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***New technique:***

# Detection and location of partial discharge in cast-resin dry-type transformers using a waveguide and a new acoustic emission sensor pair design*

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**Abstract:** The acoustic emission (AE) method could be used to detect and locate partial discharges (PD) in cast-resin dry-type transformers. However, due to the high sound attenuation in the filled epoxy, the signal is prone to interference from external noises and thus, in practice, there is little possibility of detecting PD. In this study, two techniques were developed to alleviate the shortcomings of the AE method. First, a waveguide is installed on the high-voltage (HV) windings, so that the acoustic signals of PD will propagate to the AE sensors that are installed on both terminals of the waveguide. The location of the winding that has PD can then be detected from the difference in arrival time of the acoustic signals. Test results indicate that the waveguide technique is able to enhance the safety of a measurement system and offers the advantages of easy installation and higher flexibility. Second, a specially designed AE sensor pair is used to distinguish whether acoustic signals are generated by PD inside the HV winding or by the corona outside the transformers. Using these two techniques of waveguide and AE sensor pair not only greatly improves sensitivity but also increases the reliability of the measurement system. Practical test results show that the new techniques can be used to locate precisely the PD in HV windings.

**Key words:** Partial discharge, Acoustic emission, Cast-resin dry-type transformer, Waveguide, Acoustic emission sensors
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## 1 Introduction

The main problem in cast-resin dry-type transformers is the degradation of isolation. In such transformers, electric isolation has a limited duration in acceptable conditions, and its degradation during the period in service results from the accumulation of mechanical, thermal, and electric effects. In fact, partial discharges (PD) are electric phenomena which are a major shortcoming of the isolation. If a correct diagnosis cannot be furnished at the time, the insulation resin in the high-voltage (HV) winding of a cast-resin dry-type transformer may break down, bringing a production line to a halt and, consequentially, causing unnecessary financial losses (Werle *et al*., 2000a; 2000b; 2002; Gockenbach *et al*., 2001).

The main advantage of the acoustic emission (AE) method is its ability to detect and locate PD, but it has the following shortcomings when applied to cast-resin dry-type transformers: (1) Because the sound absorption in filled epoxy is very high, the AE method cannot make precise measurements (Lamela-Rivera *et al*., 2003; Wang *et al*., 2005). (2) When AE sensors are mounted directly on the HV winding of a transformer, the HV winding will generate discharge to the sensors. This will endanger the measurement system (Smith, 2005; Su *et al*., 2008). (3) It is not easy to install and replace the measurement system. (4) The AE method is prone to interference from external sound sources (Lamela-Rivera *et al*., 2003; Wang *et al*., 2005). (5) Unlike electric detection, the AE

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method cannot use oscillographic patterns from power cycles to recognize PD in the HV winding or external corona (IEEE Std C57.124-1991).

To solve the first shortcoming, Harrold *et al.* (Harrold, 1979; 1985; Ronald and Murrysville, 1979) applied a waveguide, installed inside a power transformer, to propagate inner PD signals to AE sensors on each side of the waveguide. This application improves the propagation of ultrasonic wave and enhances the sensitivity of AE sensors (Su *et al.*, 2008), and a PD location can be estimated from the difference in arrival time of the terminal signals (Chen *et al.*, 2008). Skubis (1982) designed a reflection transducer for power transformers, which could concentrate the input signal energy. A hydrophone is located at the focal point of the reflector to increase the sensitivity of detection.

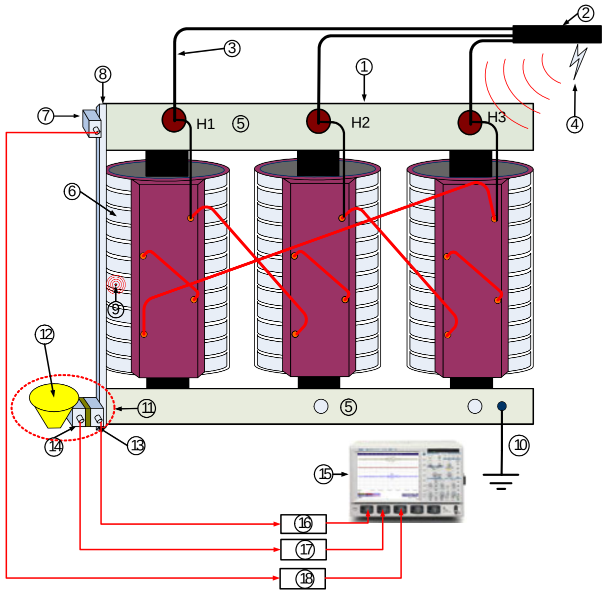
To solve the second shortcoming, TransiNor As (2003) manufactured the acoustic insulation analyzer, and developed a hot stick for cable termination and cable joint measurements. Fiberglass is used as the waveguide and the AE sensor is mounted in the handle. The acoustic signal is transferred to the sensor through the fiberglass rod with very little attenuation. Because AE sensors are not mounted at cable terminations or cable joints, safety issues can be avoided.

To solve the above five shortcomings, this paper presents new techniques using a waveguide and specially designed AE sensor pairs for PD detection in cast-resin dry-type transformers. First, a newly designed waveguide is mounted on the HV winding and the sound wave is transferred to the sensors through the waveguide. Therefore, the heavy sound absorption in filled epoxy is reduced. The waveguide is easy and flexible to install and provides a safe distance between the HV winding and the AE sensors. This enhances safety for operators. Second, an AE sensor pair is developed and used to distinguish PD in the HV winding and in the external corona. By combining these two techniques, the location of PD in the HV winding can be detected more precisely. The techniques improve the sensitivity of acoustic measurement, enhance the safety of the detection system, and offer flexibility for system installation.

## 2 Techniques

### 2.1 Waveguide technique

Fig. 1 shows the configuration of the experimental apparatus.




① Cast-resin dry-type transformer ② Power cable ③ Cable termination ④ Corona
⑤ Clamping frame ⑥ High voltage winding ⑦ AE sensor 3 ⑧ Waveguide
⑨ Hsu-Nielsen source ⑩ Grounding ⑪ A pair of AE sensors ⑫ Concentrator
⑬ AE sensor 1 ⑭ AE sensor 2 ⑮ Oscilloscope ⑯ AE amplifier & filter 1
⑰ AE amplifier & filter 2 ⑱ AE amplifier & filter 3

**Fig. 1 Configuration of the experimental apparatus**

Taking the H1 phase as an example, the waveguide and the acoustic emission (AE) sensor pair are mounted on the high-voltage (HV) winding of the H1 phase. In actual measurement, three sets of waveguides and AE sensors can be installed on the HV winding of three phases. The length of the waveguide is equal to the distance between the upper and lower clamping frames. AE sensor 3 is mounted close to the upper clamping frame and the AE sensor pair (AE sensors 1 and 2) is mounted close to the lower clamping frame. The waveguide is made of tempered glass, which has very good electrical isolation and very low sound attenuation. Thus, the waveguide can provide a very good propagation path for the AE signals, where the amplitude of signal in the waveguide is ten times that in the HV winding, and the sensitivity of measurement can be improved (Su *et al.*, 2008). The winding of the partial discharges (PD) can be estimated from the difference in arrival time of the AE signals at AE sensor 3 and AE sensor 1

### 2.2 Acoustic emission sensor pair technique

The AE method is prone to interference from external sound sources. In this work, the AE signals can be distinguished by using the AE sensor pair. Fig. 2 shows the configuration of the AE sensor pair. AE signals can be generated from the PD in the HV winding or from the corona outside the transformer.

AE sensor 1 detects mainly the PD signals from the HV winding, and AE sensor 2 detects the ultrasonic signals from the external corona. AE sensors are easily affected by interference from external sound sources. When a heavy external corona occurs, the ultrasonic signals will be detected by AE sensor 1 as well as by AE sensor 2 and almost at the same time. The sound-absorbing material between AE sensors 1 and 2 ensures that there is no propagation path for the ultrasonic signals. The ultrasonic signals detected by AE sensor 2 must come from the external corona. When PD occurs, the ultrasonic wave propagates from the HV winding into the waveguide. The ultrasonic signals are detected by AE sensor 1, and AE sensor 2 detects nothing. The signals of AE sensor 1 and AE sensor 2 are separately transferred to the AE amplifier and filter 1 and AE amplifier and filter 2 through a BNC (Bayonet Neill-Concelman) connector. Finally, the acoustic signals can be observed on the oscilloscope.

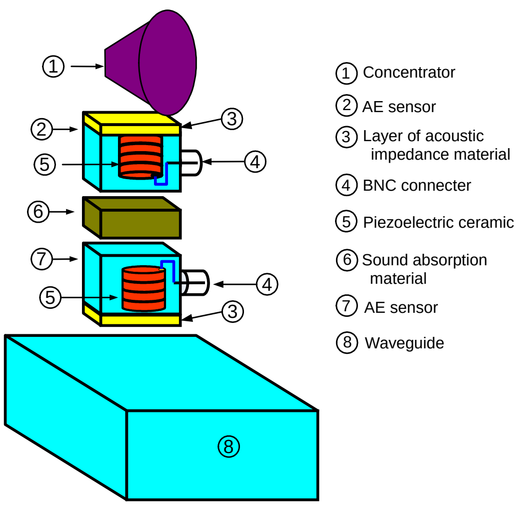



**Fig. 2 Configuration of the pair of acoustic emission (AE) sensors**

The principle of the AE sensor pair is as follows: the AE sensor pair comprises AE sensor 1 and AE sensor 2. Between the two sensors is sound absorbing material which can ensure that there is no propagation path for the ultrasonic wave. On the bottom of AE sensor 1 is a layer of acoustic impedance coupling material, which is used to guarantee the maximum energy transfer between the piezoelectric ceramic and the waveguide. On top of AE sensor 2 there is also a layer of acoustic impedance coupling material used to guarantee the maximum energy transfer between the piezoelectric ceramic and the concentrator. The piezoelectric ceramic disc has a cross-sectional diameter of 10 mm and a layer thickness of 5 mm. A piezoelectric stack actuator is composed of four piezoelectric discs and its bandwidth is from 30 to 80 kHz

## 3 Measurement methods and results analysis

### 3.1 Acoustic emission signals from partial discharges in a cast-resin dry-type transformer

PD in an HV winding was simulated using a Hsu-Nielsen source (Fig. 1) (Prosser and Gorman, 1994; ASTM E976-00, 2000). The external corona was simulated using a spark lighter. The gain of the preamplifier was 40 dB. The bandwidth of the filter was from 30 to 200 kHz (Su *et al.*, 2009). The principle of installation of the waveguide and AE sensors is as follows. If the measurement system is intended only to detect an AE signal and to recognize whether the signal is PD in the HV winding or the noise from an external corona, the waveguide and the AE sensor pair need to be installed. But if the measurement system is intended to locate the winding of PD, AE sensor 3 is also required (Fig. 1).

### 3.2 Principle of measurement and recognition with the pair of acoustic emission sensors

#### 3.2.1 Background noise

Fig. 3 shows typical background signals detected by the AE sensor pair under the condition that there is no noise source while measuring the transformer. If the ultrasonic signal is absent from AE sensors 1 and 2, then there is no PD in the HV winding or in the corona in the air.

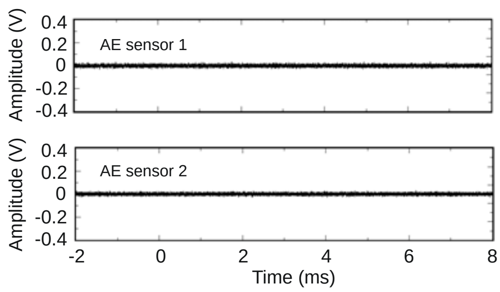



**Fig. 3 Background signal detected by the acoustic emission (AE) sensor pair**

#### 3.2.2 Ultrasonic noise from external corona

When heavy external sound occurs, part of the noise can be rejected by the filter, but some noise still passes through the filter and amplifier (Fig. 1). If we use a spark lighter to simulate the corona from a power cable, the ultrasonic signals detected by the AE sensor pair are as shown in Fig. 4. The signals arrive at each sensor at almost the same time.

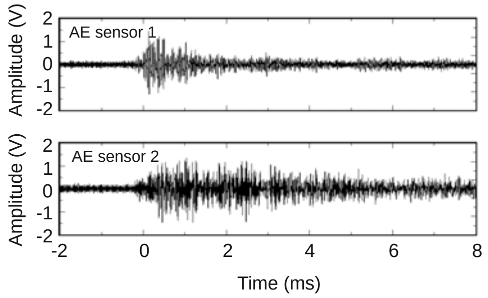



**Fig. 4 Ultrasonic signals from the corona of a power cable**

While using the technique of the AE sensor pair to detect PD in the HV winding, no matter what signal AE sensor 1 detects, the signal detected by AE sensor 2 must be from the external corona.

### 3.2.3 Acoustic emission signals from partial discharges in high-voltage winding

When PD occurs in the HV winding, the ultrasonic signals can be detected by AE sensor 1. Because of the sound-absorbing material between the sensors, the ultrasonic signals fail to propagate from AE sensor 1 to AE sensor 2. Also, because the acoustic impedance of resin material is greatly different from air, ultrasonic sound in resin will cause strong reflections. Thus, the concentrator of AE sensor 2 cannot receive the ultrasonic signals generated by PD in HV winding (Fig. 5). When AE sensor 2 has no signal from the concentrator but AE sensor 1 has signal from the waveguide, it can be concluded that PD is occurring in the HV winding.

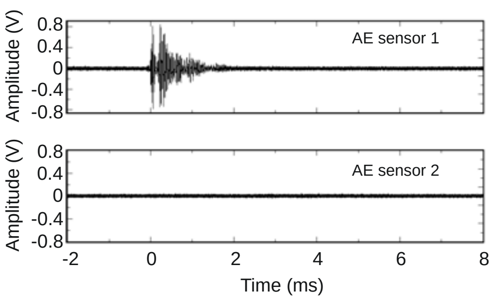



**Fig. 5 Acoustic emission (AE) signals from partial discharges in high-voltage winding detected by the AE sensor pair**

### 3.2.4 Location of partial discharges in high-voltage winding

When PD occurs in the HV winding, the location of the PD can be estimated from the difference in arrival time of the ultrasonic signals. Fig. 6 shows the principle of operation for locating the winding of PD.

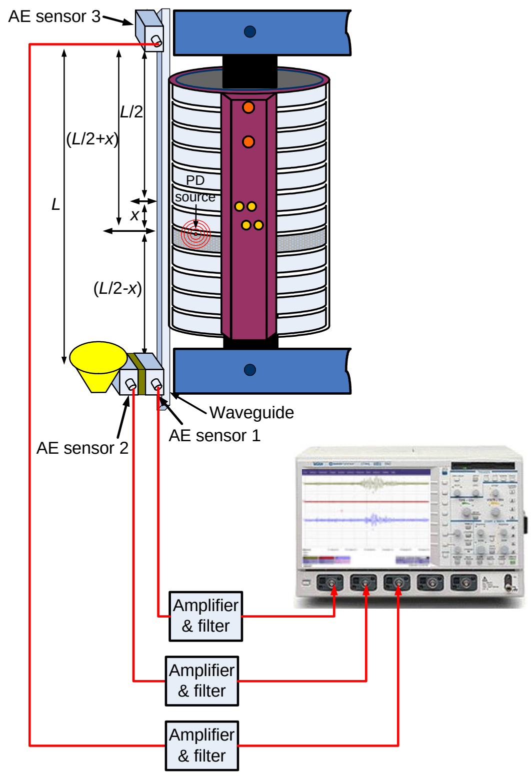



**Fig. 6 Principle of operation to locate the winding package of partial discharges (PD) in high-voltage winding**

The waveguide is mounted on the HV winding and its length is *L*. Acoustic emission (AE) sensor 3 is placed on the upper terminal of the waveguide, and the AE sensor pair is placed on the lower terminal of the waveguide. Then, by calculating the time difference of the ultrasonic signals arriving at AE sensor 3 and AE sensor 1, we can determine the location of the PD

If the distance from the winding of the PD to the center of the waveguide is denoted by $x$, then $x$ can be estimated from the following formula:

$$x = v_{\text{glass}}(\Delta t/2) = 3413\,(\Delta t/2), \quad (1)$$

where $v_{\text{glass}}$ is the velocity of the ultrasonic wave in the waveguide ($v_{\text{glass}}\approx 3413$ m/s) and $\Delta t$ is the time difference between ultrasonic signals arriving at AE sensors 1 and 3.

### 3.2.5 Results of the laboratory test

Fig. 7 shows the principle of operation of an actual test, using induced voltage balanced winding in the laboratory (Chen *et al*., 2008). The three-phase auto transformer was adjusted to 130 V and induced 13 kV to the high-voltage (HV) winding. The partial discharges (PD) signal was detected (Fig. 8). $\Delta t$ is the time difference between the ultrasonic signals arriving at acoustic emission (AE) sensor 1 and AE sensor 3. From the oscilloscope, we can find Δ*t* is equal to 64.6 μs. From Eq. (1), *x* is equal to 11 cm. The winding of PD can be found accurately and its location is 11 cm lower than the center of the waveguide.

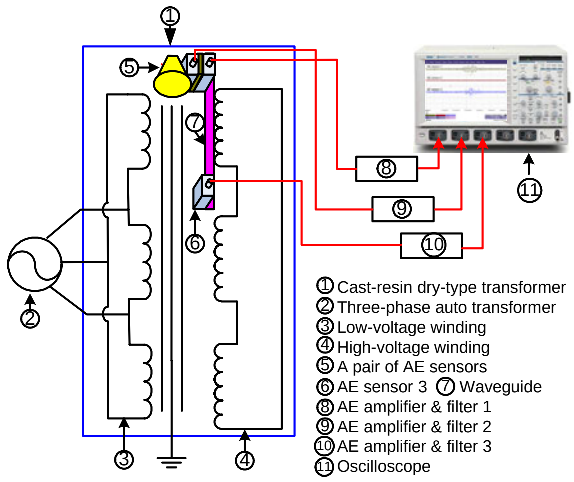



**Fig. 7  Principle of operation of an actual test, using induced voltage balanced winding in the laboratory**

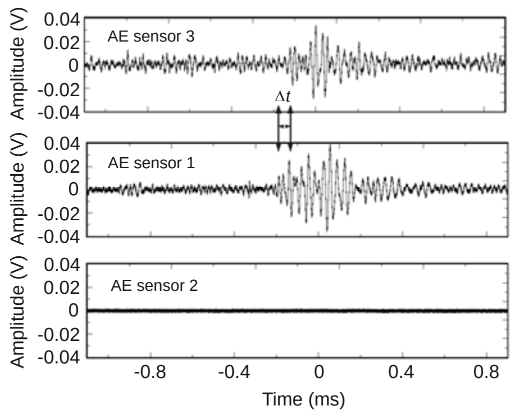



**Fig. 8  Ultrasonic signal of partial discharges detected from the pair of acoustic emission (AE) sensors and AE sensor 3**

Δ*t* is the time difference between ultrasonic signals arriving at AE sensor 1 and AE sensor 3

## 4 Discussion and conclusions

In this paper, a new method based on the AE method is presented for detecting and locating PD in cast-resin dry-type transformers. A waveguide and a pair of AE sensors are incorporated in the new PD detection system. This new system can detect the PD signal and distinguish whether the AE signal is from the PD in the HV winding or from the corona outside the transformer. The location of the PD winding can be estimated from the time difference between ultrasonic signals arriving at AE sensor 3 and AE sensor 1. The method will improve the sensitivity of acoustic measurement, enhance the safety of the detection system, and offer flexibility for system installation. Moreover, the cost of the detection system is greatly reduced. Based on research regarding the characteristics of various AE signals in the transformer, further work could be undertaken to construct a complete discrimination algorithm for cast-resin dry-type transformers.

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