EVALUATION AND COMPARISON OF ON-LINE PD DETECTION METHODS FOR HIGH-VOLTAGE POWER CABLE

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Abstract

As the high-voltage power cable insulation material growing worse, the aged insulation material can cause serious power supply problems. Most of the damages can be found in cable splice and cable terminators. This article mainly aims at developing the inspection methods for cable joints problem. We investigate the use of acoustic emission (AE) sensor, capacitive coupler (CC), and impulse current measurement methods to detect the electrical partial discharge (PD) signal in power cable. We analyze and compare the signals to find out the actual spot of the problem and to investigate and compare the advantages and disadvantages of different methods. To speak from the degree of sensibility, the impulse current method has the best sensibility, while the capacitive coupler and AE methods are less sensible. To speak from the noise-resist ability, it is contrary to the degree of sensibility. The impulse method is prone to be interrupted by noise. To speak from the PD signal source location ability, the AE method is better than the other two methods.

1. Introduction

The causes of the power cable insulation breakdown are usually due to bad construction, squeezing, crimping, or fraying damage. The other problems may due to electrical, heat, or chemical environmental factors. Among the electric power cable faults occurred in the past, the most critical cause of the faults, representing the majority of the faults, is attributed to the cable connectors' work quality, which mostly leads to insulation failures; the second cause is attributed to the cables' internal damages resulted in sharp turns made during field cable burying and installing. This study, hence, focuses on the cable connector-related faults and how to diagnose such faults before they occur. We will first investigate the differences among various existing detection and measurement methods to search for the most suitable field measurement method to be applied on line.

In general, cable connectors are divided into cable splices and cable terminators for cable connection and extension. Some cable splices and terminators, improperly treated during the construction stage, often create PDs which cause rapid deterioration on the insulation layer and, eventually, lead to cable insulation failures. To detect and to remove, in advance, the PDs to prevent said cable insulation failures from occurring [1, 2], hence, is vital to the electric power industry. The PD measurement methods can be categorized into two types, namely the electric and the non-electric types. However, so far there is no acceptable and effective inspection method for all of the situations, each method has its suitable conditions and restrictions. In this study, three PD measurement methods [3] useful for power cable inspection are adopted; they are introduced as follows:

(a) The impulse current measurement method: This method connects a detection resistance in series to the ground wire of the object under detection. When a PD occurs, its impulse current will be measured from the detection resistance, as part of a detection circuit. This method is highly sensitive and can measure an impulse with ease. The unit adopted in measuring the PD impulse current, regulated by IEC, is pico coulomb or pC [4, 5].

(b) The capacitive coupler measurement method: When a PD occurs inside a cable, the impulse EM signal will propagate, with the fault site as the origin, in opposite directions along the cable toward its two ends [6]. If we install capacitive-coupler type PD detectors on both the left and the right sides of the fault site, as shown in Figure 1, we can utilize the polarity feature of the discharge impulse to identify if there exists a PD power source in the A or B zone. If yes, we can further assess the fault site's location as well.

(c) The AE measurement method: When a PD, i.e. an impulse, occurs inside a cable, the impulse will produce a mechanical pressure wave in the dielectric and formulate an acoustic source to emit acoustic waves. The AE measurement method uses an AE sensor to adhere to the equipment's (or the cable's) surface and utilizes a piezoelectric material inside the sensor to convert the mechanical pressure into an electric AE signal, which will be amplified via a pre-stage amplifier [7, 8], as shown in Fig. 2.

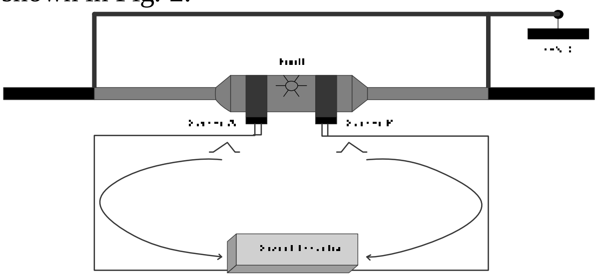

Figure 1：*The capacitive-coupler type metal foil sensor.*

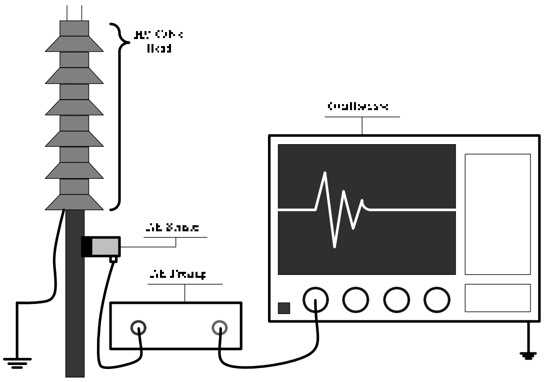

Figure 2：*The acoustic emission measurement system.*

The AE measurement method possesses a highly directional feature, which offers an advantage of precise fault-site positioning and, on the other hand, a disadvantage of short measurement distance. The acoustic waveform's magnitude is related to the distance between the AE measurement location and the PD site [9]. To locate where the acoustic waveform's magnitude reaches its maximum will help us find the discharge site's location. Thus the method's fault-site positioning capability.

2. High-Voltage Power Cable

2.1. Cable structural materials

A high-voltage power cable is comprised of the conductors, the conductor shielding, the insulation, the insulation shielding, the metallic shielding, and the jacket, as shown in Fig. 3.
(1) The conductor (s): Made into a compressed round strand with high-conductivity, high tension-resistance soft copper strands, which are in conformance to ICEA Class B materials.
(2) The conductor shielding: Made of a pressed conductive mixture. The shielding must adhere to the insulation. This shielding facilitates a uniform electric flux- line distribution between the low-resistance central conductor(s) and the high-resistance insulation layer.

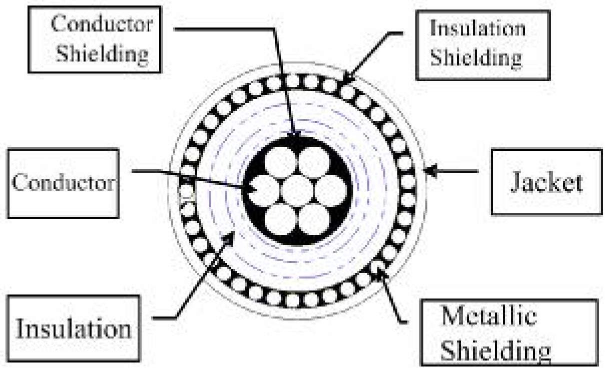

Figure 3：*The base cross-sectional structure of power cable.*

(3) The insulation: Made of solid dielectric thermosetting cross-linked polyethylene (XLPE). The insulation possesses features including high thermal durability, repeated usability, tolerance for shorted high current or overloads, low damage rate during short circuits, etc.
(4) The insulation shielding: Made of a pressed conductive mixture. The shielding must adhere to the insulation. This layer's function lies in making the electric flux lines distributed symmetrically and radially in the insulation to eliminate the tangent or longitudinal electric stress to minimize the surface discharge.
(5) The metallic shielding: Made of tinned soft copper strands. This layer's role is to make the charge current flow back to keep the insulation shielding at zero voltage level, with respect to the ground, and to provide a loop for a ground-shorted current.
(6) The jacket: Using PVC or nylon materials as the outer skin for cable protection.

2.2. Cable connectors

Cable connectors are used for a connection between two cables (or among cables) or between a cable and a cable terminator an elbow connector. The connectors' main purpose lies in controlling the electric field distribution inside the cable's insulation to make the electric stress uniformly distributed at the connectors and to reduce the electric stress, or voltage gradient, near the shielding edges. Cable connectors include cable splices and cable terminators.

A cable splice is used for connecting two cables, as shown in Fig. 4. A cable terminator is mainly used for underground power distribution and for connecting the upper/lower cables with the switches on the electric poles in a high-above-ground wiring system, as shown in Fig. 5.

Figure 4：*The cable splice.*

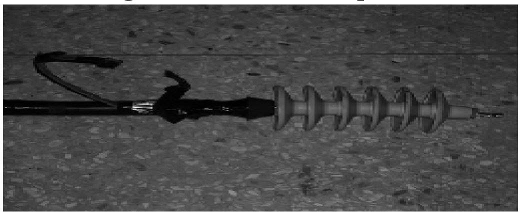

Figure 5：*The cable terminator.*

3. Research Methods and Results

In this study, we adopt two approximately two-meter long, 25 kV power cables to conduct experiments. To simulate the insulation faults caused by human negligence in field, we made some flaws on the cable splice and the cable terminators. The wiring diagram is shown in Fig. 6.

In Fig. 6, ch1 represents the impulse current signal from the detection resistance; ch2 denotes the output signal from the capacitive coupler sensors; ch3 displays the acoustic emission signal, and ch4 shows the output signal of the capacitive coupler. The AE measurement method adopts a 60~150 kHz detector, with an amplifier capable of handling signals in the range of 20~300 kHz [10]; the capacitive coupler utilizes a frequency band of 300 kHz~70 MHz.

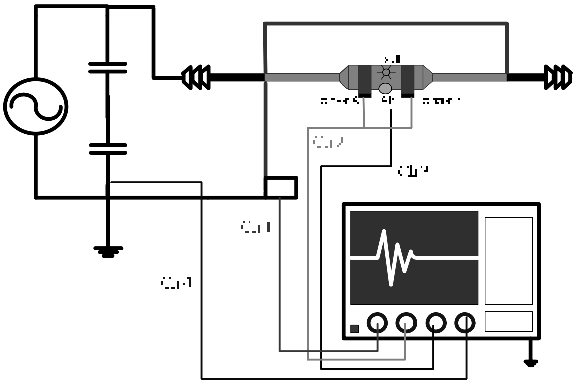

Figure 6：*The field wiring diagram.*

3.1 Investigating the PD on cable splices

To investigate the three detection methods mentioned, we connect, in parallel, a capacitive coupler to the test sample and use the coupler's output signal as the reference signal. We then simulate the measurement method described in IEC60270. The measurement results are shown in Fig. 7, where ch1 represents the signal measured from the capacitive-type sensors, ch2 denotes the signal measured by the AE measurement method, ch3 displays the signal measured by the impulse current measurement method, and ch4 shows the signal measured from the capacitive coupler. Comparing the measured signals simultaneously measured by all the detection methods under our investigation, we discover that the acoustic waves' propagation speed is slower, and the acoustic waves reach the AE sensor's probe after certain delays.

We observe from Fig. 7 that the acoustic wave's time duration is approximately 5 ms; its main frequency is, after the Fourier frequency spectrum analysis, around 44 kHz, as shown in the second waveform in Fig. 8. When two consecutive PDs occur, two overlapped acoustic waveforms will be generated, as shown in Fig. 9. The impulse current measurement method applied to ch3 lengthens the signal, which attenuates rapidly; the signal's main frequency is approximately 5 MHz. This high frequency represents a higher cost for sampling and analyzing the measured signal. The electric signal acquired from the capacitive coupler measurement method attenuates even faster; through frequency spectrum analysis, the lowest frequency of the signal in ch4 is approximately 200 kHz.

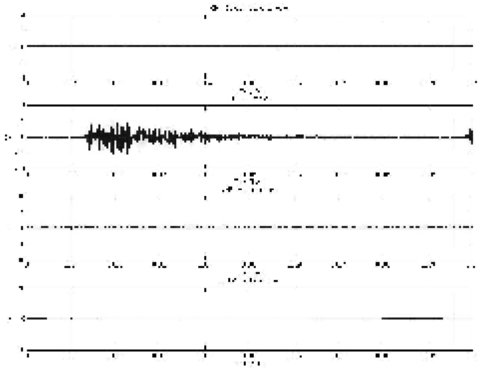

Figure 7：*The cable splice's PD signal.*

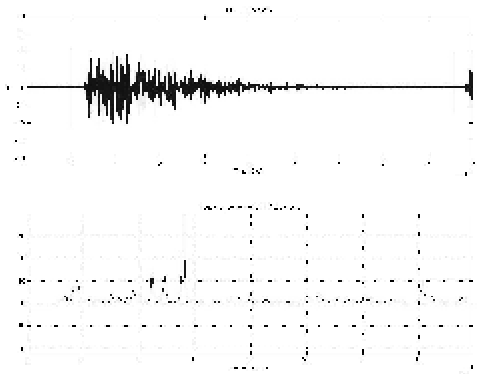

Figure 8：*The AE signal's main frequency.*

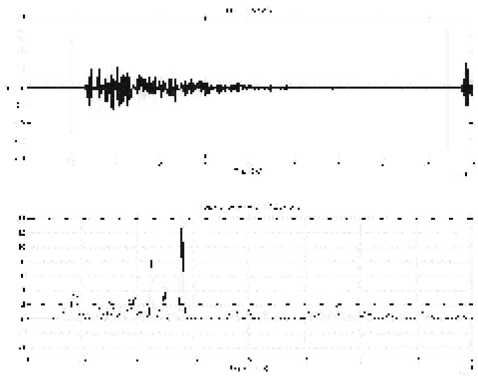

Figure 9： *The acoustic signal waveform and the spectrum under consecutive discharges.*

3.2 Investigating the partial discharge on cable terminators

We intentionally make a gap around the cable terminator under test to produce a corona discharge phenomenon. To analyze the relationship between the discharge time and the voltage phase angle, this study changes the ch4 signal into a power-source voltage signal and re-conduct the experiment using the method described in Section 2.1; the result is shown in Fig. 10. The ch1 waveform shown in Figure 10 is acquired by the capacitive type sensors, while ch2 by the AE measurement method; there exists a specific phase angle relationship between the impulse current signal of ch3 and the power-source voltage signal of ch4. From Figure 10 we observe that the impulse current signal (ch3) is relatively stronger, followed by the signal acquired by the AE measurement method; the capacitive-type sensors (ch1) are, on the other hand, inactive.

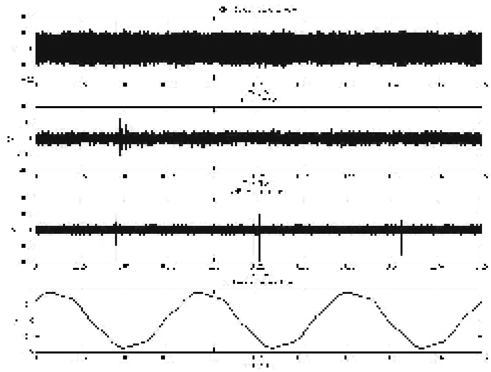

Figure 10：*The cable terminator's PD signal.*

3.3 Investigating on positioning the fault site

To further investigate the AE measurement method's positioning capacity over the fault site, we place the AE sensor in two different locations [11], as shown in Figs. 11 and 12. The magnitude of ch2 in Fig. 11 is greater than that of ch2 in Fig. 12, indicating that there is a close correlation between the sensor's location and the fault site. Thus, we can achieve positioning the fault site by moving our AE sensor's location in search of the maximum PD- signal magnitude.

The other positioning method can be derived from the signals shown in Fig. 7. From Fig. 7 we observe that after the impulse current signal (ch3) occurs, the AE signal will be produced with a time delay. The fault site's exact location now can be computed by multiplying the AE signal's propagating speed with the time delay between said impulse current signal and said AE signal if the delay can be attained.

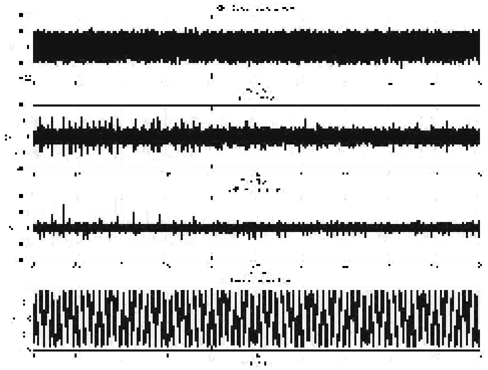

Figure 11：*Approach the cable splice's PD signal.*

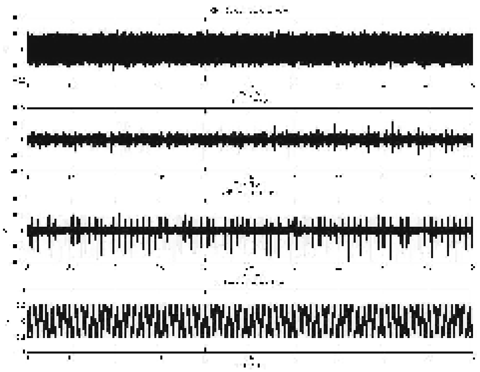

Figure 12：*Far cable splice's PD signal.*

4. Conclusions and Discussion

The fault-occurrence possibility of cable splices and cable terminators has been known to show a steadily-increasing trend year after year. It has thus become a vital issue to determine an electric power cable's degree of deterioration in its insulation via measurements and pre-diagnoses. As far as we know in this field, there has yet been a unification of applying the different measurement methods up to date.

This study investigates three measurement methods and evaluates their features and pros and cons. From the experiments we conducted, we observed that the signals obtained through a detection resistance connected, in series, to the grounding terminal of the cable's shielding layer possess a higher sensitivity; such method, however, is prone to field noise interferences, which will impose a detrimental effect to the measurement results. Since the signal acquisition speed required by this method is rather high, the cost in applying this method thus will be high too.

The capacitive coupler measurement method is suitable for applications to cable splices. The acoustic-emission measurement method is effective to both cable splices and cable terminators. The AE measurement method is not prone to field EM interferences and holds a signal frequency band much lower than that of the impulse current measurement method, namely requiring a sampling rate of only several hundred kHz to acquire a discharge signal. The AE measurement method's equipment-building cost, hence, will be lower. The AE measurement method is superior in positioning the fault site, i.e. with a better directional capability. There is, hence, a great potential in developing a diagnostic technique for positioning the cable's fault sites using this method.

5. Acknowledgements

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