Algorithms for Automated Arrival Time Estimation of Partial Discharge Signals in Power Cables

C. Herold[1*], T. Leibfried[1], S. Markalous[2], and I. Quint[3]
[1] Institute of Electrical Energy Systems and High Voltage Technology, University of Karlsruhe, 76131 Karlsruhe, Germany
[2] LDIC GmbH, Radeburger Str. 47, 01468 Volkersdorf / Dresden, Germany
[3] AVISO GmbH, Industriestraße 3/3a, 67063 Ludwigshafen, Germany
*Email: herold@ieh.uni-karlsruhe.de

Abstract: Partial discharges within power cables can indicate damages of the cable insulation or incorrect installed joints. Therefore the location of such discharges is a reasonable maintenance tool to identify defective cable parts in time. The location of partial discharges in shielded cables can be done with the Time Domain Reflectometry method. There, delay times between pulses set off by a partial discharge and traveling through the cable are used to determine the origin of the partial discharges. For this delay times the arrival times of the traveling pulses are needed which can be estimated by different approaches. The most commonly used arrival time estimation technique is the peak detection. But frequency-dependent attenuation and distortion of fast pulses within power cables can lead to location failures rising with the cable length. To avoid this problem pulse onsets should be detected. This paper describes the application of the Energy Criterion and the Akaike Information Criterion as onset detection methods for simulated partial discharge pulses.

1 INTRODUCTION

Time Domain Reflectometry (TDR) is a standard technique for the location of partial discharges (PD) in power cables. Incorrect installed cable joints or cavities in paper-insulated lead-covered (PILC) cable are typical sources for partial discharge. If the applied AC test voltage reaches the PD inception voltage, the discharge is ignited and two pulses travel along the cable; one to the measuring end and one to the opposite, open end of the cable. The pulse traveling to the open end of the cable will be completely reflected and secondly reaches the measuring unit with a time delay, related to the direct and therefore first pulse. The second pulse is called indirect pulse. In the TDR it is essential to determine this delay between the direct and the indirect PD pulse to estimate the ignition point (PD site) of the PD within the power cable. Picking the peaks of both pulses would be an ad hoc method to estimate the delay time but might create a cable length dependant failure. Due to dispersion the pulses are deformed leading to location errors depending on the PD site location [1]-[4]. This low-pass characteristic of the cable must not be neglected at power cable diagnostics, with typical cable lengths up to several kilometers being tested. A higher accuracy could be achieved with the determination of the true pulse onsets.

It may be feasible to determine the time delay between the onset of the direct and the indirect pulse manually for one pulse pair. But performing that for several pulse pairs is time-consuming, as there may be a lot of PD pulses to analyze in one period of a 50Hz AC test voltage. An automated and robust detection process for this purpose eases the interpretation of measuring data acquired in the field. Algorithms already utilized in acoustics are especially designed for finding the arrival time of signals and can be utilized for automated detection of partial discharges in the TDR. This paper compares the arrival time estimation methods peak detection, Energy Criterion and Akaike Information Criterion concerning the achievable location accuracy and the suitability for automated cable PD location software.

2 PD LOCATION

Locating partial discharge pulses within power cables can be done by analyzing and interpreting reflectograms, a sample of direct and indirect pulses and their reflections, obtained by a PD measurement system. This paper deals with PD reflectograms acquired during offline measurements at a RG58 C/U coaxial test line (length: 529.4 m) with several joints to bring in artificial PD pulses at known places. Although the electrical characteristics of such a model cable differ from power energy cables, it was chosen to test the functionality of arrival time estimation algorithms for PD location in principle.

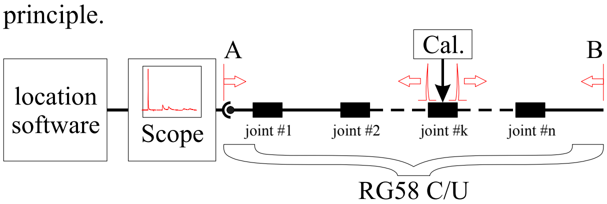

Fig. 1: Coaxial line test setup

The partial discharge pulse was simulated by a calibration pulse with a charge of 100 pC injected at various joint locations (e.g. *joint #k* in Fig. 1). An oscilloscope was used to acquire reflectograms with matched (50 Ω) or unmatched (1 MΩ) input. To reduce noise and interferences the data was averaged. The sampled data was analyzed by a location-software based on the Time Domain Reflectometry method working with different detection algorithms presented in the following.

2.1. Time Domain Reflectometry (TDR)

TDR is a common tool to locate origin of pulses within a shielded cable. First, a calibration procedure is applied on the cable under test. This is done by injecting a pulse at the "near cable end" (point A in Fig. 1) and recording the direct and indirect pulse traveling to the measuring unit as well as their reflections if the input of the unit is not matched. As the propagation speed is limited and the indirect pulse, reflected at the far open end of the cable (point B in Fig. 1), has to travel twice the cable length until it reaches point A again, a time delay t_L is occurring between the direct and indirect pulse. The measured signal is called "calibration reflectogram".

Now a pulse shall be ignited within the cable length which results in a "PD reflectogram" similar to Fig. 2. The time difference t_x between the first pulse of the pulse triple (direct pulse) and the second pulse (indirect pulse) can be measured, accordingly. Also, the calibration delay time t_L can be found again as time difference between the first and the third pulse of the pulse triple, unless the input impedance of the measurement unit is matched for the characteristic wave impedance of the cable.

The absolute position of the pulse origin can be determined by

$$x = \left(1 - \frac{t_x}{t_L}\right) \cdot L \tag{1}$$

where x is the distance of the pulse origin from the "near cable end" and L is the total cable length.

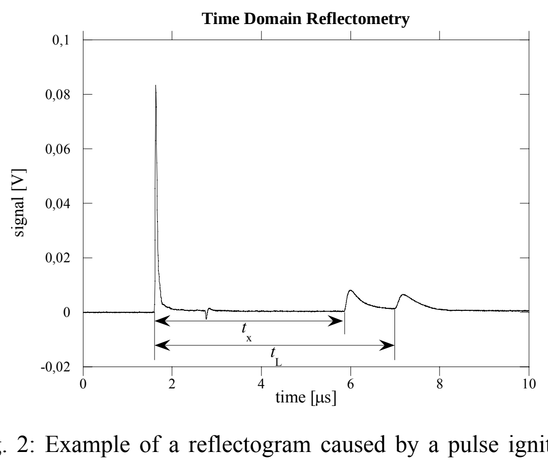

Fig. 2: Example of a reflectogram caused by a pulse ignited near 20 % of the cable length (RG58 C/U, input impedance 1MΩ).

Thinking about an automated software tool to identify PD sites by analyzing such reflectograms, the estimation of arrival times is an important element. The peak detection and the estimation of the true pulse onsets are two of the possibilities to estimate arrival times. Depending on the cable type and its condition pulses traveling through the cable are damped and distorted. This so-called dispersion causes besides a reduction of the pulse amplitude a broadening of a pulse and therewith a displacement of the pulse peak point dependent on the traveling time [1]-[4].

Following algorithms for arrival time estimation are presented under the assumption that the reflectograms are given in clean (denoised) condition.

2.2. Peak detection

The peak detection is a widely implemented easy and robust method to find the maximum values of signals. In cable PD site location peak detection is used to find the maxima of the direct and indirect pulse to determine the time difference t_x and therewith the absolute position of the PD site.

2.3. Energy Criterion (EC)

The Energy Criterion algorithm bases on the assumption that the arrival of a wavelet corresponds to a change in energy. Used in acoustics [5] and unconventional PD location [6] to locate sources of sonic emission it can be applied to determine the arrival times of fast electrical signals like PD pulses.

The energy S_i of a 1-D sampled signal x is defined by the cumulative sum of the squared signal samples

$$S_i = \sum_{k=0}^{i} x_k^2 \quad \left(i = [0 \ldots N], i \in \mathbb{N}_0\right). \tag{2}$$

Adding a negative trend δ (4) the now resulting function

$$S_i^{'} = S_i - i\delta = \sum_{k=0}^{i} \left(x_k^2 - i\delta\right) \tag{3}$$

marks the onset of the signal as global minimum. The trend

$$\delta = \frac{S_N}{\alpha \cdot N} \tag{4}$$

is dependent on the total energy S_N of a signal, signal length N and a factor α which was introduced in [5] to reduce the delaying effect of the negative trend δ. Fig. 3 shows computed energy curves with α=[1,2,5,100] to detect the onset of an averaged calibration PD pulse.

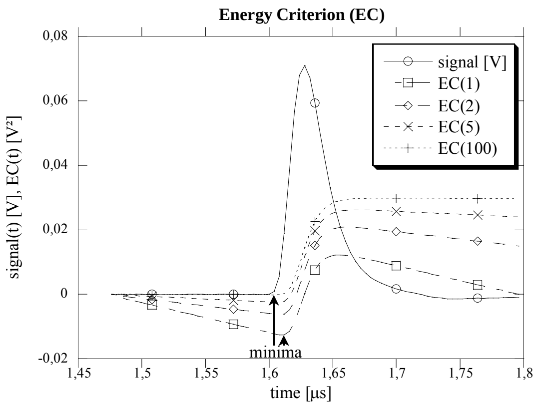

Fig. 3: Application of the Energy Criterion with increasing parameter *α* on a calibration PD pulse signal.

The global minimum of the EC curve is moving towards the pulse onset for rising parameter *α* as the delaying effect of *δ* is compensated.

2.4. Akaike Information Criterion (AIC)

The Akaike Information Criterion is an autoregressive (AR) time picking algorithm capable of detecting arrival times of signals. Also used in PD location [6] and seismology [7], [8], AIC divides the sampled data into two stationary parts which are each modeled by an AR process. Changes in the value or order of the AR coefficients before and after a pulse occurrence indicate the onset by a global minimum.

Analyzing a sampled signal with a total length of *N* elements the AIC algorithm is defined as

$$AIC(k) = k \cdot \log\left(\operatorname{var}\left(x(1,k)\right)\right) + (N-k-1) \cdot \\ \cdot \log\left(\operatorname{var}\left(x(k+1,N)\right)\right) \quad (5)$$

where var(*x*) denotes the variance function and *x*(1,*k*) and *x*(*k*+1,*N*) provide the data input windows before and after the *k*th sample. The AIC function is displayed in Fig. 4 where the onset is marked by a strong global minimum of the AIC curve.

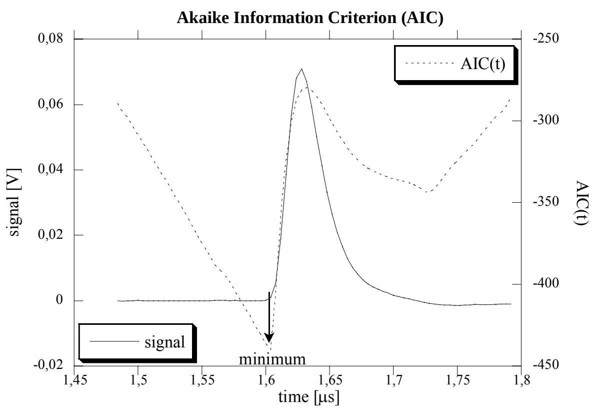

Fig. 4: Application of the Akaike Information Criterion on a calibration PD pulse signal.

Due to its high sensitivity the AIC algorithm needs a predefined window to operate as well as denoised or filtered data.

3 IMPLEMENTATION AND RESULTS

As the onset detection algorithms are being integrated into automated PD detection software there are some further aspects to be considered.

3.1. Defining a time window

As mentioned before the AIC algorithm is needed to be supplied with a certain time window to operate properly. Since the algorithm needs information of the noise before the appearance of a pulse onset, it works quite well in a time window with a ratio of at least two-thirds noise and one third pulse rise time [6]. Therefore the dimension of the pulse rise time is required. This can be measured manually during the calibration procedure.

The time window for the EC algorithm was chosen accordingly.

3.2. Application of the onset detection

To perform an onset detection with the EC or AIC the peak detection has to be applied first, as both algorithms are working best in signal data where just one onset occurs. Having the maximum value of the direct and indirect pulse a data window is defined as described above and the EC or AIC functions are calculated for the window by (3) and (5), respectively. The normalized curves are plotted for an artificially disturbed indirect pulse signal (standard deviation of white noise: *σ=1e-3*) in Fig. 5 and Fig. 6. The parameter *α* of the EC was increased up to *α=10* to optimize onset detection as the signal to noise ratio was high enough.

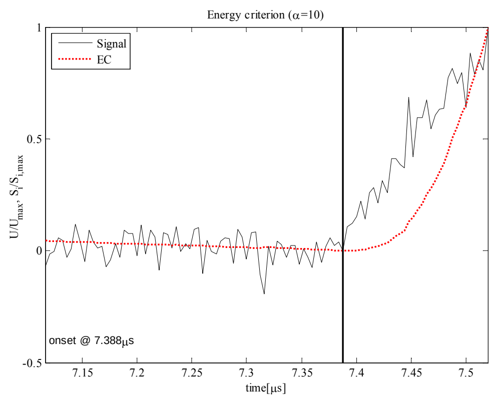

Fig. 5: Application of the EC algorithm on an indirect pulse: onset found at 7.388 µs.

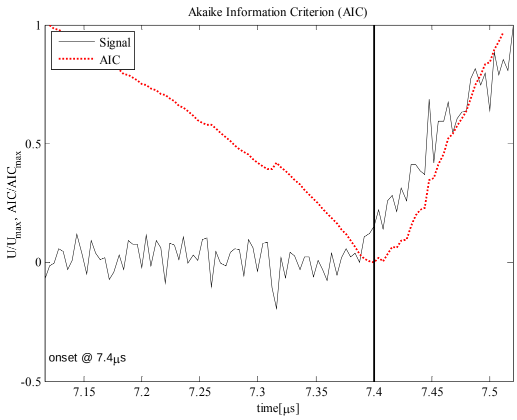

Fig. 6: Application of the AIC algorithm on an indirect pulse: onset found at 7.4 µs.

After the computation of the EC and AIC curves, the minimum of each curve is determined. Its time value marks the onset of the pulse and therewith the arrival time.

The application in combination with TDR means onset detection of each the direct and indirect pulse of the calibration reflectogram and the PD reflectogram, calculating the delay times t_L and t_x, and using (1) to compute the absolute location of the PD.

3.3. PD close to cable ends

If a PD site is situated close to the near or far cable end pulse overlapping occurs.

If the input of the measurement unit is not matched (e.g. 1 MΩ input of the oscilloscope) the indirect pulse of a "near cable end" PD is overlapping with the reflection of the direct pulse making the peak detection more inaccurate than onset detection. Fig. 7 shows the merging of the indirect pulses with the respective direct pulses for pulses starting from about 1 to 30 m away from the "near cable end".

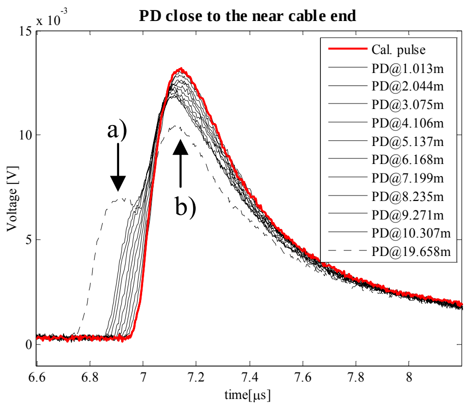

Fig. 7: Overlapping effect of indirect pulse (a) and reflection of direct pulse (b) for PD sites close to the near cable end.

In the first 10 m the global pulse maximum results from superposition of the indirect pulse and the reflection of the direct pulse, the third pulse within a reflectogram. The onset is drifting significantly to the left without being altered by the third pulse following close. Not until the distance of the PD site from the "near cable end" is rising, the indirect pulse comes out off the third pulse making peak detection possible again.

For PD sites close to the "near cable end" peak detection does not work well. Instead, onset detection should be used for higher accuracy. Using a matched measurement unit (e.g. 50 Ω input impedance of the oscilloscope for the RG58 coaxial line) the reflections and therewith the overlapping effect do not occur any more and the peak detection can be used, too.

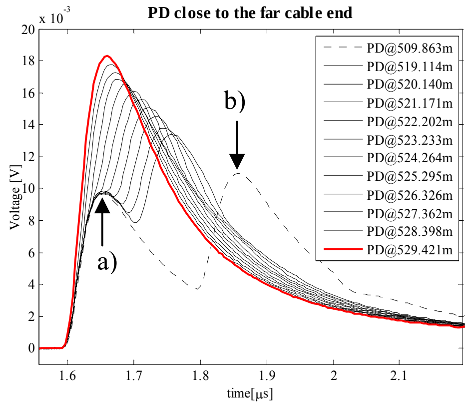

Fig. 8: Overlapping effect of direct (a) and indirect pulse (b) for PD sites close to the far cable end (total length L=529.4 m).

On the opposite side, the "far cable end", pulse overlapping occurs, too. There, the direct and indirect pulses are superposing leading to reflectograms similar to Fig. 8. The peak or onset detection algorithms only can be applied if two peaks are still visible at the overlapping pulse. In Fig. 8 about 5 m from the "far cable end" only a turning point (a) may be noticeable which have to be interpreted by an analyst manually.

3.4. Location accuracy

To analyze the absolute location accuracy of the presented algorithms a RG58 C/U coaxial line was built up out of 26 pieces of about 20 m length and ten 1 m pieces. The 1 m cables were used to simulate PD close to the "near cable end" as well as the "far cable end".

The results are shown in Fig. 9. As brought up in 3.3 peak detection does not work well for PD sites close to the "near cable end" (failure up to -8 m) while the onset algorithms EC and AIC handle those PD-sites better (failure of about 0.5 m in that region).

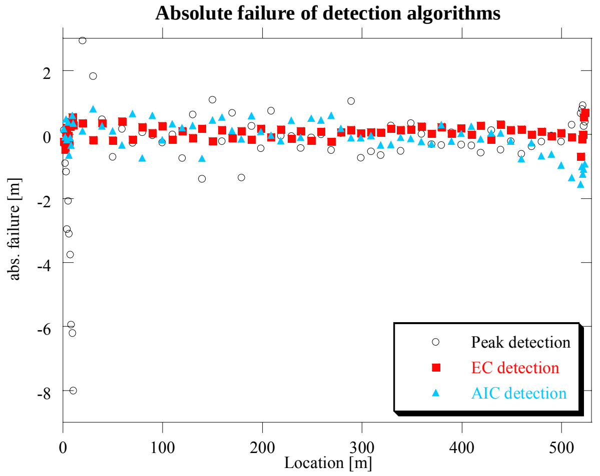

Fig. 9: Comparison of the three detection algorithms by measuring the absolute failure of detection over the cable length.

The maximum, minimum, mean and standard deviation (STDV) values of the absolute failure are presented in Tab. 1.

Tab. 1: Maximum, minimum, mean and standard deviation values of the detection algorithms of absolute failure measurements.

abs. failure	Peak	EC	AIC
max	*-8.01 m*	*0.69 m*	*-1.55 m*
min	*0.001 m*	*0.001 m*	*-0.022 m*
mean	*-0.50 m*	*0.07 m*	*-0.10 m*
STDV	*1.71 m*	*0.24 m*	*0.53 m*

Looking on the overall absolute failure, the peak detection method is resulting in a mean difference to the true initial pulse location of (-0.5±1.71) m for the examined RG58 cable. The standard deviation of the peak detection absolute failure is reducing as the initial pulse location is shifted towards the "far cable end".

With the onset algorithms good results are obtainable if the parameters (time window size, α) are well defined. There, a mean absolute failure value of (0.07±0.24) m and a maximum failure of 0.69 m were achievable by the EC algorithm. The AIC algorithm has a slightly higher scatter of the measured values than the EC (mean value of (-0.1±0.53) m), but the results are comparable.

4 CONCLUSION

Peak detection is a reasonable tool to pre-select reflectograms out of massive measurement data and to define time windows for further processing. Using peak detection as delay time estimation method is working quite well for short cable lengths and PD sites near the "far cable end", as both pulses, the direct and indirect one, traveled almost the same distance, and therefore have been influenced by almost the same dispersion effects before they reach the measurement unit. But for rising cable lengths and for PD sites close to the "near cable end" the location errors due to frequency-dependent propagation of pulses and overlapping effects may be increasing. To meet the demand for higher accuracy for PD site location onset detection can be provided as an additional tool within PD location software to reduce such failures.

The Energy Criterion and the Akaike Information Criterion presented in this paper both are algorithms able to detect onsets of cable PD pulses.

Ongoing research focuses on testing the presented algorithms and improving them during measurements in noisy environments on long power energy cables with defined PD sites.

5 REFERENCES

[1] F.H. Kreuger, M.G. Wezelenburg, A.G. Wiemer and W.A. Sonneveld, "Partial discharge Part XVIII: Errors in the location of partial discharges in high voltage solid dielectric cables", *IEEE Electrical Insulation Magazine*, Vol. 9, No. 6, pp. 15-22, 1993.

[2] J.P. Steiner, P.H. Reynolds, W.L. Weeks, "Estimating the location of partial discharges in cables", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 27, No. 1, pp. 44-59, 1992.

[3] C.H. Knapp, R. Bansal, M.S. Mashikian and R.B. Northrop, "Signal processing techniques for partial discharge site location in shielded cables", *IEEE Transactions on Power Delivery*, Vol. 5, No. 2, pp. 859-865, 1990.

[4] J. Veen, "On-line signal analysis of partial discharges in medium-voltage power cables", *Ph.D. thesis*, Eindhoven University of Technology, Eindhoven, The Netherlands, 2005.

[5] C.U. Große and H.-W. Reinhard, "Schallemissionsquellen automatisch lokalisieren", *MP Materialpruefung*, Vol. 9, pp. 342-347, 1999.

[6] S. Markalous, "Detection and Location of Partial Discharges in Power Transformers using acoustic and electromagnetic signals", *Ph.D. thesis,* Universitaet Stuttgart, Stuttgart, Germany, 2006.

[7] J.H. Kurz, C.U. Grosse and H.-W. Reinhardt, "Strategies for reliable automatic onset time picking of acoustic emissions and of ultrasound signals in concrete", *Ultrasonics*, Vol. 43, pp. 538-546, 2005.

[8] Haijiang Zhang, C. Thurber and C. Rowe, "Automatic P-Wave Arrival Detection and Picking with Multiscale Wavelet Analysis for Single-Component Recordings", *Bulletin of the Seismological Society of America,* Vol. 93, No. 5, pp. 1904-1912, 2003.