Level Switch for Non-Conductive Liquids

In this article, I discuss how our company repurposed a liquid level probe intended for conductive liquids to work with non-conductive liquids, as well.

FEATURES

By
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Not too long ago, our company developed and built a gas conditioner for fuel cell research. Before supplying hydrogen and air to the fuel cell, the gases had to be humidified and warmed up to a controlled level. Humidification was performed using a membrane-based, flow-through system, which required distilled or deionized water. As a result, the level of distilled water had to be monitored throughout the operation of the gas conditioner, and the water had to be replenished automatically to compensate for the water carried away with the gas. The task seemed to be quite simple, and there was no shortage of various level sensors and switches available at Grainger or McMaster-Carr. Unfortunately, they did not fit one way or another—either too big, or too expensive, or outside the temperature range. Therefore, we came up with our own solution.

It is important to understand that distilled water is not conductive, but rather "polar." This means that a water molecule is a dipole having partial positive and negative charges. Other molecules, including ethanol, ammonia, and acetic acid (vinegar) are also polar. **Figure 1** shows the distribution of charges across the water and ammonia molecules. The dipole characteristic of these molecules is going to be very useful for us.

When a polar liquid is placed into an electric field, the molecule dipoles orient themselves along the field lines, effectively reducing the electric field within the liquid. This phenomenon is described through a dielectric constant, ε. For water at 20°C, ε=80; for liquid ammonia at -34°C, ε=22. If such liquid is placed into a capacitor, its capacitance would increase ε times, compared to an air-filled capacitor. Our level switch utilizes this phenomenon according to the diagram shown in **Figure 2**, which is effectively a voltage divider.

The voltage on the resistor part of the divider is applied to the sensor, whose capacitance depends on the liquid level. As the liquid reaches the sensor's rod, the capicitance increases, and the voltage drops. A good candidate for an airtight sensor is the Dwyer CLP-1 liquid level probe (**Figure 3**). Contrary to our requirements, the probe is specifically designed to work with conductive liquids! But as we will see, our solution makes it perfectly suitable for bot conductive and non-conductive liquids. (Although Dwyer is not producing such sensors anymore, there is a wide variety of similar products at Grainger under the category "Conductivity Level Probes." For example, item #6EJP7, Liquid Level Probe: Industrial, 1/2 in NPT, 304 Stainless Steel.)

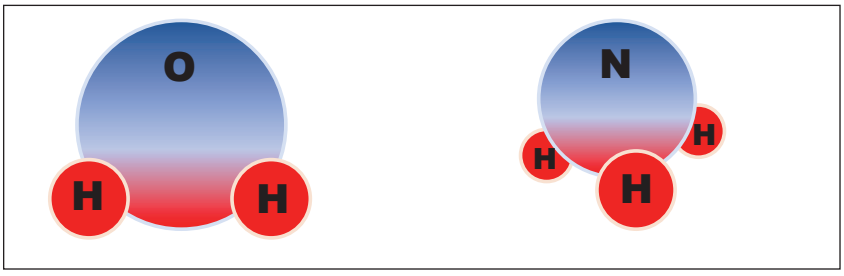

FIGURE 1
This is a schematic representation of electron density distribution in water (left) and ammonia (right) molecules. Blue to red indicates the transition from negative to positive partial charges.

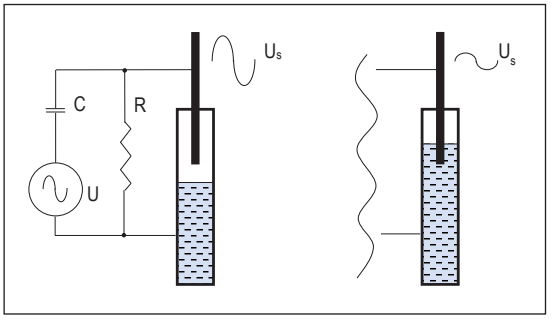

FIGURE 2
Outer shell and a sensor rod make a liquid-filled capacitor, which is the liquid level sensor. The capacitance increases as the rod is being immersed.

Condition	U_s, Vp-p	C_s, pF
Air	8.80	14.0
Distilled water, 1-2 mm immersion	0.72	1288.0
City water, 1-2 mm immersion	0.13	7592.0

TABLE 1
The results of our experiments with a sine wave generator to determine the capacitance of our system with and without distilled water or city water

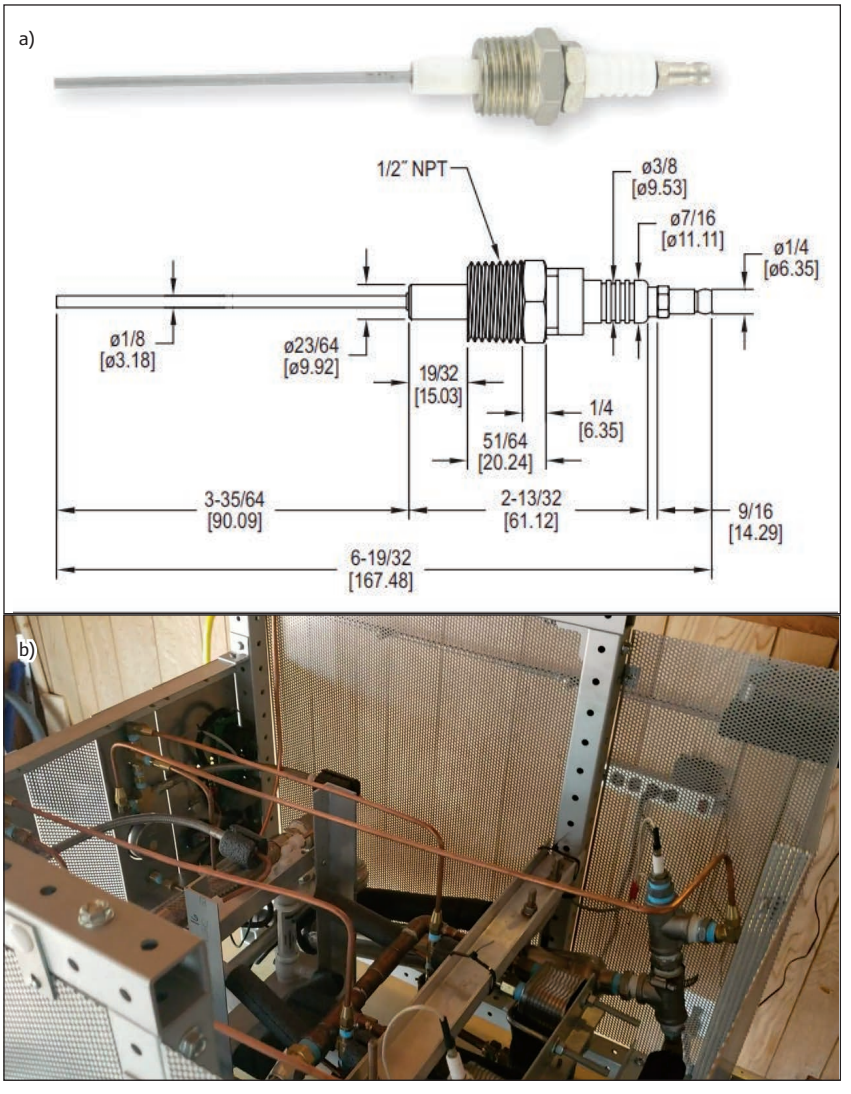

FIGURE 3
a) Dwyer Instruments CLP-1 liquid level probe (Image adapted from dwyer-inst.com); b) The probe placed into the gas conditioner

We did not know the capacitance of our system with and without the distilled water. Therefore, we conducted initial experiments with a sine-wave generator, 500Hz, U=10Vp-p, C=100pF and R→∞ (removed). Capacitor C and the liquid level sensor with capacitance C_f make a divider:

$$U_f = \frac{UC}{C + C_f};\ \text{therefore}\ C_f = \frac{C\left(U - U_f\right)}{U_f}$$

Measurements produced the results shown in **Table 1**. These findings are quite revealing. First, our physical model seems correct. Indeed, the distilled-water-filled capacitor is about 80 times higher than the air-filled capacitor! Second, as a side note, the capacitance in the case of distilled water is quite high—1.3nF—which explains why any digital electronics should not be turned on wet, even if the wetness is due to non-conductive distilled water or dew. Such capacitance at the megaHertz-scale frequencies presents itself as low impedance of a few hundred ohms.

Knowing the order of magnitude of the capacitance in our configuration, the final design for a two-channel liquid level switch was created and tested. The schematic for it is shown in **Figure 4**. A sine-wave oscillator is built around U1.1, which produces approximately 3kHz. The oscillator is followed by the buffer U1.2. The signal is split into two identical channels built around U2.1 and U2.2. (In our design we had to humidify two different gases. In principle, there may be one, two, or more channels).

Let's focus on one of the channels in Figure 4 outlined with a red-dashed rectangle. The 100pF capacitor, as explained above, is a part of the voltage divider. The 390kΩ resistor shunts statics and electromagnetic noise that may occur in the sensor and wires leading to it. The outer shell of the sensor is tied with ground (GND_COMMON). Measured amplitudes on the sensor with respect to ground were 0.18V and 2.88V, with and without distilled water, respectively.

The U2.2 digitizes the sine-wave signal such that when water is present, the output of the comparator becomes high impedance. In this case, this is because the voltage on the inverting input is below that of the non-inverting input. Diode D5 acts as a very high-impedance device, preventing any significant current flow into the base of transistor Q3. Hence, the transistor Q3 is not conducting, resulting in low voltage at the gate of the FET Q4. Thus, the Q4 is blocking the current through the solenoid. When water falls below the sensing rod, the output of the comparator produces negative voltage pulsing. These pulses are integrated with the 470kΩ resistor R9 and the 22nF capacitor C7. The integrated voltage affects (lowers) the voltage

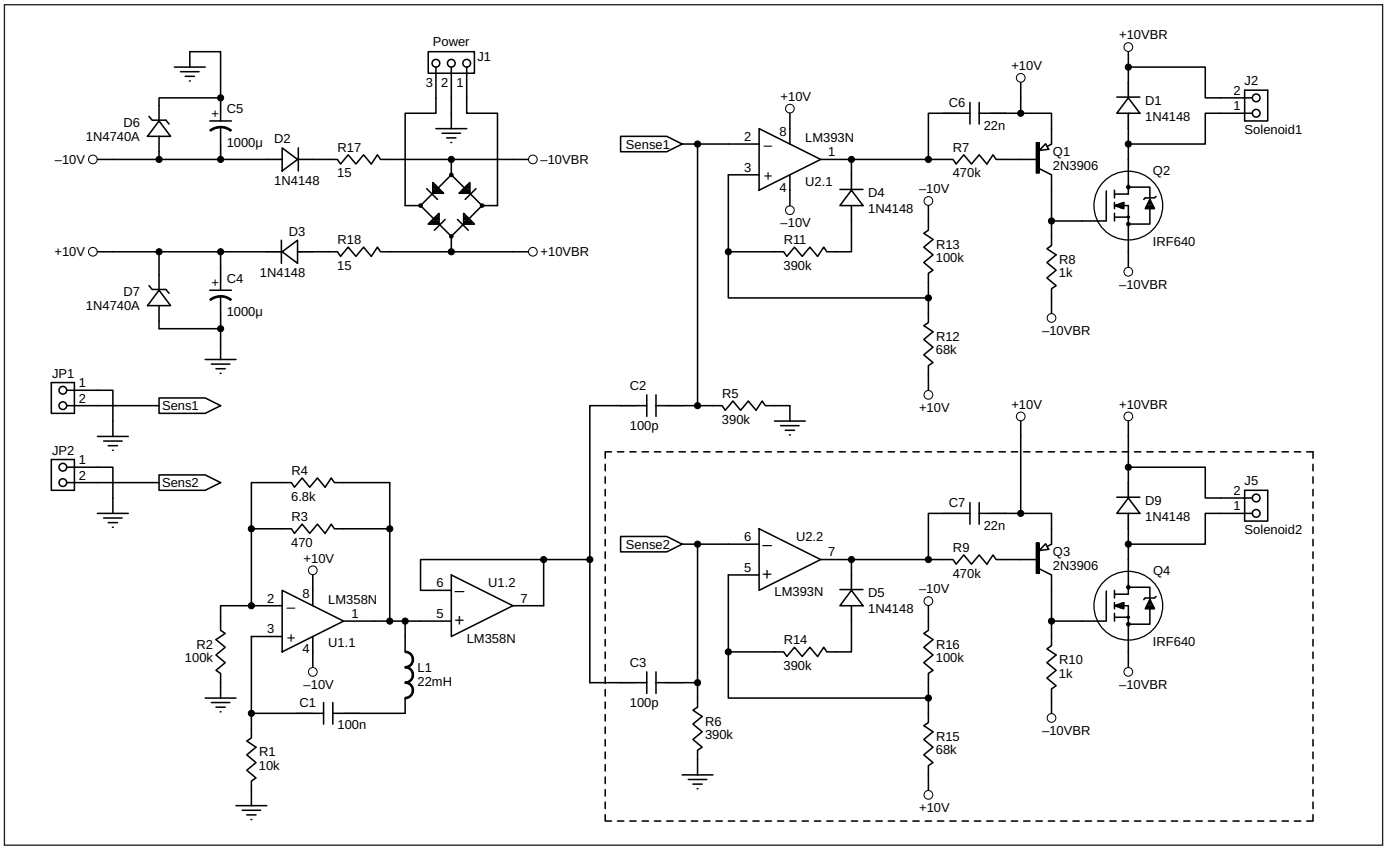

FIGURE 4
Schematic of a two-channel liquid level switch

on the non-inverting input of the comparator through R14, D5, thus providing a hysteresis. Hence, the transistor Q3 turns on, resulting in increased voltage at the gate of the FET Q4. Thus, the Q4 opens and the current is flowing through the solenoid. The current through the Q4 energizes the solenoid, and water begins filling up the system. Note that the solenoid is fed with unregulated pulsing voltage "VBR" (20V). The power source for the level switch was a 14VAC transformer with a center tap.

The liquid level switch has been shown to work well with distilled (and city) water. But how will it perform with other liquids, and what is the appropriate frequency range? Let us theoretically analyze the divider in Figure 2 and make some predictions. Simple manipulations of complex math reveal the voltage on the sensor as shown in the equation:

$$U_s = \frac{UC(C+C_s)R^2w^2}{1+(C+C_s)^2R^2w^2}$$

where w is angular frequency ($w=2\pi f$), and

C_s is the capacitance of the sensor, which depends on the presence or absence of liquid and its dielectric constant. For a system being designed, one has to experimentally determine C_s in air and in liquid. After that, it is possible to come up with optimal C and w, such that the voltage on the sensor is within reasonable limits, and the difference between U_s^{air} and U_s^{liquid} is greater than noise. R should be at hundreds of kilohms.

Detecting the level of conductive and non-conductive (but polar) liquids was accomplished by utilizing the difference in the dielectric constants of air and the liquid. There is a wide variety of liquid level probes on the market, which may be labeled "for conductive liquids." But fear not—our solution will repurpose them for the non-conductive liquids as well!

ABOUT THE AUTHOR

Dr. Alexander Pozhitkov, PhD, has an MSc degree in Chemistry and a PhD in Genetics from Albertus Magnus University in Cologne, Germany. His expertise is in interdisciplinary research involving molecular biology, physical chemistry, and electrical engineering. Alexander has worked in academia (University of Washington and Planck Institute) and in the private sector (MidNite Solar). He owns a small family business, Buddy Engineer, which specializes in the design and manufacturing of research equipment. He is a researcher at the City of Hope Medical Center in Los Angeles CA.

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