Comparison of Arrival Time Estimation Methods for Partial Discharge Pulses in Power Cables

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Abstract -- Accurate location of partial discharges in power cable systems, based on arrival times, is critical for the identification and assessment of defects. This paper evaluates different time-of-arrival algorithms in order to determine which method yields most accurate location under different circumstances. These methods are based on threshold, Akaike’s information criterion, energy criterion, Gabor’s signal epoch and phase in frequency domain. Several criteria are defined by which the algorithms are evaluated. These criteria include the sensitivity to noise, pulse shape and effect of load impedance. The sensitivity of the methods upon varying these quantities is evaluated analytically and by means of simulations. From the results the energy criterion method and the phase method show the best performance.

Index Terms -- Delay estimation, defect location, partial discharges, power cables, signal analysis.

I. NOMENCLATURE

\[ E_x, E_s, E_n \] signal energy in \( x_k, s_k \) and \( n_k \) (\( E_x = \sum_{k=1}^{N} x_k^2 \))

\( k \) index ranging from 1 to \( N \)

\( n_k \) additive, uncorrelated Gaussian noise

\( N \) number of samples in signal

\( P_x, P_s, P_n \) mean signal power of \( x_k, s_k \) and \( n_k \) (\( P_x = E_x / N \))

\( x_k \) recorded signal (\( x_k = s_k + n_k \))

\( s_k \) noise-free pulse signal

\( t_c \) cable propagation time

\( t_{oa} \) time-of-arrival

II. INTRODUCTION

PARTIAL discharge (PD) diagnostics is a proven method to assess the condition of a power cable system. It is essential to determine the origin of the discharges to estimate the likely defect type and severity. Furthermore, it is only possible to replace parts in a cost-effective manner if the defect locations are known.

The accuracy of defect location depends on the accuracy of the time-of-arrival estimation of each PD pulse and how accurate the propagation time of the entire cable is known. The methods to estimate the time-of-arrival analyzed in this paper are generally applicable to different PD locating systems. However, our main interest concerns online application [1] with its important advantages, but also its inherent additional complications. Ring Main Units (RMUs) or substations distort

III. EVALUATION CRITERIA

In order to make a well-founded comparison of the strong and weak points of each method a set of evaluation criteria is defined on which the methods are judged. The following criteria are used. The methods should ideally be:

- independent of noise level and spectrum.
- independent of pulse shape and amplitude.
- independent of length of recorded signal.
- independent of the pulse location (in time) in the record.
- insensitive to reflections of the main pulse on joints and RMUs.
- resulting in accurate location of PD origin. For PD diagnostics on power cables a location accuracy of 1% of the cable length is usually considered to be sufficient.

A \( t_{oa}\)-method that meets all these criteria would be the perfect method. But even if not all criteria are met, the method can be useful in specific situations.

IV. TIME-OF-ARRIVAL METHODS

All five \( t_{oa}\)-methods are briefly described in the following sections. A more detailed description can be found in [2].

A. Trigger level method

The trigger level method positions \( t_{oa} \) at the time at which the signal \( x_k \) exceeds a certain threshold level \( x_{free} \). This is a straightforward method that can easily be implemented and is therefore used in many PD detection systems. The threshold level is chosen relative to the noise level, making it always as
low as the noise permits without too many false triggers:

\[ x_{\text{thres}} = m \cdot \sqrt{P_n} \quad (1) \]

where \( m \) is a parameter chosen by the user. In this paper the value \( m = 5 \) is used for all simulations. In Fig. 1a a recorded pulse is plotted together with the threshold \( x_{\text{thres}} \).

B. Akaike Information Criterion method

The Akaike Information Criterion (AIC) is a measure of the goodness of fit of a statistical model to a set of observations. It can be used to estimate the arrival time of PD pulses [3]. This method defines the curve \( AIC_k \) as:

\[ AIC_k = k \cdot \ln(\sigma^2_{m,n}) + (N - k - 1) \cdot \ln(\sigma^2_{k+1,N}) \quad (2) \]

where \( \sigma^2_{m,n} \) is the variance of signal \( x_k \) from index \( m \) up to and including index \( n \). The value \( AIC_k \) is calculated for each sample in the signal \( x_k \). The \( \text{toa} \) is the global minimum of all \( AIC_k \) values. In order to prevent ambiguous results the signal is cropped such that the pulse onset occurs in the second half of the signal, as suggested in [4]. Fig. 1b shows a signal and its corresponding \( AIC_k \) curve.

C. Energy criterion method

The energy criterion (EC) method is based on the energy content of the signal. This method combines the partial signal energy with a negative trend [3]. The signal \( EC_k \) is defined as:

\[ EC_k = \sum_{i=1}^{k} x_i^2 - k \cdot P_x \quad (3) \]

The value \( EC_k \) is calculated for \( k \) ranging from 1 to \( N \). The global minimum of all \( EC_k \) values coincides with the \( \text{toa} \). Fig. 1c shows a PD pulse along with the \( EC_k \) curve.

D. Gabor centroid method

Gabor defines the “epoch” of order 1 of a signal [5]. Assuming that the signal is real, converting it to time-discrete form and adding two extra terms to remove noise-dependency this epoch is defined as:

\[
t_{\text{oa},g} = \frac{\sum_{k=1}^{N} t_k x_k^2 - P_x \sum_{k=1}^{N} t_k}{\sum_{k=1}^{N} x_k^2 - P_x \cdot N} \quad (4)
\]

where \( t_k \) is the time corresponding to index \( k \). In Fig. 1d a PD pulse is plotted and \( t_{oa,g} \) is marked.

E. Phase method

The phase method converts the recorded signal \( x_k \) to frequency domain \( \hat{X}(\omega) \) and retrieves the phase for a chosen frequency. This phase can be interpreted as a time delay \( (\tau) \). Unfortunately, due to the periodicity of \( 2\pi \) the phase is ambiguous:

\[ \tau = -\frac{\angle \hat{X}(\omega)}{\omega_c} + m \cdot \frac{2\pi}{\omega_c} \quad (5) \]

where \( m \) is an unknown integer and \( \omega_c \) is a chosen frequency (in rad/s) for which the delay is calculated. For consistency, \( \omega_c \) must be the same for all measurements. Taking the average over a small frequency range around \( \omega_c \) reduces the sensitivity to noise and reflections in the signal. The periodicity problem can be solved by applying a (negative) time delay \( \tau_{ch} \) to \( \hat{X} \) first. This can be achieved using:

\[
\hat{X}(\omega) = \hat{X}(\omega) \cdot \exp(jm\omega \tau_{ch}).
\]

The delay \( \tau_{ch} \) must be chosen such that the phase does no longer wrap around (jump from \( -\pi \) to \( \pi \), or vice versa) in a frequency range where \( \hat{X}(\omega) \) has sufficient energy (see Fig. 2). Since \( \tau_{ch} \) is unknown a priori, an iteration loop is used to find the correct time delay. Once the correct \( \tau_{ch} \) has been found the arrival time is given by:
impedance. This pulse starts with a long low bump (charging) pulse source design, different injection coil and different load not included in this paper, are summarized in section VI. See absence of complications due to a load impedance (influenced by dispersion and attenuation of the cable. In the pulse is also an inductively coupled pulse, but with different pulse source design, different injection coil and different load impedance. The second pulse is concentrated in the beginning of the pulse. The second PD measurement in an MV cable system. Most energy of this pulse is a short pulse with a width of about 100 ns. This pulse is a short pulse with a width of about 100 ns. This pulse is similar to a real PD pulse that has propagated through a power cable over a short distance.

The major advantage of this method is that it is not influenced by dispersion and attenuation of the cable. In the absence of complications due to a load impedance ($Z_{load}$) at the cable ends the location error will be zero.

V. SIMULATIONS

Several simulations have been conducted to evaluate the $t_{oa}$-methods using the criteria proposed in section III. For all simulations a model for a cable system of 1 km is used. The characteristic impedance and propagation coefficient for this cable were measured on a field-aged 3-core MV PILC cable of 200 m to obtain realistic values in the simulations. At each end the cable is terminated with a load impedance ($Z_{load}$), representing the effect of an RMU or substation, where the sensor is installed. The sensor is assumed to be an ideal current probe that measures the current through the load impedance. The transmission coefficient from cable to load is calculated using the load impedance and the characteristic cable impedance. The load impedance can be varied to investigate the effect on the $t_{oa}$-methods. In the other simulations the load impedance is matched to the cable impedance (real-valued, frequency-independent impedance of 12 $\Omega$).

Two “measurements” are simulated: first, a measurement of the total propagation time of the cable ($t_c$) using pulses injected at both ends, and second, the PD measurement itself. The $t_c$-measurement is simulated using chosen pulse shapes for the injected pulse. Since PDs are short phenomena with respect to $1/f_d$ ($f_d$, detection bandwidth) a PD signal is represented by a $\delta$-pulse at the origin. All pulses in the simulated signal are normalized to a maximum amplitude of one, so that the signal-to-noise ratio is about the same for all pulses. Uncorrelated Gaussian noise with a specified spectrum is added to the signal to simulate realistic noise conditions.

Each simulation is repeated 1000 times. The mean and standard deviation of those 1000 repetitions give a good estimate for the accuracy and precision of the methods.

The results of all simulations, including also simulations not included in this paper, are summarized in section VI. See [2] for a complete overview of all simulations.

A. Sensitivity to pulse shape

A $t_c$-measurement is performed using pulses injected by the measurement system. The cable propagation time $t_c$ is independent of the pulse shape. Therefore, a $t_{oa}$-method should yield the same $t_c$ for different pulse shapes. Fig. 3 shows three different pulse shapes of injected pulses. Pulse 1 is an inductively coupled pulse that was measured during an online PD measurement in an MV cable system. Most energy of this pulse is concentrated in the beginning of the pulse. The second pulse is also an inductively coupled pulse, but with different pulse source design, different injection coil and different load impedance. This pulse starts with a long low bump (charging) and then a short steep pulse (discharging). Thus, most low frequency content is located in the first part of the pulse and most high frequency content comes about 1 $\mu$s later. The third pulse is a short pulse with a width of about 100 ns. This pulse is similar to a real PD pulse that has propagated through a power cable over a short distance.

The mean and standard deviation of each simulation set is summarized in Table 1. Except for the phase method, all methods are sensitive to the pulse shape. Especially pulse 2 yields unacceptable results. There, most high and low frequency content of the pulse are concentrated at different time instants. At injection the start of the high-frequency part is chosen as time-of-arrival, because it contains most energy. After propagating through the cable most high-frequency content is attenuated, and the low-frequency becomes dominant. Therefore, at the far end the time-of-arrival is determined by the low-frequency part. The only method that is not influenced by the pulse shape is the phase method, because it analyzes the pulse in frequency domain and uses a fixed frequency for all analyses. The differences in $t_c$ of the Gabor method are less than 2%, which is twice the target accuracy of 1%. The differences of the other methods are unacceptable. This can be improved by calculating the channel’s impulse response using the detected pulses, but this falls beyond the scope and space of this paper. See [2] for further details.

B. Sensitivity to load impedance

This section deals with the location accuracy in general and the influence of the load impedance on the accuracy. In order to be able to locate PDs both a $t_c$-measurement simulation and a PD measurement simulation are required. Since the load impedance at each cable end has a significant influence on the pulse shape the location simulations are conducted with different load impedances. Three different impedances are used: an impedance matching the cable impedance, a capacitive load, and an inductive load. The $t_c$-measurement is simulated using the short PD-like pulse (pulse 3 in Fig. 3). The noise is white and has a constant level for all simulations.

In the first simulation the load impedance at both cable ends is equal to the characteristic cable impedance. Therefore

\[
t_{oa,p} = t_{ch} - \frac{\chi_a(\omega_f)}{\omega_c}
\]  

(6)

Fig. 3. Pulse shapes used in injection in pulse-shape-sensitivity simulations. Pulse 1: measured inductively coupled pulse, pulse 2: measured inductively coupled pulse (different pulse source), and, pulse 3: ideal PD-like pulse.

<table>
<thead>
<tr>
<th>Pulse</th>
<th>Threshold</th>
<th>AIC</th>
<th>EC</th>
<th>Gabor</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6230 ± 6</td>
<td>6209 ± 8</td>
<td>6241 ± 3</td>
<td>6355 ± 7</td>
<td>6399 ± 5</td>
</tr>
<tr>
<td>2</td>
<td>5333 ± 10</td>
<td>5272 ± 12</td>
<td>5391 ± 10</td>
<td>6318 ± 11</td>
<td>6399 ± 3</td>
</tr>
<tr>
<td>3</td>
<td>6231 ± 7</td>
<td>6228 ± 8</td>
<td>6256 ± 6</td>
<td>6445 ± 12</td>
<td>6399 ± 4</td>
</tr>
</tbody>
</table>

Table 1

MEAN AND STANDARD DEVIATION OF $t_c$ OF THE PULSE-SHAPE-SENSITIVITY SIMULATIONS. ALL VALUES ARE IN NANOSECONDS.
the pulse shape will not be distorted at the transition from cable to load impedance. This simulates the location accuracy of the $t_{oa}$-methods when the PD pulse shape is only influenced by the dispersion and attenuation of the cable. The mean and standard deviation of the location error of the simulations are plotted in Fig 4. This figure shows that all methods provide an accurate location ($< 0.1\%$ of cable length). Note that the location error of the phase method is virtually zero. The standard deviation of the Gabor method is larger than the other methods, which are similar to each other.

In the second simulation the near end is terminated with an inductance of 1 $\mu$H and the far end is terminated with a capacitance of 2 nF. These impedances do not represent field conditions, but are meant to test the methods for different loads with opposite phase shift at both ends. This is a worst-case scenario for the phase method because the errors introduced due to the phase shift at the transitions to the load impedances at both ends accumulate. The results of the simulations are plotted in Fig 5. As expected the phase method performs poorly for this configuration. But, if the transmission coefficient at the test frequency $c$ would be known, the phase shift at the transmission to the load impedance could be corrected. The accuracy of the Gabor method is also not within the 1% target accuracy limit and has a relatively large standard deviation. The other three methods have a mean error less than 0.5% of the cable length.

Fig 4. Mean and standard deviation of the location error for PDs from different locations in the cable. Load impedances at both cable ends are matched to the characteristic impedance of the cable.

Fig 5. Mean and standard deviation of the location error for PDs from different locations in the cable. Load impedance at near end is and inductance of 1 $\mu$H and the load impedance at the far end is a capacitance of 2 nF.

Table 2

<table>
<thead>
<tr>
<th>Summary of strong and weak points of $t_{oa}$-methods. See section III. For a description of the criteria.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
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<td>Noise</td>
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<tr>
<td>Pulse shape</td>
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<tr>
<td>Record length</td>
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<tr>
<td>Pulse location in record</td>
</tr>
<tr>
<td>Reflections in signal</td>
</tr>
<tr>
<td>Location accuracy</td>
</tr>
</tbody>
</table>

a) by incorporating channel’s impulse response
b) if load impedances are known accurately

VI. CONCLUSIONS

The $t_{oa}$-methods discussed in this paper have been evaluated analytically and with simulations to investigate the strong and weak points of the methods. Due to the lack of space in this paper not all simulations are described in detailed here, neither is the analytical evaluation and the experimental validation. See [2] for the complete analysis. The results of the complete analyses are summarized in Table 2.

Altogether, no single method performs superior on all criteria. Depending on the situation either the EC method or the phase method will provide the most reliable overall performance. The EC method has good accuracy in most situations. The only point where it failed is on its sensitivity to particular pulse shapes. The strongest point of the phase method is its complete insensitivity to the pulse shape. The second advantage is the high accuracy, provided that the load impedance and characteristic cable impedance can be measured or estimated. If the load impedance is unknown, or if there are other locations in the cable circuit where the phase changes suddenly the accuracy of the phase method is limited.

VII. REFERENCES


