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NONLINEARITY MEASUREMENTS USING ALTERNATING CURRENT

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The nonlinearity measurement technique described uses an adapted conventional lock-in-amplifier. This technique enables us to measure small nonlinearities over a wide frequency band and is more sensitive than the 1/f noise measurement used to detect non-homogeneous structures in conductors, resistors and semiconductor components. Results illustrating uses of this method are presented for different types of resistor and semiconductor structures.

1. INTRODUCTION

With demands for increasingly reliable electronic components, there is need for new methods of measurement which are suitable for estimation of the quality parameters of the components. Current noise measurement is used at present as a measure of the reliability of resistances and contacts between metals and semiconductors. However, measurement of the ohmic nonlinearity of resistors is found, in many cases, to be a more precise method.[1] The measured nonlinearities are usually very small and cannot be evaluated from the d.c. voltampere characteristics. Therefore, alternating currents are used for such measurements. When applied to nonlinear components, odd harmonic frequencies are generated. The necessary equipment is usually a commercial product specially designed for measurements at one basic frequency (e.g. 10 kHz).[2] The nonlinearity level is evaluated by a third harmonic selective voltmeter.

However, it is often possible to adapt ordinary laboratory equipment to give the high sensitivities required for nonlinearity measurements and to perform the measurements at different frequencies.

In this paper the equipment used is described and results are interpreted. The measurements of resistors are compared with measurements obtained using special component linearity test equipment (CLT 1a – Radiometer)[2] and the measurement of current noise.

2. EXPERIMENTAL APPARATUS

The measurement assembly consists of an alternating generator connected to a resistance bridge and a two channel selective amplifier of the lock-in-amplifier type (Figure 1). In our apparatus we have used the lock-in-amplifier PAR Mod 121 A[4] which has a built in signal generator, SG.

FIGURE 1 Basic equipment connections.

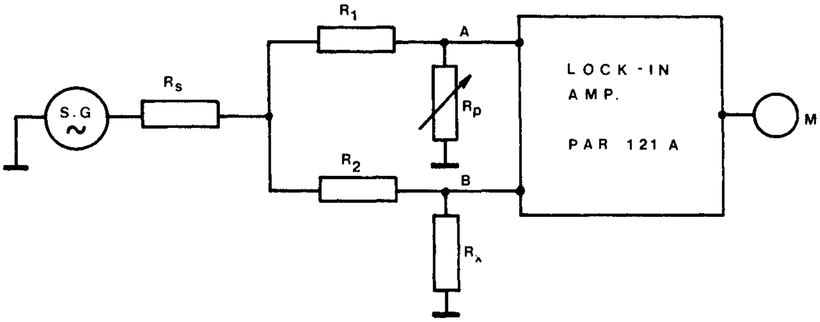


FIGURE 2 Detailed scheme of the resistance bridge with lock-in-amplifier.

Using this equipment, frequencies from 1 Hz to 33 kHz were fed to the bridge, generating up to 11V across the component being measured.

The resistance bridge consists of four resistors, one of which is the component R_x to be measured (Figure 2). The resistances R_1 and R_2 have the same resistive values and the same nonlinearities. The resistance R_p is used to trim the the resistor in branch A to the value of resistor R_x which is in branch B. The resistance bridge is supplied from the SG generator which has an internal impedance R_s.

The voltages from both branches of the bridge are connected, via channels A and B, to the inputs of selective synchronously controlled amplifiers which are a part of the lock-in-amplifier. After amplification the signal can be measured separately for each channel or the output signals from the branches A and B can be compared and the difference voltage measured.

In the case of a balanced bridge, i.e. $R_1 = R_2$ and $R_x = R_p$, the difference voltage for the basic output frequency would be equal to zero. Usually it is not possible to reach the exact balance conditions as R_p can be only approximately equal to the value R_x and therefore there is a residual voltage, U_{1R}, at the output.

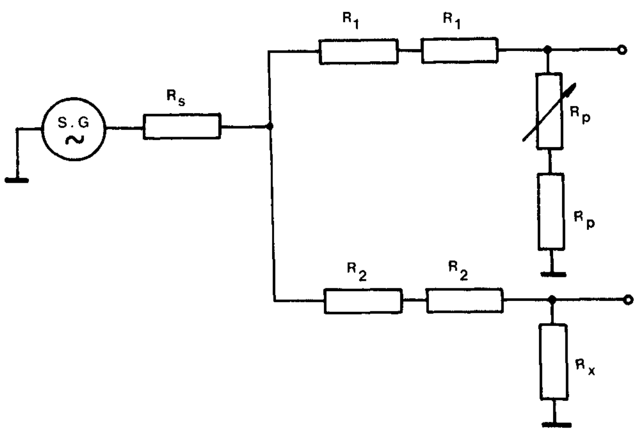


FIGURE 3 Scheme for higher values of the resistors.

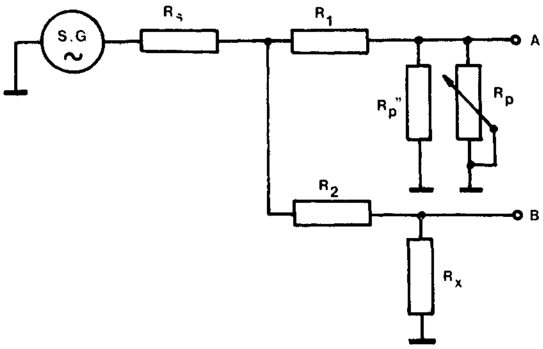


FIGURE 4 Scheme for lower values of the resistors.

In order to increase the range of measurement to higher values of R_x, it is possible to use two series connected resistors, $R_1 + R_1'$ and $R_2 + R_2'$ and to connect a resistor R_p' in series with R_p (Figure 3). For lower ohmic values of resistors, parallel connection of the resistors is more suitable, as in Figure 4.

To obtain the optimum operating conditions for the apparatus, the load impedance of the bridge and the internal impedance R_s of the SG generator should be matched.

In the developed equipment, impedance matching for ohmic values of R_x $10^1\,\Omega$ to $10^4\,\Omega$ was possible.

The choice of frequency for the measurements depends on the characteristic of the signal generator and on the properties of the amplifiers. At very low frequencies, the sensitivity of the apparatus was lower because of harmonic frequencies appearing in the signal generator, SG. Therefore, we have used the frequency band 5 kHz to 33 kHz.

3 THE MEASUREMENT TECHNIQUE

The SG voltage is adjusted to the required value U_{1f}, measured on resistor R_x using channel B which is

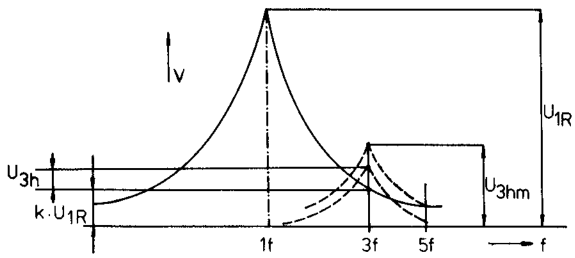


FIGURE 5 Relation between the magnitude of the basic frequency (1f) voltage and the third harmonic frequency.

tuned to the required frequency. This voltage is set in branch A by changing the ohmic value of R_p. In order to reach the minimum difference between the voltages in branches A and B, the differential voltage between both branches is determined at a higher amplification and is adjusted to a minimum by fine tuning of R_p so that the residual voltage $U_{1R} = 0$ (valid if $R_p = R_x$).

In order to balance the resistors of the bridge, voltages of odd harmonics, generated by application of the basic alternating current across the resistor R_x, are measured. Harmonic voltages, which have the maximum values, are chosen to optimise the procedure. Thus, maximum accuracy is achieved, depending both on the magnitude of the noise level and on the value of U_{1R}. The lock-in-amplifier has a limited selectivity defined by the Q factor of the circuits. (Using Equipment 124A it is possible to reach a maximum Q value of 100.)

The magnitude of the harmonic signals decreases with the increasing order of harmonic[1] and therefore, measurements of the third harmonic are used.

The frequency of the selective amplifiers is changed to the third harmonic of SG in order to measure the third harmonic voltage U_{3hm} for resistor R_x. Similarly, U_{5hm} is the fifth harmonic voltage.

The measured value of the third harmonic voltage also contains a part of the residual voltage U_{1R}, related to the limited selectivity of the amplifiers.

The value of the third harmonic peak voltage for R_x will then be according to Figure 5.

$$U_{3h} = U_{3hm} - k\,U_{1R} \tag{1}$$

where k is the coefficient which depends on the value of Q. For $Q = 100$, $k = 0.003$ for the third harmonic and $k = 0.002$ for the fifth harmonic. These assumptions are valid only if the nonlinearity of R_1 is equal to the nonlinearity of R_2 and the nonlinearity of $R_p = 0$, or if the nonlinearity of $R_x \gg R_p$.

4. THE CALIBRATION OF THE NONLINEARITY OF THE RESISTOR R_p

For accurate measurements of small nonlinearities, it is necessary to consider the nonlinear properties of R_p, usually realised with a Helipot. When using identical resistors for R_1 and R_2, nonlinearities of these components have no effect on the measurements and it is not necessary to consider them. For the determination of the nonlinearity of R_p, a calibration resistor, laboratory made from manganin, constantan or similar alloys, is used. Making a perfect contact (preferably by welding), it is possible to make a resistor which closely fulfils the given demands.

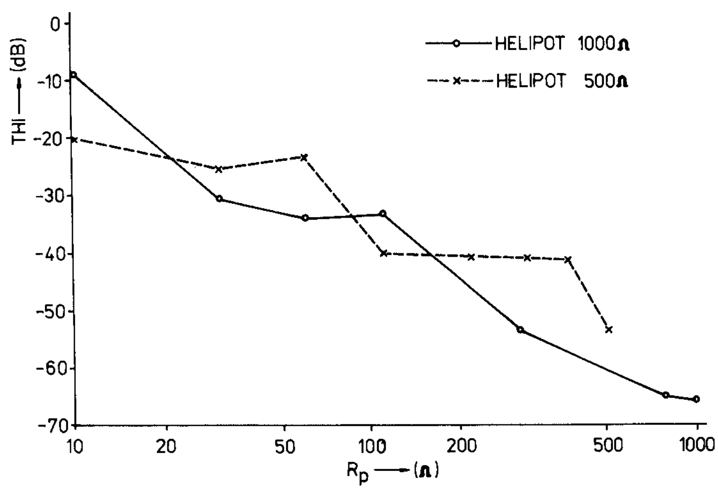


FIGURE 6 Dependence of THI on the value R_p for Helipots.

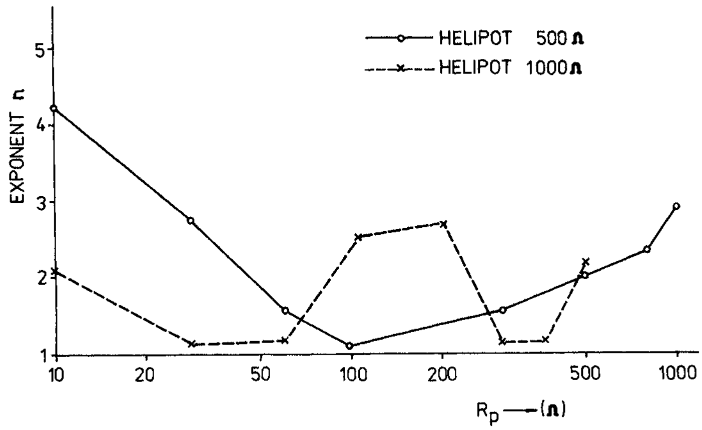


FIGURE 7 Dependence of the exponent "n" on the value of R_p for Helipots.

From measurement of the dependence of nonlinearity of Helipot potentiometers of value 500 Ω and 1000 Ω (equipment CLT 1a), at 10 kHz using the third harmonic, it can be seen that the nonlinearity is dependent upon the ohmic value of the resistor and therefore the calibration resistor R_{cal} is made equal to R_x. In this way it is possible to keep the value of the nonlinearity of R_p in the range of R_x. Figure 6 shows the nonlinearity of the Helipot potentiometers as a function of the third harmonic index. The index, *THI*, in dB, is defined by the relation:

$$THI = 20 \log \frac{U_{3f}}{U_{1f}^n} \left(\frac{\mu V}{V}\right) \qquad (2)$$

The exponent "*n*" in commercial resistors is roughly equal to 3. In the measured Helipot the value of "*n*" changed according to the set resistive value R_p. This dependence is shown in Figure 7. By calibration of resistor R_p, resistor R_{cal} is connected into the branch B of the resistor bridge. Resistor R_{cal} must be without a nonlinear characteristic.

The actual voltage U_{3h} created by the nonlinearity of R_x can be found after subtracting the voltage appearing on R_p, defined by U_{3Hel}.

Consider harmonics as generated by application of a.c. voltage U_{1f} to resistors R_x and R_p. The following situations may arise as shown in Figure 8.

4.1 *Case 1*

$$U_{3h} < U_{3Hel} \qquad (3)$$

The voltage of the third harmonic U_{3h} generated in R_x is greater than zero but does not reach the value U_{3Hel}. The measured voltage U_{3c} is given by the relation:

$$U_{3h} = (U_{3c} - U_{3Hel}) \qquad (4)$$

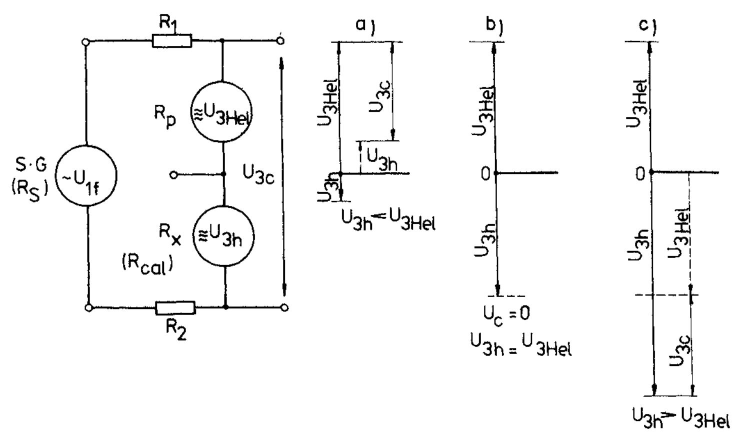


FIGURE 8 Relation between U_{3Hel} and U_{3h} in calibration of R_p.

When resistance R_{cal} instead of R_x is connected in branch B of the bridge, then $U_{3hcal} = 0$ and we measure only $(U_{3Hel} - U_{3c})$. This case is suitable only for determination of the nonlinearity of R_p.

4.2 Case 2

$$U_{3h} = U_{3Hel}$$

The output voltage U_{3c} will here be equal to zero because the nonlinearities of R_x and R_p are identical.

4.3 Case 3

$$U_{3h} > U_{3Hel}$$

This case is most common and applicable to the presented method. For $U_{3c} \gg U_{3Hel}$ it can be considered that $U_{3h} = U_{3c}$ and the relation Eq. (1) can be used directly for the determination of U_{3h} without correction for the nonlinearity of R_p.

5. EVALUATION OF THE MEASUREMENTS

In order to compare measurements on various nonlinear components, it is possible to make use of the expression for the third harmonic index expressed in dB as in Eq. (2). The exponent "n" can be determined from the dependence of the third harmonic voltage on U_{1f}.[1,2]

For the method described here it is, however, more suitable to introduce a relative scale derived directly from the voltage of the third harmonic and determined for the value of U_{1f}. Thus it is possible to limit the number of measurements. It is necessary to determine the exponent "n".

The third harmonic voltage is given by:[3]

$$U_{3h} = D \,.\, U_{1f}^{\,n} \tag{5}$$

where D is a constant characterising the nonlinearity.

$$D = \frac{U_{3h}}{U_{1f}^{\,n}} \tag{6}$$

If we choose $U_{1f} = 1$ V, then $D = U_{3h}$ for any "n" and the value of the nonlinearity can be expressed by the voltage of the third harmonic at $U_{1f} = 1$ V. In cases where it is not possible to apply the voltage 1 V to the measured resistor R_x, it is possible to approximate the values U_{3h} for 1 V from the dependence $U_{3h} = f(U_{1f})$ determined by measurement at a lower voltage.

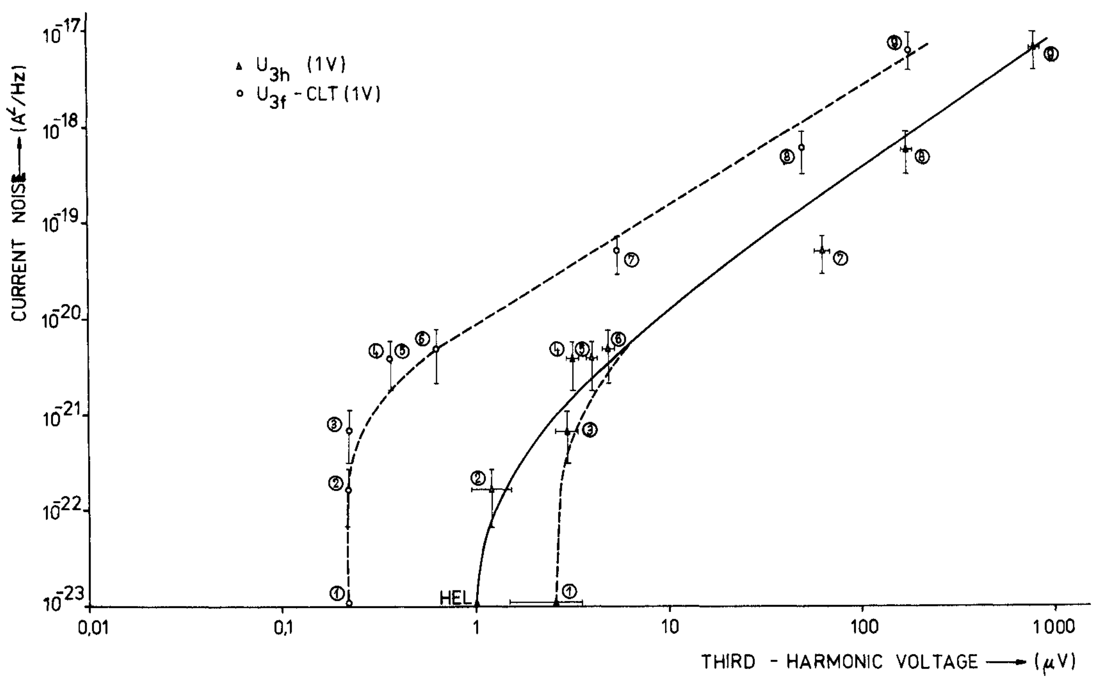


FIGURE 9 Dependence of the current noise on the third harmonic voltage.

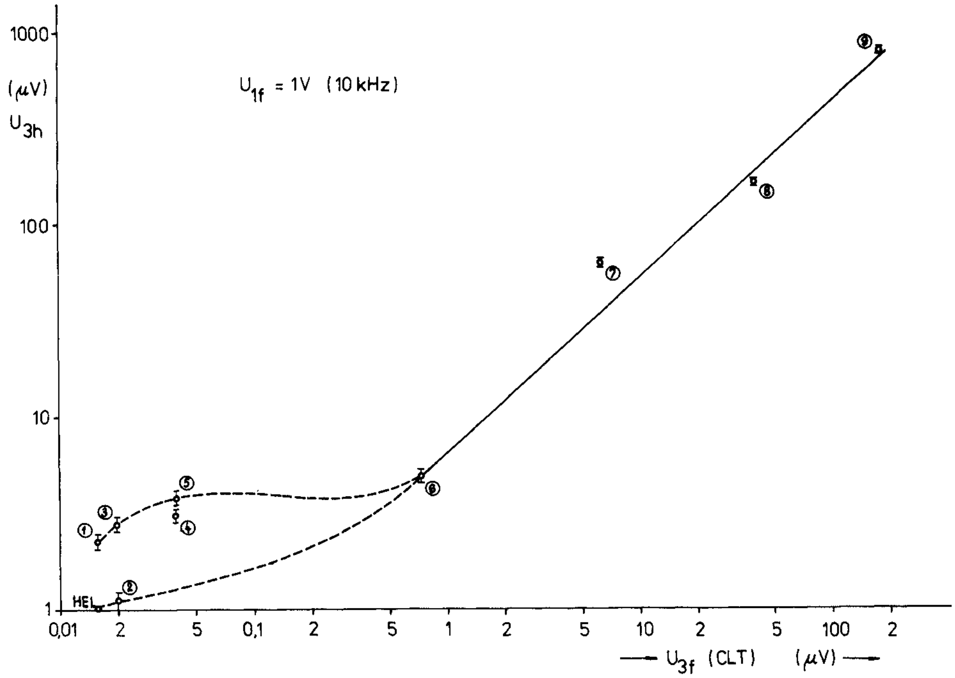


FIGURE 10 Dependence of the third harmonic U_{3h} (obtained by the described method) on U_{3f} (measured using the equipment CLT 1a).

6. EXPERIMENTAL RESULTS

To verify the method, some commercial resistors with values from 150 Ω to 220 Ω were randomly chosen and semiconductor layers PbTe and PbSeTe with differently arranged contacts, were also selected.

The measurement was performed both by the presented method and by the equipment CLT 1a[2] and the results were compared with the current noise measurements.

The dependence of the current noise on the third harmonic voltage is presented in Figure 9 and the accuracy of the measurements is indicated. The units of current noise (A^2/Hz) are common in physical models (see, for example, the conference on Physical Aspects of Noise in Electronic Devices, held at the University of Nottingham 11–13 November, 1968), where three papers were published using this criterion. The units are useful for comparing the nonlinearity or current noise, or more accurately the "energetic spectrum" of noise, whereas the noise index in dB is more suitable for a component classification. The dependence of the value of the nonlinearity U_{3h} (from the measurement by PAR 121 A) on the third harmonic voltage U_{3f} (measured by CLT 1a), is presented in Figure 10.

The specimens of the semiconductor layers with different arrangements of contacts of In and Au (see Figure 11), were measured at lower voltages in order to limit the influence of the temperature dependence of the samples. The resistance of the semiconductor samples was 650 Ω.

The dependence of the third harmonic voltages A, B and C on U_{1f} at 5000 Hz are shown in Figure 12. These correspond to the PbTe layers with contact arrangements as shown in Figure 11.

When the layer was aged at 150° for 4 hours, the nonlinearity changed as shown by the curve A in Figure 12.

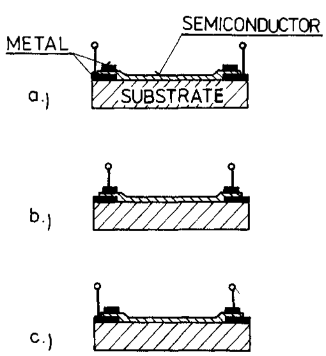


FIGURE 11 Different arrangements of contacts on the semiconductor layers.

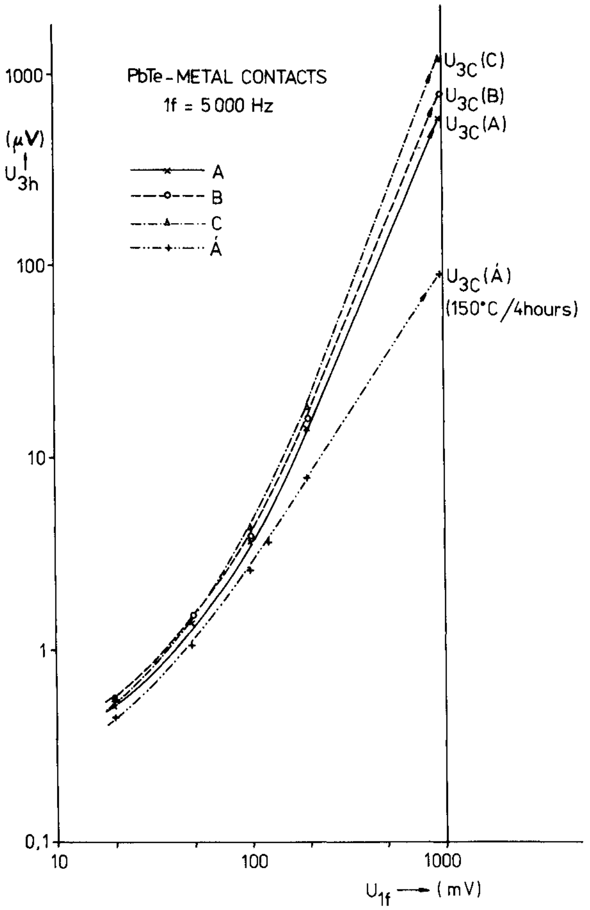


FIGURE 12 Nonlinearity of the system metal–PbTe–metal according to Figure 11.

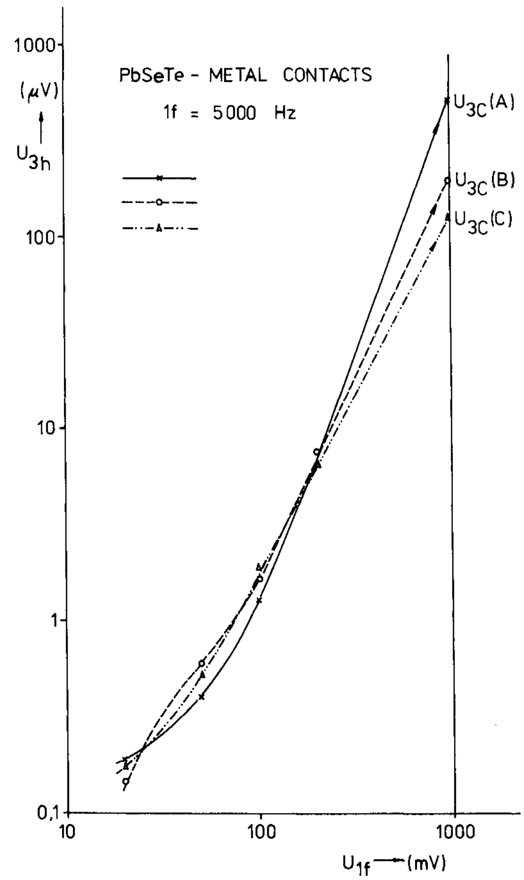


FIGURE 13 Nonlinearity of the system metal–PbSeTe–metal according to Figure 11.

For the PbSeTe layers with similar arrangements of the contacts as in Figure 11, the dependencies $U_{3h} = f(U_{1f})$ are shown in the graph in Figure 13.

The current noise for both types of layers with differently arranged contacts was found to be very small.

7. CONCLUSIONS

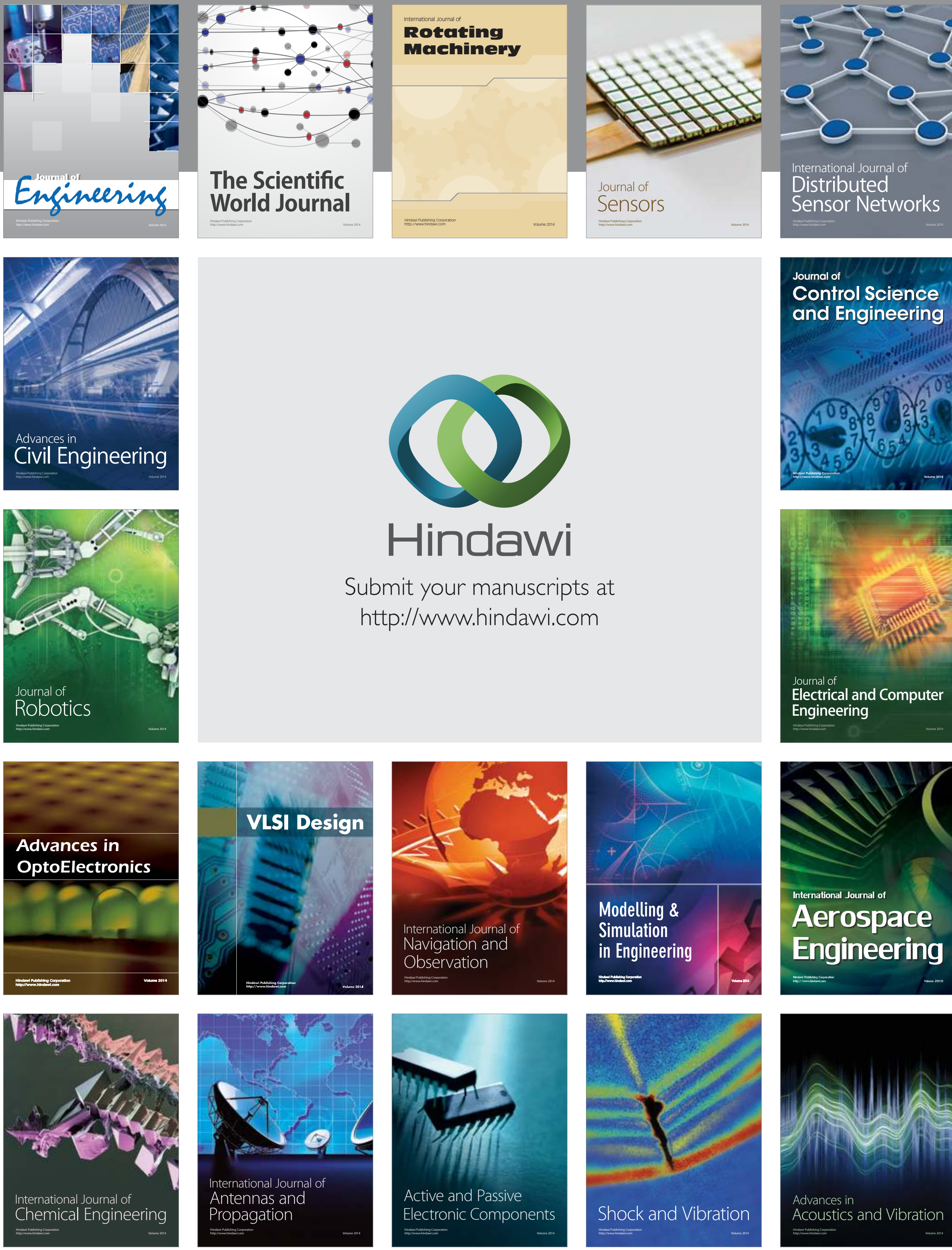
From the measurements performed on resistors and semiconductor layers with differently arranged contacts, it can be concluded that the method presented is suitable for a quantitative evaluation of different electronic components where the ohmic nonlinearity is small. Accuracy is higher than that which can be attained by the current noise measurements and is comparable with that attained using special single purpose equipment. Furthermore, this method allows measurement of the nonlinearities in a broad range of frequencies using simple laboratory apparatus and accessories.

For the evaluation of the measurements, it is advantageous to use the third harmonic voltage at 1 V the basic frequency. However, the values of nonlinearity derived from the third harmonic voltage cannot be taken as "absolute values" for nonlinearity, as the influence of the higher harmonics has not been taken into account. The method is suitable for comparison of different technological steps as was documented by measurements on a system metal–PbTe–metal, and metal–Pb–Te–metal where influence of ageing after 4 hours, is found.

The quantification of the nonlinear behaviour of the resistance enables prediction of component behaviour,[1,3] and is also suited to the control of the reproducibility of important steps in the technological processes of production of components.

REFERENCES

1. P. L. Kirby, "The nonlinearity measurement of fixed resistors", *Electronic Eng.*, **37**, 722 (1965).
2. Radiometer, "Manual for model Component Linearity Test Equipment CLT 1a", Copenhagen, Denmark.
3. J. C. Anderson and V. Ryšánek, "Prediction of the stability of thin film resistors", *The Radio and Electronic Eng.*, **39**, 321 (1970).
4. Princeton Research Corporation, "Manual for model 124 A – Lock-in-amplifiers. Accessories". Princeton, New Jersey.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