In the previous article, the basics of Time Domain Reflectometry (TDR) were discussed. In this segment, we will discuss the application of TDR to liquid level sensing.

**Impedance of a coaxial transmission line**

Figure 1 shows a coax cable with an inner conductor, an outer conductor and an insulator that provides electrical isolation between the two conductors.

![Figure 1: Basic Coax Dimensions and Construction](image)

The basic impedance equation for a coax cable is:

\[
Z_0 = \frac{1}{2\pi} \sqrt{\frac{\text{perm}}{\varepsilon_r}} \ln \left( \frac{d_0}{d_1} \right)
\]
Where:

\( \mu_o \) is the magnetic permeability of free space

\( \mu_r \) is the relative permeability of the conductors in the coax

\( e_o \) is the dielectric permeability of free space

\( e_r \) is the relative dielectric of the insulating material

\( d_o \) is the outer conductor diameter

\( d_i \) is the inner conductor diameter

\( \mu_o, \mu_r, \) and \( e_o \) can be treated as constants in Equation 1, simplifying equation 1 to:

\[
\text{Equation 2} \quad Z_o = \frac{55.958}{\sqrt{r}} \cdot \ln\left(\frac{d_o}{d_i}\right)
\]

The coax will be constructed with air as the insulator, for which \( e_r \) is 1. Using a 3/16” stainless-steel rod and a .430” outer conductor forms almost exactly a 50 Ω coax. This can be formed using a .5” diameter stainless-steel tube with a .035” wall. Using \( d_o \) of .430” and \( d_i \) of .1875”, the equation 2 becomes

\[
\text{Equation 3} \quad Z_o = \frac{49.766}{\sqrt{r}}
\]

**Applying TDR to Liquid-Level Sensing**

We have formed a coax with air as the insulation, which has a relative dielectric of 1 and characteristic impedance of \( Z_o \sim 50 \Omega \). If the air with a relative dielectric of 1 is displaced with a liquid that has a relative dielectric greater than 1, the impedance \( Z_o \) will be changed as defined by Equation 3. Table 1 is a list of the Dielectric constant, Impedance, and % change of impedance from 50 Ω.
From Table 1, it can be seen that displacing air with a liquid will cause a change of impedance that can be measured. Figure 2 and Figure 3 illustrate how if we have an air-filled coax that is shorted at the end, a reflection will be generated. If air is displaced with a liquid then two reflections are created; the first from the air-liquid interface, and the second from the short at the end of the coax.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Dielectric Constant</th>
<th>Impedance</th>
<th>% change in Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>49.8</td>
<td>0</td>
</tr>
<tr>
<td>Diesel</td>
<td>1.8</td>
<td>37.1</td>
<td>25.8%</td>
</tr>
<tr>
<td>Gas</td>
<td>2</td>
<td>35.2</td>
<td>29.6%</td>
</tr>
<tr>
<td>Isopropyl Alcohol</td>
<td>18.3</td>
<td>11.6</td>
<td>76.8%</td>
</tr>
<tr>
<td>Water</td>
<td>68</td>
<td>6.9</td>
<td>88.0%</td>
</tr>
</tbody>
</table>

Table 1: Dielectric and Impedance for Common Liquids

From Table 1, it can be seen that displacing air with a liquid will cause a change of impedance that can be measured. Figure 2 and Figure 3 illustrate how if we have an air-filled coax that is shorted at the end, a reflection will be generated. If air is displaced with a liquid then two reflections are created; the first from the air-liquid interface, and the second from the short at the end of the coax.

A measurement is made when a Vpulse is sent out, and when the reflection from the air-liquid interface returns. For a resolution of 0.02", a time measurement with a resolution of 3.5 ps must be made (details discussed in next article).
Additional Information

By measuring the amplitude of the step, additional information can be determined regarding the liquid. In automotive applications, it could be determined whether if diesel was used to fill the tank instead of gasoline, allowing the prevention of starting the car. The ethanol content of gasoline could be determined as well, allowing for the tailoring of fuel mixture and ignition.

Liquid Tolerance

TDR measurement can be used with any liquid to measure level. It has the advantage of being immune to the different properties of liquids, such as:

Dielectric constant

- Ionic
- Non-ionic
- Conductive
- Non-conductive

Benefits of TDR Level Sensing

Compared to a float system:

- No moving parts in a TDR system; there is nothing to wear out
• Stainless-steel construction means no corrosion
• Better resolution, with a demonstrated resolution of 0.02"

Compared to an ultrasonic solution:

• TDR probe cost can be pennies in high-volume manufacturing, as opposed to dollars for ultrasonic sensors
• Drive and measurement circuitry is much simpler and at lower voltage
• More resistant to corrosion
• TDR probe is immune to mechanical shock

Compared to capacitive level sensing:

• TDR is independent of liquid, when measuring liquid
• TDR can differentiate between liquids; i.e., TDR can differentiate gas from diesel or ethanol

In the final article, an actual implementation of this technique will be discussed.