 I}{\pi \sqrt{\left(\frac{D}{2}\right)^2 + h^2}} ds \quad (7)$$

The detection amplitude ξ is expressed as:

$$\xi = \omega \int_s \frac{\mu_0 I}{\pi \sqrt{\left(\frac{D}{2}\right)^2 + h^2}} ds \quad (8)$$

3. DESIGN OF SYSTEM DETECTION PLATFORM

3.1. Overall System Design

The schematic diagram of EMF detection system based on electromagnetic induction is shown in Fig. 4. It includes a class E power amplifier circuit combined with a DE150-501N04A signal generator

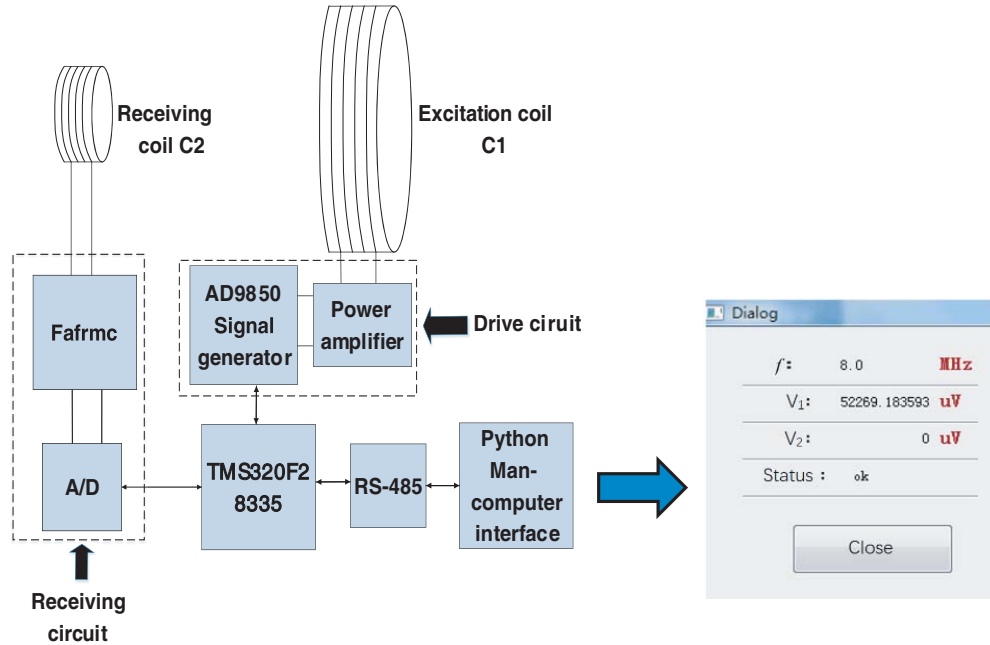


Figure 4. System schematic diagram. (Explain: Fafrmc is Forward amplifier frequency reduction modulation circuit).

(transmitter) and a transmitting coil to provide excitation signal. The structure of single excitation, double coils is designed as the measurement model, which provides an experimental platform for the efficiency detection among coils. The output signal is amplified and smoothed by the single coils detection module (receiver). The data processing center based on TMS320F28335 is used to measure the magnitude and other information of the system, and the data are transmitted to Python human-machine interface through communication 485 interface to collect the experimental data. The technical principle and structure of the detection system are shown in Fig. 4.

3.2. Transmitter Principle

The transmitter employs a class E power amplifier circuit, which includes a power supply module, a data transmission module of receiving circuit, an output signal module of excitation coil, and a driving signal module. In electromagnetic detection, the transmitter provides the field source signal [20–22]. Transmitter is an important module of a detection system and the basis of a normal operation of the system. The design block diagram of a class E power circuit is shown in Fig. 5.

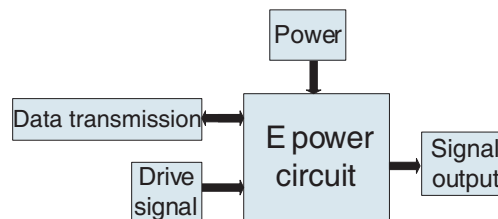


Figure 5. Design block diagram of transmitter circuit.

A picture of transmitter circuit of the system is shown in Fig. 6.

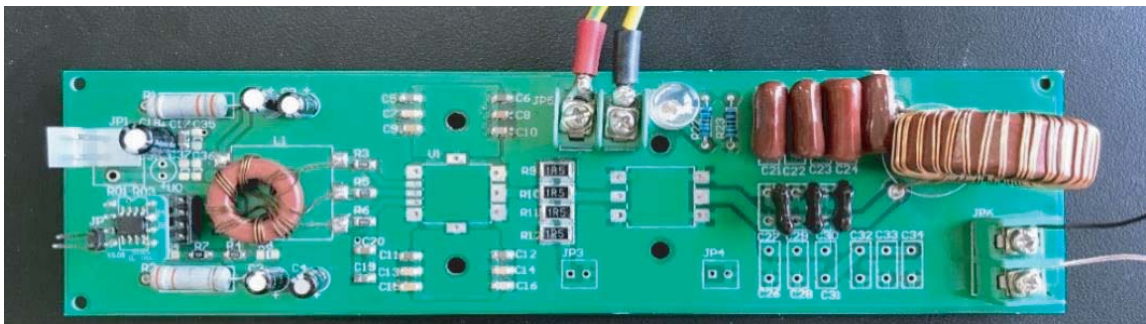


Figure 6. Real product picture of transmitter circuit.

3.3. Theory Consideration of the Receiver

The receiving circuit consists of the following modules: power supply module, Fafrmc power amplifier module of the energizing circuit, and RS485 serial communication module. A TMS320F28335 DSP controller is used to control the whole circuit. The design diagram of system is showed in Fig. 7.

Using CSEM (Controlled Source Electromagnetics Method) in frequency domain, signals are always transmitted by a transmitter. Because there is a lot of interference in the signal transmission, the SNR is small in the frequency band. The way to acquire valid signals in the receiver should be taken into consideration during the design.

At the present stage, there are two general ways to increase the SNR [23]. One way is using a broad band analog signal transmission channel to realize high-speed data acquisition and digitization. However, the signal processing will be difficult because the noise will be acquired and digitized along

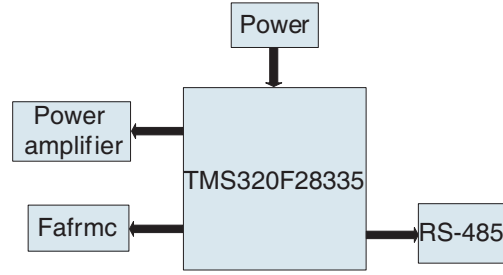


Figure 7. The design diagram of the receiver circuit.

with signal. The other way is using a narrow band analog signal transmission channel along with signal detection devices to acquire the signal. The disadvantage of the method is that the circuit will be very complex while a large number of detection devices are needed. And the circuit is not flexible to adjust the frequency in different situations.

To overcome these drawbacks, a receiver is designed based on the properties of field source signal and the principle of multiplicative frequency conversion. The schematic diagram of the designed receiver is as shown in Fig. 8.

In the schematic diagram, a multiplier is designed based on the principle of multiplicative frequency conversion. The signal processing will be simplified by using the multiplier to change the frequency of signal, and it can make the signal move to a lower frequency.

$$A_n \sin(\omega_n + \phi_n)t \times \sin \omega_L t = \frac{1}{2} A_n \cos((\omega_n + \omega_L)t + \phi_n) - \frac{1}{2} A_n \cos((\omega_n - \omega_L)t + \phi_n) \quad (9)$$

where ω_n is the frequency of the signal, A_n the amplitude of the signal, ϕ_n the phase of the signal, and ω_L the frequency of the DDS output signal. According to Formula (9), two new signals are generated by multiplying the received signal and DDS output signal, and the frequencies of the new signals are $\omega_n - \omega_L$ and $\omega_n + \omega_n$.

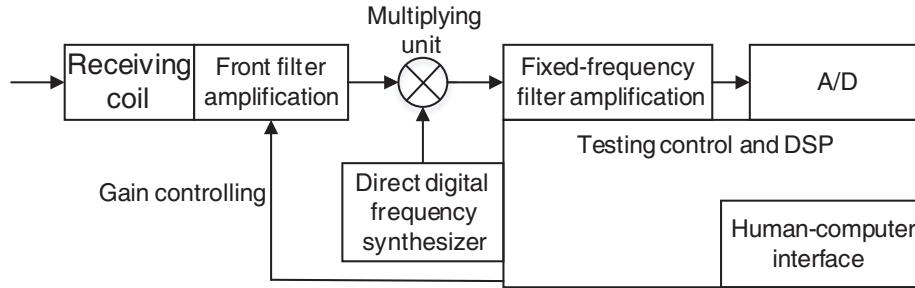


Figure 8. The schematic diagram of the designed receiver.

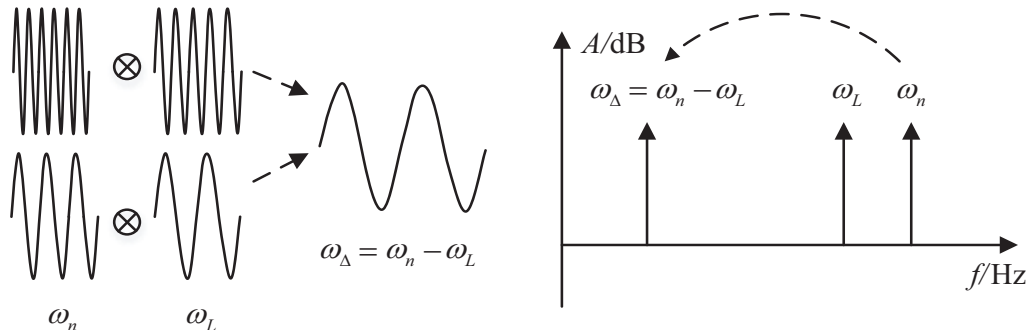


Figure 9. The schematic diagram of frequency conversion.

After signals pass the filter circuit, $-A_n \cos((\omega_n - \omega_L)t + \varphi_n)/2$ component is filtered out, and $A_n \cos((\omega_n + \omega_L)t + \varphi_n)/2$ component of the new signals will be kept. It can save the information of the original signal.

The original signal information is preserved while the frequency is changed to another frequency. Applying the method to original signals with different frequencies and choosing a same aiming frequency will reduce the number of signal processing channels and simplify the circuit. The schematic diagram of frequency conversion is showed in Fig. 9.

The experimental receiver is shown in Fig. 10.



Figure 10. The PCB of experimental receiver.

4. EXPERIMENTS

4.1. Experimental Platform

Experimental platform of the electromagnetic induction efficiency detection system is shown in Fig. 11. The platform includes the following parts: Transmitter coil C1, detection coil C2, drive circuit, receive circuit, RS485 communication, and receiver coil C3 used for efficiency detection. The system controller is TMS320F28335. The sine-wave excitation source in the signal-generate end is based on a class-E amplifier circuit. The signal generator combined with low pass filter and power amplifier circuit excites transmitter coil C1 to generate an alternating magnetic field.

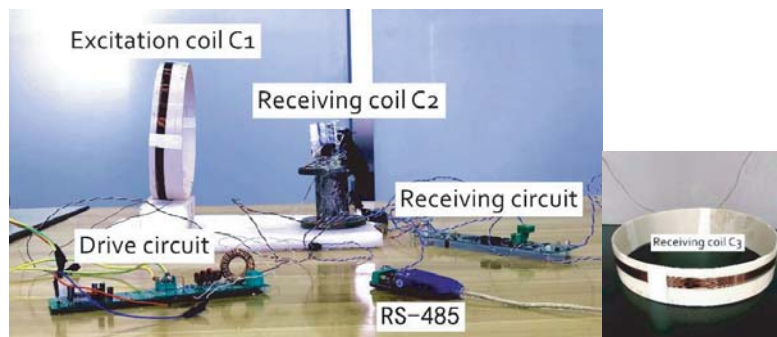


Figure 11. Experimental platform.

At the receiving end of the signal, the signal detected by coil C2 will be processed by front stage amplifier and frequency reduction circuit. The EMF (Electromotive Force) information is acquired by phase discriminator from processed signal. The phase discriminator is formed with the platform controlled by TMS320F28335. The EMF information is then transmitted by RS485 interface. Finally, the amplitude data will be shown in the man-machine interface established with Python.

4.2. Fluctuation Experiment

Recurrent fluctuations of distance within 0.2 m $\sim$ 0.3 m between transmitter coil and detection coil is executed to simulate the distance change caused by topography, bends, climbs, and other situations. 30 groups of amplitude data are detected by the system and recorded by python man-machine interface.

The Amplitude-Distance curve acquired by the detection system is shown in Fig. 12. It can be shown in Fig. 12 that while the excitation signal is constant, the amplitude and distance are under a negative correlation, which is consistent with the theoretical situation. The results show that the system has a good performance.

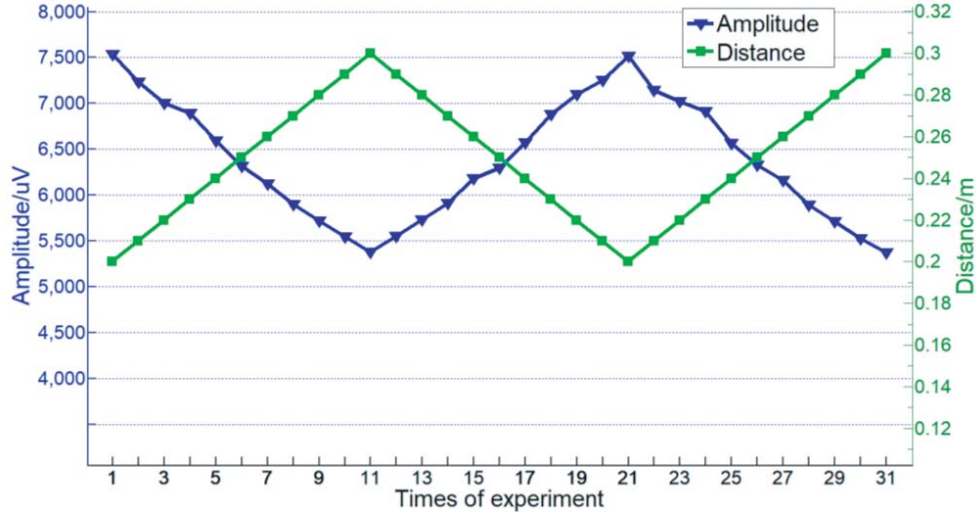


Figure 12. The amplitude — distance curve of system.

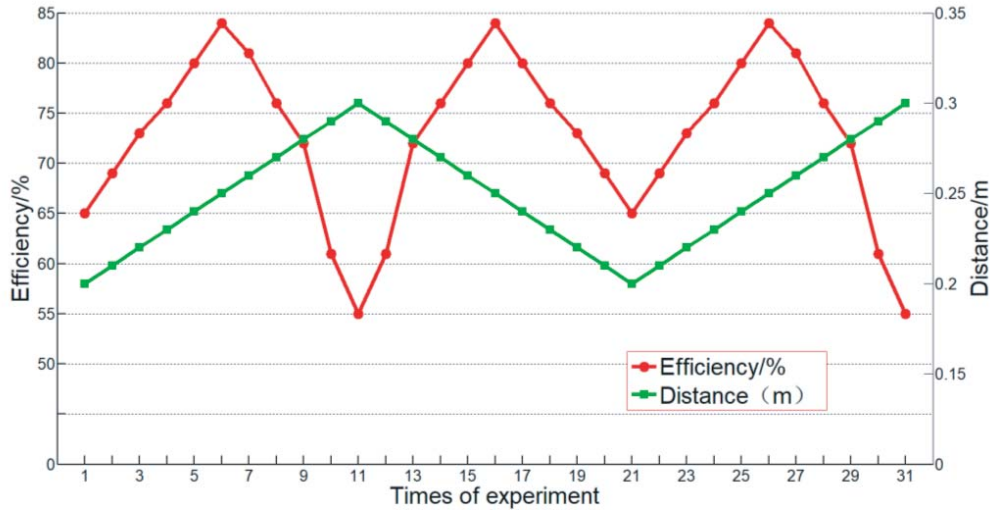


Figure 13. The coil efficiency-distance curve of system.

The EMF-Coil Efficiency curve is shown in Fig. 13. The detection coil is replaced by C3, which has same physical parameters as the transmitter coil. Under 8 MHz detection frequency, the distance-efficiency curve is obtained by changing distance between transmitter coil and detection coil, as shown in Fig. 13. From the curve, we can see that the best efficiency is reached at a distance of 0.25 m, and the 10 cm fluctuation has a great interference to efficiency. The results show that an optimal constant distance between coils is important to the system.

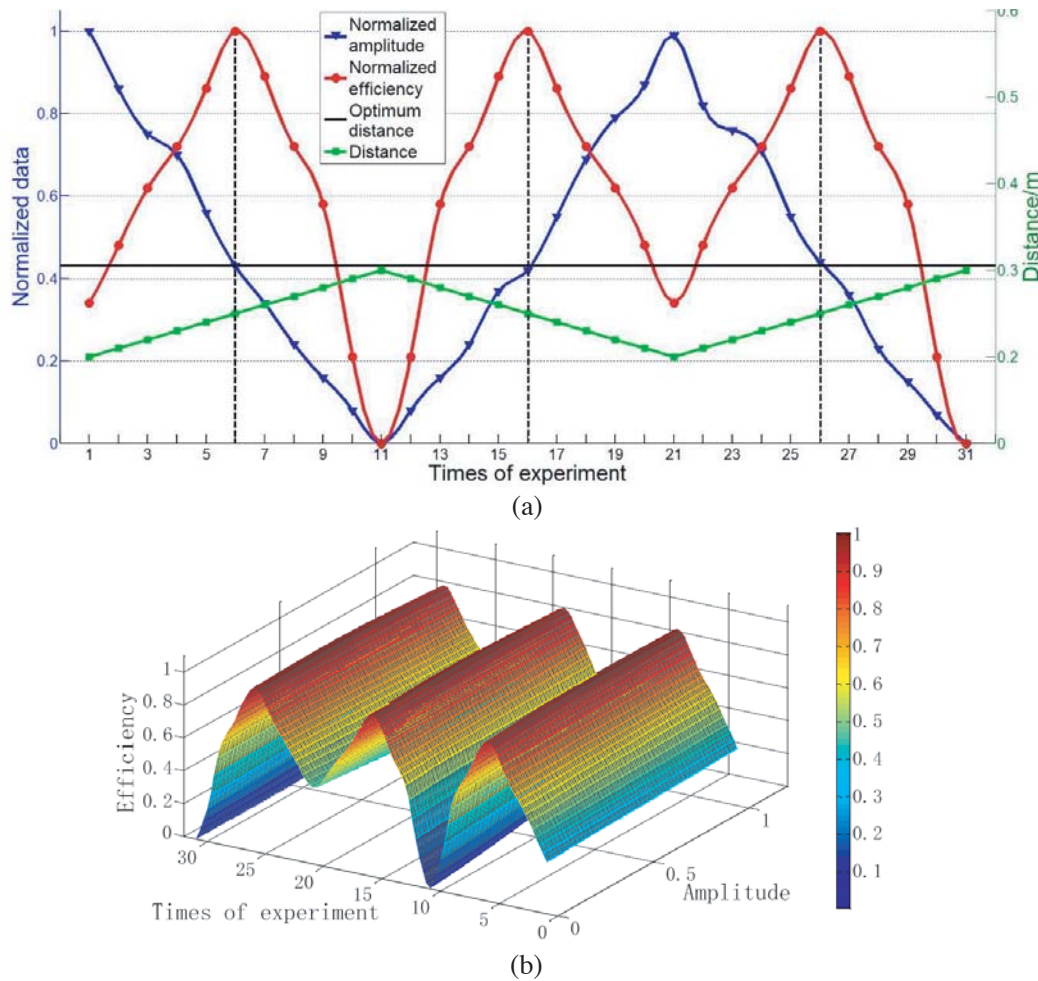


Figure 14. (a) The relation between the normalized data and the distance. (b) The three-dimensional curve between the normalized data and the distance.

It is inconvenient to analyze the data because of the different dimensions between amplitude and coil efficiency. Data normalization by min-max standardization is used in the paper. The normalized results are shown in Fig. 14, including the relations among the normalized amplitude, normalized coil efficiency and distance, and the forms of two-dimensional curve and three-dimensional curve.

Figure 14(a) shows that the amplitude and efficiency are not under a proportional relationship. The reason is that magnetically coupled resonant energy transfer mode has frequency classification characteristics. However, amplitude of the optimal efficiency distance is constant in the experiment. Therefore, detecting amplitude changes provides an approach to transmission efficiency adjustment on the line. Fig. 14(b) shows the three-dimensional curve of amplitude, efficiency, and distance, it provides a vivid way to see the disturbance to efficiency from distance.

5. CONCLUSION

In the paper, a single coil detection method is proposed based on electromagnetic induction. Detection structure fabrication, detection system design, and man-machine interface design are realized based on the method. The fluctuation experiment is proceeded, and the relationships among coil distance, detection coil amplitude, and coil efficiency are analyzed. The conclusions are as follows:

(1) The research results show that the change of optimal efficiency on the radio power transmission line can be acquired by electromagnetic detection. Optimization can be reached according to the relation

between amplitude and coil distance. In experiments of the paper, when an optimal transmission efficiency is 84% the amplitude is 63000 uV, and coil distance is 0.25 m.

(2) Dynamic radio power transmission in the rail transit field has a problem of efficiency fluctuation. In the paper, an electromagnetic detection solution is proposed, which has great significance for dynamic radio power transmission rail engineering.

Dynamic radio power transmission technology has a wide application in rail transit field. The influences of excitation signal, coil radius, coil relative position, and other factors are also a hotspot that needs to be studied.

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