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Diagnosis of inhomogeneous insulation degradation in electric cables by distributed shunt conductance estimation ☆

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ABSTRACT

For the diagnosis of inhomogeneous insulation degradation in electric cables, the estimation of distributed shunt conductance is studied in this paper. Gradual growth of the shunt conductance is a consequence of degradation of the dielectric properties of the insulator. The proposed estimation method is based on voltage and current measurements at a single end of the cable. After the linearization of the bilinear term of the telegrapher's equations through a perturbation approach, the Kalman filter is applied to transform the problem of dynamic system parameter estimation to a simple linear regression problem. Results of numerical simulations are presented to demonstrate the feasibility of the proposed method. In particular, it is shown that the weak sensitivity of the available measurements to the shunt conductance can be compensated by long time data samples.

1. Introduction

Electric cables are widely used for power supply and for signal transmission in modern engineering systems (Paul, 2008; Ulaby, Michielssen, & Ravaioli, 2010). Such electric cables have often been considered reliable and neglected in the design of fault diagnosis devices. Today the reliability of some wired networks is becoming more and more critical, such as wired telecommunication networks and power lines in automotive vehicles, but little effort has been paid to the research on fault diagnosis for such networks. To satisfy new requirements on security and on quality of service, it is necessary to develop techniques for the monitoring of electric cables (Bock et al., 2004; Wheeler, Timucin, Twombly, Goebel, & Wysocki, 2007). For the diagnosis of *insulator gradual degradation* in electric cables, the estimation of the distributed shunt conductance is studied in this paper. After spatial discretization, it amounts to solving a large parameter estimation problem in a dynamic system. Similar problems are frequently studied in various fields. For example, recently the least-squares method has been employed for physical parameter estimation in MEMS gyroscopes (Hao, Li, Han, & Jia, 2012), in electro-hydraulics (Mohanty & Yao, 2011a,b) and in magnetic suspension (Yang, Hu, & Ding, 2012). The main particularity of the problem considered in the present paper is related to its bilinear and distributed nature. The proposed solution consists of a series of transformations to achieve an appropriate problem formulation, which is suitable for the application of the efficient least-squares method, as developed in this paper.

1.1. Telegrapher's equations

In an electric cable with good dielectric properties, the shunt conductance per unit length, usually denoted by G, is very weak (Moore, 1997). Gradual growth of the shunt conductance is a consequence of the degradation of the dielectric properties of the insulator. As illustrated in Fig. 1, in order to infer about the shunt conductance distributed along a cable through experiments, it is assumed in this paper that a voltage source and a measurement instrument (such as a signal generator and an oscilloscope) are connected to the *same* end of the cable. The diagnosis method presented in this paper is based solely on the signals observed at this end of the cable, since it is unrealistic to make measurements all along the cable in most practical situations. Measurements could be made simultaneously at both ends of the cable, but the proposed method is intended for the diagnosis of long cables (hundreds of meters in length), it is more convenient to work at only one end of a cable.

A cable excited by a signal generator can be characterized by the telegrapher's (Dworsky, 1979; Paul, 2008; Sadiku, 2009)

$$\frac{\partial}{\partial z}V(t,z)+L(z)\frac{\partial}{\partial t}I(t,z)+R(z)I(t,z)=0 \tag{1a}$$

$$\frac{\partial}{\partial z}I(t,z)+C(z)\frac{\partial}{\partial t}V(t,z)+\varepsilon G(z)V(t,z)=0 \tag{1b}$$

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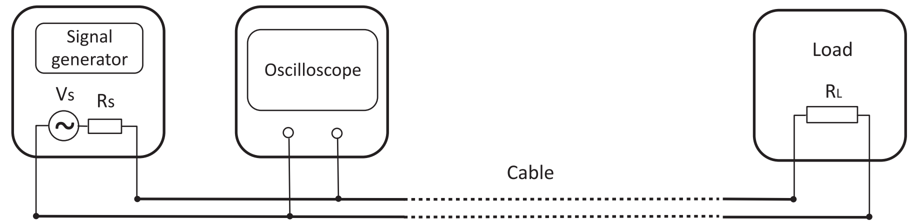

Fig. 1. Cable and measurement illustration.

where $t \geq 0$ represents the time, $z \in [a,b] \in \mathbb{R}$ is the longitudinal coordinate along the cable, $V(t,z)$ and $I(t,z)$ are respectively the voltage and the current in the cable at the time instant t and at the position z, $R(z), L(z), C(z)$ and $\varepsilon G(z)$ denote respectively the series resistance, inductance, capacitance and shunt conductance per unit length of the cable at the position z. As typically the shunt conductance is very weak (Moore, 1997), a small positive value ε is introduced so that $G(z)$ has an order of magnitude similar to those of the other parameters.[1] The left end of the cable (corresponding to $z=a$) is connected to a voltage source $V_s(t)$ with internal impedance R_s and to a measurement instrument so that the current $I(t,a)$ at the left end can be computed through simple calculations. The quantities $V_s(t)$, R_s, $V(t,a)$ and $I(t,a)$ are related by

$$V(t,a) = V_s(t) - R_s I(t,a). \tag{2}$$

At the right end of the cable (corresponding to $z=b$), if the cable is connected to a load of impedance R_L, then

$$V(t,b) = R_L I(t,b) \tag{3}$$

or if the right end is open circuited, then

$$I(t,b) = 0. \tag{4}$$

Before an experiment starting at $t=0$, it is assumed that the tested cable was at rest so that, for all $z \in [a,b]$,

$$V(0,z) = 0 \tag{5a}$$

$$I(0,z) = 0. \tag{5b}$$

The input of this system is naturally $V_s(t)$, whereas its output is $I(t,a)$. The usual input–output notations $u(t)$, $y(t)$ will also be used in this paper, with

$$u(t) = V_s(t)$$
$$y(t) = I(t,a).$$

If $V(t,a)$ is measured with an instrument such as an oscilloscope, then $y(t) = I(t,a)$ can be simply computed through Eq. (2).

1.2. The considered estimation problem for fault diagnosis

The values of $R(z)$, $L(z)$, $C(z)$ are assumed known (typically independent of z), as well as the values of the source impedance R_s and of the load impedance R_L. Then the diagnosis of *inhomogeneous* insulation degradation can be achieved by estimating the distributed shunt conductance parameter $G(z)$ for all $z \in [a,b]$, from the sole voltage and current measurements made at the left end of the cable.

There are two main difficulties for the estimation of $G(z)$:

- The bilinear nature of the estimation problem: $G(z)$ and $V(t,z)$ are both unknown for $z \in (a,b]$ in the bilinear term $\varepsilon G(z)V(t,z)$ of the telegrapher's equations (1).
- The very weak sensitivity of the observed signals to $G(z)$: variations of $G(z)$ affect very weakly the measurements made at the end of the cable.

[1] $\varepsilon \ll 1$ is not used in the usual form of telegrapher's equations. Here it is introduced to prepare the perturbation method presented in Section 2.

To overcome the first difficulty, the bilinear term $\varepsilon G(z)V(t,z)$ in Eq. (1b) will be linearized through a perturbation method. For the second difficulty, it will be shown that the lack of sensitivity can be compensated by processing signals collected over a large time interval.

1.3. The proposed method

After the linearization of the bilinear term $\varepsilon G(z)V(t,z)$, the (rescaled) shunt conductance $G(z)$ will appear in the linearized telegrapher's equations (12) in an additive term, as if it was a voltage source distributed all along the cable. The involved partial differential equations are discretized first in z then in t in order to approximate the original infinite dimensional continuous time system by a (large) finite dimensional discrete time system. Before estimating the discretized $G(z)$, a Kalman filter is applied to the discretized system by assuming $G(z)=0$ all along the cable. The effect of the $G(z) \neq 0$ neglected by the Kalman filter appears in the innovation sequence (residual) as an additive term, thanks to the linearization of the bilinear term $\varepsilon G(z)V(t,z)$. The unknown $G(z)$ is then estimated by the least squares method from the Kalman innovation sequence.

1.4. Numerical simulations

Results of extensive numerical simulations will be presented in this paper to illustrate the performance of the proposed method for shunt conductance estimation. The data used for testing the estimation method are generated by numerically solving the telegrapher's equations (1), without linearizing the bilinear term.

Despite the long history of the telegrapher's equations, they are still considered a standard mathematical model of electric cables in engineering practices (McCammon, 2010). It is reported in Kowalski (2009) that excellent agreement has been obtained between a full 3-dimensional simulation of coaxial cables and the simulation based on the telegrapher's equations. In Oumri, Zhang, and Sorine (2010), numerical simulations based on the telegrapher's equations of two networks of electric cables are compared with true measurements from laboratory experiments, and the simulated results are in good agreement with the true measurements. The telegrapher's equations used in the numerical simulations of this paper are thus reliable enough for generating realistic signals.

1.5. Previous publication and organization of this paper

A shortened version of this paper has been presented at the IFAC Symposium SYSID-2012 (Zhang & Tang, 2012). Due to space limitation, some important technical details have been omitted in the shortened paper: the proof of the observability of the considered system formulated in state space equations, the proof of the invertibility of the system matrix of the discretized state space model, and the description of the parameter estimation method used for the estimation of $G(z)$. These details are fully provided in the present paper.