A multi-level gauging system for crude oil settling mass tanks using a one-port time-domain technique

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Abstract

A low-cost multi-level gauging system employing a one-port time-domain measurement in a short-circuited coaxial geometry inserted vertically in a liquid tank is designed and presented in this paper. For small physical liquid levels, the attenuation inside the coaxial cable sensor (attenuation coefficient, α) may be neglected and both the physical liquid levels and liquid permittivity can be measured simultaneously, whereas, for large physical liquid levels, as in the crude oil mass storage tank, the attenuation coefficient of the liquid filled coaxial cable sensor should be considered and predetermined for all level materials in the tanks, and then both liquid levels and permittivity can be measured simultaneously. In this work a multi-level liquid tank contains four different materials; air, combustion engine oil, water, and mud, with physical levels of 30-cm, 60-cm, 10-cm and 5-cm, respectively, was examined to measure both physical levels, assuming them unknown, and permittivity of each level content. From the measured data, the error of the calculated levels was less than 0.01, which may be improved to be almost neglected by considering the attenuation in the coaxial sensor and using a signal processing unit to display the levels accurately.
Keywords: attenuation, coaxial sensor, crude oil, level gauge system, one-port, permittivity, oil storage tank, time-domain, TDR.

1 Introduction

The oil refining industries have developed methods for measuring and controlling liquid levels in storage tanks as well as removing impurities and contaminants, called emulsions, from crude oil that make it unusable in its raw

WIT Transactions on Engineering Sciences, Vol 81,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/PMR120231

form. Methods continue to evolve, and new ways to measure the emulsions in oil have made it possible to be more precise when calculating the thickness of the non-oil layers in settling mass tanks. Moreover, measuring and controlling liquid levels contained in storage tanks and processing vessels is important in many other industrial processes.

Improved level measurement accuracy makes it possible to reduce chemical-process variability, resulting in higher product quality, reduced cost, and less waste. Regulations, especially those governing electronic records, set stringent requirements for accuracy, reliability, and electronic reporting. The newer level measurements technologies and researches in this field help meet these requirements.

Different tank gauging systems are available commercially to measure the liquid levels in storage tanks, *e.g.,* float and tape, gauge board, displacer, radar, hybrid radar, servo, hybrid servo, acoustic, and magnetostrictive. Figure 1 shows three of the common gauging systems that are employed commercially. Some of these systems are simple and low cost but limited to level gauging with no more than one interface level, whereas, the others are complicated and high cost but able to gauging two interface levels. The accuracy of level gauging system plays an important role for the oil refining industries. Thus, the need for accurate and reliable gauging system is essential to avoid costly mistake.

Liquid level measurement based on the capacitance change principle was suggested by Greenwood [1]. A microwave multi-level gauging system employing a Frequency Step Continuous Wave (FSCW) radar measurement technique was presented by Weiβ and Knöchel [2]. Although this technique shows a millmetric accuracy gauging with levels dielectric constant (permittivity) measurement, it is limited to two interface levels gauging only, and considered as an expensive technique due to the need of the Vector Network Analyzer. A microwave-level gauging system using the FSCW radar with sub-millimetre accuracy has been described for industrial applications with simultaneous monitoring of the permittivity (Weiβ and Knöchel [3]). A time domain reflectometry (TDR) was presented by Dozer [4] to measure the level of liquids and solids in a tank. U.S. Navy engineers at the David Taylor Research Center in Annapolis, MD, developed a TDR liquid level sensor system for the measurement of fuel oil in seawater compensated fuel storage tanks on United States Navy warships [5]. TDR is used commercially as a diverse array of liquid level sensing instrumentation (Nemarich [6] and Di Sante [7]). The competitive cost and unique advantages of TDR level sensors make them worth considering especially for interface and hostile applications. TDR level sensors have been successfully used in petrochemical, pulp and paper, mining, cement production, and military applications worldwide. Courtney and Motil [8] used one-port time-domain technique for measuring the approximate complex permittivity and complex permeability of materials. In such measurement the material sample length should be known.

This paper proposes an algorithm suitable for both one-port time-domain and TDR techniques, where it was examined successfully to determine the physical levels and permittivity simultaneously in multi-level liquid tanks.

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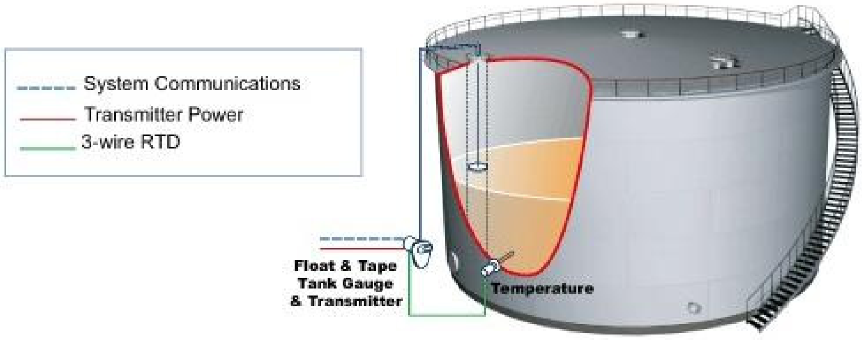
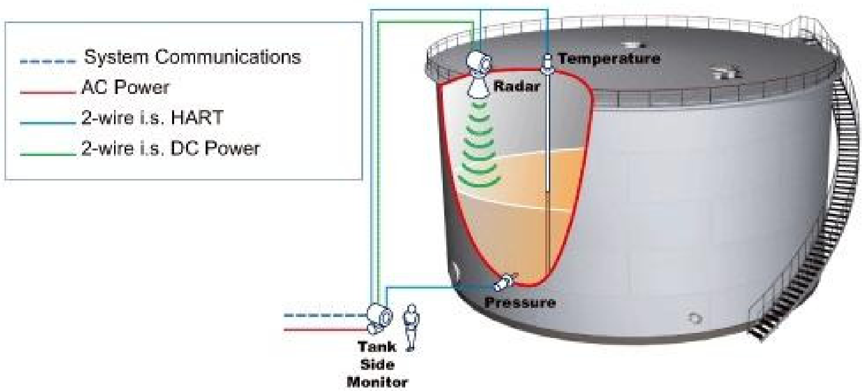


(a)



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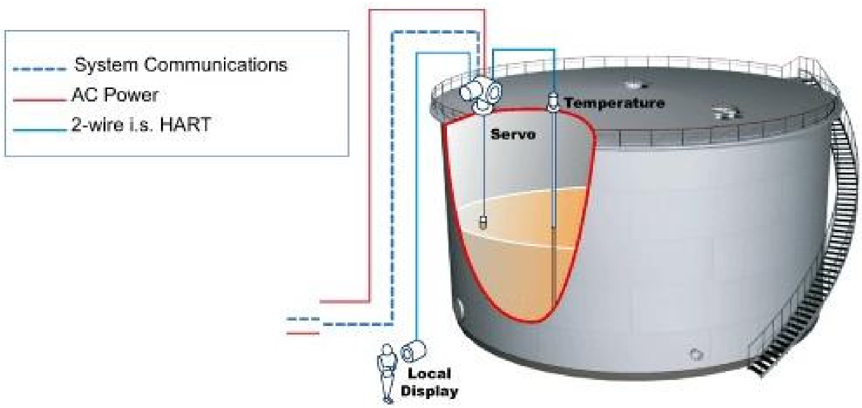

(c)

Figure 1: Different commercial tank gauging systems; (a) float and tape system, (b) radar system, and (c) servo system. Images are taken from http://www.tankgauging.com/.

The main advantages of the adopted technique using the proposed algorithm are;

1. Low cost instrumentation, especially as a gauging system only.
2. A competitive gauging accuracy, comparing with other techniques.
3. Levels number to be measured in liquid tanks is unlimited.
4. Measuring the permittivity enables level content properties monitoring.

For low viscosity liquids, the sensor can be a perforated coaxial cable inserted vertically in the liquid tanks to measure the levels and permittivity, whereas, for high viscosity liquids, TDR probe can be used, acting as the inner conductor of the coaxial cable sensor, while, the outer conductor is the tank itself. Fig. 2 shows the both arrangement setups that are suitable for the proposed computation algorithm.

In this work a multi-level liquid tank with four different materials; air, combustion engine oil, water, and mud was examined to measure both the physical height and permittivity of each level (supposing that the levels contents are unknown). The measurement inaccuracy was less than 0.01. A short-circuited coaxial transmission line was used as a sensor with a pulse generator to generate a pulsating signal of 0.2 ns pulse width. The coaxial line sensor was perforated to allow liquids to get-through the space between the inner and outer conductors of the sensor. The adopted technique is based on measuring the reflected pulse from each level surface and the time delay between each two successive reflected pulses. From the relation between the incident and reflected pulses at each level surface, one can calculate the reflection coefficient at the surface of each level and then calculating the level content permittivity, whereas, the physical level of liquid can be calculated from the time delay between each two successive reflected pulses.

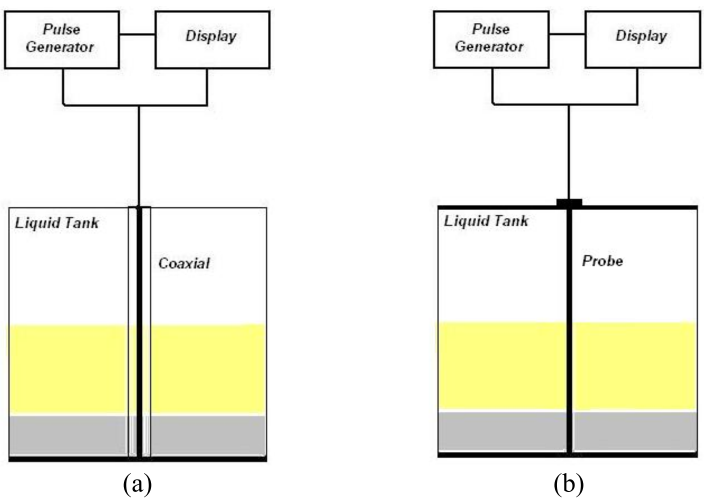

Figure 2: Measurement setup for; (a) low viscosity liquids using a coaxial cable sensor, and (b) high viscosity liquids using TDR probe.

2 Measurement setup

The arrangement setup of the adopted technique is shown in Fig. 3, where a perforated coaxial line inserted vertically in a liquid tank contains four different liquid materials. A pulse generator was used to introduce a pulse signal of 0.2 ns width at the excitation port and allowed to propagates to and through the interface, whereas, a high frequency oscilloscope was used to display input and reflected pulse waveforms. The pulse is partially reflected at each sample material interface and partially transmitted. The transmitted portion travels to the next sample until reaches the end of the line and reflected by the terminating short circuit at the bottom of the tank. Figure 4 shows the liquids that held in the perforated short-circuited coaxial line sensor.

All required waveforms are recorded at the same measurement port, and in order to segregate them from one to another, time isolation must be provided. This can be accomplished when the liquid physical height is long (relative to the pulse width) or by using an excitation with a pulse width that is narrow, relative to the round-trip propagation time in the liquid level. These requirements are exist in the adopted application in this work.

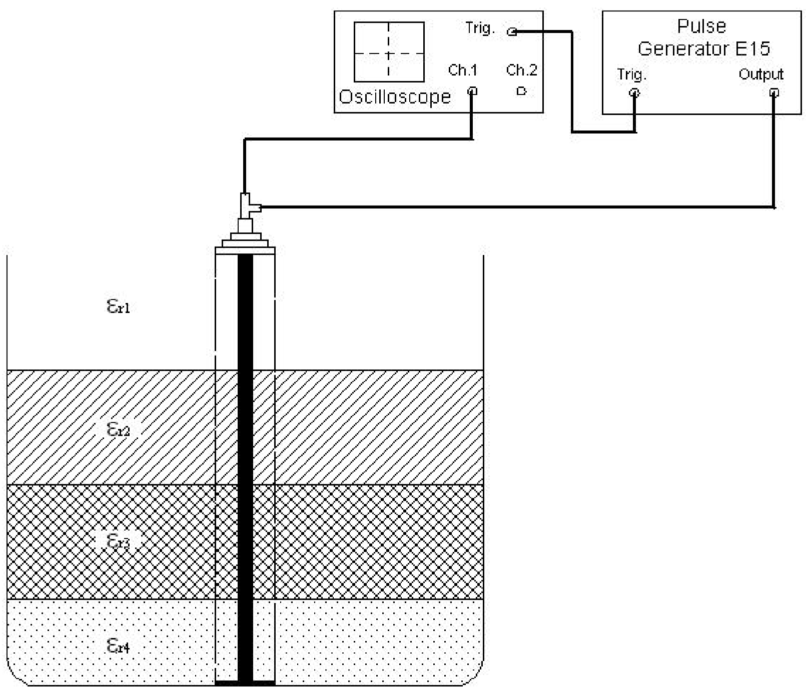

Figure 3: The adopted arrangement setup used for simultaneous measurement of both liquid level and permittivity in multi-level liquid tank.

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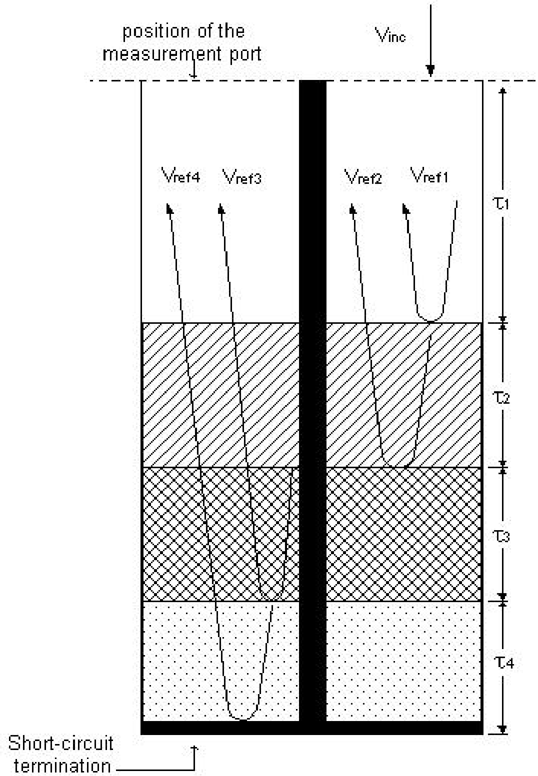

Figure 4: Liquids are held in a perforated short-circuited coaxial transmission line. The time histories of the incident and reflection from each interface are recorded at a location in the measurement port.

3 The proposed algorithm and procedure

The complete time history would consist of the incident pulse and an infinite number of reflected pulses. This history is illustrated in the bounce diagram as shown in Fig. 5. Each sample material is defined by its electrical property, complex relative permittivity $(\varepsilon_r = \varepsilon_r' - j\varepsilon_r'')$, and complex permeability $(\mu_r = \mu_r' - j\mu_r'')$.

For liquid materials, we may consider; $\mu_r = 1$ and $\varepsilon_r' \gg \varepsilon_r''$. Thus, we can suppose that;

$$\varepsilon_r = \varepsilon_r' \tag{1}$$

As shown in Fig. 5, supposing that the incident pulse is $V_{inc}(t)$ and considering a lossless coaxial transmission line $(\alpha = 0)$ then, the reflected pulse from interface level #1, #2, #3, and S.C. that reached to the measurement port can be written as follows, respectively;

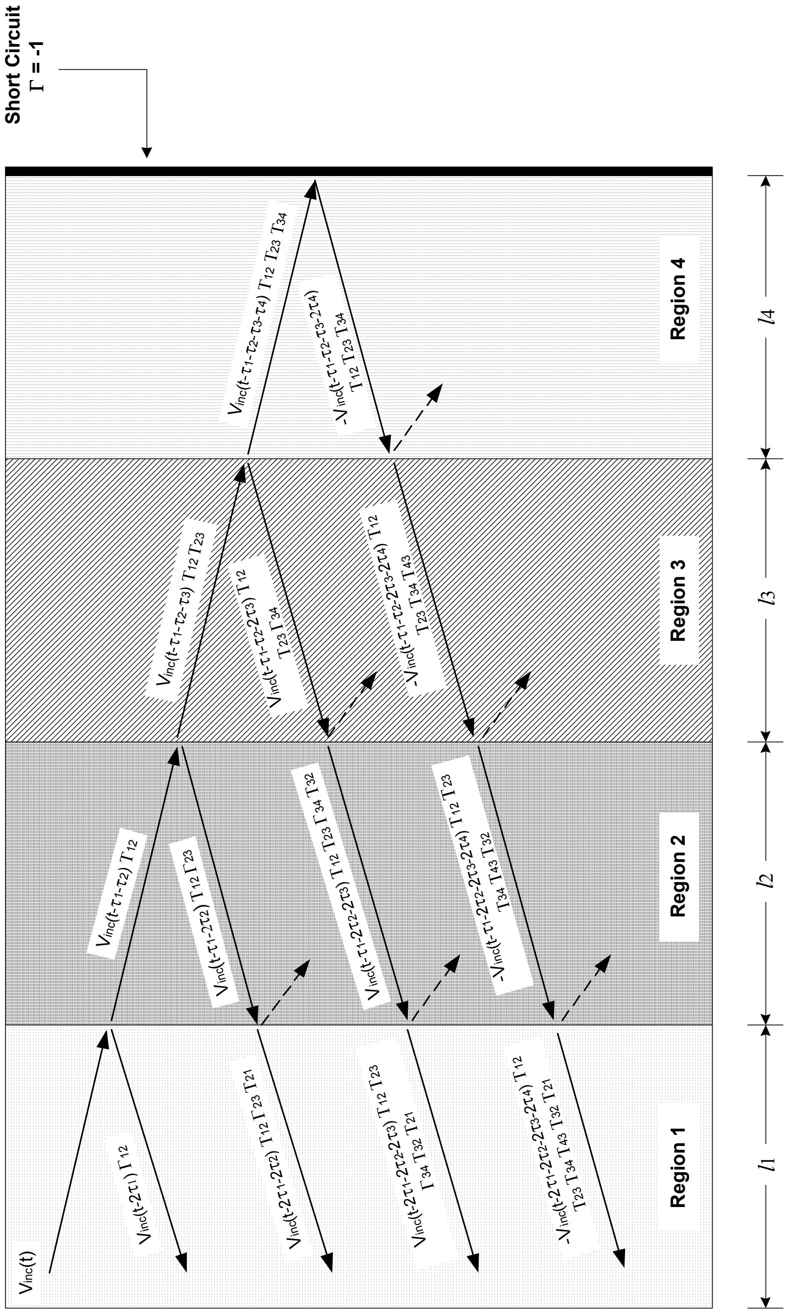

Fig. 3 A bounce diagram for the geometry depicted in Fig. 2 is shown

Figure 5: A bounce diagram for the geometry depicted in Fig. 4.

1. $V_{ref1}(t) = \Gamma_{12} * V_{inc}(t - 2\tau_1)$
2. $V_{ref2}(t) = T_{12} * T_{21} * \Gamma_{23} * V_{inc}(t - 2\tau_1 - 2\tau_2)$
3. $V_{ref3}(t) = T_{12} * T_{23} * T_{32} * T_{21} * \Gamma_{34} * V_{inc}(t - 2\tau_1 - 2\tau_2 - 2\tau_3)$
4. $V_{ref4}(t) = -T_{12} * T_{23} * T_{34} * T_{43} * T_{32} * T_{21} * V_{inc}(t - 2\tau_1 - 2\tau_2 - 2\tau_3 - 2\tau_4)$

where the operator * indicates the convolution,(τ_n) is the propagation (transient) time in the nth level (region thickness), (Γ) is the reflection coefficient, and (T) is the transmission coefficient.

Γ_{12} is the reflection coefficient at region 1/2 interface
Γ_{23} is the reflection coefficient at region 2/3 interface
Γ_{34} is the reflection coefficient at region 3/4 interface

(Γ) and (T) can be written as follows

$$\Gamma_{12} = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \tag{2}$$

$$\Gamma_{23} = \frac{\sqrt{\varepsilon_{r2}} - \sqrt{\varepsilon_{r3}}}{\sqrt{\varepsilon_{r2}} + \sqrt{\varepsilon_{r3}}} \tag{3}$$

$$\Gamma_{34} = \frac{\sqrt{\varepsilon_{r3}} - \sqrt{\varepsilon_{r4}}}{\sqrt{\varepsilon_{r3}} + \sqrt{\varepsilon_{r4}}} \tag{4}$$

$$\Gamma_{12} = -\Gamma_{21} \tag{5}$$

$$\Gamma_{23} = -\Gamma_{32} \tag{6}$$

$$\Gamma_{34} = -\Gamma_{43} \tag{7}$$

$$T_{12} = 1 + \Gamma_{12} \tag{8}$$

$$T_{21} = 1 + \Gamma_{21} \tag{9}$$

$$T_{23} = 1 + \Gamma_{23} \tag{10}$$

$$T_{32} = 1 + \Gamma_{32} \tag{11}$$

$$T_{34} = 1 + \Gamma_{34} \tag{12}$$

$$T_{43} = 1 + \Gamma_{43} \tag{13}$$

To determine the liquid levels, the following relation can be used [2];

$$l_n = \tau_n . \frac{c}{\sqrt{\varepsilon_{rn}}} \qquad n = 1, 2, 3 \text{ and } 4 \tag{14}$$

where l_n is the nth liquid level or thickness, and c is the velocity of light which is equal to 299792458 m/sec. The time delay between two successive reflected pulses is equal to 2τ, as shown in Fig. 6.

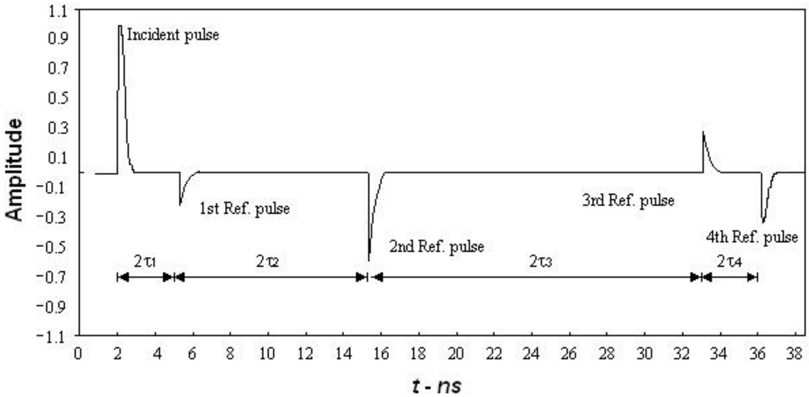

Figure 6: The simulated incident and computed first, second, third, and fourth reflected pulses.

Considering the attenuation constant (α) of the material filled coaxial sensor, the amplitudes in frequency domain of the reflections at the measurement port may be written as follow:

$$A_1 = A_o.\Gamma_{12}.\exp\left(-\alpha_1\tau_1\right) \quad (15)$$

$$A_2 = A_o.\mathrm{T}_{12}.\mathrm{T}_{21}.\Gamma_{23}.\exp\{-(\alpha_1\tau_1 + \alpha_2\tau_2)\} \quad (16)$$

$$A_3 = A_o.\mathrm{T}_{12}.\mathrm{T}_{23}.\mathrm{T}_{23}.\mathrm{T}_{21}.\Gamma_{34}.\exp\{-(\alpha_1\tau_1 + \alpha_2\tau_2 + \alpha_3\tau_3)\} \quad (17)$$

$$A_4 = -A_o.\mathrm{T}_{12}.\mathrm{T}_{23}.\mathrm{T}_{34}.\mathrm{T}_{43}.\mathrm{T}_{32}.\mathrm{T}_{21}.\exp\{-(\alpha_1\tau_1 + \alpha_2\tau_2 + \alpha_3\tau_3 + \alpha_4\tau_4)\} \quad (18)$$

$\alpha_n$denotes the nth material filled sensor attenuation coefficient, andA_n denotes the nth reflection amplitude;

$$A_o = \mathcal{F}[V_{inc}(t)] \quad (19)$$

$$A_n = \mathcal{F}\left[V_{refn}(t)\right] \quad (20)$$

where $\mathcal{F}$ is the Fourier Transform. The negative sign of (A_4) in equation is due to the reflection coefficient at the short circuit termination, *i.e.,* $\Gamma = -1$.

To demonstrate the validity of the equations above for determining liquid levels and permittivity, a simulated waveform was generated to apply through a coaxial transmission line model filled with the following materials; air, crude oil, water, and mud. The physical levels (thickness) are; 50-cm, 100-cm, 30-cm, and 20-cm, respectively.

The incident waveform was specified to be so-called super Gaussian [8] with amplitude of 1 volt. Fig. 6 shows the simulated incident and computed first, second, third and fourth reflected waveform components. The 3rd reflection is $+ve$ since the incident pulse passes from high permittivity region (water) to low permittivity region (mud).

3.1 Determination of physical levels only

In case of need to measure the liquid levels only, *i.e.,* multi-level gauging system, the levels material permittivity (ε_r) should be known. The arrangement setup shown in Fig. 3 can be used to measure the transient time through each liquid level (τ_n), then eqn. (14) is used to compute (l_n).

3.2 Determination of physical levels and permittivity simultaneously

In case of need to measure both liquid level and permittivity, simultaneously, the device setup shown in Fig. 3 is used, but a Scalar Network Analyze (SNA) is needed in addition to the high frequency oscilloscope to measure incident and reflection amplitudes (A_n). Based on measuring (A_n) and (τ_n) for a low loss or lossless material filled sensor ($\alpha \cong 0$), the procedure will be as follow;

1. Using eqn. (14), l_1 can be calculated after measuring the transit time (τ_1), where $\varepsilon_{r1} = 1$. The material between the port of measurement and the first liquid interface level is the air.
2. From the amplitude of the measured first reflected pulse amplitude (A_1), Γ_{12} can be calculated according to eqn. (15). Solving eqn. (2) using MathCAD™ [9], ε_{r2} is determined and then l_2 can be determined too using eqn. (14).
3. Repeat step 2 to calculate Γ_{23} and then determine both ε_{r3} and l_3, and so on for the next Γ, ε_r and l.

In case of long coaxial sensor, α should be measured and considered in calculation of the reflection coefficient (Γ), eqn. (15) - (18). α can be computed easily for every level material by filling the coaxial sensor with the material and measuring the output voltage (V_{out}) at one end for a certain applied input voltage (V_{in}) at the other end and using the following relation;

$$\alpha = \frac{V_{out}}{V_{in}} \quad [Nepers/m]$$

4 Experimental results

To further illustrate the measurement procedure, a liquid tank contains four different materials; air, combustion engine oil, water, and mud, with levels of 30-cm, 60-cm, 10-cm and 5-cm respectively were used. The technique shown in Fig. 2 was used to measure both liquid levels and permittivity in the multi-level tank. The device setup shown in Fig. 3 was used, one time with a high frequency oscilloscope to measure (τ_n) and another time with a SNA (BOONTON 2300 scalar network analyser available at the MW and Radar Engg., The Higher Institute of Electronics, Beni-Walid, Libya) to measure (A_n). A perforated coaxial line adapted with an HN-type connector was used. The measured transient time through each liquid region were; $\tau_1 = 1.0\, nsec$, $\tau_2 = 3.0\, nsec$, $\tau_3 = 2.96\, nsec$, and $\tau_4 = 0.37\, nsec$.

The calculation of both physical levels and permittivity was as in the following two cases;

Case #1; where ($\alpha_n = 0$) is not considered. The following were obtained:

1. The first material (air) has a permittivity of $\varepsilon_{r1} = 1.01$ and a physical level of $l_1 = 29.83$ cm. $Inaccuracy = 1.7\ mm = 0.57\%$.
2. The second material (oil) has a permittivity of $\varepsilon_{r2} = 2.29$ and a physical level of $l_2 = 59.43$ cm. $Inaccuracy = 5.7\ mm = 0.95\%$.
3. The third material (water) has a permittivity of $\varepsilon_{r3} = 80.5$ and a physical level of $l_3 = 9.89$ cm. $Inaccuracy = 1.1\ mm = 1.10\%$.
4. The fourth material (mud) has a permittivity of $\varepsilon_{r4} = 5.1$ and a physical level of $l_4 = 4.91$ cm. $Inaccuracy = 0.9\ mm = 1.76\%$.

Case #2; where (α_n) is measured. The following were obtained:

1. The first material (air) has a permittivity of $\varepsilon_{r1} = 1$ and a physical level of $l_1 = 29.98$ cm . $Inaccuracy = 0.23\ mm = 0.07\%$.
2. The second material (oil) has a permittivity of $\varepsilon_{r2} = 2.28$ and a physical level of $l_2 = 59.56$cm. $Inaccuracy = 4.4\ mm = 0.73\%$.
3. The third material (water) has a permittivity of $\varepsilon_{r3} = 80.3$ and a physical level of $l_3 = 9.9$ cm. $Inaccuracy = 1.0\ mm = 0.97\%$
4. The fourth material (mud) has a permittivity of $\varepsilon_{r4} = 5.04$ and a physical level of $l_4 = 4.94$cm. $Inaccuracy = 0.6\ mm = 1.18\%$

Table (1) summarises these measurement results.

Table 1: The measured liquid levels and permittivity.

Region	Actual Permittivity*	Measured Permittivity	Measured Level (thickness) mm	%inaccuracy (mm)
($\alpha_n = 0$) is not considered				
Air	1.00	1.01	298.3	$(1.70\ mm)$ 0.57%.
Oil	2.30	2.28	594.3	$(5.70\ mm)$ 0.95%.
Water	80.0	80.5	98.90	$(1.10\ mm)$ 1.10%.
Mud	5.00	5.10	49.10	$(0.90\ mm)$ 1.76%.
(α_n) is considered and measured at each level				
Air	1.00	1.00	299.8	$(0.23\ mm)$ 0.07%.
Oil	2.30	2.29	595.6	$(4.40\ mm)$ 0.73%.
Water	80.0	80.3	99.00	$(1.00\ mm)$ 0.97%.
Mud	5.00	5.04	49.40	$(0.60\ mm)$ 1.18%.

*This actual permittivity values were measured using the techniques proposed by Yahya [10].

It is obvious that the measurement accuracy was improved by considering the attenuation in the coaxial sensor (α). The measurement accuracy is affected by the human reading accuracy via measurement devices, *i.e.,* high frequency oscilloscope. The suggested setup may be upgraded by way of replacing the oscilloscope by a signal processing unit with a display to avoid the human error.

5 Conclusion

An algorithm applied to a one-port time domain measurement technique was presented and successfully implemented in this paper. The adopted technique measures the input and reflected pulses and their time delay at the measurement port of a short-circuited coaxial sensor inserted vertically in a multi-level liquid tank, and with the aid of the proposed algorithm, both liquid levels and permittivity can be computed with inaccuracy less than 0.01. The inaccuracy can be minimized to be neglected, sub-millimetres, by considering the attenuation in the liquid filled coaxial sensor and replacing the measurement devices by a signal processing unit with a display. The proposed technique as a multi-level gauging system is more suitable for huge liquid tanks, since the excitation with a narrow pulse width, relative to the round-trip propagation time in the sample, can be guaranteed. The main advantages of the adopted technique are; firstly, it can be applied in multi-level liquid tanks with unknown liquid types and unknown levels, secondly, this technique is not limited to a number of levels, and thirdly, this technique is considered as a low-cost and accurate technique, relatively.

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