An efficient technique based on DORT method to locate multiple soft faults in wiring networks

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Decomposition of the time reversal operator (DORT) recently adopted to wiring fault detection and localization presented effectual results when dealing with a single soft fault along with complex network configurations. On the other hand, it failed in handling the task of locating multiple faults within even simple ones. In this article, we propose an enhanced version of the standard DORT technique (EDORT) which is based on a complementary procedure enabling the accurate and selective localization of multiple soft faults in various wiring systems.

Introduction

The emergence of electrical employments geared the indispensable use of electrical cables in nearly all modern systems. They became the backbone structures that are widely utilized to distribute power and communication signals throughout nuclear power plants, industrial machinery, human facilities and transportation systems which made their reliable and safe operation a pivotal issue. The increasing complexity of modern systems was accompanied with a huge increase in the lengths of cables. From few hundreds of meters in vehicles few decades ago to about 4 km in modern ones, wires lengths increased to several hundred km in civil and military airplanes. Moreover, estimates show that about 5000 km are present in power plants which skyrockets to 40000 km of cables in railway infrastructures of large countries [1]. All these examples, show that the massive use of wiring networks in nowadays systems became crucial, especially that some of these cables are integrated in control and safety operations of many of these systems. Consequently, the searching phase for the detection and repair of a wiring fault counting on the human capabilities intervention is both expensive, time consuming and non-efficient. Besides, this was accompanied with an inability of detection in many of the cases especially that most of the wires are embedded in the body structure of the systems where as an example, studies reported that 70 % of checked vehicles were returned fault free although they were defected. Thus, proper and efficient wire diagnosis tool is strongly recommended to prevent the drastic consequences that may occur [1].

Whatever the application is, wires are subject to unwanted modifications and breakdowns that can be classified into two main categories: hard faults (open or short circuits) or soft faults, typically featured by minor alterations as insulation defects, cracks, or frays which can lead to drastic consequences if not early rectified. It is worthy to note that our interest in soft faults shoved off from the studies that were conducted on cables and showed that 30% to 50% of detected wiring faults are considered to be soft which might be far dangerous than hard ones due to their detection difficulty [1]. Several techniques have been lately innovated for the task of cable testing, but the widely used ones were the reflectometry based methods whose aim is to detect the presence of an impedance discontinuity by submitting a testing signal and monitoring the reflected one [2]. These high frequency methods, include two main families: Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FRD); they differ in the form of the injected wave, or in the post processing techniques used to extract information from the reflected wave. For example, in the TDR family, standard TDR injects a step or a pulse into the wire network to be tested, and relies on the analysis of the reflected wave in the temporal domain in order to extract the fault's signature [3]. On the other hand, in FDR techniques stepped frequency sine waves are injected into the network under test (NUT), and determines the location of the fault depending on the parameter that is to be measured (frequency, phase, or stationary wave amplitude measurements) [3]. In fact, these reflectometry methods showed promising results when dealing with hard faults but failed when addressing soft ones depicted by weak reflectivities [3]. Moreover, they started flopping when complex networks evolved due to the appearance of junction related echoes that increased the complexity of analyzing the reflected signal.

Differential DORT, an acoustically originating technique [4] was adopted to guided wave propagation on transmission lines [5] and succeeded in detecting and locating a single soft fault within an NUT. Besides, it has showed a great feasibility when addressing complex wiring configurations composed from several branches and junctions. On the other hand, it started failing when handling the mission of detecting multiple faults in different NUTs. Within this context, the aim of the article is to recall the main constraints faced by the standard DORT as presented in [6] and extend the applicability of this technique to the case of multiple soft faults in transmission lines. The second section will elaborate the general concepts of DORT method along with presenting the main restrictions it faced when addressing multiple faults. This will be followed by presenting the new enhanced version of the standard DORT explaining the different steps it is composed of and interpreting the procedure of locating the multiple faults. After that, the third section will validate the new approach numerically and experimentally on different complexity NUTs with considering the presence of two different soft faults embedded in the network. Finally, the last section will draw a conclusion and a summary of this paper.

DORT METHOD

General Concept

Soft fault localization in complex NUT's is to a great extent similar to the problem of target location used in radar communication where the target's positioning becomes tough when its signature is relatively weak compared to other scatterers present in the medium [7]. It was proven that by using the time reversal (TR) properties, the reflected echo from a target can be maximized while using the same amount of energy of the excitation signal thus leading to focal spots on the target's location after a series of several iterations. DORT method, derived from the iterative TR isolates and classifies different scattering spots without the need for iterations, which is achieved by the use of the time reversal operator (TRO) [8] [9]. This TRO contains valuable information of the scattering centers in the media encapsulated in its eigenspace structure where propagating the corresponding signals conducts a focusing on the desired scatterer thus providing separate images of the scatterers in a media. Taking advantage of the properties of DORT method adopted in a standard version in guided wave propagation, it became possible to synthesize signals intended to focus on the position of an eventual fault [5]. It is worthy to note that, all subsequent quantities are function of frequency thus the frequency variable will be dropped in all of what follows.

In order to approach the benefits of the standard DORT technique (SDORT) in locating soft faults, we shall introduce first S, the baselined scattering matrix of the NUT given by:

$$\boldsymbol{S} = \boldsymbol{S}_f - \boldsymbol{S}_h \qquad (1)$$

where $\boldsymbol{S_f}$ is the scattering matrix measured by observing the testing ports of the NUT containing the soft fault whereas $\boldsymbol{S_h}$ being the scattering matrix measured in the non-faulty (healthy) version of the same NUT. This operation allows removing the spurious echoes generated by impedance discontinuities like junctions, leaving only those echoes initially generated by the interaction between the testing signals and the faults. The resulting scattering matrix $\boldsymbol{S}$ will thus only contain data related to the signals scattered by the fault, which will be used to synthesize the testing signals aiming to focus on the fault's position [5]. This is accomplished by creating the TRO $\boldsymbol{K} = \boldsymbol{S}\boldsymbol{S}^{\dagger}$, given that † refers to the Hermitian transpose, followed by an eigendecomposition process which produces eigenvalues with their corresponding eigenvectors. As a matter of fact, the number of non-zero eigenvalues hints at the number of faults present in the NUT. Whereas, the eigenvectors form the fundamentals of the testing signals which once propagated in the network will form focal spots indicating the position of the fault. Besides, theoretically DORT method as presented in open space target location techniques shows that it is possible to focus on any of the scatterers in the medium simply by propagating the eigenvectors corresponding to its eigenvalue as long as the scatterers are ideally resolved [8].

This property no longer holds in guided wave propagation along transmission lines, while waves attenuate as a factor of $1/r$ in free space [10], guided waves experience negligible attenuation. On the contrary, a new mechanism of energy exchange appears where waves cannot focus solely on a fault without interacting with the others. As a matter of this fact, ideal resolve can no longer be satisfied preventing the selective focusing on each fault separately by using its eigenvalue components. Besides, as we are dealing with soft faults, SDORT faced an impasse whenever a considerable high severity difference is present between the faults in a system. In other words, a relatively weak soft fault in the NUT with respect to the other stronger one in the configuration will have a masked signature thus reducing the chances of localizing it. In addition to that, it has stood still when the complexity of the network increases that is manifested by the appearance of junction related echoes which are able to mask the eventual position of a weak soft fault. Eventually, these restrictions are well detailed in [6] in a clear manner.

Enhanced DORT Method

While SDORT does not perform well in locating multiple faults in an NUT, it gives accurate and effective results when dealing with a single fault even in complex network configurations. This fact motivated us to maximize the profit we can gain from the DORT concept in this field which resulted in an enhanced version (EDORT) of this method. The EDORT adopts the main steps followed by the standard method to locate a single fault in the NUT, and proceeds to a complementary procedure enabling the localization of other faults present in a configuration and thus bypassing the restrictions encountered by the SDORT.

This new method commences by measuring the global baselined scattering matrix of the multiple faulty NUT $\boldsymbol{S_G^1}$, which contains information of the signals scattered by all the faults in the system. Applying the SDORT steps using this matrix will lead to several focusings on some of the faults' positions while others will not appear depending on the configuration's complexity and on the fault's severities. As a matter of what has been presented in [6], increasing the system's complexity may lead to masking the signature of the very weak soft faults. Besides, as the intensity of the soft fault becomes relatively low with respect to the others, its detection becomes very hard and sometimes impossible [6]. On the other hand, locating the position of the strongest soft fault in the NUT is always possible in the first step which is usually recognized by a dominant focal spot. Thus, after localizing the first strongest fault we will move to a complementary similar process allowing locating other faults present in the wiring network. As a matter of what has been presented in [6], the global scattering matrix $\boldsymbol{S_G^1}$ containing all the faults' signatures, can be divided into multiple scattering matrices each containing one of the fault's response that is

$$\boldsymbol{S_G^1} = \sum_{i-1}^{N_f} \alpha_i \boldsymbol{S_d^i} \qquad (2)$$

where N_f being the number of faults in the NUT, $\alpha_i$the weighting factor which will be later presented, while $\boldsymbol{S_d^i}$ designating the scattering matrix intending to focus on each soft fault separately [6]. Thus, we will become capable of providing selective focusing on each fault separately by monitoring each $\alpha_i \boldsymbol{S_d^i}$ corresponding to one of the faults. So, after localizing the strongest soft fault present in the NUT, a cloned network similar in structure to the original one will be created, but with a dummy soft fault on the position localized. The corresponding scattering matrix $\boldsymbol{S_d^1}$ will embrace the response of the strongest fault solely. After that, a weighted version $\alpha_1 \boldsymbol{S_d^1}$ will be subtracted from $\boldsymbol{S_G^1}$ leading to new scattering matrix containing the remaining faults' signatures. The SDORT steps will be then applied in order to locate the new strongest fault in the NUT, after which the procedure described before will be followed to localize all faults in the configuration.

For the sake of clarity, the steps required in the EDORT process are summarized in what follows:

1) measure the global scattering matrix $\boldsymbol{S_G^1}$ of the (eventually) multiple faulty NUT;
2) apply the SDORT method on $\boldsymbol{S_G^i}$, in order to estimate the position of the strongest soft fault;
3) include a dummy soft fault on the guessed position and compute its scattering matrix $\boldsymbol{S_d^i}$;
4) compute the only significant eigenvalue of $\boldsymbol{S_d^i}$ and its eigenvector μ_i and ω_i respectively;
5) compute the weighting factor $\alpha_i = \frac{\omega_i^T \boldsymbol{S_G} \omega_i}{\mu_i (\omega_i^T \omega_i)^2}$ and $\boldsymbol{S_i} = \alpha_i \boldsymbol{S_d^i}$;
6) remove the ith fault contribution by computing $\boldsymbol{S_G^{i+1}} = \boldsymbol{S_G^i} - \boldsymbol{S_i}$;
7) increase i and repeat from step 2) until the update $\boldsymbol{S_G^i}$ has no significant eigenvalue.

RESULTS

In order to better illustrate the benefits introduced by EDORT over its standard version, a single junction network configuration will be analyzed and its results will be presented in this section.

Analyzed Configuration & Standards

In order to support the EDORT, some rules and standards have been adopted in our study in order to organize the process of obtaining results and their display. If we consider the general network structure, illustrated in Fig. 1, we first begin by assigning a number to each of the extremities where each designates a testing port. We will consider that the one numbered by (1), be the origin, and distances will be measured according to this origin, and consequently all graphs will plotted accordingly. Concerning the path designation, each path will be assigned number that is the part of the network between the origin testing port and any of the other ports. As an example, in Fig. 1, the third path is the part of the network linking the origin to the testing port numbered (3).

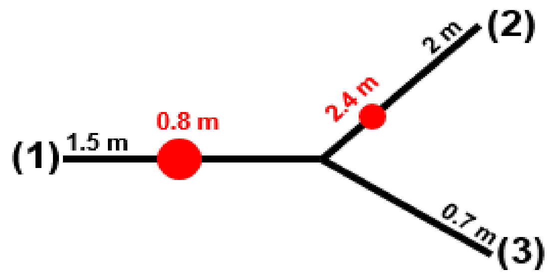

Figure 1 Layout of the NUT considered for the experimental validation where two different severity soft faults were created by partial crushing of 30-cm semi-rigid coaxial cables as presented in Fig. 2 (fault's severity depends on the radius of the circle and their positions are measured with respect to the reference port (1)).

All results obtained are treated by frequency domain simulation on Matlab, using the transmission line theory (TLT), where the transmission lines are considered to be uniform lossless lines with matched-ends in the simulation model created. This simulation model will be used for post-processing the experimental data collected. Moreover, in order to display the results for determining the actual position of the fault, a time-space (ZT diagram) tool is used which allows the observing the voltage propagation in the network both in space and time.

Experimental results

Experimental tests were conducted, considering the NUT single junction structure depicted in Fig. 1 and implemented using standard 50 Ω coaxial cables as transmission lines as shown in Fig. 2. Besides, 30 cm semi-rigid coaxial cables were used for the sake of creating the soft faults which is manifested by a crushing of a small portion of it whose severity depends on the length crushed as reproduced in Fig. 3. The stronger soft fault is produced by crushing the line for a distance of 2 cm whereas the weaker is designated by a 1 cm crushing. The ends of the cables were the testing ports for the purpose of simplicity, where three ends of the NUT were connected to a Rohde & Schwarz ZVB8 vector network analyzer (VNA) capable of covering a frequency range from 300 KHz to 8 GHz. Measurements of the scattering matrices was performed over a total bandwidth of 2 GHz and a sampling frequency of 20 MHz After calibrating the VNA using the calibration kit provided by the manufacturer studying the network consisted of two steps:

1. Measurement of $\boldsymbol{S}_h(\omega)$ of the reference system (without a fault) for a frequency range from 300 KHz to 2 GHz, where we considered the network with unaltered 30-cm semi-rigid sections.
2. Measurement of $\boldsymbol{S}_f(\omega)$of the faulty system, where the unaltered cable samples were replaced by the faulty ones.

Having measured the two transfer matrices of the considered NUT, the detailed EDORT steps are applied followed by post processing using the Matlab simulation model. The ZT diagram of Fig. 4 shows a focal spot pointing the location of the first strongest soft fault in the NUT after the first iteration of the EDORT. Consequently, the second iteration was enough to clearly localize the weaker soft fault as designated in the ZT diagram of Fig. 5. The experimental results presented, allowed the localization of the two soft faults in the single junction network of Fig. 1 which imply the feasibility and efficiency of the proposed method in locating multiple faults within wiring networks which shall be extended to include more complex NUT's.

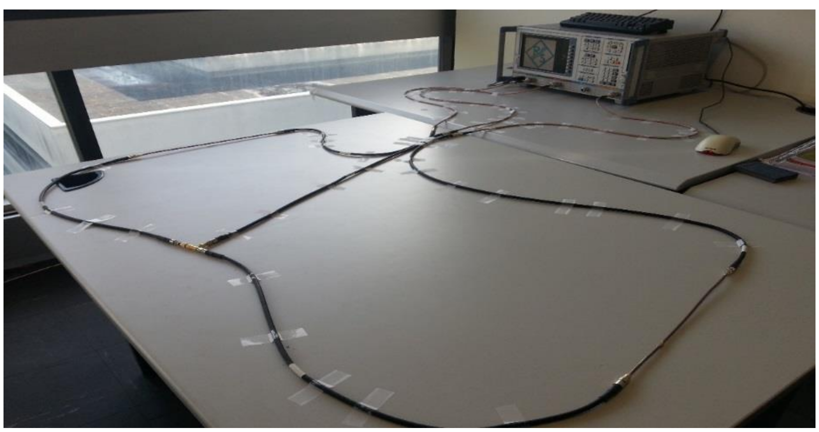

Figure 2 Implementation of the NUT described in Fig. 1 and connected to a VNA for experimental tests.

Figure 3 The two soft faults considered in the test whose severity depends on the length of crushing of the 30-cm semi-rigid cables.

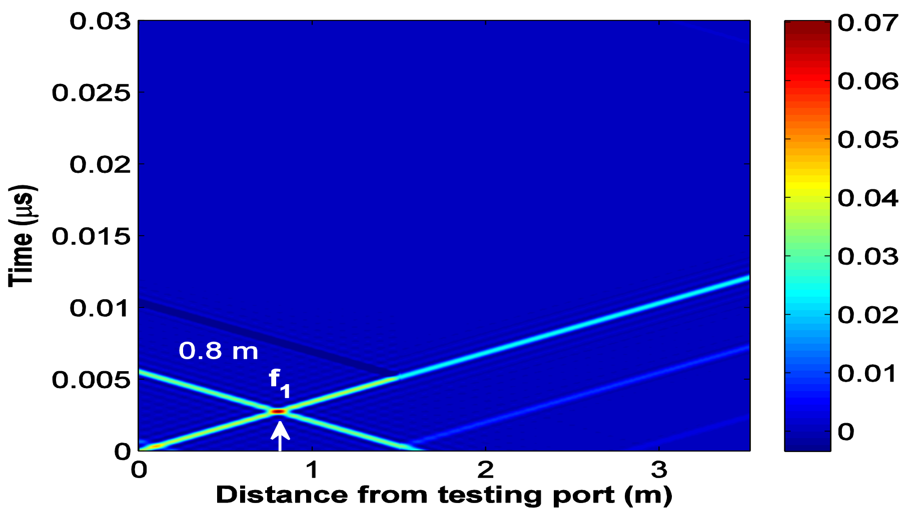

Figure 4 The voltage propagation along the second path of the network of Fig. 1 after the first EDORT iteration.

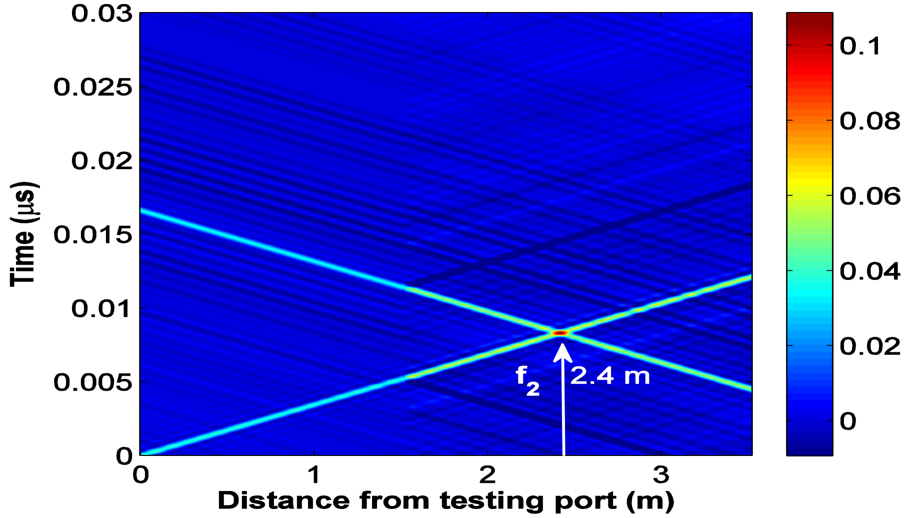

Figure 5 The ZT diagram corresponding to the NUT of Fig. 2 after the second iteration of the EDORT showing clearly the position of the second soft fault in the configuration.

CONCLUSIONS

EDORT, a new enhanced method based on the standard DORT technique, was extended to embrace the detection and localization of multiple soft faults within wiring systems. It conquered the restrictions faced by the standard technique and showed a great feasibility in the precise localization of multiple faults. Besides, it was able to preserve the main advantage gained by DORT and manifested by its efficiency when dealing with complex network configurations composed of several branches and junctions which was validated numerically and by experimental results. Further work will be needed to assess the sensitivity of the proposed technique with increased network complexity, as well as its robustness with respect to noisy signals propagating along live-tested NUT's.

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