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Comparison of On-Line Partial Discharge Detection Techniques for High Voltage Power Cable Joints and Terminations

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ABSTRACT

Cable joints and terminations play a vital role in providing dependable electrical connection, mechanical support and physical safeguard. These provide electrical stress control to shielded power cables. Despite their usefulness, they suffer from partial discharges (PD) because of enhanced voltage stress, moisture ingress and poor workmanship (during installation). Therefore, it is necessary to undertake on-line PD detection to determine their state. Some of these techniques are capacitive coupler (CC); acoustic emission (AE); and high frequency current transducer (HFCT). This article presents a literature review of these techniques based on the cost, availability, and applicability. The comparative analysis is also provided on location of their sensors, quantification and detection ability. The CC technique involves the quantification of the coupler sensor input measured in mV/pC by realizing the time of flight between two sensors for which the results are used to estimate location of the PD. Meanwhile, the AE technique has an advantage of high immunity to electrical noise, with a caveat that acoustic signals are highly attenuated within the cable joints. Additionally, the combination of the acoustic sensors and PD electrical couplers can be used to discriminate PDs from electrical noise. The HFCT has two methods – with demonising (HFCT-WiD) and without demonising (HFCT-WoD). The HFCT-WiD technique can significantly reduce the sensor's detection sensitivity due to its high value of noise to signal ratio (NSR). Comparatively, the HFCT has the best results of quantification and detection ability for PDs among all three techniques investigated. However, in places where electrical noise is severe, PD activities may be detected effectively with AE technique. Further work is needed to statistically map these methods and establish their correlation with experimental data.

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INTRODUCTION

Cable joints and terminations are weak points in the power cable and prone to partial discharges (PD). This is due to the fact that, they are man-made and combine interfaces of different insulating materials (Kirkcaldy et al., 2019; Tian et al., 2000; Wei et al., 2000). It is very important to regularly monitor PD within the cable joints to avoid severe damage of the cable ~~itself~~ and consequently the system failure (Gulski et al., 2008; Wester et al., 2007). It is known that high voltage transients are undesirable and need to be minized (Kadete, 1995). In early studies of cable failures, conventional electrical methods were employed in the detection of the PD activities (IEC, 1981, 2000; Kreuger, 1989; Kreuger et al., 1993) and such methods were generally conducted off-line under applied voltage higher than the nominal voltage. With conventional method, which has been summarized in (IEC, 2000), the test circuit should be able to detect permissible discharge quantity regulated for the test object. However, it is very essential to detect any deterioration of the apparatus during the normal use and this can be achieved through the on-line monitoring techniques (Chambela & Mushi, 2022; Zhu et al., 2021).

With on-line monitoring technique, sensors are placed in the cable as shown in Figure 1 whilst the cable remains in the service (Matamwe & Mushi, 2022). Sensors detect the PD signals before the signal is sent to analysing unit (oscilloscope) (Rosle et al., 2021). The teams of Choudhary and Shafiq in (Choudhary et al., 2022; Shafiq et al., 2019) reported that the characteristics of PD signals are mainly affected by applied voltage, defect size and location, insulating material and environmental condition. Thus, the application of the on-line monitoring techniques must consider the sensitivity of the sensor used since the sensitivity decreases with increase in cable length and environmental noise (IEEE, 2007). In other studies researchers discovered that the PD detection with on-line techniques needs the sensors' sensitivity with wide bandwidth, since PD signals can be distorted if the bandwidth is narrow (Fukunaga et al., 1992; Mulroy et al., 2012; Wei et al., 2000). Moreover, other parameters like voltages, currents and temperature can be monitored on-line to determine a defected portion of the cable (Abdullah et al., 2020, 2021; Ghaedi et al., 2016).

This paper presents a comparative analysis on location, quantification and detection of three potential on-line techniques to detect PD activity within the cable joint. The techniques are selected based on the cost, availability and applicability within the cable joints.

LITERATURE REVIEW

Capacitive Coupler Technique

Capacitive coupler test arrangement

In previous studies, the capacitive coupler equipment was installed by cutting about 100 mm of a metal sheath and 40 mm wide tin tape which serves as coupler sensor covering around the exposed outer semicon layer (Tian et al., 2002). Figure 2 shows the capacitive coupler mounted on top of the semicon layer which acts as the power frequency ground due to its lower conductivity. In this arrangement, the coupler does not affect the internal field distribution in the cable. However, the arrangement causes the destruction of the metal sheath. Other studies (Halim et al., 2021; Tian et al., 2003; Zhong et al., 2001) suggested the improvement on the coupler installation so as to prevent the metal sheath from destruction. Thus, the cable near the prefabricated rubber is wrapped by the copper wire mesh instead of the rigid metal sheath. The capacitive coupler can then be placed before the wrapping of the copper wire mesh as shown on Figure 3 in order to reduce uncertainty of the results due to roughness of the copper wire mesh inner surface, a smooth shielding electrode is placed under the copper wire mesh and polyvinyl chloride insulator acts as means of isolation between coupling electrode and shielding electrode. In this way PD signals can be coupled by the PD detection sensor in a similar way as capacitive voltage divider.

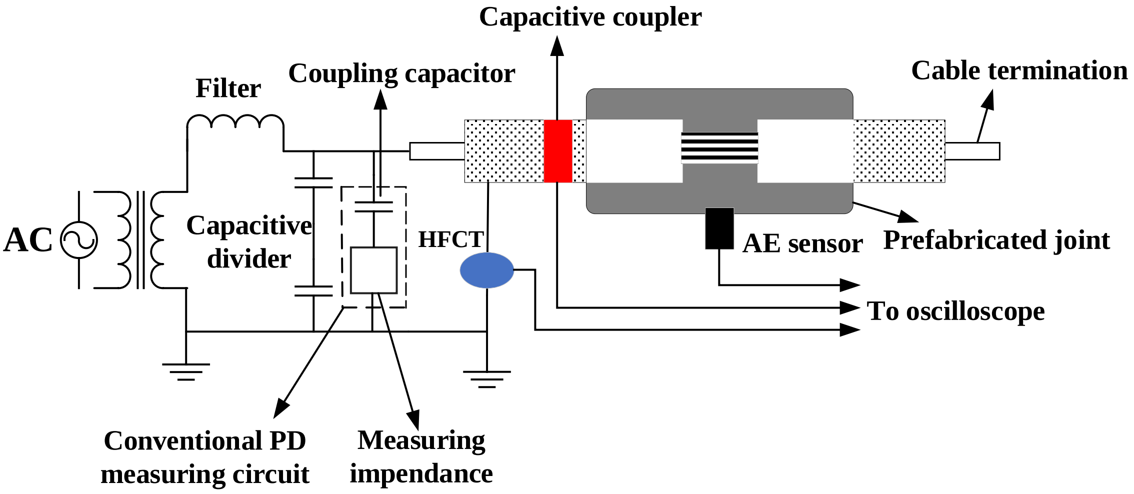

Figure 1: General test arrangement for PD measuring (Tian et al., 2002).

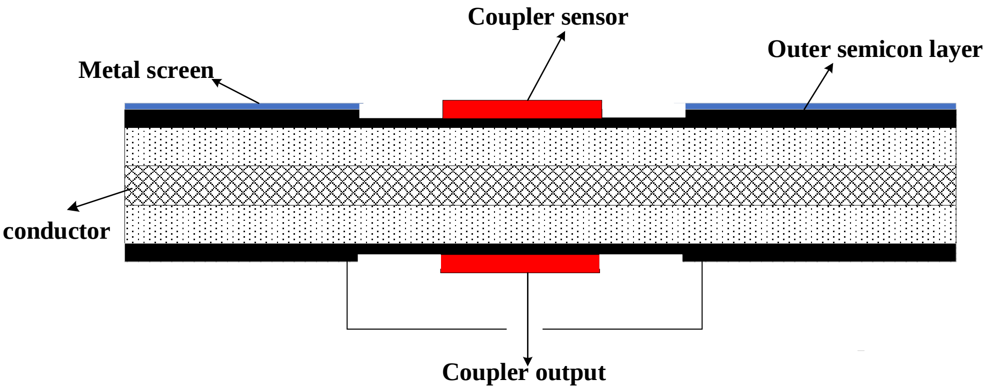

Figure 2: Diagram of a capacitive coupler with 100 mm section removed from the cable (Tian et al., 2002).

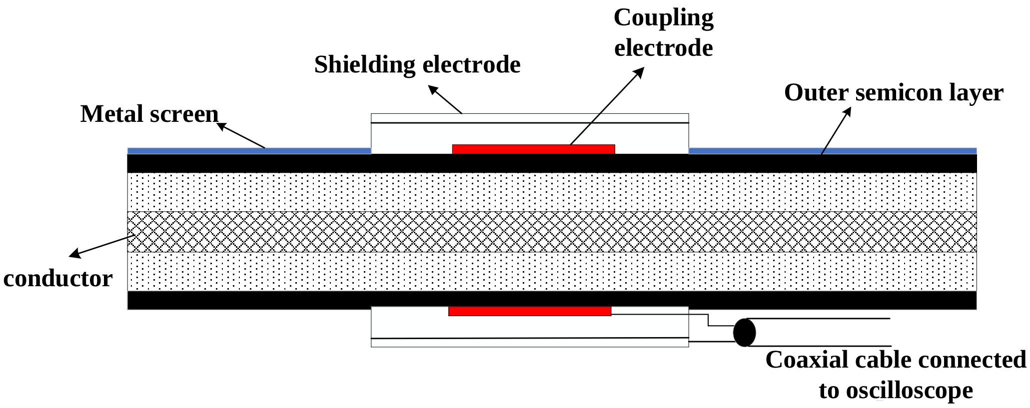

Figure 3: Diagram of a capacitive coupler without 100 mm section removed from the cable (Ruan et al., 2019).

Capacitive coupler quantification

The sensitivity of the capacitive coupler can be determined by injecting a known calibration charge into the system and comparing it with the measured amplitude from the detector output (Chambela & Mushi, 2022; Tian et al., 2002). The sensitivity factor S is given by the Equation (1).

$$S = A / q \tag{1}$$

where A is the output voltage measured from the detector (mV) and q is the injected pulse (pC). The large value of S indicates higher sensitivity of the coupler. The quantification results obtained may not only depend on magnitude of the injected pulse, but also its wave form and its frequency spectrum that reaches the detector (Halim et al., 2021; Kirkcaldy et al., 2019; Ruan et al., 2019).

The experiments done by Tian et al., (2002) indicated a nearly relationship between A and q which gives the quantification results of approximately 0.7 mV per pC when the pulse was injected at the cable termination. When the two couplers are installed at either ends of the cable termination the quatification results was found to be 0.97 mV per pC. That paper commented that methods were inappropriate for on-line quantification of calibration of cable joints due to attenuation of the pulses within the cable and reflection at the cable terminations which introduced significant errors. On the other hand, this study (Ruan et al., 2019) reported sensitivity of the couplers ranging from 0.04 to 1.2 mV per pC. That study revealed the couplers were insensitive to some defects which could results into dead zones during PD detection. An alternative method was suggested by (Wang et al., 2005), the quantification of the coupler was done through frequency response measurement and a coupler model was expressed as the transfer function ($H(w)$) type 0 system. This system can be expressed to have a low frequency zero (w_z), a high frequency pole (w_p), and a scalar gain (G), i.e.

$$H(w) = \frac{G\left(1+\frac{jw}{w_Z}\right)}{\left(1+\frac{jw}{w_Z}\right)} \tag{2}$$

INTERNAL AND CORONA DISCHARGE DETECTION WITH CAPACITIVE COUPLER

Internal Discharge Detection

Figure 1 indicates the test arrangement conducted by Gulski et al., (2008) and Tian et al., (2002). From this arrangement, two couplers was installed at either sides of the cable joint; the discharge pulse travelling within the cable joint can be determined by injection of the step wave into one end of cable termination and time delay between two couplers was found to be 6.7 ns. For a given distance of 1.05 m between couplers, the pulse travelling speed was estimated to be 0.157 m per ns. The output of the couplers seeing the same discharge pulse with one coupler leads another coupler by time flight of 3.4 ns. This important information obtained from that study was very useful in estimating the accurate location of the PD activity. The coupler's frequency spectrum was within the range of 10 to 300 MHz.

The results indicated a presence of some reflections at the cable terminations. With known speed of the travelling pulse, the reflected pulse would continue to travel along the cable and further be reflected by the terminations. However, further reflections were not observed due to attenuation of the pulse. Experiments ~~done~~ conducted by Wang et al., (2005) revealed a time flight of 4 ns between the two couplers with their frequency spectrum in the range of 500 Hz to 500 MHz. The results were used to estimate the location of the PD source and the propagation velocity of the PD signal.

Corona discharge detection

To study the response of the capacitive coupler, the corona discharges are generated by hanging a pair of scissors from one termination and pointed at the bottom electrode. For this set up (Tian et al., 2002) used an inception voltage of 21 kV, and found discharge level of 250 pC. A similar test can be done by replacing the pair of scissors with aluminium wire using an inception voltage of 14 kV, with a possible discharge level of 30 pC. This technique yields fewer frequency components of longer duration than the internal discharge technique. Another study conducted by Jiang et al., (2018) reported the discharge level of 10 pC with the inception voltage of 110 kV. Generally, the results obtained reveal that if the two couplers are installed at either side of the cable joint, then it is possible to distinguish the PD generated within the cable joints from external noise (Rosle et al., 2021; Zhang et al., 2021).

METHODS AND MATERIALS

Acoustic Emission Technique

Partial discharges produce both electrical and acoustic signals. The experimental investigation undertaken on 132 kV cable terminations reported by (Tian et al., 2000), indicated acoustic emission (AE) sensor’s ability to detect discharges above 10 pC when the sensor is placed near the PD site and applied voltage is 36 – 42 kV. However, when the sensor was moved 70 mm away from the PD site 10 pC discharges were no longer detected. Thus, it is necessary to locate the PD activity by AE sensor before the PD pattern identification is undertaken. Another experimental investigation reported by Tian et al., (2002) reveals that AE sensor is not affected by the external electrical signals. To investigate the AE signal attenuation within the cable joint, two AE sensors were installed 85 mm away from each other. To determine the feasible location of the PD, the two sensors are moved along the cable joint surface until the peak magnitude signal occurs at minimum time of flight. In cases where electrical noise is severe, PD activity may be detected effectively with acoustic sensors rather than electrical couplers. In addition, the combination of acoustic sensors and PD electrical couplers can be used to discriminate PD from electrical noise (Ma et al., 2018).

High Frequency Current Transducer Technique with Wavelet De-Noising

High frequency current transducer (HFCT) is used to detect the discharge current pulses that are propagating to ground (Refaat & Shams, 2018; Rodrigo-Mor et al., 2020). The HFCT is clamped around the conductor connecting the power cable metallic sheath to the earth. The typical frequency range of HFCT is 2.5 kHz to 150 MHz. The output is then amplified and sent to a digital oscilloscope. However, in this case the noise to signal ratio (NSR) is usually very high which results to low detection sensitivity. Thus, improvements can be made by employing a filtering technique. Many techniques have been developed and applied to discriminate PD from noise interference, but the most popular one is wavelet de-noising. With wavelet de-noising the NSR is improved, since the signal is decomposed into a series of approximation and detail coefficients at different scales (Tian et al., 2002). Choosing the threshold value for wavelet coefficients is performed by retaining all wavelet coefficients corresponding to discharge events and discarding all noise coefficients, see Equation (3); where the noisy signal is $X[n]$, filtered signal is $f[n]$, noise signal is $W[n]$, and n represents the analogue to digital sampling time instant. Finally discharge signals are reconstructed using the modified approximation and detail coefficients. This technique has been found to give the best results of sensitivity and frequency response (Tian et al., 2000, 2002).

$$X[n] = f[n] + W[n] \tag{3}$$

COMPARISONS OF THREE PD DETECTION METHODS

The preceding sections gave detailed explanations for the four methods to detect PD on HV cables. Therefore, this section compares experimental data obtained from different studies, weaknesses and strengths of each method in Table 1.

Table 1: Comparison of three methods for PD detection

S/N	Method	Measurement capability	Weaknesses	Strengths
1	Capacitive coupler	a) Frequency range 50 Hz-300 MHz b) Time of flight 3.4 – 4 ns c) Discharge levels of 10 pC and 30 pC at test voltage of 110 kV and 14 kV respectively for the case of corona discharge	a) Errors in measurement b) Introduction of dead zones during measurement	a) On site measurements is possible b) Can be placed inside/beside device under test
2	Acoustic emission	a) Time of flight 45 – 93 µs b) When the sensor is near PD site, discharges above 10 pC can be detected at 36 – 42 kV test voltage	a) It needs smart and computation intensive methods to locate PD b) It requires expensive equipment and processors	a) Has good noise robustness b) Can prevent breakdown of HV system
3	HFCT	a) Frequency range 10 kHz – 200 MHz b) Discharge levels of 35 pC at 15 kV	a) It needs a filter b) Has low detection sensitivity	a) Can give excellent PD detection if filters are properly configured b) Can distinguish type of PD from noise

CONCLUSIONS

This article gives a general overview on on-line techniques of detecting PD activity in power cable joints and terminations. This review covered three most applied techniques, namely: - capacitive coupler (CC), acoustic emission (AE) and high frequency current transducer (HFCT). The comparison was based on their sensitivities, pulse shapes, frequency spectra and time of flight between internal discharge and external noise. The findings were as follows. The combination of the acoustic sensors and PD electrical couplers can be used to discriminate PDs from electrical noise. The HFCT-WiD technique can significantly reduce the sensor's detection sensitivity due to its high value of noise to signal ratio (NSR). Comparatively, the HFCT has the best results of quantification and detection ability for PDs among all three techniques investigated. However, in places where electrical noise is severe, PD activities may be detected effectively with AE technique. Further work is needed to statistically map these methods and establish their correlation with experimental data.

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