Inverse Scattering for Electrical Cable Soft Fault Diagnosis

Demonstrator Extended Abstract

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Abstract: The reliability of electrical connections becomes a crucial issue, because more and more connecting cables are involved in modern engineering systems. In this demo, the tested cable is a twisted pair of 10 meters, with faults created during the demo by locally untwisting the cable. Easily reparable for the purpose of demo, such geometrical deformations are soft faults, since they do not cause impedance discontinuity in the cable. A network analyzer connected to one end of the cable collects spectral data, which are processed by an algorithm in real time to estimate the characteristic impedance profile distributed along the cable. The faults created during the demo are detected, localized and quantified in real time through the estimated characteristic impedance profile. As the impedance estimation algorithm does not make any assumption about the shape of the characteristic impedance profile, this method is particularly suitable for the diagnosis of multiple and distributed faults. The demo will be shown in real time with a true cable connected to a network analyzer. A video is available online.

Keywords: Fault diagnosis, electrical cable, inverse scattering, reflectometry.

1. INTRODUCTION

The fast development of electronic devices is accompanied by more and more connecting cables. Though the probability of failure is small for each connecting cable, the reliability of electrical connections becomes a crucial issue because of their large numbers (Auzanneau, 2013). In this context, a promising technology for cable fault diagnosis is *reflectometry*, which consists in analyzing the reflection and the transmission of electrical waves observed at the ends of a cable. It has been reported that this technology is able to efficiently detect and to locate hard faults (severe impedance discontinuities, typically open circuit or short circuit). For soft faults, the problem is much more difficult, in particular when no impedance discontinuity is caused by such faults, as most methods for soft fault diagnosis are based on the detection of (relatively weak) impedance discontinuities (Kafal et al., 2016).

Recently, the *inverse scattering* theory has been applied to the reflectometry technology for cable soft fault diagnosis (Zhang et al., 2011; Tang and Zhang, 2011; Loete et al., 2015). By estimating the profile of the characteristic impedance distributed along a cable, this method is particularly efficient for the diagnosis of soft faults that do *not* imply impedance discontinuity. Without assuming any particular shape of the impedance profile of the monitored cable, it is well adapted to the case of multiple or spatially distributed faults. Its fast numerical computation is suitable for real time applications.

2. CABLE MODEL AND INVERSE PROBLEM

The telegrapher's equations are widely used as a mathematical model of electrical cables in engineering practice (Paul, 2008) :

$$\frac{\partial}{\partial z}v(t,z) + L(z)\frac{\partial}{\partial t}I(t,z) + R(z)i(t,z) = 0 \tag{1a}$$

$$\frac{\partial}{\partial z}i(t,z) + C(z)\frac{\partial}{\partial t}v(t,z) + G(z)v(t,z) = 0, \tag{1b}$$

where t represents the time, z is the longitudinal coordinate along the cable, $v(t,z)$ and $i(t,z)$ are respectively the voltage and the current in the cable at the time instant t and at the position z, $R(z), L(z), C(z)$ and $G(z)$ denote respectively the series resistance, inductance, capacitance and shunt conductance per unit length of the cable at the position z. As in typical cables $R(z)$ and $G(z)$ are very small (respectively at the order of 10^{-2} ohm and 10^{-9} siemens per meter), they are neglected in most studies for fault diagnosis.

In reflectometry, the geometrical coordinate z is often replaced by the wave propagation time from the position 0 to the position z, which is denoted by x and usually referred to as the coordinate in *electrical distance*. The transformation $z \to x(z)$ is invertible, so is the inverse transformation $x \to z(x)$. After this coordinate transformation, by neglecting the series resistance $R(z)$ and the shunt conductance $G(z)$, the telegrapher's equations (1) characterized by the 4 distributed parameters $R(z), L(z), C(z), G(z)$ are then reduced to a simpler form characterized by a single distributed parameter, the characteristic impedance

$$Z_0(x) \triangleq \sqrt{\frac{L(z(x))}{C(z(x))}}. \tag{2}$$

A common reflectometry instrument is the *network analyzer* that, when connected to one end of a cable, can measure its reflection coefficient $r(f)$ defined as

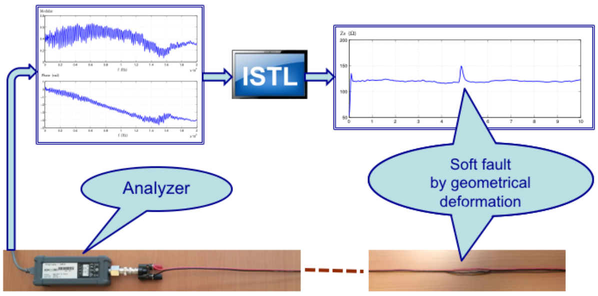

Fig. 1. Illustration of the demo setup.

$$r(f) \triangleq \frac{V(f,0) - Z_{\text{ref}} I(f,0)}{V(f,0) + Z_{\text{ref}} I(f,0)} \tag{3}$$

where f is the frequency, $V(f,0)$ and $I(f,0)$ are respectively the Fourier transforms of $v(t,0)$ and $i(t,0)$ (the voltage $v(t,z)$ and the current $i(t,z)$ at the position $z = 0$), and Z_{ref} is the reference impedance of the network analyzer (typically 50 ohm).

In the field of reflectometry, an important *cable inverse scattering problem* is the determination of the characteristic impedance profile $Z_0(x)$ along a cable from its reflection coefficient $r(f)$ measured at one end of the cable. The word "inverse" refers to the "direct problem" that is the simulation of reflectometry measurements for a given profile of $Z_0(x)$. Quite often "inverse problems" are much more difficult than "direct problems".

A method for solving this cable inverse problem, based on the inverse scattering theory, has been presented in (Zhang et al., 2011) and experimentally validated in (Loete et al., 2015). It is implemented in a software, ISTL (Inverse Scattering for Transmission Lines).

3. THE DEMO FOR REAL TIME FAULT DIAGNOSIS

The demo setup is illustrated in Figure 1. A two-wire cable (with parallel or twisted wires) is connected at one end to a network analyzer, which measures the reflection coefficient $r(f)$ of the cable. The reflection coefficient is processed by ISTL in real time to compute the characteristic impedance profile $Z_0(x)$, which is displayed on a screen.

The tested cable of 10m long (a twisted pair) is shown in Figure 2. The values of $r(f)$ are measured for f =1,2, . . . , 500MHz. The characteristic impedance $Z_0(x)$ is computed for the tested cable discretized at 1000 points, without any assumption about the shape of the profile of $Z_0(x)$.

The demo *repeats continuously* a cycle of operations involving data acquisition, computation of $Z_0(x)$, and display of the curve of $Z_0(x)$. Each cycle takes about 1 second, which is fast enough for real time fault diagnosis.

Soft faults are typically caused by chemical corrosion, overheating, mechanical wearing and geometrical deformation. In this demo, soft faults are artificially created by geometrical deformations (locally untwisting the twisted pair). Such deformations lead to local *smooth* variations of the cable characteristic impedance, and have the advantages of being reversible and easily operational in a real time demo. The effects of such created faults are displayed on the impedance curve with a delay of about 1 second. Figure 3 shows an example of locally untwisted cable, whose effect on the impedance curve is indicated by the solid red circle.

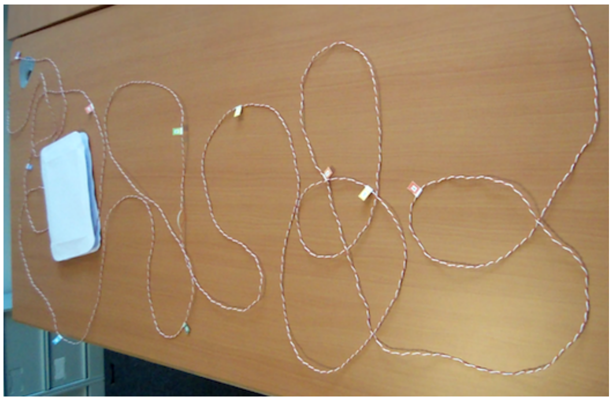

Fig. 2. A twisted pair cable of 10 meters.

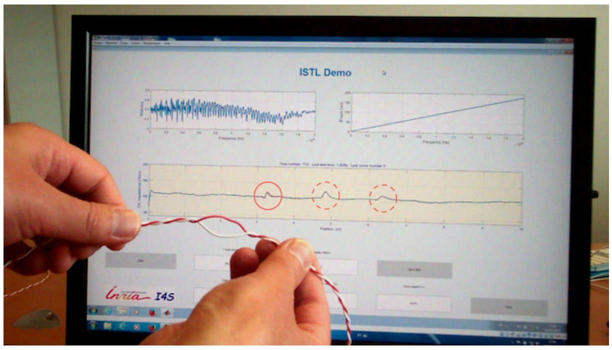

Fig. 3. Soft fault created by untwisting the cable and its effect on the impedance curve (in the solid red circle).

The abscissa indicates the position along the cable, and the ordinate the characteristic impedance. The other circles indicate the effects of two other similar faults.

The demo will be shown in real time with a true cable connected to a network analyzer. A video is available online (Zhang, 2016).

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