Interface System for Impedance Measurement Based on a Relaxation Oscillator

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Abstract

An interface system for impedance measurement based on a first-order oscillator is presented. It is intended for sterility testing of aseptically packed food products by measuring the conductivity changes of the packaged food. For this application the measured impedance is modeled as a resistor (representing the conductivity of the food) in series with a capacitor (due to the walls of the food container). The measurement range is: from 50 pF to 220 pF for the capacitive component and from 10 Ω to 150 Ω for the resistive component. By means of an auto-calibration three-signal method a relative error of 0.3 % for the resistive component R_x and 0.1 % error for the capacitive component C_x of the unknown impedance is achieved. The output signal of the interface system is time-period. To calculate values for R_x and C_x a data processing circuit based on microcontroller is developed. The principle of operation is discussed and practical realization is presented.

I. Introduction

Nowadays different concepts and electronic circuits are used to interface capacitive, inductive or resistive sensors [1][2]. Among them, first-order oscillators are considered as low-cost, accurate and sensitive solutions [3]. However, the above-mentioned sensors often show a complex electrical behaviour, which can be modelled by a multiple-component equivalent circuit. The main objective of the interface circuits is to convert one of the impedance components and to be immune to the effects of the rest. Unfortunately, the undesired components often limit the range of the measured physical quantity and usually cause non-linearity to the transfer characteristic. Moreover, only one component is measured, while there may be others, which are also informative.

The problem is even more interesting in the special case, when we have directly to measure the electrical properties of the object of interest. A lot of applications for such measurements can be found in medicine and biology [4][5].

In this case the equivalent electric circuit of the object can be pretty complica-ated, so that at different frequencies of the applied signal different components may have dominant influence on the measured impedance. By just doing multi-ple-frequency impedance measurements, we can obtain information about many aspects of the object of interest.

Our objective is to measure both components R_x and C_x of the unknown impedance, presented with a serial model. The output signal for both impedance components is time period and can directly be supplied to a micro-controller iin-put without the need of an analog-to-digital converter.

With the reported in [6] technique the values of the capacitive and the resistive component are measured in four steps with the help of modified Martin oscillator, built with an integrator, voltage and current sources and a comparator.

The generated times in the four steps are:

$$T_1 = 2(\frac{C_1 U_1}{I} + 2t_d) \quad (1),$$

$$T_2 = 2(\frac{C_x U_1}{I} + 2t_d) \quad (2),$$

$$T_3 = 2(\frac{C_1 U_1}{I} - 2R_x C_x + 2t_d) \quad (3),$$

$$T_4 = 4t_d \quad (4),$$

where C_1 is a reference capacitor, U_1 is the output voltage of a voltage source, I is the integrating current. The propagation delay in the comparator and the delay in the current source switching define t_d.

From the ratio $(T_2 - T_4)/(T_1 - T_4)$ is calculated C_x:

$$C_x = C_1 \frac{(T_2 - T_4)}{(T_1 - T_4)} \quad (5)$$

From the difference $T_1 - T_4 = 4R_x C_x$ is calculated R_x:

$$R_x = \frac{1}{4C_x}(T_1 - T_3) \quad (6)$$

There are two main problems related to the above-presented method. Firstly, the capacitive component value depends on the value of R_x, because in the second step (2) the period T_2 is too short for all the charge in C_x to be trans-ferred to the integrating capacitor. It brings an error for the capacitive compo-nent (5) and for the resistive component (6) later.

Secondly, to eliminate the influence of the undesired parasitics and the long-term temperature drift of the oscillator frequency the three-signal method should be applied for the resistive component, as well.

This paper describes how to solve the problems and to improve the accuracy. In section II a possible solutions and the principle of operation is presented. The practical realization of the interface circuit is in section III. In section IV the experimental results are presented. The conclusions are in section V.

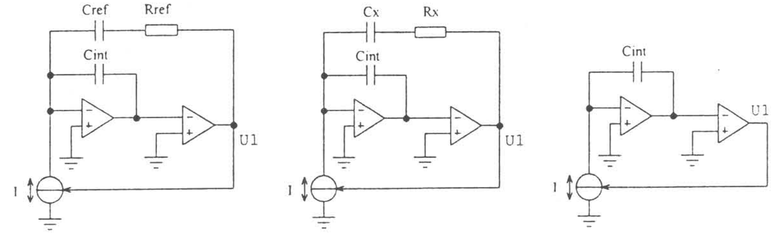
II. Principle of operation

The principle of operation is based on the above presented method [6].

To reduce the effect of the shorter period T_2 (2) the integrating current is decreased from 3 mA to 0.5 mA. After decreasing the current, the time constant $C_l U_l/I$ in the third step (3) becomes much larger than the unknown time constant $R_x C_x$. The sensitivity for R_x is reduced and quite heavy requirements for the stability of the output voltage of the comparator and the integrating current are required. One possible solution is to remove the first component of equation (3) that means the capacitor C_l to be disconnected. Then T_3 will equal $T_3=-4R_xC_x+4t_d$. To be sure that $4t_d>4R_xC_x$ a small additional delay time is added by increasing t_d.

To solve the second problem – to apply the three-signal method for the resistive component, reference resistor is needed. The best choice is to place the reference resistor in series with the reference capacitor. As a result six measurement steps and two reference elements are introduced.

Figure 1 shows the three measurement steps for the capacitive component C_x.



$$T_1 = 2\frac{C_{ref}U_1}{I} + 4t'_d \quad (7) \qquad T_2 = 2\frac{C_xU_1}{I} + 4t'_d \quad (8) \qquad T_3 = 4t'_d \quad (9)$$

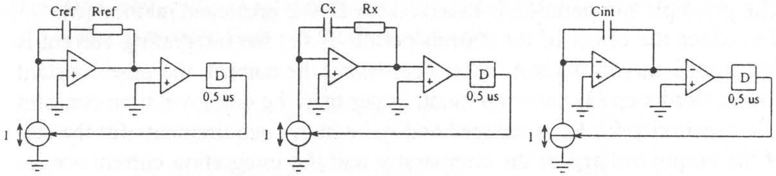
Fig.1. Three steps for measuring the capacitive part of the unknown impedance.

From the ratio $(T_2-T_3)/(T_1-T_3)=C_x/C_{ref}$ we calculate C_x:

$$C_x = C_{ref}\frac{T_2 - T_3}{T_1 - T_3} \qquad (10)$$

There are two limitations: $R_{ref}C_{ref} << T_1$; $R_xC_x << T_2$. If these requirements are not met the generated periods T_1 and T_2 will be too short for all the charge in C_{ref} and C_x to be transferred to C_{int}. This will bring an error for the capacitive component and for the resistive component.

By means of the next three steps (Fig.2) the auto-calibration three-signal method is applied to measure R_x.



$T_4 = -4C_{ref}R_{ref} + 4t_d''$ (11) $\quad T_5 = -4C_xR_x + 4t_d''$ (12) $\quad T_6 = 4t_d''$ (13)

Fig.2. Three steps for measuring the resistive part of the unknown impedance.

From the ratio $(T_6-T_5)/(T_6-T_4)=R_xC_x/R_{ref}C_{ref}$ we calculate R_x. The result from the first three steps $(T_1-T_3)/(T_2-T_3)=C_{ref}/C_x$ is needed, to remove C_x/C_{ref} from the equation above.

$$R_x = R_{ref}\frac{(T_6 - T_5)\,(T_1 - T_3)}{(T_6 - T_4)\,(T_2 - T_3)} \qquad (14)$$

If the requirements $4C_{ref}R_{ref}<4t_d''$, $4C_xR_x<4t_d''$ are not met in the fifth and in the sixth steps, the period of the output frequency will be $4t_d''$ and the circuit will not be sensitive anymore to the values of R_x and C_x.

C_{ref} and C_{int} have to be high-quality capacitors with small loss resistance and values in the order of C_x. The best value of the reference resistor is in order of R_x.

Figure 3 shows the simplified impedance interface circuit, with which the six measurement steps can be performed. Table 1 sows the state of the switches in each step.

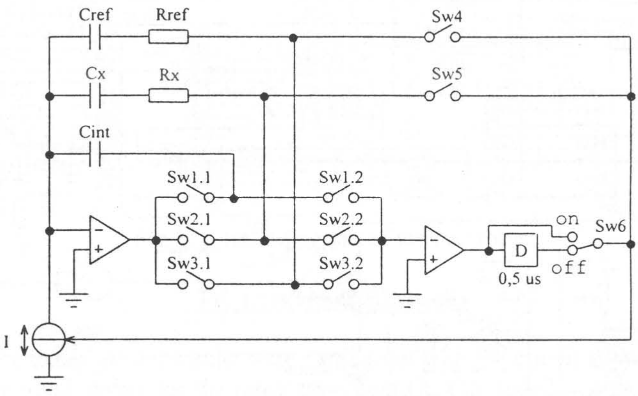


Fig.3. Simplified impedance interface circuit

Table 1

Step	1	2	3	4	5	6
Sw1	on	on	on	off	off	on
Sw2	off	off	off	off	on	off
Sw3	off	off	off	on	off	off
Sw4	on	off	off	off	off	off
Sw5	off	on	off	off	off	off
Sw6	on	on	on	off	off	off

III. Practical realization

Figure 4 shows the circuit diagram of the impedance sensor interface. The integrator was realized with the high-speed amplifier LM7171 (NS) with a unity-gain bandwidth of 200 MHz and a slew rate of 4100 V/us. The comparator used was AD8598 (AD) with propagation delay of 7 ns. The analog switches were MAX333A (MAXIM). We used an integrating current of ± 0.45 mA. The switching of the current direction was done with MOSFET switches SD211DE (Siliconix).

The output resistance of the current generator and the input resistance of the integrator (U1, Fig.4) have to be high, otherwise the value of the current I will depend of the inevitable excursions of the voltage at the inverting input of the amplifier during every transition period. Also part of the current will be lost, as it will go through the input resistance of the amplifier. The main requirement for the comparator (U2.1, Fig.4) is to have a very small voltage hysteresis, otherwise the delay time t_d will depend of C_x, C_{ref} and C_{int} in the last three steps (Fig.2). This will bring additional error for the resistive component.

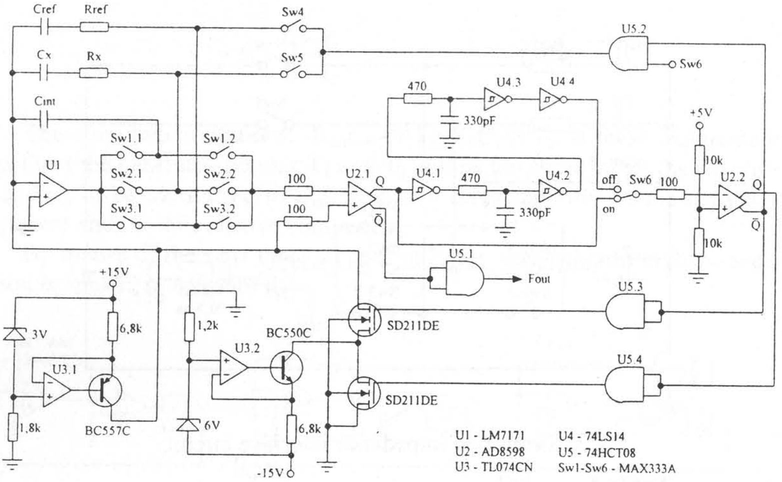


Fig.4. Circuit diagram of the impedance sensor interface

Another problem is the limited gain factor of the amplifier LM7171, which brings a small potential at the inverting input of the integrator. This potential causes an error when we measure R_x, because the comparator will not switch exactly when the voltage over the component in the negative feedback of the integrator is zero. To ensure the last requirement the non-inverting input of the comparator and the inverting input of the amplifier (U1) are connected. This leads to limited range for the capacitive component - the error for the resistive component grows when the values of the capacitors C_x, C_{ref} and C_{int} are not in the same range.

A transition process with a sine form of the output signal of the integrator during every transition period is another problem. To have enough time the transition process to calm down the additional delay time is increased from 300 ns to 500 ns. The additional delay time circuit is realized with Schmitt-trigger 74LS14 and two RC groups.

A controller, based on PIC16F876 is developed to control the analog switches and to measure the generated frequency. Figure 5 shows the circuit diagram of the controller.

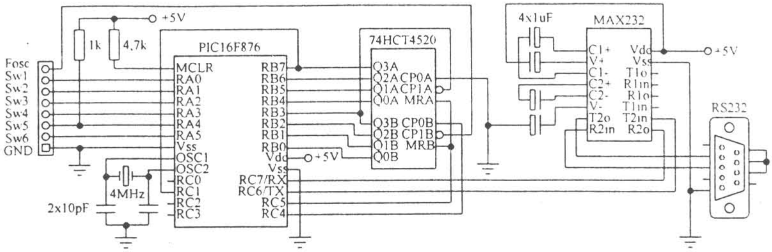


Fig.5. Circuit diagram of the controller

IV. Experimental results

The experimental results were carried out with the circuit shown in Fig.4. We used equal values for the three capacitors C_x, C_{ref} and C_{int} in the range between 50 pF and 220 pF. The reference resistor value R_{ref} was 82 Ω, the range for the resistive component was between 10 Ω and 150 Ω. We measured both components R_x and C_x, as we changed value of the resistive component. The frequency range was between 180 kHz (for capacitor value of 220 pF) and 665 kHz (for capacitor values 55 pF). When we measured the offset, the frequency of the oscillator was $F=1/4t_d'=6250$ kHz. As a reference the Impedance Analyzer HP4195A was used, whose error for this frequency range did not exceed 0.1 %.

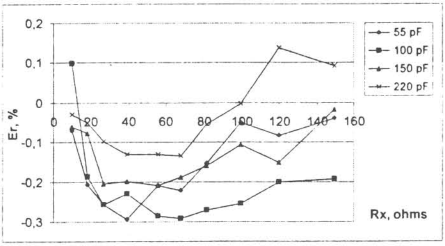


Fig.6. Relative error of the measured resistive component R_x.

The relative error of the resistive component (see Fig.6) is mainly due to the excursions of the output siignal of the integrator, during each transition period.

The sensitivity for R_x depends on the capacitive component value and grows for the larger values of C_x, because the time constant R_xC_x will be larger. This is clearly visible for the capacitive component values of 220 pF and 150 pF.

The relative error for C_x did not exceed 0.1 %, but was slightly dependent on the value of the resistive component. Figure 7 shows the absolute error

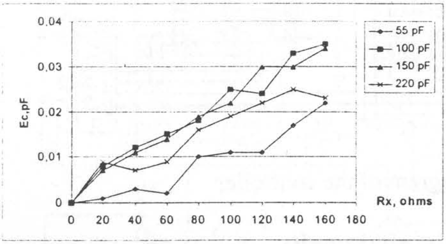


Fig.7. The dependence of the measured capacitive component value on the value of the resistive component, presented with the absolute change of C_x value.

due to this dependence. To check the accuracy of the circuit discrete elements were used. The parasitic capacitance of the resistor brings an additional error.

For values R_x>150 Ω and C_x>250 pF the transition process brings big error.

The frequency was measured by counting the generated pulses for time intervals of 250 ms. With this measurement time, the sensitivity was better than 0.05 Ω for the resistive component and better than 0.05 pF for the capacitive component.

V. Conclusions

A low-cost and accurate system for impedance measurement is presented, based on relaxation oscillator. It is intended for measuring impedance, which can be presented with a serial R-C model. With a six-signal technique and two reference elements a continuous auto-calibration for both components is achieved. This technique ensures inaccuracy less than 0.3 % for the resistive component R_x and less than 0.1 % for the capacitive component C_x. The measurement range is: from 50 pF to 220 pF for C_x and from 10 Ω to 150 Ω for R_x. The output signals for the components of the unknown impedance are time-period and special measurement circuit was developed to calculate their values. By counting the generated pulses for time intervals of 250 ms a sensitivity of 0.05 Ω for R_x and 0.05 pF for C_x is achieved. The frequency range is from 180 kHz to 680 kHz.

VI. References

[1] C. Kolle and P. O'Leary, Low-cost, High-precision Measurement System for Capacitive Sensors, *Measurement Science and Technology,* Vol.9, pp.510-517, 1998.