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Interface circuit for oil quality assessment considering dielectric losses and stray capacitances

Abstract: Dielectric spectroscopy is becoming a popular technique in addition to the chemical and optical methods for oil quality assessment. It is based on the measurement of the variation of the dielectric properties of oil corresponding to the change of its chemical and physical properties. In this investigation an interface circuit for the measurement of the dielectric properties of oil is proposed using the capacitance-to-voltage conversion technique. The circuit measures the variation of capacitance of the sensor. The output voltage of the circuit is a DC voltage proportional to the capacitance of the sensor with a resolution of 5 mV/pF. The differential technique was used to eliminate stray capacitances caused by the circuit. Regression analysis has been carried out to describe a mathematical relation between the change of the capacitance and the output voltage. Simulations show a maximum relative deviation of 0.03 % for capacitance in the range of 100 pF to 1000 pF while experimental results show a maximum relative deviation of 2 % for the same capacitance range. The effects of stray capacitances and dielectric losses are also investigated. Stray capacitances decrease the measurement accuracy to 0.1 %, while the parallel resistance, which represents the dielectric losses does not affect the accuracy, if its value is higher than 10 M Ω . For resistance values lower than 10 M Ω the circuit is not stable and it is therefore not possible to estimate the capacitance value using the output voltage.

Keywords: dielectric spectroscopy, capacitive sensor, capacitance measurement, capacitance-to-voltage conversion

1 Introduction

The measurement of small capacitance changes is very important in industrial applications and in particular for the measurement of dielectric properties of liquids such as oils. In fact, the measurement of a sensor capacitance dipped in oil can be used to

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measure the dielectric properties of the oil. Many investigations used this technique to characterize edible oils [1], detect the adulteration [2] and estimate the water content [3] or the total polar components in fried oils [4]. A typical measurement setup consists of a capacitive sensor connected to an impedance analyzer or an LCR meter, which measures the capacitance of the sensor and thus deduces the dielectric properties. Such a measurement setup is accurate and simple to use but it has some limitation since it is not designed for online or mobile applications but only for laboratory measurement.

Since new investigation are not focusing only in laboratory conditions but also in online industrial applications where the ideal conditions are not guaranteed and a smaller mobile setup with low energy consumption is required. It consists of an embedded measurement circuit connected to a well designed capacitive sensor. The measurement circuit converts the capacitance to measurable data (voltage, frequency, time, etc.), while the sensor is used in such a way that the change in the dielectric properties will cause a change in the capacitance.

The capacitance measurement circuits can be classified into three main categories according to the type of conversion the circuit does:

- capacitance to time,
- capacitance to frequency,
- capacitance to voltage.

The capacitance-to-time conversion includes the charging/discharging and phase shift techniques. The working principle of the charging/discharging technique is simple; the capacitance to be measured is charged during a known period of time and then the required time to discharge the capacitor is used to measure its value. It is also possible to measure the capacitance during the charging process by measuring the required time to charge the capacitor to a certain voltage. CMOS switches are usually used as switches to charge and discharge the capacitor; in fact the use of switches increases the stray capacitances and hence the measurement errors [5, 6]. The second technique is the capacitance-to-phase angle conversion; one of the capacitor electrodes is connected to an AC voltage source while the second electrode is connected to a charge amplifier and a compensating capacitor excited by a compensating signal. The use of this compensation permits a gradual phase shift in response to the change of the capacitance. This enables the circuit to measure very small capacitance changes but in a very limited range. The phase angle of the output signal of the charge amplifier is compared to that of the input signal and the difference in phase is converted to time using a Schmitt trigger [7].

Another techniques to measure capacitance is to convert its value to a periodic signal. Oscillation and resonance circuits are the main two types of the capacitance-to-frequency conversion technique. The oscillator produces a periodic signal with a frequency proportional to the capacitance C_x [8]. The resonance technique is based on the use of a parallel or serial inductance and resistance to the capacitance to be

measured in order to create a resonator. The circuit is excited by an AC voltage with a variable frequency; the voltage and the current in the circuit should be measured at each frequency until the resonance happens where the current or the voltage is maximum, in case of a serial or parallel circuit, respectively [9].

The capacitance-to-voltage type includes mainly two techniques of conversion: the transducer and the I/Q modulation. The transducer circuit is simple and fast; it consists basically of a current-to-voltage converter, a rectifier and a low-pass filter in such a way that it provides a DC output voltage with an amplitude depending on the value of the capacitance of the sensor [10, 11]. This type of circuit does not consider the effect of dielectric losses existing in capacitive sensors. The I/Q modulation circuit considers the capacitive sensors as a complex impedance which includes not only a capacitance C but also a parallel resistance R representing the dielectric losses. In an I/Q modulation circuit, the sensor is fed by an AC voltage, the currents I_c and I_r flowing through the capacitance and the resistance, being converted to voltage and sent to two phase sensitive detectors which compare this voltage with two 90° phased voltages. The two output voltages of the phase sensitive detectors are proportional to the values of C and R . This type of circuit is complex and the accuracy of the measurement is influenced by multiple factors, such as the accuracy of the phase shifters and the phase sensitive detectors [12]. Another type of circuit uses only the Q modulation in order to compensate the effect of the parallel resistance. A feedback controls the phase of the input signal in such a way it compensates the phase shift caused by the sensor resistance [13].

The use of the capacitance-to-voltage type of circuit is also to be considered; in this type of circuit only an accuracy of mV is required, while the capacitance-to-time type requires nanosecond accuracy and the capacitance-to-frequency type requires MHz accuracy. Among the capacitance-to-voltage types the transducer circuit is selected because of its simplicity and its high accuracy to measure capacitance changes compared to the I/Q type. The circuit proposed by Preethichandra in [10] is a capacitance-to-voltage type of circuit. A reference capacitance is used to compensate the effect of stray capacitance caused by the measurement circuit. It consists of two similar sub-circuits, one for the capacitance to measured C_x and one for the reference capacitance C_{ref} . Each sub-circuit consists of a current-to-voltage converter, a rectifier and a low-pass filter. The difference between the two output signals is calculated with a differential amplifier. The final output voltage V_{out} depends on C_x and C_{ref} . Since C_{ref} is kept constant, V_{out} depends in reality only on C_x . The bias voltages caused by stray capacitances in both sub-circuits are eliminated by the differential amplifier.

In this chapter, we study the possibility of using the capacitance-to-voltage type of circuit for the measurement of oil quality considering the effects of stray capacitances and dielectric losses.

2 Measurement circuit

A simplified schematic of the measurement circuit is presented in Fig. 1. The working principle is to inject a sinusoidal signal to the sensor and a reference capacitance; this creates currents flowing through these two capacitances. These currents are then converted to voltage, rectified and filtered. The filters outputs two DC signals depending on the sensor capacitance and the reference capacitance. The final output of the circuit, V_{out} , is the difference between both signals; V_{out} is maximum when C_x is minimum and it is theoretically 0 when $C_x = C_{ref}$. The circuit was adapted to oil measurement by adding a parallel resistance R_x to C_x and stray capacitances (C_{s1} , C_{s2} and C_{s3}) connected to C_x and C_{ref} .

Fig. 1: Capacitance measurement circuit considering stray capacitances and dielectric losses.

2.1 Active rectifier

A precise full-wave rectifier is used in this circuit. This type of rectifier is considered more precise comparing with the half-wave rectifier, which keeps only half of the original input signal. In fact the full-wave rectifier reverses the negative part of the input signal and combines it with the positive part. The average (DC) output voltage is higher than for the half-wave rectifier and has much less ripples, producing a smoother output waveform.

The input amplifier (Fig. 2) controls the biasing of the diodes D1 and D2 to change the signal path based on the polarity of the input signal. Diode D1 provides the positive half wave to the output amplifier while the diode D2 provides the negative half. The negative part is inverted and summed to the positive half at the output amplifier.

Fig. 2: Full-wave precision rectifier.

2.2 Low-pass filter

A low-pass filter is used to eliminate the ripples and high-frequency noises. A second-order filter based on Sallen–Key topology is used (Fig. 3). At low frequencies the capacitors C_1 and C_2 are considered open circuit and the signal is buffered directly to the output. At high frequencies C_1 and C_2 cannot be considered as open circuit and the input signal is shunted to the ground. The cut-off frequency of the filter can be calculated as follows:

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}. \quad (1)$$

A low cut-off frequency can guarantee a smooth DC output, but this will decrease the quality factor Q and the gain of the filter.

Fig. 3: Sallen–Key low-pass filter.

2.3 Differential amplifier

The function of the differential amplifier is to calculate the difference between the two output voltages of the low-pass filters, which represent the measured capacitance C_x and the reference capacitance C_{ref} .

The offset voltage caused by the non-ideality of the amplifiers should be low so that the output voltage is 0 when $C_x = C_{ref}$. It is possible to measure capacitances

higher than the reference capacitance C_{ref} but only if the differential amplifier is supplied with $\pm V_{\text{cc}}$. In the case the amplifier is supplied with $+V_{\text{cc}}$ and the ground, it is only possible to measure capacitances lower than C_{ref} .

3 Simulation results

The circuit blocks were first separately implemented in the simulator in order to study their behaviors and select the values of their components. The full circuit is then implemented for further investigation. The current flowing through C_x is converted to voltage across the resistance R_1 of the rectifier (R_1 in Fig. 2). This voltage is then rectified and filtered by the full-wave rectifier and the low-pass filter; C_x and R_1 form a high-pass filter with a variable gain and cut-off frequency changing with the change of C_x and R_1 . For frequencies higher than the cut-off frequency the gain of the filter is equal to 1; in this case it is not possible to detect the change of the capacitance because the amplitude remains constant, but for frequencies lower than the cut-off frequency the gain will depend on the value of C_x and the output amplitude will be changing with respect to the change of C_x . The gain can be calculated as follows:

$$\text{Gain} = \frac{R_1}{\sqrt{R_1^2 + \frac{1}{(\omega C_x)^2}}}. \quad (2)$$

The sensitivity of the filter gain to the change of the capacitance is studied. The input frequency f_{in} and the resistance R_1 are varied in the ranges of 100 Hz to 100 kHz and 1 k Ω to 10 M Ω . The maximum frequency is set at 100 kHz due to the limitation of the amplifiers. In fact the amplifiers to be used in such measurement circuits should have a low offset voltage and low bias current, though amplifiers which have a low offset voltage, in the range of μV , and bias current, in the range of pA, have very limited bandwidth in the range of 100–1000 kHz.

The maximum sensitivity (0.08 gain change for 100 pF C_x change) was found at different combinations of f_{in} and R_1 . The input frequency f_{in} is selected to be 10 kHz (much smaller than 100 kHz), corresponding to $R_1 = 20 \text{ k}\Omega$.

In a first investigation, the circuit is simulated without stray capacitance and dielectric losses. The reference capacitance C_{ref} is kept constant at 500 pF and the voltages V_1 , V_2 and V_{out} are recorded (Fig. 1). The voltage V_1 changes linearly with the change of the capacitance C_x , thus the voltage V_{out} changes also linearly with C_x (Fig. 4). The simulations were done using the ADA4522 amplifier, which has a maximum offset voltage equal to 5 μV and a maximum input bias current equal to 50 pA.

Ideally the output voltage equals to 0 V when $C_x = C_{\text{ref}}$, but due to the non-ideality of the amplifiers there is a voltage offset equal to 0.013 V at the output voltage. The relation between C_x and V_{out} is linear with a resolution of 2 mV/1 pF. A curve fitting

Fig. 4: Output voltage of the measurement circuit.

was used in order to find the relation between C_x and V_{out} , following the following equation:

$$C_{calc} = 0.495V_{out} + 492.3, \quad (3)$$

where C_{calc} is given in pF and V_{out} in mV.

To evaluate the goodness of the fit, the relative deviation was calculated using the following equations:

$$\text{Deviation} = |C_x - C_{calc}|, \quad (4)$$

$$\text{Relative deviation} = \frac{\text{Deviation} * 100}{C_x}. \quad (5)$$

The relative deviation decreases with the increase of the capacitance C_x ; it has its maximum value 0.1 % at 1 pF and decreases to 0.02 % at 1000 pF, which means high linearity between C_x and V_{out} in the ideal case. In fact, the assessment of oil quality using capacitance sensors suffers from two main stray effects:

- the stray capacitances caused mainly by the sensor geometry and the interface between the sensor and the measurement circuit;
- the parallel resistance which represents the dielectric losses.

The effects of stray capacitances C_{s1} , C_{s2} and C_{s3} were first studied (Fig. 1). The values of C_{s1} , C_{s2} and C_{s3} were set at 10 pF, 50 pF and 100 pF.

A total of nine simulations have been made and the capacitance C_{calc} , the deviation and the relative deviation were calculated using equations (3), (4) and (5). The capacitance C_{s3} has minor effects on the measurement since it is connected in parallel to the voltage source, which has a low input resistance. The stray capacitances C_{s1}

and C_{s2} also have minor effects when their values are equal; this is because the error in voltage caused by C_{s1} is compensated by the error caused by C_{s2} ($V_{out} = V_2 - V_1$). The deviation in the former case was less than 1% in all cases ($C_{s1} = C_{s2} = 10, 50$ or 100 pF). The deviation caused by $C_{s1} \neq C_{s2}$ is much higher than in the previous cases. It increases to a maximum of 8.5% at 100 pF, decreases significantly around the reference capacitance and increases again up to 2.5% at 1000 pF (Fig. 5). The importance of the reference sub-circuit is to compensate the stray effects. Using the reference capacitance it is possible to guarantee a maximum deviation of 1% in the range of 400–600 pF in the presence of 100 pF stray capacitance.

Fig. 5: Relative deviation caused by the stray capacitances.

The second parameter to be considered is the parallel resistance to the sensor capacitance; this resistance R_x represents the dielectric losses of the dielectric medium under investigation. The value of this parallel resistance varies depending on the sensor geometry and the type of the medium. In the case of edible oils the value of R_x varies depending on the type and quality of the oil. A typical value of R_x is in the M Ω range. For this purpose, a parallel resistance is added to the capacitance C_x as illustrated in Fig. 1. The circuit is simulated with and without stray capacitances for resistance R_x in the range of 1–100 M Ω .

With the presence of the parallel resistance, C_x , R_1 and R_x form a high-pass filter expecting that the gain is constant at low frequencies (Fig. 6). We have

$$H(w) = \frac{R_1}{R_1 + \frac{R_x}{1+j\omega C_x R_x}} \quad (6)$$

Fig. 6: Magnitude Bode plot of the filter formed by C_x , R_1 and R_x .

The new transfer function depends on C_x , R_1 and R_x (equation (6)); at low frequencies ($\omega = 0$), $H(\omega) = \frac{R_1}{R_1 + R_x}$, while at high frequencies ($\omega = \infty$), $H(\omega) \approx 1$. The gain at low frequencies equals $\frac{R_1}{R_1 + R_x}$, which is different from the case without R_x .

In the case $R_x = 100 \text{ k}\Omega$, the relative deviation is higher than 100 % and it was not possible to calculate C_x using equation (3). In this case the current flows through R_x only. This makes the circuit behave like an inverting amplifier with a constant gain independent of the value of C_x . For higher values of R_x the relative deviation decreases; at $R_x = 10 \text{ M}\Omega$ it has its maximum (1 %) at 100 pF while it has its minimum (0.6 %) for values near the reference capacitance (Fig. 7). In the case where both stray capacitance

Fig. 7: Relative deviation caused by the parallel resistance.

and parallel resistance are added to the circuit, the deviation effect is more by the parallel resistance; in fact, at a stray capacitance of 10 pF and when $R_x = 10 \text{ M}\Omega$, the maximum deviation was 2 % at 100 pF and it decreases for higher capacitance values.

4 Experimental results

The circuit was designed and implemented on a printed board for experimental investigation. The amplifier ADA4522 was used in the circuit and it was selected because of its low offset voltage and bias current. Two amplifiers were used so that the two rectifiers and the two low-pass filters (measurement and reference branches) could be implemented in a way the error caused by stray capacitances of the measurement circuit would be similar and hence compensated in the differential amplifier. The diode BAS16VY was used in the rectifier circuit; it was selected because of its very small reverse recovery time (minimum time to switch from passing to blocking modes and vice versa).

The measurement circuit is excited by a sine wave signal with a 2-V_{pp} amplitude at a frequency of 10 kHz. The waveform generator AD9933 was used because of its low cost, simple interface and stable output frequency and amplitude, especially at low frequencies. A micro-controller with an accurate ADC (12 bits resolution and 250 kS/S sampling rate) was used to measure the output voltage.

A set of 30 capacitances in the range of 1–700 pF were accurately measured with a precision impedance analyzer for the calibration of the measurement circuit. The reference capacitance is chosen to be 500 pF; this limits the measurement range to 500 pF, so that no negative voltage will be in the output of the circuit, which can damage the ADC of the micro-controller.

An offset voltage of 60 mV was measured when $C_x = C_{\text{ref}} = 500 \text{ pF}$; this can be caused by the measurement circuit and the error of the analog-to-digital conversion. It was not possible to measure capacitances lower than 10 pF because the output voltage was not sensitive to the change of capacitance in this range, while it linearly decreases with the increase of capacitance in the range of 10–500 pF. The practical relation between the output voltage and input capacitance was developed using the curve fitting tool, yielding

$$\text{Capacitance} = 0.5304V_{\text{out}} + 468.3. \quad (7)$$

The maximum relative deviation is 30 % for capacitances smaller than 70 pF while it decreases to 2 % at 100 pF and decreases further when the input capacitance increases. A minimum change of 3 pF was accurately detected, corresponding to a change of 6 mV in the output voltage.

5 Conclusion

The proposed measurement circuit is suitable for the measurement of small capacitance changes in the pF range in the capacitance range from 10–500 pF. It was possible to reduce the effect of stray capacitances using the reference principle. The measurement accuracy increases for capacitance values near the reference capacitance and hence it is advised to use a reference capacitance equal to the nominal capacitance of the sensor. The dielectric losses have major effects on the measurement; in fact this circuit is not suitable for the measurement of high-loss materials, though it is possible to use this circuit for the assessment of oil quality since it has low dielectric losses.

Bibliography

- [1] H. Lizhi, K. Toyoda, and I. Ihara, “Dielectric properties of edible oils and fatty acids as a function of frequency, temperature, moisture and composition”, *Journal of Food Engineering*, vol. 88, no. 2, pp. 151–158, 2008.
- [2] H. Lizhi, K. Toyoda, and I. Ihara, “Discrimination of olive oil adulterated with vegetable oils using dielectric spectroscopy”. *Journal of Food Engineering*, vol. 96, no. 2, pp. 67–171, 2010.
- [3] A. Fendri, O. Kanoun, and H. Ghariani, “Dielectric spectroscopy for assessment of water content in edible oils”, In: *Systems, Signal & Devices (SSD)*, 14th International Multi-Conference on Sensor System & Devices. IEEE, 2017.
- [4] A. Y. Khaled and S. A. Aziz Rokhani, “Capacitive sensor probe to assess frying oil degradation”. *Information Processing in Agriculture*, vol. 2, no. 2, pp. 142–148, 2015.
- [5] A. Heidary and G. C. Meijer, “An integrated interface circuit with a capacitance-to-voltage converter as front-end for grounded capacitive sensors”, *Measurement Science & Technology*, 2008.
- [6] R. Nojdelov and S. Nihtianov, “Capacitive-sensor interface with high accuracy and stability”. *IEEE Transactions on Instrumentation and Measurement*, 1633–1639, 2000.
- [7] M. Z. Aslam and T. B. Tang, “A high resolution capacitive sensing system for the measurement of water content in crude oil”, pp. 11351–11361.
- [8] R. A. Brookhuis, T. S. Lammerink, and R. J. Wiegerink, “Differential capacitive sensing circuit for a multi-electrode capacitive force sensor”, *Sensors and Actuators A, Physical*, pp. 168–179, 2015.
- [9] M. D. Benadda, J. C. Carru, and C. Druon, “A measuring device for the determination of the electric permittivity of materials in the frequency range 0.1–300 MHz”, *Journal of Physics E, Scientific Instruments*, 1982.
- [10] D. M. Preethichandra and K. Shida, “A simple interface circuit to measure very small capacitance changes in capacitive sensors”. *IEEE Transactions on Instrumentation and Measurement*, pp. 1583–1586, 2001.
- [11] S. M. Huang, C. G. Xie, A. L. Stott, R. G. Green, and M. S. Beck, “A capacitance-based solids concentration transducer with high immunity to interference from the electrostatic charge generated in solids/air two-component flows”, *Transactions of the Institute of Measurement and Control*, pp. 98–102, 1988.
- [12] D. Marioli, E. Sardini, and A. Taroni, “High-accuracy measurement techniques for capacitance transducers”, *Measurement Science & Technology*, 1993.
- [13] A. Pinter and I. Dénes, “Interface circuit for measuring small capacitance changes in sensor networks”, *IET Science, Measurement & Technology*, pp. 570–578, 2015.