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On-line PD detection in power cables using matched filters

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Abstract

On-line measuring of partial discharge (PD) is generally impeded by noise, and in many cases PDs cannot be detected without filtering. Solely the pulse propagation path and the response of the detection circuit determine the shape of a PD pulse; therefore a PD can be regarded as a deterministic signal embedded in additive noise. The optimal filter for this class of signals is the matched filter, which maximises the signal-to-noise ratio at the filter output. Matched filters allow making reliable observations of PD signals embedded in noise and precise estimations of signal parameters, such as arrival time and charge. In order to obtain PD matched filters; knowledge of the PD wave shapes is crucial. A cable propagation model provides such knowledge, and matched filters can be designed specifically for the cable under test. Moreover, by estimating noise statistics the matched filters can be tailored for a practical measuring situation. Experimental results show that partial discharge detection greatly benefits from matched filtering.

Keywords: on-line, power cable, PD-measurements, noise reduction, matched filters, propagation model.

1. Introduction

In high voltage equipment, PDs occur as a result of insulation defects. By monitoring these PDs on-line, progressive deterioration of the insulation can be indicated. It is clear from numerous publications that noise is the primary impediment to practical PD measurements. Especially in case of on-line measurements, PD signals are corrupted to a large extent and cannot be detected without some kind of pre-filtering [1,2]. Conventionally, band-pass filters are used in order to improve PD detection; however, as a result of ever increasing computing power, in recent years also more advanced signal processing techniques have been applied [3..5]. In this paper we discuss the application of matched filters to improve PD detection.

A PD pulse originates with duration of at most a few nanoseconds [6]; therefore the waveform that is measured at the cable-end approximates the impulse response of the channel through which the pulse propagates. Since the channel characteristics are generally constant during measurements, a PD signal can be regarded as being deterministic. Matched filtering is a standard technique for detection of deterministic signals in the presence of noise and the basic theory can be found in many textbooks [7..9]. The matched filter is optimal in the sense that the signal-to-noise ratio (SNR) at the output of the filter is maximised, provided that the signal waveform and the noise spectral energy distribution are known or can be estimated.

The principle of matched filtering and its application to PD detection are discussed in Section 2. In Section 3 additional properties of matched filters, which enable a high level of PD measuring automation, are described. Section 4 gives the results of the technique applied to real data and Section 5 concludes the paper.

2. Partial discharge matched filtering

In the context of PD measuring, signals that are not related to partial discharges are regarded as being noise or interference. Moreover, we distinguish noise and interference in order to classify respectively disturbing signals that are continuously present during measurements and disturbing signals of relatively short duration. Noise encountered in practice primarily results from radio communication and broadcasts, which are continuously present and can be considered as stochastic processes. Transients caused by thyristors and switching operations are common examples of interference, which have relatively short duration. In this paper, we will focus on detection of PD signals in noise, since matched filtering applies to this class of disturbance.

Generally, PDs are detected by comparing a measured signal to some threshold; thus the detection performance highly depends upon the SNR. Since the matched filter is aimed at maximising the SNR at the filter output, it is an excellent detection pre-filter.

2.1 Matched filtering

The transfer function of the matched filter is given by

$$H(f) = C\frac{S^*(f)}{P_N(f)} \tag{1}$$

where C is a constant, $S^*(f)$ is the complex conjugate of the PD signal's Fourier transform, and $P_N(f)$ is the power spectral density function (psdf) of the noise.

The magnitude of the transfer function is directly proportional to the amplitude spectrum of the PD signal; therefore the optimal detector bandwidth is automatically selected. Furthermore, the transfer function is inversely proportional to the noise psdf. Consequently, each frequency component of the input signal is weighted corresponding to that specific component's SNR, see Figure 1. Frequency components with relatively high SNR contribute to the output signal to a large amount, while signals with a low SNR do not, thus optimising the overall SNR of the output signal.

If the noise is white, then the noise power is equally distributed along the frequency spectrum and the noise psdf is constant. By choosing an appropriate filter gain, the transfer function is rewritten as

$$H(f) = S^*(f) \tag{2}$$

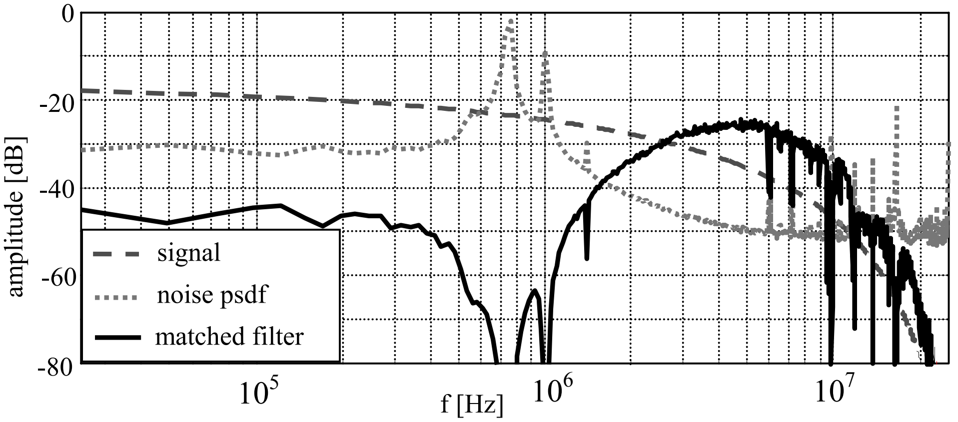

Figure 1. Example of a matched filter amplitude spectrum.

and the impulse response equals

$$h(t) = s(-t) \tag{3}$$

which explains the term matched filter. Thus essentially the operation of a matched filter is equivalent to correlating a signal with a copy of itself. In this context, a fairly general interpretation of the matched filter for coloured noise is a cascade of a whitening filter and a whitened matched filter. The transfer function of the cascade is expressed as

$$H(f) = H_W(f)H_M(f) = \frac{1}{\sqrt{P_N(f)}} \frac{S^*(f)}{\sqrt{P_N(f)}} \tag{4}$$

The whitening filter $H_W(f)$ flattens the noise spectrum, and the whitened matched filter $H_M(f)$ is matched to the signal as filtered by the whitening filter. Note that expression *(3)* does not represent a causal filter, nor does expression *(1)*; however, this problem is overcome by delaying the impulse response such that $h(t) = 0$ for $t < 0$.

Figure 2 shows an example of a deterministic signal, embedded in coloured noise, which is filtered by a matched filter. Clearly, the signal is de-noised to a large extent.

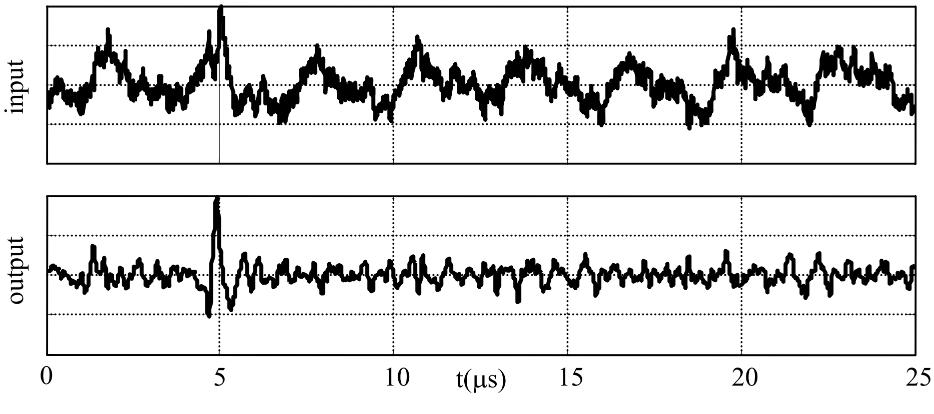

Figure 2. Matched filtering example.

2.2 PD pulse shape

In order to obtain a PD matched filter, accurate knowledge of PD pulse shapes is required. A PD signal cannot be measured without noise, so the best we can do is to model its shape. The PD pulse is mainly determined by the high frequency attenuation and dispersion introduced by the cable, which can be characterised by a transmission line model [10,11]. Also the cable load impedance and the detection circuit itself may change the PD pulse shape. If the cable under test is a single-phase cable, or a cable in which every phase is separately shielded, a two-conductor transmission line model applies. For belted cables (in several countries, e.g. the Netherlands, extensively used for the MV grid), a number of propagation channels exists. Two distinct propagation channels can be defined in such a cable, the Shield-to-Phase (SP) channel, the sum current of the three phase conductors returning through the shield, and the Phase-to-Phase (PP) channel, the difference between two phase currents (with zero current in the third phase). These channels have their own propagation characteristics and the cross talk between the two channels can usually be neglected [12].

In an on-line measuring situation, the propagation parameters can be estimated in the field by injecting a known pulse into a propagation channel, measuring the pulse at the other end and/or its reflections. Given the length of the cable, the propagation channel characteristics can be calculated and thus a model for the pulse shape as a function of propagated distance is obtained.

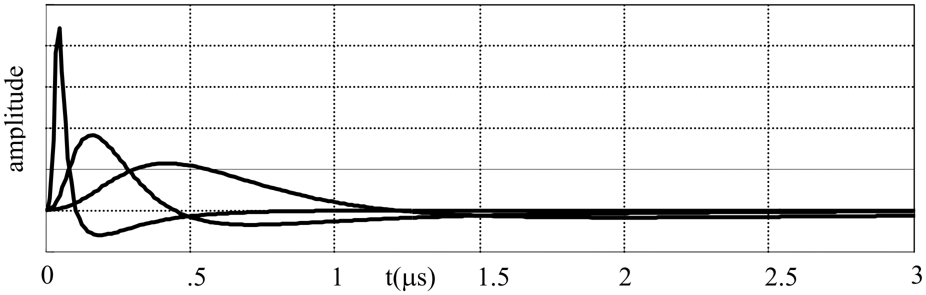

Figure 3. Examples of modelled PD pulse shapes for various distances propagated.

2.3 Matched filter bank

Generally, partial discharges originate from various locations within the cable under test, resulting in an equal variety of signal waveforms at the sensor(s) (see Fig. 3); therefore the measurement system must employ multiple matched filters. Theoretically, the diversity of waveforms is infinite since there exists an infinite number of possible PD locations. However, since signals that originate from nearby locations are almost equally damped they cannot be distinguished in practice, and a limited number of filters is sufficient.

Applying a measured signal to a bank of matched filters results in multiple output signals. If the filters have equal energy, then the filter that matches best to a PD signal gives maximum output at the relative time of arrival (TOA) of the PD signal. However, the maximum response of one filter does not necessarily occur synchronously to the maximum response of another filter; therefore simply selecting the highest output at a certain time instant does not give the desired result and the output signals must be evaluated on a certain time interval. Seeing that the matched filter bank is derived from a cable model, the origin of a PD signal can be estimated using only the waveform itself. Clearly, this initial guess is not very accurate, since signals that originate from a range of locations are almost equally damped, as mentioned. Nevertheless, an initial guess can be used to verify results that are obtained later on in the localisation process.

2.4 Adaptive matched filtering

Formally, application of a matched filter is restricted to stationary noise only; for now we will assume this restriction holds for PD measurements. In addition, we assume that the statistical averages of the process can be obtained from measurements, and thus an estimator for $P_N(f)$ in expression *(1)* can be derived. The usual non-parametric estimator of a stationary process' psdf is the periodogram [13]. In order to improve the estimator, the periodograms of several observations are averaged, thus the overall estimation variance is decreased. The averaged periodogram is obtained directly from the definition of the psdf and is expressed as

$$\hat{P}_N(f) = \frac{1}{R}\sum_{i=1}^{R}\left|N_i(f)\right|^2 \tag{5}$$

where *R* equals the number of observations of the noise and $N_i(f)$ is the Fourier transform of the *i*-th noise observation.

In reality the noise encountered in PD measurements is not wide-sense stationary but rather slowly varying with time. Nevertheless, the noise appears stationary on a short time base, i.e. with respect to the duration of a PD signal; therefore we can still use expression *(5)* as an estimator. Moreover, seeing that the equation can be written in a recurrent form, the estimator will track the changing noise statistics, as new observations become available. Therefore, replacing $P_N(f)$ in expression *(1)* by the averaged periodogram results in a filter that changes with the measuring conditions, leading to the so-called adaptive matched filter.

3. PD source localisation and charge estimation

In order to localise a PD source, multiple PD signals are recorded, either a direct pulse and its reflections arriving at a single sensor or measurements from multiple sensors. The various pulses arrive at the sensor(s) on different time instants, and the difference in arrival time provides a measure of the PD source location if a signal propagation model is available. In general, the TOA of a PD pulse is defined at the start of the rising edge of the pulse. By defining the start of the time-reversed matched filter equal to the pulse start of the model wave shape, the maximum filter output occurs on the TOA of a PD pulse, see Fig.4, therefore the matched filter is a valuable tool to accurately estimate the source location in a noisy environment. Obviously, the quality of the estimated TOA is related to the signal wave shape, the noise spectrum, and the SNR. The variance of any estimator is lower bounded by the Cramer-Rao bound (CRB) [7]; in this case the bound on the variance of the TOA estimate equals

$$\mathrm{var}\,(\hat{\tau}-\tau) \geq \left(\int f^2 \frac{P_S(f)}{P_N(f)} df \right)^{-1} \tag{6}$$

where τ equals the time-of-arrival, $\hat{\tau}$ is the estimate, and $P_S(f) = |S(f)|^2$ is the signal power spectrum. Thus frequency components with low SNR contribute to the estimation variance to a large extent. Moreover, the SNR of each component is weighted proportional to the squared frequency; therefore relatively high frequencies with high SNR contribute largely to the quality of estimation, which is intuitively valid. If the noise is Gaussian, this expression approximates equality and the matched filter provides the maximum likelihood (ML) estimate of the PD signal's TOA.

The charge of a measured PD pulse is unknown by forehand, therefore the filter is matched to a scaled version of the actually measured pulse, i.e. $s(t) = Ah(-t)$. Assuming that $s(t)$ is a current, the magnitude of the received PD pulse equals

$$Q = \int s(t)dt = A\int h(-t)dt \tag{7}$$

If $h(t)$ is scaled such that the filter has unit energy, then the peak of the output signal is an estimate of the scaling factor A, and since the integral of the filter is known by forehand, an estimate of the PD magnitude can be obtained.

The lower boundary of the variance of this estimation, the CRB on $\hat{A}$, equals

$$\mathrm{var}\,(\hat{A}-A) \geq \left(\int \frac{P_S(f)}{P_N(f)} df \right)^{-1} = \frac{1}{SNR} \tag{8}$$

So, in addition to its noise suppressing capabilities, a matched filter also provides a means to determine PD charge and source location, provided that a signal propagation model is available. . These properties enable the design of fully automated PD detection and localisation systems.

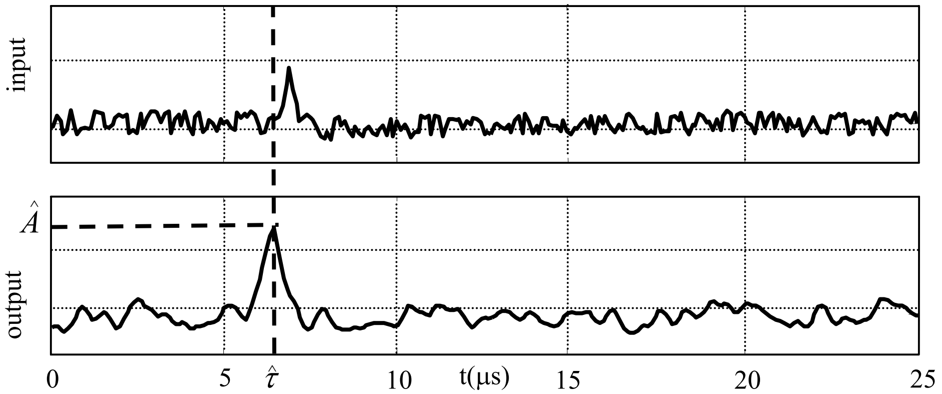

Figure 4. A matched filter can be designed such that the maximum output value is proportional to the PD charge, and such that this maximum occurs at the start of the measured PD pulse.

4. Experimental results

In an experiment, blocks of data were recorded during on-line PD measurements on a 500 m paper insulated lead covered (PILC) cable system. Based upon knowledge of the cable system a matched filter bank was designed. The recorded data blocks were used to estimate the noise spectral distribution, and the matched filter bank was adapted to the noise. Subsequently, the measurements were whitened and applied to the matched filter bank. In Fig. 5, a small frame of measurement data and the corresponding output of the best matching filter are plotted. Clearly, the matched filter is able to suppress the noise and pinpoint the arrival time of the PD pulses.

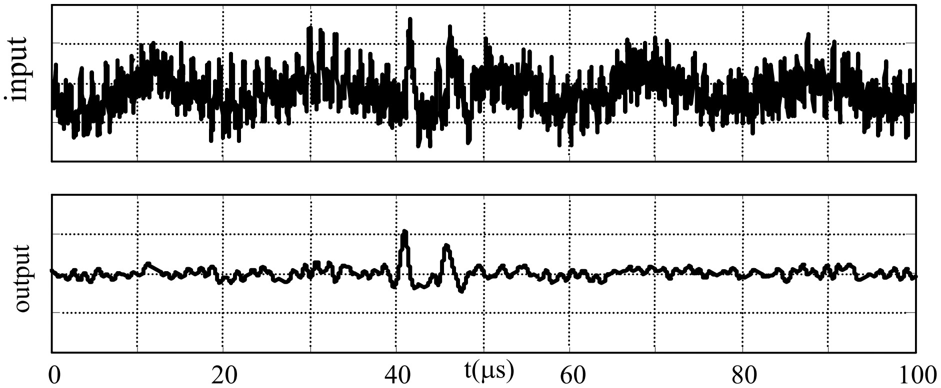

Figure 5. A noisy PD signal obtained in an on-line experiment and the signal after matched filtering.

5. Conclusions

In practice PD signals are mainly corrupted by narrow-band noise due to e.g. radio communication; therefore matched filters are very well suited for PD detection, since they optimally exploit frequency components with high SNR. Nevertheless, it must be stressed that matched filters can only be obtained for systems of which the signal propagation characteristics are known, either by measurement, modelling, or a combination of these.

By applying the concepts from the previous sections, a matched filter bank can be designed specifically for the system under test, and tailored for a practical measurement situation. Since noise in PD measurements is usually slowly varying with time, an estimator can track noise statistics, resulting in an adaptive filter bank that changes with the measuring conditions.

Matched filters can be designed such that they give maximum response at the start of a measured PD signal, therefore accurate estimations of pulse arrival times, and thus PD source locations, can be made. In addition, matched filters can be used to estimate PD charge. These combined properties make the matched filter a valuable tool for automated PD detection and source localisation.

6. Acknowledgement

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