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Resistive Products | Application Note

Basics of Linear Fixed Resistors

In the shadow of microelectronics, passive components such as discrete resistors would seem to have fallen out of the field of view in electronics. Yet, it is the rare circuit that can do without resistors. And a look at a modern circuit board will show that it has become more difficult to locate them visually.

OVERVIEW

Linear fixed resistors are classified as film, foil, composition, Power Metal Strip®, and wirewound resistors, depending on the material used. Film resistors can be further subdivided into carbon, metal and thick film resistors.

COMPONENT	TECHNOLOGY	RESISTIVE MATERIAL
Resistors	Film	Carbon
		Metal
		Paste
	Power Metal Strip®	Metal
	Foil	Metal
	Wirewound	Metal
	Composition	Carbon

Fig. 1 - Linear fixed resistors technologies

Going by sales figures, metal film and thick film resistors are the most widely used types. Aside high volume commodity use of standard carbon film resistors special carbon film resistors are used in applications requiring high pulse stability. Film resistors in general are characterized by a resistive layer on a ceramic base. Metal film resistors are often produced by sputtering, while thick film resistors are manufactured using screen and stencil printing processes.

Once the terminations are attached, the resistor is trimmed to its final value. Formerly this was done by grinding or sandblasting, but today, lasers are frequently used. A final lacquer coat is applied to protect the component from mechanical and climatic stresses. Commonly the resistance value is then marked using the familiar color rings or stamped on in plain text. Before packaging, the resistors are subjected to extensive quality control testing.

Film resistors can be used essentially anywhere. Metal film resistors possess very good noise characteristics and low non-linearity. Parameters such as tolerance, temperature coefficient, and stability are excellent. Thick film resistors, on the other hand, can be more cheaply produced and have sufficient quality for applications where low noise, low temperature coefficient, and low drift are not a priority.

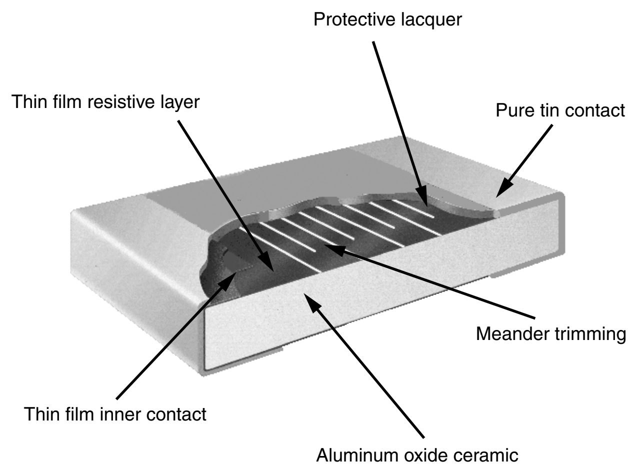

Fig. 2 - Metal film chip resistor

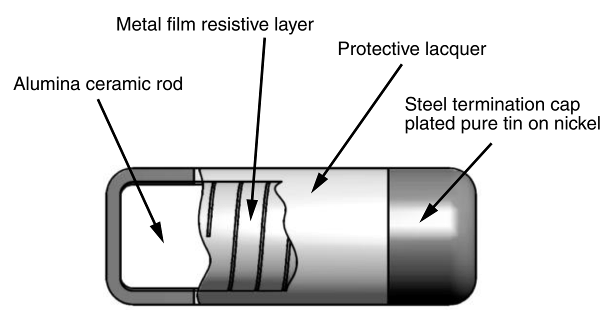

Fig. 3 - MELF resistor

With composition resistors, the entire body of the resistor acts as the resistance element. The resistor composition is pressed together with the termination wires and hardened. Since there is no trimming, the tolerances on delivery are relatively high (± 10 %, ± 20 %). The advantages of the composition resistor are its very good high-frequency characteristics and the high capability to overload relative to the component size. These factors mean that these relatively expensive resistors are used in applications like power supplies, welding controls and as “dummy loads”.

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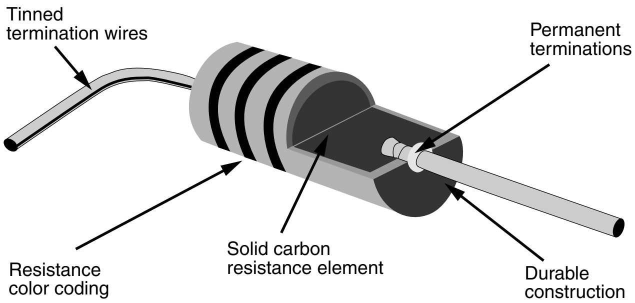

Fig. 4 - Composition resistor

The interior of a wirewound resistor consists of a ceramic or fiberglass base wound with resistor wire to the desired resistance value. The wire ends are pressed or brazed to the caps. The outstanding characteristic of this type of resistor is the very high surface temperature it can take, up to + 450 °C, which makes it very tough indeed. Their areas of application are comparable to those of the composition resistor, with the reservation that the high frequency characteristics of the wirewound resistor are substantially worse.

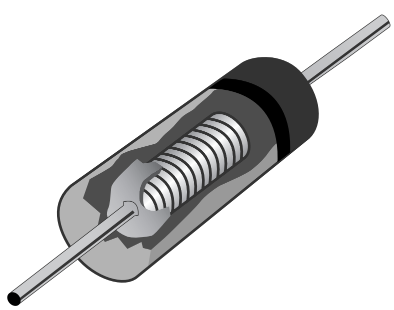

Fig. 5 - Wirewound resistor

Power Metal Strip resistor construction consists of solid, self supporting, resistance element which is welded to copper terminals. The resistive element is trimmed to a desired resistance value by increasing the current path. Finally the resistor body is encapsulated and the terminals plated for solderable connection. Power Metal Strip resistors are characterized by very low resistance values (1 Ω to 100 µΩ), tight resistance tolerance (± 1 % standard, ± 0.5 % available), low temperature coefficient (TCR) (below 75 ppm/K) and low thermal EMF (below µV/K). Power Metal Strip resistors are commonly used as shunt resistors. Areas of application include DC/DC converters, Li-Ion battery management, power supplies, and automotive controls for body, power train and safety.

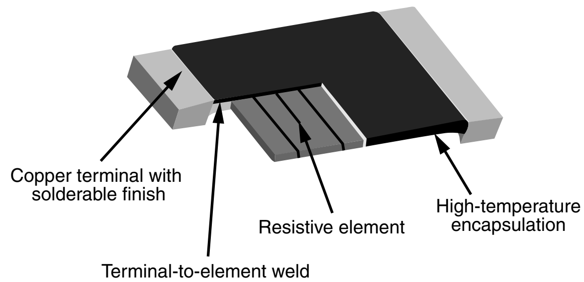

Fig. 6 - Power Metal Strip resistor

The metal foil resistor consists of an electrically insulated etched metallic foil mounted on a material of high heat conductivity. Metal foil resistors are used today in large quantities as low-ohm current measuring resistors (shunts), as well as precision resistors for measurement applications. The most important requirements for these applications are low temperature coefficient, low thermoelectrical potential difference with reference to copper, and high long-term stability.

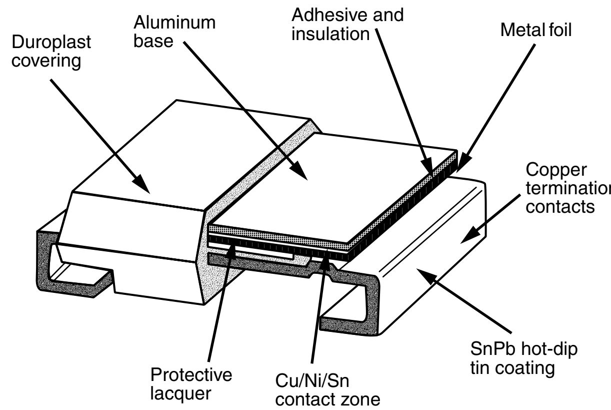

Fig. 7 - Metal foil resistor

These requirements are met extremely well by foil resistors manufactured by etching technology and using manganese-ceranin alloys. Among their other technical advantages are extremely low inductivity and good pulse loading capability. Foil technology is particularly suitable for resistors in the 2 mΩ to 150 kΩ range.

Besides the basic types which have been discussed so far, there are several special resistor types:

- Trimmable resistors which are trimmed by laser to the nominal value only after installation in the application;
- High-frequency resistors optimized for microwave applications;
- Fusible resistors which become high-resistive when a defined current is exceeded;
- Customer specific resistor arrays configuration.

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CHARACTERISTICS

The essential characteristic of a linear resistor is a constant quotient of voltage and current, or put differently:

$$R = \frac{U}{I} = \text{constant}$$

The ideal resistor never deviates from its rated value, is unaffected by temperature, can handle any electrical load, and does not change its specifications over the course of its life.

However, in the real world physics always gets in the way of this ideal. Thus, even with something that at first glance seems as simple as a resistor, there are properties that a development engineer should consider, whether for analogue or digital circuits. If he wants to guarantee a certain circuit behavior, such as very high pulse stability or a good signal to noise ratio, there is no way to get around perusal of the specification sheets. In the following all relevant characteristics will be discussed one by one.

Nominal Value: The nominal value is the value the resistor should have at 20 °C based on its design. Although it is theoretically possible to produce any kind of resistor, in practice the need for inventory simplification has led the industry to settle on the E-series in accordance with IEC 60063. Based on the principle of constant tolerance and resistor values of 1 Ω, 10 Ω, 100 Ω and 1 kΩ, it forms a geometric sequence of ratings by the following formula:

$$k = (\sqrt[n]{10})^m$$

(n: number of values within a decade; n = 6, 12, 24, 48, 96, 192; m: element counter; m = 0,..., n-1; number rounded to 2 or 3 significant digits)

Tolerance: The tolerance on delivery is the range within which the resistor can deviate percentually from the value at the time of delivery. During operation further deviation can occur, such as drift and temperature coefficient. Often the values from the E-series are combined with the tolerance so that the spreads of two successive ratings overlap slightly.

Example: E24/5 % E96/1 % E192/0.5 %

Temperature Coefficient of Resistance (TCR): Unfortunately, the resistance value changes in a slightly non-linear fashion with temperature. The temperature coefficient α is the relative change in the resistance value within a given temperature interval.

$$\alpha = \frac{R_\vartheta - R_{20}}{R_{20}(\vartheta - 20\ °C)}$$

ϑ: Operating temperature in °C
R_ϑ: Resistance value at temperature J
R_{20}: Resistance value at + 20 °C

The TCR is thus the mean rise in the temperature resistance curve and is valid only in the temperature range specified. Usually, recommended temperature ranges (climatic categories) are used in standards, e.g. - 55 °C ≤ ϑ ≤ + 125 °C for TCR = ± 50 ppm/K (1). Using $\Delta R = R_\vartheta - R_{20}$ and $\Delta\vartheta = \vartheta - 20$ °C, the maximum resistance change can be calculated for any temperature change within this range:

$$\frac{\Delta R}{R_{20}} = \Delta\vartheta \cdot \alpha$$

ΔR = Resistance change
$\Delta\vartheta$ = Temperature rise (K)

Converting the deviation into percentage scales the TCR spans a permissible range within the resistance value varies.

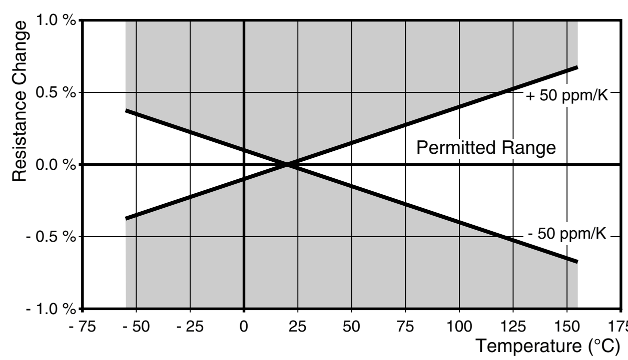

Fig. 8 - Example of possible relative changes in the resistance value due to the TCR

Stability: The resistance value can change under thermal, electrical, or mechanical influence. Stability classes indicate the maximum permissible change. Stability is tested by procedures defined in standards. Short-term tests include overloading, mechanical sturdiness of the terminations, resistance to soldering heat, rapid temperature changes, and vibrations. Long-term testing includes criteria such as climate sequences, damp heat, long-term exposure to the maximum permissible temperature and long-term exposure at + 70 °C ambient temperature with cyclic electrical load (load life).

Note
(1) ppm/K = parts per million per Kelvin, 1 ppm = $1 \cdot 10^{-6}$

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This table shows the permissible resistance value change to the assignment of stability classes:

STABILITY CLASSES	LONG-TERM TESTING	SHORT-TERM TESTING
2	± (2 % · *R* + 0.1 Ω)	± (0.5 % · *R* + 0.05 Ω)
1	± (1 % · *R* + 0.05 Ω)	± (0.25 % · *R* + 0.05 Ω)
0.50	± (0.50 % · *R* + 0.05 Ω)	± (0.10 % · *R* + 0.01 Ω)
0.25	± (0.25 % · *R* + 0.05 Ω)	± (0.05 % · *R* + 0.01 Ω)
0.10	± (0.10 % · *R* + 0.02 Ω)	± (0.05 % · *R* + 0.01 Ω)
0.05	± (0.05 % · *R* + 0.01 Ω)	± (0.025 % · *R* + 0.01 Ω)

Rated dissipation: The rated dissipation is the maximum dissipation the resistor is capable of up to a defined ambient temperature (the rated temperature, typically + 70 °C). At this loading, the temperatures at the component do not exceed the maximum. Above this temperature the resistor can only utilize a reduced level of power. This is described by a derating curve:

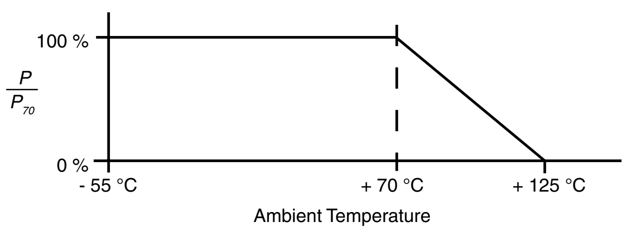

Fig. 9 - A typical derating curve

Operating Voltage: This is the highest DC voltage or the effective sinusoidal AC voltage that can be continuously applied to the resistor.

Non-Linearity: Due to inhomogeneities in the resistor material or substrate and/or poor transitions between terminations and resistor material, even linear resistors are not completely linear, i.e. the current-voltage characteristic is not exactly linear. The non-linearity is determined by measuring the 3rd harmonic of a 10 kHz sine oscillation. The voltage ratio

$$A_3 = 20 \cdot \lg \frac{U_{10\ kHz}}{U_{30\ kHz}}$$

is a quality criterion of a resistor. Faulty resistors can be identified by excessively low A_3 values. The measurement procedure is specified by IEC/TR 60440.

Noise: There are two kinds of noise: the thermal noise and the current noise by the applied voltage. While thermal noise remains constant over a wide frequency range (white noise), current noise declines with rising frequency. IEC 60195 lays down the measurement arrangement and procedure, in order to ensure that noise voltage specifications are comparable. This standard also includes a code number for the noise of an individual resistor, the current noise index.

Pulse Stability: If a resistor is exposed to pulses instead of constant loading, it can accept multiples of its rated loading for short periods without impairing its long-term stability.

In order to get comparable measurements, there are two standardised pulses according IEC 60115-1, 4.27: 1.2/50 µs and 10/700 µs. The first figure stands for the rise time and the second for the pulse duration (pulse voltage drop to 50 %). The 1.2/50 measurement is taken with 5 pulses at intervals of at least 12 s; the 10/700 measurement with 10 pulses at intervals of at least 60 s. The pulse load capabilities for these conditions are established based on suitable criteria, i.e. an appropriate permissible resistance change after pulse load. We prefer to set such criteria in relation the product’s long term stability, e.g. ± 0.5 %.

For a resistor to possess sufficient pulse suitability for a specific application, the following criteria must be met:

- The average load must not be greater than the rated loading at the required ambient temperature;
- The permissible pulse loading as a function of the pulse duration must not be exceeded;
- The pulse voltage at the resistor must be lower than the permissible pulse peak voltage.

Thermal Resistance: The thermal resistance counteracts the dissipation of the heat generated in the resistor. Since thermal resistance depends in large measure on the assembly conditions, the value given in catalogs is taken from a standardised test assembly.

For a specific application, the following formula is used to determine the temperature increase over the ambient temperature:

$$\Delta_{\vartheta} = P \cdot R_{th}$$

P = Power load of the resistor (W)
R_{th} = Actual thermal resistance (K/W)

High Frequency Characteristics: In addition to the resistance value, as frequency increases parasitic properties become noticeable. This includes the inductivity of the windings in cylindrical resistors and the capacity between component terminations. A resistor has good high frequency characteristics when the parasitic elements in the frequency range in question are negligible.

A resistor should also be modelable, i.e., capable of description using a simple equivalent circuit diagram. Its high frequency characteristics must be reproducible in series production.

Special trimming processes for film resistors and winding processes for wire-wound resistors substantially improve the high frequency characteristics of these components.

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CHARACTERISTICS IN FIGURES

The following table brings together some typical figures. It ignores specialities, such as ultra-precision metal film resistors (± 0.01 % tolerance, TCR = ± 2 ppm/K) or metal film resistors for temperature above 155 °C.

RESISTORS	CARBON FILM	METAL FILM	THICK FILM	METAL FOIL	CARBON COMPOSITION	WIREWOUND	POWER METAL STRIP
Resistance Value	10 Ω to 22 MΩ	0.22 Ω to 22 MΩ	1 Ω to 100 MΩ	2 mΩ to 1 MΩ	1 Ω to 20 MΩ	0.1 Ω to 300 kΩ	0.1 mΩ to 1.0 Ω
Tolerance [%]	± 2 to ± 10	± 0.1 to ± 2	± 1 to ± 5	± 0.005 to ± 5	± 5 to ± 20	± 0.1 to ± 10	± 0.5 to ± 1
Temperature Coefficient [ppm/K]	- 200 to - 1500	± 5 to ± 50	± 50 to ± 200	± 2 to ± 50	- 200 to - 1500	± 1 to ± 200	± 30 to ± 250
Maximum Operating Temperature [°C]	+ 155	+ 155	+ 155	+ 150	+ 150	+ 400	+ 275
Rated Dissipation P_{70} [W]	0.25 to 2	0.063 to 1	0.063 to 0.25	0.25 to 10	0.25 to 1	0.25 to 100	0.1 to 5
Stability at P_{70} (1000 h) $\Delta R/R$ [%]	± 0.8 to ± 3	± 0.15 to ± 0.5	± 1 to ± 3	± 0.05	+ 4/- 6 (typical - 3)	± 1 to ± 10	± 1 to ± 2
Operating Voltage $U_{max.}$ [V]	200 to 1000	50 to 500	50 to 200	200 to 500	150 to 350	25 to 1000	$\sqrt{P_{70} \times R}$
Current Noise [µV/V]	< 1	< 0.1	< 10	< 0.025	2 to 6	negligible	negligible
Non-linearity A_3 [dB]	> 100	> 110	> 50	negligible	~ 60	negligible	negligible

SHAPES AND SIZES

The most elementary distinction is between leaded and SMD [(2)]. High-power resistors are also available with termination clamps.

Surface-mounted resistors are further subdivided into cylindrical MELF [(3)] and rectangular chip devices.

The following table decodes the size designations. It applies to film resistors in general. Wirewound, composition and foil resistor manufacturers often use proprietary sizes.

SHAPE	STANDARDIZED PER	EXAMPLE	DESCRIPTION
Cylindrical (MELF)	DIN [(4)]	0204	Dimensions: Rounded. Maximum in mm Sequence: Diameter - Length Dia. = 2 mm; L = 4 mm
	EN [(5)]	RC 3715 M	Dimensions: Maximum in 1/10 mm Sequence: Length - Diameter Resistor, Cylindrical L = 3.7 mm; Dia. = 1.5 mm
Rectangular (Chip)	EIAJ [(6)]	3216	Dimensions: in 1/10 mm Sequence: Length - Width L = 3.2 mm; W = 1.6 mm
	EN	RR 3216 M	
	Inch Size	1206	Dimensions: in 1/100" Sequence: Length - Width Resistor, Rectangular L = 0.12"; W = 0.06"

Notes

(2) SMD - Surface Mounted Device
(3) MELF - Metal Electrode Face bonding, component fastened to the circuit board by its metal surface (termination surface)
(4) DIN - German Standards Institute (Deutsches Institut für Normung)
(5) EN - European Norm
(6) EIAJ - Electronic Industries Association of Japan

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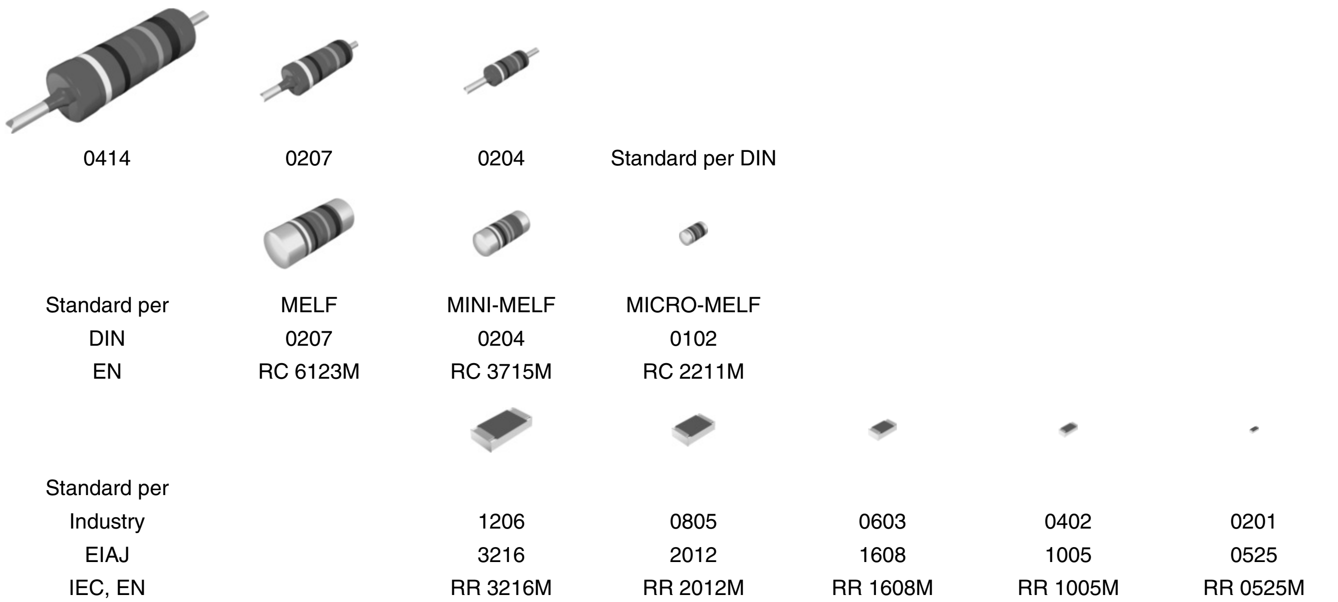

Figure 10. Common shapes and sizes

TRENDS

Developments in the world of resistors are by no means over. Miniaturization will continue in the years to come. Size 0402 and even 0201 will increasingly be used for applications where every square millimeter counts, such as cellular phones. Individual resistors will be combined in arrays with the objective of gaining space and functional performance.

Another trend runs opposite to this. There is an increasing demand for SMD resistors that can handle dissipation power over 0.25 W and are stable under mains voltage. The demand for MELF size 0207 underlines this development.

Especially for voltage divider and feedback circuits Thin Film Chip Resistor Arrays became the preferred solution. Such chip arrays combine two and more resistors on one ceramic substrate and have special advantages in terms of stability, tolerance matching and TCR tracking.

Along with the extension of resistance value ranges upwards and downwards, high frequency properties and pulse stability are being improved.

Specialities are increasingly coming into their own. For example, trimmable (by the component user) resistors eliminate the need for costly, time-consuming trimming by expensive mechanical trimmer potentiometers.

Increasing applications in sensors, automobiles, industry and mobile telephones will further anchor the role of the resistor as the most-needed electronic component.

STANDARDISATION

The properties of resistors are described in the datasheet of the manufacturers, which come in a variety of scopes and comprehensiveness or even terminology. Almost needless to mention that also the tests and applied requirements rarely match.

Fortunately some technical cultures have supported the harmonisation of such descriptions, definitions, methods and requirements into widely accepted standards. This road was paved by the principles of involvement of all interested parties and of consensus between all those. It had started within the national environments (e.g. DIN, JIS, EIA) long time ago and matured from there to international levels (e.g. CECC, CENELEC and finally IEC). Nowadays the national committees act as members of the IEC [7] in the drafting and maintenance of component standards, which are then adopted back on the national level. In the European Community, CENELEC [8] acts as an intermediate ratification level before these standards are published by national standardisation bodies (e.g. DIN, BSI, UTE, ...).

Component standards usually come in a hierarchical structure of generic, sectional and detail. While a generic specification deals with the terms, definitions and preselection of applicable test methods e.g. for all fixed resistors, a sectional specifications provides more specific details for a general kind of products, e.g. for surface mount resistors. Lowest level and thus closest to the individual product or product family is the detail specification with its exact details and requirements, including sophisticated test schedules.

Notes

[7] IEC - International Electrotechnical Commission; www.iec.ch

[8] CENELEC - Comité Européen de Normalisation Electrotechnique (European Committee for Electrotechnical Standardization); www.cenelec.eu

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INTERNATIONAL RESISTOR STANDARDS			
	HIERARCHICAL LEVEL	**STANDARD**	**OWNER**
	Generic	IEC 60115-1	IEC
		EN 60115-1	CENELEC
	Sectional	IEC 60115-2 (9)	IEC
		EN 140100 (10)	CENELEC
	Detail	EN 140101-806	CENELEC
	Sectional	IEC 60115-8 (9)	IEC
		EN 140400 (11)	CENELEC
	Detail	EN 140401-801	CENELEC
		EN 140401-802	CENELEC
		EN 140401-803	CENELEC

Notes

(9) Outdated documents, currently under revision

(10) To be succeeded by EN 60115-2

(11) To be succeeded by EN 60115-8

Component users benefit from this standardisation first through the unambiguous perception of all details in a product description and then may even be able to save the efforts involved in establishing an own company-internal set of component specifications.

QUALITY ASSESSMENT

Now component standards or specifications not only support the harmonisation of the product descriptions, but also serve as a major prerequisite for a reliable quality assessment. Of course every vendor feels entitled to assess the quality of his products on his own, but how would these individual self-assessments compare? Already the CECC (12) had developed a "Harmonized System of Quality Assessment for Electronic Components" which involves accredited National Supervision Inspectorates responsible for auditing and certification. In 2003 IECQ had taken over the quality assessment of CECC. This system offers different kinds of approval:

- Under Qualification Approval the quality of finished components is assessed through lot-by-lot and periodic inspections in comparison to the requirements prescribed by the detail specification, regardless of how the established quality management system would contribute to achieving the compliance.
- Under Capability Approval the general capability of an organisation to produce a wide variety of different products within a range of technology in line with prescribed requirements is assessed through dedicated qualification samples, much like under Qualification Approval.
- The superior level is marked with the Technology Approval, which in addition to the requirements of Qualification Approval assesses the effectiveness of the whole established quality management system towards safeguarding the production only of compliant components.

Any granted approval is expressed by a certificate, of which the manufacturer will be pleased to provide a copy. An approval can be verified any time in the certificates database on the IECQ (13) website. Attestation of the component's conformity does not require any individual certificates, but may simply be expressed by a proper standard reference and application of the CECC logo as the mark of conformity on the package label.

Fig. 11 - CECC Logo

Notes

(12) CECC = CENELEC Electronic Components Committee

(13) IECQ = IEC Quality Assessment System for Electronic Components; www.iecq.org

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Once an approval has been granted, the benefit is with the component users again, who can save efforts for extensive incoming inspections and vendor audits and instead rely on an independent inspectorate supervising the production and verifying compliance with the stated requirements on a tight periodical schedule.

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