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Technical note

Model-based identification of wire network topology

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ABSTRACT

A new technique is proposed to locate wire faults and identify wire network topology using Impedance Spectroscopy (IS). The propagation along the cables is analytically modelled with flexible multi section cascading features utilizing frequency dependent scattering parameters. Therefore, it does not have the common numerical method problems. The transmission line model has the same spectrum as the measured reflection coefficient (ρ) of wire under test (WUT) so that same practical effects such as skin and proximity effects, signal loss, dispersion and frequency dependent signal propagation can be exactly incorporated. For determination of model parameters an inverse problem should be resolved and differential evolution (DE) approach is proposed. The novel method allows locating hard (short and open circuit) and soft (frays and junctions) faults and also for characterization of defects in the branches of network. Results are presented to validate and illustrate the performance of this proposed method.

1. Introduction

The increasing use of the wiring in vehicles, communication and power systems has caused growing requirement for characterization of wire network and location of wire faults. The most widely used technique is reflectometry. Thereby, a high-frequency signal is send down the cable. The reflected signal including information about changes of cable impedance is used to locate wiring faults. Over the last decade, many methods, such as Time Domain Reflectometry (TDR) [1,2], Frequency Domain Reflectometry (FDR) [3,4], Ultra Wide Band (UWB) based TDR [5], and Spectrum Time Domain Reflectometry (STDR) [6] were developed. They use different incident signal and signal processing methods. However, these techniques fail to detect soft faults such as frays or chafes and identification of the network topology in practice.

Some improved TDR methods [7] use the baseline method, in which the output signal of the faulty wire is compared with the output of the healthy wire, in order to enable to detect and locate the soft faults. The TDR method has the advantage to identify the type of wire faults. Other methods focus more on improving location accuracy.

But for all these methods, the wave propagation velocity is approximately considered as a constant parameter which is only dependent on the permittivity of the cable. It limits the accuracy of wire fault location because the time of flight is transformed to the location by means of the wave propagation velocity, which is dependent on the wire type and the available frequencies of the excitation signal.

Furthermore, soft faults, such as frays and chafes, and multiple faults are difficult to detect by the baseline method. Especially at higher complexity of the wire topology there are practical difficulties because of noise, multiple reflections, unknown load impedances, mechanical variations and changes of electrical parameters due to different wires types.

The aim of this study is the development of an automated method for the wire fault location. With this new method the type of wire faults can be identified and the network topology can be characterized. In this study the propagation along the cables is analytically modelled with

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flexible multi section cascading features using frequency dependent scattering parameters. The computation time of this analytical model is nearly constant and independent on the wiring length. The simulation and measurement in this study are both implemented in the frequency domain, so that the Fourier transform is not necessary and the resolution and computation time of this approach is improved. The same practical effects such as skin and proximity effects signal loss, dispersion and frequency dependent signal propagation can be exactly incorporated by the forward model. Therefore, this model is much more efficient, accurate than the numerical methods and is able to simulate the very tiny wire faults. The results shown good matching between simulation and measurement data and consequently the optimization technique has a fast convergence and best accuracy. For determination of model parameters an inverse problem should be resolved and differential evolution (DE) approach is proposed. The input reflection coefficient is measured to locate the wire faults and identify the types of wire faults.

Section 2 explains the modelling of the transmission line. Section 3 the parameter extraction using global optimization techniques is described. Section 4 gives the results and analysis. Section 5 describes the conclusions.

2. Transmission line model

Model based system identification methods are used to reconstruct the transmission line parameters. These algorithms consist of two parts. The first part is forward modelling which is used to simulate the transmission line. Then optimized techniques are used to solve the inverse problems. The simulated result of the forward modelling is applied to compare with the measured data. If they match each other, the wiring system can be identified and the wiring parameters can be reconstructed so that the wiring faults can be detected and located.

In this study *ABCD* matrix and *S* parameters methods are used to simulate the transmission lines in frequency domain with frequency dependent parameters in order to solve the limitations of the time domain transmission line modelling. The same occurring effects such as signal loss, dispersion and frequency-dependent signal propagation can be exactly incorporated by the transmission line model [8]. With these methods transmission lines can be directly simulated in the frequency domain with realistic results. The simulation time of this algorithm is independent of the wire length because it is an analytical solution and flexible multi section cascading features so that this method has higher efficiency for the simulation and better accuracy than the time domain transmission line modelling.

The input reflection coefficient of WUT is measured in frequency domain by Impedance Spectroscopy (IS). The *ABCD* model and *S* parameters have been setting as the same spectrum as the measured input reflection coefficient of the transmission line system so that there is good matching between simulation and measurement data and consequently the optimization technique has a fast convergence and best accuracy.

2.1. ABCD matrix and S parameters

Fig. 1(a) illustrates the cross section of a simple coaxial cable. The inner conductor has a radius a. The outer conductor (shield) has an inner radius b and thickness Δ. The outer radius of the shield is c. Both of the conductors have the same electrical conductivity σ. The cable interior is filled with a lossy dielectric having a relative permittivity $\varepsilon_{\mathrm{rel}}$. The magnetic permeability is assumed to be that of free space μ_0. The relative permittivity is assumed to be frequency dependent.

The per-unit-length line outer inductance parameter L'_{out} and capacitance parameter C' can be described by the following equations [9]:

$$L'_{out} = \frac{\mu_0}{2\cdot\pi}\cdot\ln(b/a)\ \mathrm{H/m} \quad C' = \frac{2\cdot\pi\cdot\varepsilon_0\cdot\varepsilon_{rel}}{\ln(b/a)}\ \mathrm{F/m} \tag{1}$$

When the conductors of the coaxial line are finitely conducting, there will be additional per-unit-length impedance elements in the transmission line model that take into account both the magnetic flux penetration into the conductors and the resistive loss [9,10]. For the inner conductor with radius a, the per-unit-length impedance is given by following equation:

$$Z'_a(\omega) = \frac{\eta}{2\cdot\pi\cdot a}\left[\frac{J_0(\gamma\cdot a)}{J_1(\gamma\cdot a)}\right]\ \Omega/\mathrm{m} \tag{2}$$

where J_0 and J_1 are modified Bessel functions of order zero and one. ω is the angular frequency. The term η is the wave impedance in the lossy conductor, and if the displacement current in the conductor is neglected, this term η and ζ are given as:

$$\eta \approx \sqrt{\frac{j\cdot\omega\cdot\mu_0}{\sigma}} \quad \zeta = \sqrt{j\cdot\omega\cdot\sigma\cdot\mu_0} \tag{3}$$

The per-unit-length impedance of the outer shield is derived by following equation:

$$Z'_b(\omega) = \frac{\eta}{2\cdot\pi\cdot b}\left[\frac{J_0(\zeta\cdot b)\cdot K_1(\zeta\cdot c)+J_1(\zeta\cdot c)\cdot K_0(\zeta\cdot b)}{J_1(\zeta\cdot c)\cdot K_1(\zeta\cdot b)-J_1(\zeta\cdot b)\cdot K_1(\zeta\cdot c)}\right]\ \Omega/\mathrm{m} \tag{4}$$

where K_0 and K_1 are the modified Bessel functions of the second kind, and c is the outer radius of the shield.

The transmission line model is composed of discrete resistors, inductors, capacitors and conductance. A length z of transmission line can conceptually be divided into an infinite number of increments of length Δz (dz) such that series and shunt R', L' G' and C' are given as shown in Fig. 1(b). Each of the parameters R', L' and G' is frequency dependent. For example, R' and L' will change in value due to skin effect and proximity effect. G' will change in value due to frequency dependent dielectric loss [10–17]. From Eqs. (1)–(4) we can calculate the shunt R' (Ω/m), L' (H/m), G' (S/m) and C' (F/m):

$$\begin{aligned} R' &= \mathrm{real}[Z'_a(\omega)+Z'_b(\omega)] \\ L' &= \mathrm{imag}[Z'_a(\omega)+Z'_b(\omega)]/\omega + L'_{\mathrm{out}} \end{aligned} \tag{5}$$

$$G' = \frac{\pi\cdot\omega\cdot\varepsilon''}{\ln(b/a)} = \omega\cdot\tan\delta\cdot C' \quad C' = \frac{2\cdot\pi\cdot\varepsilon_0\cdot\varepsilon_{\mathrm{rel}}}{\ln(b/a)} \tag{6}$$