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PenTech FAQ # 9 by Gary G. Sanders, Director of Engineering

Basis for Capacitance Level Measurement

Background:
Electrical energy may be directly stored in two different energy field forms (in contrast to indirect storage, e.g., chemical [a battery]). The commonly known form is a magnetic field created by current flowing in a conductor. Perhaps you recall from your school experience making a coil of wire, establishing current flow in it and creating a magnetic field. The device that stores electrical energy (current) as an electromagnetic field is called an inductor. The other form of storage is an electrostatic field, which stores electrical charge. The device that stores electrical energy (voltage·charge) electrostatically is a capacitor. Again from your school experiences, perhaps you were exposed to a Leyden jar, which is a capacitor. Physically, a capacitor is two electrical conductors separated by an insulator. Electrically, positive charges collect on one conductor, negative on the other. Following the rule that opposites attract; but in this case with an insulator between them so no galvanic current flow is possible; the charges establish electrostatic flux lines in a field between the conductors through the insulator.

Once a fixed physical geometry of the two conductors (area of each and their separation distance) is established then the ease of creating electrostatic flux lines in the insulator determines the energy storage capability of the capacitor. This characteristic of the insulator, called its dielectric constant (symbolically ε), is the ratio of ease of forming an electrostatic field compared to that formed in a vacuum. Since it is a ratio of like units, it is a dimensionless number, i.e., without units. The SI unit of measure for a capacitor's storage capability is the farad, named after Michael Faraday. For almost all real world applications, the farad is too large a unit (as is the bel, poise, stoke, etc.). In common usage is the microfarad, μF which is one millionth (10^{-6}) of a farad; the nanofarad, nF, one billionth (10^{-9}) of a farad and the picofarad, pF, one trillionth (10^{-12}) of a farad.

Basics:
To use capacitance to measure level, a physical capacitor must be established in the vessel. Usually this means inserting a conductive (e.g., metal) rod, plate or cable – all called a probe into the vessel. Assuming that the vessel walls are conductive (metal) and not in contact with the probe – a capacitor is formed with air/gas/vapor as the dielectric material. In an operational system this establishes a base value capacitance. This base capacitance is normally nulled by external electronic circuitry to provide a zero point.
The physical geometry of the capacitance system is now fixed. If another material (the process material) is allowed to fill the vessel, it will replace the air/vapor/gas. Assuming the process material has a dielectric constant different than the air/vapor/gas (liquids and solids do), then the total system capacitance value will change.

<u>Application:</u>
Two conductors and an insulator are required to form a capacitor. Normally the walls of a vessel are conductive and establish a grounded reference conductor. If the vessel is nonconductive (e.g., polymer, FRP, glass, cement, etc.), then a second conductor that contacts the process material and establishes a reference must be provided. This commonly takes the form of a concentric sheathing tube surrounding the probe or occasionally another reference probe placed parallel to the active probe.

Examples of commonly used systems for a metallic, cylindrically vertical vessel:
Single Point Level:
Optimally the probe is inserted through a side wall horizontally. When the probe is in air/gas/vapor, system capacitance is at its minimum. When process material covers the probe, it has maximum capacitance. This rapid change of total capacitance from minimum to maximum value as process material covers the diameter of the probe provides a reliable form of switching.
Continuous Level (also **Multi-Point Switching**)**:**
The probe is inserted from the top (occasionally bottom) of the vessel vertically. As process material covers a portion of the probe, that portion will be at maximum capacitance for the process material ε, the uncovered portion will remain at base capacitance for the geometry. Thus the total system capacitance is the sum of the two. If the base capacitance has been electronically nulled then the change in capacitance indicates the proportion of the probe covered by the process material (span).
Interface: this is a tertiary ratiometric measurement:

1. Base capacitance where the probe is in air/gas/vapor with the dielectric constant ≈ 1.
2. Non-polar phase, often a liquid aliphatic hydrocarbon with a low dielectric constant, e.g., $\varepsilon \approx 2$ to 4).
3. Water or other polar material with a high dielectric constant, e.g., $\varepsilon \approx 80$.

A. Total capacitance is sum of all three parts, assume the base capacitance is nulled.
B. If the ratio of polar to non-polar dielectric constant values is high, then the system output will approximate the level of the polar material.
C. If the ratio of polar to non-polar dielectric constant values is low, then the system output will approximate the total columnar level of liquids.
D. Caution: with large columnar immersion of non-polar (low dielectric constant) material and small columnar immersion of polar (high dielectric constant) material, the output may easily be misinterpreted as a larger column of polar material.

One equation used to approximate the total system capacitance for level applications is:

$$C - 29.5 \cong \frac{7.36 \cdot \varepsilon}{\log\left({}^{D_o}\!/_{D_i} \right)}$$

where: C = system capacitance in pF/foot of probe
ε = dielectric constant
D_o = inner diameter of conductive vessel wall
D_i = outer diameter of conductive portion of probe
note: the 29.5pF is a constant offset for Penberthy probe's sealing gland capacitance

To use this formula two conditions must be considered:

1. If the process material is non-conductive (non-polar) and the probe is bare metal then use the formula as stated.
2. If the process material is conductive (polar or has a dielectric constant $\gtrsim$ 20), an insulator must be provided. Commonly, PTFE (polytetrafluoroethylene - Teflon [tm]) or other insulation material is used to encapsulate the probe. As the conductive process media fills the vessel – effectively the vessel walls are electrically transferred into contact with the outside surface of the encapsulation material. D_o is now the outside diameter of the encapsulated probe, D_i is the outside diameter of the metallic portion of the probe and ε is the dielectric constant of the encapsulating material (for PTFE, $\varepsilon = 2.0$).

Some other considerations:

1. For continuous level measurement (not switching) a linear capacitor is required. Examples for applying this requirement are horizontally cylindrical or spherical vessels. Near the bottom and top of the vessel, the probe is close to the vessel walls with the separation distance increasing toward the centerline. Since the reference (vessel wall) to probe separation distance is constantly changing over the length of the probe, the total system capacitance would be changing with two variables – depth of probe immersion and separation. Although it is possible to write an algorithm for linear correction, a simpler solution is to provide a reference that is parallel to the probe (grounded concentric sheathing being the most common).
2. Probe is not centered in the vessel or the vessel is not round. For these conditions when using a non-encapsulated probe, simply consider D_o to be twice the distance from the probe to the nearest vessel wall.
3. If the dielectric constant of the process material is very small, the system capacitance will also be small. If the probe to reference conductor distance is reduced, system capacitance increases. This is another use for concentric sheathing since it is designed to approximate the minimum allowable separation distance especially for encapsulated probes.
4. Capacitive probes are high impedance electrical devices, somewhat akin to antenna. They will pick-up ambient electrical noise (e.g., TV/radio/cell phone/ac wiring/motor starting hash/motor brush hash, etc.). If the probe is placed inside a grounded conductive (metallic) vessel, the vessel will act as a electrical shield otherwise, consider using concentric sheathing.
5. This caution is directed to capacitive devices using 4-20 mA control loops. Instrumentation standards state that control loops shall not be grounded. For certain measurements, e.g., thermocouples in electrically noisy environments, grounding may be necessary to achieve measurement. For capacitance level measurement, vessel walls are the capacitor's reference conductor. Vessels, for electrical safety, are typically bonded to earth either directly or through piping. Instrumentation loops in both cases will work if, and only if, the loop terminus / power supply (perhaps inside a controller, PLC, DCS, PC, A-to-D card, etc.) is ***not*** also grounded. If this double grounding exists, then a ground loop is formed. If a system with a ground loop happens to work, any and all measurements are suspect. If both the probe reference and the loop terminus / power supply must be grounded, then consider inserting a loop isolator which will break galvanic continuity.

6. Horizontally mounted probes for single point level switching may not operate correctly if high viscosity or a slurry process material clings to the probe and the vessel wall after the level has receded below the probe. To the system this condition is sensed as if the probe was still immersed. To counter this condition, a low impedance signal identical to the probe signal may be placed on a separate isolating electrode added to the probe. This signal electrically isolates the sensing probe from direct access to its ground reference and flux line continuity can only be through the bulk of the material. This approach is called ‘coating rejection’, it uses a three terminal probe. The three terminals are: [ground] reference, [high impedance] sensing probe and [low impedance] isolation collar on the probe.
7. Once installation geometry is fixed, then only by changing the dielectric constant will a change in system output occur. The desired change in the dielectric constant comes from the difference of probe immersion in air/gas/vapor (whose dielectric constant is essentially close to 1) and the dielectric constant of the process material. Unfortunately the dielectric constant of most materials change with: temperature (for liquids), moisture content and packing density (for solids) and may change as concentration ratios change in a mixture (if the dielectric constants of the components of the mixture are different). For single point level switching, none of these conditions will normally cause problems. For continuous level measurement, two variables now form the output – probe immersion and change of dielectric constant. If external data processing is available, a second probe placed such that it is continuously immersed in process material may be used as a change of dielectric constant sensor. The level sensor, the change of dielectric constant sensor and a fairly simple algorithm will correct for the varying dielectric constant.

<u>Summary:</u>

1. For single point level switching, use probe mounting to achieve maximum change in capacitance as the process material encounters the probe, i.e., horizontal mounting. Do not create ground loops in the system.
2. For continuous level measurement, a larger change of capacitance creates a better measurement, therefore, use installation techniques that maximize the change of capacitance, e.g., minimize the separation distance between the sensing probe and its ground reference. Establish a good, low impedance ($< 1\ \Omega$) ground reference that is parallel to the sensing probe. Shield the sensing probe from all electrical interference. Do not create ground loops in the system.

For more information and graphic representation of some of these concepts, request a copy of Penberthy Bulletin # 2210, “New Wave Capacitance[tm] Level Instruments” from our web site [www.pcc-penberthy.com] or your local representative.

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