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Florent Loete, Qinghua Zhang, Michel Sorine

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F. Loete *. Q. Zhang. M. Sorine*****

* *GeePs | Group of electrical engineering – Paris, UMR CNRS 8507, CentraleSupelec, Univ Paris-Sud, Sorbonne Universités, UPMC Univ Paris 06, 11 rue Joliot Curie, Plateau de Moulon F91192 Gif sur Yvette CEDEX (e-mail: florent.loete@supelec.fr).*
*** INRIA Rennes, Campus de Beaulieu, 35042 Rennes, France (e-mail: Qinghua.Zhang@inria.fr).*
**** INRIA Rocquencourt, Domaine de Voluceau, 78153 Le Chesnay, France, (e-mail: michel.sorine@inria.fr).*

Abstract: Recently published theoretic and experimental results have shown the ability of inverse scattering-based methods to detect and to locate soft faults in electric cables, in particular, faults implying smooth spatial variations of cable characteristic parameters. The purpose of the present paper is to further experimentally evaluate the inverse scattering method for retrieving spatially distributed characteristic impedance from reflectometry measurements. With high quality coaxial cables connected in parallel, composite cables of piecewise constant characteristic impedance profiles are built in order to evaluate the accuracy of the inverse scattering method and its robustness in the presence of impedance discontinuities.

Keywords: Inverse scattering, cable health monitoring, soft fault diagnosis, frequency domain reflectometry.

1. INTRODUCTION

The number of wired connections in modern engineering systems has been rapidly increased during the last decades, to the point that the reliability of electrical connections becomes a crucial issue. For example, in a modern automotive vehicle, the total length of on-board cables can reach up to 4 km. These cables, composed of twisted pairs, coaxial cables and simple wires, are subject to aging or degradations caused by severe environmental conditions. In this area, reliability becomes a safety issue. In some other domains, cable defects may have catastrophic consequences (Furse et al. [2006]). It is thus a crucial challenge to design smart embedded diagnosis systems able to detect wired connection defects in real time. This fact has motivated research projects on methods for fault diagnosis in electric transmission lines.

Many diagnosis methods based on Time or Frequency Domain Reflectometry (TDR or FDR) have been developed to detect, locate and characterize defects in electrical harnesses (Furse et al. [2005], Lelong et al. [2008], Smail et al. [2010], Furse et al. [2003], Smith et al. [2005], Furse et al. [2002], Chung et al. [2005], Loete et al. [2012a]). These methods are based on the same principle as radar technology, but applied to guided waves in electric cables. A high frequency electrical signal is sent down a cable, where it is reflected at impedance discontinuities or at other inhomogeneities along the cable. The reflected wave is analyzed to detect, locate and characterize the defects. It has been reported that this technology is able to detect and to locate hard faults (open or short circuits) up to an accuracy of about 3 cm (Smith et al. [2005]). On the other hand, it is a much more difficult problem to deal with soft faults which imply only slight and localized characteristic impedance changes in electric cables. Some recently reported methods amplify fault signatures to improve the detection of the small echoes caused by soft faults (Franchet et al. [2011], Franchet et al. [2012], El Sahmarany et al. [2012a,b], Abboud et al. [2012], Abboud et al. [2013]). However, to our knowledge, few satisfactory experimental results on reflectometry-based methods for the diagnosis of such *soft faults* have been reported (Loete et al. [2012a]), (Loete et al. [2012b]).

The characteristic impedance Z_0 is the main parameter characterizing an electric cable. When a healthy and uniform cable is considered, the characteristic impedance is usually specified as a single value for the whole cable. In order to deal with localized defects, it is necessary to consider distributed characteristic impedance all along the cable, denoted as $Z_0(x)$ with x indicating the position along the cable in some coordinate system.

In traditional reflectometry-based methods, the reflected waveforms are visualized and analyzed in the time domain (TDR) or in the frequency domain (FDR), and sometimes a mixture of them is used. As these methods do not directly analyze the characteristic impedance of the cable, it may be difficult to interpret their results for soft faults diagnosis, in particular when such faults cause only small variations of the characteristic impedance along the cable. It is thus useful to develop inverse methods retrieving the spatially distributed characteristic impedance profile from reflectometry measurements (in opposition to direct methods simulating reflectometry measurements from specified cable characteristics), but few methods of this nature have been reported (Smail et al. [2011]). The inverse scattering theory

(Jaulent [1982]) provides a powerful theoretic framework for the estimation of distributed characteristic impedance from reflectometry measurements, in particular for smoothly varying characteristic impedance profiles along cables. Based on this theory, the ability of directly visualizing and analyzing the distributed characteristic impedance of a cable represents an important progress in the interpretation and processing of reflectometry measurements, notably for the purpose of soft fault diagnosis.

The theoretic study and numerical simulations reported in Zhang et al. [2011] and Tang et al. [2011] have shown that the inverse scattering method is a promising tool for soft fault diagnosis through the estimation of distributed characteristic impedance. The experimental results reported in Loete et al. [2012b] have confirmed the ability of this method for detecting and locating soft faults. In these experiments, the tested twisted pair cable is untwisted at a small portion in order to create a smooth local variation of the characteristic impedance. Such experiments provide a simple solution for hard wire simulation of soft faults, but it is not easy to accurately control the characteristic impedance profile of the untwisted portion in order to evaluate the accuracy of the inverse scattering method.

The purpose of the present paper is to evaluate the accuracy of the method through new experiments designed with parallel coaxial cables whose characteristic impedances are known with a good accuracy. As in theory the inverse scattering method assumes smooth characteristic impedance profiles, the piecewise constant characteristic impedance profiles used in the experiments realized with coaxial cables allow to evaluate the robustness of the method when the smoothness assumption is not satisfied.

This paper is organized as follows. After briefly recalling in Section 2 the inverse scattering method for electric cable monitoring, experimental results with coaxial cables will be presented in Section 3 to evaluate the accuracy and the robustness of the inverse scattering method. Section 4 then concludes the paper.

2. THE INVERSE SCATTERING METHOD

This section shortly recalls the inverse scattering method for lossless cables. More details can be found in Zhang et al. [2011]. For the electric cables of less than 10 meters studied in this paper, losses are neglected. A lossless cable driven by a harmonic voltage wave can be modeled by the frequency domain telegrapher's equations

$$\frac{d}{dz} V(k,z) - ik\, L(z) I(k,z) = 0 \tag{1a}$$

$$\frac{d}{dz} I(k,z) - ik\, C(z) V(k,z) = 0 \tag{1b}$$

where k is the angular frequency (denoted so because it is strongly related to the wavenumber in the inverse scattering theory), z indicates the position along the cable, $V(k,z)$ and $I(k,z)$ denote the voltage and the current of frequency k at the position z, $L(z)$ and $C(z)$ are distributed inductance and capacitance along the cable; i is the imaginary unit. The boundary conditions associated to (1) represent a generator at the left end and a load at the right end of the cable.

Define the electrical distance, the characteristic impedance, the reflected and direct power waves, as follows[1]

$$x(z) = \int_0^z \sqrt{L(s)C(s)}ds, \quad x \in [0,l]$$

$$Z_0(x) = \sqrt{\frac{L(x)}{C(x)}} \tag{2}$$

$$\nu_1(k,x) = \frac{1}{2}\left(Z_0^{-\frac{1}{2}}(x)V(k,x) - Z_0^{\frac{1}{2}}(x)I(k,x) \right) \tag{3a}$$

$$\nu_2(k,x) = \frac{1}{2}\left(Z_0^{-\frac{1}{2}}(x)V(k,x) + Z_0^{\frac{1}{2}}(x)I(k,x) \right) \tag{3b}$$

Some direct computations then lead to the following *Zakharov-Shabat* equations (Jaulent [1982]):

$$\frac{d\nu_1(k,x)}{dx} + ik\nu_1(k,x) = q(x)\nu_2(k,x) \tag{4a}$$

$$\frac{d\nu_2(k,x)}{dx} - ik\nu_2(k,x) = q(x)\nu_1(k,x) \tag{4b}$$

where

$$q(x) = -\frac{1}{4}\frac{d}{dx}\left[ln\frac{L(x)}{C(x)}\right] = -\frac{1}{2Z_0(x)}\frac{d}{dx}Z_0(x) \tag{5}$$

At the left end (corresponding to $x = 0$), the reflection coefficient $r(k) = \nu_1(k,0)/\nu_2(k,0)$ is typically measured with a network analyzer. It is known (Zhang et al. [2011]) that the characteristic impedance $Z_0(x)$ can be computed from $r(k)$ measured at the left end of the cable through the following steps:

1. Compute the Fourier transform of the reflection coefficient $r(k)$

$$\rho(x) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} r(k)\exp(-ikx)\, dk$$

2. Solve the integral equations (known as Gel'fand-Levitan-Marchenko equations) for their unknown kernels $A_1(x,y)$ and $A_2(x,y)$:

$$A_1(x,y) + \int_{-y}^{x} A_2(x,s)\, \rho(y+s)ds = 0$$

$$A_2(x,y) + \rho(x+y) + \int_{-y}^{x} A_1(x,s)\, \rho(y+s)ds = 0$$

3. Compute the potential function $q(x)$ through

[1] $x(z)$ is a monotonic (and thus invertible) function, corresponding to the inverse function $z(x)$. By abuse of notation, $V(k,z(x))$ will be simply written as $V(k,x)$, so will other similar notations depending on $z(x)$.

$q(x) = 2A_2(x,x)$

4. By solving equation (5) for $Z_0(x)$, compute

$$Z_0(x) = Z_0(0)exp\left(-2\int_0^x q(s)\, ds\right)$$

where $Z_0(0)$ is equal to the internal impedance of the signal generator connected to the left end of the cable (typically integrated in a network analyzer).

3. EXPERIMENTAL EVALUATION OF THE INVERSE SCATTERING METHOD

Since equation (4) contains the spatial derivative of the characteristic impedance, it is assumed in theory that $Z_0(z)$ is derivable. Consequently, the inverse scattering method presented in section II is, in theory, limited to smooth characteristic impedance profiles, thus excluding the case of impedance discontinuities. The ability of the inverse scattering method for detecting and locating characteristic impedance smooth variations has been experimentally validated Loete et al. [2012b]. However, impedance discontinuities are frequently present in practice, typically at the connection between the network analyzer and the tested cable if there is an impedance mismatch or at the junction between several branches. The aim of this section is to study the robustness of the inverse scattering method in presence of impedance discontinuities and to quantify its accuracy in such situations.

The experiments presented in this section are designed with 50 Ω coaxial RG-58 cables with low loss characteristics. They also have good noise immunity, and a well-controlled spatially homogeneous 50 Ω characteristic impedance. The tested configurations are very simple, but they are in no way favorable to the inverse scattering method, because of impedance discontinuities. The accuracy of the characteristic impedance of the coaxial cables allows us to quantitatively evaluate the error of the inverse scattering method. The measurements are carried out over the 4 MHz – 2204 MHz bandwidth with 4 MHz frequency steps.

Coaxial cables will be used to build composite lines with piecewise constant characteristic impedance profiles. However, the applied inverse scattering algorithm is exactly the same one as in the previous section, which does not assume piecewise constant characteristic impedance profiles.

Remark that this study is for the purpose of evaluating accuracy and the robustness of the inverse scattering method at the presence of the impedance discontinuities. The fact that the tested cable has a piecewise constant characteristic impedance profile is ignored by the inverse scattering method, which has been designed for arbitrary smooth characteristic impedance profiles. In practice if it is known in advance that the cable has a piecewise constant characteristic impedance profile, some other methods designed for this particular case may be more appropriate. However, the piecewise constant profile assumption is not reasonable if the tested cable is possibly affected by soft faults.

3.1 Characteristic impedance drop on a single segment

Two identical 50 Ω coaxial cables in parallel (Fig. 1) are used as an equivalent cable of 25 Ω. Similarly, three and four identical cables in parallel form respectively equivalent 16.67 Ω and 12.5 Ω cables. Such a composite segment is then connected to simple 50 Ω coaxial cables as shown in Fig. *1* and illustrated in Fig. 2, in order to build a cable with piecewise constant characteristic impedance. The advantage of this configuration is the accuracy of the characteristic impedance (50 Ω, 25 Ω, etc.) in each segment, based on the high quality coaxial cables used in the experiment.

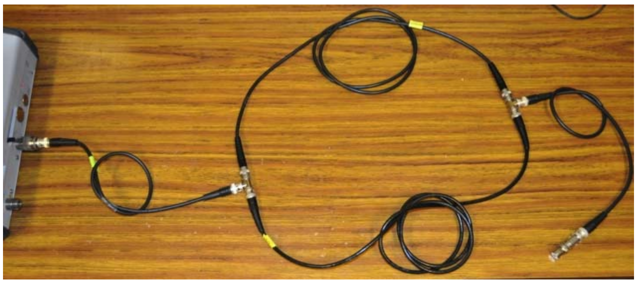

Fig. 1. Composite line including two RG-58 50 Ω coaxial cables in parallel.

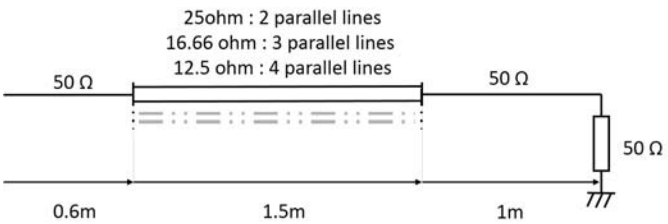

Fig. 2. Topology of the composite lines used. Equivalent cables of characteristic impedance smaller than 50 Ω are realized by putting multiple 50Ω coaxial cables in parallel.

Fig. 3 shows the inverse scattering results carried out on the cables illustrated in Fig. 2. The location of the impedance discontinuities, as well as the impedance level of the composite segment, are estimated with a good accuracy. Nonetheless, one can see some artifacts in the part immediately following the segment composed of parallel cables, especially for strong impedance discontinuities. It is possible to remedy this drawback by increasing the bandwidth of the reflectometry measurements, but in practice the network analyzer has a limited bandwidth. By adding zeros to complete high frequency measurements (zero padding), these artifacts are also reduced, because the inverse scattering algorithm then uses a smaller integration step size. For example, in one of the experiments, the same reflection coefficient is processed twice by the inverse scattering method, first with zero padding up to 15 GHz and then up to 30 GHz. The results are shown in Fig. *4* confirming that a higher zero padding improves the result. However, the practice of zero padding is limited by the computer memory size when the data are processed. The results shown in Fig. 3 have been obtained with zero padding up to 30 GHz.

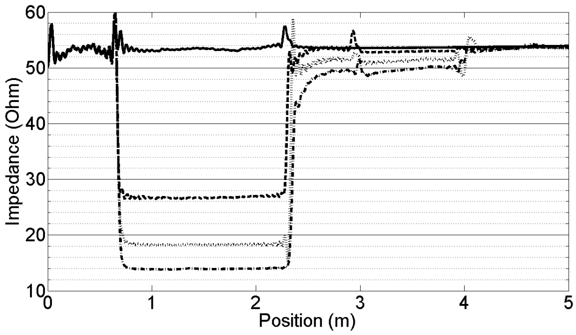

Fig. 3 $Z_0(z)$ profiles obtained by inverse scattering on the line including an (equivalent) segment of (-) 50 Ω (- -) 25 Ω (▪▪) 16.6 Ω and (▪ —) 12.5 Ω.

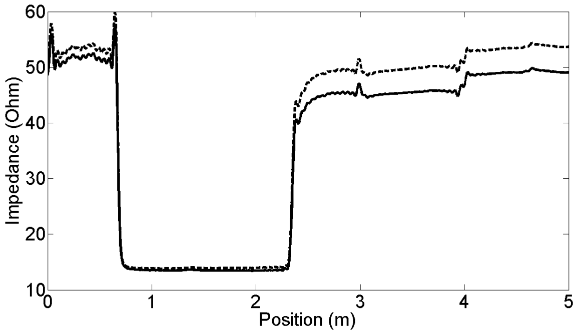

Fig. 4 Comparison of two $Z_0(z)$ profiles obtained by inverse scattering on the same line including an (equivalent) segment of 25 Ω with zero padding up to 15 GHz (-) and 30 GHz (--). These results show that a higher zero padding leads to a more accurate result

3.2 Double characteristic impedance drop

This example is intended to study the ability of the inverse scattering method to estimate more complex discontinuous characteristic impedance profiles.

In Fig. 5, the estimated characteristic impedance profile exhibits spikes at each junction between the different segments of the line (*e.g* at the injection point, at the connection of the 50 Ω coaxial cable and the segment of doubled cables etc…). These are caused by the 50 Ω connectors which are slightly improperly adapted to the line and furthermore locally add some extra lengths to the line (each straight or Tee connector adds about 2cm to the 50 Ω coaxial line). This explains the small two first impedance spikes observed at $z = 0\ m$ and $z = 0.6\ m$. The spike at the third connection point (between the 25 Ω and the 16.66 Ω segments) is all the more observed since 3 BNC Tees are stacked in order to connect the doubled and tripled cables segments.

As shown in Fig. 5, in the middle of a 50 Ω coaxial cable, a segment of doubled cables and another one of tripled cables are inserted, with equivalent characteristic impedances of 25 Ω and 16.67 Ω. The result of the inverse scattering method is also shown in Fig. 5. The characteristic impedance profile is estimated with a good accuracy, despite the multiple discontinuities present in the characteristic impedance profile

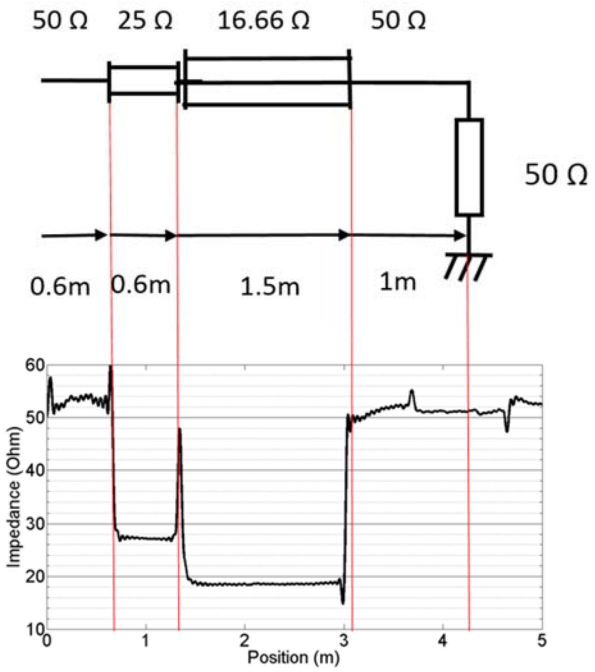

Fig. 5 Above: Two segments of doubled and tripled cables inserted in the middle of a 50 Ω coaxial. Below: Result of the inverse scattering method.

3.3 Accuracy of the inverse scattering method in the case of piecewise constant characteristic impedance profiles.

Remind that, in theory, the case of characteristic impedance with discontinuities is not suitable for the inverse scattering method. Nevertheless, the reported experiments show that this method can tolerate discontinuities to some extent. The results of section 3.1 show that, the higher is the step jump of the characteristic impedance, the larger is the error of the inverse scattering method. To complete these results, numerical simulations have been made to further characterize the errors. The simulated cable configurations are similar to that of Fig. 2, but the characteristic impedance level jump in the middle segment can be freely chosen for numerical simulations. The reflection coefficients of the simulated cables with various impedance level jumps *ΔZ* are simulated in the $[-50\Omega\ ;\ +350\Omega]$ range and then are given as input to the inverse scattering method. The relative accuracy of the inverse scattering method was calculated as:

$$Relative\ accuracy\ (\%) = \left|\frac{\Delta Z_{IS} - \Delta Z}{\Delta Z}\right|$$

where ΔZ_{IS} is the impedance level jump of the middle segment estimated by the inverse scattering method. The results are plotted in Fig. 6. As expected, the error is increasing with *ΔZ*.

Therefore, in presence of strong impedance jumps, the error term can rapidly reach quite high values. Nevertheless, when $\Delta Z \in [-50\Omega\ ;\ +100\Omega]$, the error is less than 5%. So one must be careful when interpreting impedance values computed in presence of strong discontinuities.

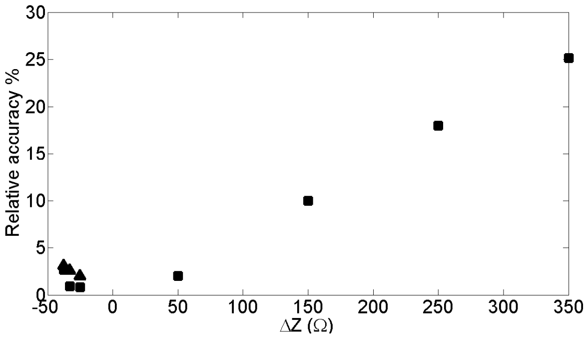

Fig. 6 Inverse scattering method accuracy in case of impedance discontinuities. (▲)Accuracy obtained from the inversion of experimentally measured reflection coefficient. (■) Accuracy obtained from the inversion of simulated reflection coefficient.

When both smooth variations and discontinuities are present in the characteristic impedance profile of a cable, the reflection coefficient measured at one end of the cable is the result of all these imperfections of the cable. As waves injected in a cable are essentially reflected at the discontinuities, too strong discontinuities may mask the effects of the reflections caused by smooth variations. It is thus important to avoid strong discontinuities when smooth variations should be monitored. In the experiments reported in Loete and al. [2012b], it was shown that an impedance jump of 60 Ω (impedance mismatch between the network analyzer and the 110 Ω cable), and another one of 110 Ω (impedance mismatch between the 110 Ω cable and the 220 Ω load) are well tolerated when smoothly varying characteristic impedance profiles are estimated, with a satisfactory accuracy for the purpose of soft fault detection, location and characterization.

4. CONCLUSION

The experimental results presented in this paper confirm the previously reported theoretic results and numerical simulations about the inverse scattering method. These results provide a new way for the interpretation of reflectometry measurements. To characterize the errors of the inverse scattering method, high quality coaxial cables were then used to build composite lines with piecewise constant characteristic impedance profiles. It is shown that the inverse scattering method can tolerate to some extent impedance discontinuities.

The results reported in this paper, together with those of Loete et al. [2012b], confirm the ability of the inverse scattering method for distributed characteristic impedance estimation, with a satisfactory accuracy for the purpose of soft fault diagnosis in electric cables. Moreover, the implemented inverse scattering algorithm is numerically efficient: for each of the experiments presented in this paper, the processing of the data by the inverse scattering algorithm takes less than a second on a typical notebook computer.

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