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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

the pulse shape of both PD signals and injected signals at the cable ends. Furthermore, when a cable remains in service it also is connected to the rest of the grid. Therefore, the measurements are impeded with higher noise and disturbance levels.

PD location in cable systems can be achieved with a single sensor if the far end is disconnected, or with two sensors (one at each cable end) if the cable is in normal operation (see [1]). Both methods need to estimate the total propagation time of the cable (t_c) and the time-of-arrival (t_{oa}) of PD pulses in order to locate the origins of the PDs. The propagation time t_c is determined using the time-of-arrival of injected pulses and their responses.

The evaluation criteria for the t_{oa} estimation methods are described in section III. These criteria are applied to five methods, described in section IV. The methods are analyzed using simulations in section V.

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_{thres} . 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

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low as the noise permits without too many false triggers:

$$x_{thres} = m \cdot \sqrt{P_n} \quad (1)$$

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_{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:

$$AIC_k = k \cdot \ln(\sigma_{1,k}^2) + (N - k - 1) \cdot \ln(\sigma_{k+1,N}^2) \quad (2)$$

where $\sigma_{m,n}^2$ 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 t_{oa} 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 t_{oa} . 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:

$$t_{oa,g} = \frac{\sum_{k=1}^N t_k x_k^2 - P_n \sum_{k=1}^N t_k}{\sum_{k=1}^N x_k^2 - P_n \cdot N} \quad (4)$$

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 ($X(\omega)$) and retrieves the phase for a chosen frequency. This phase can be interpreted as a time delay (τ). Unfortunately, due to the periodicity of 2π the phase is

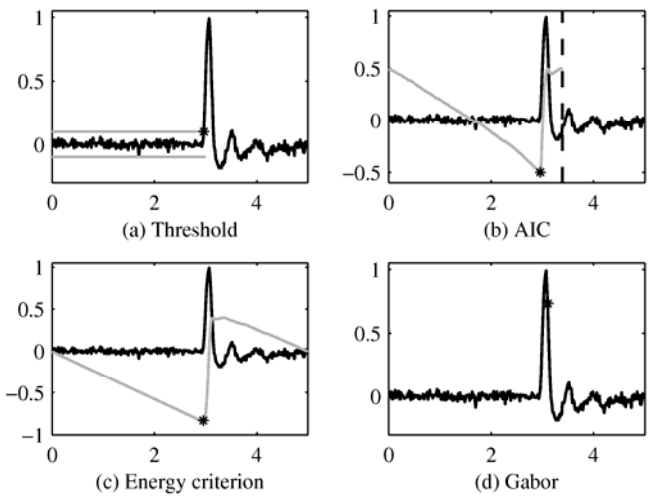


Fig. 1. Example of recorded pulse with four t_{oa} -methods applied. Time axes are in μ s. Black line: recorded PD signal, gray line: threshold^(a) / normalized & shifted AIC curve^(b) / normalized EC curve^(c), *: time-of-arrival, and dashed line: end of record used for AIC analysis.

ambiguous:

$$\tau = \frac{-\angle X(\omega_c)}{\omega_c} + \frac{m \cdot 2\pi}{\omega_c} \quad (5)$$

where m is an unknown integer and ω_c is a chosen frequency (in rad/s) for which the delay is calculated. For consistency, ω_c must be the same for all measurements. Taking the average over a small frequency range around ω_c reduces the sensitivity to noise and reflections in the signal. The periodicity problem can be solved by applying a (negative) time delay τ_{ch} to $X(\omega)$ first. This can be achieved using: $X_{ch}(\omega) = X(\omega) \cdot \exp(j\omega\tau_{ch})$. The delay τ_{ch} must be chosen such that the phase does no longer wrap around (jump from $-\pi$ to π , or vice versa) in a frequency range where $X(\omega)$ has sufficient energy (see Fig. 2). Since τ_{ch} is unknown a priori, an iteration loop is used to find the correct time delay. Once the correct τ_{ch} has been found the arrival time is given by:

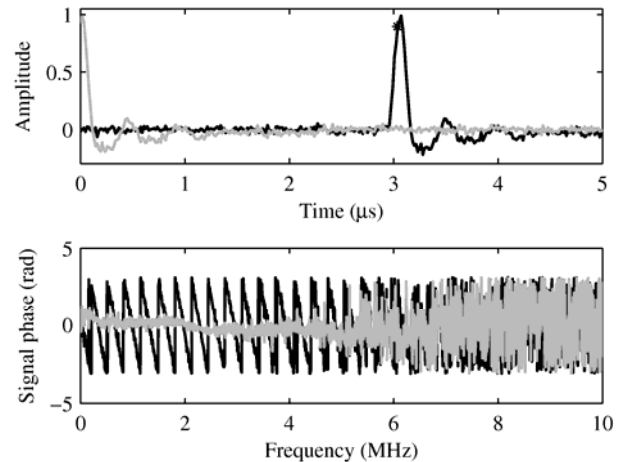


Fig. 2. Signal before and after iteration loop. The signal is plotted in time domain and the phase in frequency domain. The iteration loop ended with $\tau_{ch} = 3.05 \mu$ s. Black line: original signal before iteration loop, gray line: signal after iteration loop, and *: time-of-arrival.

$$t_{oa,p} = \tau_{ch} - \frac{\angle X_{ch}(\omega_c)}{\omega_c} \quad (6)$$

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 Ω).

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 δ -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)

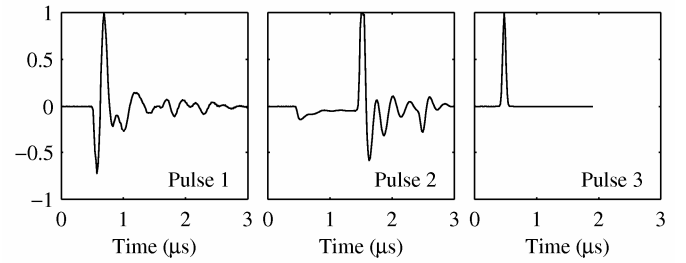


Fig. 3. Pulse shapes used in injection in pulse-shape-sensitivity simulations. Pulse 1: measured inductively coupled pulse, pulse 2: measured inductively coupled pulse (different pulse source), and, pulse 3: ideal PD-like pulse.

TABLE 1
MEAN AND STANDARD DEVIATION OF t_c OF THE PULSE-SHAPE-SENSITIVITY SIMULATIONS. ALL VALUES ARE IN NANOSECONDS.

Pulse	Threshold	AIC	EC	Gabor	Phase
1	6230 \pm 6	6209 \pm 8	6241 \pm 3	6355 \pm 7	6399 \pm 5
2	5333 \pm 10	5272 \pm 12	5391 \pm 10	6318 \pm 11	6399 \pm 3
3	6231 \pm 7	6228 \pm 8	6256 \pm 6	6445 \pm 12	6399 \pm 4

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 μ 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

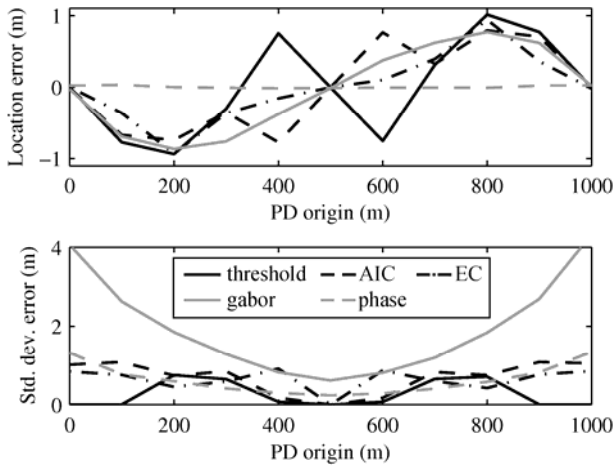


Fig 4. Mean and standard deviation of the location error for PDs from different locations in the cable. Load impedances at both cable ends are matched to the characteristic impedance of the cable.

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 $1 \mu\text{H}$ 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 ω_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.

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

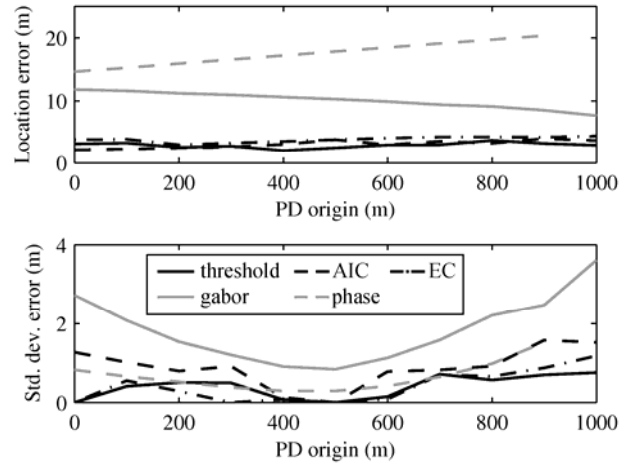


Fig 5. Mean and standard deviation of the location error for PDs from different locations in the cable. Load impedance at near end is an inductance of $1 \mu\text{H}$ and the load impedance at the far end is a capacitance of 2 nF .

TABLE 2
SUMMARY OF STRONG AND WEAK POINTS OF t_{oa} -METHODS. SEE SECTION III.
FOR A DESCRIPTION OF THE CRITERIA.

	Threshold	AIC	EC	Gabor	Phase
Noise	-	-	+	0	+
Pulse shape	- / 0 ^a	- / 0 ^a	- / 0 ^a	- / 0 ^a	+ / + ^a
Record length	+	+	0	+	+
Pulse location in record	+	0	+	+	+
Reflections in signal	+	+	+	-	+
Location accuracy	+	+	+	-	- / + ^b

a) by incorporating channel's impulse response

b) if load impedances are known accurately

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.

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