High Accuracy Location of Faults on Electrical Lines Using Digital Signal Processing

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Abstract—A signal processing algorithm is developed to estimate the location of a discontinuity, e.g., a fault, on an electrical line. It is applied to sampled time-domain reflectometry (TDR) data and performs "pecstrum" analysis of the transmitted and reflected pulse signals. The "Pecstrum" algorithm is based on a transform similar to the one used in the well-known "Cepstrum" technique; i.e., the "time domain" versus "quefrency domain" transformation. However, in this paper it is demonstrated that the performance of the "pecstrum" estimator is significantly better than the methods proposed so far. The proof of this statement is given on a theoretical as well as on a practical basis; the proposed solution has been tested out firmly, is operational in industrial digital reflectometers, and has been shown to be robust and successful in practice.

I. INTRODUCTION

CAble fault detection techniques have been developed over a long period, and today, quite sophisticated methods are available for locating faults in underground cables [1]. At the present time, the preferred method of location is the pulse-echo technique, which is based on the time-domain reflectometry (TDR) principle [2]. A pulse stimulus propagates down the line and reflects whenever a change in impedance occurs. The set of information (stimulus, reflections), when recorded in the time domain, is called a reflectogram.

Today, the localization procedure—after a fault on a power cable has been detected—consists of the measurement of the delay between the stimulus (emitted pulse) and the reflection from the fault. This is done by a time-to-voltage conversion principle in the analog-based reflectometers or by a discrimination (even with interpolation) between the samples of a reflectogram in a digital fault detection unit [3]. The operator searches for the transition points of the pulses; i.e., the locations where the signals seem to "start."

Unfortunately, the echoes in a reflectogram do not just appear as "scaled down" versions of the stimulus, but are considerably distorted. This is due to the characteristics of (power) cables at high frequencies [4] and to the behavior of cable faults under impulse conditions [2]. Most parameters of a transmission line vary in a nonlinear way with frequency, and hence, the phase of the spectral components of the applied pulses is strongly affected.

The transmission lines causes a dispersion and attenuation of the observed reflections in the time domain. The sharp transitions at the start locations of the signals are smoothed so that the measurement process is strongly related to subjective interpretation. Because of this, the actual measurement accuracy is limited to approximately 5 m for power cables up to 1 km in length. Pulse-echo testers are, therefore, used only for the rough location of faults, and the precise location is generally confirmed by an acoustic method [2].

The question is whether it is possible to avoid the human interpretation in the measurement process by automation and signal processing, and whether it is possible to improve the accuracy of the fault location estimation. Automated location of a discontinuity using a digitized sequence of measured data, i.e., the measurement of the distance between the instrument and a fault, therefore, requires a detection and localization algorithm. To attain the goal of automated objective localization of faults on power cables, a parameter estimation technique is proposed. To investigate the influence of the nonlinearities of the transmission line parameters, a validated model of the electrical line was established [5], which enables the simulation of a reflectogram. Thus the development of optimal estimators for the fault distance parameter using these models becomes possible. Distortions due to the skin-effect (planar and cylindrical approximations, see [6], [7]) and dielectric losses of the line are incorporated.

The main advantage of the algorithm that is described is that it estimates some parameters from the recorded (al- liaised) data with a minimal bias without estimating all the parameters of the system. The propagation speed of the signals in the cable must be known. Then, only the fault-distance parameter is extracted from the acquired measurement data. In some cases, e.g., multiphase lines with a sound, noncorrupted conductor, this method can also be used to estimate the propagation speed. It is shown, furthermore, that this method is also extremely efficient to characterize transmission lines [9], [10].

II. THEORY

A transmission line of finite length \( z \), terminated by an impedance \( Z_L \) and stimulated by a generator with internal impedance \( Z_e \) is assumed (see Fig. 1). The response to a certain stimulus applied to the electrical line is given in the frequency domain by

\[
G(\omega) = \frac{H(\omega)}{2} \cdot \frac{(1 + \rho_2) \cdot (1 + \rho_1 e^{-2iz})}{(1 + \rho_1 \rho_2 e^{-2iz})} \tag{1}
\]
The principal idea of the "Pecstrum" estimator is to process the reflectograms so that an objective approach both in the modeling procedures as well as in the validation of the data generated afterwards [5], [9], [12]. The development of fault locating estimators, therefore, requires an alternative approach both in the modeling procedures as well as in the validation of the data generated afterwards [5], [9], [12].

The principal idea of the "Pecstrum" estimator is to obtain a single, well pronounced line in the "quefrency" domain [8], [13], [14] indicating the location of the fault. To achieve this, one should manipulate the reflectogram in a rational way. Firstly, in the "Pecstrum" technique the evolution of a vector, obtained from the processed transfer function in the frequency domain and different from the one used in the "Cepstrum" approach, is observed [8], [13] (for proof see Section III.). Secondly, the "Pecstrum" algorithm does not treat the entire sequence of sampled data but uses an adequate windowing technique; i.e., the stimulus and reflections are cut out of the reflectogram and placed into separate time windows (Dirichlet type [15]). This is possible since, under normal conditions, reflections appear separated in time. If the applied pulses are too long, or if the discontinuities are separated by short distances, then the pulses are interwoven. Extraction algorithms may be used to separate mixed pulses (shape reconstructors [9] and homomorphic deconvolution [9], [13], [14]). Special efforts are made to correctly calculate the spectra of the pulse waveforms of the stimulus and of the reflection(s). This means that the errors introduced by an fast Fourier transform (FFT) algorithm, used to compute the discrete Fourier transform (DFT) in the digital instrument have to be compensated. This is not trivial since pulse signals are not band limited, so that aliasing always occurs. However, the use of validated models for the pulses generated, i.e., finding appropriate analytic time functions for the description of the stimuli and the calculation of the Fourier integral instead of the DFT, which enables a correct computation of the spectrum, allows an a posteriori correction of the results of the FFT by the means of a digital finite impulse response (FIR) filter [9]. This digital, a posteriori, anti-aliasing filtering has proved to be very successful [5], [12]. To improve the frequency-domain resolution, zeros are appended to the windowed pulses. Here one must take care to avoid signal discontinuities at the borders of the time windows. Leakage errors would otherwise occur [15] which would further falsify the expected spectra. As an example of a modeled pulse, one might consider the following analytic function:

\[
 h(t) = A \cdot e^{-\gamma t} \quad t \geq 0
\]

\[
 h(t) = 0 \quad t < 0
\]

where \( A, B, n \in \mathbb{R}_0 \). In the case where \( n = 1 \) the spectrum is obtained easily as

\[
 H(\omega) = \frac{A}{|B + j\omega|^2}. \tag{3}
\]

The parameters \( A \) and \( B \) are adjusted to choose the amplitude and transition duration of the applied pulse \( h(t) \). However, one can immediately see that the simple case \( n = 1 \) is not very realistic since a discontinuity already occurs in the first derivative of \( h \) with respect to \( t \) at the origin. When windowed with a Dirichlet-kernel [15] and when the operation \( \mathcal{F}^{-1} (\hat{g}(h(t))) \) is performed using an FFT, a nonsmooth curve is obtained if the origin \( (t = 0) \) does not coincide with a sample period. Instead strong oscillations are observed [9].

III. "Pecstrum"

The "Pecstrum" algorithm is now explained very briefly. If the high frequency approximation is accepted
for the phase factor of the line [4] and if the generator is matched to the electrical line under test (most reflectometers match the generator for high frequencies using an adjustable resistor), then the transfer function of the system in Fig. 1 becomes, from (1)

$$\frac{G(\omega)}{H(\omega)} = \frac{1}{2} [1 + \rho_1 e^{-2\gamma \tau}] \quad (4)$$

where $\rho_1 = 0$, $\gamma = \alpha + j \omega / \nu$ and $\nu$ is the propagation speed of the signals. This can be rewritten as

$$\frac{2G(\omega)}{H(\omega)} - 1 = \rho_1 \cdot e^{-2\omega \tau / \nu} \cdot e^{j2(\omega \tau / \nu)} \quad (5)$$

The desired unknown parameter is $z$, whereas $\alpha$ and $\rho_1$ are unknown functions of $\omega$. Nevertheless, the left-hand side of (5) can be computed from the measured windowed data, $h(t)$ and $g(t)$. Dividing (5) by its modulus then results in:

$$\left| \frac{2G(\omega)}{H(\omega)} - 1 \right| = e^{-2(\omega \tau / \nu)} \quad (6)$$

The application of a second Fourier integral on (6), transforms the frequency domain into the quefrency domain, resulting in:

$$\mathcal{F}(e^{-2\omega \tau / \nu}) = \delta(\tau - 2 \frac{z}{\nu}) \quad (7)$$

The Dirac-distribution obtained has an argument, which is directly proportional to the unknown distance $z$. To show the advantage and the superiority of the "Pecstrum" over the "Cepstrum," both algorithms are applied to the same noiseless reflectogram model. In Fig. 2, the "Cepstrum" generates a broad peak of low "gammitude" in the "quefrency" domain. The maximum corresponds with the location of the fault. However, it should be noticed that the logarithmic operator in the "Cepstrum" has been omitted, since it was demonstrated [9] that the "Log-Cepstrum" performs less well as a spectral lifter in these cases. The expected peaks are indeed much smaller with the "Log-Cepstrum" and are, for small reflection factors, buried in the exponentially decreasing function.

In Fig. 3 the "Pecstrum" algorithm is applied to the same reflectogram as in Fig. 2. One can see that a very sharp peak is obtained at the expected location of the fault. The "gammitude" of the peak is always equal to 1 and the decreasing function, as in the case of the "Cepstrum," is absent. This enables us to detect and locate faults which occur very close to the generator. In the case of the "Cepstrum," those faults might generate non-detectable peaks in the "quefrency" domain.

Some remarks must be made when attempting to apply the "Pecstrum" technique in practice. The assumptions made to obtain formula (6) are too strong, and hence, direct application of (6) will not yield sufficient results. The precautions, such as alias correction, zero appending, interpolation of the FFT [11] etc., which are mentioned above, were necessary to correct the "Pecstrum." As is mentioned earlier, the "Pecstrum" will not treat the reflectogram entirely, which is suggested by (6) and (7). Instead, the time functions $h(t)$ and $g(t)$ are extracted from the reflectogram and the "Pecstrum" algorithm computes the delay between the two windowed functions. Since the location of the time windows is known exactly (a multiplication factor of the sample period), an extra delay is added to obtain the final result for $z$.

The additional computations in the practical "Pecstrum" modify the expected Dirac-distribution (side lobes are introduced), but the maximum of the "pecstral" function is still a very good estimate of the distance to the fault (see Fig. 4). The vertical line in Fig. 4 indicates the exact location of the fault. The computed maximum is quite close to the expected one.

**IV. RESULTS**

Several results were obtained. For cable fault locations, accuracies up to 30 cm were obtained when a 20 MHz–8 bit sampler was used for the acquisition of the pulse sig-
nals in the reflectogram. Several signal processing techniques were implemented to eliminate aliasing (since no analog filter was provided). A prototype was built using a M68000 microprocessor as a "number cruncher" (slave) for the treatment of the reflectogram. The acquisition of the signals and the display on a monitor was achieved with a TRW 30 MHz-8-bit TDC 1007-J ADC and was controlled by a M6809 microprocessor (master). The first version was already operational in 1983. The average computation time for the complete location procedure of a cable-fault is about 2.5 s and the accuracy is better then 50 cm for cable lengths up to 2 km. Calculations are performed using floating point (FFT included) and code generation is done by a MODULA-2 compiler on a CDC-Cyber machine.

For the new generation of digital fault-locators, computer-aided fault locator (CAF) from the German company SEBA Dynatronic, an adapted "pecstral" analysis program was written in C on an IBM-compatible PC (M24SP Olivetti). The sequentially sampled data, together with the instrumentation setup information is read into the PC using the serial RS-232 link. The combination of these reflectometers (CAF-α, δ or η) and the PC has improved the accuracy significantly (see Table I and Fig. 5). In Fig. 5 the accuracy of the digital fault locator CAF-δ is compared with the results of "pecstral" analysis applied to the same reflectograms. As one can see, an overall improvement with an averaged factor of 4.7 is obtained. In the next generation of its reflectometers, SEBA will offer "pecstral" analysis as a feature. At present, efforts are being made in the laboratory to implement automatic fault-detection algorithms. These algorithms are based on AI methods and generate the most probable reasons for the nature of faults as well as their locations.

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