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A novel calibration method for PD measurements in power cables and joints using capacitive couplers

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Abstract
Partial discharge (PD) measurements are universally accepted as a technique giving some indication of the state of the insulation in high-voltage apparatus. Cable end users are keen to adopt online PD monitoring during commissioning of systems. However, because of noisy environments and the problems of interference the conventional methods are difficult to implement. As a consequence, ultra-high frequency (UHF)/very high frequency (VHF) techniques of on-site detection of partial discharges have been developed. A technique based on capacitive coupling has received much attention. It has been demonstrated that it is possible to use the technique to monitor the partial discharge in cables, particularly in joints/terminations. However, in order to obtain quantitative information about PD, calibration is required for this technique. Existing calibration methods are difficult to implement on-site. In this paper, a novel method is proposed and compared with the conventional method on a short piece of cable. It has been shown that an individual capacitive coupler can also be accurately calibrated on-site and online using the new method, therefore it provides quantitative information about the amount of apparent discharge. In practice, this is important for electricity utilities as the quantitative information about PD can be used to determine the quality of the cable system and to decide whether the system needs to be repaired or replaced.

Keywords: partial discharge, calibration, XLPE cable, capacitive coupler, insulation degradation, defects

(Some figures in this article are in colour only in the electronic version)

1. Introduction

For electric power distribution industries, cyclical and continuous monitoring of installed and operating high-voltage apparatus is of particular importance from safety and reliability points of view. Partial discharge (PD) measurement has been considered as an effective and reliable tool to bring up any faulty parts in the insulation [1, 2]. Over 50 years, a conventional method has evolved to detect partial discharge activities in cables, transformers, GIS systems and other high-voltage apparatus. The conventional method for detecting PD involves a coupling capacitor parallel-connected with the testing object and discharge signals are measured across an external impedance. The external impedance usually consists of a resonant circuit. The function of the resonant circuit is to expand the discharge current pulses in the time domain so they are easier to detect. In the event of partial discharge taking place, a quantitative parameter is required to decide whether the apparatus needs to be repaired or replaced. This means that the detected signal needs to be accurately calibrated. In most cases, calibration is done by injecting a known amount of charge and measuring the voltage amplitude from the detector.

It is generally accepted that the conventional PD detection technique is very difficult to implement on-site for cable insulation because of the limited sensitivity due to the strong high-frequency attenuation of high-voltage cables. For power cables, different sensor types and methods to distinguish noise and PD have been proposed and partially put into service. A review on non-conventional methods can be found in [3]. If it is the aim to detect PD occurring in the cable itself, detection techniques operating in a frequency range of not more than a few MHz have to be utilized due to the high attenuation at higher frequencies in shielded polymer insulated cables [4, 5]. The high interference level in this frequency range requires sophisticated methods for noise suppression [6, 7]. However, due to recent advances in cable manufacturing technology it has been generally recognized that the PD in cable insulation itself is no longer a major threat. Consequently, attention has been paid to the cable accessories such as cable joints/terminations where the complex structure and the construction can cause potential hazard to the whole system. For polymer-insulated cables, pre-moulded slip-on joints are increasingly being used owing to their advantages over conventional taped joints, including production of the active part under optimal conditions in the factory, each joint is routinely tested in the factory prior to the installation and the reduction of risk of introducing imperfections during jointing work. However, compared with cable the accessories are prone to partial discharges due to several interfaces between insulating materials and possible contamination during on-site assembly [8]. In our earlier paper [9], it has been demonstrated that placing two capacitive couplers close to the cable accessories is an attractive option. Theoretical simulation and laboratory tests have shown that the technique has several advantages, such as on-site PD tests, online monitoring, high signal-to-noise ratio, high sensitivity and accurate location. However, the conventional calibration method based on the charge injection from the end of a cable was used to quantify the apparent discharge. This is not a problem when a piece of short cable is concerned in a laboratory. From a practical point of view this is not suitable since the high-frequency components will be lost over a long cable. In this paper, a new method has been proposed and the results compared with the conventional method as well as existing non-conventional methods.

The paper begins with a brief description of the capacitive coupler, and then continues with the application of the conventional PD calibration method to the coupler in the laboratory. This is followed by a review of the existing calibration methods which are in use. A new method is proposed and compared with the existing methods.

2. Capacitive coupler

Figure 1 shows a schematic diagram of the capacitive coupler. It consists of a metallic foil electrode in contact with the semi-conducting screen at a metal screen cut. Reinstatement of the outer metal screen over the coupler with some adequate insulation in between ensures screening of the coupler and the continuation of the fault current capability of the outer screen. Any discharge in solid insulation close to the coupler will be picked up by the coupler.

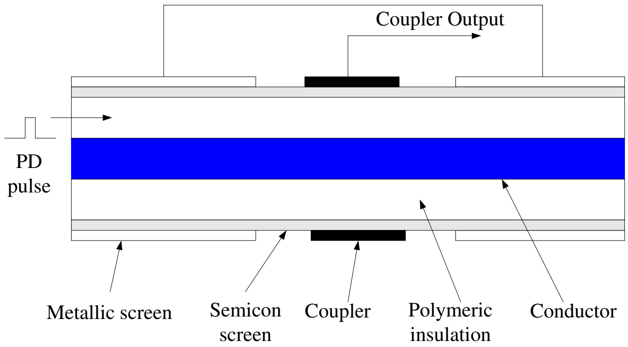

Figure 1. Schematic diagram of cable coupler.

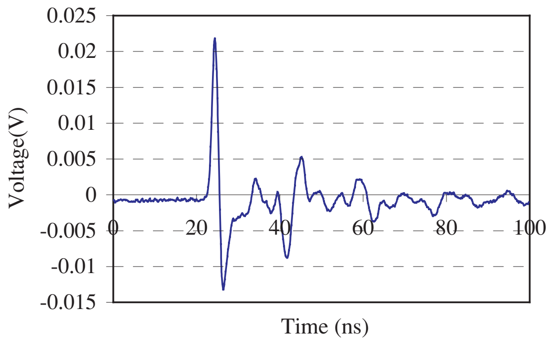

Figure 2. Typical output from capacitive coupler.

The cable used in this research is an 11 kV commercial XLPE cable with inner and outer insulation diameter being 11.9 mm and 19.6 mm, respectively. The coupler was formed by wrapping a tin foil of 30 mm width on the semiconductor. The capacitance of the coupler is around 8 pF without considering the effect of the semiconductor.

3. Conventional PD calibration

In order to establish the relationship between the magnitude of a discharge in the cable sample and the signal received, calibration is always needed. Conventionally, this can be done by connecting a standard discharge calibrator across the sample, usually before testing [10]. A rectangular step voltage of amplitude V_0, in series with a small known capacitance C_0, is connected to one end of a cable. The charge injected into the cable is equivalent to a discharge of magnitude:

$$Q = V_0 C_0. \tag{1}$$

The calibration pulse should have a rise time such that the duration of the current pulse through C_0 is short compared to $1/f_2$ (the upper cut-off frequency). The capacitive coupler often works in the frequency range from a few MHz to several hundred MHz and this requires the rise time of the step voltage around 1 ns. The fast rise time can be realized using a HP 250 MHz pulse generator with maximum amplitude of 5 V. A typical output from a coupler is shown in figure 2.

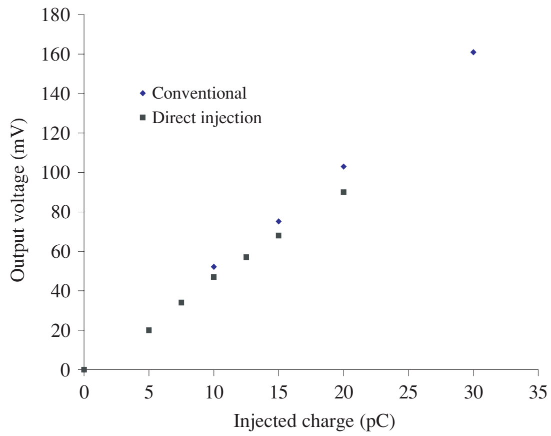

Figure 3. Calibration factor for coupler 1.

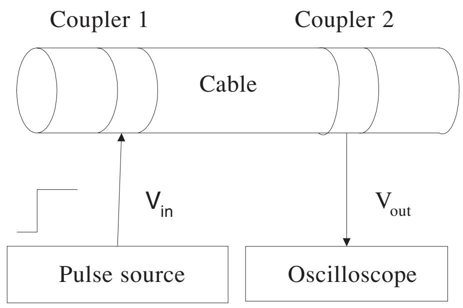

Figure 4. Schematic diagram of calibration using two adjacent couplers.

As the injected charge between the conductor and shield is known, the calibration factor k which is the ratio of PD measurement voltage output, V, and the injected charge, Q_0, can be calculated as

$$k = \frac{V}{Q_0} = \frac{V}{V_0 C_0}. \quad (2)$$

Figure 3 illustrates the relationship between the discharge magnitude and the signal received from the coupler. As expected a linear relationship is obtained, indicating a constant k. This method is suitable for laboratory tests where a short piece of cable is often encountered.

4. Existing calibration methods

On-site PD measurement is required to ensure proper installation of high-voltage cable system accessories. For on-site detection, it is, however, difficult to calibrate from either end of a cable as the signal attenuation at high frequencies in a long cable is significant. Several methods have been proposed and some of them have been used in practice.

As pointed out in our previous paper two couplers can be placed on either side of a cable joint. The option is to calibrate one coupler by injecting signal from another coupler as shown in figure 4. Currently, there are two existing ways how this can be implemented.

4.1. Using coupler's capacitance

From the geometric size of the cable, the insulation material and the width of the coupler, the coupler's capacitance, C, can be calculated. Therefore, the amount of charge injected into the system can be calculated with a known magnitude of pulse voltage. The calibration factor, k in this case, can be determined from the output voltage of the second coupler, V,

$$k = \frac{V}{C V_0}. \quad (3)$$

The result obtained is also plotted in figure 3 for comparison. Clearly, there is a difference between the two methods.

Theoretically, the calibration should not change with how charge is injected. However, comparing the results in figure 3 it is obvious that the signal detected based on injection from the coupler is generally lower than the standard method. There are two reasons for the deviation. The first one is the stray capacitance preventing accurate calculation of charge injected into the system, especially at high frequencies. The second reason, probably the most important one, is that at high frequencies the influence of the semicon layers on the total capacitance is significant. However, it is extremely difficult to obtain the capacitance analytically. In order to overcome this problem, a new method is proposed which can evaluate the capacitance experimentally.

4.2. Using coupling efficiency

This method has been used in PD detection using a directional coupler [11] and recently a capacitive coupler [12]. From the signal transmission point of view, the signal attenuation in the high-frequency range is composed of two parts: (i) longitudinal attenuation, α_l, along the cable length due to the resistance and inductance of the conductor and (ii) radial attenuation, α_r, originating from the dielectric and semiconducting materials [4]. As α_r represents the signal transferred from the coupler into the cable conductor or vice versa, it is also called the coupling coefficient [11]. Both α_l and α_r depend on the configuration of the cable and materials used.

From the measurement point of view, if a particular cable is selected then α_l and α_r depend on the separation distance between the two couplers and the size of the couplers themselves. In the case of figure 4, if a signal V_{in} is injected from one coupler and measured as V_{out} from another the attenuation experienced by the signal is α_{r1}, α_l and α_{r2}, i.e.,

$$\frac{V_{\text{in}}}{V_{\text{out}}} = \alpha_{r1}\alpha_l\alpha_{r2} \quad (4)$$

where α_{r1} and α_{r2} are the attenuation coefficients for coupler 1 and coupler 2, respectively. If the distance between the two couplers is short, which is the case for the joint or termination, α_l is close to unity due to low resistance and inductance of the conductor, the above equation becomes

$$\frac{V_{\text{in}}}{V_{\text{out}}} = \alpha_{r1}\alpha_{r2}. \quad (5)$$

In practice, it is always intended to construct the two couplers with the same size. Assuming the stray capacitance small compared to the coupler's capacitance, the two couplers should have the same characteristics, i.e., $\alpha_{r1} = \alpha_{r2} = \alpha_r$, therefore we have

$$\alpha_r = \sqrt{\frac{V_{\text{in}}}{V_{\text{out}}}}. \quad (6)$$

The same coupling coefficient can also be applied to the charge injected. Now if Q_0 is assumed to be the amount of charge injected into one coupler, the output from another coupler is V. Then the equivalent amount of discharge in the cable Q is given by

$$Q = \alpha_r Q_0. \quad (7)$$

The calibration factor k can be calculated as

$$k = \frac{V}{Q} = \frac{V}{\alpha_r Q_0}. \quad (8)$$

However, in practice it is impossible to construct two couplers exactly the same, i.e., $\alpha_{r1} \neq \alpha_{r2}$. In addition, due to limited size of the coupler, the stray capacitance is often comparable with the coupler's capacitance. Therefore, the accuracy of k determined using this method is questionable. Additionally, the accuracy of Q_0 is also affected by the stray capacitance.

5. Calibration using two-step injection method

If the stray capacitance is included in C then the calibration should be the same as that calibrated from the end. In order to accurately find C, we adopt a two-step injection method. The first step is the same as that in the above section and assumes that the input from the step voltage is V_0 and the output from the second coupler is V_1. The corresponding charge is

$$Q_1 = V_0 C. \quad (9)$$

The second step is to use a known capacitor, C_0, connected in series with C and applying the same voltage V_0 to the system. The charge injected in this case is

$$Q_1' = \frac{V_0 C C_0}{C + C_0}. \quad (10)$$

The output from the second coupler in this case is V_1'. The sensitivity of the same coupler should be the same, i.e.,

$$\frac{V_1}{Q_1} = \frac{V_1'}{Q_1'}. \quad (11)$$

This leads to

$$V_1 = \frac{V_1'(C + C_0)}{C_0}. \quad (12)$$

Therefore, capacitance C which includes the stray capacitance and the contribution from the semiconducting layers can be obtained

$$C = \frac{(V_1 - V_1')C_0}{V_1'}. \quad (13)$$

Once C is known the calibration can be done through either equation (9) or equation (10). The calibration factor for coupler 2 is

$$k_2 = \frac{V_1}{Q_1} = \frac{V_1'}{Q_1'} = \frac{V_1 V_1'}{V_0(V_1 - V_1')C_0}. \quad (14)$$

A typical calibration is shown in figure 5. It can be seen that this method provides an accurate calibration for the coupler as the data are indistinguishable from the data obtained by the conventional method. The same principle can be applied to the first coupler. Therefore, each coupler is individually calibrated which will give a more accurate discharge magnitude.

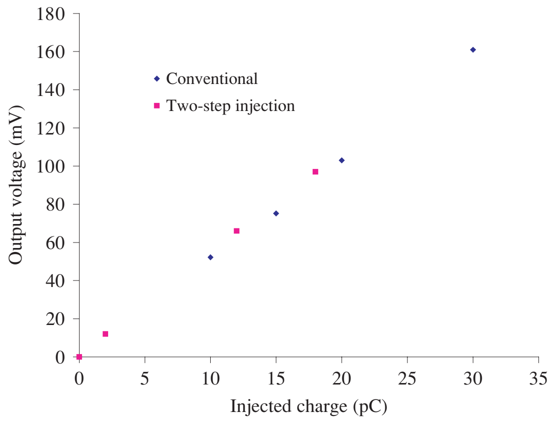

Figure 5. Calibration using two-step injection method.

Table 1. Summary of calibration factor k for two couplers.

Calibration methods	k_1 (mV pC^{-1})	k_2 (mV pC^{-1})
Injection from cable end	5.37	5.23
Direct injection to coupler	4.52	4.94
Coupling coefficient	5.12**	5.70*
Two-step method injection	5.38**	5.33*

Note. Calibration factor obtained based on injection from coupler 1* and coupler 2**, respectively.

6. Discussions

Apart from the calibration methods described above another method has been proposed and used for a directional coupler [3]. If a joint from the same batch is available then one can cut the cable close to the joint and inject a calibration pulse directly into the cable. In this way, distortion or attenuation does not affect calibration accuracy. However, as mentioned in the previous section, it is not an easy task to manufacture two couplers with the same characteristics. This will undoubtedly influence the accuracy of the calibration. Therefore, this method is not utilized in this research.

The conventional method from one of the cable ends is not suitable for on-site calibration where long cables on both sides of a joint are encountered. However, it can serve as a reference for the other methods. Table 1 summarizes the results from a short piece of cable in laboratory conditions using various methods described in previous sections.

Table 1 clearly illustrates that the two-step method proposed shows a good agreement with the standard calibration method for both couplers. The direct injection method gives a low calibration factor for both couplers. This is consistent with the result presented in figure 3. The main reason is that the method fails to take both stray capacitance and the effect of semiconductor at high frequencies into account. If the capacitive effect of semiconductor becomes comparable to insulation capacitance then we expect a lower response from the second coupler.

The calibration method based on coupling coefficient gives a low calibration factor if one injects the pulse voltage from coupler 1 and a high value from coupler 2. At this stage, it is not known why the calibration factor depends on which coupler the pulse is injected into. This may have something to do with the stray capacitance. The average value of the two calibration factors is 5.41 which is close to the value from the standard method.

The influence of C_0 on the calibration can be estimated from equation (13). For a particular set of couplers, C will be fixed and if the magnitude of the pulse voltage V_0 is fixed then the V_1 will be fixed. V_1' is a function of C_0,

$$V_1' = \frac{C_0 V_1}{C + C_0}. \quad (15)$$

It is clear that the magnitude of V_1' will increase with C_0. As the magnitude of V_1 is typically around 25 mV for 5 pC calibration pulse, the comparable value to C is acceptable. C_0 used in the measurements has a value of 6 pF. From the measurements carried out in two-step injection methods, the calculated value using equation (13) for C is 5.2 pF which is different from the 8 pF estimated from the coupler's geometry. The reduction in C is believed to be the combination effect of stray capacitance and the influence of two semicon layers in series with XLPE insulation with the latter having a strong effect.

The new calibration method proposed can be simply carried out under operating conditions without removing high voltage.

7. Conclusions

Several methods have been examined for accurate calibration of PD using a capacitive coupler. A suitable calibration technique using the couplers as injection points for the calibration signals has been developed. With the adoption of the new calibration technique each coupler can be individually calibrated and it is applicable under operating conditions without removing the high voltage. It is believed that the current technique gives a more accurate calibration which is essential if quantitative discharge information is required. More importantly, the proposed method can be used on-site and online without causing any discontinuity of power supply.

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