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Method to Improve Fault Location Accuracy Against Cables Dispersion Effect

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Abstract—The paper presents a new method of dispersion compensation. It aims to reduce the dispersion effect of the wave throughout its propagation in the cable. The main objective is to improve the defects localization accuracy in electrical cables. This suggested method can be applied to any test signal injected in the line under test.

1. INTRODUCTION

Cables are present in almost all modern systems. Independent of their application domain, they can be exposed to aggressive environments that can create defects and therefore serious consequences [1]. Reflectometry methods are among the most commonly used methods for wire diagnosis [2]. In this study, we focus our work on Multi-Carrier Time Domain Reflectometry (MCTDR) method [3].

During its propagation in the cable, the signal is affected by two main phenomena: attenuation and dispersion. The attenuation of the signal is related to the conductance of the dielectric materiel (loss tangent effect) and the linear resistance of the cable (joule effect losses) which increases with the frequency. The dispersion is caused by the fact that all the signal frequencies do not propagate at the same speed [4]. Attenuation and dispersion are limits of the reflectometry methods. They lead to a deformation of the reflected signal and make the fault localization inaccurate. This letter overcomes the existing methods and reflectometry's limitations by proposing a new approach to compensate the dispersion undergone by the signal during its propagation. It aims to improve the faults localization accuracy.

2. MCTDR REFLECTOMETRY

MCTDR method [3] models the test signal as a sum of a finite number of sinusoids in order to enable a precise control of the spectrum of the injected signals. The test signal has the following form:

$$s_n = \frac{2}{\sqrt{N}} \sum_{k=0}^{N/2} c_k \cos\left(\frac{2\pi k}{N} n + \theta_k\right) \tag{1}$$

where c_k and θ_k represent respectively the amplitude and phase of the subcarrier k; N is the carriers number; and n is the sampling index. Its Fourier transform (positive frequencies), with a digital system operating at the sampling frequency $f_e = 1/T_e$ and DAC output, is given by:

$$X(f) = \operatorname{sinc}(\pi f T_e) \sum_{n=0}^{M-1} \sum_{k=0}^{N/2-1} c_k e^{j\theta_k} \delta\left(f - \left(\frac{k}{N} + n\right) f_e\right) \tag{2}$$

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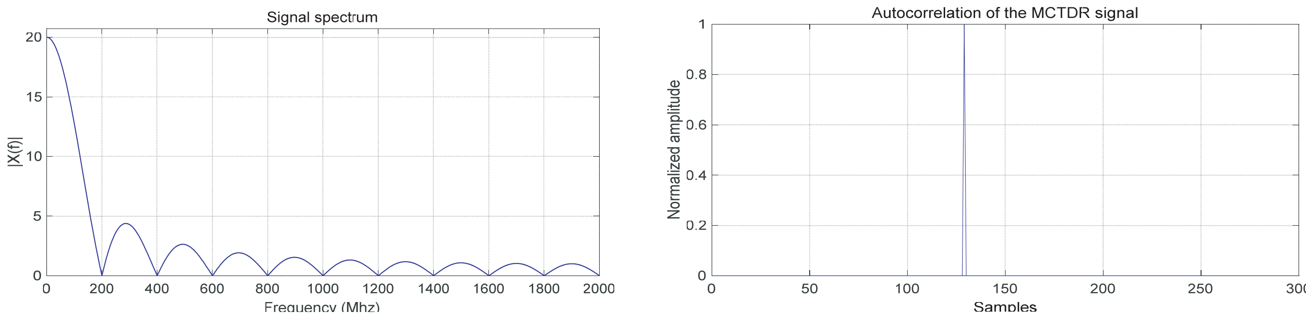

(a) (b)

Figure 1. MCTDR signals: (a) signal spectrum and (b) autocorrelation.

where M represents the number of lobes of the MCTDR spectrum. Moreover, it has good autocorrelation properties allowing a good accuracy of defects localization. Figure 1(a) represents $|X(f)|$ as a function of the frequency. Figure 1(b) shows the autocorrelation of the injected signal which is obtained as follows:

$$R_{xx} = F^{-1}\left\{|X(f)|^2\right\} \tag{3}$$

where F^{-1} is the inverse Fourier transform.

3. CABLE RESPONSE

Cable response is given by cable losses and all impedance discontinuities. Figure 2 gives information about the propagation behaviour of the signal along the cable (with length L and impedance Z_c) and the amount of energy returned to the source.

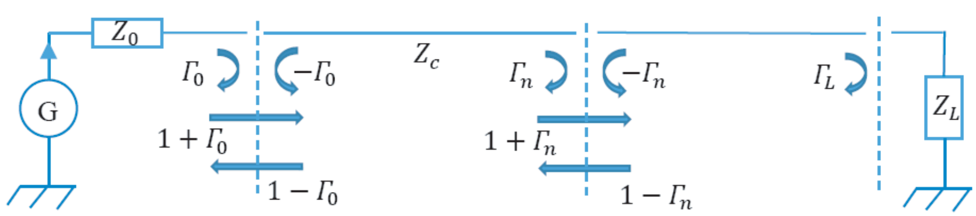

Figure 2. Reflection (Γ_i) and transmission ($1-\Gamma_i$) coefficients related to cable faults.

Z_0 is the source impedance, and Z_L is the load impedance.

Each cable fault is associated with a reflection coefficient. For an impedance discontinuity Z_n, it is given as following:

$$\Gamma_n = (Z_n - Z_c)/(Z_n + Z_c) \tag{4}$$

After passing through the wired network, the injected signal $X(f)$ in the frequency domain becomes:

$$Y(f) = X(f)H(f) \tag{5}$$

Similar to radar, reflectometry injects a wideband test signal into the cable under test. This signal propagates along the cable. Each mismatch encountered (such as junctions, connector, and defects) reflects a part of its energy back to the injection point, and the other part continues to propagate as shown in Figure 2. We thus simultaneously exploit the reflected part of the cable transfer function H, noted H_1 and the transmitted part noted H_2. The analysis of the reflected part is then used to locate the fault, and the transmitted part is used to estimate the propagation celerity.

The cable transfer function H_1 of reflected part of the signal, if ignoring multiple echoes, is written as follows:

$$H_1(f) = \sum_{j=1}^{N} \Gamma_j \prod\nolimits_i \left(1 - \Gamma_i^2\right) e^{-2\gamma(f) l_j} \tag{6}$$

Γ_j, Γ_i represents the reflection coefficients of impedance discontinuities j and i, respectively. The default Γ_j depends on all the previous defects $\Gamma_i\,(j > i)$. l_j is the impedance discontinuities position.

The cable transfer function H_2 of transmitted part is given by:

$$H_2(f) = \prod\nolimits_i (1 - \Gamma_i)\, e^{-\gamma(f) L} \tag{7}$$

γ is the propagation constant, depending on frequency f, given by:

$$\gamma(f) = \alpha(f) + j\beta(f) \tag{8}$$

where α represents the attenuation of the wave amplitude during its propagation, and β represents the wave phase rotation.

4. ANALYTIC MODELS

In general, a line is dispersive when the propagation celerity (v_p) depends on the frequency as following:

$$v_p(\omega) = \omega/\beta(\omega) \tag{9}$$

where $\omega = 2\pi f$ angular frequency (rad/s).

This makes the injected pulse reflected as spread impulse (Figure 3). Consequently, the location of the fault is less accurate.

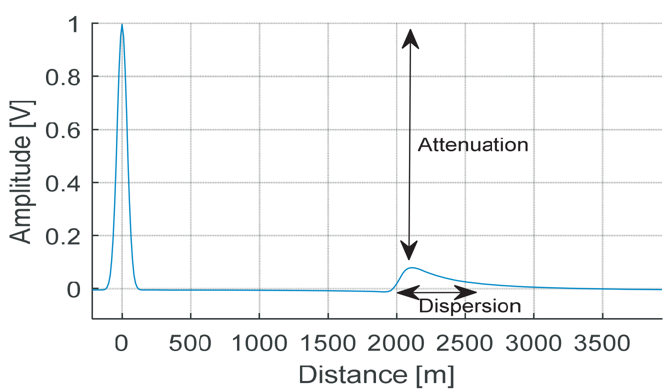

Figure 3. Dispersion and attenuation of the test signal.

The compensation of the dispersion includes the following steps:

(1) Estimate the propagation celerity $v_p(f)$ in the cable.

(2) Make a first injection (without dispersion compensation) of the test signal into the cable: fault position estimation.

(3) Make a second injection of the test signal by compensating the dispersion undergone by the signal at the fault position pre-estimated in step (2): fault position correction.

4.1. First Step — Estimate the Propagation Celerity

The authors in [5] have proposed a new distributed diagnosis method for complex wire networks to ensure the communication between sensors. However, to estimate the propagation celerity, we are interested in the transmitted part of the test signal after passing through the wired network. The received signal following the injection of MCTDR signal is given by:

$$Y(f) = X(f)H_2(f) \tag{10}$$

$$= \operatorname{sinc}(\pi f T_e)\, e^{-\alpha l} \prod_i (1-\Gamma_i) \sum_{n=0}^{M-1} \sum_{k=0}^{N-1} c_k e^{j(\theta_k - \beta l)} \delta\left(f - \left(\frac{k}{N} + n\right) f_e\right) \tag{11}$$

where $M = 1$, because the phases sequence θ_k is transmitted on the main lobe of the MCTDR spectrum which contains major part of the energy.

The phase of this signal is given by:

$$\arg(Y(f)) = -\beta(f)L + \sum_{k=0}^{N-1} \theta_k \delta\left(f - \frac{k}{N} f_e\right) \tag{12}$$

We note that $Y(f)$ depends on $\{\theta_k\}$. Therefore, to estimate the propagation speed, we make a first measurement (Y_0) by sending a zeros phases sequence $\{\theta_k\} = \{0\}$.

$$\operatorname{phase}(Y_0(f)) = -\beta(f)L \quad \text{with} \quad \beta(f) = \omega/v_p(f) \tag{13}$$

The estimated speed obtained is:

$$V_{\text{estimated}}(f) = -\omega L / \arg(Y_0(f)) \tag{14}$$

4.2. Second Step — Fault Position Estimation

In the case of a single fault in the cable, H_1 becomes as follows:

$$H_1(f) = \Gamma_d e^{-2\gamma(f) l_d} \tag{15}$$

where Γ_d is the fault reflection coefficient, and l_d is the fault position.

The measured reflected signal in the frequency domain is given by:

$$Y(f) = X(f)H_1(f)$$

$$= \operatorname{sinc}(\pi f T_e) \sum_{n=-\infty}^{+\infty} \sum_{k=0}^{N-1} c_k e^{j\theta_k} \delta\left(f - \left(\frac{k}{N} + n\right) f_e\right) \cdot \Gamma_d e^{-2\gamma(f) l_d} \tag{16}$$

Unlike first step, here "n" is between $-\infty/+\infty$ because we need the complete MCTDR spectrum to make the diagnosis and build the reflectogram.

From Eqs. (12) and (7), $H_1(f)$ becomes:

$$H_1(f) = \Gamma_d e^{-2\alpha(f) l_d} e^{-2\frac{\omega}{v(f)} l_d} \tag{17}$$

where $e^{-2\alpha(f) l_d}$ represents the attenuation impact and $e^{-2\frac{\omega}{v(f)} l_d}$ the dispersion one. We note that the propagation celerity in the dispersion term depends on the frequency, which can lead to a fault position error noted Δx.

We can write:

$$\frac{l_d}{v(f)} = \frac{l_d + \Delta x}{v_m} \rightarrow e^{-2\frac{\omega l_d}{v(f)}} = e^{-2\frac{\omega(l_d + \Delta x)}{v_m}} = e^{-2\omega\frac{l_d}{v_m}} \cdot e^{-2\omega\frac{\Delta x}{v_m}} \tag{18}$$

where v_m is the average propagation celerity.

The equation of reflected signal in frequency becomes:

$$Y(f) = \operatorname{sinc}(\pi f T_e) \sum_{n=-\infty}^{+\infty} \sum_{k=0}^{N-1} c_k e^{j\theta_k} \delta\left(f - \left(\frac{k}{N} + n\right) f_e\right) \Gamma_d e^{-2\alpha(f) l_d} e^{-2\omega\left(\frac{l_d + \Delta x}{v_m}\right)} \tag{19}$$

From Eq. (18), the cable fault is localized with accuracy error $\Delta x / v_m$.

4.3. Third Step — Fault Position Correction

The proposed dispersion compensation method consists in replacing $v(f)$ with v_m (average speed) to ensure that the signal frequencies propagate at the same speed.

The injected signal $X(f)$ is replaced by:

$$X_1(f) = X(f)G(f) \tag{20}$$

$G(f)$ is the compensation dispersion term.

$$G(f) = e^{j4\pi f_e \frac{k}{N}\left(\frac{1}{v(f)} - \frac{1}{v_m}\right) l_{est}} \tag{21}$$

where $l_{est} = (l_d + \Delta x)$ represents the fault distance from injection point, and Δx is the fault position error.

The reflected signal in frequency domain, whose propagation speed is independent of frequency, becomes finally:

$$Y(f) = X_1(f)H_1(f) \tag{22}$$

$$Y(f) = \operatorname{sinc}(\pi f T_e) \cdot \sum_{n=-\infty}^{+\infty} \sum_{k=0}^{N-1} c_k e^{j\theta_k} \delta\left(f - \left(\frac{k}{N} + n\right) f_e\right) e^{j4\pi f_e \frac{k}{N}\left(\frac{1}{v_{(f)}} - \frac{1}{v_m}\right)\Delta x} \cdot \Gamma_d e^{-2\alpha(f) l_d} e^{\frac{-2\omega}{v_m} l_d} \tag{23}$$

From Eq. (22), the fault position will be localized with accuracy error $(|1/v_m - 1/v_{(f)}|\Delta x)$. We note that the error obtained after dispersion compensation is smaller than that obtained without compensation.

$$|\Delta x/v_m - \Delta x/v(f)| < \Delta x/v_m \tag{24}$$

5. SIMULATION RESULTS

The efficiency of the new approach is evaluated with a simulation tool. We use a twisted pair wire (CVZ) cable model, 500 m length, with an open-circuit at its end, which is considered as a defect. Two injected signal types MCTDR signal (Figure 4) and Gaussian pulse (Figure 5) are used in our simulation. If we look at the location of the maximum peak of the curve, we find 508.5 m (relative error is 1.7%) for the reflectogram without dispersion compensation and 500 m with the compensation one. We note that the post-processing improves the fault location, and the relative error is equal to 0%.

Now, let's take the same example, with 2000 m instead of 500 m. If we look at the location of the peak maximum of the curve (Figure 5), we find 2177 m for the reflectogram without dispersion

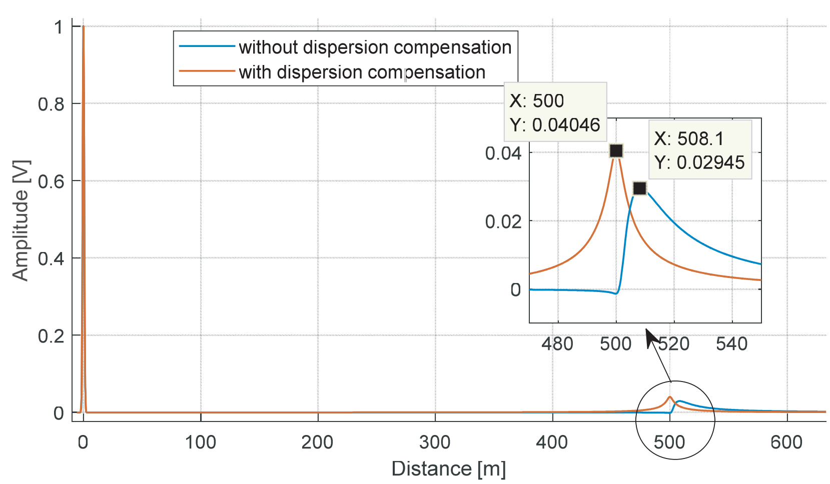

Figure 4. Simulation result for a 500 m length cable by injecting an MCTDR test signal ($f = 200$ MHz).

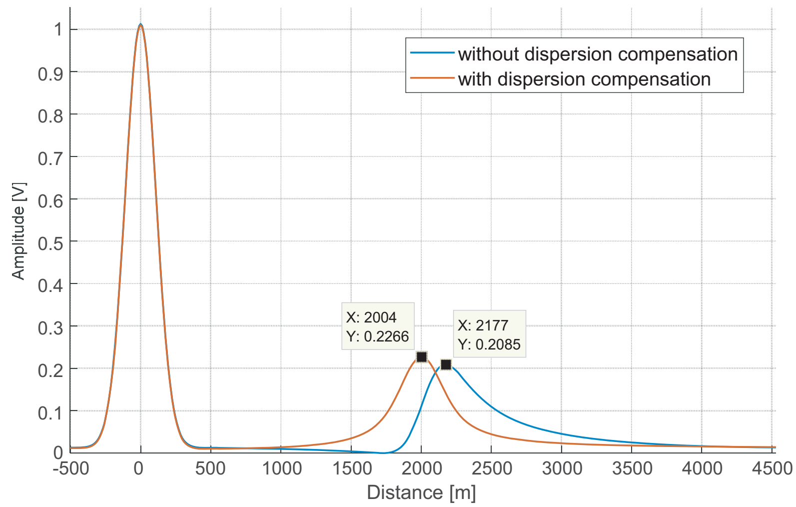

Figure 5. Simulation result for a 2000 m length cable by injecting a Gaussian pulse at the input (width at half height equal to 1 µs).

compensation and 2004 m for the compensation one. Our method result is very close to the real value of 2000 m (relative error is 0.2%).

Furthermore, we make a comparison with the dynamic cross-correlation method proposed by [6]. For the same cable model (2000 m length), we find 2004 m (relative error 0.2%) with the new approach and 2073 m (relative error 3.7%) with the dynamic cross-correlation method. We note that the new method improves the fault location accuracy.

Therefore, in the case of several faults in the cable, we proceed iteratively by improving the localization of the faults one by one. We can also note that the losses can be compensated by multiplying the received signal by $e^{2\alpha l_d}$, where l_d represents the distance of the detected fault from the injection point, and α is the linear attenuation parameter. Furthermore, the authors in previous work [5] show that the MCTDR test signal is reliable and robust against noise. The proposed method will not be affected by the measurement noise in the case where the fault peak amplitude is above the sensor detection threshold. However, it remains limited in the case where the fault peak amplitude is low and undetectable by the sensor, and it will be drowned in the measurement noise.

6. CONCLUSION

This paper presents a new post-processing approach which aims to compensate the dispersion effect of the wave during its propagation in the cable. The test results have shown the advantages of this new approach to have a localization of a defect with a better precision, especially over long distance cables. Accurate fault location would reduce the cost and time of maintenance. The intervention is not easy especially in the case of cables whose access is difficult. By knowing the fault type and location more accurately, a maintenance operator should be able to access to faulty cable to repair it and to avoid unnecessary interventions causing a loss in resources. In future works, we aim to apply this approach in the case of complex wired networks with experimental validation. We will also focus on techniques of data fusion and communication between different sensors for an optimized distrusted diagnosis using MCTDR test signal.

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