2015

Application of Time Domain Reflectometer for measuring liquid level

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ABSTRACT

APPLICATION OF TIME DOMAIN REFLECTOMETER FOR MEASURING LIQUID LEVEL

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Northern Illinois University, 2015

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The present research is related to the Time Domain Reflectometer (TDR) level measurement device capable of generating and receiving electromagnetic waves. The primary objective is to measure the height of water in a tank and design an efficient measuring device. The TDR is based on the reflection mechanism, in which the time delay between the transmitted and reflected signals helps to determine the distance from the source to the surface of water, which is later used to deduce the height of water in the tank. The TDR is built using a 74AC14 IC, which is capable of producing pulse signals with very low rising and falling time that provide greater accuracy. Thus, the generated pulse signals are transmitted into the probe inserted in a tank. The total time taken by the probe to travel the path to and fro is found out, which in return helps in calculating the height of the liquid in the tank. The functioning of the proposed TDR circuit and the bi-axial probe is also tested in the laboratory.

NORTHERN ILLINOIS UNIVERSITY

DEKALB, ILLINOIS

AUGUST 2015

APPLICATION OF TIME DOMAIN REFLECTOMETER FOR MEASURING LIQUID LEVEL

BY

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A THESIS SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

Thesis Director: Dr. Michael J. Haji-Sheikh

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my advisor, Dr. Mansour Tahernezhadi for his continuous support, encouragement and guidance.

I owe my gratitude to my thesis director, Dr. Michael J. Haji-Sheikh and my committee member Dr. Martin Kocanda for their inputs and encouragement throughout my Master's program. Their expertise and constant guidance helped me greatly during my research and thesis writing.

I want to thank my parents and sister, who inspired and supported me all throughout my Master's program. I also want to thank my friends for their motivation and support.

Last but not the least, I want to thank Electrical Department office members for funding my research and providing their assistance whenever asked.

Dedication

To my mom, dad and sister

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CHAPTER-1

INTRODUCTION

1.1 Motivation

Level estimation is used to determine the linear vertical separation between a reference point and the surface of the liquid or top of a pile of divided solids. [10] Here, the water level in a tank such as underground septic tank, overhead water tank and airplane septic tank has to be estimated. It is necessary to know the level of water in the tank to avoid problems, such as overflow and leakage. There are many ways to estimate the water level in tanks, such as sight glasses, hydrostatic devices, capacitive level sensors and microwave sensors. Sight glasses are susceptible to leakage and also conceal visible level of water due to the sediment buildup on it. Hydrostatic devices such as displacers, bubblers and differential pressure transmitters have reduced measurement accuracy, due to the shift in the liquid's gravity based on change in temperature. In case of capacitive sensors, long conductive cables suffer cable breakage due to extreme mechanical tension. Radar systems through-air are affected by divergence problems. [27]

In order to estimate the level of water in the tank, engineers have to come up with a technique, which is more efficient than the above mentioned procedures. The trending technology these days is measurement of distance between the source and liquid level by time-based measurement, which replaced mechanical and pressure-based measurement tools. One such method is Time Domain Reflectometry where the probe provides the focused path. [27]

Time Domain Reflectometer (TDR) is fundamentally a radar in which a voltage pulse is launched along a co-axial cable. Whenever distortion occurs along the cable, a reflection of the transmitted wave occurs. The location of the cable deformation is determined by the reflection travel time, and the reflection magnitude is proportional to the magnitude of the deformation. In case of water level measurement, a hollow co-axial cable can be installed in a monitoring tank, and it is observed that the reflection occurs at the air-water interface. This strong reflection makes it possible to monitor changes in water level.

TDR technique was introduced in the early 1980s. Since its introduction, it has gained interest by many fields of science for various applications. [2] It has wide variety of applications and is very efficient compared to other measurement techniques. TDR is used for measuring impedance of the transmission lines, dielectric constant of the medium of transmission, electrical conductivity and types and position of faults in the transmission lines.

1.2 Literature Review

Tomi Engdahl designed a simple TDR using 74AC14 IC, which was primarily used to detect faults along the cable. He also analyzed the outputs and classified them into different types of distortions. [7]

Jim Bartling worked on a ‘Low cost, high resolution Time Domain Reflectometer’ which was designed using a 16-bit microcontroller and a Charge Time Measurement Unit (CTMU) peripheral on-chip that is used to measure time with a high degree precision and resolution. The main goal of his work was to find out transmission-line length, location of faults due to opens and location of faults due to shorts. [1]

Jim Bartling also developed a 'Time Domain Reflectometer for liquid level measurement'. He has designed a TDR using PIC microcontroller and used it with a probe to measure the level of liquid. Time measurement is again accomplished using CTMU. It provides information of the fluid composition as well. [5]

Brian Kenner and John Wettroth designed a TDR using Intel 87C51 microcontroller to measure length and termination impedance of co-axial cables commonly used in computer networks, such as Ethernet, Arcnet and so forth. A high-speed comparator is enabled to measure the length. The software consists of approximately 3K of 8051 assembly language. [3]

James R. Andrews analyzed 'Time Domain Reflectometry and Timer Domain Transmission Measurement fundamentals' in 2004. The main aim of his study was to identify the nature of the Device Under Test (DUT). [4]

Scott B. Jones, Jon M. Wraith and Dani Or discussed 'Time domain reflectometry measurement principles and applications' in 2002. Their main motive was to determine the porous media water content based on dielectric properties and electrical conductivity of the medium. [2]

Kevin M O'Conner and Charles H. Dowding worked on 'Real-Time monitoring of infrastructure using TDR technology'. His study reveals the summary of principles involved in various applications of TDR. This work was primarily intended to provide background on the principles involved in geotechnical and infrastructure applications of TDR. [13]

Xinbao Yu and Xiong Yu studied on ‘Measurement of simulated scour by Time domain reflectometry’ in 2006. “TDR instrument and analyses framework can be potentially refined into a useful tool for bridge scour surveillance”. Their study shows the determination of dielectric constant, electrical conductivity, the depth of the scour and properties of the soil sediments (porosity, density). [15]

A. Thomsen, B. Hansen and K. Schelde proposed a TDR technique for measuring water level in tanks collecting surface water runoff and soil moisture in their paper ‘Application of TDR to water level measurement’ in 2000. They designed a two-wire closed loop TDR probe with balun transformer for transforming impedance from 50Ω to 200Ω. The water level calibration depended on time-based measurements. [12]

D. Moret, M. V. Lopez, J. L. Arrue worked on water level measurement and volumetric water content of the soil in Mariotte reservoir using TDR method. Their work was published as ‘TDR application for automated water level measurement from Mariotte Reservoirs in tension disc infiltrometers’. A three-rod TDR probe was designed that was used for simultaneous measurements of both water flow and volumetric water content of soil below the infiltrometer disc, placed at the bottom of the reservoir. The measurement was done considering the summation of pulse travel times. [11]

W. F. Kane studied ‘Embankment monitoring with time domain reflectometry’, where the slope movement and peizometric levels were determined. The work proposed the use of coaxial cable which was embedded in the vertical hole to locate shear failure in the embankment, rate of ground movement and water levels. It was the first application of TDR in civil engineering in 1998. [16]

1.3 Scope of Work

The objective of this study is to determine the level of water in a septic tank by planting a TDR at the top of the tank. A TDR probe is immersed in the water tank, through which a pulse signal is launched. The impedance mismatch occurs at the air-water interface and the bottom of the tank, which results in the reflection of the signal. This reflected signal looks algebraically added to the incident signal. From the time difference between the incident and reflected signal, the distance between the TDR and the surface of water is calculated. The distance is generally twice the time traveled by the wave. Thus, obtained distance helps in finding out the length of water in the tank. The waveform is extracted as a CSV file. A MATLAB code is written for determination of the peaks and the time difference between them. It estimates the height and also warns if there is very high increase in the liquid levels.

CHAPTER-2

TIME DOMAIN REFLECTOMETRY BASICS

2.1 Introduction

Time Domain Reflectometry, also called Guided-wave RADAR, is a method that uses the reflected energy of a pulse sent down the transmission line to determine its characteristics. Time Domain Reflectometer (TDR) device has the capability to generate and transmit the electromagnetic waves.

The Time Domain Reflectometry method was introduced in early 1980s. It has gained immense interest in the electromagnetic methods based on different principles. The TDR method is evolving and its applications are spreading vastly into various fields. [2]

Initially, TDR generates a pulse signal that is transmitted down a transmission line or a cable, which partly reflects back to the source on hitting the discontinuity. The reflected signal appears to be algebraically added to the incident signal as shown in the figure 2.1 below. Mostly, step function and impulse are used as time domain test signals. A good deal of information can be obtained from the reflected signal such as impedance of the transmission line, quality of connectors, length of the transmission line, faults due to shorts and opens in the line. [1]

The Time Domain Reflectometry technique was primarily developed to detect faults along power transmission lines. The TDR device is connected to one end of the transmission line, which transmits a pulse signal and records all the reflections from the discontinuities along the line. These reflections tell the position and kind of faults along the line.

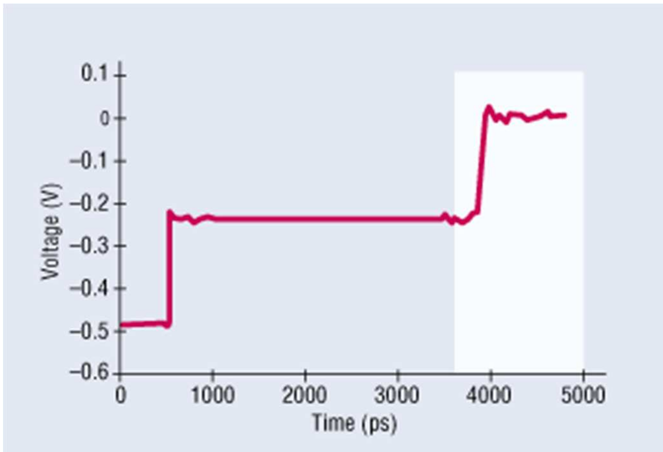


Figure 2.1: A TDR waveform showing the incident signal and the reflected signal (highlighted area). [24]

2.2 Propagation on Transmission Line

In order to obtain complete knowledge about Time Domain Reflectometry, it is necessary to know the about transmission lines and the propagation of electromagnetic waves along them. EM-waves consist of electric and magnetic fields propagating along the direction of travel but are oriented perpendicular to each other. This is true along the length of a normal transmission line. This concept is known as principle mode or Transverse Electric and Magnetic (TEM) mode and is possible only when there are two conductors. [18]

A transmission line is supposed to be made up of a continuous structure of R's, L's and C's as in figure 2.2. The review of its equivalent circuit tells about the various characteristics of the transmission line. [6]

Consider that R, L, C and G are defined per unit length, then

The characteristic impedance of the line is

$$Zo = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

$$\gamma = \sqrt{ZY} = \sqrt{(R + j\omega L)(G + j\omega C)}$$

where, γ is the propagation constant of the transmission line.

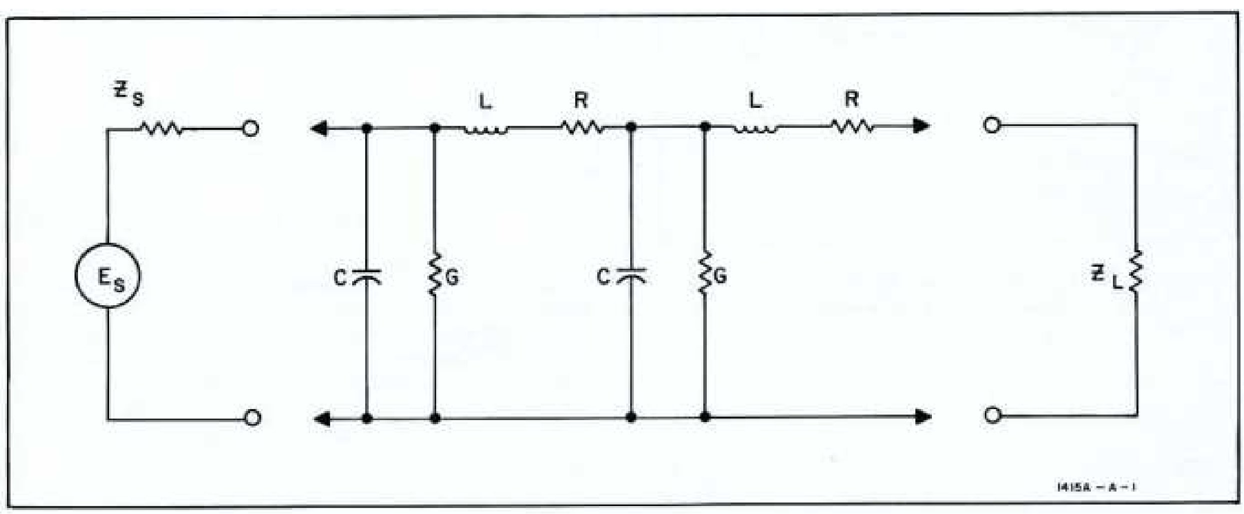


Figure 2.2: Classical model of a transmission line. [6]

The velocity of propagation of voltage down the line is given by, [8]

$$v_p = \frac{v_c}{\sqrt{\epsilon_r}}$$

where, v_p is the velocity of propagation of voltage along the line,

v_c is the speed of light and

ϵ_r=k is the dielectric constant of the medium.

The voltage pulse, which passes the transmission line of finite length, is terminated at load. When impedance of the load matches the transmission line impedance, then there is no reflected voltage. But, if the impedance mismatch occurs, then a part of the incident voltage reflects back to the source from the mismatch and the remaining part moves toward the load.

Such reflections in the transmission lines degrade their performance. The quality of the transmission line is given by the factor called voltage reflection coefficient, ρ. The ratio of the reflected wave to incident wave originating from the source is called reflection coefficient and is related to transmission line impedance. [8]

$$\rho = \frac{E_r}{E_i} = \frac{Z_L - Z_o}{Z_L + Z_o}$$

where, Z_L is the load impedance.

2.3 TDR Measuring System

TDR was basically developed to check for faults in the cables. That is from where it got its name as 'cable tester'. [2]

TDR is also called as guided-wave RADAR, i.e. the positive pulse generated by TDR, travels along the cable or a metal rod under test. The signal waveform is seen on the Oscilloscope, which is connected at the source and DUT connection. This explains the basic TDR setup. It generates a step signal or an impulse with fast rising and falling edges. The rise and fall time of the pulse matters, less the time, greater the resolution. [15]

Once the incident pulse is fed into the DUT, the waveform displayed by the Oscilloscope is monitored. If the load impedance matches the characteristic impedance of the line, no reflection is seen, as the whole signal transmitted is absorbed at the load. The only thing seen on the Oscilloscope screen is the incident pulse. But, if the load impedance does not match the characteristic impedance of the line, part of the incident pulse is reflected back to the source, which is recorded by the Oscilloscope as in the figure 2.3 below. This reflected pulse can be easily noticed as there is a time difference between incident and reflected pulses. [6]

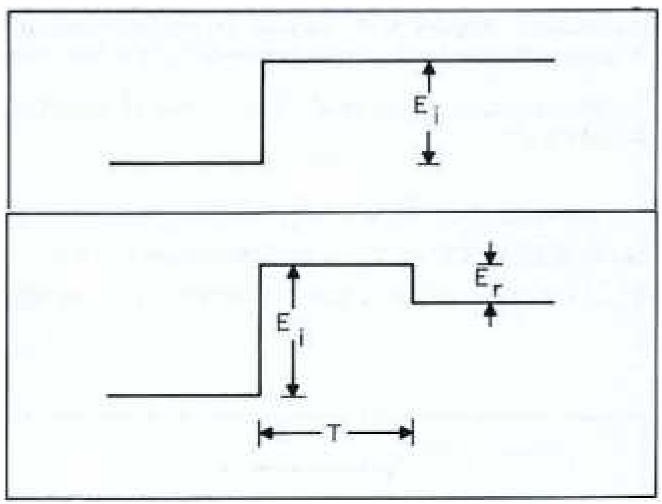


Figure 2.3: (above)Oscilloscope display when load impedance matches characteristic impedance. (below) Oscilloscope display when load impedance mismatched characteristic impedance. [6]

For cable testing, a cable of known length with velocity of propagation, V_{p}, is taken, and reflections from discontinuities are observed on the Oscilloscope screen. The time difference and the voltage difference between the incident and the reflected peaks are noted down, from which the distance of the discontinuity from the source can be calibrated. The time difference is the time taken by the wave to travel the round trip (i.e. two times the length, L) between source and discontinuity. Therefore, propagation velocity is,

$$v = \frac{2L}{t}$$

where, L is the length of the discontinuity from the source,

t is the time difference (total time taken from source to discontinuity and again back to source).

TDR is also used to measure the properties of the materials surrounded by the probe, such as impedance, dielectric constant, its conductivity and velocity of propagation.

2.3.1 Analyzing the Reflections

A much information can be traced out from the waveform displayed on the Oscilloscope. The voltage difference, time difference and also the shape of the waveform tells about the nature and magnitude of the mismatch. [6]

The reflection coefficient of the transmission line is,

$$\rho = \frac{E_r}{E_i} = \frac{Z_L - Z_o}{Z_L + Z_o}$$

E_r (Reflected Voltage) and E_i (Incident Voltage) can be seen on the Oscilloscope. Z_L can be found out from the above equation as Z_o is known and vice-versa. Consider some well known cases (refer to figure 2.4). [6]

1. $E_r = E_i$,

=> $\frac{Z_L - Z_o}{Z_L + Z_o} = 1$

This is possible when Z_L tends to infinity, i.e. the termination end is an open circuit.

2. $E_r = -E_i$,

=> $\frac{Z_L - Z_o}{Z_L + Z_o} = -1$

This is possible when Z_L is equal to zero, i.e. the termination end is a short circuit.

3. $E_r = 1/3\ E_i$,

=> $\frac{Z_L - Z_o}{Z_L + Z_o} = 1/3$ and $Z_L = 2Z_o$

The line is terminated at $Z_L = 2Z_o$.

4. $E_r = -1/3\ E_i$,

=> $\frac{Z_L - Z_o}{Z_L + Z_o} = -1/3$ and $Z_L = ½\ Z_o$

The line is terminated at $Z_L = ½\ Z_o$.

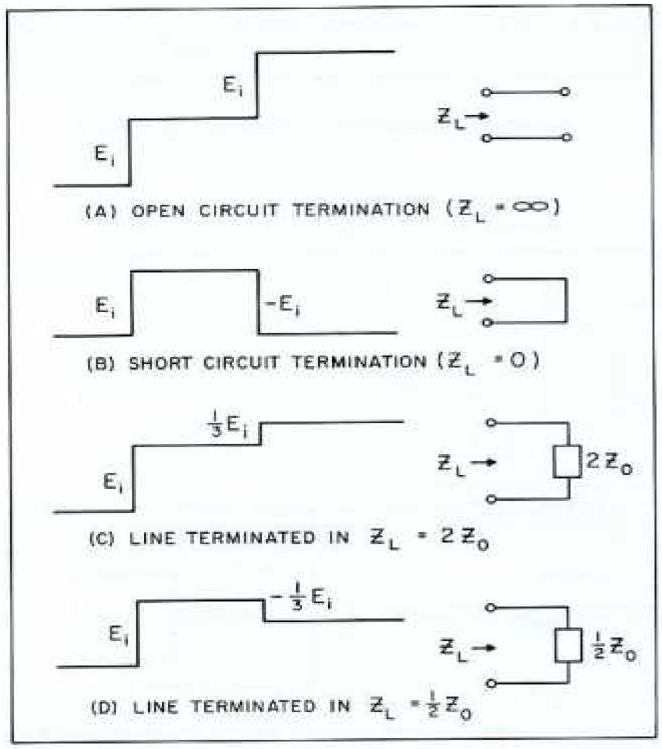


Figure 2.4: TDR displays for different loads. [6]

The above discussed terminations were only for the resistive loads, where the shape of the reflected pulse is similar to the incident pulse. In case of complex loads, the shape changes according to the component at load (i.e. inductor and capacitor).

Until now the mismatches at the load were discussed. Coming to the discontinuities in the line, they are no different from the load terminations except for their position on the line and also the waveform. TDR has an advantage with recording discontinuities compared to other testing methods. It has the ability to record multiple discontinuities.

2.3.2 Advantages and Disadvantages of TDR

TDR has many advantages compared to other measurement techniques.

1. It has the ability to measure reliably even in temperature and pressure fluctuations, dust and noise, condensation and steam generation.
2. TDR can be used to measure the level of any kind of liquid. It is immune to different properties of liquids like dielectric constant.
3. Multiple discontinuities can be measured at same time unlike other techniques.
4. It is a non-destructive method of testing.
5. It has the ability to provide thorough time series measurement at multiple locations. [2]
6. It provides simultaneous measurement recording.
7. It has other advantages like the TDR probe is resistant to corrosion and also immune to mechanical shock, TDR parts do not wear out, circuitry is simple and operates at low voltage and better resolution compared to other techniques. [5]

There are also few limitations and disadvantages in TDR.

1. Discontinuities that are either small or closely spaced are smoothed into single irregularity. This effect does not show up all the discontinuities and also leads to inaccurate impedance readings. If the distance between the two neighboring discontinuities is less than half the rise time of TDR, then this happens. [14]
2. TDR system's resolution can be affected by rise time, settling time and pulse aberrations.
3. By the time the incident pulse reaches the end of the cable, the rise time and settling time might be degraded, which affects the resolution and accuracy of the system. [14]
4. Internal reflections from the mismatches and random noise induce error.
5. The electrical interface from coaxial cable to probe might cause localized disturbance.

But the advantages of TDR technique are far too promising to consider the disadvantages.

2.4 Two-wire Transmission Line

There are many transmission lines that can be used along with TDR, of which few are coaxial cable and 2-wire transmission line [13]. These cables are either tested or used as probes for various applications of TDR.

Coaxial cables are highly used with TDR's. These cables consist of an outer and inner conductor separated by an insulating material (refer to figure 2.5). Characteristic impedance of these cables depends on the thickness of insulation. The coaxial cable appears to look like a two-wire transmission line in longitudinal view (refer to figure 2.6), where the outer and inner conductors are represented by forward and return conductors. [13]

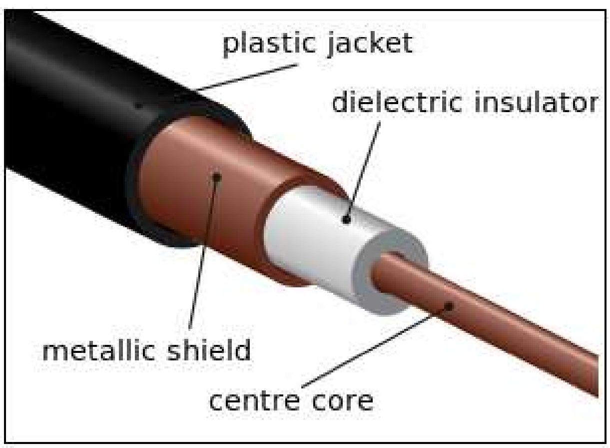


Figure 2.5: Coaxial cable [25]

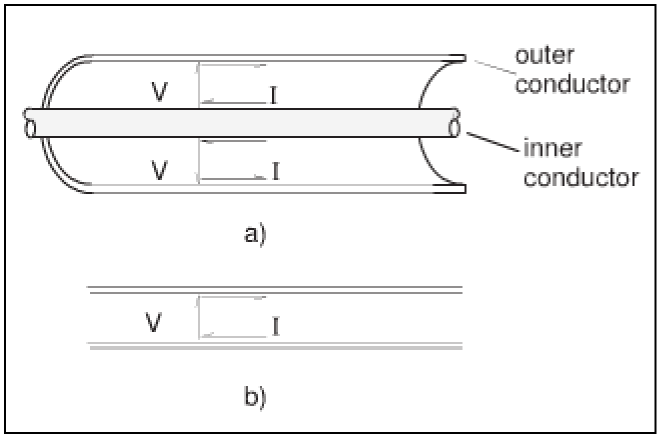


Figure 2.6: voltage pulse propagation through a) coaxial cable and b) two-wire transmission line. [13]

Coming to the parallel wire transmission lines, one must first study the geometry of the lines (refer to figure 2.7). There are two parallel conductors of diameter 2a and conductivity, σ_c are separated from each other by length d in a medium of permeability μ, permittivity ϵ and conductivity σ. [18] Parallel wire lines have many uses such as in connecting TV aerials and receivers are tuning elements, AC line cord and in laboratories for measurement on electromagnetic waves.[19]

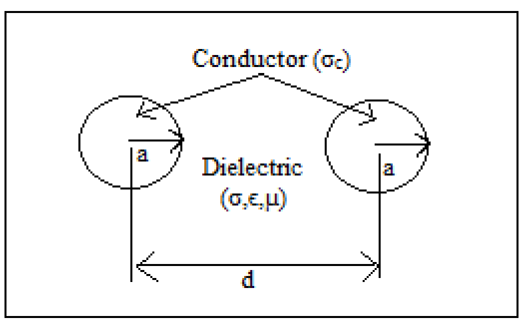


Figure 2.7: Geometry of a 2-wire transmission line [17]

A voltage pulse, V, is introduced into the line. Current I is created by the potential difference caused by the voltage pulse, which propagates through the two conductors. The current and voltage (i.e. propagation of wave) through the two-wire transmission line is governed by the following four parameters. [13]

1. Capacitance per unit length, C

$$C = \frac{\pi\epsilon}{cosh^{-1}(\frac{d}{2a})}$$

(or)

$$C = \frac{\pi\epsilon}{\ln(\frac{d}{a})}$$

(a<<d)

2. Inductance per unit length, L

$$LC = \mu\epsilon$$

$$L = \frac{\mu}{\epsilon} cosh^{-1}(\frac{d}{2a})$$

(or)

$$L = \frac{\mu}{\epsilon}\ln(\frac{d}{a})$$

(a<<d)

3. Conductance per unit length, G

$$G = \frac{\pi\epsilon}{cosh^{-1}(\frac{d}{2a})}$$

4. Resistance per unit length, R

$$R = \frac{1}{\pi a \delta \sigma_c}$$

Using the Capacitance and the Inductance, one obtains the characteristic impedance for a lossless case *(R=G=0)*,

$$Z_o = \sqrt{\frac{L}{C}}$$

$$Z_o = \frac{1}{\pi}\sqrt{\frac{\mu}{\epsilon}}cosh^{-1}(\frac{d}{2a})$$

The two-wire transmission line has the advantage of minimal soil disturbance compared to other probes in soil properties measurement application. These probes also have a larger sample area.

2.5 Applications of TDR

There are several applications of TDR not only in analyzing the functioning of cables but also in civil and geotechnical fields.

1. The major cause for developing TDR is to check the functionality of the power transmission lines by locating faults. These faults can be recognized by looking at their

waveform on the Oscilloscope. The figure 2.8 below shows some of the common examples of the faults and their resultant waveforms.

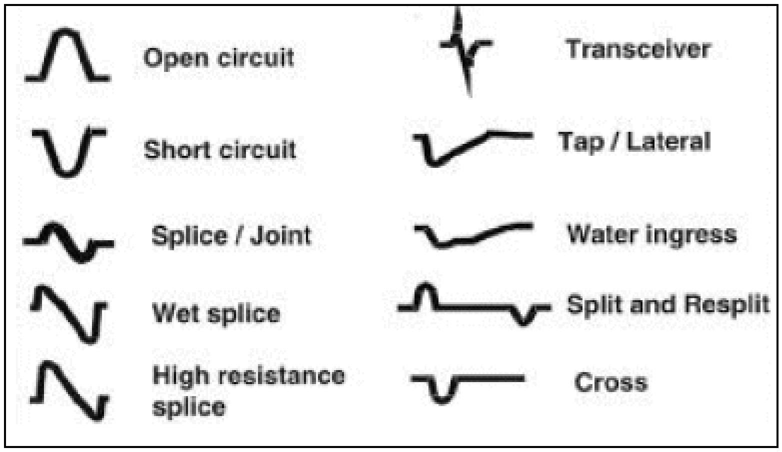


Figure 2.8: Faults and their waveforms. [7]

2. TDR is a measurement technique for calibrating the

   a. impedance of the transmission lines using the formula, which was already discussed,

$$Zo = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

   b. Dielectric constant of the medium it is travelling through, which is also found out using the formula below,

$$k = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2L}\right)^2$$

where, k is the dielectric constant, c is the speed of light in vacuum, v is the velocity of wave in dielectric medium and t is the time taken to travel the length, L to and fro.

   c. It can also find out the unknown length, L of the transmission line using the formula,

$$L = \frac{vt}{2}$$

where, v is the velocity of propagation of wave and t is the time taken to travel the path 2L (up and down).

3. TDR is used in earth and agricultural sciences. The water content and the electrical conductivity in soil can be found out as discussed by Scott B. Jones, Jon M. Wraith and Dani Or. The water content of the soil can be deduced from the dielectric permittivity of the medium and the electrical conductivity can be summarized from TDR signal attenuation. [2]
4. Water level measurement is possible by calibrating the distance from air-water interface reflection as by D. Moret, M.V. Lopez, J. L. Arrue. Soil hydraulic properties are also found out using TDR. [11]
5. TDR is used in geotechnical and infrastructure applications. The confined shear in the rock or soil mass will deform the cable resulting in a reflected signal that in return determines the position of the shear. It also analyzes the presence of water in that column of soil mass as discussed by Kevin M. Connor and Charles H. Dowding. [13]
6. Xianbu Yu and Xiong Yu proposed the use of TDR in scour monitoring system for bridges. This is possible by considering the reflections from air, water and soil sediments due to the large difference in their dielectric constants. [15]
7. TDR is also used as cable tester to detect the movement of shear in mines and embankment monitoring. The rate of ground movement can be estimated from the change of amplitude with time of a TDR signal. This was proposed by W. F. Kane. [16]

8. TDR has many other applications like checking failures in Printed Circuit Boards (PCB); to locate defects in semiconductor device packages, IC packages, maintenance of aviation wiring, evaluating cable losses in the transmission lines, identifying faults in concrete dam anchor cables and maintenance of telecommunication lines. [9]

CHAPTER-3

PROPOSED CIRCUIT

3.1 Introduction

In the previous chapter, TDR basics and transmission line basics were discussed. Their functioning and various applications have been analyzed. In this chapter the proposed circuit and the experimental setup for measuring the water level in the tank will be studied.

The TDR circuit discussed in this thesis draws lines from Alan Wolke's TDR circuit. This simple circuit comprises of a Schmitt trigger for generation of a square wave which acts as the source of incident voltage pulse.

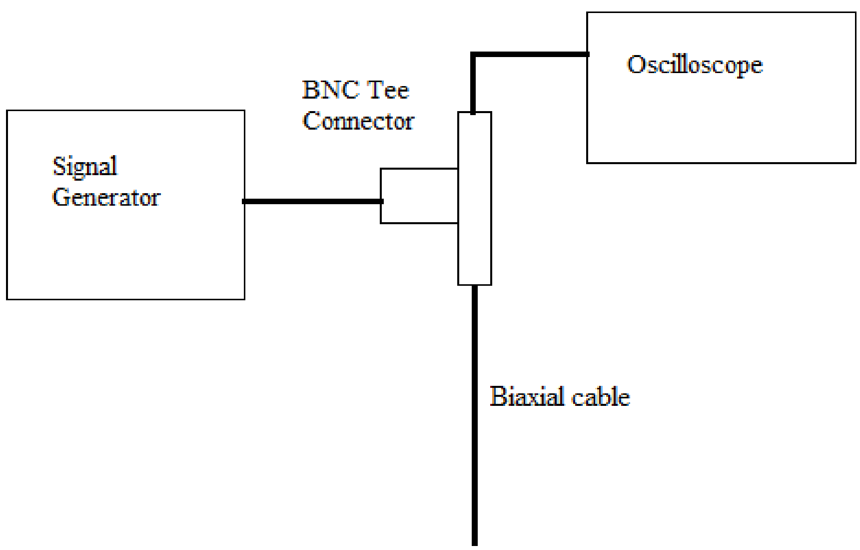


Figure 3.1: Block Diagram

The figure 3.1 above shows the block diagram of the experimental setup. The setup is divided into three main parts. The signal generation, TDR probe and Oscilloscope. The signal generation is carried out by the simple TDR circuit built in the laboratory. The Oscilloscope is used to check the waveforms and also to extract the data in the digital form. The probe used here is a bi-axial probe built using two brass rods. All these three parts are inter-connected using a BNC Tee-connector.

In the sections below, all the parts will be discussed. Firstly, the Oscilloscope used here is 'Agilent technologies Digital Storage Oscilloscope DSO1102B'. It is a 2-channel, 100 MHz Input bandwidth oscilloscopes with a sample rate of 500MSa/s – 1GSa/s. [21]

3.2 Signal Generator

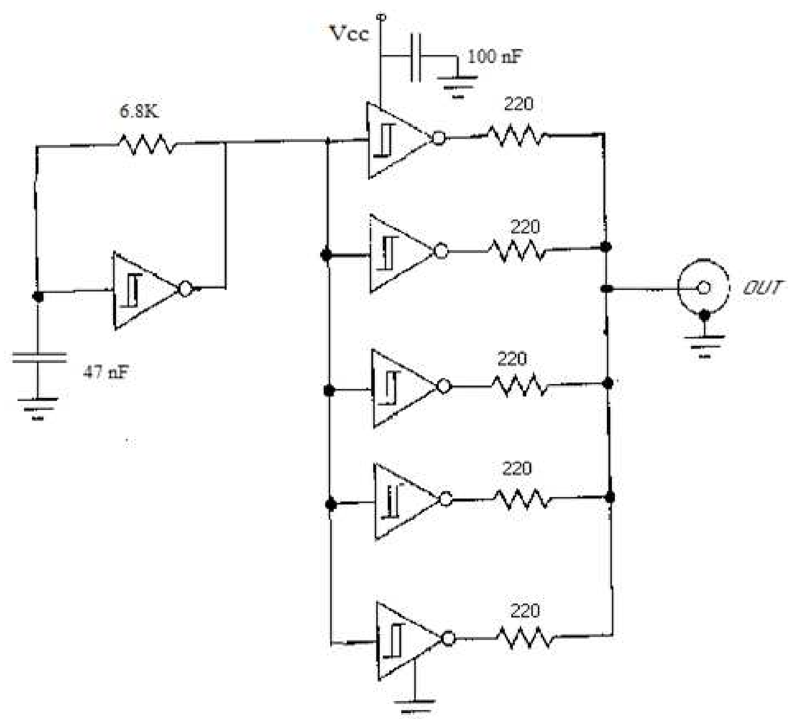


Figure 3.2: Circuit Diagram of TDR circuit [23]

Signal generation is done by a simple TDR circuit, built using 74AC14 IC as shown in the figure 3.2 above. It generates a square wave with fast rising and falling edges, which is transmitted to the biaxial cable that is immersed in the water tank. This TDR circuit has the Schmitt trigger in the circuit which yields the square wave.

It is necessary to know about 74AC14 IC and Schmitt trigger to understand the functioning of the TDR circuit.

3.2.1 74AC14 IC

It has six inverter gates all with Schmitt trigger inputs and it also has the ability of transforming gradually changing input signals to sharply stipulated, jitter-free output signals. It has the greater noise margin than most of the regular inverters. The device output source or sink current is about ±50mA. It does not matter which inverter is being used as which part of the circuit because all are the same. The figure 3.3 below shows the pin description of 74AC14 IC. [22]

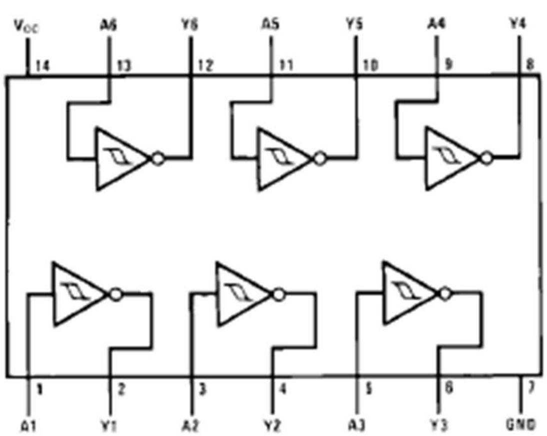


Figure 3.3: Pin Diagram of 74AC14 IC. [7]

It is a 14 pin IC. The A_n pins are the input pins of the inverter, Y_n pins are the output pins of the inverter and V_{cc} and Gnd are the pins for power supply.

3.2.2 Schmitt Trigger

Schmitt trigger is a comparator circuit, in which a positive feedback is applied to the non-inverting input of the comparator. Its input logic threshold is bi-stable, i.e. it changes its output value to one of the two values depending on the internal logic status. In non-inverting configuration, when the input is higher than the upper threshold voltage level, the output becomes high; and similarly when the input is less than the lower threshold voltage level, the output becomes low as in figure 3.5. In between the two levels, the output remains same, which is why it is called a trigger. [20]

It is used for producing clean logic switching on slowly changing or noisy inputs and also as Oscillators. The Schmitt triggers are generally built from CMOS devices for producing output close to 50% duty cycle. Here, the IC used is 74AC14, in which 'C' indicates CMOS device. The figure 3.4 below is the circuit of Schmitt Trigger.

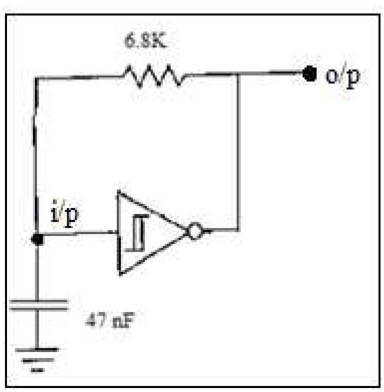


Figure 3.4: Schmitt trigger (in TDR circuit)

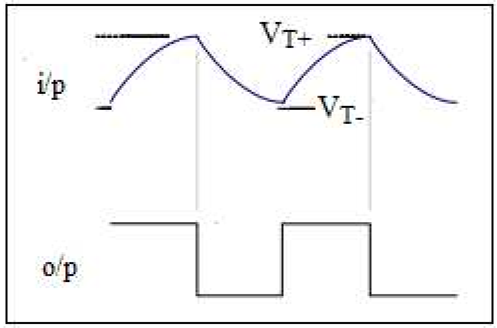


Figure 3.5: Input and Output waveforms of Schmitt trigger (V_{T+} and V_{T-} are upper and lower threshold values). [26]

3.2.3 Functioning

Coming back to the functioning of the TDR circuit, one of the inverters of 74AC14 IC is used for Schmitt trigger which generates a square wave with fast rising and falling edges. This square wave is given as the input to the remaining five inverters which are parallel to each other. Each of the inverter has a 220Ω resistor in series to it, so the overall output impedance is approximately 50Ω. This circuit can now drive loads up to 50Ω pretty easily, and if the circuit gets shorted, the resistors can protect the inverters from getting destroyed or over-loaded. The 100nF capacitor is the decoupling capacitor for the power supply.

As the sink current of the device (i.e. 74AC14) is ±50mA, the five inverters which are placed in parallel become capable of driving a load with high current (i.e. ±250mA). The above circuit operates at 5V.

3.3 TDR Probe

The TDR probe used here is a bi-axial probe (i.e. 2-wire transmission line). It is made out of two 3/32 brass rods which are 36 inches long and have 2.38 mm diameter.

These two brass rods which have to be immersed in water and are connected to a coaxial cable at one end. Firstly, the outer conductor of the coaxial cable is de-braided and connected to one of the brass rods, and the inner conductor is connected to the other rod using crimp connectors. The coaxial cable used here is RG 59B/U E-24340. The functioning of the two-wire transmission line and its parameters are studied in the previous chapter.

3.4 Procedure

The TDR circuit and probe built are now used to calibrate the level of water in the tank. Firstly, the TDR launches the voltage pulse into the probe. This incident pulse reflects at the bottom of the tank and the air-water interface, due to change in impedance. As the probe is open at the end, reflection accounts there. At air-water interface, due to large difference in the dielectric constants of air and water (i.e. 1 and 80.4 respectively) impedance mismatch occurs. The incident and reflected signals are captured on the Oscilloscope screen. The time difference between the two peaks (i.e. the incident and reflected peaks) is found out, which in return helps to find out the height of water in the tank.

3.4.1 Derivation of Height Formula

The figure 3.6 below shows the setup in the water tank. The propagation velocity of the probe inserted in the medium must be known to find out the height of water. The wave propagates through coaxial cable, air and water mediums. The velocity of propagation is different in each section. The total time will be the summation of travel times in all the phases (coaxial cable, air and water). Then from the measured travel time, it will be easy to find out the level of water in the tank. [11]

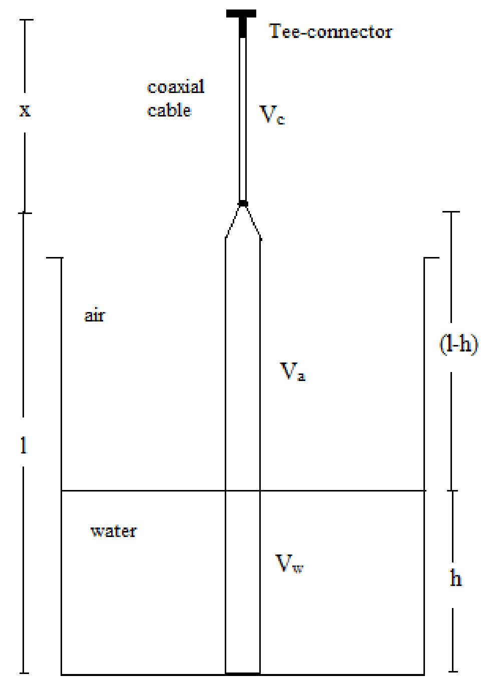


Figure 3.6: Probe setup in the tank.

The coaxial cable used here has a solid polyethylene dielectric with dielectric constant 2.23, and characteristic impedance 50Ω. The velocity factor of coaxial cable is 67%, i.e. the velocity of propagation of wave in coaxial cable is 0.67 times the velocity of propagation in air (i.e, $3X10^8$ m/s). Therefore, the velocity of propagation of wave in coaxial cable is $2X10^8$ m/s.

The dielectric constant of water is 80.4. The speed of EM wave propagating through a dielectric medium is given by

$$V = \frac{c}{\sqrt{k}}$$

where, V is the velocity of wave in medium,

c is the velocity of wave in vacuum = $3X10^8$ m/s,

K is the dielectric constant of medium.

$$V_w = \frac{3 * 10^8}{\sqrt{80.4}} = 0.33 * 10^8 m/s$$

where, V_w is the velocity of wave in water.

The velocity of propagation of wave in water column is equal to $0.33X10^8$ m/s. The velocity of the TDR pulse in water to air is in the ratio of 1:9. [12]

The sum of all the travel times in different media will be equal to the total measured time. The wave travels the total length twice, i.e, to and fro.

$$time = \frac{2 * length}{velocity}$$

$$t = 2\left(\frac{x}{V_c} + \frac{(l-h)}{V_a} + \frac{h}{V_w}\right)$$

where, t is the total time taken to travel the probe

h is the height of the water in the tank

x is the length of coaxial cable

l is the length of the bi-axial cable

V_c is the velocity of wave in coaxial cable = $2X10^8$ m/s = 7.9 inches/ns

V_a is velocity of wave in air = $3X10^8$ m/s = 11.8 inches/ns

V_w is velocity of wave in water = $0.33X10^8$ m/s = 1.31 inches/ns

For a given tank, by substituting all the known values and constants into the above equation, the relation between time and height can be derived. In this way the height of water can be found out. The data obtained at the Oscilloscope screen is extracted into a CSV file, and a MATLAB code is written to find the height of the water in the tank from the digital data acquired.

CHAPTER-4

RESULTS AND ANALYSIS

4.1 Introduction

The experiment has been carried out in the laboratory to check it's functioning, using the TDR circuit and the bi-axial probe proposed in this thesis. Below is the figure 4.1, which shows experimental setup and TDR circuit.

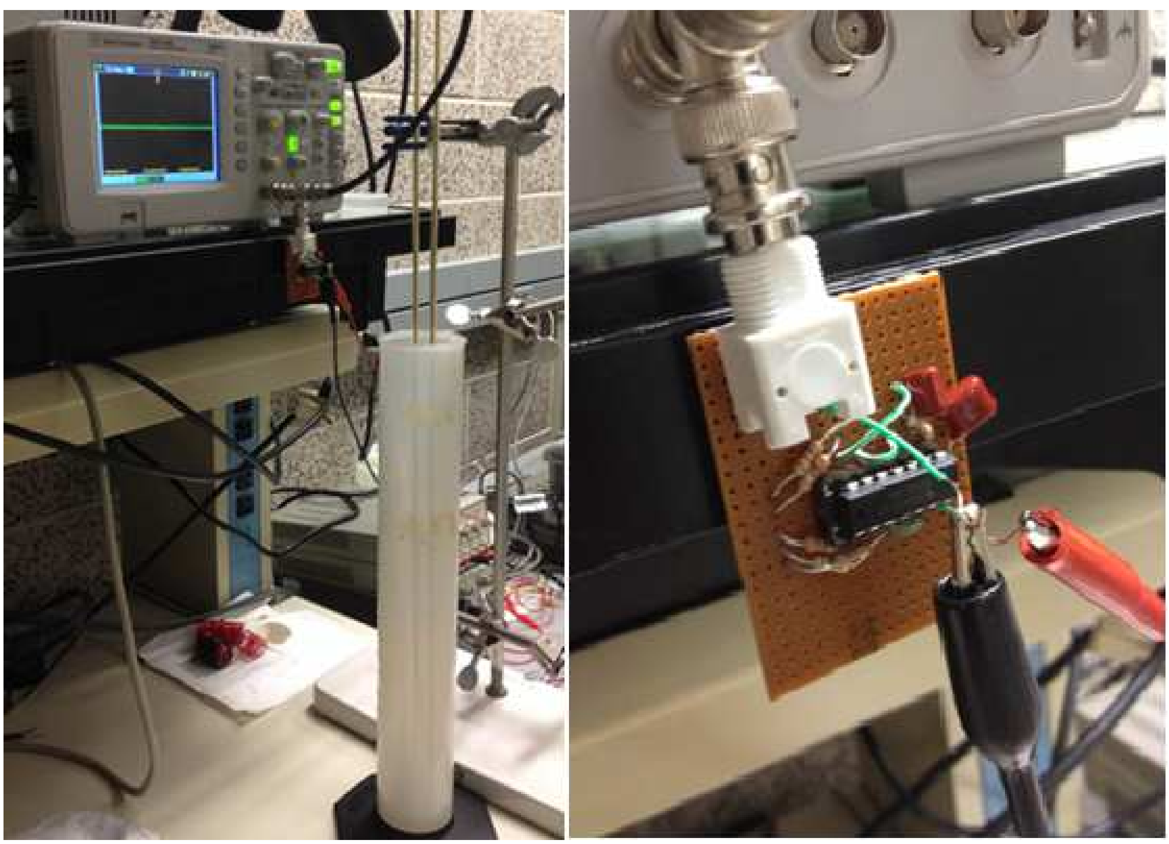


Figure 4.1: a) Experimental Setup, b) TDR circuit built.

4.2 Results and Analysis

As studies in the previous chapter the Schmitt trigger is responsible for generation of pulse. On testing the functioning of the Schmitt trigger in laboratory, the waveforms in the figure 4.2 were obtained. The yellow waveform (triangular waveform) is the input to the circuit, and the green waveform (square waveform) is the output. The square wave generated by Schmitt trigger has a time period of 352µs (i.e. 2.84 KHz) and rise time of about 4ns.

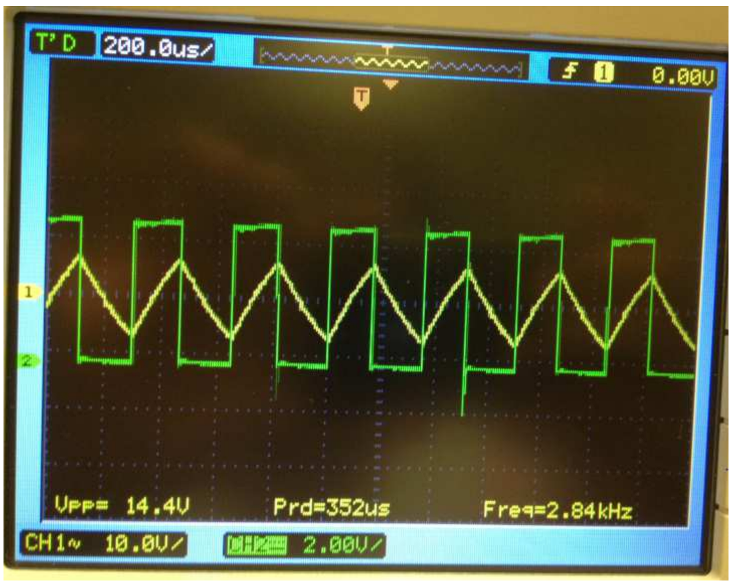


Figure 4.2: Schmitt trigger outputs.

On testing the functioning of the TDR circuit, a square wave which does not have clean edges was obtained. There was little bit ringing on the edges, which will be used to identify the spot of the reflected signal, in order to calculate the distance between the source and surface of water. The square wave generated by the TDR circuit has amplitude of about 5.2V and frequency 2.84 KHz. In the figure 4.3 below, the output of the TDR circuit when the probe was not connected is seen.

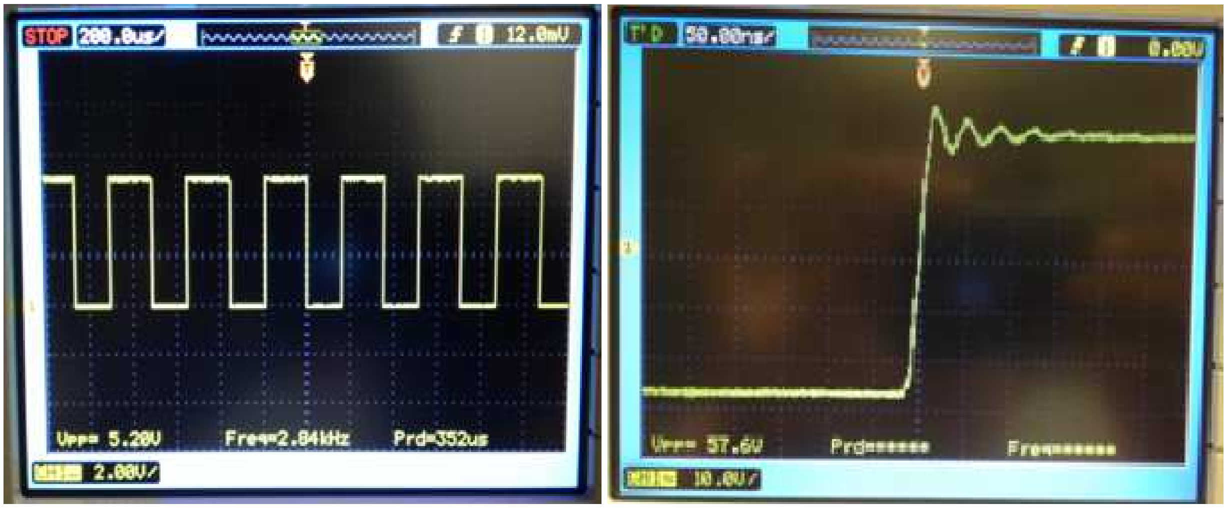


Figure 4.3: Outputs of TDR circuit.

Consider a tank, of height 40.5cms (16 inches) and 6cms diameter. The experiment was carried out in the given tank. Above are the output waveforms of TDR circuit, when no load is connected. When the probe is connected to circuit, a small reflection in the waveform due to the mismatch at the termination end of the probe can be seen, as in figure 4.4.

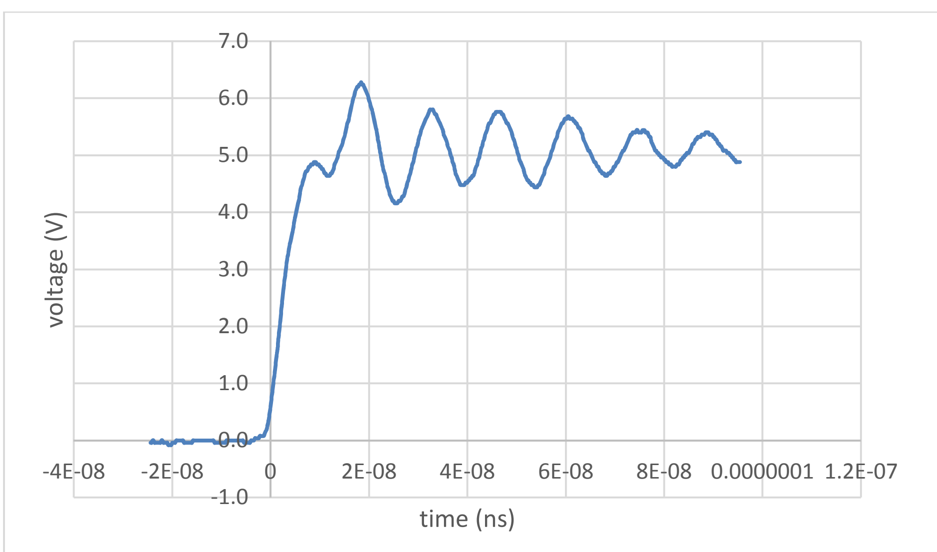


Figure 4.4: Output due to reflection from probe termination.

The above waveform is the screenshot of the Oscilloscope. Here, the x-axis represents time and y-axis represents voltage. The first peak here is the incident peak, whereas the second peak is the sum of incident and reflected peaks. The other peaks are the ringing at the edge of the square wave.

Later, water is added into the tank, and the readings are noted at regular intervals (for every 100 ml addition of water). The time difference between the incident and reflected peaks is observed. The height of the water in the tank is also noted manually by measuring it with a scale, which will later be used for verification. Below is the table 4.1 of readings from the experiment.

Table 4.1: Readings of TDR Experiment.

S.No.	Height (cms)	Time difference (ns)	Voltage difference (mV)	Volume (ml)
1	3.6	13.79	1360	100
2	7.1	14.4	1120	200
3	10.2	17	800	300
4	13.7	19	520	400
5	17.3	28	640	500
6	20.3	29.5	640	600
7	23.9	31	680	700
8	27.4	33	720	800
9	30.5	33.7	560	900
10	34	34	520	1000

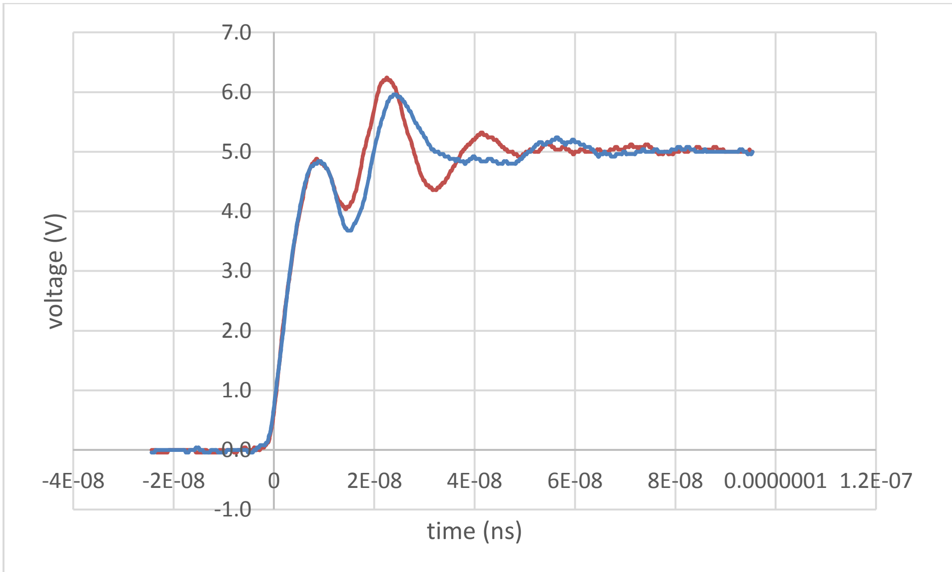


Figure 4.5: Waveforms at 100ml (red line) and 200ml (blue line) water.

Many points can be made out from the above graph (refer 4.5). Firstly, here the red line represents the x-y plot at 100 ml and blue line at 200 ml. The second peak reflects from the bottom of the tank. We can see that as the height of the water increases, the reflected signal shifts toward right. This is because, as the water height increases, the signal travels more water than before. Therefore, the time taken to travel the complete path also increases.

The bottom of the tank, i.e. the probe termination and air-water interface are both considered as discontinuities. But, there is only one reflection. This is because the discontinuities placed at close proximity from each other are smoothened into single discontinuity.

As the water level increases, the distance between the discontinuities also increases, because of which two reflections can be seen. Below is the waveform at 400 ml water, i.e. 13.7cms height (refer figure 4.6).

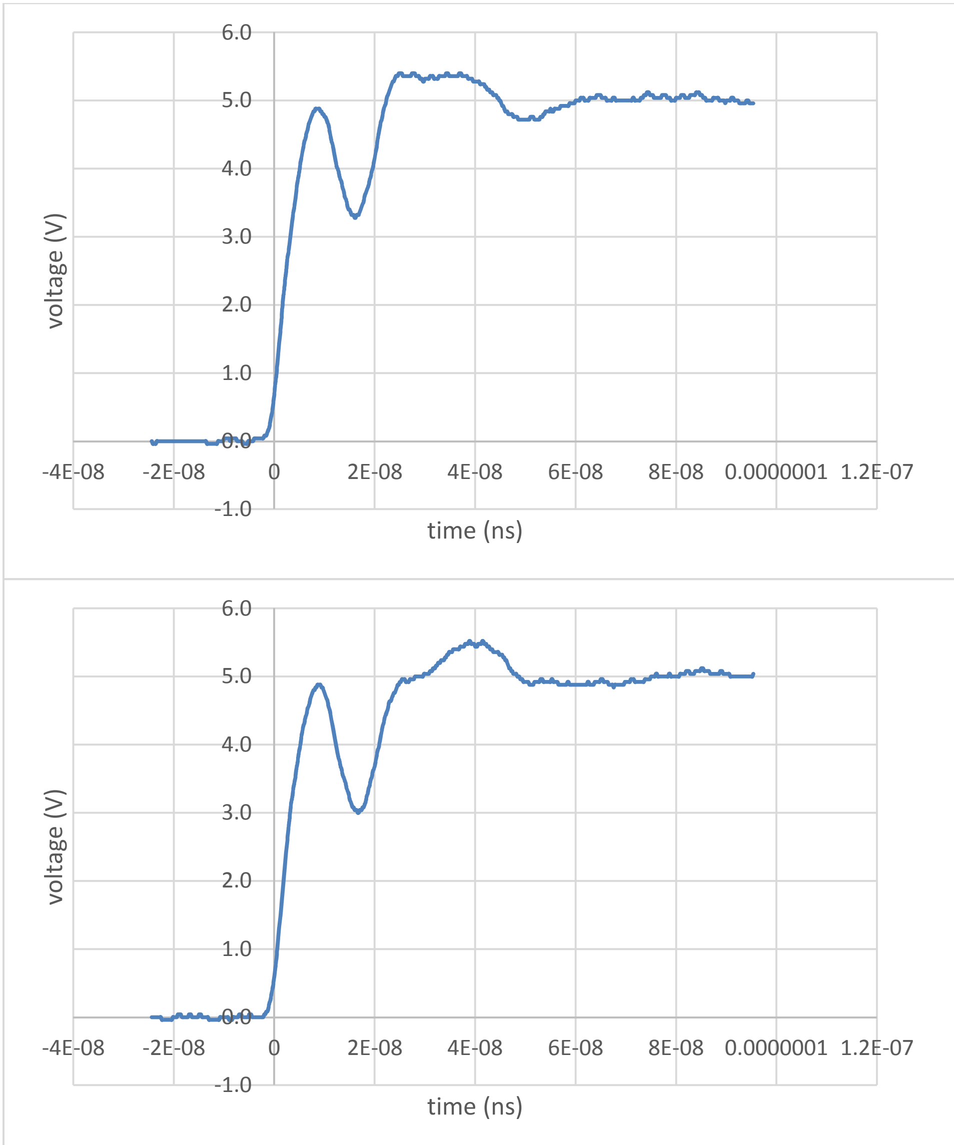


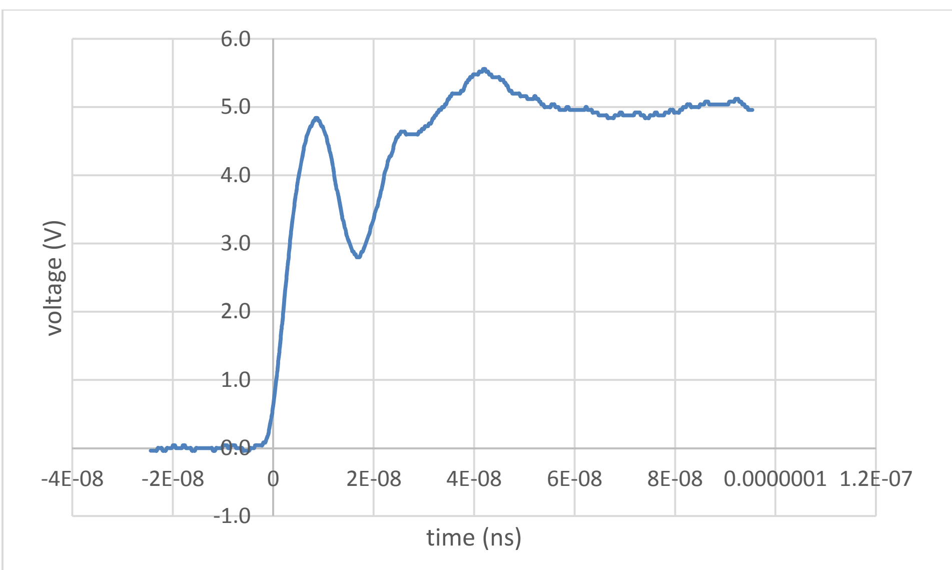
Figure 4.6: a) x-y plot at 400 ml water (13.7 cms), b) x-y plot at 600 ml water (20.3cms).

The shape of the reflected peak flattens when the height of the water is about 13.7cms. At 20.3cms height water, two reflections can be seen, one from the bottom of the tank and the other from air-water interface. It is not possible to distinguish two neighboring discontinuities, if they are spaced at a distance less than half of the system's rise time. [14]

$$T_{spacing} = \frac{1}{2} T_{r(system)}$$

The rise time of this system is 4ns. Only if the discontinuities are spaced 2ns away from the each other, they can be notified separately or else they will be considered as single discontinuity.

From the graphs below (refer figure 4.7) one can observe that the time difference between the incident peak and reflected peak increases as the water level increases. At the same time one can also notice that the reflection from air-water interface is moving closer to the incident peak. But, it is very hard to observe the reading from the reflection of air-water interface, as the change is very minute. Therefore, one will consider the time difference between the incident peak and reflected peak from bottom of the tank to measure the height of water.



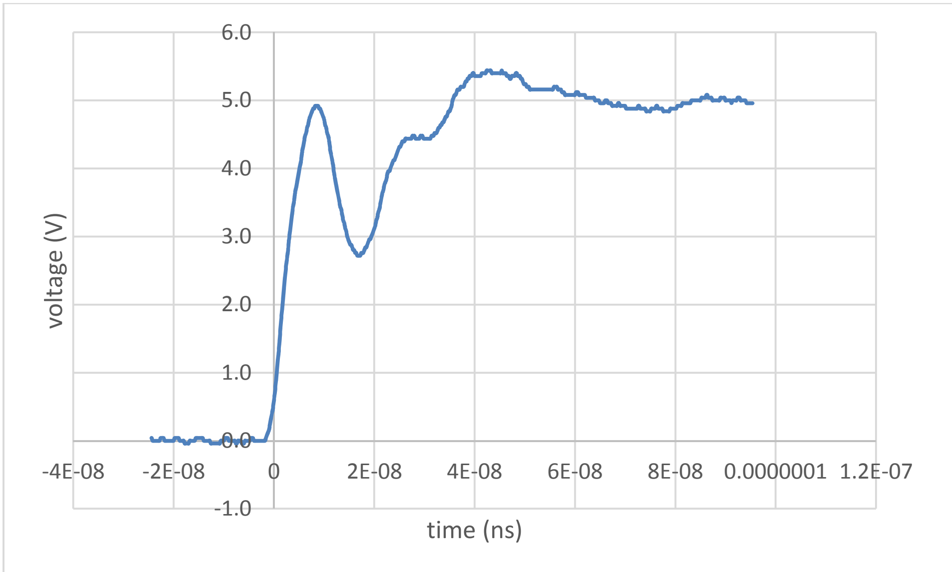


Figure 4.7: a) x-y plot at 800ml water (27.4 cms), b) x-y plot at 1000ml water (34 cms).

In the previous chapter, we have derived the equation for total travel time of the pulse through different paths of the tank.

$$t = 2\left(\frac{x}{V_c} + \frac{(l-h)}{V_a} + \frac{h}{V_w}\right)$$

where, x = 56cms (length of coaxial cable);

l = 91.4cms (length of bi-axial probe).

$$t = 11.68 + 0.534h$$

$$h = \frac{t - 11.68}{0.534}$$

In this way one can calculate the height of water from the time difference obtained. Below is the table 4.2 of empirical heights and actual heights. There is an error in the height values obtained. This can be rectified by error correction method, in which the polynomial of the error is obtained and subtracted from the empirical height. In this way one can obtain the actual height. The difference between empirical and actual heights can be seen in the figure 4.8 below.

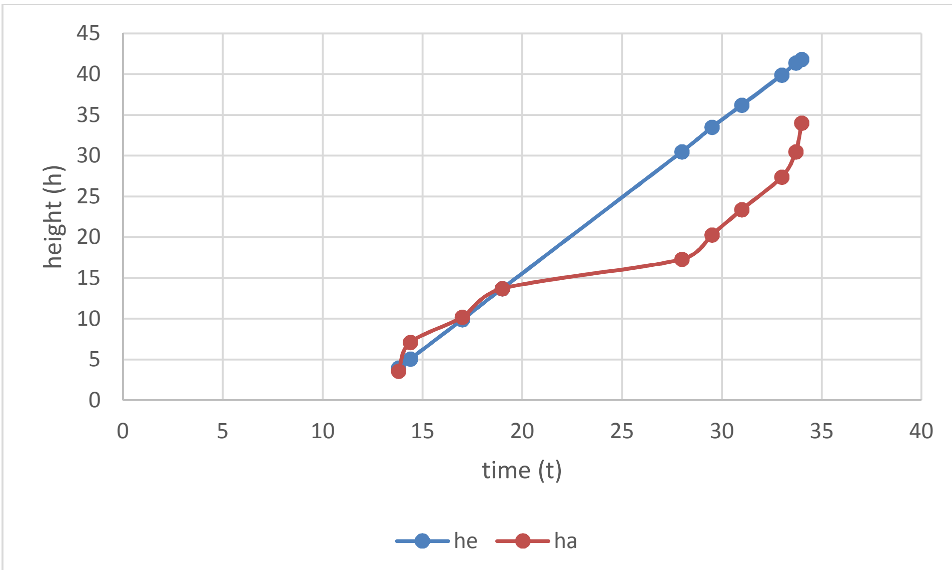


Figure 4.8: a) empirical height vs. time difference, b) actual height vs. time difference.

Table 4.2: Error between Empirical and Actual Heights.

S.No.	Time Difference (ns)	Empirical height, h_e (cms)	Actual height, h_a (cms)	Error (h_e-h_a) (cms)	Normalized error
1	13.79	3.97	3.6	0.37	10.27
2	14.4	5.09	7.1	-2.01	-28.3
3	17	9.9	10.2	-0.3	-2.94
4	19	13.7	13.7	0	0
5	28	30.5	17.3	13.2	76.3

(Continued to next page)

Table 4.2: Continued

S.No.	Time Difference (ns)	Empirical height, h_e (cms)	Actual height, h_a (cms)	Error (h_c-h_a) (cms)	Normalized error
6	29.5	33.5	20.3	13.2	65.0
7	31	36.17	23.4	12.8	54.7
8	33	39.92	27.4	12.5	45.6
9	33.7	41.4	30.5	10.9	35.73
10	34	41.8	34	7.8	22.94

In the above table 4.2, error is calculated for all the readings and is plotted against empirical height.

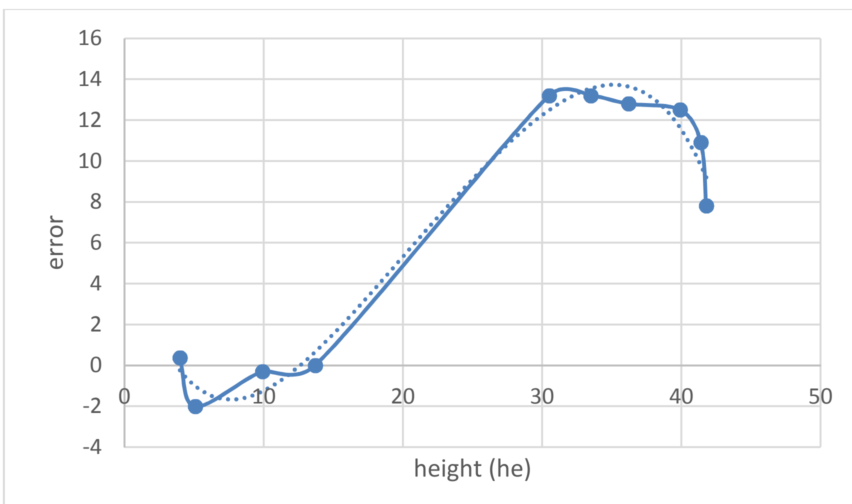


Figure 4.9: Error vs. empirical height

The above plot is the error plot (refer figure 4.9). One can see that the polynomial equation does not fit in properly. To overcome this, the error plot is divided into three parts, and each part has a polynomial equation of its own, which is subtracted from the empirical height. In this way, the error is corrected. Below are the graphs of three divided error plots (refer figures 4.10, 4.11, 4.12).

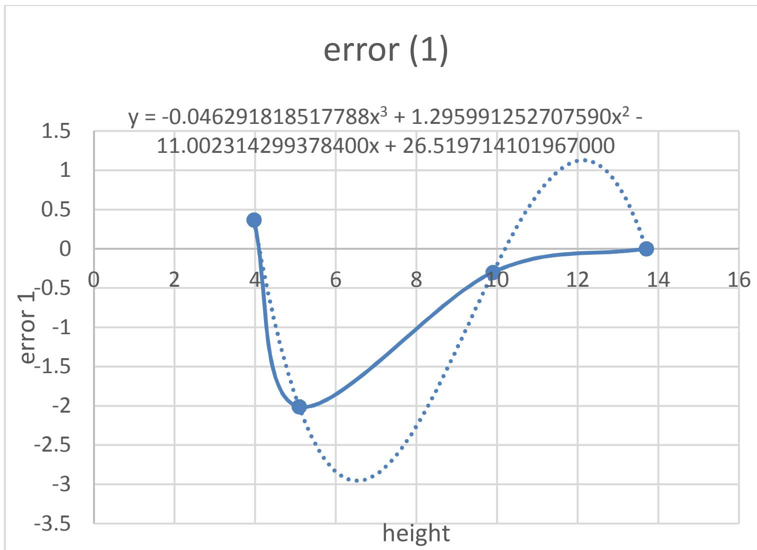


Figure 4.10: First error plot

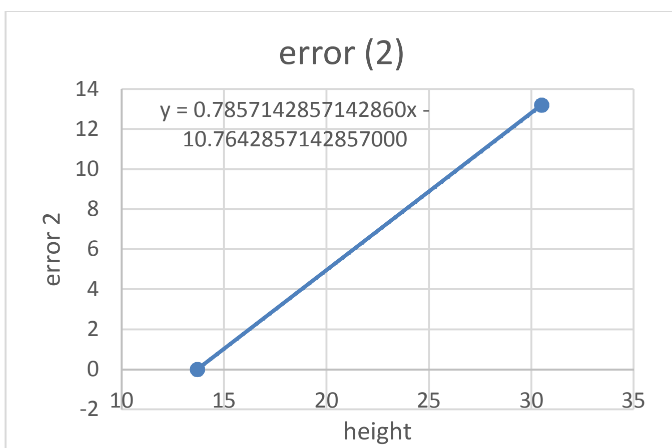


Figure 4.11: Second error plot

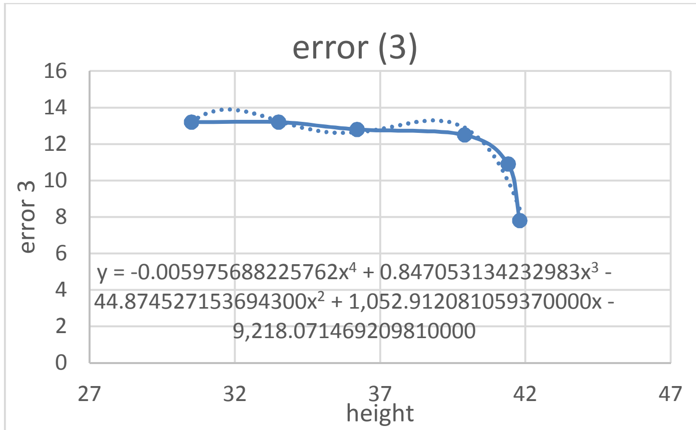


Figure 4.12: Third error plot

Table 4.3: Table of Actual and Obtained Heights

Time difference (t)	Actual height (h_a)	Empirical height (h_e)	Obtained height (h_o)
13.79	3.6	3.97	3.6
14.4	7.1	5.09	7.1
17	10.2	9.9	10.1
19	13.7	13.7	13.7
28	17.3	30.5	17.3
29.5	20.3	33.5	20.3
31	23.4	36.17	23.5
33	27.4	39.92	27.04
33.7	30.5	41.4	31.5
34	34	41.8	33

The error obtained is subtracted from the empirical height to get the correct height.

$$h_o = h_e - e(h)$$

From the above table 4.3 one can see that the obtained values are very close to the actual values of the height. The above data shows that there is 98% accuracy in height measurement (as in figure 4.13). As the polynomials don't fit in the error plots exactly they are not 100% accurate. The graph represents the rate of precision of the Time Domain Reflectometer system.

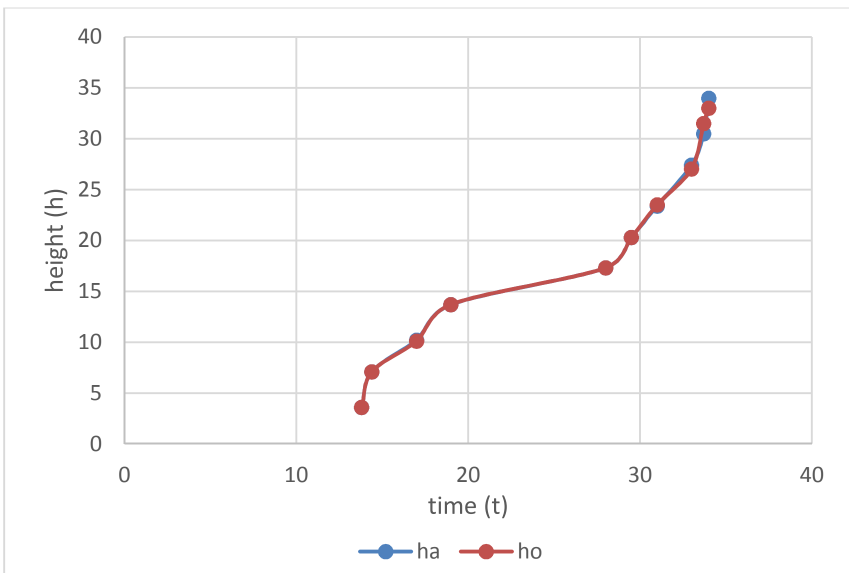


Figure 4.13: Obtained height and actual height graph.

The data is extracted from the Oscilloscope as a CSV file, from which the data is simulated in MATLAB to find out the time difference between the incident and reflected peaks. Using the above process, the height is derived from the obtained time difference.

CHAPTER-5

CONCLUSION

5.1 Conclusion

The TDR technique has been developed for calibration of liquid level in the tank, with high accuracy. The TDR probe used in this thesis is a bi-axial cable which is designed using two brass rods. They were assembled in such a way that the characteristic impedance was close enough to 50Ω, which matches with the source impedance. The transmission of the wave through the probe and its parameters were studied. The TDR circuit was built with 74AC14 IC for signal generation. Thus, generated signal was transmitted through the bi-axial probe, where part of the incident signal was reflected back to the source on hitting a discontinuity. This TDR technique was tested in the laboratory, in a plastic jar from which few conclusions were drawn. The TDR technique is simple and accurate for measurement of liquid level, and it is a non-destructive technique. Finally, an efficient TDR technique was developed.

5.2 Recommendations

This study was concluded with the setup of TDR using an Oscilloscope and a PC. It is recommended to use a highly efficient ADC with high frequency clock speed to digitize the data, without the use of Oscilloscope.

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APPENDIX A

IMPEDANCE OF THE BI-AXIAL PROBE

Bi-axial probe is nothing but a two-wire transmission line. The characteristic impedance of the two-wire transmission line is

$$Z_o = \frac{1}{\pi}\sqrt{\frac{\mu}{\epsilon}}cosh^{-1}(\frac{d}{2a})$$

where, $\mu = 1.257 \text{ X } 10^{-6}$ H/m (permeability of dielectric medium),

$\epsilon = 8.85 \text{ X } 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$ (permittivity of dielectric medium),

d = 20 mm (distance between the two conductors),

a = 1.19 mm (radius of each conductor).

On substituting all the values into the above equation, the characteristic impedance will be equal to 337Ω.

Figure A.1: TDR probe.

But at the beginning of the bi-axial cable (i.e. at its connection with the coaxial cable) the two conductors are separated by a distance of 2.6 mm, due to which its characteristic impedance is approximately equal to 50Ω (refer figure A.1). Thus, no mismatch occurs at the coaxial cable and bi-axial cable connection.

APPENDIX B

MATLAB CODE

```
voltage=xlsread('file.csv','B3:B602');

time=xlsread(‘file.csv','A3:A602');

m=max(voltage);

a=0;

b=0;

for i=1:599

if(voltage(i)>1 && voltage(i)>voltage(i+1) && a==0)

    v1=voltage(i);

    t1=time(i);

    point=i;

    a=1;

end

if(voltage(i)==m && b==0)

    p1=i;

    t2=time(i);

    b=1;

end

end

double x;

x=(t2-t1)*10^9;

disp(x);

double g1;

double error;
```

```
double h;
h=(x-11.68)/0.534;
disp(h); %empirical height
if (x<19)
    error = -0.046291818517788*h^3 + 1.295991252707590*h^2 -
11.002314299378400*h + 26.519714101967000
   end
if (x>19 && x<28)
        error = 0.7857142857142860*h - 10.7642857142857000;
   end
if(x>28)
  error = -0.005975688225762*h^4 + 0.847053134232983*h^3 -
44.874527153694300*h^2 + 1052.912081059370000*h - 9218.071469209810000;
end
vd=m-v1;
a=h-error;
disp(a); %measured height
maxh=40.5;
if((a/maxh)>0.95)
    disp('Water level is above 95%');
elseif((a/maxh)>0.75)
   disp('Water level is above 75%');
else
    disp('Water level is below 75%');
end
```