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Impact of Network Topology on Matched-Pulse-Based Fault Detection

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Abstract— An evaluation of the performance of the Matched-Pulse approach and the standard Time Domain Reflectometry is presented. The effect of the network topology on their effectiveness is studied, first through physical interpretation, then by means of a mathematical analysis. All the discussed ideas are finally illustrated through simulation results.

1. INTRODUCTION

The problem of fault detection and location in wire networks has gained an increasing importance in the last few years [1]. Wired networks are found in all modern systems, and are used to transmit different signals (control, alarm, etc.). That is why the issue of safe and reliable wiring systems is among the primary concerns of researchers and government agencies today [2].

There are several methods for wire testing, such as visual inspection, impedance testing [1], and reflectometry methods which are widely used today to help detecting and locating wire faults. These methods send a predefined testing signal down the wire network to be examined. They include Time Domain Reflectometry (TDR), which uses a fast rise time step or pulsed signal as the testing signal, Frequency Domain Reflectometry [3] which uses multiple sinusoidal signals, sequence TDR [4] which uses pseudo noise, etc. Generally, hard faults (open and short circuits) are detectable through standard reflectometry, while soft faults (damaged insulation, etc.) are more critical to detect, especially when dealing with complex wire networks configurations.

In [5], we introduced the Matched Pulse approach, based on the properties of Time Reversal [6], as an improvement of the existing standard TDR. The MP method proposes to adapt the testing signal to the network under test, instead of using a predefined testing signal, as for reflectometry methods. We have shown that this method results in a higher echo energy from the fault to be detected, when compared to TDR.

In this paper, we propose to study the impact of the network topology on the performances of the TDR and MP approaches. That is, to analyze the effect of the network elements (discontinuities, loads, etc.) on the effectiveness of these two methods, in order to have a tool which will allow us to predict, for any system, to which extent the MP might present an advantage over the TDR concerning the detectability of an eventual fault, and which are the elements governing directly those performances.

We first propose to establish the general assumptions under which we will be working in this paper, and then begin our study with a physical interpretation to analyze the impact of the wire network elements on the performances of the TDR. Then, in order to be able to compare our two approaches, we consider a mathematical study based on the definition of correlation functions. A validation of the discussed points is finally presented through simulation results.

2. GENERAL ASSUMPTIONS

We consider uniform lossless single-conductor transmission lines. Here we point out that, in this paper, we are not interested in studying the effect of the length of these lines, provided that they will only introduce time delays. So, as long as any branch in the network is longer than the spatial support of the injected pulse, the time resolution will not be affected and the separation of the first echoes propagating in the system is insured.

We also consider that the testing signal (i.e., the injected signal) is the input to our system, and the reflected signal is the output; the transfer function of such a linear system in the absence of

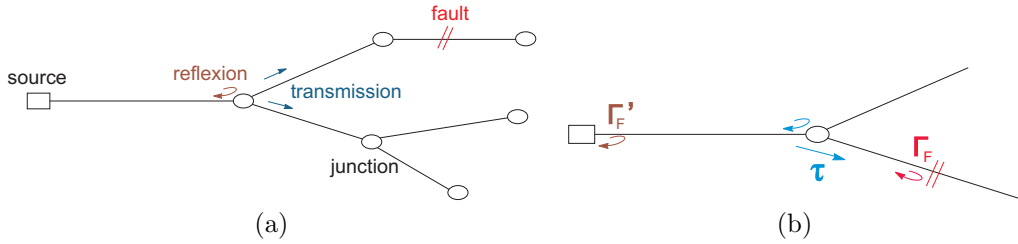


Figure 1: (a) Equivalent topological representation of a wire network; (b) an example illustrating the reflection coefficients Γ'_F and Γ_F .

the fault is denoted as $H_0(f)$ and in the presence of the fault as $H_F(f)$. Generally, we can either analyze the reflected signal directly [7], or take the difference of the two reflected signals (with and without the fault), especially when considering soft faults [8], so that the echo from the fault is more easily detected. This latter method is the one we will be using, assuming that our system is linear time invariant. Analyzing the difference of the two reflected signals is consequently equivalent to analyzing the output of an equivalent system whose transfer function $H(f)$ is defined as follows

$$H(f) = H_F(f) - H_0(f) \quad (1)$$

This equivalent system will be referred to as the difference system. We also note that the reference pulse we will be using is denoted as $I_0(f)$ in the frequency domain (and $i_0(t)$ in the time domain). This pulse is the same as the injected signal in the standard TDR.

3. PHYSICAL STUDY

We evaluate the impact of different elements in the network on the performance of the standard TDR. But first we propose an equivalent representation of the wire network to better illustrate the discussed ideas.

3.1. Equivalent representation of the wire network

We propose to represent any wire network as illustrated in Figure 1(a), where uniform scalar transmission lines are represented with lines (here the transmission lines are not physical objects, they only introduce delays, based on the general assumptions), junctions and terminal loads with circles, and the source is represented with a square. Two parallel lines indicate the position of the fault. We remind that the input to our system (the injection point) and the output (where we analyze the reflected signal) are the same.

3.2. Impact of the position of the network elements

Based on this representation, we notice that the system can be divided into two main parts: the one in front of the fault (i.e., from the source side or upstream of the fault), and the other downstream of the fault. When we use the difference system, the first peak obtained when examining the TDR echo would correspond to the first interaction with the fault. Furthermore, this first reflection on the fault does not depend on the elements behind it, so any change in the elements upstream of the fault would affect all the echoes propagating in the system, including this first peak, whilst any change in the elements downstream of the fault will not affect this first peak.

3.3. Equivalent reflection coefficient of the fault at the source position

We denote by Γ_F the reflection coefficient at the fault position (see Figure 1(b)). Here we point out that this coefficient is observed in the time domain; it describes the first interaction with the fault. Consequently, in the difference system, and if the fault is in front of the source (i.e., not separated from the source by any other discontinuity), the first peak we will be observing when examining the reflected signal would correspond to this first interaction; but if the fault is masked from the source by one or more discontinuities, then this first peak would undergo several reflections before arriving to the source position. Consequently, the equivalent reflection coefficient at the source position, denoted as Γ'_F , would change according to the network topology; more precisely, and based on the analysis in the previous paragraph, according to the discontinuities separating the fault from the source.

So why should we be interested in this first peak? because in standard TDR, when determining the presence of an eventual fault, we are also interested in locating this fault. The first peak we observe will help us determine the time delay required to reach the fault from the source, and eventually the position of this fault. We also note that this first peak might or not have the highest amplitude, depending on the system's configuration, along with the nature and position of the fault.

Consequently, we will now determine an expression of Γ'_F , in terms of the network topology. We consider the example illustrated in Figure 1(b), where τ is the transmission coefficient from the first junction. We are interested in finding the amplitude of the first peak arriving to the source position and corresponding to the first interaction with the fault. The amplitude of the voltage wave passing through the first junction of the network is modified by a factor of τ . This wave arrives to the fault and then a part is reflected; its amplitude is modified by a factor of $\tau\Gamma_F$. This wave will next follow the reverse path, and when arriving to the source, the modification in the amplitude will be $\tau^2\Gamma_F$. This whole path is the shortest one to the fault, and since we are considering the difference system, any other echoes which may interact with the first peak or arrive to the source position before it will not be observed in the TDR echo (they are the same with and without the fault, thus the subtraction of the reflected signals in both cases eliminate them).

So, in the general case, where N denotes the number of discontinuities separating the source from the fault, τ_i the transmission coefficient associated with the discontinuity number i , α_i the amplitude of the peak number i , and A the amplitude of the injected pulse, then we can say that, in the TDR case, when analyzing the echo, the amplitude α_1 of the peak corresponding to the first interaction with the fault, as seen from the source would be:

$$\alpha_1 = A\Gamma'_F = A\Gamma_F \prod_{i=1}^N \tau_i^2 \quad (2)$$

One important point is that, while we have till now seen that the highest peak in the standard TDR case does not necessarily correspond to the position of the fault, we did not examine the problem in the MP case. Here, it is difficult to try to follow the path of the dominant echo. Nevertheless, by analyzing the problem mathematically, let us inject our reference pulse into the network. The obtained TDR echo contains several peaks. If t_i denotes the instant when the peak number i appears, then the first peak will be situated at a time delay t_1 from the source. Before time reversing this echo, let us define a time reference by shifting this echo of t_1 . The first peak is now the one situated at the origin. Also, the testing signal is now a time-reversed shifted version of the impulse response of the system $h(t)$. By injecting it into the system, we are convoluting it again with $h(t)$, thus effectively autocorrelating $h(t)$. By calculus, one can easily verify that this autocorrelation has a maximum at the position t_1 , which amplitude is $A \sum_i \alpha_i^2$, actually corresponding to the position of the first peak in the TDR case. Thus, in the MP case, we know (by construction) that the peak with the highest amplitude corresponds to the fault.

So far we have analyzed some of the factors influencing the MP and TDR performances, but not yet compared the two approaches. In the next section, we propose a mathematical tool which will allow us to do that.

4. DETECTION GAIN

To be able to evaluate the advantages of the MP method, we need to find a criterion that enables us to compare it with other methods, such as standard TDR.

In [5], we defined a gain based on the normalized energies of the echoes in both cases. But in the detection process, we know that we are interested only in the peak corresponding to the fault. That is why we propose to define a new gain, referred to as the detection gain G .

Let $\mathcal{E}_{\text{TDR}}^1$ denote the energy of the first peak in the TDR case, and $\mathcal{E}_{\text{MP}}^1$ the energy of the peak corresponding to the fault in the MP case. We consider that the energy of the template $I_0(f)$ is normalized, so $\mathcal{E}_{\text{TDR}}^1$ is the square of the cross correlation function of the TDR echo with $i_0(t)$ at time t_1 . The same definition applies in the MP case, at the instant t'_1 corresponding to the fault. We have

$$\mathcal{E}_{\text{TDR}}^1 = \left| \int H(f) |I_0(f)|^2 e^{-j2\pi f t_1} df \right|^2 \quad (3)$$

and

$$\mathcal{E}_{\text{MP}}^1 = \left| \int |H(f)|^2 (I_0^*(f))^2 e^{-j2\pi f t_1} df \right|^2 \quad (4)$$

If \mathcal{E}_{TDR} and \mathcal{E}_{MP} are respectively the energies of the testing signals in the TDR and MP cases, then G is defined as

$$G = \frac{\mathcal{E}_{\text{MP}}^1 / \mathcal{E}_{\text{MP}}}{\mathcal{E}_{\text{TDR}}^1 / \mathcal{E}_{\text{TDR}}} \quad (5)$$

We will now determine a simplified expression of this gain based on the previously discussed ideas.

In general, we know that any spectrum can be represented by a sum of sub spectrums where the spectrum is a constant. So let us consider the case where $|I_0(f)|$ is constant. Under the hypothesis that the coefficients α_i and α_j are uncorrelated, we have:

$$\mathcal{E}_{\text{TDR}}^1 = \alpha_1^2 \quad (6)$$

and

$$\mathcal{E}_{\text{MP}}^1 = \left| \sum_{i=1}^N \alpha_i^2 \right|^2 \quad (7)$$

The detection gain in this case is

$$G = \frac{\sum_{i=1}^N \alpha_i^2}{\alpha_1^2} \quad (8)$$

We notice that $G \geq 1$. This result is very interesting; first it proves that the MP is always beneficial compared to standard TDR, when it comes to detecting an eventual fault. We also notice that, the more we have peaks in the TDR echo (which is the testing signal in the MP case), the more the MP is effective compared to standard TDR, where the different peaks (besides the one corresponding to the fault) are considered to be a nuisance in the detection process.

In the next section, we consider numerical examples in order to validate all the previously discussed ideas.

5. SIMULATION RESULTS

5.1. Analyzed configurations

We consider the configurations illustrated in Figure 2, where the fault is in front of the source (Figure 2(a)) in the first case, then masked from the source by several discontinuities (Figure 2(b)) in the second case.

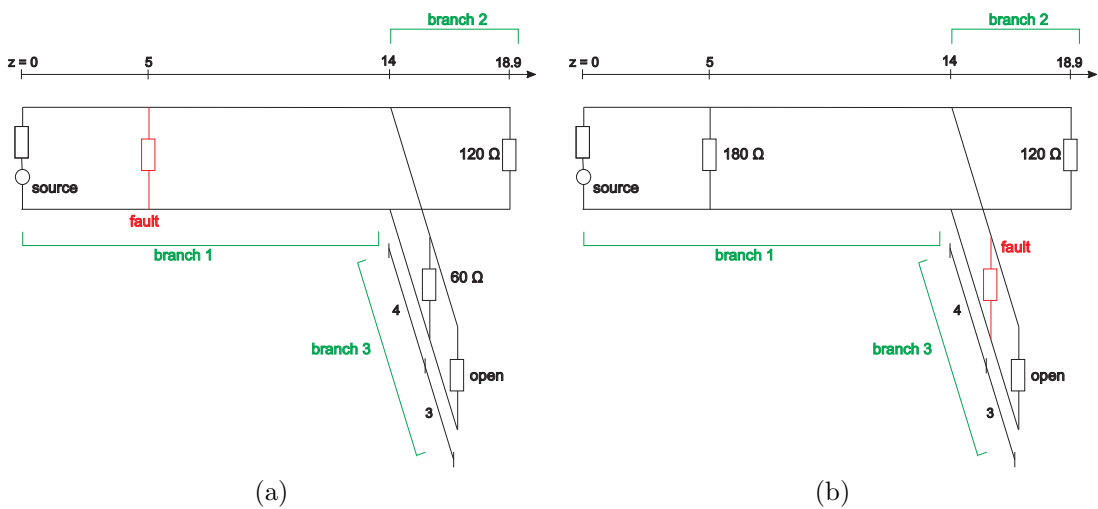


Figure 2: The analyzed networks, showing the positions of the faults in the two studied cases. All lengths are in meters.

Table 1: Numerical results

Fault value (Ω)	Predicted gain (threshold)	Calculated gain
Short	2.33	2.6
30	3.4	4
600	7.7	9.22

5.2. numerical results

We simulated the voltage propagation in the configurations of Figure 2 using the transmission line theory as presented in [9]. The characteristic impedance of the lines is chosen to be 75Ω (such as for some coaxial cables). We will verify the obtained values of the detection gain according to the general formula (Equation 5) and the simplified formula (Equation 8). In this last case, we will be examining a certain number of peaks, thus specifying an inferior limit to the gain (referred to as a threshold in the Table 1).

In the first case (Figure 2(a)), we chose a value of the fault equal to 600Ω , corresponding to a soft fault. The inferior limit of G in this case is 1.55. When we calculate its exact value, we find $G = 1.73$. In the second case (Figure 2(b)) when the fault is masked from the source by several discontinuities, we chose several values of the fault, illustrated in Table 1. In this configuration, the fault is separated from the source by a discontinuity at 5 m and a junction at 14 m. The numerical values obtained when calculating the inferior limit of the detection gain, along with its exact values are illustrated in Table 1. When examining those results, we notice that the more the fault is soft (i.e., the reflection coefficient at the source position is small), the more the MP becomes effective when compared to standard TDR. If we also compared the two configurations of Figure 2 when the fault's value is 600Ω , we notice that when the fault is embedded in the system, the gain's value is greater than the case where the fault is directly in front of the source. In fact, in the first case we have a greater number of peaks than in the second case; so as predicted by the Equation 8, we have a greater value of the detection gain.

6. CONCLUSION

In this paper, we evaluated the impact of the network topology on the performance of the TDR and MP approaches. A physical study allowed us first to state what are the most influencing factors on the effectiveness of the TDR, then a mathematical analysis proved the advantage of the MP method over the standard TDR. The discussed ideas were finally verified through simulation results. This whole study allowed a better understanding of the factors influencing the TDR performance, thus enabling us, for any configuration, to predict the effectiveness of the MP approach compared to standard TDR.

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