Wire Fault Diagnosis Based on Time-Domain Reflectometry and Backtracking Search Optimization Algorithm

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Abstract ─ The development of a robust and accurate fault diagnosis approach under various system and fault conditions is a research area of great interest. The objective of this paper is to develop a new non-destructive approach for wiring diagnosis based on Time Domain Reflectometry (TDR) in one hand and on Backtracking Search Optimization Algorithm (BSA) in the other hand. Real-world case studies are investigated to demonstrate the effectiveness and robustness of the proposed approach. Simulation results evaluated from experimental data demonstrate that the proposed approach can be used for effective diagnosis of complex wiring networks.

Index Terms ─ Backtracking search optimization algorithm, time domain reflectometry, wiring diagnosis.

I. INTRODUCTION

Electrical wiring diagnosis is a challenge for maintenance engineers. Aging of wires can result in: loss of critical functions of the equipment energized by the system, loss of critical information relevant to the decision making process and operator actions and may cause a break in power supply [1].

In order to detect electrical failures and reduce maintenance cost in electrical wiring networks, diagnosis approaches that can detect, localize and characterize defects are required. Ideally, the approach should be non-destructive and accurate [2], [3].

Time Domain Reflectometry (TDR) is a measurement technique used to determine the characteristics of electrical lines by observing reflected waveforms [4]. The key benefit of TDR over other testing technique is that is non-destructive [5]. It has been proven that TDR is able to detect hard faults in coaxial cables. However, a TDR response is not self-explanatory and consequently it cannot be used alone for complex wiring networks. Over the last decade, many inverse techniques were used along with TDR in order to detect faults in wiring networks [6], [7], [8], [9].

The Backtracking Search Optimization Algorithm (BSA) is a new Evolutionary Algorithm (EA) developed to solve real-valued numerical optimization problems. It is based on three basic and well-known operators that are selection, mutation and crossover [10].

The aim of this paper is to develop an efficient approach for wire fault diagnosis based on TDR and BSA. This approach is used to detect, localize and characterize hard faults (open or short circuit) that can affect a wiring network.

The rest of this paper is organized as follows. In Section II the developed approach is presented. In Section III, the developed approach is applied to three case studies. Finally, conclusions are drawn in Section IV.

II. APPROACH

The proposed TDR-BSA based approach consists of using a forward model in order to generate the TDR response, and the BSA in order to solve the inverse problem as shown in Fig. 1. Therefore, BSA is used to

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minimize the difference between the measured TDR response and the generatedone. Mathematically, we can formulate the inverse problem as an optimization problem with the following objective function:

$$F = \left(\frac{1}{N}\sum_{n=1}^{N}\left(\text{M\_TDR\_res}(\mathbf{x}) - \text{G\_TDR\_res}(\mathbf{x})\right)^2\right)^{\frac{1}{2}}, \quad (1)$$

where F is the objective function to be minimized, N the number of points, M_TDR_res and G_TDR_res are the measured and generated TDR responses, respectively and **x** is the vector of design variables that are the lengths (L_i) and the termination loads (R_i) of different branches.

In other words, knowing the topology of the network (healthy one), the target is to detect, to localize and to characterize faults in a given wiring network through finding the length and the termination load of each branch. If a calculated length L_i is different (shorter) than the length of the healthy branch, then a fault has occurred in that branch where L_i represents the location of the fault and R_i indicates whether the fault is an open circuit or a short circuit. If $R_i = 1$ the fault is an open circuit otherwise if $R_i = 0$, the fault is a short circuit.

In the following sections, both the forward model and the BSA are described. It is worth mentioning that the forward model has been presented and discussed in detail in [9] and in the following only briefly recalled for sake of completeness and clarity.

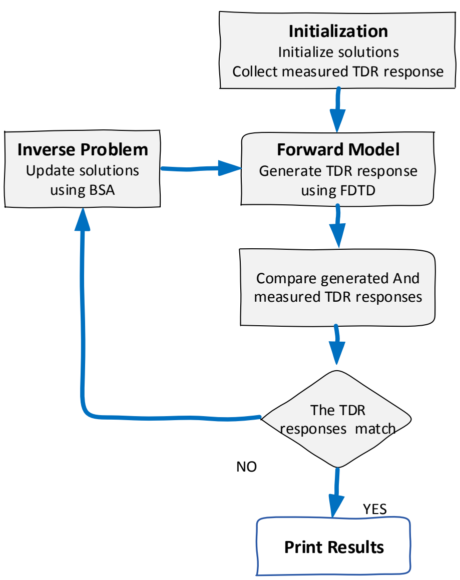

Fig. 1. The proposed TDR-BSA approach for wiring diagnosis.

A. The forward model

The TDR response is computed by solving the Kirchhoff law applied on the electrical model of the multiconductor transmission line [11], using the Finite Difference Time Domain (FDTD) method [14]:

$$\frac{\partial V(z,t)}{\partial z} = -RI(z,t) - L\frac{\partial I(z,t)}{\partial t}, \quad (2)$$

$$\frac{\partial I(z,t)}{\partial z} = -GV(z,t) - C\frac{\partial V(z,t)}{\partial t}. \quad (3)$$

In (2) and (3) V and I are the vectors of line voltages and line currents, respectively. The position along the line is denoted as z and time is denoted as t. The R (resistance), L (inductance), C (capacitance) and G (conductance) are the matrices of the per-unit-length parameters. The values of these parameters are computed analytically as in [9].

B. Experimental setup

The principle of TDR is to inject a signal into the inner conductor of the coaxial cable, which propagates along the cable; when the signal meets a discontinuity of impedance, a part of its energy is reflected back to the injection point where it is observed. The analysis of the response (the reflected signal) is used to detect, localize and characterize defects based on the amplitude and timing (or location) of the reflected signal.

The echo responses of the different network configurations are measured by means of a Vector Network Analyzer (VNA) connected to the testing network, as shown in Fig. 2. The VNA is an Anritsu MS4624B network analyzer, with a frequency range of 10 MHz to 9 GHz.

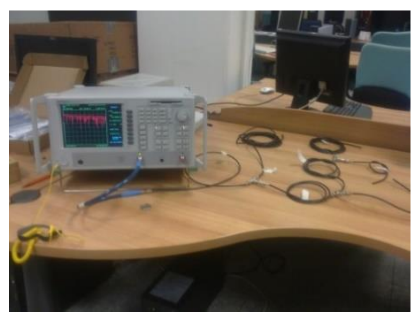

Fig. 2. Experimental setup.

The measured one-port scattering parameter S_{11} represents the frequency response of the network, thus it can be simply multiplied by the spectrum of the same input pulse used in the FDTD simulation. The Inverse Fast Fourier Transform is applied to convert the frequency domain response to the time domain response.

In order to measure, using VNA, the same network, the frequency band is 10 MHz - 1 GHz, and for the complex configuration we use a frequency band of 1 GHz - 2 GHz; then the two sets of data are combined together to achieve a 2 GHz bandwidth data with a doubled frequency resolution (f = 618 kHz based on

1601 samples per measurement). The reconstructed S_{11} is multiplied by the spectrum of the input pulse. The input pulse is a raised cosine pulse, with a rising time of 4 ns and amplitude of 1 Volt.

C. The backtracking search optimization algorithm

The BSA is used for solving the inverse problem. As previously mentioned, the BSA is a new EA and global optimization method developed in [10] for solving real-valued numerical optimization problems. It uses the three basic and well-known EA operators that are selection, mutation and crossover.

The main steps of the BSA are given in Algorithm 1. BSA is a population based optimization method; thus, it starts by randomly generating a population in the search space. In the Selection-I stage, the historical population that is used for calculating the search direction is determined. In the Mutation stage, the initial form of the trial population is generated while in the Crossover stage the final form of this trial population is generated. In this stage the best trial individuals for the optimization problem are used to evolve the target population individuals [10]. At the end of the Crossover stage, the individuals that go beyond the search space limits are redefined inside these limits. In the Selection-II stage, the trial population is used to update the population using a greedy selection. More details about the BSA can be found in [10].

Algorithm 1: General structure of BSA [10]

```
  1. Initialization
  repeat
      2. Selection-I
      Generation of Trial-Population
          3.Mutation
          4.Crossover
      End
      5. Selection-II
  until stopping conditions are met
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III. APPLICATIONS AND RESULTS

A. Model validation

Before using the developed TDR-BSA approach for the diagnosis of wiring networks, the validation of our forward model is carried out using the healthy YY-shaped network shown in Fig. 3. The measured and generated (using the forward model) TDR responses of this network are given in Fig. 4. The comparison between these two TDR responses shows the accuracy of the developed forward model. This is also confirmed by the small values of GRADE and SPREAD (GRADE = 2, SPREAD = 1) that are the figures of merits of the Feature Selective Validation (FSV) technique [12], [13] that is suggested by the IEEE Standard [14] as the preferred algorithm for quantitative data comparison.

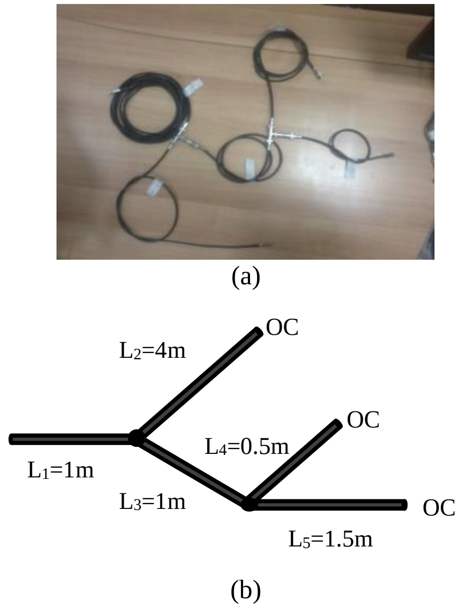

Fig. 3. The YY-shaped network: (a) the experimental network and (b) the schematic representation.

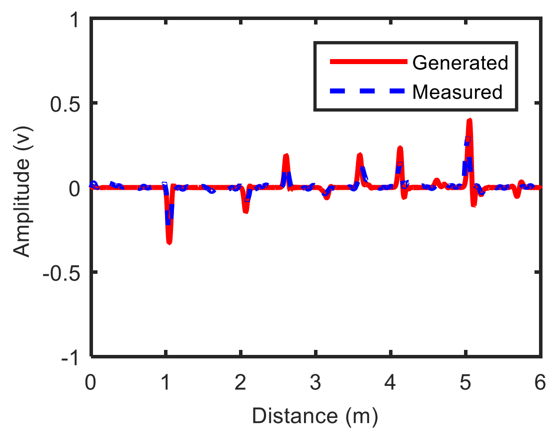

Fig. 4. Comparison between the healthy measured and generated TDR responses of the YY-shaped network.

B. Case studies

In order to evaluate the performance of the developed TDR-BSA approach we consider in this paper three case studies.

1. CASE 1

The first case study investigated in this paper is a YY-shaped network affected by an open circuit in L_2 at 2 m from the first junction as shown in Fig. 5. Thus, the design variables for this case are L_2, L_4, L_5, R_2, R_4 and R_5. It is worth mentioning that, the main branches L_1 and L_3 are assumed to be healthy, i.e., they are not considered as design variables. Because if the first main branch L_1 is affected by a fault it means that the investigated YY-shaped network is reduced to a simple line. Now if the second main branch L_3 is affected by a fault the network is reduced to a simpler network which is the Y-shaped network.

A simple comparison between the healthy and the faulty measured TDR responses of Fig. 6 allows us to make a first comment about the status of the wiring network under study: the network is not healthy. This phase is called the detection and it constitutes the first phase in our diagnosis as previously mentioned.

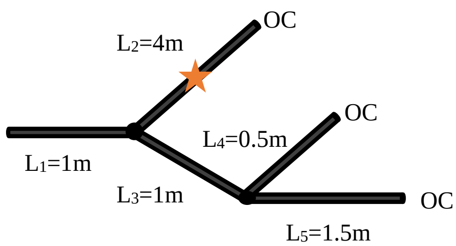

Fig. 5. The wiring network for CASE 1.

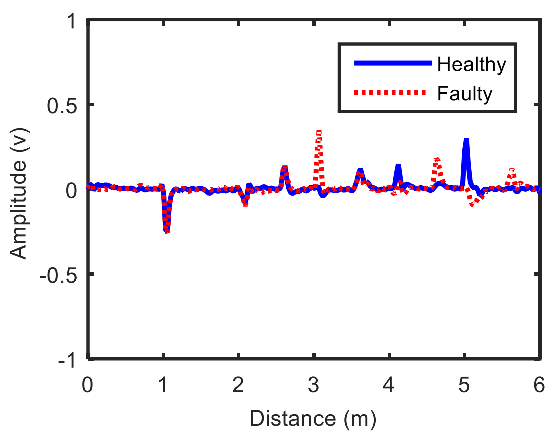

Fig. 6. Comparison between the healthy and the faulty measured TDR responses for CASE 1.

The developed TDR-BSA approach has been run for this case and the obtained results are given in Fig. 7 and in Table 1.

It can be seen from Fig. 7 that there is a good matching (FSV GRADE = 2 and SPREAD = 1) between the TDR response generated using the developed approach and the one obtained from measurements.

Table 1 compares the lengths and termination loads that correspond to the healthy network with those generated using the developed TDR-BSA approach. From this table, we can make the following conclusions: the analyzed network has a fault in L_2 at 2.04 m and the type of fault is an open circuit because $R_2 = 1$. It is worth mentioning here that, there is an error of estimating the fault distance of 0.04 m. These two conclusions represent the second and third phases of our diagnosis that are localization and characterisation, respectively.

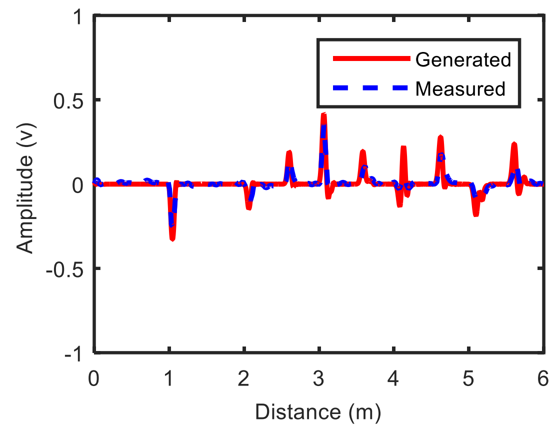

Fig. 7. Comparison between the measured and the generated TDR responses for CASE 1 (FSV GRADE = 2 and SPREAD = 1).

Table 1: Optimal results found for CASE 1

Design Variables		
Name	Generated Values	Healthy Network Values
L_2	2.04	4.00
L_4	0.50	0.50
L_5	1.50	1.50
R_2	1	1
R_4	1	1
R_5	1	1

2. CASE 2

The second case investigated is a faulty YY-shaped network with a short circuit in L_4 at 0.4 m from the second junction as shown in Fig. 8. Thus, the design variables for this case are L_2, L_4, L_5, R_2, R_4 and R_5. For the same reasons explained before, L_1 and L_3 are not considered as design variables here.

For the detection phase, a simple analysis of the TDR responses of Fig. 9 allows to detect the presence of faults.

The developed TDR-BSA approach has been run for this case and the obtained results are given in Fig. 10 and in Table 2.

From Fig. 10 we can say that there is a good agreement (FSV GRADE = 2 and SPREAD = 1) between the TDR generated using the proposed approach and the one measured using experimental setup. From Table 2 we can make the following conclusions about the localization and characterization of faults: the analyzed network has a fault in L_4 at 0.42 m and the type of fault is a short circuit because R_4=0.It is worth to mention here that, there is an error of 0.02 m and 0.021 m in estimating L_2 and L_4, respectively.

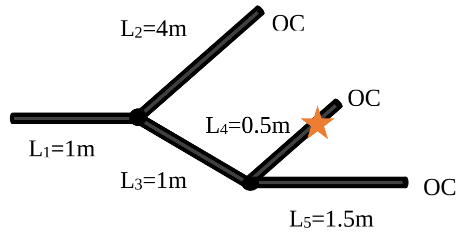

Fig. 8. The wiring network for CASE 2.

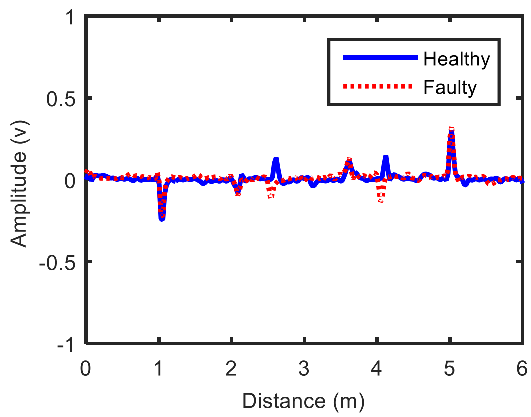

Fig. 9. Comparison between the healthy and the faulty measured TDR responses for CASE 2.

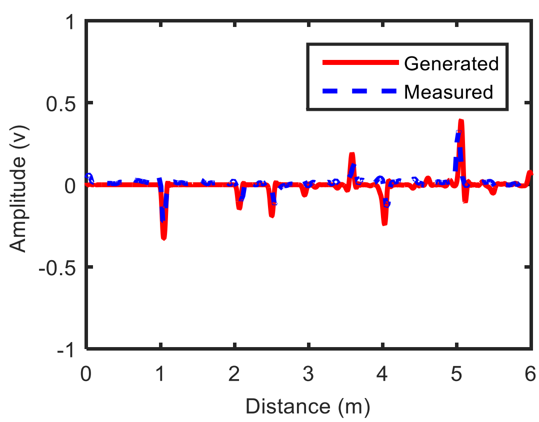

Fig. 10. Comparison between the measured and the generated TDR responses for CASE 2 (FSV GRADE = 2 and SPREAD = 1).

Table 2: Optimal results found for CASE 2

Design Variables		
Name	Generated Values	Healthy Network Values
L_2	3.98	4.00
L_4	0.42	0.40
L_5	1.50	1.50
R_2	1	1
R_4	0	1
R_5	1	1

3. CASE 3

To prove the robustness of the developed approach against more complex networks, the third case study investigated in this paper is a YYY-shaped network affected by two hard faults, a short circuit in L_2 at 2 m from the first junction and an open circuit in L_4 at 0.4 m from the second junction as shown in Fig. 11.

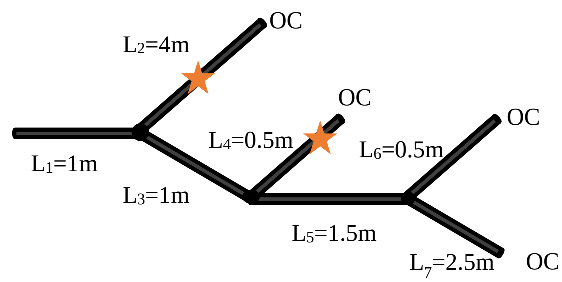

Fig. 11. The wiring network for CASE 3.

Therefore, the design variables for this case are L_2, L_4, L_6, $L_{7,}$ R_2, R_4, R_6 and R_7.The detection phase is similar to the ones explained in CASE 1, and CASE 2. In order to avoid undesired repetition, we have not put it here.The developed TDR-BSA approach has been run for this complex case and the obtained results are given in Fig. 12 and in Table 3. Figure 12 shows the good matching (FSV GRADE = 2 and SPREAD = 2) between the TDR generated and the one measured experimentally. From Table 3 we can make the following conclusions about the localization and characterization of faults: there is a short circuit (R_2=0) in L_2 at 2.02 m from the first junction and an open circuit (R_4=1) in L_4 at 0.42 m from the second junction. The error in estimating fault locations is0.02m for both L_2 and L_4.

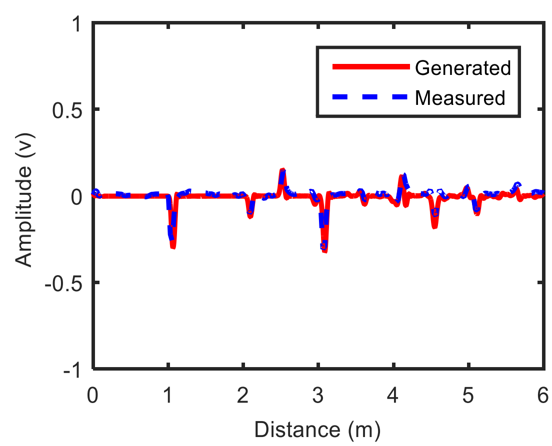

Fig. 12. Comparison between the measured and the generated TDR responses for CASE 3 (FSV GRADE = 2 and SPREAD = 2).

Table 3: Optimal results found for CASE 3

Design Variables		
Name	Generated Values	Healthy Network Values
L_2	2.02	4.00
L_4	0.42	0.50
L_6	0.50	0.50
L_7	2.50	2.50
R_2	0	1
R_4	1	1
R_6	1	1
R_7	1	1

IV. CONCLUSION

In this paper, a new approach using TDR and BSA is developed and used for the diagnosis of wiring networks. The TDR is used to measure the TDR response of a given network. The BSA is used to compare this response with a generated one using a developed forward model.

In order to assess the effectiveness and robustness of the proposed approach, three different case studies using YY-shaped and YYY-shaped networks are tested. The obtained results show that the developed approach has excellent performance and it is very accurate for the diagnosis of wiring networks. Moreover, by using the same values of convergence threshold there is an improvement (a decreasing) of around 70% of CPU time between the BSA that is proposed in this paper and the TLBO that was used in [9].

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