Security Monitoring of Railway Power Cable Joints Based on AD7606 AC Synchronization Sampling

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Abstract. To avoid the frequent accident of burning loss of railway 10kV power cable joints, an online monitoring device is developed based on tanδ, the tangential value of loss angle of the cable’s main insulation, and other state variables, to carry out real-time monitoring and safety evaluation of the cable’s running state, so as to timely alarm and predict hidden accident danger for abnormal cable joints. The measurement of tanδ adopts a frequency correction method based on AD7606 AC synchronous sampling and FFT phase difference frequency correction, which can avoid the spectrum leakage effect of asynchronous sampling and the phase-locked loop synchronization circuit with complicated cost. This paper regards the current source of grounding wire of railway cable when no electric locomotive passes through the railway electrical section as leakage current of the main insulation of cable. Tanδ is monitored by collecting and processing the voltage of cable bus-bar potential transformer and the current of cable grounded wire.

1. Introduction
With the rapid development of China's railway industry, the proportion of 10kV power cable lines in railway construction is constantly increasing, especially the new high-speed railways generally adopting the mode of Entire Cable Line along the automatic blocking line[1]. As the capacitance earth current of the long-distance power cable is much higher than that of overhead line, and because of the complicated railway electromagnetic environment, excessive backflow of traction ground, abnormal contact resistance, and other factors, the fire loss accident of railway automatic blocking line frequently occurs. This seriously threatens the safety of railway operation, and more than 90% of cable faults occur at the cable joints[2].

At present, the overhaul operation of railway power cables is still mainly in the traditional periodic preventive test stage, which does not meet the rapid development and efficient operation of railway[3]. And there are problems such as blind maintenance, excessive maintenance, and maintenance difficulties. The on-line monitoring of electrical equipment is an effective means of equipment state management, which can make up for the shortage of single traditional maintenance operation for power failure, and promote the transition of cable equipment maintenance from "planned maintenance" to "state maintenance"[4-5].

Some achievements have been made in the online monitoring of power cable joints at home and abroad, but most of the online monitoring is still single monitoring of a certain state quantity, and the research on the accurate evaluation of cable operation state has not been thoroughly carried out, which leads to the low utilization rate of data and has little reference value for the formulation of maintenance plan[6]. In view of the above problems and combined with the operation status of railway power cables, this paper proposes a multi-parameter monitoring method for cable operation status.
Through the design of high-performance hardware and software circuits, a multi-parameter comprehensive judging device based on tanδ and the cable outer sheath temperature is developed. It provides a decision basis for effectively evaluating cable operation status, timely dealing with cable operation abnormality and predicting accident hidden danger.

2. Monitoring Principle of Power Cable Joints

2.1. Selection of Monitoring State Quantity

According to the development status of on-line monitoring technology, combined with the specific situation of railway power cable, this paper designs a real-time monitoring method for cable sheath temperature, cable sheath induction voltage, cable grounding wire current and tanδ to carry out real-time monitoring and evaluation of the cable operation status. In the above-mentioned state quantities, the monitoring of tanδ is relatively complex. It needs AC synchronization sampling, and the time and frequency domain change calculation shall be carried out using the Fast fourier-transform algorithm. The implementation of other monitoring quantities is relatively simple.

Temperature is an important non-electric quantity indicator to measure the normal operation condition of power cable. The IEC-60287 standard stipulates that the temperature limit for long term operation of XLPE power cable conductor is 90°C. Railway three-core cables generally adopt double-end grounding. The current in the metal shield of cable generally comes from the induction current, traction return current, leakage current when the main insulation of cable deteriorates and capacitance current when the cable is charged or discharged due to unbalanced three-phase load. However, the induction current due to unbalanced three-phase load and capacitive current when the cable is charged or discharged can be neglected in the current monitoring of cable grounding wire.

The railway 10kV power cable is generally buried along the channel within 100 meters from the railway. When an electric locomotive passes along the railway, part of the traction current will flow back along the rail, and there will be a discharge between the rail and the ground, which will lead to the traction return current. Taking the direct feeding system as an example, the traction current can reach 500-1500A, and the traction return current can reach 30-40% of the total traction return current[3]. The current in the cable sheath of a 10kV switchboard measured by the technician can reach 30A. The current will affect the heating of the cable to some extent, but the current has the characteristic of periodic fluctuation. When there is no electric locomotive passes through, the current will disappear. In addition, since the railway 10kV power cable is basically buried underground, the induction voltage of the adjacent parallel alive circuit in the surrounding air can be ignored. Therefore, when no electric locomotive passes through the electrified section, the current in the grounding wire of 10 kV power cable can be mainly considered as the leakage current of the main insulation.

The measurement of tanδ is widely used for quality management, insulation monitoring and deterioration judging of electrical equipment. The actual equivalent circuit of the dielectric and the voltage and current vector diagram are shown in figure 1, where \( \ell \) is the power factor angle of the dielectric equivalent RC parallel circuit, and \( \delta \), the residual Angle of \( \ell \), is the dielectric loss angle. From Figure 1, the tangential value of dielectric loss angle the tangent of dielectric loss angle can be calculated as:

\[
\tan \delta = \frac{U}{I R} = \frac{1}{\omega C_p} \quad \text{(1)}
\]

\[
i(t) = I_0 + \sum I_{ixa} \sin(kx + \delta_x) \quad \text{(2)}
\]

\[
u(t) = U_o + \sum U_{ixa} \sin(kx + \delta_x) \quad \text{(3)}
\]

Fig.1 Equivalent circuit and phasor diagram

Formula (1) is the theoretical calculating formula of the tangential value of dielectric loss angle, while the discrete Fourier transform is used in practice. The current flowing through the cable ground
wire and the voltage at both ends of the main cable insulation are transformed with the fast Fourier transform. The formula is (2) and (3).

The measured value of dielectric loss angle can be obtained:
\[ \delta = \frac{\pi}{2} |\delta - \delta'|. \]

2.2. FFT Phase Difference Frequency Correction
The actual frequency \( f \) of the power grid is not necessarily equal to \( f_0 \), the initial fundamental frequency collected in advance. Proper frequency correction should be carried out to accurately measure the actual frequency and achieve synchronous sampling.

The fundamental current signal of voltage can be expressed as:
\[ u(t) = U_m \sin(2\pi f_0 t + \ell_0) \quad (4) \]

In the formula, \( U_m, f_0, \ell_0 \) are respectively the amplitude, fundamental frequency, and initial phase. Voltage signal frequency can be obtained according to the definition of frequency:
\[ f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \frac{d\ell}{dt} = \frac{1}{2\pi} \frac{d(2\pi f_0 + \ell_0)}{dt} = f_0 + \frac{1}{2\pi} \frac{d\ell}{dt} \quad (5) \]

The frequency fluctuation of power grid caused by the initial phase change of voltage on various points can be obtained from formula (5). When the fluctuation of voltage signal frequency is attributed to the time-varying initial phase angle, the signal frequency can be accurately monitored using phase difference.

Rewrite the voltage \( u(t) \) as a combined sine-current signal with single frequency, let it be as follows:
\[ u(t) = U_m e^{j(2\pi f_0 + \ell_0)} \quad (6) \]

In the formula, \( U_m, f_0, \ell_0 \) are respectively the amplitude, fundamental frequency and initial phase of signal \( u(t) \). The signal is segmented with rectangular segments, and the \( N \) points are collected in the time window \([0, T]\) and \([T, 2T]\) evenly segmented, respectively. The sample sequences can be expressed as:
\[ u_1(n) = U_m e^{j(2\pi f_0 T + \ell_0)} \quad (7) \]
\[ u_2(n) = u(n)e^{j2\pi f_0 T} \quad (8) \]

\( n = 0, 1, 2, \cdots, N-1 \)

\( (n) = 0, 1, 2, \cdots, N-1 \)

Carry out \( N \) point RFFT to \( u_1(n) \) and \( u_2(n) \) to obtain the following discrete spectrum:
\[ U_1(k) = \frac{U_m}{N} \sin(\pi(k - f_0 T)) e^{j(1 - (f_0 - 2k_0) \pi)} \quad (9) \]
\[ \sin(\pi(k - f_0 T)) \]
\[ (k = 0, 1, 2, \cdots, N-1) \]
\[ U_2(k) = U_1(k)e^{j2\pi f_0 T} \quad (10) \]
\[ (k = 0, 1, 2, \cdots, N-1) \]

According to the maximum spectral line, the signal frequency can be roughly measured as:
\[ f_k = \frac{k_0}{T} \quad (11) \]

Use \( \ell_1 \) and \( \ell_2 \) to respectively present the phase at the maximum spectral line, the difference between the two is:
\[ \Delta \ell = \ell_2 - \ell_1 = 2\pi f_0 T - 2k_0 \pi \quad (12) \]

Suppose the actual frequency difference in the two sampling is \( f_\delta \), then
\[ \Delta \ell = 2\pi (f_k + f_\delta) T - 2k_0\pi = 2\pi T (13) \]

It can be estimated from the deviation between \( \Delta \ell \) and \( f_k \) (the frequency of maximum spectral line of \( f_\delta \) and FFT):

\[ f_\delta = \frac{\Delta \ell}{2\pi T} \quad (14) \]

That is, the frequency of the power grid can be estimated as:

\[ f = f_k + f_\delta = \frac{k_0}{T} + \frac{\Delta \ell}{2\pi T} \quad (15) \]

2.3. Fundamental Current Calculation of Actual Power Grid

Use amplitude search to obtain the maximum value \( U_m[k_1] \) and \( U_m[k_2] \) of sequence \( U_m[i] \) and \( U_m[j] \) transformed through RFFT. \( U_m[k_1] \) and \( U_m[k_2] \) are respectively the fundamental current amplitude of two period, \( k_1 \) and \( k_2 \) are the fundamental current frequency coefficient, then the two successive fundamental phases are \( \ell_{k_1} \) and \( \ell_{k_2} \). The fundamental current frequency of the voltage can be obtained from formula (11):

\[ f_k = \frac{k_2}{T} = k_2 \times \frac{f_T}{N} \quad (16) \]

In the formula, the sampling frequency \( f_T = \frac{N}{T} \). After the phase difference correction, the actual fundamental current frequency of power grid is:

\[ f = \frac{k_2 \times f_T}{N} + \frac{\ell_{k_1} - \ell_{k_2}}{2\pi T} \quad (17) \]

Set the fundamental current frequency \( f \) as the new one \( f_0 \), continue the uniform data sampling for the next cycle, and repeat the above procedures.

3. Hardware Design of Monitoring Device

The hardware structure of the monitoring device is shown in figure 2, which is mainly composed of the following parts: cable outer sheath temperature acquisition module which is the three-wire PT100 temperature transmission circuit, AC synchronous acquisition module which is the AD7606 analog-digital converter circuit, cable ground line current acquisition module which is the current transformer circuit, cable sheath induction voltage acquisition module which is the voltage transformer circuit, CPU core board (including CPUSMTM32F103ZET6 and peripheral circuit, Extended FLASH, SDRAM, communication interface and man-machine interactive interface), GPS orientation module, 4G network communication module, LCD Module, power module and keyboard input module.

![Fig.2 The hardware structure of the monitoring device](image-url)
3.1. Selection of Processor
The control chip adopts STM32F103ZET6 processor which is of high performance and low power with 32-bit high-performance ARM cortex-m3 kernel, which is responsible for data processing and communication. The extended storage capacity is 521K flash and 64K SRAM, which can run large codes and store large capacity data and programs. Meanwhile, it has three ADCs with 12-bit precision (21 external measurement channel), 12 DMA channels, 5 USART interfaces and 3 SPI interfaces, which can effectively meet the requirement of data acquisition of monitoring device on the processor I/O resource and the requirements of peripheral module on the quantity of USART interface and SPI interface.

3.2. AC Synchronous Sampling Circuit
The monitoring of tanδ adopts the AC synchronous sampling circuit as shown in Fig. 3. The circuit uses ADI company's 8 channel, 16-bit bipolar synchronous sampling ADC conversion chip AD7606. The integrated input of AD7606 chip includes a amplifier, over-voltage protection circuit, second-order analog anti-aliasing filter, analog multiplexer, 16-bit 200 kSPS SAR ADC and a digital filter. In order to meet the absolute accuracy requirement, it uses the external precise reference voltage source ADR421 with small tolerance and low drift. Voltage signals are transmitted through precision voltage transformer along the bus-bar potential transformer, filtered by a second-order RC filter circuit, and then enter ADC for acquisition. Then the data of the voltage signal is read by serial SPI communication. When the data is read out, 64 data points sampled in each period are processed by one-cycle Fourier algorithm.

![Fig. 3 Synchronous sampling AD conversion circuit](image)

4. Software Design of Monitoring Device
The core control system software development of the device uses KEIL5 as the development platform. After the system is powered on, the 4G communication module establishes a handshake connection with the background server and configures the processor related registers. After the cable joints operation state judgment function is completed, the cable joints state information, the cable joints status information, cable joints state judgment result and the location information are packaged and transmitted to the remote server. The overall framework of the program is shown in Fig. 4.

4.1. Design of the Main Program
The main program mainly realizes the acquisition and transmission of cable joints monitoring quantity and the evaluation of cable joints safety condition. After the initialization is completed, the data
collection of monitoring quantity of cable joints is carried out circularly and displayed in real time on LCD. The monitoring threshold is adjusted and the receiver’s phone number is changed through keyboard input. When the timed cable joints status information sent by cable joints state function shows the cable joints operation status is abnormal, the abnormal operation state function of the cable joints is transmitted. The main program flow chart is shown in Fig. 5.

Fig. 4 program overall framework

Fig. 5 main program flow chart

4.2. Software Program Design of AC Synchronous Sampling
A high-level pulse of at least 50ns must be applied to the RESET pin before data sampling starts. Reset the AD7606, when the pins of CONVSTA and CONVSTB changed into a high level, starting AD conversion of the entire analog input channel at the rising edge. Input SCLK as the serial clock, the CS trailing edge departures the data output route DOUTA and DOUTB from three states, and the MSB of the conversion result is output one by one. Then the SCLK rising edge sends all subsequent data to serial data to output DOUTA and DOUTB. After both CONVSTA and CONVSTB reach the rising edge, the level of BUSY pin becomes logic-high and maintains until the conversion process of all channels is completed. The BUSY trailing edge indicates that the converted data is being locked into the output data register and can be read after time T. The software programming flow chart for AC synchronous sampling is shown in Fig.6.

4.3. Cable Joints Status Information Determination and Transmission Function
This part mainly realizes the cable joints state judgment and information package transmission. The software programming flow chart for AC synchronous sampling is shown in Fig.7. The temperature information of the outer sheath of the cable joints comes from the temperature transmission circuit processed by the microcontroller ADC. The current of grounding wire and the induction voltage of metal shield of cable are respectively processed by the current transmitter and voltage transmitter and sent to IO port of the microcontroller. The environmental temperature and humidity are sent to the microcontroller IO port through environmental temperature and humidity sensor. Tanδ sent by serial SPI communication is obtained through the time-frequency domain transform in the microcontroller after being sent by the precision current and voltage sensor to the AD7606 AC synchronous sampling circuit.

5. Conclusion
In view of the frequent occurrence of burning accidents of 10 kV power cable joints in railway, a multi-parameter monitoring device based on Tangential value of dielectric loss angle of the cable’s
main insulation (tanδ) and other state variables is developed to monitor and evaluate the operation status of cable in real time, so as to realize timely alarming of cable joints in abnormal state and prediction of the hidden danger of cable joints. The measurement of tanδ adopts a method based on AD7606 AC synchronous sampling and FFT phase difference frequency correction, which can avoid the spectrum leakage effect of asynchronous sampling and the phase-locked loop synchronization circuit with complicated cost. This paper regards the current source of grounding wire of railway cable when no electric locomotive passes through the railway electrical section as leakage current of the main insulation of cable. Tanδ is monitored by collecting and processing the voltage of cable bus-bar potential transformer and the current of cable grounded wire.

Fig. 6 Software programming flow chart for AC synchronous sampling

Fig. 7 Cable joints status information determination and transmission flow chart

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