TECHNICAL DEVELOPMENTS AND PRACTICAL EXPERIENCE IN LARGE SCALE INTRODUCTION OF ON-LINE PD DIAGNOSIS

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Abstract: On-line Partial Discharge (PD) detection and location systems for medium-voltage cables are at present being introduced in Dutch utilities and worldwide. The technical challenges now move from the development of the diagnostic technique itself to efficient implementation on a large scale. In this paper we discuss several implementation related challenges and will propose adequate solutions. These challenges include robust algorithms to determine time of arrivals of distorted PD waveforms, signal propagation along cable types and configurations as three-core and cross bonded cables, and effect of ring main units or substations on signal propagation. Algorithms based on signal energy and on phase angle in frequency domain are preferred above e.g. threshold detection to determine PD arrival times. By introducing effective dielectric properties, cable parameters for accurate fault location as characteristic impedance and propagation velocity can be estimated also if data on semiconducting layers are unavailable. Models are proposed for cross-bonded connections and for three-core cables with common earth screen. A pulse injection circuit, already included in the PD equipment for time synchronisation, can be employed to extract a model for PDs passing ring main units or even entire substations.

1. INTRODUCTION

Partial discharge (PD) monitoring solutions have been introduced for HV cable circuits (≥ 50 kV) based on sensors per accessory. This approach is unpractical for MV cable circuits (≤ 36 kV), because of the sheer number of components installed. Therefore, in case of MV cable connections a solution with only two sensors per cable connection, one at each cable end, is preferred. Two sensors can cover a cable connection with several cable segments, simply by measuring the difference in arrival time at both sensors. Such an on-line PD measuring system works for all types of MV cables and all types of accessories installed. To realise this approach the following problems have been addressed:
- Synchronisation of the PD detection units at both cable ends
- Coupling to the cable for PD signal extraction from the cable
- Recovering real PD signals from noise inherent to on-line measurement
- Handling vast amount of data from continuous data streams

At the CIRED 2005 conference, a prototype of the PD measuring system, called PD-OL, was presented for the first time [1]. PD-OL stands for Partial Discharge monitoring On-line with Location. In this system inductive signal coupling was preferred to allow for installation without need to switch off the cable connection. The synchronisation between PD units at both cable ends, which is required for PD location, was realised through including a pulse injection unit which sends a reference pulse to the other side. PD signals have to be distinguished from disturbances from e.g. power equipment inside and outside the grid. A technique based on matched filtering was adopted [2]. Finally, the arrival time and magnitude of the detected waveforms, after being processed locally at either cable side, are communicated to the control centre for further analysis and interpretation.

Approximately 120 PD-OL systems have been put in operation since it became commercially available in 2007. One PD-OL system consists of two separate units (Figure 1), each of them to be installed at one of the cable circuit ends in either substation or ring main unit (RMU).

Figure 1: PD-OL installation, with at each cable end a control unit (PD-OL - CU) for signal processing and communication via internet and a sensor/injector unit (PD-OL - SIU) for the actual measurement and pulse injection.

Each measurement unit consists of:
- A sensor / injector unit (PD-OL - SIU). This unit contains both a sensor, to measure pulses from the cable, and an injection device, to inject pulses into the cable. This unit can be split in two parts and in this way clipped around the cable or cable earth connection, which all can be done on-line.
A controller unit (PD-OL - CU). This unit is connected to the SIU by means of an optical fibre. It controls the measurement sequence, the data collection and the signal processing. It has also communication facilities on board in order to upload the resulting data via the internet to the control centre for further interpretation. Furthermore, the PD-OL units can be remotely reached via the internet for diagnostic purposes and updates.

In actual MV grids many complicating factors arise. In order to extend the application range of PD-OL even further, PD-OL has to be capable to cope with factors impeding the signal waveform. PD signals are affected by the cable types and cable connections used. Further, PD signals are distorted by the effect of the components in and the size of substations or RMUs. Correct timing of the detected PD waveforms may be impeded by these factors as well. In this paper the following aspects are analysed:

- Location accuracy: To obtain high location accuracy, algorithms are developed which are robust with respect to noise level, signal distortion during propagation, reflections on accessories in the MV circuit.
- Cross bonding joints: In long connections the cable screens can be cross bonded, which disturbs PD signals during propagation.
- Cable parameters: Models for several types of cable are encountered in the field including three-core cables with common earth screen and cables from which not all relevant specifications for signal propagation are available.
- Connection with RMUs: Diagnosing several cable connections interrupted by a RMU with a single set of PD-OL units requires models for signal propagation through these RMUs and even through an entire substation.

2. LOCATION ACCURACY

The accuracy of defect location depends on the accuracy of the time-of-arrival $t_{\text{oa}}$ estimation of each PD pulse. The PD signals in on-line applications are distorted by other components. Also additional reflections can confuse measured waveforms. Further, the expected noise level is higher, due to contribution from the connected grid. Different techniques to link a time of arrival to a signal waveform are compared. These techniques are illustrated in Figures 2 and 3, including their mathematical formulation [3],[4]:

$$t_{\text{oa},p} = t_{\text{ch}} - \frac{\tau(\alpha)c}{\alpha_{\tau}}$$

Figure 2: Example of recorded pulse with four time-of-arrival methods applied. Time axes are in μs. Black line: recorded PD signal, grey line: threshold (a) / normalised and shifted AIC curve (b) / normalised EC curve (c) , *: time-of-arrival, and dashed line: end of record used for AIC analysis.

In Table 1, a summary of the strong and weak points of each of the five $t_{\text{oa}}$ methods:

<table>
<thead>
<tr>
<th>Method</th>
<th>Noise</th>
<th>Pulse shape</th>
<th>Signal reflections</th>
<th>Location accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>AIC</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>EC</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>+</td>
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<tr>
<td>Gabor</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Phase</td>
<td>+</td>
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- Trigger threshold: The instance that a signal exceeds some threshold level $x_{\text{thresh}}$, which equals the average noise power $P_n$ multiplied by some chosen factor $m$, defines the $t_{\text{oa}}$.

Table 1: Summary of strong and weak points of five $t_{\text{oa}}$ methods.
- **Akaike information criterion (AIC):** The AIC method detects the signal by giving suitable weights to the cumulative variance before and after each sample point. This results in a curve with a global minimum, which position corresponds to the \( t_{oa} \).

- **Energy criterion (EC):** The EC is determined by the cumulative energy of the signal up to a sample point corrected for the average energy of the complete signal. Similarly as for the AIC method, this results in a global minimum corresponding to the \( t_{oa} \).

- **Gabor centroid:** Gabor defines the \( t_{oa} \) according to a weighted average based on the sample energy. A correction is made for the noise power.

- **Phase method:** From the converted signal in frequency domain \( X \), a narrow band around \( \omega_c \) is chosen. The \( t_{oa} \) in the time domain corresponds to the phase angle in frequency domain, up to an ambiguity with \( 2\pi n \). To remove the ambiguity, \( X(\omega) \) is first shifted in time over \( \tau_{ch} \) such that the phase jumps (Figure 5, bottom) from \(-\pi\) to \(+\pi\) vanish.

The simulated results with respect to noise, sensitivity to waveform distortion, presence of reflections and to location accuracy are summarised in Table 1. The simulations are performed on a 1000 m cable having characteristics obtained from a real power cable. The simulation is based on 1000 runs with added Gaussian noise. Also the test waveforms are based on field experience. Details are given in [4]. From Table 1 it is concluded that the energy criterion and phase method perform best. However, the phase method is sensitive to the load seen at the cable ends. A phase angle introduced there directly translates into a location error (compare Figure 4a and Figure 4b). The PD-OL system enables, owing to its included pulse injection unit, to determine this phase shift and compensate for it by creating a proper model for the load experienced at the cable ends. The reproducibility of the phase angle method and the energy criterion are excellent under all conditions as shown in Figure 4c.

### 3. CROSS BONDING JOINTS

In a cross bonding (CB) joint the earth screen of each phase is interrupted and connected to the earth screen of another phase. Usually, the actual cross-bonding occurs in a CB box. The CB cables are either single core or coaxial (as shown in Figure 5). CB joints act as reflection points for the signal. In addition, part of the pulse may start travelling between cable sheaths, i.e. the intersheath mode. To simulate pulse propagation, measurements were performed on an artificial CB system made up of 50 \( \Omega \) measuring cables. Reflected and transmitted signal are measured upon a square pulse (3 V, 50 ns) injected in cable A. The signals shown in Figure 5 are the reflected signal in A, the transmitted signal in B, and a pulse entering C, one of the other cables. The signals D-F are similar to C (D and F have opposite polarity, E has same polarity). The calculated waveforms are based on the CB model shown left. Since a complete model as given in [5] involves many, in practice unknown, parameters a simplified model is proposed [6]. The model consists of a series impedance \( Z_{jp} \) which represents the inductance of the loop in the CB connection, and a parallel impedance \( Z_{pi} \) representing its capacitance and taking the intersheath mode into account.

**Figure 4:** Figure a: location error if cable load matches the cable impedance; figures b and c: error and standard deviation in case that the load impedance at the near end is an inductance of 1 \( \mu \)H and the load impedance at the far end a capacitance of 2 nF.

**Figure 5:** Schematic drawing of CB joints, cables and box; left, model of each joint; right reflected and transmitted signals upon injected signal at point A (dashed measured, grey simulated waveforms).
Figure 6: Measured voltages after pulse injection in the yellow phase; a: normal mode signals in all three phases; b: indicated in grey an inductively measured intersheath current.

A field measurement was conducted on a 150 kV cable circuit under construction with a set of CB joints at 2150 m interconnected with single-core CB cables, followed by an open end 1100 m further. A pulse (3.5 V, 120 ns) is injected in the yellow phase. This signal and its reflection at the transition from injection (50 Ω) to HV cable (26 Ω) are truncated utmost left in Figure 6a. The reflection at 13 μs occurs at a regular joint. The reflections at the CB joints and at the far end are indicated within dashed rectangles. They occur both in the yellow phase and in the other phases. The existence of an intersheath mode is shown in Figure 6b. To this end the earth connections between two HV phase cables were directly connected and an inductive probe was placed around it. The black line is the normal mode signal also shown in Figure 6a, propagating with 185 m/μs. The grey line represents the intersheath mode after reflection on the first CB joint, travelling with 102 m/μs. Qualitatively the signals can be explained, but considering the signal amplitudes, deviations from the proposed model occur. E.g. the reflections in the red and blue phases should be equal. The reason is related to the use of single phase CB cables which couple mutually depending on their actual positions. This problem does not arise for CB joints interconnected with coaxial CB cables.

4. CABLE PARAMETERS

Models of power cables require detailed knowledge of the dielectric properties of the applied materials. Especially the complex relative permittivity $\varepsilon_r$ of semiconducting layers is often not available. Still, for PD-OL a cable model is required to reliably estimate the PD magnitudes and time of arrival. Typical XLPE cables, both single-core and three-core cable, which can be encountered in the field are depicted in Figure 7.

A simplified model is presented, where the unknown parameters related to the semiconducting layers of the dielectric material are omitted and “effective” parameters are introduced. Clearly, signal attenuation can not be predicted in such a model, since the losses are caused to a large extent by the semiconducting cable properties. The characteristic impedance and propagation velocity depend less critically on these properties. An effective relative permittivity, for a single-core cable, is introduced according to [7],[8]:

![Figure 7: Left, schematic drawing of a typical single-core XLPE cable equivalent circuit and definition of effective parameters to model the cable characteristics; right, three-core XLPE cable type with semiconducting layers around each conductor. Conductors and earth screens are indicated in light grey; the semiconducting layers in dark grey.](image-url)
Figure 8: Measured and estimated characteristic impedance of a single-core XLPE cable (a), and of the two distinct propagation modes of a three-core XLPE cable (b,c).

\[ e_{\text{eff},r}(\omega) = e_{\text{eff},r,\text{ins}}(\omega) \left( \frac{\ln \left( \frac{L_r}{L_r - L_{\text{tr}}} \right)}{\ln \left( \frac{L_r}{L_r + L_{\text{tr}}} \right)} \right) \]

The symbols are defined in Figure 7. The effective relative permittivity is defined such that the standard equation for the capacitance of a coaxial structure holds. The characteristic impedance and the propagation velocity are now obtained from:

\[ Z_{\text{eff}}(\omega) = \frac{\mu_0 e_{\text{eff},r,\text{ins}}}{2\pi} \ln \left( \frac{r_c}{r_r} \right) \quad v_p = \frac{1}{\sqrt{\mu_0 e_{\text{eff},r,\text{ins}}}} \]

If the cable earth screen has a helical structure, the reduction of the propagation velocity can be taken into account according to [8],[9]. Figure 8a shows the measured characteristic impedance and the estimate according to equation 2.

On MV level three-core power cables are often applied. If each core has its own metallic screen they can be treated as three independent single-core cables. The cable shown in Figure 7 (right) has only one common earth screen. However, each core is surrounded by its own semiconducting layer and swelling tape, which restricts the electric field but not the magnetic field. In the shown trefoil symmetry, the cable exhibits two distinct propagation modes [10]. The behaviour of this cable type can be approximated by numerical techniques. Figures 8b and 8c show the match between the measured and estimated (numerically using a boundary element method) characteristic impedance of the two distinct propagation channels. Detailed information, also on comparison of other cable characteristics, can be found in [9].

5. CONNECTION VIA RMU

The efficiency of PD-OL implementation can be greatly improved if a single set of PD-OL units is capable to diagnose multiple consecutive cable sections including RMUs. A hypothetical situation is shown in Figure 9. In fact the situation shown is part of a real MV grid from which the measurements are taken. In order to model such a system the transfer function of cable sections, RMUs and substation have to be known. The transfer through the RMU halfway hardly affects passing PD signals. This can be expected, since a PD signal, either coming from the right or from the left, experiences a load formed by the outgoing cable in parallel to the distribution transformer. The latter impedance, capacitive in nature for frequency components in the sub and low MHz range [10], is typically an order of magnitude larger than the cable impedance. If incoming and outgoing cable impedances are equal, the signal

![Diagram of PD-OL unit and RMU configuration](image-url)
passes the RMU virtually undisturbed. At a substation many cables are connected and incoming pulses reflect at and transmit into these cables. Moreover, the size of a substation can not be neglected with respect to wavelengths corresponding to the frequency contents of the PD signals.

In Figure 9 the signals are shown, measured at the incoming cable and three of the four outgoing cables. From these signal the transfer functions in the substation from the incoming cable to the outgoing cables are determined. The dashed lines in Figure 10 are obtained from a substation model which includes impedances to take into account the effect of the inductances from the connections, the resistive (radiation) losses and the capacitances to simulate the MV/LV transformer, its connecting cable and a measurement transformer. The parameters are optimised for a best least square fit on the measured transfer functions combined with parameters are optimised for a best least square fit on the measured transfer functions in the substation.

![Figure 10: Measured (solid) and simulated (dashed) transfer functions from one incoming cable to three outgoing cables in a substation.](image)

6. DISCUSSION AND CONCLUSION

Application of the PD-OL system to monitor extended cable systems including RMUs or substations seems feasible. In order to maintain the sensitivity and the high location accuracy realised for single cable sections, models have to be designed to account for the influence of all components on the PD waveform. This paper presented models for cross-bonded cables, cables for which the data on the semiconducting layers are unavailable and on how to treat multi-conductor cables. Also the effects of substation components could be adequately modelled. Since the PD waveform is affected by all transfer functions a robust time of arrival algorithm is required. The energy criterion and phase methods (if an adequate model for the complete cable link is present) satisfy this requirement.

Recognition of PD signals is presently done on basis of a predefined matched filter bank. However, in complex cable connections this bank may not be optimal. Present and future work is directed to the design of an adaptive filter set, which adapts automatically to the waveforms of real PDs encountered for a specific connection.

7. REFERENCES