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Design and Development of Liquid Level Transmitter using an Improved Linearized Network

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Abstract*—In this paper, a liquid level transmitter using cylindrical capacitive sensor and an improved linearized network for capacitance measurement has been proposed to measure the liquid level and to convert level changes into an electrical current which can be transmitted to a remote indicator. The change in capacitance of cylindrical capacitive sensor due to change in liquid level is measured by an improved linearized capacitance measuring network. The offset capacitance of the cylindrical capacitive sensor and the stray capacitances that exist between sensor electrodes & metallic tank are measured before the liquid level measurement. The measured capacitances are used in the proposed capacitance measuring network to minimize the effects of offset capacitance and stray capacitances on liquid level measurement using dc control voltage and operational amplifiers with high input impedance. The experimental investigations have been performed to sense water level of metallic tank in both increased and decreased level conditions. In the first phase of experiment, a linearized network has been simulated using LabVIEW (laboratory virtual instrument engineering workbench) and studied with the test capacitance, and in the second phase, the experimentation was done by replacing the test capacitance with a cylindrical capacitive sensor for the measurement of liquid level. As a result of investigations conducted, it has been observed that the variation in liquid level from 0 to 25cm having linear relationship with output dc voltage in the range of 0 to 5.5V. Corresponding to liquid level variations, the dc output voltage further converted into an electric current of 4 to 20mA for remote indication and control purpose. The experimental results of liquid level transmitter are found to have good linearity of about ± 0.2% and a resolution of about 1 cm. The sensitivities of the capacitance measuring circuit and level transmitter have been found about 6.5 mV/pF and 250mV/cm respectively.

***Index Terms*—Cylindrical capacitor, LabVIEW, Capacitance measurement, Phase sensitive detector, Linearization.**

I. INTRODUCTION

Sensor technology is in the process of a slow migration from discrete dumb instruments, expensive and inflexible, to smart, self-calibrating, silicon-based units, and the measurement method of choice for discrete instruments is moving from a variety of transducer technologies, such as magnetic, optical, and piezoelectric, to capacitive. Capacitive sensors [1] electronically measure the capacitance between two or more conductors in a dielectric environment, usually air or a liquid. These sensors can directly sense a variety of things—motion, chemical composition, electric field—and, indirectly, sense many other variables which can be converted into motion or dielectric constant, such as pressure, acceleration, fluid level, and fluid composition.

Cylindrical capacitive sensor had been originally introduced by Chapman [2] for its advantages, which are the insensitivity to geometric errors by the averaging effect, which is derived from a simple intuition that the summation of geometric errors eventually converges to zero since the mean of geometric errors is zero and the high resolution with large sensing area compared to probe-type sensors.

In any process industry, liquid such as water, chemicals, and solvents in a storage vessel is required to be measured and controlled. The amount of such liquid stored can be found by measuring liquid level in a container or vessel. The liquid level affects the quantity delivered in and out of the container. The pressure and flow rate of liquid affects the liquid level of the container.

The change in capacitance of a capacitive sensor due to a change in process variable is generally very small. Hence, various attempts have been made by different investigators [3]–[17] to accurately measure this change in capacitance. In the conventional bridge methods, the Schering bridge [11] is best suited for the measurement of capacitance but the bridge methods are tedious and time consuming, as convergence toward balance requires several iterative steps. Automatic balancing bridges [12]–[14] have been developed but with increased complexity and cost. The direct-reading technique of capacitance measurement reported in [15] though useful, requires involved computation for determining the parameters from measured voltages. The microprocessor based switched-battery capacitance meter proposed in [16] is simple, but the measured values do not reflect the accepted equivalent circuit parameters applicable to sinusoidal excitation. In the method reported [17], the unknown capacitance changes the frequency of an oscillator and the frequency deviation is used as a measure of the capacitance. A new method of measuring capacitance, using oscillator circuits [18] requires a standard capacitor of value nearly equal to that of the nominal value of the unknown capacitor. The above two methods have a limitation that the unknown capacitor

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cannot be tested at a desired frequency and voltage. A simple scheme for the measurement of capacitance and dissipation factor of capacitor proposed in [19] has less resolution and hence it is not suitable for low value capacitance measurement. In this scheme, the accuracy of the prototype unit for the measurement of capacitance has been found as ±0.2%. Hence, it is aimed to improve the linearity of capacitance measuring circuit of about ±0.1% and to compensate the stray and parasitic capacitances exist in the capacitive sensor, capacitance measuring circuit.

This paper proposes a design of virtual instrument system for the measurement of small level changes using improved linearized network for capacitance measurement. A uniform right circular cylinder made of polyvinyl chloride has been used as a cylindrical capacitive sensor in the designed virtual instrument system. The offset capacitance of the cylindrical capacitive sensor and the stray capacitances that exist between sensor electrodes & metallic tank are measured before the liquid level measurement. The measured capacitances are used in the proposed capacitance measuring network to minimize the effects of offset capacitance and stray capacitances on liquid level measurement using dc control voltage and operational amplifiers with high input impedance. In this instrument, resolution and linearity have been improved. The output current has been found to be linearly related to the level changes. The capacitance changes have been measured and interfaced to PC-LABVIEW through NI-PXI-4072. The proposed system is easy to implement and convenient for various applications.

II. PRINCIPLE OF CYLINDRICAL CAPACITIVE SENSOR

Consider a cross section of solid cylindrical conductor of radius r_1 surrounded by a coaxial cylindrical shell of inner radius r_2. The length of both cylinders is L which is to be much larger than $r_2 - r_1$, the separation of the cylinders, so that edge effects can be neglected. The capacitor is charged so that the inner cylinder has charge $+Q$ while the outer shell has a charge $-Q$. To calculate the capacitance, the electric field produced by charge on cylinder is computed. Due to the cylindrical symmetry of the system, gaussian surface is to be chosen as a coaxial cylinder with length $l<L$ and radius r where $r_1<r<r_2$.

Using Gauss's law,

$$\oiint \vec{E}\cdot d\vec{A} = EA = \frac{\lambda l}{\varepsilon_0} \qquad (1)$$

$$E = \frac{\lambda}{2\pi\varepsilon_0 r} \qquad (2)$$

Where $\lambda = Q/L$ is the charge per unit length; ε_0 is the absolute permittivity of free space. It is to observed that the electric field is non-vanishing only in the region $r_1<r<r_2$. For $r< r_1$, the enclosed charge is zero since any net charge in a conductor must reside on its surface. Similarly, for $r>r_2$, the enclosed charge is $\lambda l - \lambda l = 0$, since the gaussian surface encloses equal but opposite charges from both conductors.

Therefore, the potential difference between two cylindrical electrodes is given by

$$\Delta V = V_{r_2} - V_{r_1} = -\int_{r_1}^{r_2} E_r dr = -\frac{\lambda}{2\pi\varepsilon_0}\ln\left(\frac{r_2}{r_1}\right) \qquad (3)$$

The change in capacitance, ΔC with respect to the liquid column of height, h_1 and remaining height, h_2 of the metallic tank with air as the dielectric is given by

$$\Delta C = \frac{2\pi\varepsilon_0(\varepsilon_1 h_1 + \varepsilon_2(L-h_1))}{\ln\left(\frac{r_2}{r_1}\right)} \qquad (4)$$

Where h_1 is the height of liquid column, L is length of the cylindrical capacitor, r_1 is the radius of solid cylindrical conductor , r_2 is the inner radius of coaxial cylindrical shell and ε_0, ε_1 & ε_2 are the permittivity of free space, liquid and air respectively.

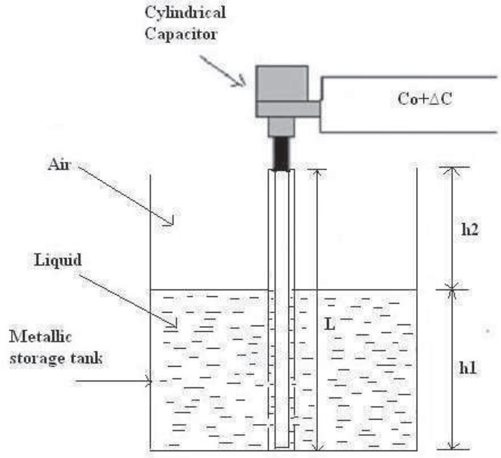

Figure 1. Liquid filled metallic storage tank with cylindrical capacitor.

The cylindrical capacitor immersed in the liquid filled metallic storage tank and it touches the metallic storage tank as shown in figure 1. The inner conductive cylinder of the capacitive sensor is filled with the air. There is another capacitance C_0 between the metallic storage tank or other metallic objects and the cylindrical capacitor. This capacitance may be assumed to be the parallel combination of parasitic capacitances exists: between metallic vessel and upper part of the probe above the liquid level; between metallic vessel and lower part of the probe below the liquid level. This capacitance in the order of pF may be assumed to be connected in parallel with the test capacitance between the liquid column of height h_1 and the sensing probe. The stray capacitance which exists between the electrodes and measuring circuit is independent of liquid level to be measured. It alters the effective values of measuring circuit components. The effective capacitance of the sensor consists of the parasitic and stray capacitances. Hence, the effective capacitance of the sensing probe, C_s with respect to the liquid column of height, h_1 may be given by

$$C_s = C_0 + \Delta C \qquad (5)$$

Combining (4) and (5), we have

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$$C_s = C_0 + \frac{2\pi\varepsilon_0(\varepsilon_1 h_1 + \varepsilon_2(L - h_1))}{\ln(\frac{r_2}{r_1})} \qquad (6)$$

Or $$C_s = k_1 h_1 + k_2 + C_0 \qquad (7)$$

Where $k_1 = \dfrac{2\pi\varepsilon_0(\varepsilon_1 - \varepsilon_2)}{\ln(\frac{r_2}{r_1})}$ and

$$k_2 = \frac{2\pi\varepsilon_0\varepsilon_2 L}{\ln(\frac{r_2}{r_1})} \qquad (8)$$

Thus, (7) indicates that C_s is linearly related to the liquid level, h_1.

III. MEASURING CIRCUIT

An improved linearized network using op-amps and phase sensitive detector has been designed as shown in figure 2 to measure the capacitance of the cylindrical capacitive sensor. The amplifiers, A_1 and A_2 are two similar TLC 274CN Precision quad operational amplifiers. The phase sensitive detector is a high precision balanced modulator/demodulator, AD-630 that combines a flexible commutating architecture with the accuracy and temperature stability afforded by laser wafer trimmed thin film resistors and the multiplier is a wideband linear four-quadrant multiplier, MC-1495. A sinusoidal voltage V_{in}, is applied to the capacitance C_s to be measured and also it is applied to the multiplier. A variable dc control voltage, V_c which is a function of V_{in} is connected to the multiplier as other input. For an excitation voltage, V_{in} the current passing through C_s and C_m would be i_s and i_m respectively.

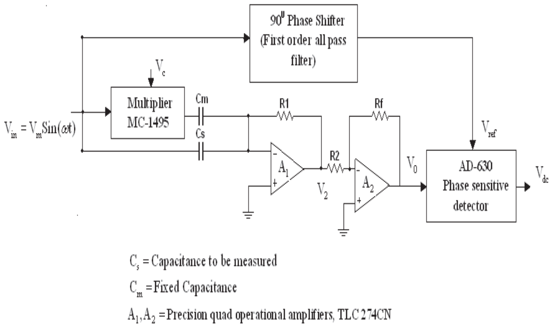

Figure 2. An improved linearized network for capacitance measurement.

The output voltage, V_{dc} of the circuit is a linear function of the capacitance, C_s as established by the following expressions.

$$\mathrm{V_{in}} = \mathrm{V_m Sin}(\omega \mathrm{t}) \qquad (9)$$

$$\mathrm{V_2} = -\mathrm{R_1 C_s}\frac{\mathrm{dV_{in}}}{\mathrm{dt}} - \mathrm{R_1 C_m}\frac{\mathrm{dV_c}}{\mathrm{dt}} \qquad (10)$$

Let the control voltage V_c be the function of input voltage V_{in}

$$\mathrm{V_c} = \mathrm{kV_{in}} \qquad (11)$$

Where k is the constant and selection of its value depends on the offset capacitance of the sensor.

Therefore using equations (9)-(11), the outputs of A_1 and A_2 Op-amps, V_2 and V_O respectively can be written as,

$$\mathrm{V_2} = -\mathrm{R_1}\omega\mathrm{V_m}(\mathrm{C_s} + \mathrm{kC_m})\mathrm{Sin}(\omega\mathrm{t} + 90^0) \qquad (12)$$

$$\mathrm{V_O} = \frac{\mathrm{R_f}}{\mathrm{R_2}}(\mathrm{C_s} + \mathrm{kC_m})\mathrm{R_1}\omega\mathrm{V_m Sin}(\omega\mathrm{t} + 90^0) \qquad (13)$$

V_{in} is phase shifted by 90^0 and is used as the reference signal V_{ref} for the phase sensitive detector. The output of phase sensitive detector which includes the rectification, amplification and filtering is given as

$$\mathrm{V_{dc}} = \frac{4\mathrm{R_f}}{\pi\mathrm{R_2}}(\mathrm{C_s} + \mathrm{kC_m})\mathrm{R_1}\omega\mathrm{V_m} \qquad (14)$$

For a fixed value of capacitance C_m, excitation frequency ω, R_1, R_2, R_f, the output of phase sensitive detector is a dc voltage directly proportional to C_s to be measured. The effect of stray capacitances between the capacitor electrodes and the ground on the measurements is very small due to use of high input impedance op-amps in the measuring circuitry. The effects if any can be subtracted in the measurement by adjusting the control voltage, V_c.

The equations (7) and (14) give

$$V_{dc} = \frac{4R_f R_1 \omega V_m}{\pi R_2}(k_1 h_1 + k_2 + C_0 + kC_m) \qquad (15)$$

Where, the value of k is used to compensate the offset capacitance, C_0 of the sensor. Hence, C_0 and kC_m are cancelled each other. If the V_{dc} is the circuit output voltage, then

$$V_{dc} = \alpha((\varepsilon_1 - \varepsilon_2)h_1 + \varepsilon_2 L) \qquad (16)$$

Where $\alpha = \dfrac{8\varepsilon_0 R_f R_1 \omega V_m}{R_2 \ln(\frac{r_2}{r_1})}$ = constant (17)

That is the output voltage is linearly related to change in the liquid level if the capacitive transducer is linear. The equation (16) depicts the linear relationship between the output voltage and changes in level, h_1. The output voltage signal is amplified to a voltage signal, V^1_{dc} in the range of 1–5 V dc, which is finally converted into a current signal (I_0) in the range of 4–20 mA dc by a voltage to current converter. After calibration, the output of the level transmitter becomes 4 mA when V^1_{dc} is 1 V and liquid level h_1 is zero cm and becomes 20 mA when V^1_{dc} is 5 V and liquid level h_1 is at the maximum range (h_{1max}). Hence, the level transmitter voltage output, V^1_{dc} in volts and the current output (I_0) in milliamperes may be written as

$$V^1{}_{dc} = \left(\frac{4}{h_{1\max}}\right)h_1 + 1 \qquad (18)$$

$$I_0 = \beta V^1{}_{dc} \qquad (19)$$

Where h_{1max} is the maximum value of liquid level selected as 25cm and β is constant. From equations (18) and(19)

$$I_0 = \beta + \left(\frac{4\beta}{h_{1\max}} \right) h_1 \qquad (20)$$

An improved linearized network using op-amps and phase sensitive detector has been used for measuring capacitance, replacing the variable capacitor by a cylindrical capacitor immersed in metallic tank. The metallic tank was fitted with a graduated scale so that level can be measured.

Since from (16), $h_1 \cong (\frac{1}{\varepsilon_1 - \varepsilon_2}) \frac{V_{dc}}{\alpha}$ for small value of $\varepsilon_2 L$, the relative measurement error E_1 expressed in percentage may be calculated by the following equation:

$$E_1 = \frac{((\frac{1}{\varepsilon_1 - \varepsilon_2}) \frac{V_{dc}}{\alpha} - h_1)}{h_1} \times 100\% \qquad (21)$$

Where h_1 is the measured level; V_{dc} is the measured output voltage.

In terms of percentage of the maximum range, it changes to (E_2); this may be defined as relative measurement error

$$E_2 = \frac{((\frac{1}{\varepsilon_1 - \varepsilon_2}) \frac{V_{dc}}{\alpha} - h_1)}{h_{1\max}} \times 100\% \qquad (22)$$

Where h_{1max} is the maximum value of liquid level change. Again, from the measured values of V_{dc} at different values of h_1, the best-fit linear characteristic may be drawn using the LabVIEW. The linear least squares fitting technique which is the simplest and most commonly applied form of linear regression, has been used to find the best-fitting curve to a given set of points (measured values of V_{dc} at different values of h_1 by minimizing the sum of the squares of the residuals of the points from the curve. The actual values of V_{dc} be obtained from the best-fit linear characteristic at different values of h_1, and the relative output voltage measurement error E_3 from linearity may then be defined as:

$$E_3 = \frac{(V_{dc-actual} - V_{dc})}{V_{dc-actual}} \times 100\% \qquad (23)$$

Where $V_{dc\text{-}actual}$ is the actual values obtained from the best-fit linear curve for a given level change, h_1.

The virtual instrument for the measurement of small liquid level changes is shown in figure 3. The output voltage of capacitance measuring circuit has been filtered and interfaced to PC-LabVIEW through NI-cDAQ 9174 in order to transmit over remote location devices. The virtual instrument provides low-cost and flexible solution for the acquisition of signals as well as transmission of analyzed signals over remote location.

IV. EXPERIMENTAL RESULTS

The experiment was performed in two phases. In the first phase of the experiment, an improved linearized network for capacitance measurement performance has been studied with a known variable capacitor and ac test signal of sinusoidal voltage ($V_{in}=V_m \sin(\omega t)$), with an amplitude V_m of 5V and a frequency of 1.0 kHz. The values of components used in the measuring circuit (as shown in Fig.2.) are R_1=100kΩ, R_2=10kΩ, R_f=15kΩ, C_m=22pF. The amplifiers, A_1 and A_2 are TLC274CN, precision quad operational amplifiers, the phase detector is balanced modulator/demodulator, AD-630 and the multiplier is a wideband linear four-quadrant multiplier, MC-1495. The 4 (4/5) digit TX3 true digital multimeter was used for measuring output voltage. An ac waveform of a particular frequency and a 90 degrees phase shifted waveform of the same frequency are applied to the signal and reference inputs of the phase sensitive detector, AD-630. The dc level of the phase detector output is proportional to the signal amplitude and phase difference between the input signals. If the signal amplitude is held constant, the output can be used as a direct indication of the phase. When these input signals are 90° out of phase, they are said to be in quadrature and the dc output of AD-630 will be zero.

The change in capacitance, ΔC in both increasing and decreasing modes has been varied in steps of 1 pF over 10pF range and at each step, the output voltage was measured. The experiment was repeated for different values of control voltage, V_c based on values of stray capacitance as shown in table 1. Three values of the stray capacitances are assumed in table 1 and the corresponding control voltages are obtained from the measuring network by considering the both sensor offset capacitance and the assumed stray capacitances. The control voltages at the input of multiplier are measured in such a way that which makes the measuring network output zero in absence of the test capacitance. Experimental characteristic graphs were then drawn by plotting the output voltage against the known variable capacitance, ΔC for different values of the control voltage, V_c as shown in figure 4. The error bar was drawn for the measurement points of output voltage and change in capacitance as shown in figure 5. From these experimental data the best fit straight-line curve was plotted by using LabVIEW 9 in each case, and the percentage error of the experimental data from this optimum straight line was calculated. The percentage deviation curve of the change in capacitance from a straight line for different values of V_c is drawn by using equation (23), as shown in figure 6.

In the second phase of experiment, the improved linearized circuit for capacitance measurement has been used for measuring level, replacing the variable capacitor by a cylindrical capacitor immersed in liquid filled metallic tank. The cylindrical capacitor of the virtual instrument system is the laboratory standard equipment with the following specification.

L:	Length of the cylinder, 300mm
r_1:	Internal radius, 4mm
r_2:	External radius, 15mm

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ε_1: Dielectric constant of water, 80.4 (at 20^0C)
ε_2: Dielectric constant of air, 1.0548 (at 20^0C
ε_0: Permittivity of free space 8.[illegible]

A. Material: High density polyethylene

The liquid filled metallic tank was fitted with a graduated scale in cm so that level can be measured. The offset capacitance of the cylindrical capacitive sensor with zero level is C_{in} = 12.6pF and it has been assumed that parasitic capacitances in the measurement as C_0=10pF. Hence, the base capacitance of capacitive sensor with zero level is approximately 22pF. Initially, the control voltage of the measuring circuit is adjusted to get zero output voltage and then, the tank is filled by a tap water having a resolution of 1cm. The output voltages for different values of the level with a selected value of V_c which depends on the value of stray capacitance, are measured in both increasing and decreasing modes. The variation of the output voltage with the change in liquid level is found to be linear as shown in figure 7. The static characteristic graph of the level transmitter was drawn by plotting transmitter output current of 4 to 20mA against liquid level variation from 0 to 25cm. as shown in figure 8. The linear characteristics over a wide range of level with good linearity, and resolution have been described.

Table I.
Control Voltage For Various Values Of Stray Capacitances.

S.No.	Sensor offset capacitance (pF)	Stray capacitance (pF)	Control Voltage, V_c (V)
1.	12.6	10	2
2.	12.6	5	1
3.	12.6	0	0

CONCLUSIONS

The basic materials for developing this liquid level transmitter are simple high density polyethylene cylindrical capacitor and the signal conditioning circuit which involves low-cost semiconductor devices. The construction technique does not involve any high-cost technology compared with existing non-contact type level sensors such as ultrasonic gauge and nuclear absorption level gauge. From the experimental study, the repeatability, linearity, and resolution are satisfactory within the tolerable limit of industrial level measurement. Hence, the present technique may be treated as a low-cost linear alternative technique of level measurement of both conducting and non conducting liquids.

The experimental characteristics of the proposed level transmitter shown in figures 4 and 7 for capacitance and level measurement, respectively, have been found to be quite linear about ±0.1% within a resolution of about 1 cm. The sensitivities of measuring circuit and level transmitter have been found about 6.5mV/pF and 250mV/cm respectively. The percentage deviation of capacitance measurement from the best fit linear graph, as shown in figure 6 has found to be within the tolerable limit. The human error in taking the reading of the level may contribute to a small percentage error as the level has been measured by a graduated scale. The offset capacitance of the cylindrical capacitive sensor and the stray capacitances that exist between sensor electrodes & metallic tank are measured and have been used in the proposed capacitance measuring network to minimize the effects of offset capacitance and stray capacitances on liquid level measurement using dc control voltage and operational amplifiers with high input impedance. The static & dynamic uncertainty analysis of level sensing technique could not be performed. From this uncertainty analysis, the proposed improved signal conditioning technique may be further modified in order to reduce the uncertainty of the liquid level measurement. The proposed virtual instrument for level measurement has very good accuracy and resolution compared to the conventional measurements available in literature.

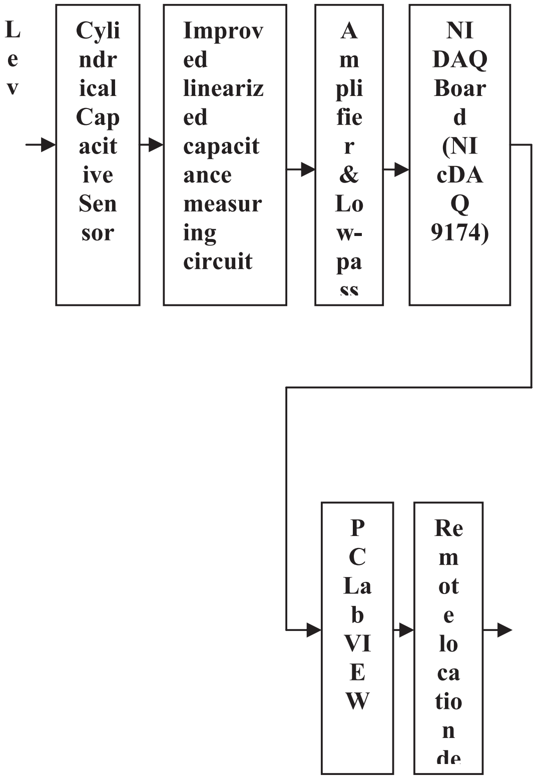

Figure 3. Block diagram of virtual instrument system for level measurement.

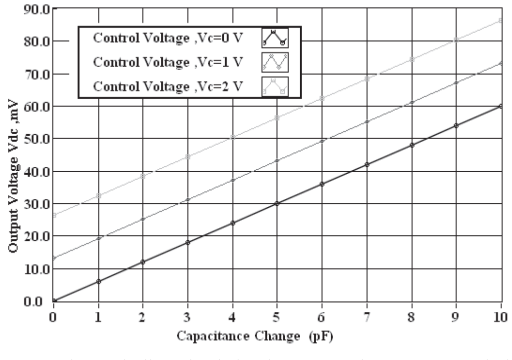

Figure 4. Change in linearized circuit output voltage versus variation in capacitance.

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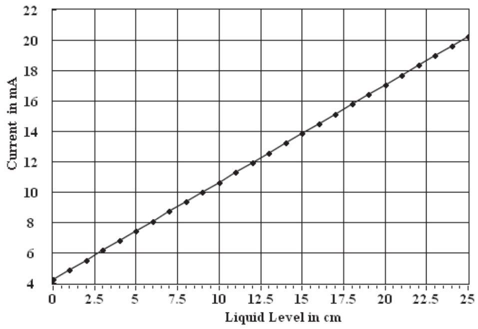

Figure 5. Error bar for measurement points of output voltage and change in capacitance.

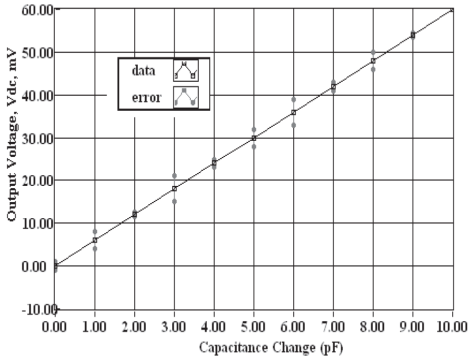

Figure 6. Percentage deviation of the capacitance from straight line characteristic.

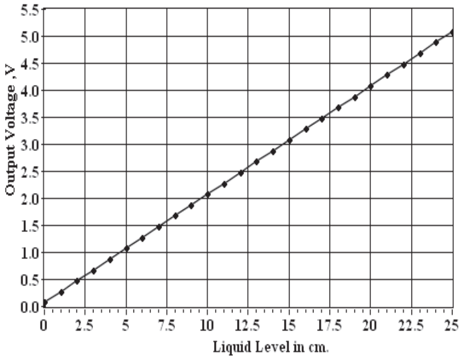

Figure 7. Variation in linearized circuit output voltage with change in liquid level.

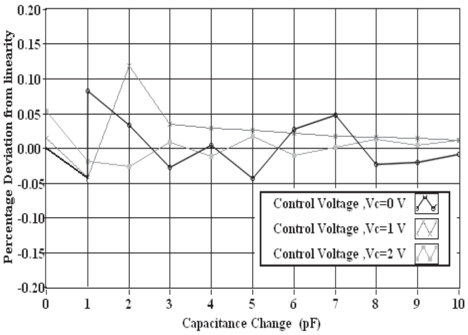

Figure 8. Variation in output current with change in liquid level of level transmitter.

REFERENCES

[1] L. K. Baxter, Capacitive Sensors, Design and Applications, IEEE Press, New York (1997).

[2] P. D. Chapman, *A capacitive based ultra precision spindle error analyzer*, *J. Precision Eng.* 7 (1985) 137.

[3] B. G. Liptak, *Process Measurement and Analysis*, Oxford, U.K. (1999).

[4] D. M. Considine, *Process Instruments and Control Hand Book*, McGraw-Hill, New York (1974).

[5] A. J. Jaworski, T. Dyakowski, and G. A. Davies, *A capacitance probe for interface detection in oil and gas extraction plant*, *Meas. Sci. Technol.* 10 (1999) L20.

[6] W. R. Yang, M. R. Brant, and M. S. Beck, *A multi-interface level measurement system using a segmental capacitance sensor for oil separators*, *Meas. Sci. Technol*. 5 (1994)1180.

[7] S. M. Herang, R. G. Green, A. Plaskowski, and M. S. Beck, *A high frequency stray immune capacitance transducer based on the charge transfer principle*, *IEEE Trans. Instrum. Meas.*37 (1998) 373.

[8] A. H. Falkner, *The use of capacitance in the measurement of angular and linear displacement*, *IEEE Trans. Instrum. Meas.*43 (1994) 942.

[9] P. Holmberg, *Automatic balancing of linear AC bridge circuits for capacitive sensor elements*, *IEEE Trans. Instrum. Meas.* 44 (1995) 805.

[10] D. Marioli, E. Sardini, and A. Taroni, *High accuracy measurement techniques for capacitance transducers*, *Meas. Sci. Technol.* 4 (1993) 343.

[11] Foley A.H, A direct reading high-voltage capacitance bridge, Transactions of American institute of electrical engineers.69 (1950) 698.

[12] O. Petersons, *A self-balancing high voltage capacitance bridge*, *IEEE Trans. Instrum. Mea.*13 (1964) 224.

[13] O. Petersons and W. E. Anderson, *A wide-range high-voltage capacitance bridge with one ppm accuracy*, *IEEE Trans. Instrum. Meas.* 24 (1975) 344.

[14] R. D. Cutkosky, *An automatic high-precision audio frequency capacitance bridge*, *IEEE Trans. Instrum. Meas.*34 (1985) 389.

[15] M. S. Ansari and M. T. Ahmed, *A novel direct reading active-RC system for measurements of in-circuit, discrete, and incremental capacitances*, *IEEE Tran. Instrum. Meas.*38 (1989) 992.

[16] S. M. Mahmud and A. Rusek, *A microprocessor-based switched battery capacitance meter*, *IEEE Trans. Instrum. Meas.*37 (1988) 194.

[17] T. Takagi and A. Yamakawa, *A simple and wide-range capacitance measuring equipment using transistor blocking oscillator*, *IEEE Trans. Instrum. Meas.* 25 (1976) 163.

[18] S. Natarajan, *Measurement of capacitance and their loss factors*, *IEEE Tran. Instrum. Meas.*38 (1989) 1087.

[19] V. Jagadeesh Kumar, P. Sankaran, and K. Sudhakar Rao, *Measurement of C and tanδ of a capacitor employing PSDs and Dual-slope DVMs*, *IEEE Trans. Instrum. Meas.*52 (2003)1592.

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