A Long Distance Optical Fiber Distributed Cable Joint Partial Discharge Monitoring System Based on C-OTDR

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***Abstract*—This paper proposes a novel COTDR based fiber optic cable joint partial discharge monitoring system, which can maintain a detection signal-to-noise ratio of 13.98 dB while being immune to electromagnetic interference.**

Keywords—COTDR, Ultrasonic, Rayleigh Scattering, Cable Joint, Partial Discharge

I. INTRODUCTION

A large number of cables are laid in underground pipe galleries, pipe stacks, cable trenches, and other power scenarios. Cable joints are the weakest link of the cable after it is put into operation, and are prone to faults. For example, defects such as air gaps and protruding metal tips in the contact area between the insulating material and the conductor can cause local discharge, and in severe cases can cause major safety accidents such as fire and explosion. Compared to electrical sensors, optical fiber sensors have significant advantages in monitoring power equipment. Due to the complex electromagnetic environment in which cable joints are located, electrical sensors are extremely susceptible to strong electric and magnetic field interference, and their low reliability makes it difficult to provide accurate monitoring results. The passive characteristics of optical fibers are particularly suitable for sensing cable status in strong electromagnetic environments, The long-distance and distributed characteristics of cable lines are also suitable for optical fiber sensing technology to exert its advantages.

φ-OTDR is one of the most advanced distributed optical fiber sensing technologies at present, and was first applied to border security. J. C. Juarez et al. discovered that this technology can detect vibrations generated by people walking on the ground[1]. Y. Lu, T et al. used heterodyne detection to achieve multi-point vibration detection[2]. The F. Peng team used Raman amplification technology to achieve intrusion detection with a spatial resolution of 15m over an ultra-long distance of 128km[3]. In the field of power system, Z. -W. Ding et al. has studied the strain characteristics of distributed optical fiber sensing technology based on φ-OTDR in overhead transmission lines, providing an effective technical means for early warning of sag galloping and icing thickness faults of transmission lines[4]. In the field of optical fiber partial discharge detection, Z. Liu et al. proposed using Sagnac interference technology to detect the discharge ultrasonic waves generated by partial discharge of high-voltage cables, However, only ultrasonic signals of a specific frequency can be measured and the positioning accuracy is only 80m[5]. Y. Hao et al. used Mach-Zender interference technology to detect partial discharge in cable joints, which improves the accuracy by 27.5% compared to the electrical measurement method. However, optical fibers need to be embedded in the joints in advance[6], which is only suitable for research in laboratory environments and cannot be promoted to field applications. S. E. U. Lima et al. produced a new type of ultrasonic sensor using Fabry-Perot technology, using optical fibers wrapped on silicone elastomers to detect partial discharge in transformers, but not applied to cable scenarios[7].

This paper proposes a fragrance sensitive coherent detection system developed on the basis of φ-OTDR and applies it to the partial discharge detection of cable joints. Compared to existing technologies, it can improve the detection sensitivity of weak discharges inside the joints. Coherent detection using COTDR can significantly improve the detection signal-to-noise ratio of Rayleigh scattering light, while avoiding strong electromagnetic interference in the on-site environment of the cable. Further, Distributed partial discharge detection of multiple cable joints can be achieved by laying optical fibers over a long distance cable line. Using this system, the highest detection sensitivity of 13.98 dB can be achieved.

II. PROPOSED METHOD AND PRINCIPLE

A. COTDR principle analysis

Generally speaking, there are two types of phase sensitive time-domain reflection methods, one is φ-OTDR, and the other is COTDR. The former directly detects the phase of Rayleigh scattered light, while the latter uses coherent detection to generate interference between the scattered light and the original light before performing phase detection. The principle of COTDR distributed optical fiber sensing technology is shown in Fig. 1.

This technology requires pulse signals with high coherence, narrow linewidth, and low frequency drift. Generally, an arbitrary waveform generator is used to drive an acoustooptic modulator to modulate continuous light to generate pulsed light with a pulse width of ns. A series of pulsed light sources are continuously injected into the sensing fiber, and the particles in the optical fiber are irradiated by light and scattered in all directions at the same frequency as the incident light, When a certain area of the optical fiber is subjected to external disturbances such as vibration knocking or ultrasonic waves, the phase of the Rayleigh scattered light signal in that area will change. At the incident end, the flow direction of the backscattered light can be controlled through a loop device and the phase of the scattered light carrying vibration information can be detected.

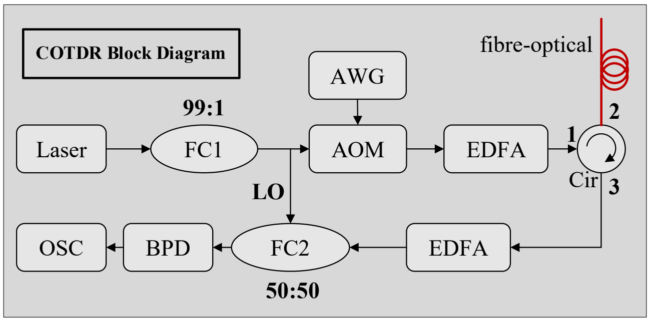

Fig.1. Structure diagram of COTDR coherent detection system; Laser: continuous light source; FC: Coupler; AWG: arbitrary waveform generator; LO: local oscillator light; AOM: acoustooptic modulator; EDFA: Erbium doped fiber amplifier; Cir: Circulator; BPD: Balanced amplification photodetector; OSC: Oscilloscope

The signal obtained from the balanced amplification photodetector in COTDR has the following representation:

$$E(t)=\sum_{k=1}^{N} A_k e^{-2\alpha\frac{c\tau_k}{2n_f}} e^{j\omega(t-\tau_k)} rect(\frac{t-\tau_k}{\tau}) \tag{1}$$

Where N is the total scattering number in the disturbed region, A_k and τ_k are the amplitude and delay of the k -*th* echo, respectively, and α is the attenuation constant of the optical fiber. $c\tau/2n_f = z_0$ is a key parameter of COTDR, which means spatial resolution, where c is the speed of light in vacuum, n_f is the refractive index of the fiber core, and τ is the pulse width.

When a pulse enters the optical fiber, it has traveled z_0 within a time range of pulse width, which can be understood as only l/z_0 pulses can be inserted into a length of l optical fiber, and it is no longer possible to distinguish the disturbance information within the distance traveled by a pulse width. Therefore, reducing the pulse width helps to improve spatial resolution. $\omega(t-\tau_k)=\varphi_k$ is the phase of the scattering point, and *rect* is the gate function. When there is a disturbance acting on the sensing fiber, the backscattered signal will vary at the same frequency as the vibration. The location of the vibration source can be determined based on the product of wave velocity and time delay in the fiber.

Another key parameter is the pulse repetition period, which must wait until the Rayleigh scattering light of the previous pulse returns to the incident port when the next pulse is emitted. Therefore, the periodic pulse repetition period must meet the following requirements:

$$T \geq 2\tau \tag{2}$$

B. *Analysis of Marx generator principle*

The Marx generator uses the charging and discharging of capacitors to achieve pulse discharge, and the schematic diagram for generating high voltage is shown in the Fig.2. The principle is to charge parallel capacitor banks. When the voltage of the first capacitor C_1 rises to break through the discharge gap g_1, it forms a series connection with the latter capacitor C_2, and the voltage at both ends rises to twice the capacitor breakdown voltage. By analogy, after the terminal capacitor C_n breaks down, it can output an input voltage U_0 of n times. High voltage pulses can be obtained using these generators, which can be used as an experimental device to simulate partial discharge[8].

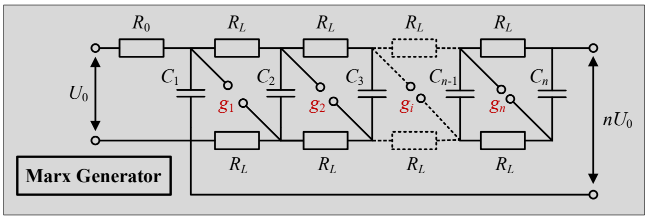

Fig.2. Schematic diagram of Marx generator; U_0: Input voltage; R_0: Protection resistance; R_L: High voltage resistance; C_i: The *i-th* high-voltage capacitor;g_i: The *i-th* discharge gap

The discharge time required for the Marx generator is:

$$t_1 = (\frac{nR_L}{2} + R_0) \cdot nC \tag{3}$$

The required charging time is:

$$t_2 = \frac{R_L C}{2} \tag{4}$$

Where R_L is the high voltage resistance value, which determines the width of the discharge pulse during the discharge process. The smaller the value, the faster the discharge speed. R_0 is the protection resistance value, and C is the high-voltage capacitor capacity.

III. EXPERIMENT AND RESULTS

Based on the above principles, it is proposed to use a Marx generator to generate partial discharge, which will be accompanied by ultrasonic signals. The discharge source is generally located at the junction of the conductor part and the insulation layer of the cable core. Although it is inside the cable connector, the attenuation of ultrasonic signal propagation in solid media is very small. This article will study whether the disturbance caused by ultrasonic waves can be sensed when the sensing optical fiber is wound around the surface of the connector.

A. *Cable joint partial discharge detection experiment*

Connect the high-voltage output electrode of the Marx generator to the copper core conductor and XLPE insulation layer inside the cable connector, and create an artificial defect on the insulation layer to simulate the air gap generated. The block diagram of the detection system is shown in Fig.3. The

Marx generator in the figure is the circuit part of Fig.2. It uses the protection resistor of R_0=10MΩ, the high-voltage resistor of R_L=1MΩ, and the ZVS driver board to obtain the input voltage of U_0=20kV, as well as the high-voltage capacitance of C=0.0022μF. Select n=10 as the amplification stage, and the output terminal can obtain the DC pulse high voltage of U=200kV, which can be used to simulate the working conditions of 220 kV high voltage cables.

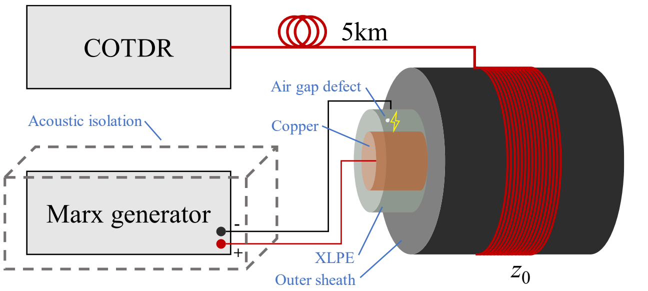

Fig.3. Block diagram of cable joint partial discharge detection system; Wrap the foam board around the Marx generator to achieve acoustic isolation from the cable connector, so as to prevent the noise generated by the spark gap in the circuit from interfering with the test.

After turning on the power supply, due to the existence of an air gap, partial discharge will occur between the high-voltage electrodes and accompanied by a buzzing discharge sound. In this physical process, the discharge generates high-frequency pulses that radiate into the internal space of the connector in the form of ultrasonic waves. The vibration generated by the ultrasonic waves is transmitted to the outer surface of the connector through the matching medium of the insulating layer and the outer sheath. Outside the cable connector, optical fiber jumpers are used to wind around the surface of the connector, with the number of turns of winding being, Select the appropriate parameters so that the following formula holds:

$$n \cdot \pi d_0 \lambda_d = z_0 \tag{5}$$

In the formula, d_0 is the outer diameter of the 220kV cable. Due to the fact that multiple layers of water blocking tape and armor layers are wrapped around the joint to enhance mechanical performance, the joint will expand compared to this experience. Therefore, a correction factor λ_d needs to be added, which can be obtained through on-site measurement of the joint diameter. z_0 refers to the spatial resolution of the COTDR system. The purpose of making the length of the wrapped optical fiber a spatial resolution is to ensure that within this entire spatial resolution, the optical fiber will be subject to vibration, thereby enhancing the detection sensitivity of the system. However, the spatial resolution is generally around 10m, so excessive winding length is not conducive to the implementation of this scheme.

Connect the jumper to a roll of 5km long optical fiber reel, simulate a cable joint with an insulation defect outside the 5km cable line, and connect the other end of the optical fiber reel to the COTDR system.

In the Fig.3, COTDR is the optical path of the optical fiber sensing section in Fig.1. Select a 100Hz ultra-narrow linewidth laser with an output optical power bit of 30mW. The output light is divided into two paths through the coupler, with a coupling ratio of 99:1. 99% of the light enters the acoustooptic modulator(AOM), and the remaining 1% is used as local oscillator light(LO). An arbitrary waveform generator(AWG) drives an acoustooptic modulator to generate a pulse sequence, with parameters such as a pulse width of 100 ns, a pulse repetition rate of 10 kHz, and a frequency offset of 80 MHz introduced by the acoustooptic modulator. The function is to modulate the signal to a high frequency band to eliminate baseband noise. Therefore, IQ demodulation is required to move the signal back to the frequency band during the demodulation process. An erbium doped fiber amplifier is added to compensate for the insertion loss of the optical path. The pulse sequence enters the sensing optical fiber through the circulator and reaches the position of the cable connector after passing through the 5km optical fiber. After being disturbed by the discharge, the back Rayleigh scattering optical signal returns to the optical path through the circulator. Coherence detection and local optical coupling beat are performed at the coupler 2, and a photodetector is used to detect the coherent optical signal and transmit it to the acquisition card. The sampling rate of the acquisition card is 200M Sample/s.

B. Measurement results

The system has collected scattering signals for a period of 5ms. According to the pulse repetition frequency of 10kHz, a total of 50 pulses have been injected into the sensing fiber during this period of time. When each pulse is transmitted to the disturbed point of the sensing fiber, Rayleigh scattering signals will be generated. Therefore, a pulse is equivalent to a sampling sample, and N=50 pulse sequences are processed and superposed using the root mean square method:

$$\sigma^2 = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(E^i(t) - \bar{E}^i)} \tag{6}$$

The result of this calculation is equivalent to statistically averaging the signal strength within 5ms, which is beneficial to improving the signal to noise ratio of the system.

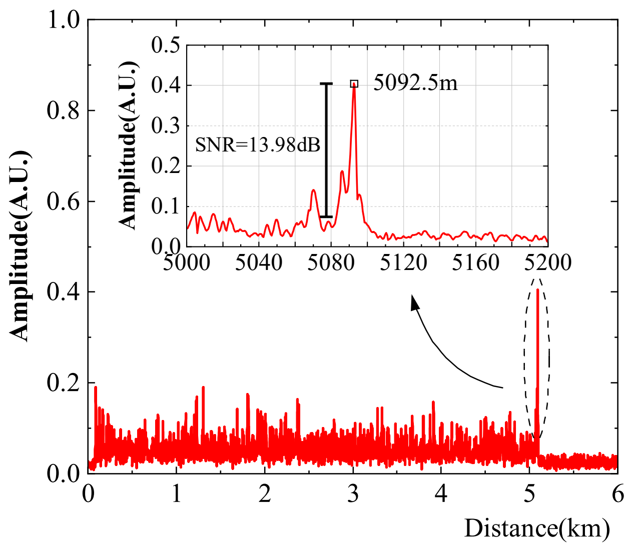

Fig.4. The measurement result is the normalized intensity curve obtained by IQ demodulation of the signal measured at the balanced amplification radio and television detector using FPGA. The partially enlarged image shows the discharge disturbance signal measured by the fiber tail jumper.

After processing the data collected by the acquisition card using FPGA, the interference signal strength over this distance can be obtained. The detection results are shown in Figure 4. It can be observed that there are significant signal peaks at the end of the 5km optical fiber, indicating that the scheme proposed by the system is effective for detecting partial discharge inside the cable joint.

The normalized intensity of the signal voltage at the detection peak is 0.4, and the normalized intensity of the noise within the first 5km distance range is 0.08, because the detection signal to noise ratio of the system is:

$$SNR = 10\log(\frac{P_s}{P_n}) \approx 13.98dB \tag{7}$$

In the formula, P_s is the signal power, P_n is the noise power, and the power is square to the signal normalized strength. Therefore, the system signal-to-noise ratio is calculated to be approximately 13.98 dB.

IV. Conclusion

This paper proposes a set of partial discharge detection schemes for medium voltage cable joints based on φ-OTDR using coherent detection technology. Based on COTDR, sensing optical fibers can be deployed along the cable line, and a spatial resolution length of optical fiber can be wrapped around each cable joint to achieve partial discharge detection for cable joints. Further, This article innovatively uses a Marx generator circuit to simulate partial discharge (PD) generated by air gap defects in the insulation layer in the cable joint. Using the above detection scheme, the ultrasonic vibration signal generated by PD has been successfully measured, with a signal to noise ratio of 13.98 dB.

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