Bounded Phase Property of Electromagnetic Time Reversal in Multiconductor Transmission Lines

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Abstract

This paper generalizes the electromagnetic time reversal (EMTR) in mismatched media based bounded phase property in locating faults in multiconductor transmission lines. The so-called direct-reversed-time transfer function is first derived in matrix notation as an analogue of its original expression in two-conductor transmission lines. The bounded phase property is then extended in both symmetrical and unsymmetrical fault scenarios.

1 Introduction

The classical applications of *time reversal* adhere to the principle of *matched media*, namely that the backward-propagation medium [in the *reversed time* (RT)] is identical to the forward-propagation medium [in the *direct time* (DT)] [1]. Inspired by the time-reversal property of focusing electromagnetic waves on the original source in *changing* or *mismatched media* (e.g., [2], [3]), the mismatched *electromagnetic time reversal* (EMTR) fault location method was recently proposed relative to the classical or matched-EMTR method [4]–[6].

The *bounded phase* property came to light in the earliest definition and application of the *lumped mismatched media* condition in the fault location problem [4]. Specifically, it was proved that the phase angle of the *direct-reversed-time transfer function* is bounded between $\pm\pi/2$ exclusively at the true fault location. In addition, the property was validated in a range of simulation cases considering two-conductor homogeneous and inhomogeneous transmission lines and Y-shaped networks.

On the other hand, it is worth noting that available analyses of applying the bounded phase property to the problem of fault location in *multiconductor* transmission lines are still lacking. In this regard, the present paper is focused on extending the concept of lumped mismatched media and the bounded phase property to the case of three-conductor transmission lines.

2 Bounded phase property in two-conductor transmission lines

2.1 Lumped mismatched-media condition

When the principle of matched media is applied to the EMTR-based fault location method in electrical power systems, since the true fault location is undetermined, a set of *a priori* guessed fault locations needs to be defined, allowing reproducing (by numerical simulation) a fault occurrence at each of those locations through a transverse branch [7], [8].

In contrast, the lumped mismatched media condition assumes a non-faulty power network in the backward-propagation stage, thus excluding the transverse branch set up at each guessed fault location to simulate a fault. Consequently, this introduces a lumped mismatch between the forward- and backward-propagation media as a result of changing the boundary condition at the fault location from the fault state to the non-fault state. Note that all the line parameters and the other boundary conditions (e.g., at the line terminals) of the targeted power network remain intact [4]–[6].

2.2 Direct-reversed-time transfer function and its bounded phase property

Considering a fault scenario wherein a two-conductor transmission line is subject to a short circuit fault, the direct-reversed-time transfer function $H(x,j\omega)$ is formulated as the ratio of $V^{\mathrm{RT}}(x,j\omega)$ and $V_f(x=x_f,j\omega)$, within the framework of lumped mismatched media [6]. $V^{\mathrm{RT}}(x,j\omega)$ is the output function (i.e., the voltage along a non-faulty power network) in the backward-propagation stage with x being the position coordinate, and $V_f(x=x_f,j\omega)$ refers to the input function (e.g., a step voltage [6]) that emulates the fault occurrence in the forward-propagation stage at an arbitrary location $x=x_f$.

The spatial dependence of $H(x,j\omega)$ enables the true fault location x_f to be distinguished from other guessed fault locations using certain features of $H(x,j\omega)$, for example, the energy or the phase angle [4]–[6].

The bounded phase property mathematically states that the phase angle of $H(x,j\omega)$ presents the following theorem

Theorem 1

if $x=x_f$, $\angle H(x,j\omega)\in(-\pi/2,\ \pi/2\,)$;

$$\forall x \neq x_f,\ \exists\, f = \omega/2\pi\colon \angle H(x, j\omega) \notin (-\pi/2,\ \pi/2).$$

The symbol $\angle$ denotes the phase angle or argument in radians.

Let us consider a fault case in a Y-shaped two-conductor transmission line network to visualize the property. Figure 1 illustrates $\angle H(x, j\omega)$ as a function of guessed fault locations and frequencies in the *x*-*f* plane. This figure plots at each guessed fault location only the out-bounded phase angle, namely $\angle H(x, j\omega) \notin (-\pi/2,\ \pi/2)$. As shown, $\angle H(x, j\omega)$ at the real fault location $x_2 = x_f = 7.9$ km exclusively features a bounded phase angle among the guessed fault locations, displaying a null distribution throughout the considered frequency range.

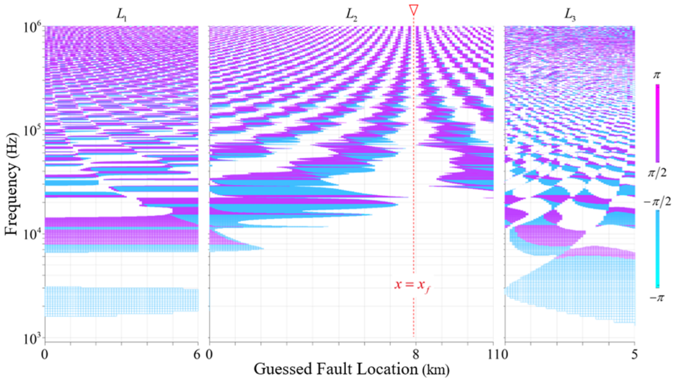

Figure 1: Phase angle of the transfer function $H(x, j\omega)$ for the case $x_2 = x_f = 7.9$ km in a Y-shaped inhomogeneous transmission line network.

3 Bounded phase property in multiconductor transmission lines

The direct-reversed-time transfer function is generalized by illustrating the concept of lumped mismatched media to address the fault location problem in multiconductor transmission lines. Without loss of generality, the investigation focuses on three-conductor transmission lines, which suffice to represent typical single-circuit power networks.

The direct-reversed-time transfer function is derived in matrix notation as an analogue of that in two-conductor transmission lines. The bounded phase property is analyzed and extended in various fault cases, including symmetrical faults (i.e., three-phase-to-ground faults) and unsymmetrical faults (e.g., single-phase-to-ground faults).

Acknowledgments

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