CONTENTS

METHOD OF MEASUREMENT OF NON-LINEARITY IN RESISTORS

1 Scope

Non-linearity testing is a method for evaluation of the integrity of a resistive element. It may be applied as an effective inline screening method suitable to detect and eliminate potential infant mortality failures in passive components. The method is fairly rapid, convenient, and the associated equipment is relatively inexpensive.

Typical effects causing non-linearity on resistors are e.g. inhomogeneous spots within a resistive film, traces of film left in the spiraling grooves, or contact instability between connecting lead or termination and the resistive element.

This international standard specifies a method of measurement and associated test conditions for determining the magnitude of non-linear distortion generated in a resistor. This method shall be applied if prescribed by a relevant component specification, or if agreed between a customer and a manufacturer.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendment) applies.

IEC 60068-1, *Environmental testing - Part 1: General and guidance*

3 Terms and definitions

Non-linearity

deviation of a component's impedance from Ohm's law, resulting in voltage of harmonic frequencies when subjected to sinusoidal current

Third harmonic ratio
A_3

ratio of the fundamental voltage over the e.m.f. of the third harmonic, expressed in dB

NOTE The third harmonic ratio has been addressed before as third harmonic attenuation. This historic convention is misleading as it wrongly suggests harmonic frequencies originating from the test equipment being attenuated or filtered by the components under test. The misleading term should therefore be avoided.

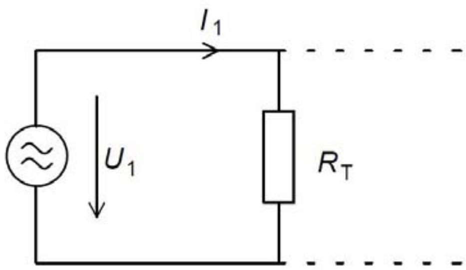
4 Method of measurement

4.1 Measurement principle

A pure sinusoidal current is passed through the component under test. If the impedance of the component is not perfectly linear, the voltage across the component will be distorted and contain harmonics. One or more of these harmonics can be measured and the magnitude of these distortions is a measure of the non-linearity in the component. It is recommended to measure the third harmonic, as this is the dominant one.

The third harmonic voltage appearing across a component must be separated from the fundamental voltage and from any other harmonic voltage for the measurement. This is accomplished by a filter circuit letting the harmonic voltage pass through while featuring very high impedance at the fundamental frequency. Likewise, the generator of the fundamental frequency needs to feature very high impedance ath the third harmonic frequency in order not to act as a load to the generated distortions.

Hence the equivalent circuit of the generator part operating at the fundamental frequency is quite simple as shown in Figure 1.

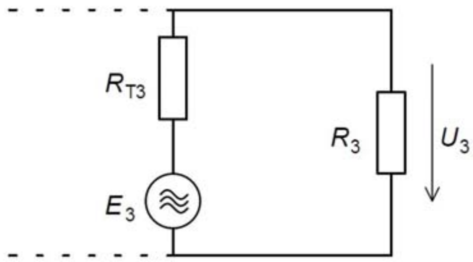


Key:

I_1	Sinusoidal current
U_1	Fundamental voltage across the resistor under test
R_T	Impedance of the resistor under test at the fundamental frequency

Figure 1 — Equivalent circuit at the fundarnenlal frequency.

The equivalent circuit for the third harmonic frequcency is built around the test specimen represented by a linear impedance with a zero-impedance harmonic generator in series. This signal source loads the measuring system represented by its impedance as seen from the test terminals, see Figure 2.



Key:

E_3	e.m.f. of the third harmonic
R_{T3}	Impedance of the resistor under test at the third harmonic frequency
R_3	Impedance of the measuring circuit at the third harmonic frequency, seen from the test terminals
U_3	Third harmonic voltage

Figure 2 — Equivalent circuit at the third harmonic frequency.

In this circuit the e.m.f. of the third harmonic E_3 is divided to the measurable third harmonic voltage U_3

$$U_3 = \frac{R_3}{R_3 + R_{T3}} \cdot U_3 \qquad (1)$$

Hence the e.m.f. of the third harmonic E_3 in the component can be determined by

$$E_3 = \left(1 + \frac{R_{T3}}{R_3}\right) \cdot U_3 \qquad (2)$$

The corrective term Δ for the reduction of U_3 to the origin E_3 is

$$\Delta = 20 \cdot \log_{10}\left(1 + \frac{R_{T3}}{R_3}\right) \qquad (3)$$

In many cases it can be shown for a range of resistors under test that the impedance R_{T3} at the third harmonic frequency is equal or very close to the impedance R_T at the fundamental frequency. Then the corrective term Δ in decibels is

$$\Delta = 20 \cdot \log_{10}\left(1 + \frac{R_T}{R_3}\right) \tag{4}$$

NOTE For fixed film resistors this equality of RT3 and RT can generally be assumed with sufficient accuracy.

Numeric values for the corrective term Δ can be obtained from Figure 3 or for specific sets of impedance R_3 and specimen resistance R_T from Table 1.

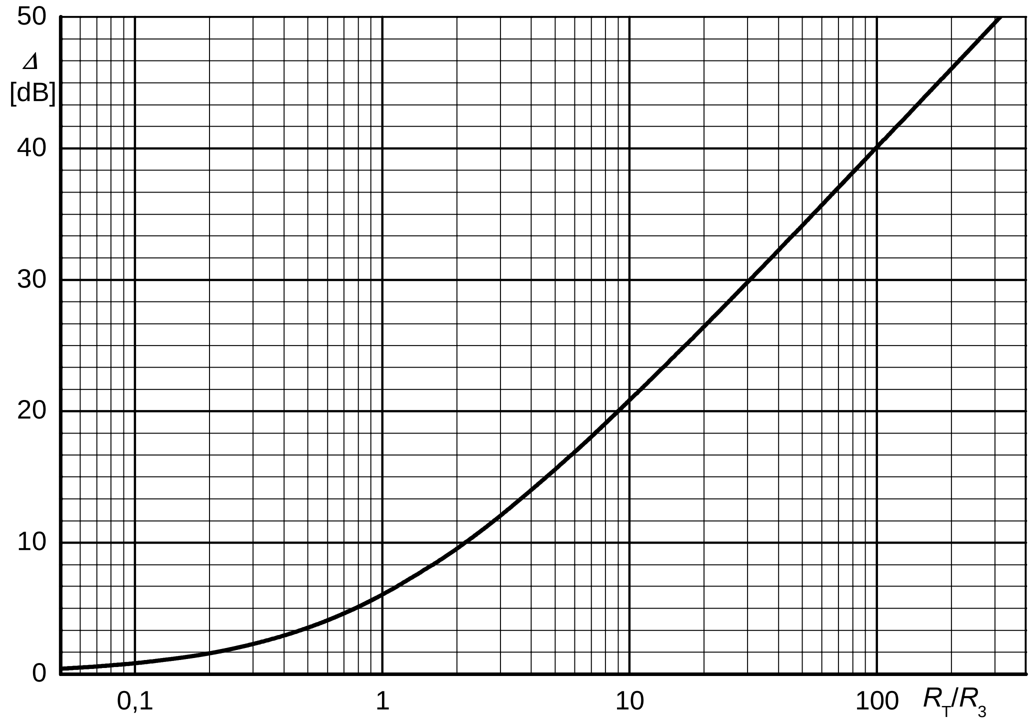


Figure 3 — Correction Term Δ

A suitable range for the fundamental frequency f_1 for measurements on resistors is between 10 kHz and 40 kHz. This frequency range enables the test circuit to be set up without too much difficulty.

NOTE Another method is using a bridge which is balanced at the fundamental frequency, where the harmonics appear across the bridge diagonal. This method requires individual balancing of the bridge for each specimen, which may be suitable for occasional use in a laboratory environment.

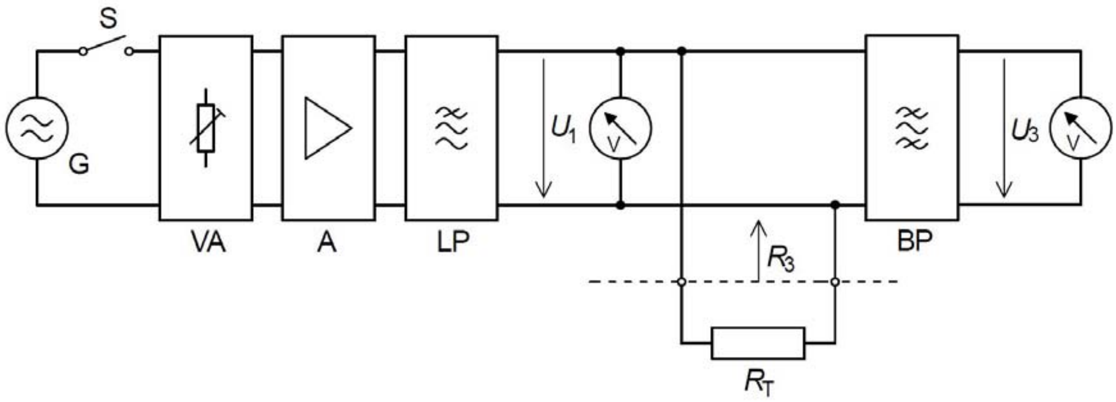
4.2 Measuring circuit

Figure 4 shows a block schematic of a suitable measuring circuit.

A distortion-free impedance matching device may be used to switch R_3 in order to achieve good matching to the test specimen R_T. Examples of suitable values of R_3 are 10 Ω; 100 Ω; 1 000 Ω; 10 000 Ω and 100 000 Ω, which values are used for specifying the test conditions in Table 1.

The suitability of the measuring circuit for measurements on resistors with resistance values covering a wide range depends on the lowest and highest available impedance R_3.of the circuit. The range of values for R_3 proposed above grants suitability for measurements on resistors with resistance values between 1 Ω and at least 10 MΩ.

However, there is an overriding influence of the correcting term Δ depending on the ratio of resistance under test R_T over impedance R_3, see Table 1 and Figure 3.



Key:

G	Oscillator, at the fundamental frequency f_1
S	Switch for applying the test signal to the test specimen
VA	Variable attenuator
A	Power amplifier
LP	Low-pass filter
U_1	R.M.S. voltage at the fundamental frequency f_1
BP	Band-pass filter
U_3	R.M.S. voltage at the third harmonic frequency f_3
R_T	Resistor under test
R_3	Impedance of the measuring circuit at the third harmonic frequency f_3, seen from the test terminals.

Figure 4 — Block schematic of a suitable measuring system

4.3 Requirements to the measuring system

4.3.1 Measuring frequency

The fundamental frequency f_1 shall be 10 kHz and thus the third harmonic frequency f_3 shall be 30 kHz, unless otherwise specified in the relevant component specification.

4.3.2 Noise level of the measuring system

The noise level referred to the test terminals shall not be higher than 0,2 µV at R_3 = 1 000 Ω.

4.3.3 Third harmonic ratio of the measuring system

The third harmonic ratio $20 \cdot \log_{10}(U_1/E_3)$ shall be higher than 140 dB for most of the impedance range when the required dissipation P is applied to a virtually linear component.

The required dissipation is 0,25 VA, as given in Table 1, or a value prescribed by the relevant component specification, e.g with reference to the rated dissipation.

4.3.4 Power amplifier

The power amplifier shall be capable of delivering an apparent power of four times the required dissipation into a resistive component under test, in order to ensure sufficient linearity.

Hence the power amplifier shall be capable of delivering an apparent power of 1 VA if the required dissipation is 0,25 VA as given in Table 1.

4.3.5 Voltmeter

The error of the voltmeter for measurement of the voltage U_1 at the fundamental frequency voltmeter shall be less than 5 % of its full scale deflection.

The error of the voltmeter for measurement of the voltage U_3 at the third harmonic frequency shall be less than 10 % of its full scale deflection.

4.3.6 Filter

The cut-off frequency of the low-pass filter shall be immediately above the fundamental freuqnecy f_1.

The band-pass filter shall permit the third-harmonic frequency f_3 to pass through, while it shall provide very high attenuation at the fundamental frequency f_1.

Precautions shall be taken to avoid non-linear distortion from the components near the test specimen in the low-pass and band-pass filters. The filter inductors for instance shall not contain cores of magnetic material.

4.3.7 Test fixture

The test fixture for the specimen R_T shall be capable of providing safe electrical connection.

4.4 Verification of the measuring system

Reference resistors with known non-linearity shall be used to verify the integrity of the measuring system.

5 Measurement procedure

5.1 Environmental conditions

Unless otherwise specified, all tests shall be carried out under standard atmospheric conditions for measurement and tests as specified in IEC 60068-1.

5.2 Preparation of specimen

The specimen shall be kept for at least 2 h in the environmental conditions prescribed in 5.1.

5.3 Measurement conditions

The choice of system impedances R_3 is determined by the properties of the actual measurement system. Table 1 is based on examples of suitable values for R_3.

The fundamental test voltage U_1 shall be chosen from Table 1, unless otherwise specified in the relevant component specification, e.g. relative to the rated dissipation.

NOTE Analysis shows that the third harmonic ratio depends significantly on the choice of the fundamental voltage as the readings of the third harmonic voltage U3 show an exponential relationship over the ratio of applied fundamental voltages. Comparison of the non-linearity of different products therefore should always be based on identical prescriptions for dissipation and voltage limitation in order to define an identical fundamental voltage for each resistance value.

The application of the fundamental voltage results in a dissipation and thus in a temperature rise within the specimen. Depending on its temperature coefficient of resistance (TCR), the specimen resistance will change, which will change the actual appplied fundamental voltage. Depending the the respective temperature rise and TCR, this effect may be neglectable or not. Limiting the duration of the application of the fundamental voltage may be a suitable way out of this problem, if set below the thermal time constant of the specimen.

The relevant component specification shall state respective requirements, if applicable.

5.4 Procedure

The specimen shall be inserted into the test fixture and properly connected to the test terminals.

The system impedance R_3 shall be selected in order to achieve the best possible impedance matching.

The fundamental voltage shall be applied, e.g. by closing the switch S in a system accroding to Figure 4, and adjusted to the prescribed value.

The third harmonic voltage U_3 shall be read.

The application of the fundamental voltage shall not exceed the prescribed duration, if applicable.

5.5 Precautions

Ferromagnetic materials give rise to harmonic distortion and care must be taken to avoid influence from, e.g. iron in the immediate vicinity of the component which can mask component non-linearities especially at high currents.

6 Evaluation of measurement results

6.1 Evaluation

The reading of the third harmonic voltage U_3 shall be used to calculate the third harmonic ratio.

The third harmonic ratio A_3 in decibels is

$$\begin{aligned} A_3 &= 20 \cdot \log_{10} \frac{U_1}{E_3} \\ &= 20 \cdot \log_{10} \frac{U_1}{U_{\text{ref}}} - 20 \cdot \log_{10} \frac{E_3}{U_{\text{ref}}} \\ &= 20 \cdot \log_{10} \frac{U_1}{U_{\text{ref}}} - 20 \cdot \log_{10} \frac{U_3}{U_{\text{ref}}} - 20 \cdot \log_{10} \left(1 + \frac{R_{\text{T3}}}{R_3}\right) \end{aligned} \qquad (5)$$

with

- U_1 Fundamental voltage across the resistor under test
- U_{ref} Basis for voltage ratios, arbitrarily set.
- E_3 e.m.f. of the third harmonic in the component
- U_3 measured third harmonic voltage
- R_{T3} Impedance of the resistor under test at the third harmonic frequency
- R_3 Impedance of the measuring circuit at the third harmonic frequency, seen from the test terminals (source impedance)

In equation 5, the logarithmic term describing the fundamental voltage may be abbreviated as D with

$$D = 20 \cdot \log_{10} \frac{U_1}{U_{\text{ref}}} \qquad (6)$$

NOTE The calculation of the third harmonic ratio requires a common U_{ref} for all used logarithms of voltage ratios; throughout this document, U_{ref} = 1 V is used for the 0 dB reference level.

The abbreviation of a logarithmic expression $20 \cdot \log_{10}(U/U\mathrm{ref})$ to $20 \cdot \log_{10} U$ is mathematically incorrect and particularly bears the risk of confusion when the used reference voltage is no longer considered. Hence the abbreviated form should not be used.

With the above definitions of *D* in equation 6 and of Δ in 4.1, equation 5 can be simplified to

$$A_3 = D - 20 \cdot \log_{10} \frac{U_3}{U_{\mathrm{ref}}} - \Delta \qquad (7)$$

6.2 Requirements

Acceptance criteria for non-linearity of tested products shall be given with reference to a required minimum third harmonic ratio A_3 in the relevant component specification.

Such acceptance criteria should be stated through a fixed minimum value, typically given as a function of the specimen resistance.

Superiour selectivity of non-linearity screening is achievable through the use of a dynamic minimum value relative to the statistical distribution of non-linearity within an analyzed batch in addition to a fixed minimum value. Such dynamic requirement should be referenced to a batch's mean value and a multiple of its standard deviation, e.g. like $\geq \overline{A}_3 - 3\sigma$.

7 Information to be given in the relevant component specification

When this test is included in a relevant component specification, the following details shall be given as far as they are applicable:

		Clause
a)	the fundamental frequency	4.2
b)	the environmental condition for this measurement	5.1
c)	the dissipation to be provided through the fundamental voltage	5.3, Table 1
d)	a limitation to the fundamental voltage, if applicable	5.3, Table 1
e)	a limitation to the duration of application of the fundamental voltage, if applicable	5.3

The relevant component specification shall specify for its own purpose:

		Clause
f)	acceptance criteria to the third harmonic ratio A_3	6.2

Table 1 — Recommended measuring conditions

R_3 Ω	R_T [a] Ω	Δ [b] dB	Specimen's rated dissipation P_r								
			$P_r \geq 0{,}25$ W			0,25 W > $P_r \geq 0{,}1$ W			0,1 W > P_r		
			U_1 [c] V	D [d] dB	P mW	U_1 [c] V	D [d] dB	P mW	U_1 [c] V	D [d] dB	P mW
10	1,0	0,8	0,50	-6,0	250	0,32	-10,0	100	0,22	-13,0	50
	1,2	1,0	0,55	-5,2	250	0,35	-9,2	100	0,24	-12,2	50
	1,5	1,2	0,61	-4,3	250	0,39	-8,2	100	0,27	-11,2	50
	1,8	1,4	0,67	-3,5	250	0,42	-7,4	100	0,30	-10,5	50
	2,2	1,7	0,74	-2,6	250	0,47	-6,6	100	0,33	-9,6	50
	2,7	2,1	0,82	-1,7	250	0,52	-5,7	100	0,37	-8,7	50
	3,3	2,5	0,91	-0,8	250	0,57	-4,8	100	0,41	-7,8	50
	3,9	2,9	0,99	-0,1	250	0,62	-4,1	100	0,44	-7,1	50
	4,7	3,3	1,08	0,7	250	0,69	-3,3	100	0,48	-6,3	50
	5,6	3,9	1,18	1,5	250	0,75	-2,5	100	0,53	-5,5	50
	6,8	4,5	1,30	2,3	250	0,82	-1,7	100	0,58	-4,7	50
	8,2	5,2	1,43	3,1	250	0,91	-0,9	100	0,64	-3,9	50
	10	6,0	1,58	4,0	250	1,00	0,0	100	0,71	-3,0	50
	12	6,8	1,73	4,8	250	1,10	0,8	100	0,77	-2,2	50
	15	8,0	1,94	5,7	250	1,22	1,8	100	0,87	-1,2	50
	18	8,9	2,12	6,5	250	1,34	2,6	100	0,95	-0,5	50
	22	10,1	2,35	7,4	250	1,48	3,4	100	1,05	0,4	50
	27	11,4	2,60	8,3	250	1,64	4,3	100	1,16	1,3	50
100	33	2,5	2,87	9,2	250	1,82	5,2	100	1,28	2,2	50
	39	2,9	3,12	9,9	250	1,97	5,9	100	1,40	2,9	50
	47	3,3	3,43	10,7	250	2,17	6,7	100	1,53	3,7	50
	56	3,9	3,74	11,5	250	2,37	7,5	100	1,67	4,5	50
	68	4,5	4,12	12,3	250	2,61	8,3	100	1,84	5,3	50
	82	5,2	4,53	13,1	250	2,86	9,1	100	2,02	6,1	50
	100	6,0	5,00	14,0	250	3,16	10,0	100	2,24	7,0	50
	120	6,8	5,48	14,8	250	3,46	10,8	100	2,45	7,8	50
	150	8,0	6,12	15,7	250	3,87	11,8	100	2,74	8,8	50
	180	8,9	6,71	16,5	250	4,24	12,6	100	3,00	9,5	50
	220	10,1	7,42	17,4	250	4,69	13,4	100	3,32	10,4	50
	270	11,4	8,22	18,3	250	5,20	14,3	100	3,67	11,3	50
1 k	330	2,5	9,08	19,2	250	5,74	15,2	100	4,06	12,2	50
	390	2,9	9,87	19,9	250	6,24	15,9	100	4,42	12,9	50
	470	3,3	10,8	20,7	250	6,86	16,7	100	4,85	13,7	50
	560	3,9	11,8	21,5	250	7,48	17,5	100	5,29	14,5	50
	680	4,5	13,0	22,3	250	8,25	18,3	100	5,83	15,3	50
	820	5,2	14,3	23,1	250	9,06	19,1	100	6,40	16,1	50
	1,0 k	6,0	15,8	24,0	250	10,0	20,0	100	7,07	17,0	50
	1,2 k	6,8	17,3	24,8	250	11,0	20,8	100	7,75	17,8	50
	1,5 k	8,0	19,4	25,7	250	12,2	21,8	100	8,66	18,8	50
	1,8 k	8,9	21,2	26,5	250	13,4	22,6	100	9,49	19,5	50
	2,2 k	10,1	23,5	27,4	250	14,8	23,4	100	10,5	20,4	50
	2,7 k	11,4	26,0	28,3	250	16,4	24,3	100	11,6	21,3	50
10 k	3,3 k	2,5	28,7	29,2	250	18,2	25,2	100	12,8	22,2	50
	3,9 k	2,9	31,2	29,9	250	19,7	25,9	100	14,0	22,9	50
	4,7 k	3,3	34,3	30,7	250	21,7	26,7	100	15,3	23,7	50
	5,6 k	3,9	37,4	31,5	250	23,7	27,5	100	16,7	24,5	50
	6,8 k	4,5	41,2	32,3	250	26,1	28,3	100	18,4	25,3	50
	8,2 k	5,2	45,3	33,1	250	28,6	29,1	100	20,2	26,1	50

Table 1 (continued)

R_3 Ω	R_T [a] Ω	Δ [b] dB	Specimen's rated dissipation P_r								
			$P_r \geq 0,25$ W			$0,25 \text{ W} > P_r \geq 0,1$ W			$0,1 \text{ W} > P_r$		
			U_1 [c] V	D [d] dB	P mW	U_1 [c] V	D [d] dB	P mW	U_1 [c] V	D [d] dB	P mW
10 k	10 k	6,0	50,0	34,0	250	31,6	30,0	100	22,4	27,0	50
	12 k	6,8	54,8	34,8	250	34,6	30,8	100	24,5	27,8	50
	15 k	8,0	61,2	35,7	250	38,7	31,8	100	27,4	28,8	50
	18 k	8,9	67,1	36,5	250	42,4	32,6	100	30,0	29,5	50
	22 k	10,1	74,2	37,4	250	46,9	33,4	100	33,2	30,4	50
	27 k	11,4	82,2	38,3	250	52,0	34,3	100	36,7	31,3	50
100 k	33 k	2,5	90,8	39,2	250	57,4	35,2	100	40,6	32,2	50
	39 k	2,9	98,7	39,9	250	62,4	35,9	100	44,2	32,9	50
	47 k	3,3	108	40,7	250	68,6	36,7	100	48,5	33,7	50
	56 k	3,9	118	41,5	250	74,8	37,5	100	52,9	34,5	50
	68 k	4,5	130	42,3	250	82,5	38,3	100	58,3	35,3	50
	82 k	5,2	143	43,1	250	90,6	39,1	100	64,0	36,1	50
	100 k	6,0	158	44,0	250	100	40,0	100	70,7	37,0	50
	120 k	6,8	173	44,8	250	110	40,8	100	77,5	37,8	50
	150 k	8,0	194	45,7	250	122	41,8	100	86,6	38,8	50
	180 k	8,9	212	46,5	250	134	42,6	100	94,9	39,5	50
	220 k	10,1	235	47,4	250	148	43,4	100	105	40,4	50
	270 k	11,4	260	48,3	250	164	44,3	100	116	41,3	50
	330 k	12,7	287	49,2	250	182	45,2	100	128	42,2	50
	390 k	13,8	312	49,9	250	197	45,9	100	140	42,9	50
	470 k	15,1	343	50,7	250	217	46,7	100	153	43,7	50
	560 k	16,4	374	51,5	250	237	47,5	100	167	44,5	50
	680 k	17,8	412	52,3	250	261	48,3	100	184	45,3	50
	820 k	19,3	453	53,1	250	286	49,1	100	202	46,1	50
	1,0 M	20,8	500	54,0	250	316	50,0	100	224	47,0	50
	1,2 M	22,3	548	54,8	250	346	50,8	100	245	47,8	50
	1,5 M	24,1	612	55,7	250	387	51,8	100	274	48,8	50
	1,8 M	25,6	671	56,5	250	424	52,6	100	300	49,5	50
	2,2 M	27,2	742	57,4	250	469	53,4	100	332	50,4	50
	2,7 M	28,9	822	58,3	250	520	54,3	100	367	51,3	50
	3,3 M	30,6	908	59,2	250	574	55,2	100	406	52,2	50
	3,9 M	32,0	987	59,9	250	624	55,9	100	442	52,9	50
	4,7 M	33,6	1084	60,7	250	686	56,7	100	485	53,7	50
	5,6 M	35,1	1183	61,5	250	748	57,5	100	529	54,5	50
	6,8 M	36,8	1304	62,3	250	825	58,3	100	583	55,3	50
	8,2 M	38,4	1432	63,1	250	906	59,1	100	640	56,1	50
	10 M	40,1	1581	64,0	250	1000	60,0	100	707	57,0	50
	12 M	41,7	1732	64,8	250	1095	60,8	100	775	57,8	50
	15 M	43,6	1936	65,7	250	1225	61,8	100	866	58,8	50
	18 M	45,2	2121	66,5	250	1342	62,6	100	949	59,5	50
	22 M	46,9	2345	67,4	250	1483	63,4	100	1049	60,4	50

[a] The parameters for other values of R_T than shown here shall be calculated using the resistance R_T, the dissipation P and, if applicable, a limitation to the fundamental voltage U_1.

[b] The given figures for the correction term Δ only apply if the measuring circuit uses the source impedances R_3 shown here.

[c] A limitation may apply to the voltage at fundamental frequency, thereby limiting the value D and the actual dissipation P.

[d] The decibel ratio D of the fundamental voltage is based upon U_{ref} = 1 V for the 0 dB reference level.

Annex X
(informative)

Cross reference

The revision of this standard has resulted in a new clause numbering. The following table provides a cross reference between the clause numbering of this revision compared to the prior revision of this standard.

IEC/TR 60440:1973 1st edition Clause	IEC 60440:201X 1st edition Clause	Notes
1 2	1	Scope and object are merged into one
—	2	New clause
—	3	New clause
3 4.0	4.1	—
4.1 4.2	4.2	—
4.3 4.4	4.1	—
4.5	4.3	Divided in to subclauses
4.6	5.1	—
4.7	4.3.7	—
5	5	Divided into subclauses
—	6	New clause

BIBLIOGRAPHY

Danbridge A/S, *“Reliability Testing of Nominally Linear Components by Measuring Third Harmonic Distortion”*, Application Note, 2002

IEC 60027 (all parts), *Letter symbols to be used in electrical technology*

ISO 60617, *Graphical symbols for diagrams*

ISO 1000, *SI Units and recommendations for the use of their multiples and of certain other units*

Kühl, R.W. and Ewell, G.J., “*Third Harmonic Testing: Current Resistor Applications*”, Proceedings, 15th European Passive Components Symposium CARTS-EUROPE 2001, Copenhagen, Denmark, 2001, pp. 85 - 93.

Kuehl, R.W., “*Reliability of thin-film resistors: Impact of third harmonic screening*”, Microelectronics Reliability 42 (2002), pp. 807 - 813.