Research on live detection technology of cable joint defects based on high-speed light sensing and pressure wave method

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ABSTRACT: With the widespread application of stable high-voltage power cables, cable failures have gradually become the main source of major accidents in the process of power transmission. The most easily damaged part is the cable joint. Since the cable joints are made on site, it is easy to introduce high-voltage cable defects and cause insulation failures. Therefore, the defect detection of high-voltage voltage joints is particularly important. In order to promote the process of urbanization, ensure people's life quality and personal safety, the popularization of high-voltage cables is an inevitable trend. However, difficulties will be encountered in the detection of cable joint faults. To improve the detection efficiency, relatively extensive research has been carried out on the detection of high-voltage cable joints at home and abroad. Based on the high-speed light sensing and pressure wave method, the online detection method of cable joint defects proposed in this paper has accurate, fast, convenient and non-contact online detection features.

1. Introduction
At present, cables are one of the devices with a higher probability of failure in the power grid. Due to the installation process, laying environment, external force damage, operating conditions and other factors, some hidden defects often appear inside. The internal hidden defects often have characteristics of slow development and sudden appearance. The state of observability is inherently insufficient, so in the handover and operation stages, defects cannot be found in time, which eventually leads to insulation defects. Among the hidden dangers and accidents due to insulation
failure, the insulation failure in the cable intermediate joint and terminal head has the highest proportion\cite{1}.

When insulation faults occur at the cable joint and partial discharge occurs, various physical and chemical reactions will happen. For example, charge exchange leads to distortion of the electric field distribution, electromagnetic wave radiation, sound waves generated by the thermal expansion of internal gas, and the decomposition of insulating materials to produce new substances, etc. Through the collection of various physical or chemical signals, it can be judged whether the cable structure is malfunctioning\cite{2}.

When a partial discharge occurs at the cable joint part due to insulation failure during the operation of the power cable (partial discharge will cause the redistribution of charged particles between the electrodes), various physical and chemical phenomena will be triggered. Methods for the insulation failure detection can be roughly divided into two categories: electrical measurement and non-electric measurement. Pulse current measurement, radio interference voltmeter, dielectric loss analysis are the typical method of the electrical measurement for the insulation detection. Non-electric measurement mainly includes acoustic wave measurement method, discharge light detection and thermal infrared detection\cite{3}. The most applied method of electrical measurement is the pulse current method, which obtains the impedance change via measuring partial discharge pulse current signals in various insulation defects. The measurement accuracy and the data credibility is valid. However, despite the poor anti-interference ability and low frequency response, this method can not achieve the goal of online detection. Generally, specific sensors are used in the non-electric measurement method, ultrasonic, infrared, etc., which requires high measuring accuracy and resolution ratio for electronic devices, simple operation, and intuitive results, but it is greatly affected by interference and signal attenuation.

This paper proposes a non-contact live detection technology for the cable joint defect identification based on high-speed light sensing and pressure wave detection, which can well solve the problems of the above detection methods. The non-contact live detection technology does not rely on electrical signals. Meanwhile, the anti-interference ability and the time response are improved.

2. Research on Mechanism of Pressure Wave Method and High Speed Light Sensing

2.1. Research on the Mechanism of Pressure Wave

Due to the imbalance of forces caused by the two phase current between the air gap and the solid insulating medium, the air gap vibrates and sends out a vibration signal. After multiple cycles of attunement, the force between air gap and the solid insulation are finally balanced. The air gap become larger because of this pressure wave, causing permanent damage to the solid insulation in the cable.

Pulses are directly injected into the metal shielding box of the test unit. The cable joint is regarded as a coupling capacitor. The pulse signal is injected into the cable joint from the electrode lower. Passing through the current limiting resistor, the test pulse voltage is directly applied to the cable joint connector of which conductor is used as the high-voltage electrode of the measurement system\cite{4}. During the detection process, the semi-conductive layer outside the cable joint and the bottom electrode plate are kept in close contact. The piezoelectric sensor is closely attached to the bottom electrode. Below the sensor, there exists a layer of polymethyl methacrylate acoustic wave absorbing medium made of the same material without piezoelectric effect to achieve impedance matching.

Figure 1 shows the schematic diagram of the pressure wave method. When a laser pulse generates a pressure wave on the surface of the medium, an electrical signal is induced on the electrode at the same time. This signal contains the space charge distribution information of the medium. The external short-circuit current I(t) is shown by formula (1). The waveform of the pressure wave is shown in Figure 2.
In formula (1), $C_0$ is the sample capacitance, $\chi$ is the compressibility of the medium, $P(z, t)$ is the function of the pressure wave, $E(z, 0)$ is the electric field distribution of the medium, and $A$ is the coefficient related to the dielectric properties of the material, $d$ is the thickness of the medium, $z$ is Pressure wave amplitude.

If the pressure wave is a narrow rectangular pulse wave, the short-circuit current signal in this condition can be approximately expressed as the space charge distribution inside the sample\cite{5}. Suppose the pressure wave is a narrow rectangular wave with a pulse width of $\tau$ and an amplitude of $P_0$, without considering the distortion and attenuation of the pressure wave in the sample, $I(t)$ can be written as equation (2).

$$I(t) = C_0 \chi (1 + A) \int_0^\tau \frac{\partial}{\partial t} P(z,t) dz$$

In formula (2), $v$ is the speed of sound in the medium, $p(z)$ is the space charge, and $\varepsilon$ is the dielectric constant. According to the formula (2), the external current signal is proportional to the distribution of space charge density, which intuitively reflects the distribution of space charge in the sample. For cable samples, it is necessary to induce the current modifications caused by the changes in axial structure electric field on the basis of formula (2). Therefore, the current signal induced by space charge distribution can be expressed as equation (3).

$$I(t) = C_0 P_0 \chi (1 + A)v^2 \tau \frac{\rho(r)}{\varepsilon} - \frac{E(r)}{r}$$

In formula (3), $r$ is the radius of the point in the cable insulation, and $E(r)$ is the electric field at the point $r$. For ordinary power cable samples, the influence of the latter term $\frac{E(r)}{r}$ in formula (3) is very small and can generally be ignored.
2.2. Research on the high-speed light-sensitive electric field sensor

With good anti-electromagnetic interference ability and fast time response speed, the electric field sensor is applied in high-voltage power systems for the transient electric field measurement. It is also used to measure the high-speed pulse electromagnetic field, especially for the electric field determination in anti-interference test[6].

In this paper, the electric field sensor is the core component for the electric field detection of the cable. The sensor and the corresponding circuits are miniaturized through deeply research on the electric field induction technology and IC (integrated circuit) packaging technology. On the basis of improving the sensing accuracy of existing sensors, the device is miniaturized and packaged with a measurement accuracy of 0.1 V/cm to achieve the purpose of sensitively identification of the electric field[7].

3. System design

Based on the research of high-speed light sensing and pressure wave, a set of cable joint defects live detection device based on high-speed light sensing and pressure wave method was developed. The system is composed of the low-power main control module, power storage module, electric field sensor, pressure wave sensor module, internal power supply module, data storage hard disk, etc. The system components are shown in Figure 3.

![System components and functional logic](image)

The main operating logic of the device is as follows (Figure 3): The data interface (1) is connected to the pressure wave sensor module (5) and the high-speed light sensor module (6). The data detected on the power cable. The data interface is converted into a standard format by data interface (9) and then are written into the data storage hard disk (7), thereby realizing the data storage function. The main control module (2) controls data reading or writing, and the main control module are able to realize low-power operation, reduce equipment operating losses, and ensure equipment operating time. The internal power supply module (4) supplies power to the data hard disk, the data conversion module and the main control board via external power input. To ensure the stable operation of the device, the power storage module (3) is capable of maintaining the continuous power supply for the equipment after the external power supply is disconnected.

3.1 High-speed light sensing electric field sensor

The electric field sensor can detect one-dimensional or two-dimensional electric field intensity, and the detection direction is generally parallel or perpendicular to the sensor's main axis direction[8]. The high-speed light-sensing electric field sensor is based on high-precision sensing, which can quickly
identify changes in the electric field, inspect cable joints, make full use of this feature. At the same time, it also provides reliable means and basis for the protection of power cable defects. The high-speed light sensing electric field sensor is shown in Figure 4.

![Electric field sensor module.](image1)

Figure 4 Electric field sensor module.

3.2 Pressure wave sensor

Being applied a certain external excitation voltage during operation, the shielding electrode is driven to vibrate back and forth in the horizontal direction. Thereby the pressure wave sensor generates a current proportional to the vibration amplitude according to the principle of piezoelectric induction. The pressure wave can be obtained by measuring the current[9]. The pressure wave sensor is packaged and designed, as shown in Figure 5.

![Pressure wave sensor module.](image2)

Figure 5 Pressure wave sensor module.

3.3 System integration

The measurement principle is that the signals received through the cable connector are pressure wave and electric field strength signals, which is detected by the pressure wave sensor and the electric field sensor, respectively. Through the detection of pressure wave and electric field, the information of the defect is finally acquired.

By integrating high-speed light sensing and pressure wave sensor modules into a set of equipment, cable connectors defect detection software is developed based on theoretical calculation and simulation models. The high-voltage cable joint defect detection maps are generated. Compared and verified with the joint defect experiment map library, fast and accurate high-voltage cable joint insulation defect detection are achieved[10]. Integrated system is shown in Figure 6.
4. Experimental results
When the cable connector is defected, discharge will appear on its surface. The integrated system is used to live detection of the defects in cable joints. The experimental waveforms are shown in Figure 7 and Figure 8.

![System integration](image)

Figure 6  System integration.

![Test waveform of creeping discharge](image)

Figure 7 Test waveform of creeping discharge.

![Internal discharge test waveform](image)

Figure 8 Internal discharge test waveform.
From the waveform acquired, the results show that the device can target different types of defects in the cable. The developed equipment have ability to test the discharge spectra with typical phases. Comparing and analyzing typical discharge spectra, the types of the corresponding defection can be distinguished. The designed device can realize on-line inspection of cable joints, help inspection personnel to record cable joint defect data and provide hardware support.

5. Summary
Based on the principle of high-speed light sensing and pressure wave, this paper has carried out research on cable joint defects detection. On this basis, a cable joint defect live detection device has been designed based on high-speed light sensing and pressure wave method. Through the detected pressure wave and electric field signal, the defection is finally retrieved and identified, which improves the rate of successful cable joint defect detection.

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