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An evaluation of performance limits in continuous TDR monitoring of permittivity and levels of liquid materials

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Abstract

Time domain reflectometry (TDR) is commonly used for several monitoring applications, particularly in hydrology and soil science for soil water content evaluation. Furthermore, significant advantages of TDR methodology, such as its relevant performance characteristics in terms of high flexibility and high sensitivity, as well as a non-destructive detection approach, render this technique an appealing candidate for a variety of environmental and industrial applications.

In a previous paper [A. Cataldo, L. Tarricone, F. Attivissimo, A. Trotta, Simultaneous measurement of dielectric properties and levels of liquids using a TDR method, Measurement, doi:10.1016/j.measurement.2006.11.006] the authors demonstrated that TDR can be successfully used for a simultaneous real-time qualitative and quantitative monitoring of liquids. In this paper, a rigorous metrological characterization of the proposed method is formulated, and the uncertainty contributions are identified. The obtained results, confirm that the system is definitely adequate for simultaneously measuring dielectric constants and levels of liquids, with the associated relative uncertainties of 2% and 3%, respectively, for all the considered liquid samples. This way, challenging perspectives for several monitoring applications are open, especially in the processing of industrial liquids.

1. Introduction

Time domain reflectometry (TDR) is a well-established electromagnetic technique that has been used since the 1930s to determine the spatial location of cable faults. In the 1970s, TDR technology began to be applied to geo-materials, in particular to evaluate soil water content [2–10]. Other applications of TDR are in the field of environmental monitoring [11], structural deformation detection [12], electrical and electronic circuit testing [13]. TDR technique is also suitable to simply and rapidly evaluate the permittivity and conductivity of a solution or a granular material [3,14]. In such a context the Authors have recently been interested in employing low-cost TDR systems to measure the dielectric

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properties and the levels of various liquid materials. In a previous paper [1], the authors showed how TDR can be successfully used for an enhanced real-time monitoring of liquids inside tanks: in one shot, determination of levels, dielectric properties and multiple interfaces in layered media are possible. As a matter of fact, the simultaneous determination of the liquid dielectric properties and level from TDR data is a very interesting and a still open issue. Moreover, the state of the art is rather lacking in the metrological characterization of this kind of simultaneous qualitative and quantitative monitoring, based on TDR. The only paper that deals with similar issues is the one reported in [15].

To fill this gap, the present paper is focused on a metrological characterization of the proposed method and, most importantly, a calibration procedure is developed in order to minimize the systematic effect on the measurements.

The uncertainty analysis of the monitoring method proposed by the author in [1] has been worked out through the execution of measurements on different dielectric fluids, which are representative of a wide range of permittivity values. These liquids are considered, as an assumption, as lossless liquids. Although this is clearly an ideal condition, this hypothesis is not far from truth, since the liquids under test are characterized by a negligible ionic conductivity and a slightly relaxation behaviour in the considered frequency range (0–1.7 GHz). On such bases, we decided to voluntarily consider these liquid materials as dielectrically lossless, in order to include this effect in the overall uncertainty contribution evaluation. This way, a robust and unique monitoring procedure is assessed, particularly devoted to industry-related applications.

Another interesting aspect of the proposed method is its capability to deal with layered media and multiple interfaces. The detection of non-miscible liquids, in fact, can be particularly useful in many interesting application fields, such as the field of petrochemical, chemical, or for agro-food industrial processing control purposes.

The paper is structured as follows. In Section 2 the foundations of TDR are recalled and the experimental set-up is described. Section 3 addresses the typical error influences. Section 4 describes the proposed approach for the measurement method and the adopted calibration procedures. In Section 5 results related to different liquids are proposed and discussed. Finally, conclusion is drawn.

2. Basic theory and experimental set-up

The time domain reflectometry method used in this research measures the reflected voltage along a coaxial probe caused by the travelling of a step pulse with a rise time of 200 ps, and records the travel time and magnitude of all reflected signals (echo) returning back from the line [1]. It is important to note that, although higher-performance TDR instrumentation is commonly available on the market, low-cost monitoring requirements motivate the use of such a test set-up. The signal propagating down the line is reflected from a generic line section wherever an impedance mismatching occurs; this effect causes an electromagnetic discontinuity. The TDR signal's relative velocity propagation v is related to the relative dielectric permittivity ε_r of the medium (which is assumed to be lossless or at least with negligible conductivity), and to the relative magnetic permeability μ_r, by the following well-known equation [1,16,17]:

$$v = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \tag{1}$$

where $c = 3 \times 10^8$ m/s is the velocity of light in vacuo, while the relative magnetic permeability is unity in most materials, such as liquids.

When an impedance mismatch occurs, a part of the incident pulse is reflected back toward the step generator: the ratio between the reflected signal amplitude (V^-) and the primary pulse amplitude (V^+) gives the reflection coefficient ρ. Experimental results demonstrated that for the designed 50 Ω matched coaxial probes filled with the sample under test, the dielectric change at the air-dielectric material interface can be related to the reflection coefficient through the following equation:

$$\varepsilon_r = \left(\frac{1 - \rho}{1 + \rho}\right)^2 \tag{2}$$

Furthermore, in the case of a TDR probe traversing the whole height of a tank or a pipe partially filled with a liquid of level D, the dielectric constant of the liquid under test can be evaluated as

$$\varepsilon_r = \left(\frac{D_a}{D}\right)^2 \tag{3}$$

where D is the distance of the signal trip up to the new mismatch point (typically a short or open circuit terminating the probe), and D_a is the corresponding apparent distance in air, measured by