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PROPAGATION CHARACTERISTICS OF PARTIAL DISCHARGE SIGNALS IN MEDIUM VOLTAGE BRANCHED CABLE JOINTS USING HFCT SENSOR

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ABSTRACT

Rapid proliferation of underground cables in today's distribution networks need improved fault monitoring and diagnostic capabilities. Dielectric insulation is the most critical element of underground cables and exposed to various stresses. Cable joints and terminations are always needed and are the most vulnerable locations for insulation defects within the cable feeder. Partial discharge (PD) signals emerging during the progression of insulation faults, travel along the lines and split into connected branches at the T/Y splices. This makes the use of conventional diagnostics solution inappropriate as compared to straight cable section. This paper presents a study on the propagation behaviour of PD signals in a branched joint configuration. Experimental investigations are presented to study the PD propagation across the T/Y-splices. The presented study provides interesting outcomes that can be used for development of an efficient PD monitoring system to watchdog the cable feeder.

INTRODUCTION

Growing urbanization, public safety, environmental aesthetics, network reliability, and the resistance to overhead lines are the major factors for increased installation of the underground cables in the distribution networks [1]. The medium voltage (MV) cables are designed, tested, and installed, in compliance with the IEC 60840 [2] to ensure the withstanding capability of the cables during likely stresses [3]. However, due to ageing and various operational and environmental stresses cause an increased rate of insulation deterioration and eventually lead to the failure of components before their lifetime [4].
Detection and location of the insulation faults are the important tasks of predictive maintenance for MV cables. During such fault progression, fast events called partial discharge (PD) occurs across the defect site of the cable and induce high frequency current pulses on the cable conductor. These current pulses travel along the line and can be measured at the end of the cable sections using induction sensors. The propagation characteristics of the PD signal in MV cables have been studied well [5-6]. Efficient techniques are available for PD diagnosis for straight cable routes of MV feeder [7-12]. However, the study of the PD signals in branched cable topology has rarely been considered in the literature [11-12].
An MV feeder usually is not a single cable but divided into a number of shorter sections and branches that are interconnected by ring main units (RMUs) [12] as shown in Figure 1. The interconnection of cable sections, connection of transformers along the feeder, and branching-off require joints and terminations along the network. The topology/layout of a cable feeder depends upon the load density (MVA/km2), reliability of service, safety, geographical aspects, and profitability. The average length of a typical European urban/semi-urban 20 kV feeder is about 5-10 km, having 20-30 MV/LV transformers distributed along the feeder.

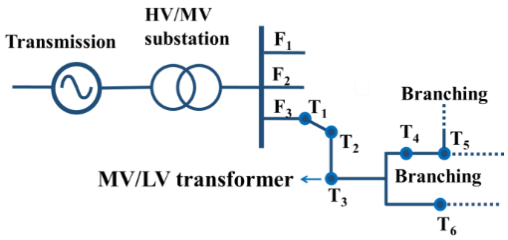

Figure 1. General layout of underground cable feeder.

This paper presents a study on the propagation behaviour of PD signals in a branched cable scenario. Multiple PD sensors have been installed at suitable locations to measure the PDs. The effect of the cable parameters and the discontinuity of impedance at the joint is studied in detail. Comparison of the measured signals is made in time domain to evaluate characteristics of the PD signals in order to identify the faulty part (cable section or joints) of the feeder.

EXPERIMENTAL INVESTIGATION ON MV CABLE JOINT

A cable feeder consists of a number of cable sections that can be of different length and size. Vaasan Sähköverkko (utility company, city of Vaasa, Finland) uses different size the MV cables such as: AHXW185, AHXW120, and AHXW85 in its distribution network. The cables may not only be of different size but can also be of different age and types of insulation such as, XLPE or oil impregnated paper. These cable sections are connected by the joints that can be straight joint that connects two cable sections or branched joint such as Y or T that connects three cable sections.

Figure 2 shows a Y-splice branched joint connecting three cable sections C_1, C_2, and C_3. The joint side ends of the cables are designated as C1_b, C2_b, and C3_b, while the far ends are C1_a, C2_a, and C3_a. If an insulation defect is located at a certain point *P* of the cable section C_1, the PD signal emerging from *P* travels away towards the ends of the cable as depicted by the arrow-headed pulse. In order to apply the TDR/TDOA techniques for fault location, measurement at the two ends are taken from the pair of sensors S_i-S_j or S_i-S_k. S_i is installed at the cable end C1_a and sensor S_j is installed at the cable end C2_a while S_k is installed at cable end C3_a. Considering the propagation route of the PD signals originated from point *P*, the pair S_i-S_j takes into account the cables C_1 and C_2 whereas the pair S_i-S_k takes into account the cables C_1 and C_3 and thus each route encounters the presence of two different cable sections. When dealing with a composite cable system, different dielectric constants, propagation velocities, and characteristics impedances affect the measurements. Similarly, due to presence of the joint, possible change in impedance at the joint also have certain impacts. Therefore, TDR or TDOA techniques cannot be applied on 'as it is' basis. Without identifying the faulty cable section, the location diagnostics cannot be made reliably.

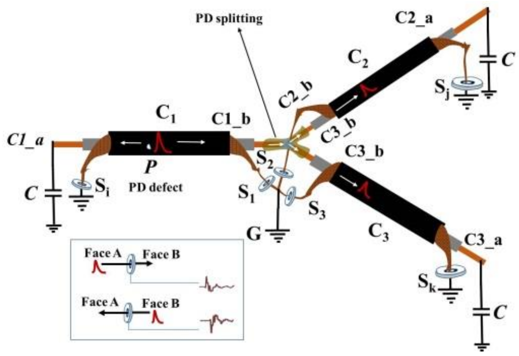

Figure 2. Lay out of the laboratory measurement setup for PD fault investigation in branched (Y) cable joint.

This paper proposes that the behavior of PDs at the joint should be investigated with the measurements at the joint. The study of the propagation behavior and splitting of PD signals at the joint leads to the identification of faulty cable section and then location task can be performed using TDR or TDOA.

Experimental Setup

The experimental investigation was carried out at the Power Systems and High Voltage laboratory, Aalto University, Finland as shown in Figure 3. Three MV cables with separated earth shielding at the cable terminations were connected together to frame-up a Y-joint. A (0-220) V/12 kV power transformer is used to supply the cable C_1 at C1_a. The far ends of the cable C2_a and C3_a were loaded with the capacitive loads of 100 pF each to measure the PD current.

As the cables were PD free, an artificial PD defect was developed at cable terminal C_1_a by winding an insulated wire around the terminal (conductor part) and the other end of the wire was grounded. The thickness of the insulation of the wound wire is about 1 *mm* that cannot withstand higher voltages. The small random gaps of the wound wire turns act as cavities between the wire and the cable conductor. These cavities develop a capacitance and at a certain PD inception voltage (PDIV), the PD pulses are emerged and travel along the cable C_1 towards the joint. These PD pulses split at the joint and continue their travel along the cables C_2 and C_3 towards the respective far ends C2_a and C3_a. The 0-220 V variable supply provides the possibility to change the voltage level to observe the PD inception levels and then to adjust the magnitude of PD fault signals high enough so that better signal-to-noise ratio can be obtained for suitable visibility of the PDs.

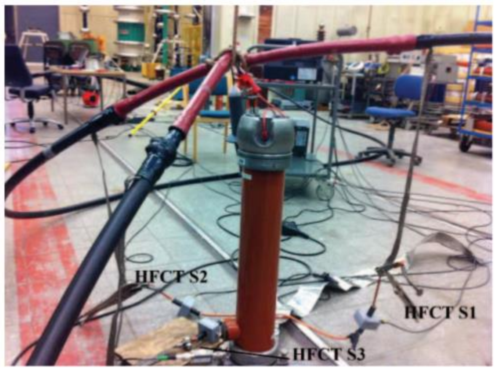

Figure 3. Measurement setup for branched (Y) cable joint.

Focusing on the behavior of PD pulses at the joint area, measurements are made using HFCTs. Three HFCTs S_1, S_2, and S_3 at the joint area with one for each cable terminal C1_b, C2_b, and C3_b respectively while the fourth HFCT S_i was used to measure the PDs at the input (feeding) cable terminal C1_a. Typically there are two possible locations for installation of HFCTs i.e., around the cable's main conductor or the cable shielding. Considering the medium voltages across the cable feeder, the dielectric insulation level of the HFCT instruments is not high enough to withstand such voltage levels. As the cable shielding does not exhibit high voltage, the most suitable locations are the shielding for current measurement.

PD signals measured by the sensors are transferred to the data acquisition system (DAS) for presentation, storage, and analysis. Impedance matching is done in order to obtain the maximum signal strength from output of HFCT to the DAS i.e., a digital storage oscilloscope (DSO). The output impedance of HFCT is 50 Ω hence a 50-Ω coaxial cable was used to connect output from the HFCT to a 50 Ω input channel of the DSO having 4 channels with the selected sampling frequency of 2 *GHz*. The HFCTs have a

15 *mm* primary window with the transfer ratio of 1:10 having bandwidth of 0.5 – 80 *MHz* at 3*dB*. All the HFCT used in the measurement have the same specifications, therefore it is assumed that all have the same behavior. The directional response of the HFCTs has been tested using an artificial PD pulse by a PD calibrator as shown in Figure 4. The time domain analysis of the measured signals is done in Matlab.

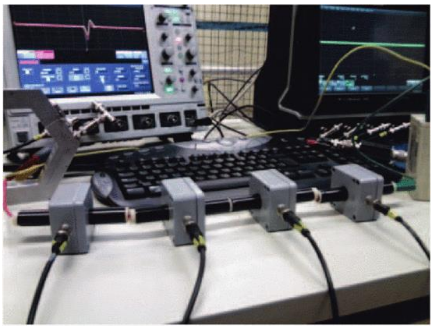

Figure 4. Directional calibration of HFCTs.

Measurements

PD activity was captured in the segments of one power frequency cycle of 20 *ms* to observe the PD current pulses during both positive and negative half cycles, as shown in Figure 5. The measured signals are described as:

- *Signal i:* measured by sensors S_i at the terminal C1_a;
- *Signal 1*: measured by sensors S_1 at the terminal C1_b;
- *Signal 2*: measured by sensors S_2 at the terminal C2_b;
- *Signal 3:* measured by sensors S_3 at the terminal C3_b.

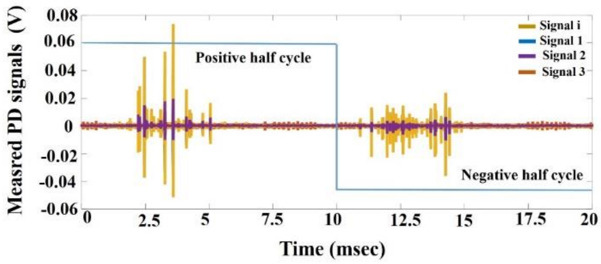

Figure 5. PD signals measured by four HFCT sensors.

The PD measurements are presented in terms of voltage. When measuring PD pulses, we are dealing with a spectrum of frequencies instead of a single frequency. Therefore, converting the output from Volts to Amperes would require to use the inverse transformation of the HFCT frequency response. The current is induced in the HFCT electromagnetically and sensitivity is the most a suitable approach that relates the output voltage of the HFCT and current. Sensitivity is defined as the voltage output of HFCT as response to the input current at certain frequency. A first approximation would be to use the ratio 10 V/A, however the authors believe that this datum will not be accurate or appropriate. It would be complicated to present the waveforms accurately in terms of current, therefore common approach of presenting the measured current in terms of voltage is adopted when plotting the signal in the time domain.

It can be seen that the polarity and amplitude of the PD signals is different. This is because of the occurrence of the PD events at different phase angles during power cycle. The polarity of PD pulses depends on the polarity of the applied voltage. During positive half cycle polarity of the PD pulses is positive while during negative half cycle, the polarity of the PD pulses is negative.

PD BEHAVIOUR ACROSS THE JOINT

The splitting of PD signals towards the connected cables depends on the geometrical parameters and dielectric properties the cables. The geometrical model of the cable used in this test is shown in Figure 6. Based on the availability of the cables in the HV Laboratory, the cables used in this investigation are of same type (cross-linked polyethylene - XLPE) and geometrical parameters as given in Table 1, while lengths of the cables are; *C_1= 10 m, C_2= 150 m, and C_3= 10 m.*

Among the three cables connected at the branched joint, cable C_1 is the faulty section containing the PD source. Analyzing the plots of Figure 7, it can be observed that *Signal 1* is mutated into *Signal 2* and *Signal 3*. The PD current drawn by the cables is determined by the characteristic impedance (Z_c) of each cable. Characteristic impedance is the instantaneous impedance that the signal comes across as it propagates down the line. When the line has the same wave propagation speed with the same capacitance per unit length down the line, the signal sees the same instantaneous impedance along every unit step. Therefore, the characteristic impedance does not depend on the length of the line.

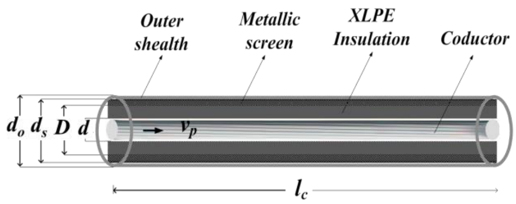

Figure 6. Geometrical model of the cable.

Characteristic impedance of the cables play significant role on the behavior of the PD signal in terms of any reflections or transmissions occurs. The characteristic impedance Z_c can be determined as,

$$Z_c = \sqrt{\frac{L}{C}} \tag{1}$$

Therefore, Z_{c1}= Z_{c2} = Z_{c3} =Z_c= 21.98 Ω for each cable.

Table 1. Cable parameters (geometrical).

Cable Parameter	Symbol	Value
Conductor diameter	d	15.7 mm
XLPE Insulation	D	27.7 mm
Metallic screen	d_s	31.5 mm
Sheath (outer Jacket)	d_o	35 mm

When the PD pulse *Signal 1* arrives at the joint through cable C_1, it encounters the equivalent impedance of cable C_2 and C_3. Because of a change of impedance at the cable joint, the incident PD signal is decomposed into reflected and transmitted signal, proportionated by the reflection and transmission coefficients, as presented in Figure 8.

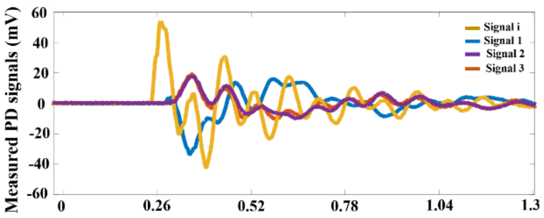

Figure 7. PD signals measured by the HFCTs at source point and the Y joint.

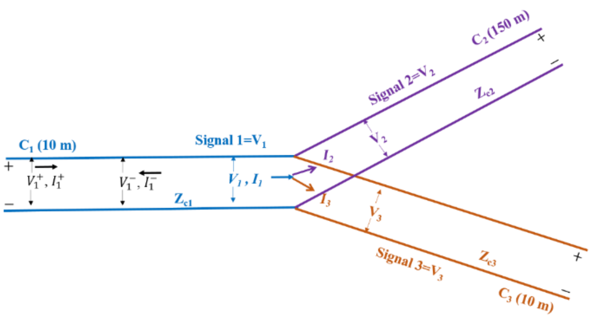

Figure 8. Splitting of the PD signal at the cable joint.

The reflection coefficient Γ is determined as,

$$\Gamma = \frac{\frac{Z_C}{2} - Z_C}{\frac{Z_C}{2} + Z_C} = -\frac{1}{3} \tag{2}$$

The transmission coefficient is determined as,

$$\tau = 1 + \Gamma = 1 - \frac{1}{3} = \frac{2}{3} \tag{3}$$

The experimentally measured PD signal in terms of voltage (using HFCT) is directly proportional to the PD current. The reflection coefficient Γ can be expressed in terms of voltage and current as follow [13],

$$\frac{I_1^-}{I_1^+} = -\frac{V_1^-}{V_1^+} = -\Gamma \tag{4}$$

Considering I_1^+ and I_1^- (see Figure 8) as the incident and reflected currents respectively at cable C_1, the transmitted current I_1 that can be expressed as,

$$I_1 = I_1^+ - I_1^- \tag{5}$$

Using eq. (3) and (4), I_1^- can be found as,

$$I_1^- = -I_1^+\Gamma = \frac{I_1^+}{3} \tag{6}$$

Considering the eq. (4) and (6), I_1 is expressed as,

$$I_1 = \frac{2}{3} I_1^+. \tag{7}$$

The plots shown in Figures 7 present the waveforms measured by the HFCTs at the cable joint. The *Signal i* is the PD generated at the cable C_1 while *Signal 1* is the transmitted part of the PD signal incoming to the joint area. The *Signal 2* and *Signal 3* are the PD signal drawn by the cable C_2 and C_3. Although the incident and reflected signals cannot be measured separately, however the measurement and calculation-based analysis is presented in the Table 2 to highlight the insight of the signal propagation at the joint. The first peak of the measured PD pulse represents the amplitude of the PD pulse.

Table 2. Analysis of the signals' magnitudes at the joint.

Type of the signal	Analysis of signals (Figure 7)	Description
Incident signal ($V_1^+ = \frac{3}{2}V_1$)	$-55\ mV$	Signal arriving at the joint.
Transmitted signal (V_1)	$-37\ mV$	Signal measured at C_1 (joint end) which is the part of the transmitted.
Reflected signal ($V_1^- = \frac{1}{3}V_1^+$)	$18.3\ mV$	Signal reflected back at C_1.
(Signal 2 + Signal 3) =– Signal 1	$\begin{pmatrix}18.2 + \\ 18.3\end{pmatrix} = -36.5\ mV$	*Signal 1* (V_1) is transmitted through the joint and split between cable C_2 and C_3s.

The polarity of the incoming signals measured at C_1 and that of the outgoing signals measured at C_2 and C_3 are opposite because of the polarity of the PD signal generated during positive and negative half cycle of the applied voltage and installed direction of the HFCTs. Considering $V\ \alpha\ I$, the above demonstration (Table 2) in terms of voltages describes the validity of $I_1 = I_2 + I_3$ as well.

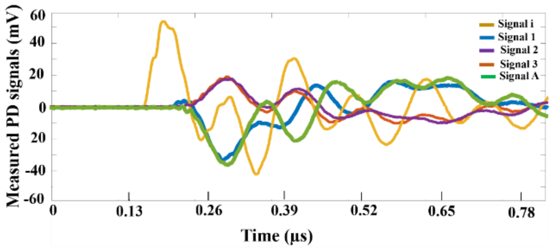

Figure 9. Validation of the signal from cable C_1 into cable C_2 and C_3.

In addition to single point analysis discussed above, a holistic picture of the PD splitting is provided considering the 'entire' part of the measured signals by adding *Signal 2* and *Signal 3* that results in *Signal A* as shown in the Figure 9. Overall signatures of the *Signal A* and *Signal 1* match. The first and the lateral part of the signals match nicely while there can be seen a deviation during the middle part of the signals. As the cables C_2 and C_3 have different lengths, the propagation characteristics of the cables depending on the length may cause such deviations however, both signals follow the same pattern/signatures considering the rising or decreasing of the amplitudes at the same instants. This means, in the case of branched cable network, when measurements from the joint sides' sensors are analyzed, the largest PD amplitude identifies the presence of the PD faults in the respective cable while the sum of the PD pulses measured at the other cables is equal to the faulty side PD signals. In case the connected cables have different impendences, different energy will split among the cables however still; the total sum will remain same.

DISCUSSION

Accurate interpretation of the measured signals play a key role to perform the reliable diagnostic. The signals at the cable joint bring the observations; the current transmitted to the branches at the junction remains continuous and the same before and after the junction. Furthermore, the PD energy is divided into the connected cables proportionally to the characteristics impedance of the cables. The first pulse and its peak provide the information about the magnitude of PD activity. The rest of the part of the signal consists of the reflections induced due to discontinuity of the impedance at the joint and oscillations due to reflections, and the sensor´s properties. The oscillations in the measured pulses are because of additive or subtractive reflections along the cable and the damping is caused by the losses. Similarly, attenuation and dispersion are two important factors that should also be taken into account.

Using directionally calibrated induction sensors, the faulty cable section can be identified based on the pulse with opposite polarity and largest amplitude. The signature of the reflected pulses with the same or opposite polarity looks similar to the original pulse. Superimposed by the oscillations, influenced by dispersion, and possible noise, the end part of the PD signals is distorted. Similarly, the internal resonance of the HFCTs also affect the measured signal.

CONCLUSION

PD study is the most effective tool for the evaluation of ongoing degradation of dielectric insulation in the MV cables. PD diagnostics in branched cables is a challenging task. The propagation behavior of a PD signal is studied in this work using experimental investigation in the branched configuration/topology of the cable joint. The characteristic impedance plays important roles and determines the split of the PD energy at the joint. A detailed analysis of the measured PD signals provides not only a comprehensive interpretation of the splitting of PD current pulses but also can identify the faulty cable section among the branched cables that are connected at the joint. Understanding the PD propagation across T/Y-splices is vital when developing an integrated condition monitoring system including cables, transformers, joints, and terminations. The presented results provide valuable understanding to improve the diagnostics capabilities of condition monitoring of MV cable feeders.

ACKNOWLEDGEMENT

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