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On the Diagnosis of Incipient Faults in Transmission Lines Using a Projection Approach Based on Phase Patterns

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Abstract— Throughout the last decade, the problem of soft fault detection in transmission lines have been overflowed with contemporary powerful technologies. However, a vast majority of state-of-the-art techniques including the well-known reflectometry methods, require bandwidths in the order of hundreds of megahertz for providing spatial resolution in the millimeter range of faults' locations. On the other hand, an emerging technique based on the analysis of multi-port transmission and reflection parameters, often referred to as the Time-reversal multiple signal classification (TR-MUSIC) ensured location accuracy and sub-millimeter resolution of multiple soft faults in complex wire networks. More importantly, this was made possible using continuous wave excitations even at low frequencies. However, as any other existing method, it suffered from the problem of attenuation inherent to transmission lines. In this paper, we will introduce a method based on Green function phase pattern analysis of tested cables relying only on reflection parameters, with no need for acquiring the transmission ones. In effect, testing long cables as in the case of power grids becomes possible. The proposed technique is shown to be robust against attenuation. Besides, it appears to be readily adapted for lively monitoring transmission lines, thanks to its continuous wave excitation abilities. The technique is shown to operate frequency by frequency, which allows the choice of specified frequency samples if distortion is present. Moreover, the proposed processing is shown to reinstate precise super-resolved estimates of soft fault locations. Experimental results based on coaxial cable implementation is provided to validate the method's feasibility.

1. INTRODUCTION

According to recent reports, at the end of 2017 there were 8.4 billion connected entities (devices) across the globe which is likely more than the total human population on earth! By 2020, different surveys project this number to be between an astounding 26–100 billion connected devices [1]. In such a more and more connected world, transmission lines are responsible of pumping life to systems delivering and connecting both energy and information. Keeping in mind the importance of having an electrical system where continuity, compliance, flexibility, and maintainability are observed and guaranteed, it is important to ensure a smooth operation of transmission lines to deliver a minimally interrupted energy supply making necessary for reliable operation of electrical cables. This need has given rise to fault detection and location techniques so that the impact of fault situations can be mitigated and their correction can be rendered simpler and precise.

Designing reliable and accurate fault locating algorithms is still considered a challenge despite the intense research and development efforts transcribed in literature. Over the years, many methods and various techniques have been harnessed for accurate fault diagnosis in different configurations of transmission line networks. Perhaps the most popular and ambitious are those based on the principles of reflectometry [2–4]. Conceptually, reflectometry is based on analyzing the reflected echo by an impedance discontinuity (junction, fault, etc.) on a cable under test (CUT) as a result of a pulse injected at one end of the cable thus providing valuable information regarding the position and nature of a fault. The location of open and short circuits (hard faults) affecting a CUT was up for grabs with almost all variants of reflectometry techniques [5]. However, minor erosions affecting wires (insulation damage, frays, etc.), which are often referred to as soft faults witnessed detection failure with many versions of reflectometry [6–9]. Although, this latter family of faults might appear seemingly harmless in their early stages, their potential degradation due to several factors (time, aggression, temperature fluctuations, etc.) might end them up to hard faults thus leading to catastrophic consequences. This has increased the attention to their criticality necessitating progressive monitoring to troubleshoot and repair avoiding a sudden system collapse.

Moreover, any method based on time-domain analysis, belonging to time-domain reflectometry (TDR) methods or not, relies on the availability of potentially large bandwidths (GHz), in order to create the conditions for spatial resolution [10]. Limitations are thus introduced by the ability of cables in a network to support such bandwidths, as in the case of low-frequency networks, such as power grids.

Online cable diagnosis is an essential research field that has seen light in the past decade. It offers the possibility of performing the diagnosis concurrently to the normal operation of the network, i.e., when voltage is on for supply wires and while communication is running for signal cables. This last condition requires harmlessness: diagnosis must not interfere with communication signals, and useful signals must not trigger any false alarm. Within this context, Spread Spectrum TDR (SSTDR) [11], Multi Carrier TDR (MCTDR) [12], Orthogonal Multi-Tone TDR (OMTDR) [13], and Chaos TDR (CTDR) [14] were introduced. One advantage is that they enable separating the spectra of the native network signals and the probe signal, thus canceling any interference while providing bandwidth efficiency and complete spectrum control. Although promising results were obtained based on full-scale field measurements, a big number of subcarriers was still needed to create the conditions of a good spatial resolution.

Time reversal (TR) based methods have been recently extensively investigated and successfully applied to the soft fault location problem in wire networks, thanks to the close relationship that exists between the problem of scatterer detection in radar and fault detection in cable networks [15]. This was possible through two of the TR variants, DORT standing for the French acronym of the decomposition of the time reversal operator [16, 17] and TR-MUSIC [18, 19]. For instance, they allow the simultaneous analysis of all network multi-port data leading to energy focusing on the position of soft faults in an imaging manner. However, the complete scattering matrix of the tested network is necessary, that includes both reflection and transmission parameters, which is unfortunately not attainable for, long cables as in power grids.

Attenuation, an inherent characteristic to transmission lines, has always devastated a vast majority of fault diagnosing techniques in terms of reducing the amplitude or strength of signals (incident or reflected) propagating along the length of a CUT [6]. This has limited the accurate location of defects especially that lots of existing methods operate using high frequency test signals where attenuation is dominant. Particularly, it has also cut chances of their practical implementation.

To sum up, several challenges as aforementioned formed an impasse towards the proper application of soft fault detection and location methods leading to either ambiguous results, false alarms or inaccuracy in location. Within this context, we will propose in this paper a novel technique for soft fault diagnosis in CUTs based on a projection process between the phase patterns of the tested networks reflection coefficients measured in the frequency domain and its post-processed simulated Green functions. Particularly, the proposed approach will be capable of returning sub-wavelength estimates of the faults locations using continuous wave (CW) excitations in live cables even in the presence of attenuation.

2. THE PROJECTION BASED FAULT LOCATION APPROACH

2.1. Background and Motivation

The proposed soft fault location method operates through a projection procedure, involving the phase patterns of both the reflection parameters of the faulted CUT and the Green function $\mathbf{g}_r(\mathbf{x}_c)$, computed at discrete positions x_c of the cable. Accordingly, for each of these points the Green function must be derived. As a matter of fact, a Green function is a complex mathematical tool which represents a wave varying both in time and space. It thus represents a propagating wave from a certain point to another where only the phase pattern of the wave is taken into account. In transmission lines, the Green function is a voltage computed at each position x_c of the line by numerically injecting test signals to a healthy version of the CUT. It is thus no more than a transfer function, considered at different line positions.

To better understand the background of the proposed approach, we will refer to TR-MUSIC applied to wire diagnosis. Particularly, TR-MUSIC applied to soft fault location operates on a similar projection process. It is performed between the CUT's Green function phase pattern and what is referred to as the noise space \mathcal{N} of the network's time reversal operator (TRO). Specifically, the TRO is the central key of most TR variants which is obtained from the measured scattering matrix as $\mathbf{K} = \mathbf{S}^\dagger \mathbf{S}$, where the superscript \dagger is the Hermitian transpose. The signal space \mathcal{S} is formed from eigenvectors having significant eigenvalues $\mathcal{S} = \text{span}\{\mathbf{u}_i : \lambda_i > \lambda_{th}\}$, with λ_i and \mathbf{u}_i being the eigenvalues and their corresponding eigenvectors, respectively; λ_{th} is set by analyzing the scree plot of the eigenvalues of \mathbf{K} . On the other hand, \mathcal{N} is formed from the remaining eigenvectors deemed to have negligible eigenvalues $\mathcal{N} = \text{span}\{\mathbf{u}_i : \lambda_i < \lambda_{th}\}$. TR-MUSIC operates on \mathcal{N} , accordingly, each fault position can be spotted by observing the singularities obtained in the

so-called pseudo-spectrum $\Phi(X_c)$ at each position x_c given by:

$$\Phi(X_c) = \frac{1}{\sum_i |\mathbf{u}_i^\dagger \mathbf{g}_r(\mathbf{x}_c)|^2}, \quad (1)$$

For instance, since the actual fault's position is not known in advance, each position x_c can be a good candidate of the fault. Accordingly, in order to clear doubts with certainty, TR-MUSIC operates by comparing the phase patterns of the eigenvectors of \mathcal{N} with those of the Green function vector at different candidate position x_c along the line. The phase patterns will coincide whenever x_c matches the real fault's location.

In particular, TR-MUSIC validated with experimental measurements on different complex-networks has been shown to enable super-resolved estimates of a fault location while using continuous-wave excitations, powering sub-wavelength imaging techniques [10]. Resolutions of the order of the millimeter have been demonstrated while testing networks with signals below 10 MHz. Similar spatial resolutions would require test signals covering bandwidths spanning several GHz when using reflectometry techniques.

Theory has it that MUSIC-based processing can potentially achieve unlimited resolution with noiseless data. Specifically, the orthogonality between the signal and the noise subspace is what make that possible. But real-life networks and the associated testing equipment are routinely affected by background noise, or signals during online tests, which might be sufficiently high to degrade the quality of MUSIC processing [19, 20]. In fact, noise greatly devastates the components of the noise subspace \mathcal{N} , thus leading to spurious results with the projection process.

2.2. Steps of the Proposed Approach

In order to bypass the limitations explained in Section 2.1, the inverse projection process is considered. In other words, instead of counting on \mathcal{N} , the orthogonal space to \mathcal{S} which can be greatly devastated by noise, we rather consider the orthogonal form $\mathbf{g}_r^\perp(\mathbf{x}_c)$ of the Green function vector $\mathbf{g}_r(\mathbf{x}_c)$. More importantly, we no longer rely on any of the TRO spaces, the phase pattern vector \mathbf{v} of the reflection parameters S_{ii} is only used. Consequently, there is no need to measure the transmission parameters of the CUT.

For the sake of simplicity and to comprehensively deliver different steps followed in the proposed approach, we will consider a simulation based simple example designated by a single branch point-to-point CUT of length 2.5 m and a soft fault inserted at 1.85 m from the first testing port as shown in Fig. 1. The choice of the cable or the soft fault has no effect on the applicability of the technique as the method can be applied on any type of cables or any kind of soft fault (insulation damage, crushed section, fray, etc.). Having set our network for diagnosis, the proposed approach is composed of 4 steps.

1. The very first step starts by measuring the reflection scattering parameters ($S_{ii}(\omega)$) of the faulty network which can be done either by simulation or by means of a vector network analyzer (VNA), etc. Notably, ω is the angular frequency. So, in our case study we will compute the two reflection scattering parameters involved which are $S_{11}(\omega)$ and $S_{22}(\omega)$ given by:

$$\begin{aligned} S_{11}(\omega) &= \Gamma_1 = \Gamma_f e^{-j2\omega\tau} \\ S_{22}(\omega) &= \Gamma_2 = \Gamma_f e^{-j2\omega(T-\tau)} \end{aligned}$$

With T being the time needed for a wave to travel along the line while τ being the exact time needed for the wave to reach the position of the fault starting from port (1). Γ_f is the reflection coefficient of the soft fault.

2. The second step includes computing the phase pattern vector \mathbf{v} of the reflection coefficients which is done by normalizing the scattering reflection parameters at each frequency sample as follows:

$$\mathbf{v} = \begin{bmatrix} S_{11}(\omega) \\ |S_{11}(\omega)| \\ S_{22}(\omega) \\ |S_{11}(\omega)| \end{bmatrix} = \begin{bmatrix} e^{-j2\omega\tau} \\ e^{-j2\omega(T-\tau)} \end{bmatrix}$$

3. The third step is a post-processing phase. We will consider, based on a transmission line simulation model developed with Matlab, a network similar in characteristics to the tested one

in terms of the length of the cable. However, we will not consider any fault. On the contrary, we will compute the Green function vector $\mathbf{g}_r(\mathbf{x}_c)$ at each candidate or hypothesized fault position x_c along the simulated CUT. Accordingly, at each candidate position x_c occurring at τ_c , $\mathbf{g}_r(\mathbf{x}_c)$ generated from such a point to both testing ports can be found as demonstrated in Fig. 2.

This is followed by deriving the orthogonal form of the Green function vector $\mathbf{g}_r(\mathbf{x}_c)$ at each x_c as follows:

$$\mathbf{g}_r^\perp(\mathbf{x}_c) = \begin{bmatrix} 1 \\ -1 \end{bmatrix} \begin{bmatrix} e^{-j2\omega\tau_c} \\ e^{-j2\omega(T-\tau_c)} \end{bmatrix}$$

In fact, this vector will be computed at each considered frequency sample or continuous wave excitation. In other words, for a given frequency sample m , there will be N Green function vectors, with N being the total number of candidate fault positions.

4. In the last step of the proposed approach, a projection procedure is done between the Green function vectors $\mathbf{g}_r^\perp(\mathbf{x}_c)$, with c ranging from 1 to N , and the phase pattern vector \mathbf{v} as follows:

$$\Psi^{(m)}(x_c) = \frac{1}{\sum_{c=1}^N |\langle \mathbf{v}, \mathbf{g}_r^\perp(\mathbf{x}_c) \rangle|^2}, \quad (2)$$

A singularity occurs once the candidate position x_c falls on the actual position of the fault, which is obtained from the resulting zero projection of the two vectors at the fault's eventual location.

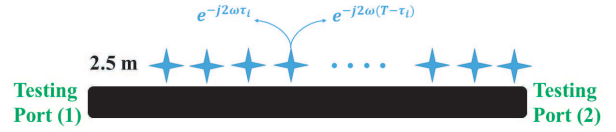
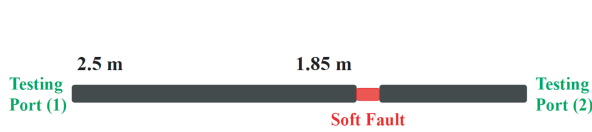


Figure 1: A single point-to-point cable affected with a soft fault.

Figure 2: Green function generation at each fault candidate position along the CUT.

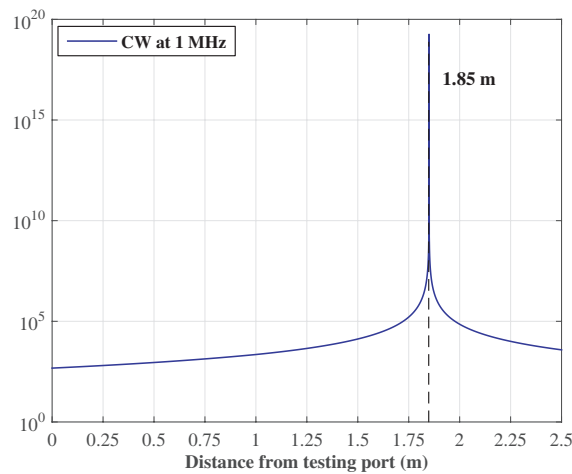


Figure 3: The singularity obtained at the fault's position as a result of the projection process between the Green function vectors and the phase pattern vector of the reflection coefficients of the CUT of Fig. 1.

Figure 3 shows the result obtained with the considered example, where a continuous wave excitation of 1 MHz was used to compute the phase vector \mathbf{v} of the reflection parameters. The projection procedure has led to a clear *super-resolved* identification of the soft faults location demonstrated by the obtained singularity.

2.3. Experimental Validation

In order to check the applicability and feasibility of the proposed technique on real-life networks, we conducted an experimental setup considering a 6.81 m point-to-point CUT. The network was implemented using standard $50\ \Omega$ coaxial cables as transmission lines. A 6-cm long sample made of semi-rigid coaxial line of 3.4 mm cross section, as that shown in Fig. 4, was used in order to introduce the fault. The soft fault was created at distance 6.28 m from testing port (1) by removing the copper sheath on a 2 mm long section. This guaranteed a soft fault with a weak reflectivity.

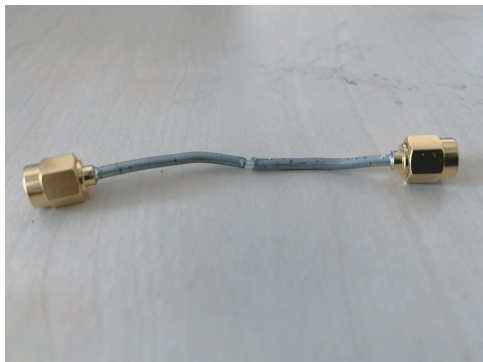


Figure 4: The faulty sample used to introduce the soft fault within the CUT for the experimental test.

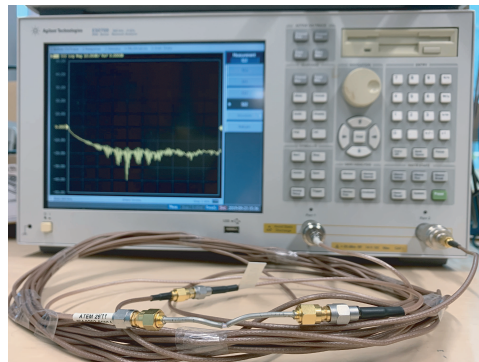


Figure 5: Experimental setup for the 6.81 m point-to-point CUT, containing a soft fault at 6.28 m from the testing port (1), connected to the VNA for the experimental tests.

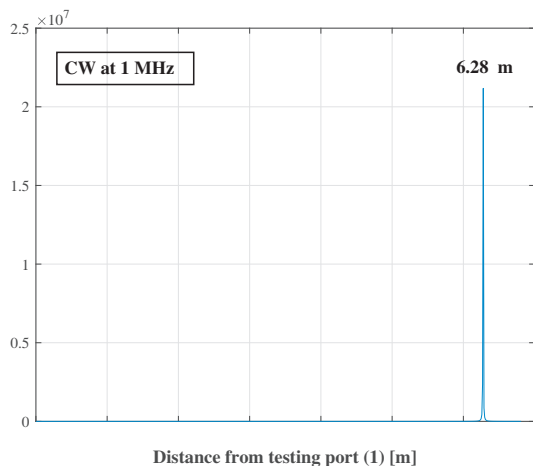


Figure 6: Pseudo-spectrum of the proposed approach applied on the CUTs computed on the basis of a continuous wave excitation of 1 MHz. Super-resolved singularity indicate the fault's positions.

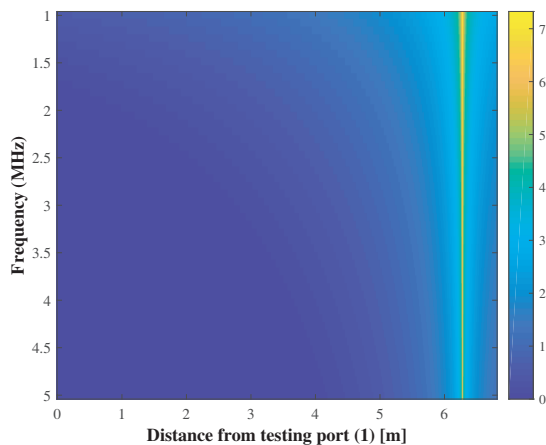


Figure 7: Pseudo-spectrum obtained for the experimental validated of the proposed approach for the CUT of Fig. 5 on a frequency range from 1 MHz to 25 MHz.

The ends of the CUT were used as testing ports, by connecting them to an E5070B Agilent technologies VNA, covering a frequency range from 300 kHz to 3 GHz, with two testing ports; an example of a complete setup is shown in Fig. 5. After calibrating the VNA using the calibration kit provided by the manufacturer, studying the network consisted of measuring the reflection parameters (S_{ii}). This was accomplished over a bandwidth ranging from 1 MHz to 25 MHz with a step of 1 MHz, so that to have CW (single frequency) testing signals at integer multiples of 1 MHz. Besides, an intermediate-frequency filter bandwidth of 100 kHz and an input power of 0-dBm harmonic excitation signal were set.

Henceforth, the procedure described in Section 2.2 of the proposed approach is applied. Fig. 6 demonstrates a remarkable feature of the proposed method, a *super resolved* singularity is obtained on the fault's position using a CW excitation of 1 MHz. On the other hand, Fig. 6 shows the pseudo-spectrum computed from experimental data on the whole set of frequencies (1 MHz to 25 MHz);

where a vertical constellation of singularities located at 6.28 m characterized by a bright vertical line is attained regardless the testing signal frequency used.

3. CONCLUSION

This paper has investigated the performance of a new proposed technique for soft fault location in transmission lines. An outstanding performance in ensuring a sub-millimeter resolution of the fault's location while utilizing relatively low test frequencies is an extraordinary feature, since obtaining such performance with state-of-art techniques is impossible unless higher test frequencies and wider bandwidths are used. Indeed, the most striking advantage is that the novel approach accurately locates soft faults while using continuous signals.

Furthermore, results have shown that the performance of the proposed method does not depend on the chosen test frequency, thus appears as more readily adaptable to the case of live testing, where the CUT would be under use over a given set of frequencies and thus test signals could ideally be allocated outside these frequencies.

Future work will need to deal with the robustness of the approach with lossy cables (attenuation) and in the presence of noise. Testing branched networks could also be interesting.

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