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Development of a User Friendly Liquid Level Measuring System

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***Abstract*— The paper deals with the theory, design, fabrication and testing of a sensor and associated measuring system, which can be used for direct display of levels of conducting as well as non-conducting liquids. The proposed sensor is based upon the coaxial concentric cylinders with suitable modifications. A novel impedance measuring system is developed, which can directly measure conductance as well as capacitance of an impedance value. In case of conducting liquids, level is directly proportional to conductance and hence conductance measuring system may be employed for the direct measurement of level. While in the case of non-conducting liquids, resulting capacitance and liquid level have straight line relationship and hence change in level is directly proportional to the change in capacitance and thus capacitance measuring system may be used to indicate the liquid level. Proto-type model has been tested for different types of liquids and results have been found satisfactory for a range of level from 0 to 30 cm.**

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I. INTRODUCTION

Due to the importance of level measurement in process industries like petrochemical, petroleum, chemical pulp and paper, mining, pharmaceutical and food processing, appreciable number of techniques have been used for its measurement. [1], [2]. Capacitive, Optical and ultrasonic techniques are used for highly precise measurement of level [2].Thermal techniques have been used to detect the surface of conducting/non-conducting liquids [1]. To measure water level, conductance method is generally employed [1]. In some cases, liquid level is also measured by measuring the mass of the overall system [3]. In this paper, a simple but accurate technique, for the measurement of the level of conducting and non-conducting liquids, is presented. It can also be used to assess the appropriateness of conducting or non-conducting technique for the measurement of liquid level by obtaining the relationships between the conductance and level as well as capacitance and level at the same time. Basically, it uses concentric cylinders based capacitive sensor with better configuration then given in earlier works [ ] as well as with new impedance measurement system. Test results, on the proto-type model, for the measurement of conducting as well as non-conducting liquids, are included which are in conformity with the theory.

II THEORY

A.Impedance Measuring System

Initially, we will discuss the theory behind the impedance measuring system and then will discuss the theory and design of the main sensor. The circuit of the proposed bridge is shown in Fig.1. A simple relationship between impedance and level is developed. Basically, it is the self –balancing version of our previous work [4] [5] & [6].Unknown impedance is connected in the forward loop of the opamp and a simple resistance is connected in the feedback loop [6] & [7]. Output of the opamp is connected to two of the four inputs of the analog switch (4066). Output voltages of the switches are connected to the oscilloscope as well as to the permanent magnet moving coil instruments. Relationships between different quantities are developed as follows:

Let Vs be the supply voltage to the system, V0 be the output voltage of the opamp which may be given by following well known expression,

$$V_0=-V_S R/Z_X \qquad (1)$$

Where, R is the feedback resistance and Z_X is the impedance of the sensor composed of the parallel combination of capacitance and a resistance. Substituting the values of components of impedance we get,

$$V_0=-V_S R[1/R_X+j\omega C_X] \quad (2)$$

Where, R_X and C_X are resistance and capacitance connected in parallel and represents the sensor.

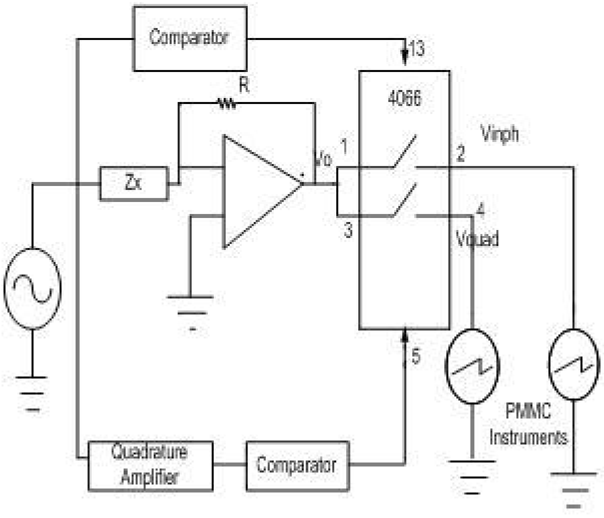

Figure 1: Circuit diagram of the proposed system

In Eq.2, V_0 is a phaser and may be represented in terms of its in-phase (V_{inph}) and quadrature (V_{quad}) components with respect to supply voltage, V_S and hence we can write,

$$V_0=-V_{inph}-JV_{quad}=-V_S R[1/R_X+J\omega C_X] \quad (3)$$

Comparing the real and imaginary parts in Eqn.(3) we get,

$$V_{inph}=V_{S.}R.G_X \quad (4)$$

and $V_{quad}=V_S R\, \omega\, C_X$ (5)

It is clear from Equations (4) & (5) that V_{inph} and V_{quad}can be calibrated in terms of conductance and capacitance of unknown impedance (sensor) respectively. For the measurement of in-phase and quadrature components of V0, analog switches with proper control voltages are used. Output of the opamp is connected to the input sides of two analog switches 1& 3 of chip 4066 as shown in Fig.1. Control signal of analog switch 1 is obtained from supply voltage by passing through an analog comparator and connected to terminal 13 of the chip. Its output will be obtained at terminal 2 and its average value will be proportional toV_{inph}.The control signal of input terminal 3, will also be taken from supply voltage by passing through a quadrature amplifier and an analog comparator. It will be connected to terminal 5. Under this condition, average value of signal available at output terminal 4 will be proportional to V_{quad} .Waveforms of input voltage, control signals and output voltages are given in Fig.2. For in phase component control signal is obtained from supply voltage and shown in (d) while control signal for quadrature component is obtained from the output of quadrature amplifier(it is identical to the output of the main circuit for the case of pure capacitance and shown in©) and shown in (e).In the case of unknown impedance equal to resistance only, average value of output voltage ,on terminal 2 ,will be equal to V_{inph} which will be maximum and negative while average value of output voltage on the terminal 4(which is controlled by the output voltage of quadrature amplifier) will be equal to V_{quad} and it will be zero for the case of pure resistance. Similarly, when unknown impedance is equal to pure capacitance, average value on terminal 2 will be zero (V_{inph}) and average value of output at terminal 4 will be maximum and equal toV_{quad}. In this way resistance and capacitance may be measured separately with out affecting one another. In the simplest form,a permanent magnet moving coil instrument can be used to measure resistance and capacitance of an impedance separately.

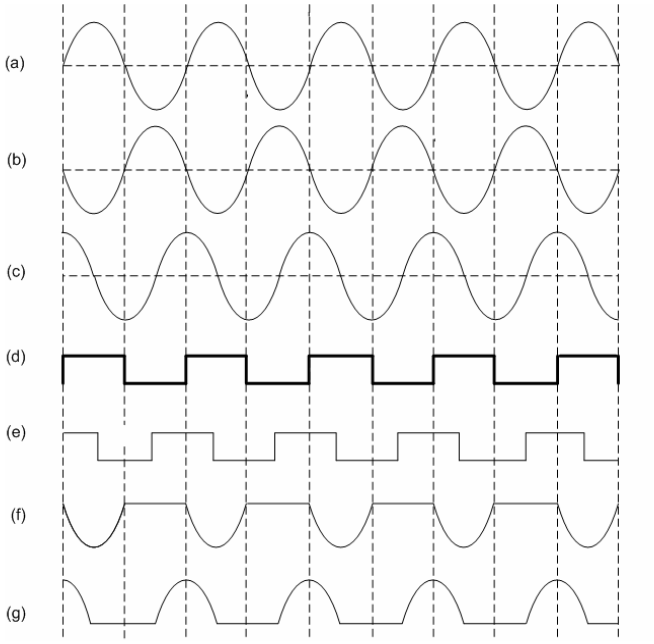

Figure 2: Waveforms of different signals: (a) Waveform of supply voltage, Vs. (b) Waveform of the output voltage when $Z_X = R_X$. (c) Waveform of output voltage when Z_X = -j X_C. (d) Waveform of control signal to obtain in-phase component. (e) Waveform of control signal to obtain quadrature component. (f) Waveform of the in-phase component when $Z_X = R_X$. (g) Waveform of the quadrature component when $Z_x=R_X$.

B Details of Level Sensor

The constructional details of the proposed prototype model of the sensor are shown in Fig.3. Dimensions of the sensor are L=25cms, r_1 = 5cms, r_2 = 6cms. Both concentric cylinders are made of brass and external cylinder is made of aluminum and acts as shield in the case of capacitive sensor. To define length accurately, cylinders are provided with proper guarding electrodes. Effective length of the cylinder, in the case of non-conducting liquids, is obtained as shown in the Fig.2, by L. Insulating gapes on the upper side and shielding ring in the bottom defines the length in the case of capacitance measurement. The heights of liquid level are not defined properly in some designs given in literature [8].Fig.3 shows the equivalent circuit of the system when liquid is non-conducting. In this case, C_{12} is the direct capacitance between cylinders; C_{13} represents the equivalent capacitance between the outer cylinder and cylinder acting as shield andC_{23} is the capacitance between inner cylinder and shielding components. The level of the liquid depends upon the value of direct capacitanceC_{12}. The capacitances C_{13} and C_{23} are undesirable capacitances and the measurement technique should be such that these capacitances do not affect the final results. It can be shown below that the circuit, used by us, is not affected by the undesirable capacitances. If Z_X of Fig.1 is replaced by the equivalent circuit of Fig.3 then circuit will measure C_{12} and final results will not be affected by C_{13} and C_{23}. The capacitance C_{13} will not affect the results because it has high impedance and appears across the source. On the other hand the capacitance C_{23} appears across the inverting and non-inverting terminals of the operational amplifier (no potential difference) and hence does not affect the final output of the circuit. It can be claimed that the proposed circuit is suitable for the measurement of small direct capacitances.

C. Measurement of level of non -conducting liquids

Suppose the effective length of the capacitive sensor is L and the level of the liquid in the sensor is h then direct capacitanceC_{12} may be given by following expression [8],

$$C_{12}=2\pi\,[h\epsilon_1+(L-h)\,\epsilon_2]/\ln r_2/r_1 \qquad (6)$$

In air, $\epsilon_2=1$ and hence Eq.6 reduces to the following form,

$$C_{12}=2\pi/\ln r_2/r_1[h\epsilon_1+L-h] \qquad (7)$$

$$=2\pi/\ln r_2/r_1[h(\epsilon_1-1)+L\,] \qquad (8)$$

$$=K_1h+K_2$$

Where $K_1=2\pi\,(\epsilon_1-1)/\ln r_2/r_1$ and $K_2=L2\pi/\ln r_2/r_1$

Equation (8) shows that the relationship between C_{12} and level of the liquid h can be represented by a straight line whose slope will be a function of dielectric constant of liquid and dimensions of the cylinders.

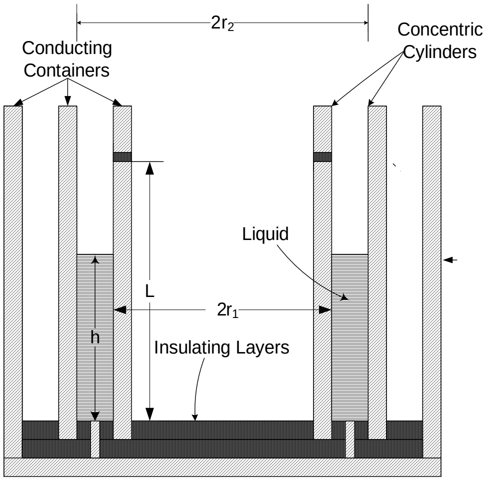

Figure 2 Proposed sensor

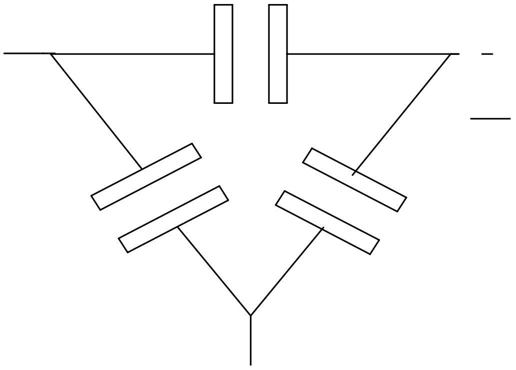

Figure 3 Equivalent Circuit of Fig.2

Where, $K_1=K(\epsilon_1-1)$ and $K_2=KL$ (10)

Assumptions made in Eq.(10) will be correct for highly homogeneous liquids and when fringing effect is negligible or steps have been taken to reduce it by using guarded electrodes. In our design proper guarding is used to decrease errors due to fringing effect. The sensitivity of measurement will depend upon the constant K_1

D. Measurement of level of conducting liquids

It is well known that stationary current distribution problems are mathematically identical to electrostatic potential distribution problems and following relationship exists between capacitance and conductance of the materials if replaced by one another [9].

$$C_{12}/\epsilon_r = G_{12}/\sigma \qquad (11)$$

Where, C_{12} is the capacitance of the system, G_{12} is the conductance of the system ϵ_r is the permittivity and σ is the conductivity of the system. Now if we replace C_{12}/ϵ_r by G_{12}/σ in Equation (6) after simplifying it, we get the expression for the case of conducting medium with identical geometry.

From Eq.6 we have

$$C_{12}=2\text{л}[h\epsilon_1+(L-h)\epsilon_2]/\ln r_2/r_1 \qquad (12)$$

Dividing both sides by C_{12}, we get

$$1=2\text{л}\,[h\epsilon_1/C_{12}+(L-h)\epsilon_2/C_{12}]/\ln r_2/r_1 \qquad (13)$$

Replacing the value of C_{12}/ϵ_2 by G_{12}/σ_1 and C_{12}/ϵ_1 by G_{12}/ϵ_2 we get

$$1=[h\sigma_1/G_{12}+(L-h)\sigma_2/G_{12}]2\text{л}/\ln r_2/r_1 \qquad (14)$$

$$1=2\text{л}h\sigma_1/G_{12}\ln r_2/r_1 \text{ because } \sigma_2=0 \text{ for air.}$$

$$\text{Or } G_{12}=h.2\text{л}\sigma_1/\ln r_2/r_1 = K_g h \qquad (15)$$

where, $K_g$is a constant for a particular configuration of the sensor and liquid. Eq. (15) shows that conductance of liquid is directly proportional to the level of the liquid in the system. For this particular case, G_{12}=G and conventional conductance measuring methods may be applied for its measurement.

III. EXPERIMENTAL METHOD AND RESULTS

Proto-type model of the sensor was fabricated as shown in Fig2. It was connected in place of unknown impedance in the Fig 1. Supply voltage to the system is set at one volt with the frequency of 1 KHz. Initially, the level of tape water is measured by the sensor. The observations were repeated at a number of time and at different ambient temperatures (by switching off cooling of the laboratory) and average of the data obtained is drawn in Fig.4. Similarly, results were recorded for the case of Engine oil (Mobil Oil), as an example of non-conducting liquid and appreciable time was given so that oil may settle down properly. Observations are repeated more than ten times in different conditions and finally average values are plotted in Fig.5. Applied voltage was checked before each reading because its variation will affect the results directly. Results shown in Fig.4 & 5 confirm the theory developed in Equations 10 & 15. In Fig.4 some output voltage is present at zero level. However, for increasing or decreasing levels result is represented by a straight line as given in Equation 10. In the case of conducting liquids, relationship between output voltage and level is appreciably linear. Permanent magnet moving coil instruments are calibrated in terms of levels of conducting and non-conducting liquids. During the measurement of level of non- conducting liquids, outer shield should be grounded as well as shielded wires must be used to decrease the effect of earth admittances at zero level.

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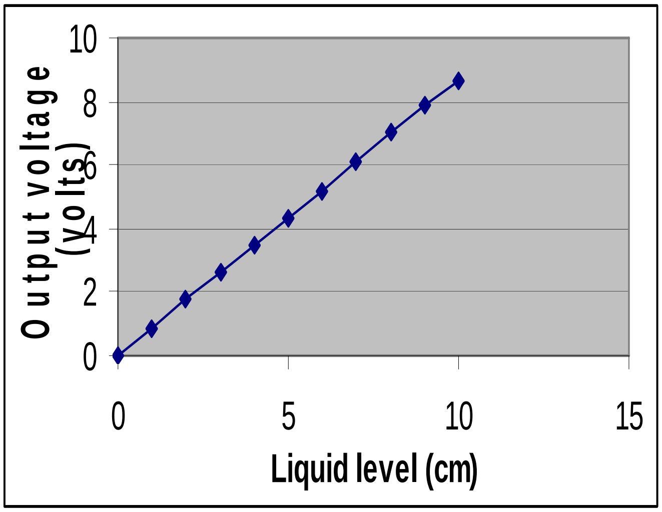

Figure 4 – Output voltage Vs level of conducting liquid

V. CONCLUSIONS

A simple, low cost and appreciably accurate liquid level measuring system is presented. It can measure the level of conducting as well as non-conducting liquids. It can be employed to help the designer to select either conductance method or capacitive method for particular liquid, by providing the calibration curves, for both techniques, when liquid level is varied in a certain range only. Linearity, sensitivity and accuracy obtained from the calibration curve will help in the selection of the appropriate measuring

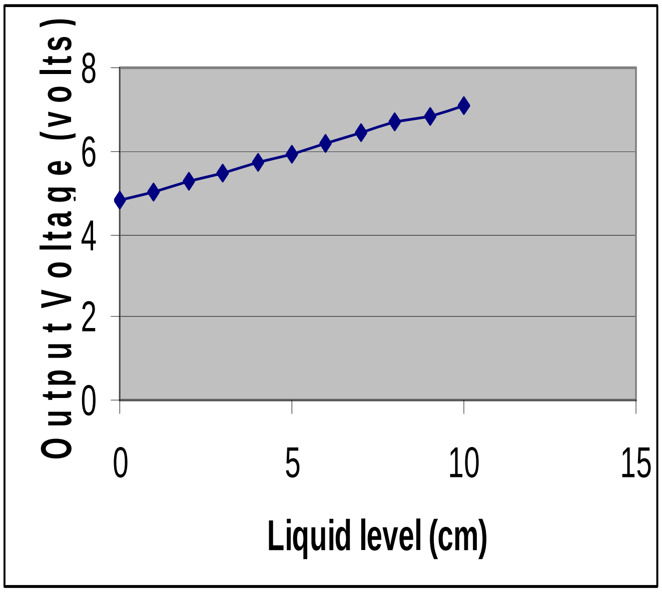

Figure 5- Output Voltage Vs Level of non-conducting Liquid

technique. Experimental results on the prototype model confirm the theoretical relationships. In case of non-conducting liquids, steps have been taken in design, to reduce the errors due to fringing effect. The accuracy of measurement may be further increased by the proper selection of components and materials. For example, using stainless steel cylinders, temperature errors may be reduced to a very low level. For better operation PMMC instruments can also be replaced by electronic averaging circuits or microcontroller. The microcontroller will improve the order of accuracy , precision and may provide intelligence to the over all system. However, compromise has to be made in cost and performance characteristics.

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