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A Joint Reflectometry-Optimization Algorithm for Mapping the Topology of an Unknown Wire Network

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Abstract—**Despite the fact that wireless systems are overwhelming most of nowadays applications, wiring networks are still forming a pivotal anchor in many controls and security units. Thus, ensuring the reliable operation of such networks necessitates investing in techniques dedicated for their protection. A vast majority of such methods rely on the presence of a reference model of the network. In this paper, we propose a non-destructive testing approach based on the tenets of reflectometry methods and genetic algorithms to retrieve the topology and load impedances of unknown embedded complex wiring networks.**

Keywords—*Wiring networks, topology reconstruction, time domain reflectometry, genetic algorithms.*

I. INTRODUCTION

Although electrical wires are often the last component taken into account during system designs, it won't be exaggerating to consider them as the body's nervous system. In fact, wires not only distribute power but also provide control and information links between multiple systems of many applications. Some are critically dangerous as nuclear power plants and aircraft industry. On the other hand, wires are subject to aging during their normal service life leading to the progressive deterioration of their physical properties and performance. Consequently, the potential hazard posed by wiring faults has generated a tremendous amount of effort invested in developing robust techniques for their detection as an early warning approach for ensuring a trustworthy usage of cables.

Although reflectometry-based techniques formed a pivotal anchor towards this target [1], major concerns sieged their feasibility due to several reasons. Essentially based on analyzing the reflected echoes generated by injecting a test signal into the network under test (NUT), weak echoes produced by soft faults, which are minor alterations that affect a cable, can pass undetected with respect to spurious signals propagating over an NUT. Such signals can be mechanical vibrations or useful communication signals as in live wire testing. A further challenging level of complexity is added to the reflectometry response when dealing with networks interconnecting several branches via junctions which is often the case in almost all real-life environments [2]. In fact, junctions create echoes that can either mask those generated by soft faults or be difficult to distinguish from those reflected by hard faults (open or short circuits). Regrettably, such undesired echoes tend to grow exponentially with an increased complexity of the NUT [3].

Within this context, baselining, a method based on comparing the faulty NUT's response with a predefined healthy one, enhanced the reflectometry's sensitivity towards detecting weak or masked faults' signatures [4]. Besides, it enabled applying a new category of time-reversal based methods that have shown promising results in locating multiple soft faults in different complexity NUTs [5]–[7]. Consequently, analyzing networks of unknown topology can therefore be particularly very difficult. This is supported by the wide range of networks whose configuration datasheets are lost especially when dealing with old wiring infrastructures. Furthermore, disconnecting embedded NUTs for testing purposes in some applications can sometimes be impossible which in turn imposes two serious constraints demonstrated first by the limited number of available testing ports that can be a single one in many cases. Second, we might be confronted by load impedances that could not be disconnected and changed.

Thus, the aim of this paper is to propose an efficient automated method to retrieve all parameters of an unknown or partially unknown wiring network, namely its topology and extremities' load impedances. A forward model is developed to generate the time domain reflectometry responses (TDR) of NUTs and the genetic algorithm (GA) is used to solve the inverse problem in order to reconstruct the right network topology. This new TDR-GA algorithm will be accomplished using a single-port access measurement without any need to disconnect the tested network.

II. THE JOINT TDR-GA APPROACH

The joint TDR-GA approach consists of two main parts. The first part comprises a numerical model for constructing NUTs in addition to a transmission line forward modeling to generate their corresponding TDR responses. The second part is the GA optimization which is used to minimize the differences between the measured reflectometry response of an unknown NUT and the responses given by the direct numerical model. The network's topology and its corresponding load impedances would be retrieved once convergence is reached between the measured response and the one corresponding to the right NUT configuration generated by the forward model. It is worthy to note that we will be dealing with NUTs composed of cables having the same characteristic impedance Z_c.

A. Numerical model

Based on the fact that the number of extremities of a black-boxed unknown network can be known, a numerical model is designed to construct all possible NUTs connecting these extremities. During this procedure all ring and mesh like configurations are dropped, where only tree like (branched)

topologies will be maintained. In fact, this assumption was based on the event that branched networks are more often found in practice than other NUT topologies [8].

In order to model the signal propagation in a branched NUT and provide its corresponding TDR response, a joint finite difference time domain (FDTD)- ABCD matrix method developed as an inhouse solver at CEA was adopted. It is a simple electromagnetic modeling tool which provides very computationally efficient time domain voltage (v) and current (i) solutions to Telegraph's equations given by (1) and (2) of the RLCG circuit model used to describe the wave propagation in a two-conductor transmission line. The quantities R (resistance), L (inductance), C (capacitance) and G (conductance) are the per unit length parameters.

$$\frac{\partial v(x,t)}{\partial x} = -Ri(x,t) - L\frac{\partial i(x,t)}{\partial t} \tag{1}$$

$$\frac{\partial i(x,t)}{\partial x} = -Gv(x,t) - C\frac{\partial v(x,t)}{\partial t} \tag{2}$$

B. The Genetic Algorithm

Genetic Algorithms (GAs) are adaptive heuristic search algorithms based on the evolutionary ideas of natural selection and genetics [9]. As such, they represent an intelligent exploitation of a random search used to solve optimization problems.

GAs simulate the survival of the fittest by starting with a random sample set (initial population) of potential solutions (chromosomes). Each chromosome is coded as a finite length vector of variables which are analogous to genes. These solutions then undergo recombination and mutation (like in natural genetics), producing new children, and the process is repeated over various generations. Each individual (or candidate solution) is assigned a fitness value (based on its objective function value) and the fitter individuals are given a higher chance to mate and yield more "fitter" individuals until an eventual convergence is reached. As a result, an optimal population is produced that will now contain the optimal solutions.

C. The TDR-GA Approach

After measuring the reflectometry response V_{mes} of the unknown black-boxed network NUT_{mes} using a single testing port, the first part of the TDR-GA approach begins by numerically constructing all N possible NUT configurations NUT_{sim}^i ($i = 1, 2, \ldots, N$) based on the knowledge of the NUT_{mes}'s m extremities. The TDR response V_{sim}^i of each NUT_{sim}^i is determined by the numerical model described section II-A.

Since the GA algorithm has shown to be a feasible and efficient tool for solving difficult optimization problems, it will be used to minimize the differences between V_{mes} and each V_{sim}^i in an effort to retrieve the best NUT_{sim}^i that best resembles NUT_{mes}. Accordingly, we will start with an initial population which is a random selection of possible solutions. Each chromosome is a model vector $X = [L, Z]$, with $L = [L_1, L_2, \ldots, L_n]$ being the lengths of n branches composing the NUT_{sim}^i, while $Z = [Z_1, Z_2, \ldots, Z_m]$ being the load impedances of its m extremities. These solutions then undergo the GA process described in sec. II-B with an objective function value defined as $F_{val}^i = \|V_{sim}^i - V_{mes}\|_2$. After

each GA process the fitness values F_{val}^i will be sorted and the NUT_{sim}^i with the highest F_{val}^i will be dropped. This process will be iterated till we reach a stopping criterion demonstrated by the lowest F_{val}^i corresponding to NUT_{sim}^i whose solution X best resembles the NUT_{mes}. For clarification purposes, the diagram of Fig. 1 summarizes all the steps we followed in the proposed TDR-GA algorithm.
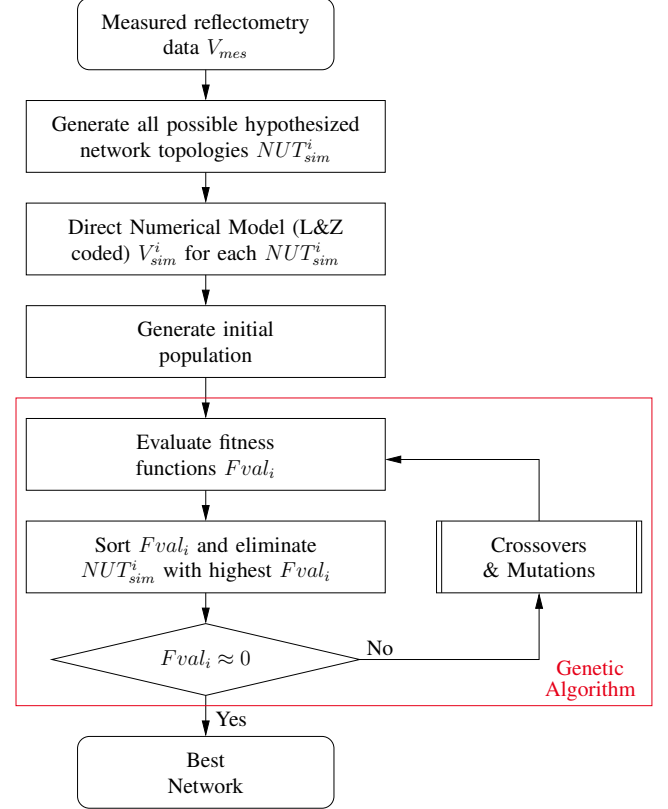

Fig. 1. The TDR-GA algorithm.

III. RESULTS AND DISCUSSIONS

In order to validate the proposed approach, we opted to test experimentally a double Y-junction NUT composed of 50Ω coaxial cables connected to different resistive loads as shown in Fig. 2. The lengths of branches as well as load impedances are illustrated on the same figure.

The standard TDR measurement was accomplished by injecting a Gaussian pulse excitation with a -3 dB bandwidth
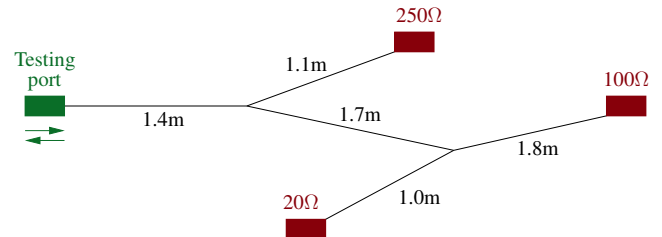

Fig. 2. Layout of the double Y-junction NUT considered for the experimental validation of the TDR-GA approach showing the branch lengths and the load impedances.
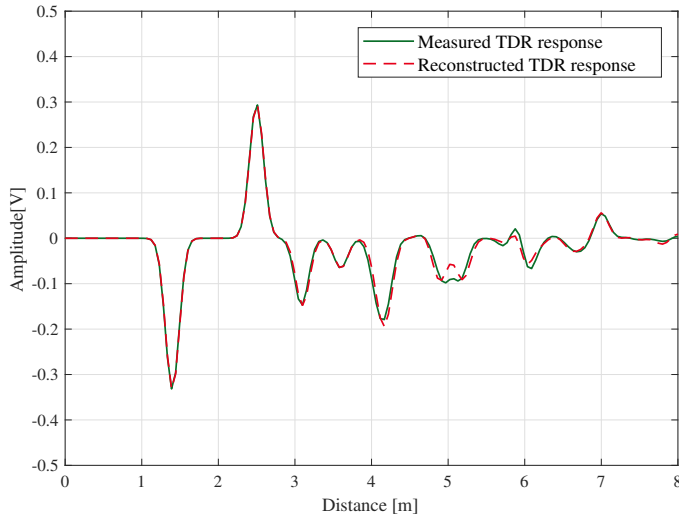
Fig. 3. The measured and simulation-reconstructed reflectometry responses of the unknown network.
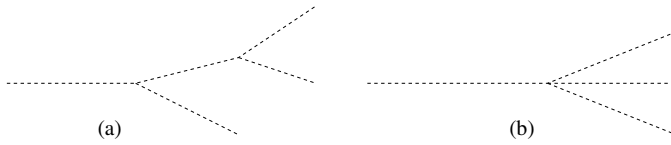

Fig. 4. The hypothesized numerical NUTs constructed based on the 4 extremities of the tested NUT: (a) a double Y-junction NUT, (b) a single Y-junction NUT.

of about 2GHz into the testing port of the network. The TDR response is retrieved by measuring the S_{11} parameter of the NUT by a vector network analyzer Rohde & Schwarz ZVB8 VNA, covering a frequency range from 300 kHz to 8 GHz. The reflectogram of Fig. 3 shows the measured time domain TDR response of the NUT after applying an inverse fast Fourier transform (IFFT) to the frequency domain measured response.

The very first step of the TDR-GA algorithm starts by numerically constructing all possible hypothesized network topologies based on the diagnosed NUT's number of extremities. Thus, based on the knowledge of 4 extremities, we can build two different tree like NUTs as shown in Fig. 4. This will be followed by applying the procedure detailed in sec. II-B which seems to exclude the hypothesized NUT of Fig. 4 (b) after the first iteration and keeps us with only the NUT of Fig. 4 (a) qualified for the second round. Consequently, the second iteration of the approach optimizes the solutions (branch lengths and load impedances) of the NUT leading to the network of Fig. 5 in 182 seconds using a standard state-of-the art computer. The comparison between the obtained NUT with the original measured network shows that the TDR-GA approach efficiently determined the topology of the tested network with accurate and precise values of the branch lengths and the extremity load impedances. Significantly, this can be clearly noticed from the agreement of the reconstructed NUT's TDR response and the measured one as seen in Fig. 3.

IV. CONCLUSION

In this paper, we have proposed a non-destructive testing approach, the TDR-GA methodology, which is based on the
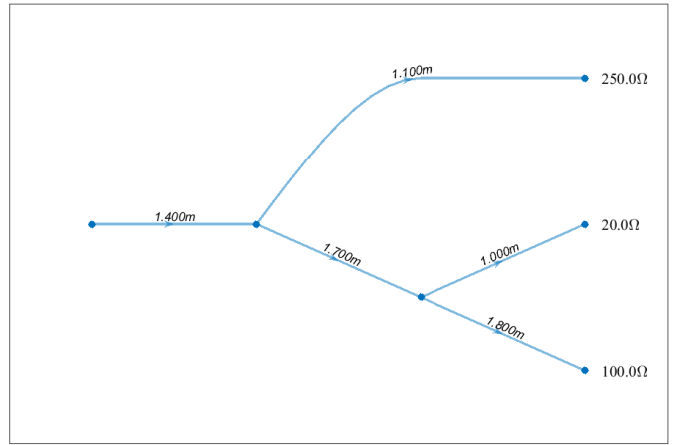

Fig. 5. The constructed NUT after applying the TDR-GA approach on the measured TDR response of the NUT of Fig. 2.

tenets of TDR and genetic algorithms for retrieving the topology of a black-boxed network. The novelty of this method is demonstrated by reconstructing a totally unknown wiring network from a single port TDR measurement while unveiling not only the branch lengths but also the load impedances at the NUT's extremities. The experimental result has proven the effectiveness and feasibility of the proposed approach in precisely reconstructing an unknown double Y-junction complex NUT. The surprising ability of TDR-GA to ensure a 1cm length precision along with a 1Ω impedance accuracy in a relatively short processing time is good news, as no similar performance has been presented so far.

Future work will need to deal with integrating the network connections as an additional variable set in the GA algorithm instead of iterating for each hypothesized NUT.

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