Harmonic testing pinpoints passive component flaws

Measuring nonlinearities in linear passive components provides a way of finding hidden flaws that can cause serious problems in complex equipment

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A fast, nondestructive testing method that saves both time and money can analyze a wide variety of nonlinearities in all types of passive electronic components.

Early detection is important because these minute flaws can indicate the presence of design or manufacturing weaknesses which later may lead to failures. These defects could not be discovered with conventional testing methods but were found by measuring the distortion they created.

The new test can uncover uneven film depositions, base material flaws, bad grindings and unreliable contacts in resistors; imperfect dielectrics and unreliable contacts in capacitors; and determine the hysteresis dissipation factor and hysteresis loss coefficient in magnetic components and materials.

The authors

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When high reliability is desired this test can be made part of an over-all screening program.

The cause of nonlinear distortion

The simplest linear passive component is the resistor. The ideal resistor should conform to Ohm's law where the current through the device is directly proportional to the voltage across it. If the resistor contains a nonlinearity, Ohm's law is no longer valid.

When a pure sinusoidal current flows through such a component, the voltage across it is distorted by any nonlinearities present. The distorted voltage can be considered the sum of a fundamental frequency voltage and a number of voltages at harmonic frequencies. The magnitude of these harmonic voltages can serve as a measure of the nonlinearity present in the component. For convenience, the third harmonic is usually chosen since it has the largest magnitude and therefore is easiest to measure.

This measuring principle is not restricted to resistors, but is also valid for the other passive, linear components, the capacitor and inductor. The nonlinearities arise from various causes in different components, coming either from the active material—the resistance material in resistors, the dielectric in capacitors and the magnetic material in inductors—or from the imperfect contact at the connections.

Certain nonlinearities are always present in the active material of components and the magnitude that can be tolerated depends on the eventual application of the component. For example, components with large nonlinearities must be avoided in circuits where intermodulation products between different frequencies are intolerable.

Other nonlinearities, especially sporadic ones

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that show up at contact points, are good indications of impending component failures.

Designing a nonlinearity tester

Nonlinearities in components can be measured with a bridge circuit, as was demonstrated by both C.E. Mulders and G.H. Millard.[1,2] One of the advantages of this approach is that the measuring voltage does not have to be filtered very well since the harmonics are partly balanced in the bridge circuit. But this method is time-consuming since the bridge must be rebalanced at the fundamental frequency for every test specimen.

Therefore a direct method has been developed that employs filters to suppress the fundamental frequency.[3] The test circuit is shown on page 95. The direct method is very fast—the test specimen is connected to the circuit, the test voltage applied and the results are available in less than a second. One difficulty with this method is that those components in the low-pass and bandpass filters situated nearest the test specimen must be free from nonlinearities or else the results will not be valid. An oscillator supplies the fundamental frequency for the test circuit; a variable attenuator enables the operator to set the test voltage at a suitable value. A power amplifier with two different output impedances is included in the circuit so a broad range of component values can be tested without loading down the oscillator. Harmonics generated by the oscillator and amplifier are eliminated with a low-pass filter.

When the test specimen is connected and voltage applied a bandpass filter attenuates the fundamental frequency and higher harmonics. A voltmeter reads the third-harmonic voltage directly.

The input impedance of the bandpass filter is capacitive. This allows a tapped inductor to be inserted between the low-pass filter and the test specimen to provide a means of possibly increasing the test voltage across high-resistance and capacitive test specimens. With this arrangement, the test voltage may be increased up to about 300 volts.

When studying very low-resistance test specimens, such as contacts, it may be advantageous to modify the test circuit according to the diagram on page 95. The resonant circuit is tuned to the fundamental frequency and produces a large increase in the test current while reducing the influence of harmonics from the amplifier. It is possible to determine the impedance of the test

Harmonics in a homogeneous material

If a sinusoidal current, I, flows through a nonlinear element, the voltage that appears across the element will contain harmonics. Only one of the harmonics need be considered since they all are a measure of the nonlinearities present. The third harmonic, E_3, is usually chosen since its magnitude is the largest. If the current is increased resulting in a corresponding increase in the current density in the component, the third-harmonic voltage, E_3, will increase in proportion to the current density, J^n, where n, an exponent characteristic of the material, is often constant over a wide current range. In many cases, n has a value of approximately three.

If two equal, nonlinear elements are connected in parallel and each carries a current, I, a third-harmonic voltage, E_3, is generated in each. The voltages have the same phase relationship and the third-harmonic voltage for the parallel combination will be E_3. E_3 is determined by the stress in the material, characterized by the current density, $J = I/A$ where A is the cross-sectional area of the component.

If the same two elements are connected in series the same current density appears in each. Again third-harmonic voltages are generated in each of the components, but this time they add. The resulting third-harmonic voltage is proportional to the total length of the nonlinear element. It is therefore possible to develop a general expression for the third-harmonic voltage generated in a nonlinear element that has a constant cross section and is made of a homogeneous material. This expression is

$$E_3 = C_3 \, l \, J^n \quad (1)$$

where C_3 is a characteristic constant for the material
l = length of the element
J = current density (= I/A)
A = cross-sectional area of the element
n = constant characteristic of the material

Substituting $J = V/\rho l$, where ρ is the material's resistivity, into equation 1 yields

$$E_3/l = C_3/\rho^n \, (V/l)^n \quad (2)$$

From this equation, it is apparent that the third-harmonic voltage generated per unit length is equal to a constant times the nth power of the applied voltage per unit length.

Properties of spiraled resistors. In the figure below, the resistor element has a diameter d and a thickness t. The length is l'. Before the spiral is made, the resistance is

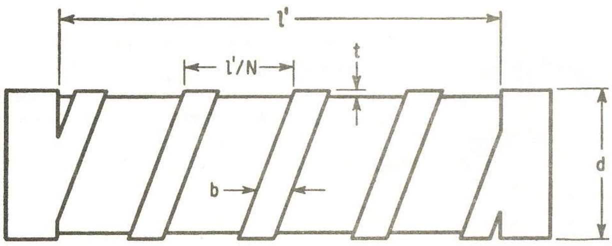
$$R = \rho l'/A_1 = \rho l'/\pi dt \quad (3)$$

where ρ is the material's resistivity and A_1 is the cross-sectional area.

When the resistor is ground, the resistance element becomes a spiral with N turns. The resistance is now

$$R' = \rho \pi d \, N^2/kl't \quad (4)$$

where
l'/N is the pitch between turns
$kl'/N = b$ is the true width of the film band
πdN is the length of the film band
$kl't/N$ is the area of the film band



specimen by reading the value of the fundamental voltage across it.

A switch turns off the voltage to the test specimen terminals during hook-up. This is necessary, especially when testing capacitive components or low-resistance specimens in the resonant circuit, since current transients could otherwise develop which might create high voltages causing premature component failure. The low-pass filter suppresses any current transients that may occur.

The original tester had two different fundamental frequencies, 10 and 50 kilohertz. However, this was reduced to one frequency—10 khz—in the later models.

In the test circuit described, the impedance of the specimen and the input impedance, Z_1, of the bandpass filter at the third-harmonic frequency, $3f_1$, form a voltage divider. In the test equipment developed, the filter's input impedance is resistive and equal to 300 ohms.

The general equation for the third-harmonic voltage, E_3, produced by component nonlinearities is

$$E_3 = V_3 (1 + Z_x/R)$$

where V_3 is the third-harmonic voltage measured at the filter input terminals, Z_x is the impedance of the test specimen and R is the input impedance of the filter. For resistors, capacitors and inductors this equation becomes, respectively

$$E_{3R} = V_3 (1 + R_x/R);$$

$$E_{3C} = V_3 \sqrt{1 + 1/(9\omega_1 C_x^2 R^2)};$$

$$E_{3L} = V_3 \sqrt{1 + \frac{9\omega_1 L_x^2}{R^2}}$$

where $\omega_1 = 2\pi$ times the fundamental frequency, f_1, and R_x, C_x and L_x are the values of the respective test specimens.

In some cases, it is convenient to express the nonlinearity logarithmically, as in the case of third-harmonic attenuation, which may be written

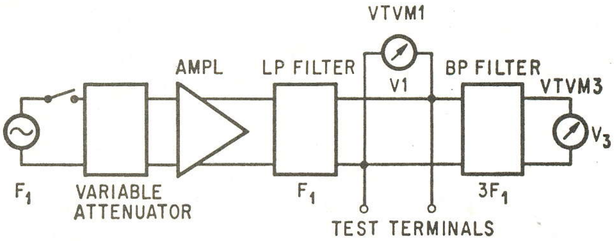
$$A_3 = 20 \log V_1/E_3 \text{ (in decibels)}$$

Third-harmonic attenuation up to 160 db can be measured in the test equipment developed when the test circuit and test specimen are matched.

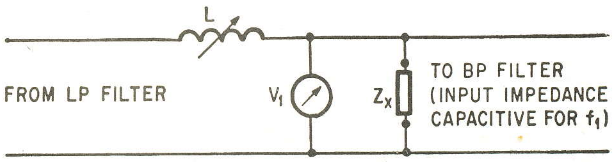
Interesting side effect

An interesting aspect of this method of testing components is the information obtained about spiraled resistors. Such a resistor is made by cutting a cylindrical film resistor into a spiral, increasing its effective length and consequently its resistance. When it is ground, the resistance element and current path become a spiral with N turns. It has been determined that, of two resistors made with identical resistive film, a spiraled resistor has a lower nonlinearity content than an unspiraled one. Also, there is a marked contrast in nonlinearity between spiraled resistors having a different number of turns. The table on page 96 compares some of these effects.

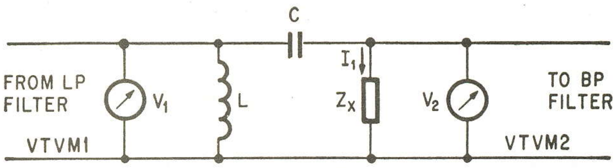
The table also shows that if the design param-



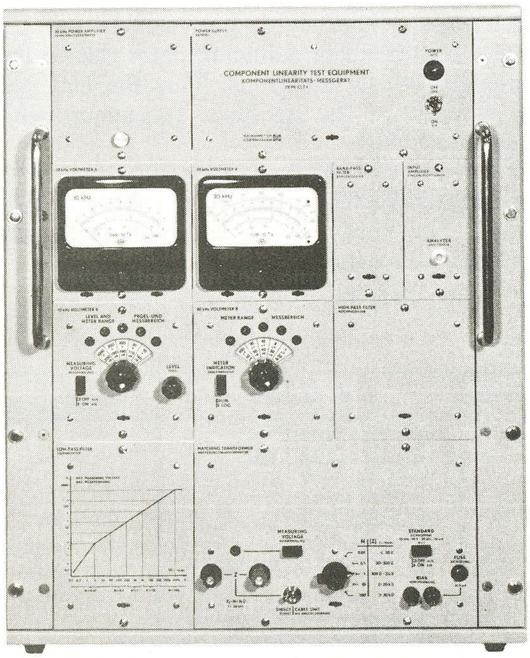
Nonlinearity measuring circuit measures the harmonic voltages generated by a component. Any harmonics generated by the drive amplifier are kept from reaching the component under test by the low-pass filter. The bandpass filter allows only the third-harmonic voltage to reach the voltmeter.



Test voltage control is increased by placing variable inductor in series with test specimens. This makes it easier to measure the nonlinearities in such specimens with the third-harmonic method.



Low-resistance specimens are easier to test if a resonant circuit is added to the test circuit. In this way, the current through these components is increased and the influence of any nonlinearities in the amplifier is reduced.



Nonlinearity tester, has a fundamental frequency of 10 kilohertz. Amplitude of the third-harmonic voltage is read directly from the meter on the instrument's front panel.

eters of the resistor are not known, it is impossible to accurately determine whether a single resistor is faulty or not from its nonlinearity level. It is even hazardous to draw a conclusion about a specific resistor type from the mean value of the nonlinearity for a batch of resistors. A high mean value of nonlinearity may only indicate a thin resistive film since thin films are more sensitive to oxidation and exhibit poor long-term stability. On the other hand, narrow film bands are more easily exposed to damage. Any small unevenness in the film may cause constrictions which lead to large nonlinearities and can result in local overheating.

Because of this, the distribution of nonlinearities has been found to be more valuable for judging the quality of a resistor type than for finding defects in individual resistors.

How the other methods fare

Two other methods for investigating deviations from ideal resistor behavior are the voltage coefficient and current noise techniques.

The voltage coefficient is

$$K_r = \frac{R_1 - R_{0.1}}{R_{0.1}} \times \frac{1}{V_1 - V_{0.1}} \times 100\%$$

where R_1 is the resistance at the rated voltage V_1 and $R_{0.1}$ is the resistance at 10% of the rated voltage, $V_{0.1}$.

This method is only suitable for resistors with high voltage coefficients since the temperature dependence of the resistor easily influences the results. Even so, Mulders and Millard have shown that it is possible to obtain the voltage coefficient by nonlinearity measurement. This measurement is simpler, more sensitive and more accurate than the direct resistance-voltage method.

The current noise technique is based on the fact that a noise voltage exists between the end terminals of a conductor or semiconductor due to thermal movement of the electrons. This thermal noise is independent of the absolute frequency within a given bandwidth.

If a direct current flows through a resistor made of a semiconducting material, the thermal noise increases. The root-mean-square value of the current noise can be written as

$$E_n = K_n F(f) V^a$$

where K_n = a constant for the resistor
V = the applied voltage
a = exponent between 0.7 and 1.1, often 1.0
$F(f) \approx (\log f_2/f_1)^{1/2}$

The current noise may also be given as the current noise index, N.I. = 20 log E_n/V where E_n is the rms value of the open circuit current noise in microvolts measured over the frequency decade ($f_2/f_1 = 10$), centered at 1,000 hertz; and V is the applied d-c voltage.

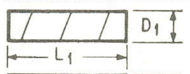
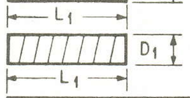
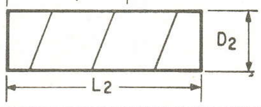
Theoretically, however, the same information that can be obtained from the current noise measurements can be gotten from measuring the third-harmonic voltage. But the third-harmonic measurements can be made much faster since a stabilizing time is required when making current noise measurements. In addition, the third-harmonic voltage increases when the applied current is increased, rapidly outdistancing system noise. With the current noise method, it is often necessary to correct the measured value for the influence of system noise.

Also, the nonlinearity measuring method is not sensitive to external fields and the reading is much more stable during measurement than the noise reading. This is important for production testing. When there is little mismatch between the test specimen and the test set, the sensitivity of the nonlinearity test method is as good as the current noise method for film resistors up to several hundred kilohms. But, unlike the current noise method, nonlinearity measurements can be made on resistances as low as one ohm.

Bad spirals

During the grinding of a film resistor to make the spiral, a flaw often develops which results in a conducting bridge of resistive material between turns. These bridges lead to high current densities that cause the resistor to show poor stability or even result in an open circuit. Measuring the third-harmonic voltage generated in a resistor can lead to the discovery of flaws of this type.

Consider the spiral resistor shown on page 97, which has a bridge between two adjacent turns. For simplicity, only a single bridge is considered and it is assumed that it has a constant area, A_2. The resistance of one turn of the spiral is $R_1 = R'/N$,

TYPE	DIMENSIONS	FILM THICKNESS	LENGTH	NUMBER OF TURNS	E_3 / E_{3A}
A		t_1	L_1	N_1	1
B		t_2	L_1	N_2	$(t_1/t_2)^{\frac{n-1}{2}} = (N_1/N_2)^{n-1}$
C		t_1	L_2	N_1	$(L_1/L_2)^{n-1}$

RESISTANCE$_{SPIRALLED}$ = $\frac{\rho \pi d N^2}{K l' t}$

E_{3A} = THIRD-HARMONIC VOLTAGE OF TYPE A, ρ = RESISTIVITY
n = CHARACTERISTIC EXPONENT OF RESISTIVE MATERIAL, l' = SPIRALLED LENGTH
N = NUMBER OF SPIRAL TURNS, t = FILM THICKNESS, d = SPIRAL DIAMETER

where R′ is the total resistance of a spiraled resistor of N turns, defined by equation 4 in the panel on page 94.

The resistance of the bridge is

$$R_2 = \frac{\rho\,(1 - k)\,l'}{NA_2}$$

If $R_2/R_1 = x$, then the resistance of the turn bridged by R_2 can be expressed as

$$R'_1 = \left(\frac{x}{1 + x}\right) R_1$$

If the bridge is removed, the relative increase in the resistance that occurs is

$$\frac{\Delta R}{R} = 1/N\,(1 + x).$$

It is now possible to compare the increase in nonlinearity caused by the bridging with the nonlinearity present without bridging. The ratio between the third harmonic in a bridged resistor and that in a faultless resistor is approximately

$$\frac{E_{3tot}}{E_{03}} \approx 1 + \frac{x^n}{(1 + x)^{n+1}}\;\frac{N^{n-2}}{(1 - k)^{n-1}}\left(\frac{\pi d}{l'}\right)^{n-1}$$

An example of the effects of such a bridge is demonstrated quantitatively with a spiraled resistor having the following characteristics:

$\frac{\text{circumference}}{\text{length}}$	$\frac{\pi d}{l'} \approx 1$
number of turns	$N = 10$
part of pitch ground away	$(1 - k) = 0.3$
characteristic exponent	$n = 3$
bridge resistance	$R_2 = R_1 = R/N, \quad x = 1$

Under these conditions, the bridging introduces a resistance decrease of

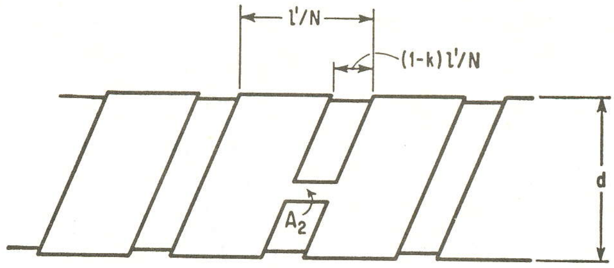
$$\frac{\Delta R}{R} = 1/10\,(1 + 1) = 0.05, \quad \text{or } 5\%$$

More significant, however, is the amount the bridging increases the third harmonic generated in the resistor. According to the equation above, this amounts to

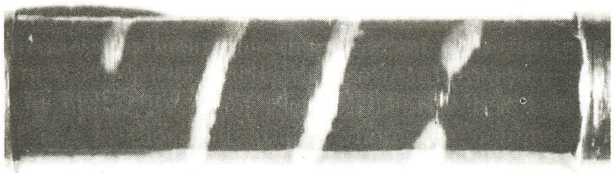
$$\frac{E_{3\,tot}}{E_{03}} \approx 1 + (1/16)\,(10/0.3^2)\,(1) \approx 8 \text{ times}$$

These calculations also serve to emphasize the degree of overheating that can result from bridging. In this example, the current density in the bridge between the turns is 16.7 times that in the normal resistance film.

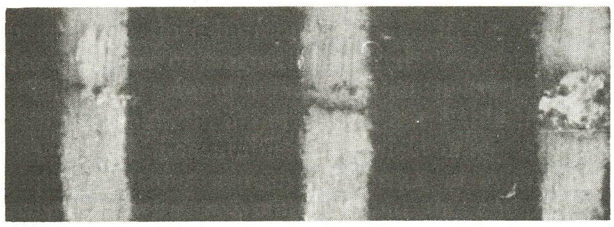
Other sources of measurable nonlinearities in film resistors are the unreliable contacts between the end termination and the film or between the end cap and the connecting wire.[4] These problems occur mostly in low-valued resistors (less than 1,000 ohms) and often show up after soldering. An unreliable contact between the end cap and connecting wire is especially hazardous because it can result in an open circuit.



Spiral resistor with a conducting bridge between two of its adjacent turns. The area of the resistive bridge is assumed to be constant and equal to A_2. The pitch of the spiral is l′/N.



Example of carbon film resistor with conducting bridge detected by the nonlinearity method. Where the dark resistive film crosses the ground spiral gap of the resistor (light area) current flow causes the nonlinearity.



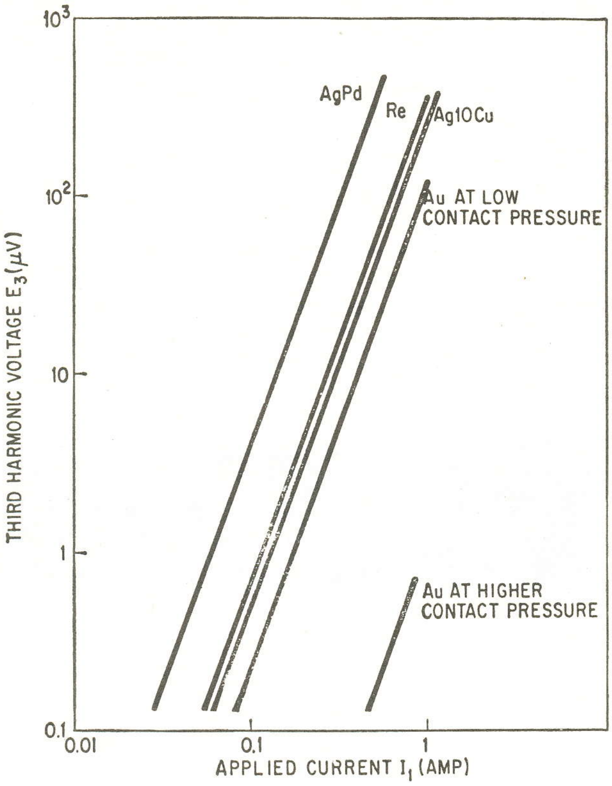
Cracks in the resistor body can also cause conductive bridges in spiral resistors. Although this type of bridge does not appear to be as clear as the previous example, chances for component failure are as great.

Nonlinearities in other resistive components

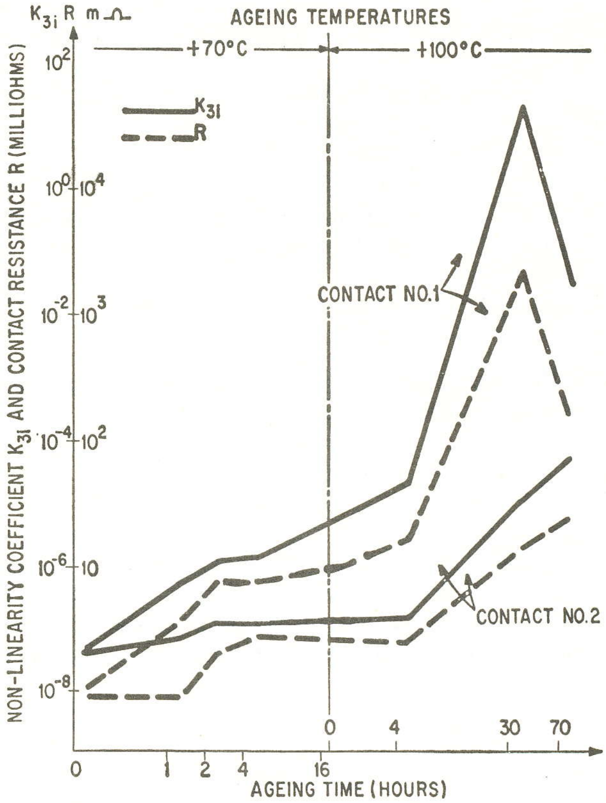
As a rule, composition resistors have much greater nonlinearities than carbon film resistors. The composition resistors also manifest more current noise. Even so, the nonlinearity test can be of use in those situations where the nonlinearity disturbs the function of equipment in which the resistors are to be used.

On the other hand, wirewound resistors made of a nonferromagnetic resistance material, with good contacts and adequate insulation between wire turns, are characterized by a very low third-harmonic voltage difficult to measure. It is possible though, for such wirewound resistors to have a measurable third-harmonic voltage if the connection wires are of magnetic material.

Thus one cannot conclude that resistors made with nonmagnetic materials are unreliable because they have a measurable harmonic voltage. For example, consider a resistor design in which the resistance wire is wound around the end of the connection wire and welded to it. Any spurious



Plot of third-harmonic voltage as a function of applied current demonstrates that even gold contacts can yield large nonlinearities. In this case, they result from low contact pressure.



Nonlinearity and contact resistance increase with age as shown by a plot of these two characteristics over a period of time.

contacts between the unconnected turns and the wire can generate third-harmonic voltages. The chances of an open circuit are slight, but a small resistance instability is possible.

Ferromagnetic resistance materials contain systematic nonlinearities. Resistors made with this material will produce a third-harmonic voltage that varies as the square of the applied voltage. The nonlinearities can be high in certain cases and will mask those caused by bad contacts or intermittent contacts between wire turns.

Potentiometer failures

Most of the previous remarks about wirewound resistors are also valid for potentiometers. However, potentiometers possess other failure mechanisms. A decrease in total resistance can occur if particles are worn off the winding to form a shunt between turns. Another problem is an increase in contact resistance between the winding and the slide wire due to oxidation. Both of these problems can be detected with normal resistance measurements; but with the nonlinearity technique it becomes possible to distinguish between galvanic resistance changes and changes caused by buildup of semiconducting films.

Some potentiometers are made with taps by connecting wire welded to resistance wire along the length of the winding. The quality of these welds varies considerably. Measurement of the third harmonic can easily detect bad welds.

Making contact

A good contact should be a purely metallic connection between two parts of a circuit. It should demonstrate a constant, low value of contact resistance, independent of current and time.

Chemical compounds build up on metal contact surfaces exposed to the atmosphere. These compounds, oxides and sulphides, for example, are semiconductive and tend to increase contact resistance. They have a nonlinear current-voltage characteristic that can be exploited to detect contamination by nonlinear measurements.

The circuit shown on page 95 measured the third-harmonic voltage generated by a number of relay contacts made of different materials. The results, shown above, indicate that contact even between electrodes of pure gold has measurable nonlinearity if the contact pressure is low. For each material, the third-harmonic voltage is proportional to the cube of the applied current:

$$E_3 = K_{3i} I_1^3$$

where the coefficient K_{31} characterizes the nonlinearity of the contact.

A test was made with contacts between two copper wires. Measurements were made of the contact coefficient with newly polished surfaces after aging in dry heat for varying time periods. The graph above shows how both the contact resistance and the nonlinearity increased with aging.

A batch of cold-solder joints was made by joining together oxidized copper wires without the aid of flux. These joints were aged in the same way as the copper contacts and the results of the nonlinearity measurements were similar.

Nonlinearity measurement is, therefore, a method for investigating contacts in such components as resistors and capacitors where it is difficult, if not impossible, to make direct measurements of contact resistance.

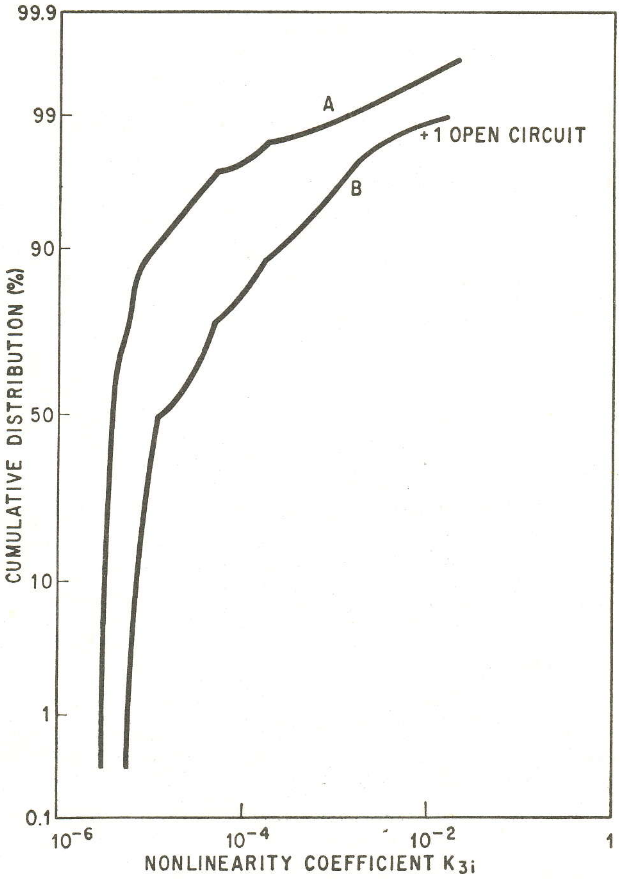
Finding capacitor flaws

Nonlinearities in capacitors can be separated into two groups—those that occur in the connections or electrodes and those in the dielectric.

Nonlinearities in connections and electrodes are caused by bad contacts from cold soldering, unreliable contacts due to low contact pressure or unsuitable materials, badly welded contacts and nonlinearities in the semiconducting materials.

Contact flaws have the greatest influence on the reliability of equipment in which capacitors are used. These faults are difficult to find before the capacitors are built into equipment where they can affect the operation of the device as the contact surfaces become oxidized with age.

Dielectric nonlinearities are caused by the use of materials with voltage-dependent dielectric constants, ferromagnetic particles in the dielectric, ionization of the dielectric by a high a-c voltage[5] or vibration of the electrodes.[6]



Distribution of nonlinearities in a group of capacitors changes considerably after aging. The nonlinearities were measured before (curve A) and after aging (curve B).

A variety of other methods exist for testing capacitor contacts, including one introduced in Germany about 15 years ago.[7] Unfortunately, with this method, one cannot obtain quantitative information about the increase in contact resistance. Other methods lack the sensitivity of the nonlinearity technique.

A batch of capacitors was measured for nonlinearity and the cumulative distribution plotted, as shown in curve A of the graph below. Some of the capacitators with large nonlinearities were dissected for further study. It was discovered that the connection to the positive terminal was made by a piece of copper wire pressed against the rivet by a rubber washer on the capacitor lid and the pressure exerted by this contact was inadequate. As the rubber ages, the contact pressure may be reduced still more and contact faults soon develop. As a test, the capacitors were stored at room temperature for six months and the nonlinearities measured again. The results, curve B of the graph, demonstrate that nonlinearities increased considerably; in fact, one open circuit was found. The first measurements were sufficient to reject this type of capacitor although the manufacturer claimed it had high reliability and long life.

Oxide film on contacts usually breaks down when capacitors are operated at high a-c voltages. As a result, capacitors with contact nonlinearities may function well for long periods. However, if the capacitors are operated at low a-c voltages, no breakdown occurs even if the capacitors are simultaneously subjected to high d-c voltages. The capacitors are charged to the d-c voltage level through the contact resistance and there is no d-c voltage drop across the contact. But the capacitor acts as an open circuit to weak superimposed a-c signals.

A test of a number of plastic-foil capacitors, encapsulated in metal cans, resulted in a fairly high percentage of nonlinearity. Dissecting the capacitor uncovered the design weakness—a cold-solder joint that resulted from joining to untinned leads.

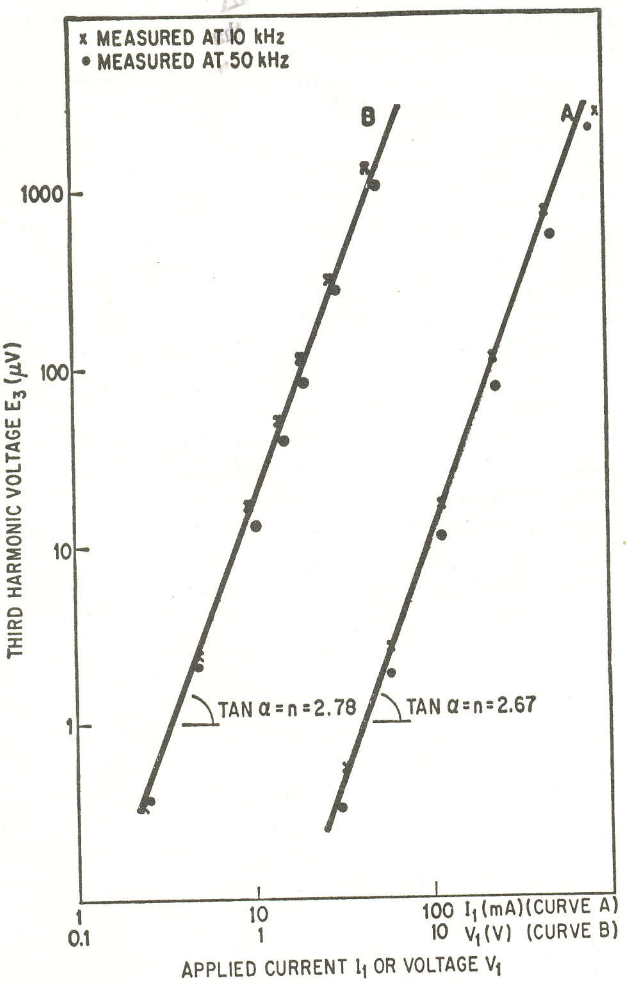
Another method of finding defective components is to subject them to a mechanical shock and test for variations in nonlinearity. If the component is connected to the test equipment and tapped, a varying measurement may indicate a faulty contact inside the component. In some cases, however, movements in the dielectric may give rise to small changes in nonlinearity.

Ceramic and dry tantalum oxide capacitors are examples of capacitors in which systematic nonlinearities are inherent. The third-harmonic voltage for each is shown in the graph on page 100. For a ceramic capacitor, the nonlinearity seems to be voltage-dependent according to the equation

$$E_3 = K_{3v} V^n.$$

Experimentally, n was found to be 2.78.

For the tantalum oxide capacitor, in which nonlinearities are believed to originate in the contact



Third-harmonic voltage is a function of current in a dry tantalum oxide capacitor (A) and a function of voltage in a ceramic capacitor (B).

material, nonlinearity appears to be current-dependent according to the relation

$$E_3 = K_{3i} V^n$$

where n is 2.67.

In both cases, the results were the same at both 10 and 50 khz. To keep the current constant, the voltage at 50 khz was one-fifth of that at 10 khz.

Testing magnetic materials

The inductance and equivalent loss resistance of an inductor with a magnetic core gains when alternating current through the winding is increased. In addition, odd harmonics are generated. These deviations from ideal behavior have importance in certain applications. In high voltage filters, for example, nonlinear distortion not only generates odd harmonics but also causes intermodulation products between different frequencies. In other applications, increases in the loss resistance or dissipation factor may be more important.

E. Peterson's work[8] led to the expression

$$E_3/V_1 = 0.6 \tan \delta_h$$

where E_3 = the generated third-harmonic voltage
V_1 = the applied voltage
$\tan \delta_h = R_h/\omega_1 L$, the hysteresis dissipation factor
$R_h = \Delta R$ = the increase in the loss resistance of the inductor due to hysteresis losses

Because of the direct relationship among changes in inductance, resistance and third-harmonic generation, measuring any one of these factors yields data on the other two.

Determining the hysteresis dissipation factor by the nonlinearity method gives results within 10% of those attained with conventional bridge circuits. Although both methods are suitable, the nonlinearity method provides more information on the generation of harmonics and intermodulation.

The nonlinearity method also furnishes a faster way to determine the hysteresis loss coefficient, eliminating the need to measure the dissipation factor at two different flux densities with an a-c bridge.

The nonlinearity method has an additional advantage of being insensitive to air gap variations.

The nonlinearity measurement principle has other uses besides studying nonlinearities in passive, linear components. N. I. Meyer and T. Guldbrandsen[9] employed the same principle to study distribution of impurities in semiconductor crystals.

The nonlinearity principle has also been used to detect unreliable contacts made to semiconductors.

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