Power line communication in online detection of cable intermediate joint

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ABSTRACT

The intermediate joint is the weakest part of the insulation in the cable line. How to efficiently and reliably transmit the status information of the cable intermediate joint is the key in the online detection of the cable intermediate joint. By analyzing the characteristics of power line channel and the coupling principle of inductive coupler, this paper builds the power line communication (PLC) system model between cable intermediate joints based on orthogonal frequency division multiplexing (OFDM), considers the influence of inductive couplers at the transmitting end and receiving end, and simulates and analyzes the relationship between different signal-to-noise ratio (SNR) and bit error rate (BER) curve. The simulation results show that the PLC system with coupler can reduce the BER and improve the transmission performance of the system by changing the encoding method and modulation method, which provides a new idea for the effective transmission of online detection data of cable intermediate joint.

Keywords: Cable intermediate joint, PLC, inductive coupler, OFDM, online detection

1. INTRODUCTION

The insulation status of cable intermediate joint directly affects the stable operation of power grid cable system. In order to find the change of insulation status of cable intermediate joint in time, it is urgent to study a kind of online detection communication technology suitable for cable intermediate joint. The cable joint temperature online detection system is established by using ZigBee and GPRS wireless communication technology[1]. These methods are susceptible to the influence of the terrain environment, and the reliability needs to be improved. The monitoring and diagnosis system of underground 22.9 kV XLPE cable is built by using optical fiber sensor and single-mode optical fiber[2]. This method has strong anti-electromagnetic interference ability, but its application cost is high and its construction is difficult. Some researchers proposed a wireless monitoring system for medium voltage cable joints using LoRa low-power outdoor communication technology[3]. Similarly, some researchers have proposed a wireless sensor network based on NB-IoT and LoRa technology to detect the insulation status of the distribution network[4]. This technology has low power consumption, but it is not mature enough to achieve full coverage at present. Considering the particularity of the working environment of the cable intermediate joint, the PLC based on the cable body is considered to be a more reliable data communication scheme at present. Many researchers have studied the PLC and used the OFDM technology to build the communication system model[5-6], but in the modeling process, they mainly focus on modulation and demodulation, channel estimation, etc. There is less research on communication coupling problem in the practical application process.

By analyzing the characteristics of power line channel and the coupling principle of inductive coupler, this paper adopts inductive coupling to realize the transmission of high-frequency carrier signal. The PLC system model between cable intermediate joints is built based on OFDM. Considering the influence of inductive couplers at the transmitting end and receiving end, the relationship between different SNR and BER curve is simulated and analyzed. The simulation results show that the PLC system can realize the effective transmission of cable joint state detection data, and the PLC system with coupler can effectively reduce the BER of the system by changing the encoding method and modulation method.

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2. CHANNEL CHARACTERISTICS AND COUPLING PRINCIPLE

2.1 Power line channel characteristics

When the medium-voltage (MV) power line transmits the high-frequency carrier signal between the cable intermediate joints, the channel characteristics are mainly divided into impedance characteristics, attenuation characteristics, and noise characteristics. Given the terminal voltage and current of the transmission line, taking the terminal of the transmission line as the starting point for calculating the distance, the voltage and current at the distance x from the terminal of the transmission line are:

$$\begin{aligned} \dot{U} &= \dot{U}_2 \cosh(\gamma x) + Z_c \dot{I}_2 \sinh(\gamma x) \\ \dot{I} &= \dot{I}_2 \cosh(\gamma x) + \frac{1}{Z_c} \dot{U}_2 \sinh(\gamma x) \end{aligned} \tag{1}$$

where U_2 and I_2 are the voltage and current at the end of the transmission line. U and I are the voltage and current from terminal x. γ is the transmission constant of the line, and Z_c is the characteristic impedance of the line:

$$\begin{aligned} Z_c &= \left(\frac{R + j\omega L}{G + j\omega C}\right)^{1/2} \\ \gamma &= \alpha + j\beta \end{aligned} \tag{2}$$

where R, L, C, G are the distribution parameters of cable per unit length. α represents the attenuation constant, and β represents the phase constant. According to a large number of measured data[7], the α can be approximated as:

$$\alpha(f) = a_0 + a_1 f^k \tag{3}$$

where a_0, a_1, k are constants. According to the attenuation model of unit length power line, the attenuation of a section of transmission line with length L can be expressed as:

$$A(f,d) = \exp[-a(f)\cdot L] = \exp[-(a_0 + a_1 f^k)\cdot L] \tag{4}$$

Since the MV power line is not directly connected with the user, the noise of the MV power line mainly comes from the relevant equipment of the distribution network and wireless interference. The overall noise of the system increases with the increase of frequency. The change of terrain and climate environment will also cause the change of noise around the cable to varying degrees, mainly including background noise and burst noise.

2.2 Coupling principle analysis

The carrier equipment needs to couple the carrier signal to the overhead line or cable line through the coupling equipment. Capacitive coupler is mostly used for overhead lines, while an inductive coupler is mostly used for cable lines. Clamp inductive coupling equipment is a coupling method based on the principle of electromagnetic induction, which can realize data communication under the condition of an uninterrupted power supply. Compared with the injection inductive coupler, it is more conducive to realize the effective transmission of cable intermediate joint state detection data.

The coupler is clamped on the cable line, and the three-phase cable core and shielding layer of the cable passes through the coupler magnetic ring. There is an air gap at the magnetic core interface, which is equivalent to a loosely coupled transformer. The coupler needs to be equivalent to a mutual inductance model for analysis. The mutual inductance M in Rogowski coil is adopted and corrected considering the influence of air gap[8-9]. The corrected expression of mutual inductance M, self-inductance L_1 of primary coil, and self-inductance L_2 of secondary coil can be expressed as:

$$M = \frac{\mu_0 \mu_{fe} l N_1 N_2 h \ln(\frac{b}{a})}{2\pi(l_1 + 2K\delta\mu_{fe})}$$
$$K = \frac{(b-a)h}{(b-a)h + (b-a+2h)\delta} \quad (5)$$
$$L_1 = \frac{\mu_{fe} N_1^2 (b-a)h}{\pi(b+a) - 4\delta}$$
$$L_2 = L_0 x$$

where l_1 is the length of the magnetic core loop, a is the inner radius of the coupler, b is the outer radius of the coupler, h is the height of the coupler, μ_{fe} is the permeability of the magnetic ring, μ_0 is the vacuum permeability, δ is the length of a single air gap, N_1 is the number of coil turns on the primary side, N_2 is the number of coil turns on the secondary side, L_0 is the distributed inductance per unit length of the cable, and x is the length of the cable, $l = l_1 + 2\delta$.

3. PLC SYSTEM MODEL

Due to the limited length of a single cable, a line usually needs multiple cable joints to extend the power supply length. The conventional data communication method has certain limitations, using the transmission line as the carrier signal transmission medium is expected to meet the practical application requirements. The structure diagram of the PLC system between cable intermediate joints is shown in Figure 1.

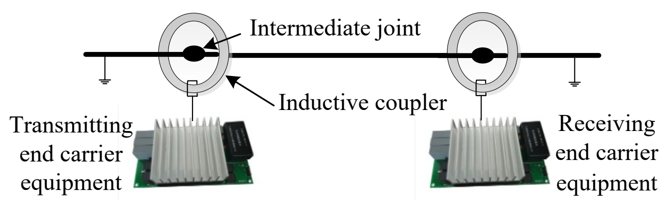

Figure 1. Structure diagram of the PLC system between cable intermediate joints.

The carrier equipment at the transmitting end modulates and amplifies the status data of the cable intermediate joint, and couples the high-frequency carrier signal to the cable shielding layer and the three-phase cable core through the high-frequency cable connection clamp inductive coupler. At the receiving end, the coupling reception is carried out through the principle of electromagnetic induction, connected with the high-frequency cable, and transmitted to the carrier equipment for demodulation processing, so as to obtain the status data of the cable intermediate joint at the transmitting end. The cable shielding layer outside the inductive coupler is grounded to form a loop.

At present, the carrier equipment mostly adopts the multi-carrier modulation technology based on OFDM. In order to ensure the effective transmission of state data between cable intermediate joints, the simulation modeling based on OFDM modulation and demodulation technology is considered, and the inductive couplers at the transmitting end and receiving end are modeled to build the simulation model of the PLC system between the cable intermediate joints.

3.1 PLC system model based on OFDM

The block diagram of the PLC system between cable intermediate joints based on OFDM is shown in Figure 2. At the transmitting end, the carrier equipment receives the state data of the cable intermediate joint to be transmitted, takes the 44-bit binary data as a frame, and expands the frame length through coding. After channel mapping and serial-parallel conversion, the PN training sequence is introduced to transform the data by IFFT. Then set the guard interval, add the cyclic prefix and parallel-serial conversion, convert the discrete digital signal into continuous analog signal through DA conversion, and transmit it to the power line through the coupling protection circuit after up-conversion. At the receiving end, after coupling protection circuit, down-conversion and AD conversion, the signal is changed back to the discrete digital signal, the cyclic prefix is removed, the subcarrier is demodulated by FFT, channel estimation and channel compensation are carried out to overcome signal distortion, and then the state data of cable intermediate joint at the transmitting end is obtained after de-mapping and decoding.

The simulation model of the PLC system designed in this paper will not include the process of signal conversion and up-down conversion, and the discrete complex signals will be transmitted in the channel. After parallel-serial conversion at the transmitting end, the real and imaginary part waveforms of the signal are shown in Figure 3.

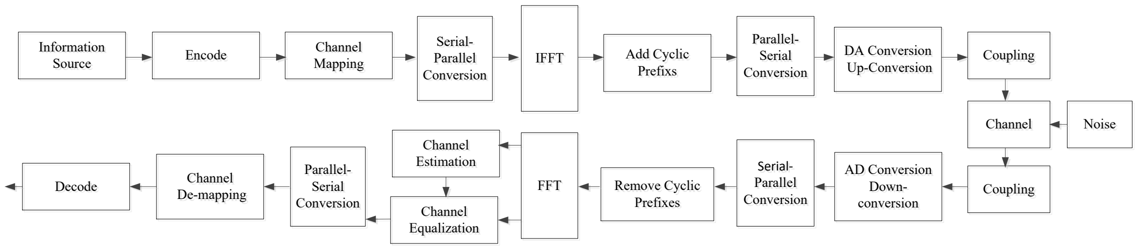

Figure 2. Block diagram of the PLC system between cable intermediate joints based on OFDM.

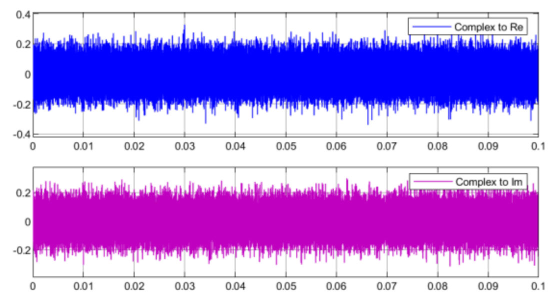

Figure 3. Real and imaginary part waveforms of the signal.

3.2 Inductive coupler model

The inductive coupler is the main coupling equipment for the carrier signal access to the cable line of MV distribution network. The coupling performance will directly affect the data transmission efficiency of the whole system. The mutual inductance of the inductive coupler is related to the internal and external radius of the coupler, the number of winding turns, the width of the air gap, and the magnetic permeability of the core material. In order to briefly analyze the mutual inductance model of the inductive coupler, the resistance of the primary and secondary coils is ignored. Suppose the self-inductance of primary coil and secondary coil is L_1 and L_2 respectively, mutual inductance between coils is M, carrier equipment is equivalent to a voltage source U_s and internal impedance R_s, and load impedance is R_L. By de-coupling, it can be further equivalent to a type T equivalent circuit. Type T equivalent circuit of inductive coupler at the transmitting end, as shown in Figure 4.

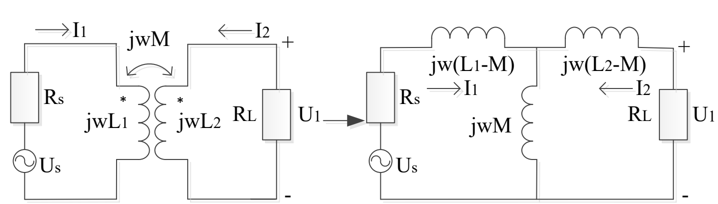

Figure 4. Type T equivalent circuit of inductive coupler at the transmitting end.

According to Kirchhoff's voltage law：

$$\begin{aligned} U_{\mathrm{s}} &= j\omega L_1 I_1 + R_{\mathrm{s}} I_1 + j\omega M I_2 \\ -j\omega M I_1 &= j\omega L_2 I_2 + R_{\mathrm{L}} I_2 \end{aligned} \tag{6}$$

After Laplace transform simplification, we get:

$$\frac{U_1}{U_{\mathrm{s}}} = \frac{R_{\mathrm{L}} M s}{R_{\mathrm{L}} R_{\mathrm{s}} + (R_{\mathrm{s}} L_2 + R_{\mathrm{L}} L_1)s + (L_1 L_2 - M^2)s^2} \tag{7}$$

The type T equivalent circuit of the inductive coupler at the receiving end is similar to that at the transmitting end, which can also be simplified by Laplace transform:

$$\frac{U_1}{U_{\mathrm{s}}} = \frac{R_{\mathrm{s}} M s}{R_{\mathrm{L}} R_{\mathrm{s}} + (R_{\mathrm{s}} L_2 + R_{\mathrm{L}} L_1)s + (L_1 L_2 - M^2)s^2} \tag{8}$$

Because the discrete digital signal needs to be transmitted in the simulation channel, the continuous data needs to be discretized by transforming from S domain to Z domain. The C2d function is provided in MATLAB, which can realize the discretization of the model and make the data transfer discrete complex signals through the coupler.

3.3 Power line channel model

Power line channel modeling mainly includes the transmission line model, the multipath model, the autoregressive model, and the FIR filter model. The transmission line model needs to calculate the path length, attenuation amplitude and time delay by using cable parameters and load impedance, so as to determine the transfer function of a specific network. Due to the limitation of experimental conditions, the calculated results cannot be compared with the actual measurement results; The multipath model is mostly used in the bus-organization of MV distribution network, which reflects the multipath reflection attenuation caused by a large number of branch lines, and is not suitable for the point-to-point data communication between cable intermediate joints studied in this paper; The autoregressive model needs to measure a large number of amplitude frequency response data for statistical analysis, needs measured data and has a large amount of calculation workload. Due to the limitations of laboratory conditions choose to use the FIR filter model for modeling.

Xing[10] considers that the power line channel is a limited impulse response channel. By comparing the measured frequency response curve of MV power line channel with that of FIR filter model, it can be seen that the 120 order FIR filter model can accurately reflect the attenuation characteristics of the channel. Therefore, based on the data[10], this paper establishes the FIR filter model of power line channel attenuation, and uses additive Gaussian white noise to simulate the noise of power line channel.

4. SIMULATION AND RESULT ANALYSIS

In order to verify that the PLC technology can realize the effective communication of cable intermediate joint detection data, the PLC system between cable intermediate joints based on OFDM is built by using SIMULINK platform. Considering the influence of inductive couplers at the transmitting end and receiving end, the relationship between SNR and BER curve is analyzed. The simulation adopts $M = 10.38 \times 10^{-6}\ H$, $L_1 = 31.14 \times 10^{-6}\ H$, $L_2 = 3.46 \times 10^{-6}\ H$, $R_{\mathrm{s}} = 75\Omega$, and $R_{\mathrm{L}} = 50\Omega$.

4.1 Channel encoding

Channel encoding is a common error control method in the communication system. RS encoding and convolutional encoding are respectively added to the simulation of the PLC system between cable intermediate joints. When QPSK modulation is adopted, the relationship between SNR and BER curve of the system under different channel coding modes is simulated and analyzed. The code type of RS encoding is (15, 11). The convolutional encoding adopts encoding efficiency of 1/2, constraint length is 7, generated polynomial is [171, 133], and Viterbi hard decision decoding method is adopted for decoding. The influence curve of channel encoding mode on system BER is shown in Figure 5.

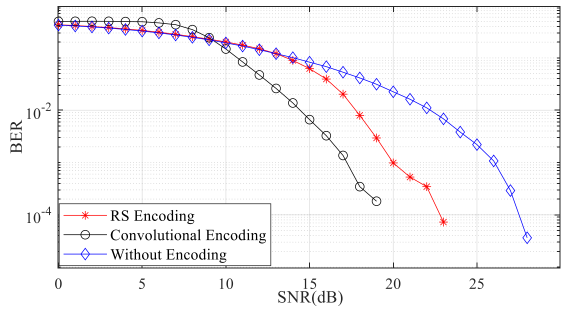

Figure 5. Influence curve of channel encoding mode on system BER.

The simulation results show that when the SNR is low, the encoding mode has little influence on the reliability of the PLC system, and the BER of convolutional encoding is higher than that of RS encoding. With the increase of SNR, the BER of the PLC system with RS encoding and convolutional encoding decreases to zero faster than that without encoding. Under the same SNR, convolutional encoding has a stronger anti-interference ability than RS. It can be seen that adding channel encoding to the PLC system between cable intermediate joints can better overcome the time-varying attenuation characteristics of medium voltage power lines and improve the communication stability of the system.

4.2 Channel mapping

When RS coding condition is selected for channel coding mode, the relationship between SNR and BER curve of the system under QPSK, BPSK, and 16-QAM mapping is simulated and analyzed. The influence curve of channel mapping mode on system BER is shown in Figure 6.

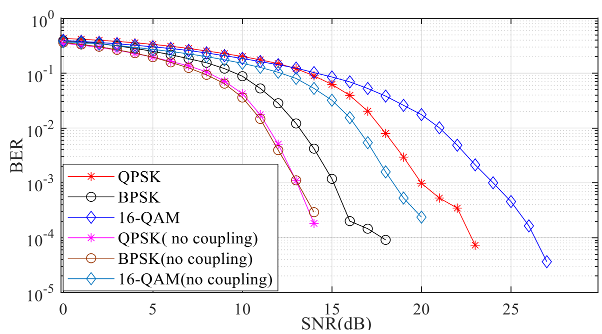

Figure 6. Influence curve of channel mapping mode on system BER.

The simulation results show that different modulation modes have little effect on the BER of the PLC system at low SNR. With the increase of SNR, the BER curve of BPSK decreases faster. When the SNR is 18dB, the BER of BPSK decreases to 10^{-4}. When the SNR is 23dB, the BER of QPSK decreases to 10^{-4}. The BER curve of 16-QAM decreases slowly, and the BER can be reduced to 10^{-4} only when it is about 27dB. BPSK modulation has the best BER performance, but the spectrum efficiency is low and the data transmission rate is slow. Choosing different modulation modes in the PLC system can meet the different communication needs of the system. In practical application, it is necessary to select appropriate modulation modes according to the system to improve the communication performance of the system.

Assuming that the communication coupling problem is not considered, the BER of QPSK, BPSK is close to 10^{-4} at about 14dB, and the BER of 16-QAM is close to 10^{-4} at about 20dB. Considering the communication coupling problem, the BER of each modulation mode is significantly increased, and a higher SNR system is required to achieve a lower BER. Therefore, the modeling of the inductive coupler is an essential step in building the PLC system model between cable intermediate joints. The existence of a coupler makes the system have a certain coupling attenuation, which will affect the BER of the PLC system.

5. CONCLUSION

In this paper, the PLC system model between cable intermediate joints is built based on OFDM. Considering the influence of inductive couplers at the transmitting end and receiving end, the relationship between different SNR and BER curve is simulated and analyzed. The simulation results show that:

(1) After adding channel coding, the anti-interference ability of carrier communication system is significantly improved, and convolutional encoding has better transmission performance than RS encoding under the same SNR;

(2) Under the condition of the same SNR, the BER of BPSK modulation is the lowest, followed by QPSK, and the BER of 16-QAM is the highest, but the utilization rate of BPSK frequency band is low;

(3) The existence of coupler makes the system have coupling attenuation, which will affect the BER of carrier communication system.

The PLC system with coupler can reduce the BER and improve the transmission performance of the system by changing the encoding mode and modulation mode, which provides a new idea for the effective transmission of online detection data of cable intermediate joint.

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