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Review article

A modified Schering bridge for measurement of the dielectric parameters of a material and the capacitance of a capacitive transducer

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Abstract

Measurement of the dielectric parameters of a material and the change in capacitance of a capacitive transducer by the bridge technique may suffer from errors due to the effect of the stray capacitance between the bridge output lead wires and between the lead wires and the ground. The conventional Wagner-earth technique used to minimise this effect may not be suitable for continuous measurements. In the present paper, a modified operational amplifier-based Schering bridge network is proposed, where the effect of stray capacitance may be assumed to be negligible and continuous measurement is possible. Moreover, the bridge sensitivity may be adjusted by a linear potentiometer. The performance of the bridge network was studied experimentally by assuming a parallel combination of known values of capacitance and resistance instead of an actual dielectric material capacitor or capacitive transducer. The experimental results reported in the present paper reveal the satisfactory performance of the bridge network.

Keywords: Modified Schering bridge; Dielectric constant; Loss angle; Capacitive transducer

1. Introduction

The accurate measurement of the dielectric parameters of a material, such as the dielectric constant and loss angle at low excitation voltage, is important in many aspects of instrumentation, such as low-voltage capacitor design, low-voltage capacitive transducer design, etc. [1,2,4,6]. The dielectric constant and loss angle of a material may be measured from an accurate measurement of the capacitance of a capacitor of a particular shape, using the material as the dielectric. Also, a capacitive transducer used for the measurement of different process variables, such as level, flow, pressure, etc., exhibits a change of capacitance proportional to the change of the process variables being measured. This change of capacitance is generally very small and may sometimes be comparable to the stray capacitance between the transducer probe and the ground. Therefore, in all these applications, measurement of the capacitance of a capacitor or a capacitive transducer is required to be made with high accuracy. There are different bridge techniques [1,2,6,9,11,15] for measuring the capacitance, but the Schering bridge technique may,

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perhaps, be considered to be one of the most sensitive techniques for this measurement. The measurement errors due to the stray capacitances with this bridge technique may be minimised by using the Wagner-earth technique with screened bridge components and lead wires. One disadvantage of this technique may be the requirement for several repetitions of bridge balance and Wagner-earth balance for each observation. Moreover, there are other techniques proposed by various investigators to minimise the error due to the effect of stray capacitances.

A modified approach of the balancing technique of the AC Wheatstone bridge network has been reported by Takagishi [8], whereas Morioli et al. [5] and Holmberg [7] have proposed self-balancing techniques to achieve highly accurate measurements. Kolle et al. [4] suggested a synchronous modulation and demodulation technique for the precision measurement of the capacitance of a capacitive transducer. Yang et al. [12] suggested an electrical capacitance tomography (ECT) technique for measurement of the change of capacitance of a multi-electrode capacitive transducer.

Various other attempts have been made to measure small capacitance of a transducer very accurately such as Capacitance to DC voltage Converter Technique [3], Charge Transfer Technique [10,13] and Circuit Theory Based Technique [14] etc.

In the present paper, a low-cost modified operational amplifier-based Schering bridge technique is proposed for the minimisation of the effect of stray capacitance without the use of the Wagner-earth technique. With this method the bridge nodal points of the bridge output lead wires are both kept at virtual ground potential so that the effect of stray capacitance between the bridge output lead wires and also between any output lead wire and the ground may always be assumed to be negligible. The bridge balance equations of this modified Schering bridge network are also identical to that of the conventional Schering bridge network. Thus, continuous measurement may be possible using this modified Schering bridge network. Moreover, this technique also provides an additional bridge sensitivity factor adjustment by a linear potentiometer. In the measurement of the dielectric constant and loss angle of a dielectric material sample, the bridge may be alternately balanced for the capacitance between two known electrodes with or without the sample between them and the capacitance between the electrodes may then be measured from these two bridge balanced conditions as for the conventional Schering bridge technique [15]. In the present investigation the experimental work was conducted with a parallel combination of a known capacitance and a known resistance instead of an actual dielectric material, and the observed calibration curve and percent error curve in terms of the bridge components for the different values of the bridge sensitivity factor potentiometer were obtained.

Moreover, the performance of the bridge network for a capacitive transducer was studied. The bridge is balanced for a particular value of the capacitance of a capacitive transducer corresponding to the minimum value of a process variable, and the unbalanced bridge output due to the change of capacitance of the capacitive transducer, which is in the from of a known variable capacitor, was observed. These experimental results reveal the satisfactory performance of the bridge network.

2. Analysis

The conventional Schering bridge network designed by Tinsley [15] is shown in Fig. 1. It is modified with an operational amplifier-based network as shown in Fig. 2. In Fig. 2, A_1 and A_2 are two high-gain operational amplifiers with their non-inverting terminals connected to the circuit common terminal, which is again connected to the rigid

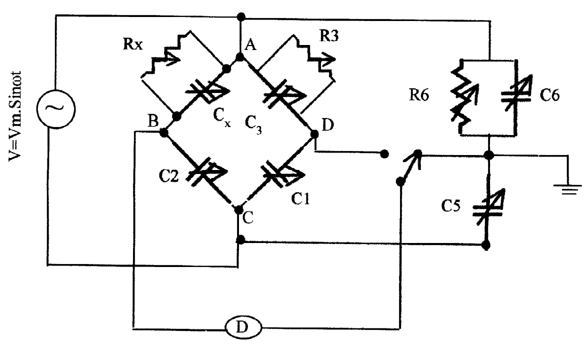

Fig. 1. Conventional Schering bridge network with Wagner-earth arrangement.

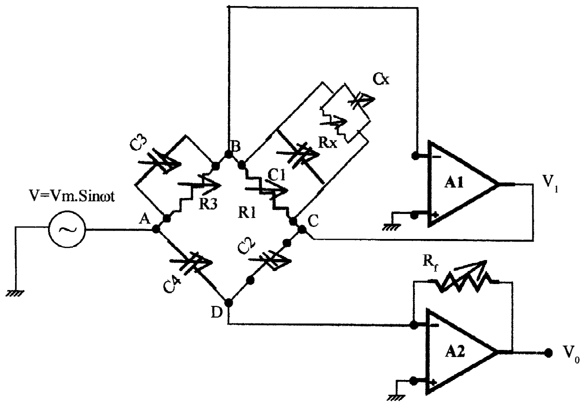

Fig. 2. Modified Schering bridge network.

ground point. Hence the output nodal points B and D of the bridge network are both virtually at the same potentials with respect to the ground. Hence the effect of the stray capacitance between the output lead wires and ground may be assumed to be negligibly small. If the bridge arm impedances in arms BC, CD, AB, and AD are Z_1, Z_2, Z_3, and Z_4, respectively, then the currents through the bridge impedances are given by

$$I_1 = V_1/Z_1,\quad I_2 = V_1/Z_2,\quad I_3 = V/Z_3,\quad I_4 = V/Z_4 \tag{1}$$

where V is the sinusoidal a.c. supply voltage and V_1 is the output voltage of amplifier A_1. If V_o is the output voltage of the operational amplifier A_2, then the current through feed-back resistance R_f is given by

$$I_f = V_o/R_f \tag{2}$$

From Kirchhoff's current law

$$I_3 + I_1 = 0 \tag{3}$$

and

$$I_4 + I_2 + I_f = 0 \tag{4}$$

Now from Eqs. (1)–(4) we obtain

$$V_o = R_f(Z_1Z_4 - Z_3Z_2)/(Z_1Z_3Z_4) \tag{5}$$

At the balance condition of the bridge, $V_o = 0$. Hence the same balance condition as in the conventional Wheatstone bridge network is obtained and is given by

$$Z_1Z_4 = Z_2Z_3 \tag{6}$$

Now for the network as shown in Fig. 2

$$Z_1 = R_1/(1 + j\omega C_1R_1),\quad Z_2 = 1/j\omega C_2,\quad Z_3 = R_3/(1 + j\omega C_3R_3),\quad Z_4 = 1/j\omega C_4 \tag{7}$$

Hence the balance equation (6) is reduced to

$$C_2(1 + j\omega C_3R_3)/R_3 = C_4(1 + j\omega C_1R_1)/R_1 \tag{8}$$

Equating the real and imaginary parts of the above equation, we obtain the following equations:

$$1/R_1 = (C_2/C_4)/R_3 \tag{9}$$

and

$$C_1 = (C_2/C_4)C_3 \tag{10}$$

The bridge is first balanced without the sample between the test electrodes by adjusting C_1, R_1, C_3, and R_3 and hence the balance equations (9) and (10) are reduced to

$$1/R_1 + 1/R_0 = (C_2/C_4)/R_3 \tag{11}$$

and

$$C_1 + C_0 = (C_2/C_4)C_3 \tag{12}$$

where C_0 and R_0 are the parallel equivalent capacitance and resistance of the air capacitor between the test electrodes, and C_1, R_1, C_3, and R_3 are the respective values of the bridge components at balance. With the unknown sample between the test electrodes the bridge is rebalanced only by changing the values of C_1 and R_1 without disturbing the other arms. Under this condition the new bridge balance equations are given by

$$1/R_1' + 1/R_x + 1/R_0 = (C_2/C_4)/R_3 \tag{13}$$

and

$$C_1' + C_x + C_0 = (C_2/C_4)C_3 \tag{14}$$

where C_1' and R_1' are the new values of C_1 and R_1 at balance and C_x and R_x are the values of the parallel equivalent capacitance and resistance between the electrodes with the sample between them. From Eqs. (12) and (14) the correct value of the capacitance between the electrodes with the sample as dielectric is given by

$$C_x = C_1 - C_1' \tag{15}$$

Also, from Eqs. (11) and (13) the parallel equivalent resistance of the sample capacitor is given by

$$1/R_x = 1/R_1 - 1/R_1' \tag{16}$$

Hence for the parallel electrode sample capacitor with sample thickness t and electrode contact area A, the dielectric constant $K = C_x t/\epsilon_0 A$ and loss angle $\delta = \tan^{-1}[1/(2\pi f C_x R_x)]$ of the sample material may be readily calculated, where f is the frequency and ϵ_0 is the permittivity of a vacuum.

Now for the given bridge arm impedances shown in Fig. 2 the bridge network output voltage under unbalanced conditions is given from Eqs. (6) and (7):

$$V_o = \frac{j\omega R_f V}{(1 + j\omega C_1 R_1)R_3}[(R_1C_2 - R_3C_4) + j\omega(R_1C_2C_3C_4 - C_1R_1R_3C_4)] \tag{17}$$

If the bridge network is used for sensing the change of a process variable by a capacitive transducer and is balanced for the minimum value C_0 of the capacitive transducer corresponding to the minimum value of a process variable, then $V_o = 0$ for $C_1 = C_0$. Under this condition

$$R_1C_2 = R_3C_4 \text{ and } C_3R_4 = C_0R_1 \tag{18}$$

Hence the value of the output voltage for a change in capacitance ΔC of the capacitive transducer produced by a change in the process variable above this minimum value is given by

$$V_o = \frac{-\omega^2 R_1 C_4 V R_1}{1 + j\omega C_1 R_1}\Delta C \text{ or } V_o \propto \Delta C \tag{19}$$

i.e. the output voltage is linearly related to the change in the process variable if the capacitive transducer is linear and the excitation frequency is kept constant.

3. Experimental results

Experiments were performed using the modified Schering bridge setup with a stabilised sinusoidal excitation signal at 1000 Hz using standard laboratory equipment.

With the help of a digital multimeter and C.R.O. as detectors, the initial bridge balance condition is obtained without C_x for a selected value of R_f by adjusting C_3R_3, C_1, and R_1 at a constant excitation frequency of 1000 Hz. Now a known resistance R_x and a known capacitance C_x are connected in parallel with C_1 and the bridge is rebalanced by adjusting C_1 and R_1 only. The observed values of C_x and R_x are now calculated using Eqs. (15) and (16), respectively. From these readings the percent error of the capacitor C_x is calculated. The calibration curves and percent error curves are shown in Figs. 3 and 4 for different values of the bridge sensitivity factor resistance (R_f).

The performance of the bridge network for a capacitive transducer was also studied by using known values of a small variable capacitor instead of an actual transducer. The variation of the unbalanced bridge output voltage with a change in capacitance (ΔC) was found to be linear, as shown in Fig. 5.

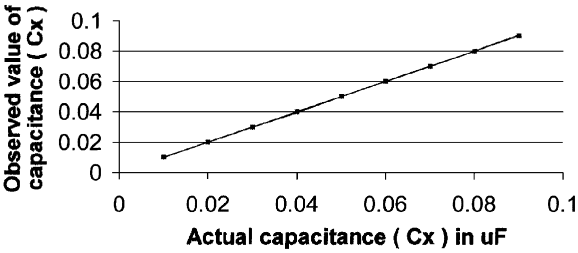

Fig. 3. Calibration curves of a capacitor for different values of the bridge sensitivity factor resistance (R_f).

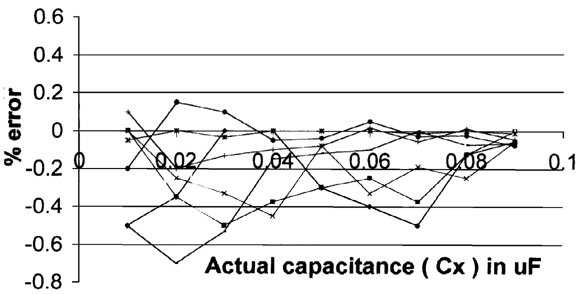

Fig. 4. Percent error curves of a capacitor for different values of the bridge sensitivity factor resistance (R_f).

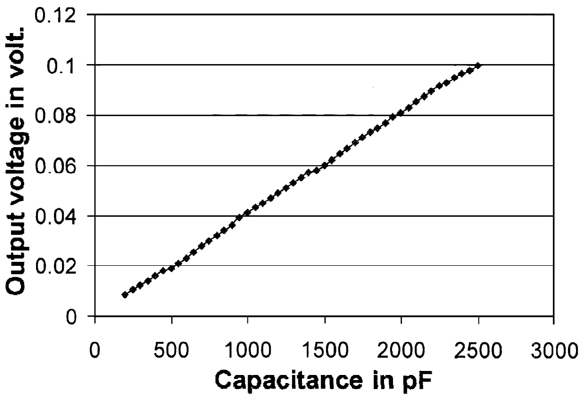

Fig. 5. Variation of unbalanced bridge output voltage (V_o) with a change in capacitance (ΔC).

4. Discussion

The maximum excitation voltage of the test capacitor in arm BC of the modified Schering bridge network in Fig. 2 depends on the maximum output voltage (V_1) of the op-amp A_1. Hence the bridge network is suitable only for low-voltage excitation of a dielectric material. To obtain optimum sensitivity, the bridge arm impedances should be selected to be nearly identical, like all other bridge networks. Before connecting the ground to the common terminal of the network, care was taken to ensure that the ground wire was at nearly zero potential and the high ground potential did not damage the ICs. The bridge balance condition was found not to be disturbed due to any change of orientation of the lead wires. The calibration curve of Fig. 3 and the percent error curve of Fig. 4 show that the effect of the stray capacitance may be assumed to be very small. The linear unbalanced bridge output voltage characteristic of the bridge network (shown in Fig. 5) shows that the bridge may be used effectively to measure a small change in capacitance of a capacitive transducer over a wide range. Experimental work with an actual dielectric material and capacitive transducer is in progress. The technique may also be used for inductance, resistance, conductance or admittance-type transducers.

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