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Study of a Modified AC Bridge Technique for Loss Angle Measurement of a Dielectric Material

S. C. BERA and D. N. KOLE
Instrumentation Engineering Section, Department of Applied Physics,
University of Calcutta, 92, A. P. C. Road, Kolkata 700 009, W. B. India
E-mail: scb152@indiatimes.com, dnkoley@yahoo.com

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Abstract: A Wheatstone's bridge network like Schering Bridge, DeSauty Bridge etc measures the loss angle or tangent of loss angle ($tan\delta$) of a dielectric material. In high voltage application this loss angle is generally measured by high voltage Schering Bridge. But continuous measurement of tan δ is not possible by these techniques. In the present paper a modified operational amplifiers based Schering Bridge network has been proposed for continuous measurement of $tan\delta$ in the form of a bridge network output voltage. Mathematical analysis of the proposed bridge network has been discussed in the paper and experimental work has been performed assuming the lossy dielectric material as a series combination of loss less capacitor and a resistor. Experimental results are reported in the paper. From the mathematical analysis and experimental results it is found that the output of the proposed bridge network is almost linearly related with $tan\delta$. *Copyright © 2008 IFSA.*

Keywords: Schering bridge, OP-AMP, Loss angle measurement, Dielectric material

1. Introduction

The loss angle of a dielectric material is a very important parameter which is required to be known accurately in dielectric material application [1, 2, 3] such as low voltage and high voltage condensers, insulating material in high voltage equipments like cable, transformer, motor, generator etc. as well as in many other aspects of instrumentation such as low voltage capacitor design, low voltage capacitive transducer design used for the measurement of different process variables like level, flow, pressure etc. In transducer application, the change of capacitance of a capacitive transducer due to change of the process variables is generally very small and may sometimes be comparable with the stray capacitance between transducer probe and ground. In low voltage application the conventional capacitance bridge circuits [1, 2, 3] like Schering bridge, DeSauty Bridge etc. can measure both dielectric loss and dielectric constant of a material accurately. But in high voltage application the Schering Bridge combined with Wagner earth mechanism [1] can be taken as one of the accurate bridge networks for the measurement of loss angle and dielectric constants of a material. The effect of stray capacitance between output nodal points and between any nodal point and ground becomes predominant in high voltage application and so the measurement of dielectric parameters by using bridge technique may suffer from errors. In the Schering bridge technique, these errors are minimized by using Wagner earth mechanism [13]. In this mechanism a repeated number of bridge balances are made in both Wagner earth and bridge position of a selector switch. Thus this technique brings the output nodal points of a bridge network almost at the same ground potential. As a result the measurement error due to stray capacitance between the output nodal points is minimized. But the repeated balancing method in each step of measurement may be troublesome during actual experimental work and continuous measurement is not possible.

There are different other techniques proposed by various investigators to minimize the error due to the effect of stray capacitances. Morioli D. et.al. [4] and Holmberg P. [5] have proposed self balancing techniques to achieve high accuracy in measurement. Yang W.Q. et al. [6] have suggested an electrical capacitance tomography (ECT) technique for the measurement of change of capacitance of a multi electrode capacitive transducer. Zhi-Niu Xu et al [7] have suggested Hanning windowing interpolation algorithm based on FFT to reduce the error of dielectric loss angle measurement. Ahmed M. [8] presented a very simple electronic circuit for direct measurement of loss angle of a leaky capacitor in terms of pulse count. A self balancing type capacitance to DC converter has been proposed by Hagiwara N. et. al [9] for measurement of capacitance in low voltage applications. Bera S.C. et al. [10] have designed an operational amplifier (OP-AMP) based modified Schering bridge for the measurement of dielectric parameters of a material and the capacitance of a capacitive transducer. But this bridge has been used for low voltage measurement whereas the same bridge has been modified by Chattopadhyay S. et al [11] to measure the loss angle of a high voltage transformer. But in this network the bridge output is non-linearly related with tangent of loss angle ($tan\delta$). An AC bridge measurement technique has been proposed by Xiaoming Zha et.al. [12] for precision measurement of loss angle.

In the present work, modified Schering Bridge proposed by Bera S.C. et al [10, 11] has been further modified to obtain a linear relationship between bridge output and $\tan\delta$ in high voltage measurement and the effect of stray capacitance is minimized as stated in [10] and [11]. The theoretical analysis of the proposed network has been described in the present paper which shows that bridge output voltage is linearly related with $tan\delta$ of a dielectric material. The performance of the network has been experimentally tested at 230V AC, 50Hz using a series combination of a standard capacitance and a resistance. Here the lossy dielectric material is assumed as a series combination of the loss less capacitor and a resistor. The experimental results reported in the paper shows that the output of the bridge network varies linearly with the equivalent value of $tan\delta$ of a dielectric material.

2. Analysis

The conventional Schering bridge network designed by M/s H.Tinsley & Co. [13] 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 the two high gain OP-AMPs with their non inverting terminals connected to the circuit common which is again connected to the rigid ground point.

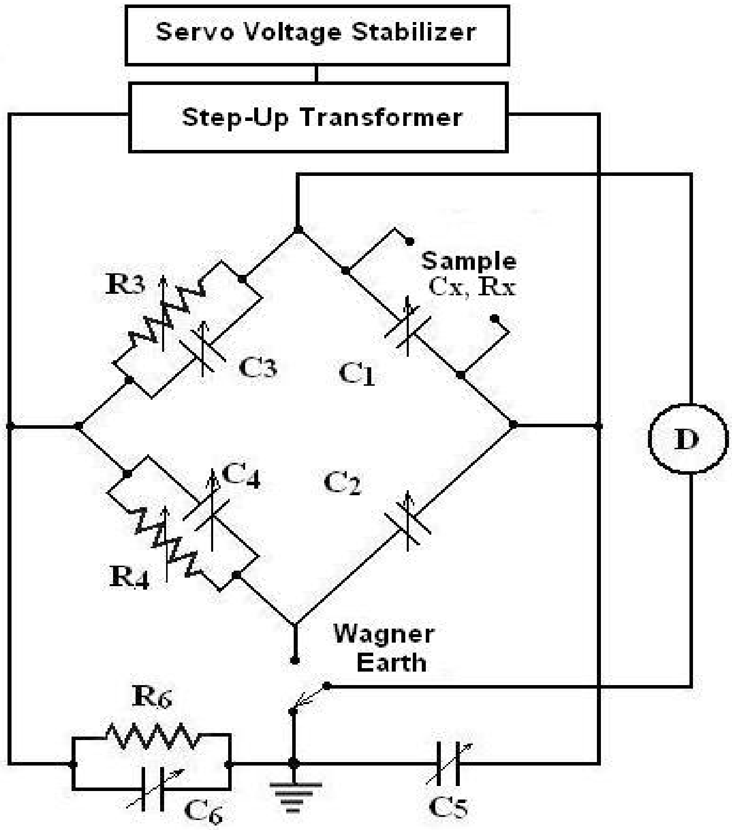

Fig. 1. Conventional Schering bridge network with Wagner-earth arrangement designed by M/s Tinsley & Co.

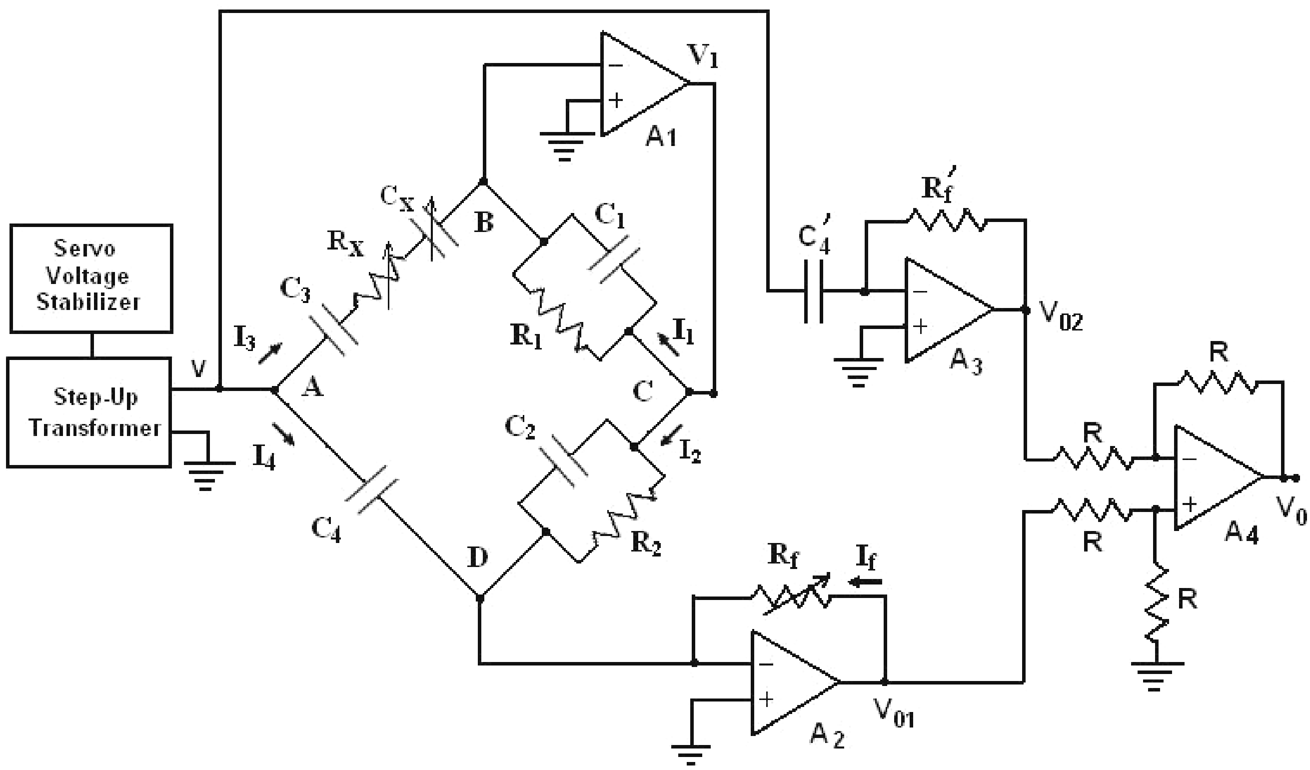

Fig. 2. Modified Schering Bridge network.

Hence the output nodal points B & D of the bridge network are both virtually at the same potential 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 the arms BC, CD, AB, and AD, be Z_1,Z_2,Z_3 and Z_4 respectively then the currents I_1,I_2,I_3 and I_4 through these bridge impedances are given by

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

where V is the sinusoidal AC supply voltage and V_1 is output voltage of the amplifier A_1. If V_{01} be the output voltage of the operational Amplifier A_2, the current through feed back resistance R_f is given by

$$I_f=\frac{V_{01}}{R_f} \tag{2}$$

From Kirchhoff's current law,

$$I_3+I_1=0 \qquad \text{and} \qquad I_4+I_2+I_f=0 \tag{3}$$

Hence from the equations (1), (2) and (3) we get

$$V_{01}=R_f V\left(\frac{Z_1}{Z_2Z_3}-\frac{1}{Z_4}\right) \tag{4}$$

Now for the network shown in Fig. 2,

$$Z_1=\frac{R_1}{1+jwC_1R_1},\ Z_2=\frac{R_2}{1+jwC_2R_2},\ Z_3=Z_{30}+\Delta Z=\frac{1}{jwC_3}+\frac{1+jwC_xR_x}{jwC_x}\ \text{and}\ Z_4=\frac{1}{jwC_4}, \tag{5}$$

$$\text{where}\quad Z_{30}=\frac{1}{jwC_3}\ and\ \Delta Z=\frac{1+jwC_xR_x}{jwC_x}$$

Now the values of R_1,R_2,C_1,C_2,C_3 and C_4 are so selected that in absence of the sample (i.e. ΔZ=0), the bridge is balanced. i.e. $Z_1Z_4 = Z_2Z_{30}$ which is possible when $R_1C_3 = R_2C_4$ and $C_2C_3 = C_1C_4$, In the present work $C_1 = C_2$, $C_3 = C_4$ and $R_1 = R_2$ are assumed. Now when the test sample (assumed to be the series combination of resistance R_x and capacitance C_x) is inserted as shown in Fig. 2 the bridge output voltage is given by

$$V_{01}=R_fV\left(\frac{Z_1}{Z_2Z_3}-\frac{1}{Z_4}\right)=R_f V\left(\frac{Z_1Z_4-Z_2Z_{30}-Z_2\Delta Z}{Z_2Z_4(Z_{30}+\Delta Z)}\right)=-\frac{R_fV\Delta Z}{Z_4(Z_{30}+\Delta Z)} \tag{6}$$

Now tangent of the loss angle of the material is given by $tan\delta = \omega C_xR_x$ and the impedance of the sample connected in series with C_3 is given by

$$\Delta Z=\frac{(1+j\,\omega C_xR_x)}{j\,\omega C_x}=\frac{(1+j\,tan\delta)}{j\,\omega C_x} \tag{7}$$

Hence from equation (6) & (7), V_{01} is given by

$$V_{01} = -\frac{R_f\, V\, j\omega\, C_4\,(1 + j\, \tan\delta)\, j\, \omega\, C_3}{j\, \omega\,(C_3 + C_x) - \omega\, C_3 \tan\delta} \tag{8}$$

Since C_3 is selected to be very small and *tanδ* is also very small so $(\omega C_3 \tan\delta)$ may be assumed to be negligible. Hence the above equation (8) is reduced to

$$V_{01} = -\frac{R_f\, V\, j\omega\, C_4\,(1 + j\, \tan\delta)\, j\omega\, C_3}{j\, \omega\,(C_3 + C_x)}$$

and so, $$V_{01} = -\frac{R_f\, V\, j\omega\, C_4\,(1 + j\, \tan\delta)}{1 + C_x/C_3} \tag{9}$$

If we assume $C_x/C_3 <<1$ then the above equation is reduced to

$$V_{01} = -R_f\, j\omega\, C_4 V(1 + j\, \tan\delta) \tag{10}$$

Now this signal is subtracted from the output V_{02} of the amplifier circuit consisting of OPAMP A_3 in the differential amplifier circuit consisting of OP-AMP A_4 as shown in Fig. 2. The output V_{02} of the amplifier circuit consisting of OP-AMP A_3 is given by

$$V_{02} = -R_f{}' j\omega\, C_4{}' V \tag{11}$$

If $R_f{}'$ and $C_4{}'$ are selected to be exactly equal to R_f and C_4 respectively then V_{02} is given by

$$V_{02} = -R_f j\omega C_4\, V \tag{12}$$

Thus the final output V_0 of the differential amplifier circuit is given by

$$V_0 = V_{01} - V_{02}$$

$$or,\ V_0 = -R_f j\omega\, C_4 V(1 + j\, \tan\delta) + R_f j\omega\, C_4 V$$

$$or,\ V_0 = Rf\, V\omega C_4 \tan\delta$$

$$\text{or, } V_0 = K \tan\delta\,, \tag{13}$$

where $K = R_f V\omega C_4$. Thus V_0 is linearly related with *tanδ*. This output voltage may be further amplified, rectified and filtered to drive a DC analog or digital voltmeter calibrated in terms of *tanδ*. Thus the tedious bridge balance method of finding *tanδ* may be avoided. Moreover from the analysis of the conventional Schering bridge network [1] as shown in Fig. 1, it is observed that the unbalanced bridge output voltage depends non-linearly on *tanδ* when it is large but becomes almost independent on *tanδ* when it is small. So continuous measurement of tanδ may not be possible by this conventional network.

3. Experiment

Experiment was performed by using the proposed modified Schering bridge network with a stabilized sinusoidal excitation signal and a high voltage transformer as shown in Fig. 2 using the laboratory standard equipments. The proposed modified Schering bridge circuit was fabricated by assuming

$C_1=C_2$=0.1 μF, 3KV and $C_3=C_4$ = 0.001 μF, 3KV and $R_1=R_2$=1 MΩ so that in the absence of the test capacitor, the bridge network was at initial balanced condition and the current passing through the ICs was very small within the safety limiting value. The bridge supply voltage was selected to be 230 V, 50Hz. Now a capacitor with a defective dielectric material may be assumed to be equivalent to a series combination of a pure resistance R_x and a pure capacitance C_x as shown in Fig. 2. So in order to test the performance of the proposed bridge network a series combination of variable decade resistance R_x and a continuously variable capacitance C_x was used instead of actual test sample.

The performance of the proposed bridge network was tested and reported in this paper. In Fig. 2 the bridge parameters were so selected that in absence of R_x and C_x the bridge output was attempted to maintain at zero value but due to the deviation from exactly identical values of the bridge components a minimum bridge output voltage was observed. Keeping R_x fixed at a low value, the value of C_x ($C_x << C_3$) was varied in steps and the bridge network output AC voltage (V_0) was measured in each step by the 3½ digit DMM and the corresponding value of *tanδ* was calculated. Now a characteristic graph was drawn by plotting V_0 against *tanδ.* The experiment was repeated for different values of R_x. The characteristic graphs thus obtained are shown in Fig. 3(a), 3(b), 3(c) and 3(d) respectively. The corresponding percentage deviation from linearity is shown in Fig. 4(a), 4(b), 4(c) and 4(d) respectively.

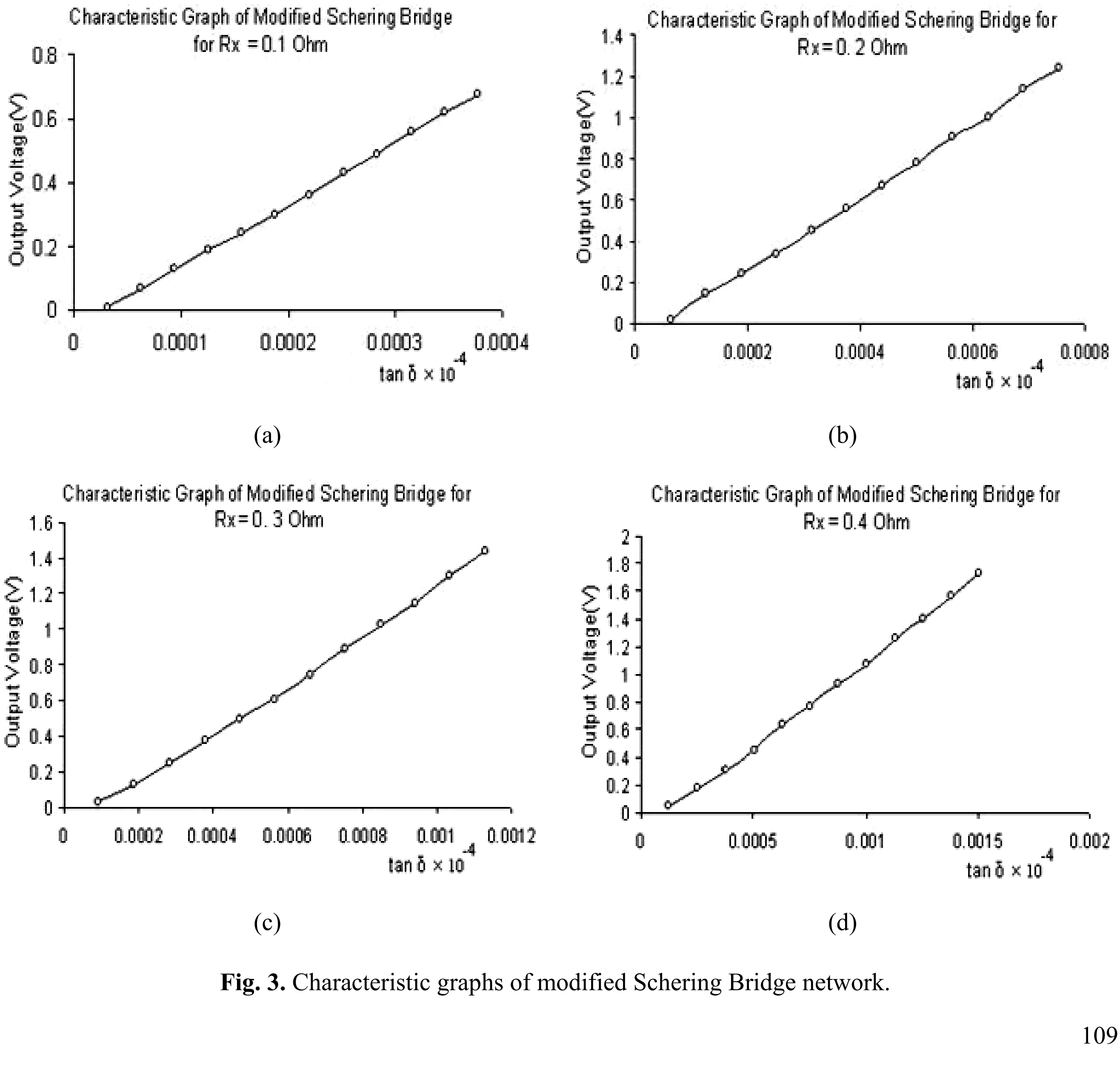

Fig. 3. Characteristic graphs of modified Schering Bridge network.

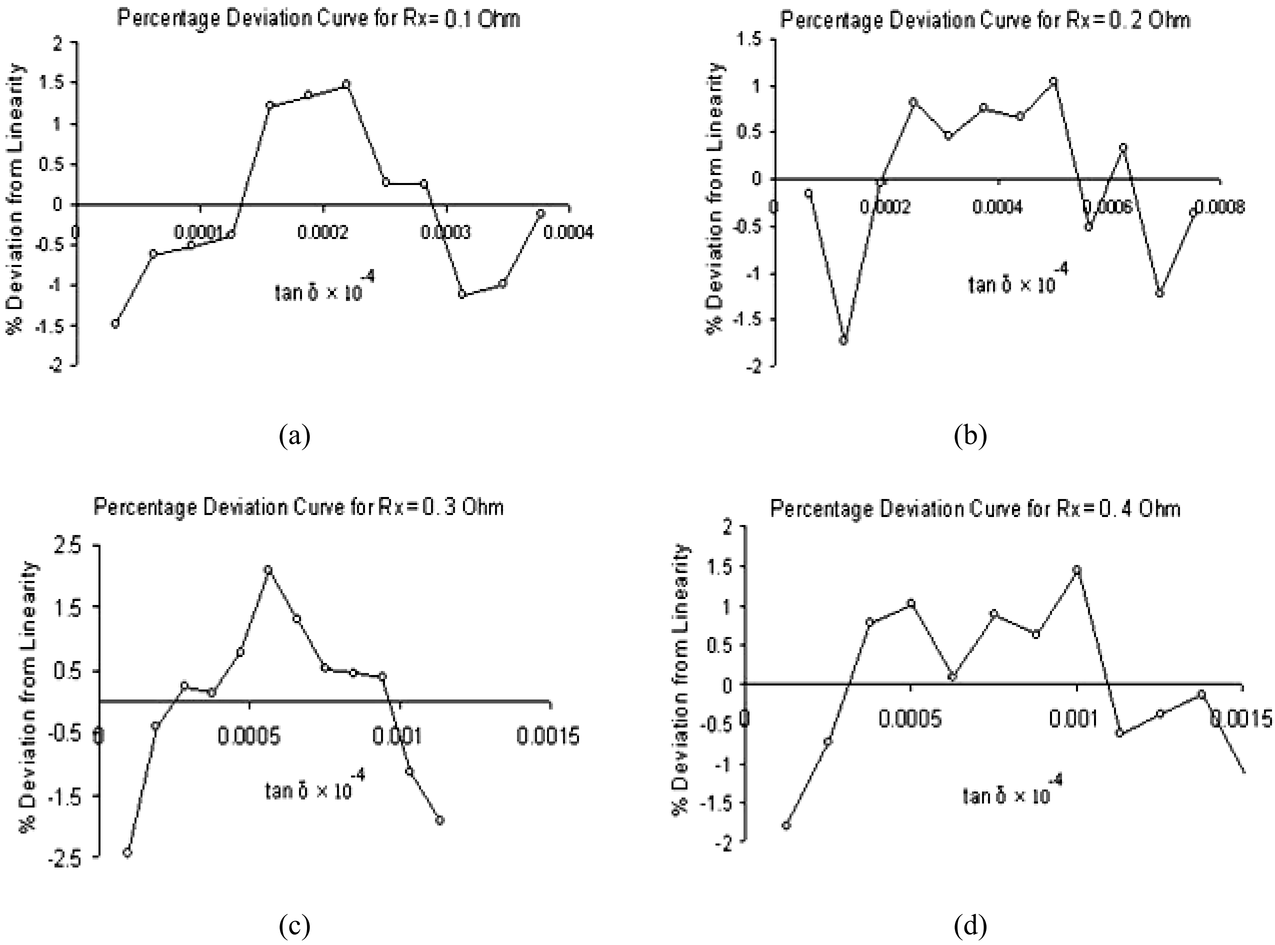

Fig. 4. Percentage deviation curve of modified Schering Bridge network.

4. Discussion

From Fig. 3 it is found that the experimental characteristic graph of the modified bridge network appears to follow a linear characteristic as explained in equation (13) and the percentage deviation curves shown in Fig. 4 reveal that the percentage deviation from linearity of the bridge output characteristic lies within tolerable limit. The major advantage of this technique is that the measurement of $\tan\delta$ does not require any tedious bridge balance method. The conventional Schering bridge network requires intermittent Wagner Earth balance for compensating stray field effect in high voltage measurement between any two consecutive readings. But the proposed network has two bridge output nodal points at the same virtual ground potential. So the measurement error due to the effect of stray capacitance appears to be minimum. Thus continuous accurate measurement of $\tan\delta$ may be possible by the proposed network.

During high voltage measurement, proper care should be taken in shielding each bridge component and rigidly connecting each shield to ground to avoid any fatal effect to ICs, output indicator as well as the operator. The values of C_1, C_2, C_3 and C_4 and other bridge capacitors as shown in Fig. 2 are selected to have very small value so that the current passing through the OP-AMPs may remain within the safety limiting value. The initial bridge balance must be ensured by using pre-selected identical bridge parameters and no variable bridge component must be present in order to avoid any fatal effect by the incidental high unbalanced voltage. Moreover the sample capacitor C_x must be so selected that it is much less than C_3 as stated earlier so that under unbalanced condition of the bridge network due to the presence of the healthy sample, the current passing through IC A_1 still remains within safety limiting value.

The proposed method has a limitation regarding the limit of high voltage supply applied to the dielectric sample since the voltage across the dielectric sample becomes less than the supply voltage due to the use of the capacitor C_3 as well as the current limitation of the OP-AMPs. But C_3 has been selected to be much greater than C_x in the proposed network and hence the voltage applied across the test capacitor C_x is nearly equal to the supply voltage. Hence the dielectric material can be tested with high voltage if the current passing through the capacitors C_3 and C_4 lie within the safety limiting current of the OP-AMPs. So very low value vacuum capacitors with high voltage rating may increase the limiting value of high voltage supply of the bridge network. However at low voltage supply higher value capacitors may be used for the bridge network.

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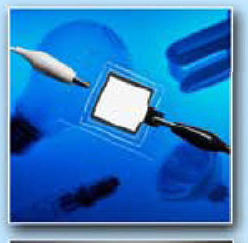

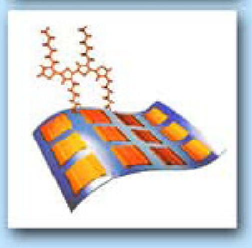

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Fundació UPC. Edifici Vèrtex
Plaça Eusebi Güell, 6, 08034 Barcelona
Tel.: +34 93 401 08 94
E-mail: susana.escriche@fundacio.upc.edu

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