The Resistor Guide
the complete guide to the world of resistors

2nd Edition
e-Book

P.F. Van Oorschot and J.W. Pustjens
THE RESISTOR GUIDE

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The resistor guide will guide you in the world of resistors. This book is designed as an educational reference. The selected topics cover the questions of most electrical engineers, students and hobbyists. The main topics are:

- Resistor Fundamentals
- Resistor Types
- Resistor Standards
- Resistor Applications

In Fundamentals, an introduction in the physical background of resistor theory is given. Also the main mathematical laws and main resistor properties are explained. Then, a broad overview is given of all popular resistor types, constructions and materials. The next chapter includes all relevant resistor standards, such as the color code, the SMD code, preferred values and packaging. Finally examples are given of resistor applications. Interactive applications for the calculations can be found at www.resistorguide.com.

Aim of this book
The aim of this book is to provide a complete and useful overview for engineers, students and hobbyists of the fundamental properties of the resistor, the different types and constructions, its use in circuits and industry standards.

How this book differs from other books
It is written in an easy to understand language. For all theoretical explanations is tried to provide examples from practice to make it easier to understand. Furthermore, example calculations help to understand theory even faster.
1. WHAT IS A RESISTOR?

The resistor is a passive electrical component to create resistance in the flow of electric current. In almost all electrical networks and electronic circuits they can be found. The resistance is measured in ohms. An ohm is the resistance that occurs when a current of one ampere passes through a resistor with a one volt drop across its terminals. The current is proportional to the voltage across the terminal ends. This ratio is represented by Ohm’s law:

$$R = \frac{V}{I}$$

Resistors are used for many purposes. A few examples include delimit electric current, voltage division, heat generation, matching and loading circuits, control gain, and fix time constants. They are commercially available with resistance values over a range of more than nine orders of magnitude. They can be used to as electric brakes to dissipate kinetic energy from trains, or be smaller than a square millimeter for electronics.

A resistor is a passive electrical component with the primary function to limit the flow of electric current.

The international IEC symbol is a rectangular shape. In the USA the ANSI standard is very common, this is a zigzag line.
2. FUNDAMENTALS

2.1. ELECTRICAL RESISTIVITY AND RESISTANCE

2.1.1. WHAT IS ELECTRICAL RESISTIVITY?

Electrical resistivity is a measure of a material’s property to oppose the flow of electric current. This is expressed in Ohm-meters (Ω·m). The symbol of resistivity is usually the Greek letter $\rho$ (rho). A high resistivity means that a material does not conduct well electric charge.

Electrical resistivity is defined as the relation between the electrical field inside a material, and the electric current through it as a consequence:

$$\rho = \frac{E}{J}$$

In which $\rho$ is the resistivity of the material (Ωm), $E$ is the magnitude of the electrical field in the material (V/m), $J$ is the magnitude of the electric current density in the material (A/m$^2$).

If the electrical field ($E$) through a material is very large and the flow of current ($J$) very small, it means that the material has a high resistivity.
Electrical conductivity is the inversion of resistivity, and is a measure of how well a material conducts electric current:

\[ \sigma = \frac{1}{\rho} = \frac{J}{E} \]

in which \(\sigma\) is the conductivity of the material expressed in Siemens per meter (S/m). In electrical engineering often \(\kappa\) (kappa) is used instead of \(\sigma\).

### 2.1.2. ELECTRICAL RESISTANCE

Electrical resistance is expressed in Ohms, and is not the same as resistivity. While resistivity is a material property, resistance is the property of an object. The electrical resistance of a resistor is determined by the combination of the shape and the resistivity of the material. For example, a wirewound resistor with a long, thick wire has a higher resistance then with a shorter and thinner wire. A wirewound resistor made from a material with high resistivity has a higher resistance value then one with a low resistivity. An analogy with a hydraulic system can be made, where water is pumped through a pipe. The longer and thinner the pipe, the higher the resistance will be. A pipe full with sand will resist the flow of water more than a without sand (resistivity property).
Hydraulic analogy of electrical resistance

2.1.3. WIRE RESISTANCE

The resistance value of a wire depends on three parameters: resistivity, length and diameter. The formula to calculate wire resistance is as follows:

\[ R = \rho \frac{l}{A} \]

in which \( R \) is the resistance (\( \Omega \)), \( \rho \) is the resistivity of the material (\( \Omega \text{m} \)), \( l \) is the length of the material (m), \( A \) is the cross-sectional area of the material (m\(^2\)).

The resistance value of a wire is dependent on three parameters; its resistivity, cross-sectional area and length.
As an example, consider a wirewound resistor with a wire of Nichrome with a resistivity of $1.10 \times 10^{-6} \ \Omega m$. The wire has a length of 1500 mm and a diameter of 0.05 mm. With these three parameters the resistance value is calculated:

$$R = \rho \frac{l}{A} = 1.1 \times 10^{-6} \cdot \frac{1.5}{0.0005} = 0.022 \Omega$$

Nichrome and Constantan are often used as resistance wire. Look in the table in paragraph 2.1.5 for material resistivity for commonly used materials.

### 2.1.4. SHEET RESISTANCE

The resistance value for a sheet is calculated the exact same way as for wire resistance. The cross-sectional area can be written as the product of $W$ and $t$:

$$R = \rho \frac{l}{A} = \rho \frac{l}{t \cdot w}$$

For some applications like thin films, the ratio between resistivity and film thickness is called sheet resistance $R_s$:

$$R = \frac{\rho \ l}{t \ w} = R_s \frac{l}{w}$$

in which $R_s$ is in ohms. The film thickness needs to be uniform for this calculation.
The resistance can be increased by cutting a pattern in the sheet.

Electrical resistance of a sheet depends on length, width, film thickness and resistivity. Often resistor manufacturers increase resistance by cutting a pattern in the film to increase the path of the electric current.

### 2.1.5. Resistive Properties of Materials

The resistivity of a material is dependent on the temperature and is normally given for room temperature (20°C). The change in resistivity as a result of temperature change is described by the temperature coefficient. For example thermistors make use of this property to measure temperature. On the other hand, in precision electronics this is usually an unwanted effect. Metal foil resistors have excellent properties for temperature stability. This is reached not only by the low resistivity of the material, but also by the mechanical design of the component.

Many different materials and alloys are used for resistors. Nichrome, an alloy of nickel and chromium, is often used as resistor wire material because of its high resistivity and it doesn’t oxidize at high temperatures. A disadvantage is that solder doesn’t adhere to it. Constantan, another popular material, is easily soldered and has furthermore a low temperature coefficient.
### Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (Ωm) at 20°C</th>
<th>$\sigma$ (S/m) at 20°C</th>
<th>Temp. Coeff. (1/°C) x10^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>1.59x10^{-8}</td>
<td>6.30x10^{7}</td>
<td>3.8</td>
</tr>
<tr>
<td>Copper</td>
<td>1.68x10^{-8}</td>
<td>5.96x10^{7}</td>
<td>3.9</td>
</tr>
<tr>
<td>Gold</td>
<td>2.44x10^{-8}</td>
<td>4.10x10^{7}</td>
<td>3.4</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.82x10^{-8}</td>
<td>3.5x10^{7}</td>
<td>3.9</td>
</tr>
<tr>
<td>Tungsten</td>
<td>5.60x10^{-8}</td>
<td>1.79x10^{7}</td>
<td>4.5</td>
</tr>
<tr>
<td>Zinc</td>
<td>5.90x10^{-8}</td>
<td>1.69x10^{7}</td>
<td>3.7</td>
</tr>
<tr>
<td>Nickel</td>
<td>6.99x10^{-8}</td>
<td>1.43x10^{7}</td>
<td>6</td>
</tr>
<tr>
<td>Lithium</td>
<td>9.28x10^{-8}</td>
<td>1.08x10^{7}</td>
<td>6</td>
</tr>
<tr>
<td>Iron</td>
<td>1.0x10^{-7}</td>
<td>1.00x10^{7}</td>
<td>5</td>
</tr>
<tr>
<td>Platinum</td>
<td>1.06x10^{-7}</td>
<td>9.43x10^{6}</td>
<td>3.9</td>
</tr>
<tr>
<td>Tin</td>
<td>1.09x10^{-7}</td>
<td>9.17x10^{6}</td>
<td>4.5</td>
</tr>
<tr>
<td>Lead</td>
<td>2.2x10^{-7}</td>
<td>4.55x10^{6}</td>
<td>3.9</td>
</tr>
<tr>
<td>Manganin</td>
<td>4.82x10^{-7}</td>
<td>2.07x10^{6}</td>
<td>0.002</td>
</tr>
<tr>
<td>Constantan</td>
<td>4.9x10^{-7}</td>
<td>2.04x10^{6}</td>
<td>0.008</td>
</tr>
<tr>
<td>Mercury</td>
<td>9.8x10^{-7}</td>
<td>1.02x10^{6}</td>
<td>0.9</td>
</tr>
<tr>
<td>Nichrome</td>
<td>1.10x10^{-6}</td>
<td>9.09x10^{5}</td>
<td>0.4</td>
</tr>
<tr>
<td>Carbon</td>
<td>5x10^{-4}</td>
<td>1.25 to 2x10^{3}</td>
<td>-0.5</td>
</tr>
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</table>

**2.2. OHM’S LAW**

Ohm’s law states that the electrical current through a conductor is proportional to the potential difference across it. Furthermore, the electrical resistance of the conductor is constant. This leads to the mathematical equation:
The equation is named after Georg Ohm. In 1827 he published his findings that form the basis of the formula that is used today. He performed a large series of experiments that showed the relation between applied voltage and current through a conductor. The law is therefore empirical. Although Ohm’s law is one of the fundamentals of electrical engineering, at the time of publication it was received with criticism. The ohm is adopted as the official SI unit for electrical resistance. Gustav Kirchhoff (known from Kirchhoff’s circuit laws) made a generalization that is more used in physics:

$$\sigma = \frac{1}{\rho} = \frac{J}{E}$$

where $\sigma$ is the conductivity parameter (material specific), $J$ is the current density in a location of that material, and $E$ the electric field in that location.
Georg Simon Ohm (1789-1854)

German physicist Georg Simon Ohm published in 1827 his complete theory of electricity with the title “The Galvanic Circuit Investigated Mathematically”. He found that the voltage drop over a part of a circuit is the product of the current through and the resistance of that part. This formed the basis of the law that we use today. The law is one of the fundamental relations for resistors. His colleagues didn’t appreciate his findings, and the law was not easily accepted. Ohm was a teacher at a gymnasium in Cologne at that time, and he decided to resign. Later he became professor of experimental physics at the University of Munich. Later in his life, he finally got recognition and received the Copley Medal in 1841 from the Royal Society.

2.2.1. OHM’S LAW AND RESISTORS

Resistors are passive elements that introduce resistance to the flow of electric current in a circuit. A resistor that functions according to Ohm’s law is called an Ohmic resistor. When current passes through an Ohmic resistor, the voltage drop across the terminals is proportionally to the magnitude of resistance. Ohm’s formula stays also valid for circuits with varying voltage or current, so it can be used for AC circuits as well. For capacitors and inductors the law can of course not be used, since their I-V curve is inherently not linear (not Ohmic).
Ohm’s formula is valid for circuits with multiple resistors that can be connected in series, parallel or both. Groups of resistors in series or parallel can be simplified with an equivalent resistance. In the chapter about resistors in series and parallel is described in more detail how to do this.

2.2.2. OHM’S LAW EQUATIONS

Ohms formula can be used when two of three variables are known. The relation between resistance, current and voltage can be written in different ways. To remember this, the Ohm triangle calculator might be helpful. Two examples below will show the use of the triangle calculator.

\[
R = \frac{V}{I} \quad \text{or} \quad V = I \cdot R \quad \text{or} \quad I = \frac{V}{R}
\]

Example 1
Consider a 1 ohm resistor in a circuit with a voltage drop from 100V till 10V across its terminals. What is the current through the resistor?

The triangle reminds us that:
Example 2
Consider a 10 ohm resistor in a circuit subject to a current of 2 Ampere and a voltage of 120V. What is the voltage drop across the resistor?

Using the triangle shows us that:

\[ V = I \cdot R = 2 \cdot 10 = 20V \]

Thus the voltage at the end terminal is 120-20 = 100 V.

2.2.3. OHM’S POWER LAW

A resistor dissipates power when a current passes through it. The energy is released in the form of heat. The power is a function of the current I and the applied voltage V:

\[ P = V \cdot I \]

where P is the power in watts. Combined with Ohm’s law, the power law can be rewritten into:

\[ P = R \cdot I^2 \]

or

\[ P = \frac{V^2}{R} \]

Ideal resistors dissipate all energy and don’t store electric or magnetic energy. Each resistor has a limit of the power that can be
dissipated without creating damage. This is called the power rating. Ambient conditions can reduce this value. For example, an enclosure around the resistor or a higher ambient temperature will reduce the amount of energy the resistor can dissipate. This effect is called derating, and can be visualized with a power derating chart. In practice, resistors seldom have an indicated power rating. However, the majority of resistors are rated at 1/4 or 1/8 watt. The circle diagram helps to quickly find the relation between electric power, current, voltage and resistance. For each of the four parameters is shown how to calculate their value.

Below several examples of Ohm’s law problems are given. You can try first to solve the problem by yourself before reading the answer.

**Example 1**
What must be the minimal power rating of this resistor?

\[ R = 50\,\Omega \]
\[ I = 100\,\text{mA} \]
According to the wheel, $P=I^2R=0.100^2\times50=0.5$ W. So the minimal power rating should be at least 0.5W, but recommended is to go high above this value for extra reliability and lifetime.

Example 2
What is the current in the circuit?

This is a basic example of Ohm’s law. Voltage and resistance are known, so we can calculate current with the equation:

$I=V/R=6/1.2=5$ A.

Example 3
An electric heater (resistor) with a consumption of 1kW is connected in a circuit with 8A current. What is the voltage drop over the heater?
Voltage can be expressed in current and power with the formula:

\[ V = \frac{P}{I} = \frac{1000}{8} = 125 \text{ V} \]

2.3. KIRCHHOFF’S CIRCUIT LAWS

Kirchhoff laws are essential for resistor network theory. They were formulated by the German scientist Gustav Kirchhoff in 1845. The laws describe the conversation of energy and charge in electrical networks. They are also called Kirchhoff’s circuit laws. Kirchhoff contributed also to other fields of science, therefore the generic term Kirchhoff law can have different meanings. Both circuit laws, the Kirchhoff Current Law (KCL) and the Kirchhoff Voltage Law (KVL), will be explained in detail.

2.3.1. KIRCHHOFF CURRENT LAW (KCL)

The Kirchhoff Current Law (KCL) states that the sum of all currents leaving a node in any electrical network is always equal to zero. It is based on the principle of conservation of electric charge. The law is also referred to as Kirchhoff’s first law. In formula form this is given by:

\[ \sum_{i=1}^{n} I_i = 0 \]

The KCL is easier to understand with an example.
Look at an arbitrary “node A” from a resistor network. Three branches are connected to this node. Two of the currents are known: $I_1$ is 2 amperes and $I_2$ is 4 amperes. The current law states that the sum of $I_1$, $I_2$ and $I_3$ must be zero:

\[ I_1 + I_2 + I_3 = 0 \]

\[ I_3 = -I_1 - I_2 \]

\[ I_3 = -2 - 4 = -6A \]

### 2.3.2. **KIRCHHOFF VOLTAGE LAW (KVL)**

The second law is also called Kirchhoff’s voltage law (KVL). It states that the sum of the voltage rises and voltage drops over all elements in a closed loop is equal to zero. In formula form:

\[ \sum_{i=1}^{n} V_i = 0 \]

Let’s take an example to explain the second law.
Consider a part of a resistor network with an internal closed loop, as shown in the picture below. We want to know the voltage drop between node B and C ($V_{BC}$). The sum of voltage drops in the loop ABCD must be zero, so we can write:

\[ V_{ab} + V_{bc} + V_{cd} + V_{da} = 0 \]
\[ V_{bc} = -V_{ab} - V_{cd} - V_{da} \]
\[ V_{bc} = -1 - 2 - 4 = -7V \]

### 2.3.3. KIRCHHOFF LAW EXAMPLES

The Kirchhoff laws form the basis of network theory. Combined with Ohm’s law and the equations for resistors in series and parallel, more complex networks can be solved. Several examples of resistor circuits are given to illustrate how Kirchhoff can be used.

**Example 1: The bridge circuit**

Bridge circuits are a very common tool in electronics. They are used in measurement, transducer and switching circuits. Consider the bridge circuit below. In this example will be shown, how to use Kirchhoff’s laws to determine the cross current $I_5$. The circuit has
four bridge sections with resistors R1 – R4. There is one cross bridge connection with resistor R5. The bridge is subject to a constant voltage V and I.

![Resistor Bridge Diagram]

The first Kirchhoff law states that the sum of all currents in one node is zero. This results in:

\[ I = I_1 + I_2 \]
\[ I = I_3 + I_4 \]
\[ I_1 = I_3 + I_5 \]

The second Kirchhoff law states the sum of all voltages across all elements in a loop is zero. This leads to:

\[ 0 = R_1 I_1 + R_3 I_3 - V \]
\[ 0 = R_1 I_1 + R_5 I_5 - R_2 I_2 \]
\[ 0 = R_3 I_3 + R_5 I_5 - R_4 I_4 \]

The six sets of equations above can be rewritten using normal algebra to find the expression for \( I_5 \) (the current in the cross branch):
The equation shows that the bridge current is equal to zero the bridge is balanced:

\[ 0 = I_5 = \frac{V(R_2R_3 - R_1R_4)}{R_5(R_1 + R_3)(R_2 + R_4) + R_1R_3(R_2 + R_4) + R_2R_4(R_1 + R_3)} \]

The equation shows that the bridge current is equal to zero the bridge is balanced:

\[ 0 = R_1R_4 = R_2R_3 \]

**Example 2: The star delta connection**

Kirchhoff’s laws can be used to convert a star connection to a delta connection. This is often done to solve complex networks. A widely used application for star delta connections is to limit the starting current of electric motors. The high starting current causes high voltage drops in the power system. As a solution, the motor windings are connected in the star configuration during starting and then change to the delta connection.

The star connection as shown in the figure above has the same voltage drops and currents as the delta connection shown on the right side, only when the following equations are valid:

\[ R_1 = \frac{R_{31}R_{12}}{R_{12} + R_{23} + R_{31}} \]
2.4. RESISTOR PROPERTIES

The function of resistors is to oppose the flow of electric current in a circuit. Therefore their primary parameter is the resistance value. The manufacturing tolerance must be adequately chosen for each specific application. The ultimate resistance value may deviate from the specification because of many reasons. One is the temperature coefficient of resistance, or TCR, which is often specified for precision applications. Stability defines the long term variations of the resistance. After a long duration of electric load, the resistance value will not return to its original value. Electric noise appears in every resistor, and is for low-noise amplifying applications of importance. For high frequency applications, the inductance and capacitance properties play a role. Next to the characteristics related to resistance value, the maximum power and voltage can be

\[ R_{12} = R_1 + R_2 + \frac{R_1 R_2}{R_3} \]

\[ R_2 = \frac{R_{12} R_{23}}{R_{12} + R_{23} R_{31}} \]

\[ R_{23} = R_2 + R_3 + \frac{R_2 R_3}{R_1} \]

\[ R_2 = \frac{R_{23} R_{31}}{R_{12} + R_{23} + R_{31}} \]

\[ R_{31} = R_3 + R_1 + \frac{R_3 R_1}{R_2} \]
specified. The maximum power rating is mainly for power electronics important, while resistors in electronic circuit boards mostly never reach the maximum power rating. For high voltage circuits, the maximum rated voltage must be taken into account. The quality of a resistor in terms of durability and reliability is for some applications more important than for others.

2.4.1. RESISTANCE

The resistance of a resistor, measured in Ohms, is dependent on its material and shape. Some materials have a higher resistivity, causing a higher value. For a detailed overview of resistivity, see chapter 2.1. The resistance value is often printed on the resistor with a number or in the form of a color code.

2.4.2. POWER RATING

The power rating of a resistor defines the maximum energy a resistor can (safely) dissipate. As is stated by Joule’s first law, the generated electrical power is related to the voltage and current:

\[ P = V \cdot I \]

When the electrical power equals the dissipated heat (by radiation, convection and conduction), the temperature of the resistor will stabilize. The temperature is not equal across the resistor. The resistor body is slightly hotter than the terminals, with the highest temperature at the center of the body. The higher the rate of heat dissipation to the environment, the lower the temperature rise will be. Larger resistors with a bigger surface area can generally dissipate heat at a higher rate. If the (average) power dissipation is
larger than the power rating, the resistor may be damaged. This can have several consequences. The resistance value can shift permanently, the lifetime can significantly be reduced or the component is completely damaged resulting in an open circuit. In extreme cases the excessive power can even cause a fire. Special flameproof resistors are available which cause a circuit-break before the temperature reaches a dangerous state.

The power rating of a resistor defines the maximum energy a resistor can (safely) dissipate.

### 2.4.2.1. RESISTOR DERATING

The nominal power rating is defined for a certain ambient temperature in free air. Note that the amount of energy that a resistor in practice can dissipate without causing damage is strongly dependent on the operating conditions and therefore not equal to the nominal power rating. For example, a higher ambient temperature can significantly reduce the power rating. This effect is referred to as derating. It should be taking into account by the designer. Often the power rating is chosen largely above the electric power. Typically resistors are rated for a temperature of 70°C, above this resistor starts to derate. This means that above this temperature the resistor can only utilize a reduced power level. This is illustrated by a derating curve.
Resistor Derating Chart – The horizontal axis represents the percentage of nominal rating for a given ambient temperature. In this case, the resistor’s full power rating is given until 70°C.

Next to the influence of the ambient temperature, there are several other factors impacting the derating. The most important factors are detailed below.

- **Enclosures**
  The rate of heat loss is limited by installing the resistor in an enclosure. The enclosure limits air flow and therefore the removal of heat by convection. Radiated heat will removed at a lower rate, because the walls of the enclosure act as a thermal barrier. The effect of the enclosure on the heat loss rate is strongly dependent on the size, shape, orientation, material and wall thickness. It is difficult to indicate how these parameters affect the temperature rise.

- **Forced cooling**
  Increasing the heat transfer by forced convection allows for higher watt dissipation than for normal natural convection. This can be achieved by creating an air flow, or even liquid cooling. Some resistors are designed with conducting air fins, to create a bigger surface for heat dissipation.

- **Component grouping**
  On a circuit board resistors are often positioned close to each other. The heat radiation of one resistor will be received by the next resistor and therefore have an extra increase in temperature for a given power consumption.

- **Altitude**
  Resistors lose heat by convection and radiation. When the air density decreases, the convection will also decrease.
Above 30 km convection has dropped so low that only heat dissipation by radiation exists.

2.4.2.2. POWER RESISTORS

For most electronic circuits the power rating is not a key parameter, since those resistors dissipate low amounts of energy of one watt or less. In power electronics however, the power rating is an important characteristic. Generally speaking hereto is referred when power ratings are one watt or higher. Typical applications include power supplies, dynamic brakes, power conversion circuits, power amplifiers and heaters.

2.4.3. INDUCTANCE

Inductance is an electrical property of conductors by which an electrical current passing through the conductor induces an electromotive force in the conductor itself (self-inductance) and other conductors nearby. Since resistors are made of conductive materials, they, too, exhibit inductance as an unwanted, parasitic effect. This effect is especially noticeable if the resistor is made out of wire formed into a coil shape. Depending on the application, resistor inductance might be easily disregarded, especially in DC circuits. However, parasitic resistor inductance can be a significant factor in high-frequency AC applications. The reason for this is that
the impedance of a resistor rises with the applied voltage frequency due to the increase in its reactance.

2.4.3.1. INDUCTORS AND RESISTORS

Electrical loads can be divided into two types: real (or resistive) loads and reactive loads. Real loads are used to convert electrical power into heat. An ideal resistor is a purely resistive load, which means that all the electrical power applied to the resistor is dissipated as heat. On the other hand, reactive loads convert electrical power into a magnetic or electric field and temporarily store it before returning it to the rest of the circuit. Reactive loads can be inductive or capacitive. Inductive load store energy in the form of a magnetic field, while capacitive loads store energy in the form of an electric field.

*The B-field of an inductor coil*

The main difference between ideal resistors and ideal inductors is therefore that resistors dissipate electrical power as heat, while inductors turn electrical power into a magnetic field. Ideal resistors have zero reactance and as a result zero inductance. Unfortunately, electrical devices are not ideal in practice and even the simplest resistors have a slight parasitic inductive reactance.
2.4.3.2. PARASITIC INDUCTANCE

Resistors are used when a purely resistive load is required, so inductance is often an unwanted side-effect and in this context it is called “parasitic inductance”. All real resistors exhibit parasitic inductance to a greater or lesser extent, depending on the design and construction of the resistor. Parasitic inductances in an AC circuit can cause unwanted couplings between system blocks, or can be the cause of delayed circuit response at high frequencies. The source of inductance problems can be either self-inductance, which exists even when the resistor is far away from other conductors or mutual inductance, which is observed when other high frequency devices are nearby. Self-inductance may distort the signal at high frequencies, while mutual inductance may introduce noise in the signal path.

Helical wire wound resistors are especially prone to having significant parasitic inductances, because of their coil shape. Resistors designed specifically for use at high frequencies are made of metal film, to avoid creating the coil shape and reduce the parasitic inductance.

2.4.3.1. REACTANCE AND INDUCTANCE CALCULATIONS

In AC circuits, Electrical impedance is the measure of the opposition that a circuit presents to the passage of a current when a voltage is applied. It is given by the formula:

\[ Z = R + j \cdot X \]
where \( Z \) is the impedance, \( R \) is the resistance, \( X \) is the reactance of a circuit, and \( j \) is the imaginary unit. In this article, it will be assumed that the parasitic reactance of a real resistor is purely inductive, and the impedance of such a resistor would be:

\[
Z = R + j \cdot \omega \cdot L
\]

where \( \omega \) is the angular frequency and \( L \) is the resistor’s parasitic inductance.

As can be seen from the above equations, the impedance of the resistor rises with the voltage frequency increase because the resistor acts as a resistor and inductor. This increase is usually negligible, but in some applications is quite significant.

<table>
<thead>
<tr>
<th>Resistor type</th>
<th>Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wirewound</td>
<td>0.03 – 56 μH</td>
</tr>
<tr>
<td>Foil</td>
<td>&lt;0.08 μH</td>
</tr>
<tr>
<td>Metal oxide</td>
<td>3 – 200 nH</td>
</tr>
<tr>
<td>Film</td>
<td>&lt;2 nH</td>
</tr>
</tbody>
</table>

### 2.4.3.2. APPLICATIONS WHERE PARASITIC EFFECTS PLAY A ROLE

Parasitic inductance usually manifests itself either in resistors with inferior properties such as helical wire wound resistors or in other resistors at very high frequencies. To demonstrate the high frequency problem, a typical foil resistor of 220 Ω with an inductance of 0.05 μH has an impedance of approximately 380 Ω at 1GHz, which is a relative change of approximately 70% above the nominal value, which an engineer would expect if parasitic effects...
were not taken into account. Microwave applications, or RF applications in general are particularly sensitive to parasitic effects.

2.4.4. **CAPACITANCE**

Capacitance is an ability of a body to store electrical energy in the form of electrical charge. Practical resistors always exhibit capacitance as a parasitic property. Depending on the application, resistor capacitance might be easily disregarded, especially in DC circuits. In some applications, such as snubber resistors, the capacitive parasitic effect is actually a desirable effect. On the other hand, parasitic resistor capacitance can be a significant factor in high-frequency AC applications, creating an unwanted effect. The reason for this is that the impedance of a resistor rises with the applied voltage frequency due to the increase in its reactance. The higher the frequency, the lower the impedance is, which means that the resistor can no longer be observed as a constant element at high frequencies, and becomes a frequency-dependent element.

2.4.4.1. **CAPACITORS AND RESISTORS**

Electrical loads can be divided into two types: real (or resistive) loads and reactive loads. Real loads are used to convert electrical power into heat. An ideal resistor is a purely resistive load, which means that all the electrical power applied to the resistor is
dissipated as heat. On the other hand, reactive loads convert electrical power into a magnetic or electric field and temporarily store it before returning it to the rest of the circuit. Reactive loads can be inductive or capacitive. Inductive load store energy in the form of a magnetic field, while capacitive loads store energy in the form of an electric field.

The main difference between ideal resistors and ideal capacitors is therefore that resistors dissipate electrical power as heat, while capacitors turn electrical power into an electric field. Ideal resistors have zero reactance and as a result their capacitance is zero as well. Unfortunately, electrical devices are not ideal in practice and even the simplest resistors have a slight parasitic capacitive reactance.

### 2.4.4.2. Parasitic Capacitance

Resistors are used when a purely resistive load is required, so capacitance is often an unwanted side-effect and in this context it is called “parasitic capacitance”. All real resistors exhibit parasitic capacitance to a greater or lesser extent, depending on the design and construction of the resistor. Parasitic capacitances in an AC circuit can cause unwanted couplings between system blocks, or can be the cause of delayed circuit response at high frequencies. There are resistors designed specifically for use at high frequencies, which are advertised as low capacitance resistors, however exact figures for the capacitances are hard to find in datasheets.
2.4.4.3. Reactance and Capacitance

In AC circuits, electrical impedance is the measure of the opposition that a circuit presents to the passage of a current when a voltage is applied. Since the parasitic capacitance is connected parallel to the resistor (the capacitance shunts the resistor), the complex impedance for such a resistor is given by the parallel connection formula:

\[ Z = \frac{Z_R \cdot jX_C}{Z_R + jX_C} \]

Where \( Z \) is the complex impedance, \( R \) is the resistance, \( X \) is the reactance of a circuit, and \( j \) is the imaginary unit. In this article, it will be assumed that the parasitic reactance of a real resistor is purely capacitive, so the reactance is:

\[ X_C = -\frac{1}{\omega C} \]

So the complex impedance of a resistor with purely capacitive parasitic effects is:

\[ Z = \frac{-R \cdot j \frac{1}{\omega C}}{R - j \frac{1}{\omega C}} \]

where \( \omega \) is the angular frequency and \( C \) is the resistor’s parasitic capacitance.

When the above equations are further analyzed, it can be seen that the total impedance of a resistor with capacitive parasitic effects decreases as the voltage frequency increases. This decrease is usually negligible, but in some applications may become quite significant.
2.4.4.4. CAPACITANCE OF DIFFERENT RESISTORS

As mentioned before, manufacturers rarely make available the typical capacitance values for their resistors. As a general rule, SMD (surface-mounted) resistors have much lower parasitics than through-hole resistors. The explanation lies in the fact that even ideal conductors under ideal conditions have a certain ability to store charge. Metal leads that connect the resistor to the rest of the circuit are an example of such conductors. The longer the leads, the more charge can be stored and the higher the parasitic capacitance. So, the shorter the leads, the less parasitic effects can be seen in a given resistor, which is why SMD resistors have less parasitic effects. If low capacitance is desired, the resistor should be kept as small and compact as possible. Wire-wound resistors should be avoided because the windings generate inter-coil capacitance, which makes them unusable above 50 kHz. Carbon type resistors are usable up to around 1 MHz. Foil resistors, on the other hand, have superior characteristics for high-frequency use, with the capacitance usually less than 0.05 pF which makes them cope with frequencies up to 100 MHz.

2.4.5. APPLICATIONS WHERE PARASITIC EFFECTS PLAY A ROLE

Parasitic effects are most prominent at high frequencies. For example, a metal foil 1 kΩ resistor at 100 MHz would, in fact, behave as a 1.001 kΩ resistor, when all parasitic effects are considered. This is an example of a good frequency response for a resistor.
For comparison, a wire wound resistor is only usable up to 50 kHz, because of both inductive and capacitive parasitic effects. Even when bifilar (non-inductive) winding methods are used, the inter-coil capacitance limits the maximum usable frequency. Some applications that are particularly sensitive to parasitic effects are: high-frequency amplifier circuits, GHz clock generators, microwave circuits and so on.

An example of a circuit that takes advantage of the capacitive parasitic effect is the snubber resistor, used to protect switching elements (switches and thyristors) from voltage spikes which are generated by inductive loads such as electric motors during current cut-off. These are most often made as bifilar wire wound resistors to reduce the inductance. For snubber applications, the resistors are designed so that the capacitance is in series with the resistor, not in parallel as is the case with standard parasitic capacitances.

2.4.6. NOISE

Noise is an unwanted phenomenon for resistors. For some applications the noise properties are important. Examples are high gain amplifiers, charge amplifiers and low-level signals. Resistor noise is often specified as microvolts noise per volt of applied voltage, for a 1 MHz bandwidth. Thermal noise is the predominant source of noise for resistors. It is dependent on three variables: resistance, temperature and bandwidth. The relation between these three parameters is described by the formula:

\[ E = \sqrt{4 \cdot R \cdot k \cdot T \cdot DF} \]

Where \( E \) is the RMS noise signal in volts, \( R \) is the resistance in ohms, \( K \) is Boltzmann’s constant, \( T \) is the temperature in Kelvin and \( DF \) is
the bandwidth in Hz. The equation shows that the noise level can be decreased by reducing the resistance, the temperature or the bandwidth. Knowing Boltzmann’s constant, the formula is simplified to:

\[ E = 7.43\sqrt{R \cdot T \cdot \Delta F} \]

Where E is now the noise voltage in nanovolts, R in kΩ, and DF in kHz.

2.4.6.1. THERMAL AND CURRENT NOISE

There are two types of noise: the thermal noise and the current noise. To understand their principle, they will be discussed in more detail. In all materials, the electrons permanently move. As temperature increases, the movements increase. The vibrations of the electrons cause an electric signal (AC) across the terminals of the component. Because the vibrations are completely random, the electrical signal is noise. This is called thermal noise or Johnson noise. It is the main contributor to noise for resistors. Thermal noise is constant over a wide frequency range. Current noise however, declines when frequency is increased. The thermal noise increases with a larger resistance value, while the current noise decreases.

2.4.6.2. NOISE STANDARDS

The way to measure resistor current noise is defined in norm IEC 60195. This makes the comparison of different manufacturers possible. The current noise of a resistor is described by the current noise index with a code number.
2.4.6.3. LOW NOISE RESISTOR

Thin film, metal foil and wire wound resistors have better noise characteristics than other types. Therefore they are often specified in low-noise amplifying applications. The carbon composition resistor and thick film are of the worst types. They cope with high noise due to the construction and material.

![Graph showing noise index (dB) for the main resistor types]

2.4.6.4. RESISTOR APPLICATIONS

In every amplifier circuit, the input resistor is critical. Any noise at the input signal will be amplified to the full gain. It is therefore of high importance to choose a low-noise resistor at the first stage, as well as a low resistance value. This is however not valid for a load resistor, since the gain that is obtained from a high resistance value outweighs the higher noise level. Because thermal noise is temperature dependent, it is very effective to cool the input stages to reach a low-noise performance.
2.4.6.5. TEMPERATURE COEFFICIENT

The temperature coefficient of resistance, or TCR, is one of the main used parameters to characterize a resistor. The TCR defines the change in resistance as a function of the ambient temperature. The common way to express the TCR is in ppm/°C, which stands for parts per million per centigrade degree. The temperature coefficient of resistance is calculated as follows:

$$ TCR = \frac{R2 - R1}{R1(T2 - T1)} \times 10^{-6} $$

Where TCR is in ppm/°C, R1 is in ohms at room temperature, R2 is resistance at operating temperature in ohms, T1 is the room temperature in °C and T2 is the operating temperature in °C. Often instead of TCR, $\alpha$ is used.

Average TCR $\Delta R/R$ in ppm for a temperature range of -55 till 25°C and 25 till 125°C

2.4.6.6. POSITIVE OR NEGATIVE TEMPERATURE COEFFICIENT OF RESISTANCE?

Resistors are available with a TCR that is negative, positive, or stable over a certain temperature range. Choosing the right resistor could prevent the need for temperature compensation. In some
applications it is desired to have a large TCR, for example to measure temperature. Resistors for these applications are called thermistors, and can have a positive (PTC) or negative temperature coefficient (NTC).

### 2.4.6.7. MEASURING METHODS FOR THE TCR

The temperature coefficient of resistance for a resistor is determined by measuring the resistances values over an appropriate temperature range. The TCR is calculated as the average slope of the resistance value over this interval. This is accurate for linear relations, since the TCR is constant at every temperature. However, many materials have a nonlinear coefficient. For Nichrome for example, a popular alloy for resistors, the relation between temperature and TCR is not linear. Because the TCR is calculated as average slope, it is therefore very important to specify the TCR as well as the temperature interval. The way to measure TCR is standardized in MIL-STD-202 Method 304. With this method, TCR is calculated for the range between -55°C and 25°C and between 25°C and 125°C. Because the highest measured value is defined as TCR, this method often results in over specifying a resistor for less demanding applications.

In the chart below the temperature coefficient of resistance is given for a wide variety of materials. Note that the exact value depends on the purity of the material as well as the temperature.
### 2.4.7. OTHER RESISTOR PROPERTIES

#### 2.4.7.1. INSULATION OF THE WIRES

Wirewound resistors are enamel insulated (possibly winded with synthetic fiber, silk or cotton) and the oxide layer of the material itself.
2.4.7.2. PROTECTION AGAINST INFLUENCES FROM THE ENVIRONMENT

For applications in very hot and humid climates, the resistor is enclosed in an airtight metal case. If the complete body is covered for example with enamel paint, special care has to be taken that all expansion coefficients are approximately equal. If this is not the case, the enamel layer might burst after the baking process.

2.4.7.3. MAXIMUM ALLOWED VOLTAGE

If the maximum allowed voltage is exceeded, it may cause a disruptive discharge permanently damaging the wire insulation. Also a discharge can pass through the solid insulating material and damaging parts that are nearby.

2.4.7.4. LONG TERM STABILITY

The stability indicates the maximum tolerable change of the resistance value. The resistance value changes on the long term due to mechanical, electrical and thermal loads. In standards several stability classes are determined. The standards define tests to define the stability classes. Short term tests include exposure to overloading, rapid temperature variations and vibrations. Long term tests are for example the damp heat test and load life tests (constant 70°C with a certain electrical load).
### 2.4.7.5. PULSE STABILITY

The pulse stability describes effect on the long term variations of the resistance value, when the resistor is loaded with short term pulses instead of constant load. The pulses can be much higher than the normal power rating, without having an effect on long term stability. Special tests with pulses are defined in standards like the IEC 90115-1, 4.27. To specify a resistor with sufficient pulse stability the following requirements must be met:

- The average load is not larger than the power rating at the normal ambient operating temperature.
- The maximum allowed pulse loading as a function of the duration must not be exceeded.
- The pulse voltage at the resistor must be lower than the allowed pulse peak voltage.

### 2.4.7.6. RESISTANCE VALUE TOLERANCE

Resistors are manufactured with a certain tolerance. Depending on the application, the tolerance must be specified.
2.4.7.7. MECHANICAL STRENGTH

The complete construction must be designed for the planned operating temperature (think for example of heating elements).

2.4.7.8. THERMO-ELECTRIC EFFECT

Between the mounting wire (copper) and the resistor material the thermo-electric effect causes unwanted electric currents. With the manufacturing of precision resistors tried to keep these loads as small as possible.
3. RESISTOR TYPES

Resistors can be divided in construction type as well as resistance material. The following breakdown for the type can be made:

- **Fixed resistors**
- **Variable resistors, such as the:**
  - Potentiometer
  - Rheostat
  - Trimpot
- **Resistance dependent on a physical quantity:**
  - Thermistors (NTC and PTC) as a result of temperature change
  - Photo resistor (LDR) as a result of a changing light level
  - Varistor (VDR) as a result of a changing voltage
  - Magneto resistor (MDR) as a result of a changing magnetic field
  - Strain Gauges as a result of mechanical load

Another breakdown based on the material and manufacturing process can be made:

- Carbon composition
- Carbon film
- Metal film
- Metal oxide film
- Wirewound
- Foil

The choice of material technology is a specific to the purpose. Often it is a trade-off between costs, precision and other requirements. For example, carbon composition is a very old technique with a low precision, but is still used for specific applications where high
energy pulses occur. Carbon composition resistors have a body of a mixture of fine carbon particles and a non-conductive ceramic. The carbon film technique has a better tolerance. These are made of a non-conductive rod with a thin carbon film layer around it. This layer is treated with a spiral cut to increase and control the resistance value. Metal and metal oxide films are widely used nowadays, and have better properties for stability and tolerance. Furthermore, they are less influenced by temperature variations. They are just as carbon film resistors constructed with a resistive film around a cylindrical body. Metal oxide film is generally more durable. Wirewound resistors are probably the oldest type and can be used for both high precision as well as high power applications. They are constructed by winding a special metal alloy wire, such as nickel chrome, around a non-conductive core. They are durable, accurate and can have very low resistance value. A disadvantage is that they suffer from parasitic reactance at high frequencies. For the highest requirements on precision and stability, metal foil resistors are used. They are constructed by cementing a special alloy cold rolled film onto a ceramic substrate.

3.1. FIXED RESISTORS

Fixed value resistors have a defined ohmic resistance and are not adjustable. Fixed resistors are the most commonly used resistors and in general one of the most used electronic components. Fixed resistors are available in axial leaded and surface mount packages as well as more customized packages depending on their application. While axial leaded resistors used to be the most used resistors, nowadays the advantages of surface mount devices make the SMD resistors the most popular.
A fixed resistor has a static, defined electrical resistance which is not adjustable.

In an ideal world a perfect resistor would have a constant ohmic resistance under all circumstances. This resistance would be independent of for example frequency, voltage or temperature. In practice no resistor is perfect and all resistors have a certain stray capacitance and inductance, resulting in an impedance value different from the nominal resistance value. The resistor materials have a certain temperature coefficient, resulting in a temperature dependency of the resistor value. The different resistor types and materials determine the dependency of the resistance value on these external factors. Depending on e.g. the required accuracy, power dissipation and noise requirements, the type and material of resistor are selected. Some common types of fixed resistors are displayed below.

3.1.1. IDENTIFYING FIXED VALUE RESISTORS

In the next table an overview of general purpose resistors is given. The types listed here are among the most used resistors in general. The carbon film is the most common axial leaded resistor which is used for applications where a very good tolerance and temperature coefficient are not necessary. The metal film is the general axial leaded resistor of choice for higher precision applications. For high power applications wirewound resistors are often used, the aluminum housing as shown in the picture is often used for power ratings from 10-250W. Surface mount or SMD resistors are in general constructed from thick or thin film material. The properties listed in this table indicate common ranges for the values followed by the most common value between brackets. However these
values should not be seen as limiting, several special purpose resistors with very different characteristics exist.

### Examples of general purpose fixed resistors

<table>
<thead>
<tr>
<th>Type</th>
<th>Carbon film</th>
<th>Metal film</th>
<th>Wirewound</th>
<th>Surface mount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerance</td>
<td>2-10% (5%)</td>
<td>0.1-5% (1%)</td>
<td>0.1-5% (1%)</td>
<td>0.1-5% (1%)</td>
</tr>
<tr>
<td>Power rating</td>
<td>0.125-2W (¼W)</td>
<td>0.1-5W (¼W)</td>
<td>1-200W (10W)</td>
<td>0.0125-0.25W (0.1W)</td>
</tr>
<tr>
<td>Temp. coefficient</td>
<td>250-450 ppm/K (450)</td>
<td>10-250 ppm/K (50)</td>
<td>20-400 ppm/K (50)</td>
<td>25-200 ppm/K (100)</td>
</tr>
</tbody>
</table>

#### 3.1.2. FIXED RESISTOR SYMBOLS

The following resistor symbols are often used to depict resistors with a fixed value. The most used symbol is the international IEC resistor symbol displayed on the left but the American resistor symbol displayed on the right is also still used.

*Fixed resistor symbol, IEC standard (left) and ANSI standard*
3.2. VARIABLE RESISTORS

A variable resistor is a resistor of which the electric resistance value can be adjusted. A variable resistor is in essence an electro-mechanical transducer and normally works by sliding a contact (wiper) over a resistive element. When a variable resistor is used as a potential divider by using 3 terminals it is called a potentiometer. When only two terminals are used, it functions as a variable resistance and is called a rheostat. Electronically controlled variable resistors exist, which can be controlled electronically instead of by mechanical action. These resistors are called digital potentiometers.

A variable resistor has an adjustable ohmic resistance value. This can be done either mechanically (potentiometer, rheostat) or electronically (digital potentiometer).

3.2.1. POTentiOMETER

A potentiometer is a manually adjustable variable resistor with 3 terminals. Two terminals are connected to both ends of a resistive element, and the third terminal connects to a sliding contact, called a wiper, moving over the resistive element. The position of the wiper determines the output voltage of the potentiometer. The potentiometer essentially functions as a variable voltage divider. The resistive element can be seen as two resistors in series (potentiometer resistance), where the wiper position determines the resistance ratio of the first resistor to the second resistor.
A potentiometer is also commonly known as a potmeter or pot. The most common form of potmeter is the single turn rotary potmeter. This type of pot is often used in audio volume control (logarithmic taper) as well as many other applications. Different materials are used to construct potentiometers, including carbon composition, cermet, wirewound, conductive plastic or metal film.

A potentiometer is a manually adjustable, variable resistor with three terminals. Two terminals are connected to a resistive element; the third terminal is connected to an adjustable wiper. The position of the wiper determines the output voltage.

A wide variety of potmeters exist. Manually adjustable potmeters can be divided in rotary or linear movement types. The tables below list the available types and their applications. Besides manually adjustable pots, also electronically controlled potentiometers exist, often called digital potmeters.

3.2.1.1. ROTARY POTENTIOMETER

The most common type of potentiometer has a wiper that moves along a circular path.
<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-turn pot pot</td>
<td>Single rotation of approximately 270 degrees or 3/4 of a full turn</td>
<td>Most common pot, used in applications where a single turn provides enough control resolution.</td>
</tr>
<tr>
<td>Multi-turn pot pot</td>
<td>Multiple rotations (mostly 5, 10 or 20), for increased precision. They are constructed either with a wiper that follows a spiral or helix form, or by using a worm-gear.</td>
<td>Used where high precision and resolution is required. The worm-gear multi turn pots are often used as trimpots on PCB.</td>
</tr>
<tr>
<td>Dual-gang pot pot</td>
<td>Two potentiometers combined on the same shaft, enabling the parallel setting of two channels. Most common are single turn potentiometers with equal resistance and taper. More than two gangs are possible but not very common.</td>
<td>Used in for example stereo audio volume control or other applications where 2 channels have to be adjusted in parallel.</td>
</tr>
<tr>
<td>Concentric pot pot</td>
<td>Dual potmeter, where the two potentiometers are individually adjusted by means of concentric shafts. Enables the use of two controls on one unit.</td>
<td>Often encountered in (older) car radios, where the volume and tone controls are combined.</td>
</tr>
<tr>
<td>Servo pot</td>
<td>A motorized potmeter which can also be automatically adjusted by a servo motor.</td>
<td>Used where manual and automatic adjustment is required. Often seen in audio equipment, where the remote-control can turn the volume control knob.</td>
</tr>
</tbody>
</table>

![Dual-gang potentiometer](image1.png) ![Concentric potentiometer](image2.png) ![Multi-turn potentiometer](image3.png)
### 3.2.1.2. Linear Potentiometer

Linear potentiometers have a wiper that moves along a linear path. They are also known as slider, slide pot or fader.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slide pot</td>
<td>Single linear slider potentiometer, for audio applications also known as a fader. High quality faders are often constructed from conductive plastic.</td>
<td>For single channel control or measurement of distance.</td>
</tr>
<tr>
<td>Dual-slide pot</td>
<td>Dual slide potentiometer, single slider controlling two potentiometers in parallel.</td>
<td>Often used for stereo control in professional audio or other applications where dual parallel channels are controlled.</td>
</tr>
<tr>
<td>Multi-turn slide</td>
<td>Constructed from a spindle which actuates a linear potentiometer wiper. Multiple rotations (mostly 5, 10 or 20), for increased precision.</td>
<td>Used where high precision and resolution is required. The multi turn linear pots are used as trimpots on PCB, but not as common as the worm-gear trimmer potentiometer.</td>
</tr>
<tr>
<td>Motorized fader</td>
<td>Fader which can be automatically adjusted by a servo motor.</td>
<td>Used where manual and automatic adjustment is required. Common in studio audio mixers, where the servo faders can be automatically moved to a saved configuration.</td>
</tr>
</tbody>
</table>

---

*Slide potentiometer*  *Motorized fader*  *Multi-turn trimpot*  *Linear*
3.2.1.3. DIGITAL POTENTIOMETER

Digital potentiometers are potentiometers which are controlled electronically. In most cases they exist of an array of small resistive components in series. Every resistive element is equipped with a switch which can serve as the tap-off point or virtual wiper position. A digital potmeter can be controlled by for example up/down signals or protocols like I²C and SPI.

3.2.1.4. MATERIALS USED FOR POTMETERS
### Resistor Types

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon composition</td>
<td>Carbon composition ink molded on a substrate (phenolic resin). Most common material, low cost and reasonable noise and wear characteristics.</td>
</tr>
<tr>
<td>Wirewound</td>
<td>Wirewound pots can handle high power, are long lasting and can be very precise. They have however a limited resolution and rough feel. Most used in high power applications (rheostats are often wirewound) or as precision pots.</td>
</tr>
<tr>
<td>Conductive plastic</td>
<td>Very smooth feel and high resolution can be constructed to perform millions of cycles. Can only handle a limited power and are expensive. Often used in high-end (audio) equipment where a high resolution and low noise are important.</td>
</tr>
<tr>
<td>Cermet</td>
<td>Very stable, low temperature coefficient and handles high temperatures well. On the other hand quite expensive and often limited amount of cycles allowed (special long-life cermet pots also exist). They are widely used for trimpots which do not have to be adjusted often.</td>
</tr>
</tbody>
</table>

#### 3.2.1.5. STANDARD VALUES

Because potmeters are variable there is no need for a wide range of values. While potentiometers can be manufactured in every resistance value you can think of, most potmeters have values in the following range of multiples.

<table>
<thead>
<tr>
<th>Common potentiometer values (multiples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10       20       22       25       47       50</td>
</tr>
</tbody>
</table>

By far the most used value for potentiometers is 10 kOhm other very common values are 1k, 5k and 100k.
### 3.2.1.6. CHARACTERISTICS

#### Taper

The potentiometer taper is the relationship between the mechanical position and resistance ratio. Linear taper and logarithmic (audio) taper are the most common forms of taper. For more information visit the dedicated page about potentiometer taper.

#### Marking codes

Potentiometers values are often marked with a readable string indicating the total resistance, such as “100k” for a 100 kOhm potentiometer. Sometimes a 3 digit coding system similar to smd resistor coding is used. In this system the first digits indicate the value and the last digit indicates the multiplier. For example a 1 kOhm would be coded as 102, meaning $10\Omega \times 10^2 = 1\,\Omega$.

The taper of a potentiometer is normally indicated with a letter. The following table lists the used coding for potentiometer taper, different standards uses the same letters which can be confusing. It is always a good idea to double check the taper by measurement.

<table>
<thead>
<tr>
<th>Taper</th>
<th>String</th>
<th>Asia (common)</th>
<th>Europe</th>
<th>America</th>
<th>Vishay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>LIN</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Log / Audio</td>
<td>LOG</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>L</td>
</tr>
<tr>
<td>Anti-log</td>
<td>-</td>
<td>-</td>
<td>F</td>
<td>C</td>
<td>F</td>
</tr>
</tbody>
</table>
Resolution

The resolution of a potentiometer is the smallest possible change in resistance ratio. Wirewound resistors often have a lower resolution because the wire turns introduce discrete steps in resistance. Conductive plastic potmeters have the best resolution. The resolution can be influenced by the wiper configuration; a wiper consisting of several spread contact points increases the potentiometer resolution.

Hop-on and Hop-off resistance

At the start and end of travel, the resistive track of a potentiometer is connected to low resistance metal parts which connect the resistive element to the end terminals. The change in resistance when the wiper enters or exits the resistive track is known as the hop-on and hop-off resistance.

3.2.1.7. APPLICATIONS FOR POTS

Potentiometers are used in a very wide range of industries and applications; it would be difficult to list all applications here. It can be used as a control input, position measurement or calibration component and much more.

User controlled inputs

Where a variable input from the user of a machine or application is required, potentiometers are often used. In automotive applications, the throttle pedal is often a potentiometer; normally
this is a dual gang pot to increase redundancy of the system. Another application of pots is joysticks for machine control.

**AUDIO CONTROL**

Volume control is often performed with a (motorized) potentiometer in audio applications. For balance control a dual-gang potentiometer can be used, where one gang has a logarithmic taper and the other gang has an inverse logarithmic taper. In professional audio equipment, faders are often used.

**Position or angle transducer**

Potentiometers are often used as a position or angle transducer to measure distances or angles.

**Calibration and tuning**

In fabrication and calibration, trimpots are often used. Trimpots are preset potentiometers which are often mounted on a circuit board and can be used to tune or adjust the circuit’s performance. They are used only during calibration of the system and are at a fixed position most of the time. Trimpots are often actuated by a small flat-head screwdriver. Trimpots are also known as presets, trimmers or trimming potentiometers.

---

### 3.2.1.8. POTENTIOMETER TAPER

Potentiometer taper is the relation between the position and the resistance of a pot. In the majority of variable resistors available this is a linear relationship, meaning that the relative position is equal to the resistance ratio. For example when the potmeter is at the
middle position, the output voltage is half of the full voltage over the potentiometer. For some applications and especially audio volume control, non-linear, logarithmic tapers are used.

**Taper is the relation between the position of the potentiometer and the resistance ratio.**

**Types**

The simple linear taper is the most common form, when we plot the position against the resistance ratio we can visualize the different position-resistance relations. The graph below shows the most used tapers. The first and last few percent of travel are often only mechanical with no change in resistance. The region between 5 and 95% where the electrical resistance changes, is called the electrical travel. The available travel for rotary pots is often denoted in degrees, a mechanical travel of 300° combined with an electrical travel of 270° is common.

**Audio taper**

The most used non-linear taper is the logarithmic (log) or audio taper. This is mainly used for audio volume control, to obtain a more natural ‘linear’ perception in sound intensity change when you adjust the volume. Because the human ear is sensitive to sound intensity in a logarithmic fashion, at low sound intensities a small change in intensity is perceived as a big change in loudness, while at high intensities a large change is required for the same change in perceived loudness. To compensate for the ears logarithmic behavior, audio taper pots were developed. While it is called logarithmic, it is actually an exponential curve (the opposite of the logarithmic behavior of the human ear). Sometimes inverse logarithmic (anti-log) pots are used, for example in audio controls
which turn counterclockwise, but also in some other specialized applications.

The dashed lines in the graph below show the ‘real’ logarithmic curves. In practice logarithmic types which are used for audio applications do not really behave in a correct exponential way, but follow the curve stepwise. The bottom thick line shows the actual taper curve of an audio potentiometer. This approximation is done because it simplifies the manufacturing process. Instead of a continuously varying resistance tracks, two different tracks are used which overlap at the middle position. As audio volume control is a non-critical operation in general this satisfies for these applications. There exist tapered potentiometers with real exponential curves for specialized applications.

![Graph showing resistance vs position for different types of potentiometers](image)

### 3.2.1.9. POTENTIOMETER SYMBOL

The following symbol is used for a potentiometer. The potentiometer symbol on the left is according to the IEC standard.
The potmeter symbol on the right is according to the old American standard.

![Potentiometer symbol](Potentiometer.png)

**Potentiometer symbol**

---

### 3.2.2. DIGITAL POTENTIOMETER

A digital potentiometer (also known as digital resistor) has the same function as a normal potentiometer but instead of mechanical action it uses digital signals and switches. This is done by making use of a ‘resistor ladder’, a string of small resistors in series. At every step of the ladder, an electronic switch is present. Only one switch is closed at the same time and in this way the closed switch determines the ‘wiper’ position and the resistance ratio. The amount of steps in the ladder determines the resolution of the digital pot. The diagram below shows the working principle of a digital potentiometer with 64 steps. Digital resistors can be controlled by using simple up/down signals or by serial protocols such as I²C or SPI.

![Resistor ladder diagram](Resistor_ladder.png)
A digital potentiometer is a variable resistor which is controlled by digital signals instead of by mechanical movement.

Properties of digital potentiometers

Digital potentiometers are integrated circuit (ICs), some variants have a nonvolatile memory (EEPROM) which remembers the ‘wiper’ position. When there is no on-board memory, the initial position of the wiper is often the middle position. Because of their relatively small size compared to conventional potentiometers, multiple potentiometers can be packed on a chip and ICs with up to 6 channels are available.

The amount of steps available determines the resolution of the digital potentiometer. The following table lists common step values available, including the bit count:

<table>
<thead>
<tr>
<th>Number of steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Steps</td>
</tr>
</tbody>
</table>

Digital resistors are available in a range of values, but 10 kΩ is the most used. Other common values are 5, 50 and 100 kΩ. The standard tolerance is 20% but nowadays digital potentiometers with a tolerance down to 1% are available.

Something to take into account when you start working with digital potentiometers is the fact that most of them are rated at 5V (to power the logic circuits). This can make it a bit tricky to use them as a direct replacement for conventional potentiometers.
Applications

Digital pots can be used in any application where normally a trimming potentiometer or preset-resistor is used. The big advantage of them is that they can be controlled in closed loop. When used for tuning, re-calibration can be done by a microcontroller at defined intervals. They are used in for example brightness and contrast control of monitors, gain control or Wheatstone bridges and even digital-analog converters. The image below shows an example application of a digipot used for volume control. The potentiometer can be controlled via up/down signals, via buttons or a rotary encoder.

![Digital potentiometer used for a volume control application.](image-url)
3.2.3. RHEOSTAT

A rheostat is a variable resistor which is used to control current. They are able to vary the resistance in a circuit without interruption. The construction is very similar to the construction of potentiometers. It uses only two connections, even when 3 terminals (as in a potentiometer) are present. The first connection is made to one end of the resistive element and the other connection to the wiper (sliding contact). In contrast to potentiometers, rheostats have to carry a significant current. Therefore they are mostly constructed as wire wound resistors. Resistive wire is wound around an insulating ceramic core and the wiper slides over the windings.

Rheostats were often used as power control devices, for example to control light intensity (dimmer), speed of motors, heaters and ovens. Nowadays they are not used for this function anymore. This is because of their relatively low efficiency. In power control applications they are replaced by switching electronics. As a variable resistance they are often used for tuning and calibration in circuits. In these cases they are adjusted only during fabrication or circuit tuning (preset resistor). In such cases trimpots are often used, wired as a rheostat. But dedicated 2 terminal preset resistors also exist.

A rheostat is a variable resistor which is used to control the current flowing in a circuit.
Types of rheostats

Several types of rheostats exist. The rotary type is the most used in power control applications. Most of the time these rheostats are using an open construction, but enclosed types are also available. Just as with potentiometers, multi-gang types are also available. They are used to control multiple applications in parallel or to increase the power rating or adjusting range. Optionally rheostats can be equipped with a mechanical stop to limit the minimum or maximum resistance. For special applications they can also be built with tapered windings.

Slide rheostats are also available and often used for education and in laboratory environments. Linear or slide types are constructed of resistive wire wound on an insulating cylinder. A sliding contact is used to increase or decrease the resistance.

Trimmers used as a variable resistance are very common on printed circuit boards. While dedicated preset resistors with 2 terminals exist, the 3-terminal trimmer potentiometer is more common and often used by wiring it as a rheostat.
**How to wire a potentiometer as rheostat?**

Any 3-terminal potentiometer can be wired as a rheostat by connecting one end of the resistive track and the wiper. It is best practice to connect the wiper together with the other end of the resistive track. Doing this prevents circuit interruption in case the wiper loses connection with the resistive track and reduces noise during adjustment.

![Potentiometer symbol](image)

*Potentiometer wired as a variable resistance*

**Rheostat symbols**

The following symbols are used according to the IEC standard.

![Rheostat symbols](image)

<table>
<thead>
<tr>
<th>Rheostat</th>
<th>symbol</th>
<th>Preset</th>
<th>resistor</th>
<th>symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC standard</td>
<td>IEC standard</td>
<td>IEC standard</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.2.4. TRIMPOT

A trimpot or trimmer potentiometer is a small potentiometer which is used for adjustment, tuning and calibration in circuits. When they
are used as a variable resistance (wired as a rheostat) they are called preset resistors. Trimpots or presets are normally mounted on printed circuit boards and adjusted by using a screwdriver. The material they use as a resistive track is varying, but the most common is either carbon composition or cermet. Trimpots are designed for occasional adjustment and can often achieve a high resolution when using multi-turn setting screws. When trimmer potentiometers are used as a replacement for normal potentiometers, care should be taken as their designed lifespan is often only 200 cycles.

Trimmer potentiometers and preset resistors are small variable resistors which are used in circuits for tuning and (re)calibration.

3.2.4.1. TYPES OF TRIMPOTS

Several different versions of trimpots are available, using different mounting methods (through-hole, SMD) and adjusting orientations (top, side) as well as single and multi-turn variations.

Single turn

Single turn trimmers/presets are very common and used where a resolution of one turn is sufficient. They are the most cost effective variable resistors available.
Multi turn

For higher adjustment resolutions, multi-turn trimpots are used. The amount of turns varies roughly from 5 to 25. Common values are 5, 12 or 25 turns are quite common. They are often constructed using a worm-gear (rotary track) or lead screw (linear track) mechanism to achieve the high resolution. Because of their more complex construction and manufacturing, they are more costly than single turn preset resistors. The lead screw packages can have a higher power rating because of their increased surface area.
3.2.4.2. TRIMPOT SYMBOLS

The following IEC symbols are used for trimpots and preset resistors. Although these are the official symbols for occasionally adjusted resistors, the standard symbols for a potentiometer or rheostat are often used.

![Trimpot Symbol](image1)
![Preset Resistor Symbol](image2)
![Potentiometer Symbol](image3)
![Rheostat Symbol](image4)

3.2.5. THERMISTOR

A thermistor is a temperature sensitive resistor; they are often used as a temperature sensor. The term thermistor is a contraction of the words “thermal” and “resistor”. All resistors have some dependency on temperature, which is described by their temperature coefficient. In most cases for (fixed or variable) resistors the temperature coefficient is minimized, but in the case of thermistors a high coefficient is achieved.
Unlike most other resistors, thermistors usually have negative temperature coefficients (NTC) which means the resistance decreases as the temperature increases. These types are called NTC thermistors. Thermal resistors with a positive temperature coefficient are called PTC thermistors (Positive Temperature Coefficient).

A thermistor is a resistor whose resistance changes significantly with a change in temperature.

### 3.2.5.1. TYPES AND APPLICATIONS

Thermistors are ceramic semiconductors. In most cases they are composed of metal oxides, which are dried and sintered to obtain the desired form factor. The types of oxides and additives determine their characteristic behavior. For NTC’s cobalt, nickel, iron, copper or manganese are common oxides. For PTC’s barium, strontium or lead titanates are commonly used.

### 3.2.5.2. NTC THERMISTOR

The NTC type is used when a change in resistance over a wide temperature range is required. They are often used as temperature sensors in the range of -55°C to 200°C, although they can be produced to measure much lower or higher temperatures. Their
popularity can be accounted to their quick response, reliability, robustness and low price.

### 3.2.5.3. PTC THERMISTOR

The PTC type is used when a sudden change in resistance at a certain temperature is required. They exhibit a sudden increase in resistance above a defined temperature, called the switch, transition of “Curie” temperature. The most common switching temperatures are in the range of 60°C to 120°C. They are often used for self-regulating heating elements and self-resetting over-current protection.

<table>
<thead>
<tr>
<th></th>
<th>NTC</th>
<th>PTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature coefficient</td>
<td>Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>Metal oxides</td>
<td>cobalt, nickel, iron, manganese, titanium</td>
<td>barium-, lead-, strontium titanate</td>
</tr>
<tr>
<td>Common temperature range</td>
<td>-55°C to 200°C</td>
<td>60°C to 120°C (switching temp.)</td>
</tr>
<tr>
<td>Applications</td>
<td>Temperature sensing and control, inrush current limiting, flow measurement</td>
<td>over-current protection, self-regulating heater, time-delays, liquid level sensing</td>
</tr>
</tbody>
</table>

### 3.2.5.4. THERMISTOR PACKAGES

Several package types and sized are available, the radial leaded type is the most common and mostly constructed from epoxy. For
applications in harsh environments, glass encapsulated packages are more suitable. Integrated packages are also available, such as threaded housings, lugs or probes for easy mounting. The following table shows some examples of available package types.

<table>
<thead>
<tr>
<th>Radial leaded</th>
<th>Axial leaded</th>
<th>Glass</th>
<th>Threaded</th>
<th>Probe</th>
</tr>
</thead>
</table>

3.2.5.5. **THERMISTOR SYMBOLS**

The following symbols are used according to the IEC standard.

- **NTC thermistor symbol**
- **PTC thermistor symbol**
3.2.6. VARISTOR

A varistor is a voltage dependent resistor (VDR). The resistance of a varistor is variable and depends on the voltage applied. The word is composed of parts of the words “variable resistor”. Their resistance decreases when the voltage increases. In case of excessive voltage increases, their resistance drops dramatically. This behavior makes them suitable to protect circuits during voltage surges. Causes of a surge can include lightning strikes and electrostatic discharges. The most common type of VDR is the metal oxide varistor or MOV.

Varistors are nonlinear two-element semiconductors that drop in resistance as voltage increases. Voltage dependent resistors are often used as surge suppressors for sensitive circuits.

3.2.6.1. PACKAGES

Here are some examples of different packages which are often encountered. The block packages are used for higher power ratings.

Disc  Block  Radial leaded  Axial leaded
3.2.6.2. CHARACTERISTICS

A voltage dependent resistor has a nonlinear varying resistance, dependent on the voltage applied. The impedance is high under nominal load conditions, but will sharply decrease to a low value when a voltage threshold, the breakdown voltage, is exceeded. They are often used to protect circuits against excessive transient voltages. When the circuit is exposed to a high voltage transient, the varistor starts to conduct and clamps the transient voltage to a safe level. The energy of the incoming surge is partially conducted and partially absorbed, protecting the circuit.

The most common type is the MOV, or metal oxide varistor. They are constructed of a sintered matrix of zinc oxide (ZnO) grains. The grain boundaries provide P-N junction semiconductor characteristics, similar to a diode junction. The matrix of randomly oriented grains can be compared to a large network of diodes in series and parallel. When a low voltage is applied, only very little current flows, caused by the reverse leakage through the junctions. However when a high voltage is applied, which exceeds the breakdown-voltage, the junctions experience an avalanche breakdown and a large current can flow. This behavior results in the nonlinear current-voltage characteristics.

The relationship between the current (I) through and the voltage (V) across the terminals is typically described by:

\[ I = k \cdot V^\alpha \]

The term \( \alpha \) describes the degree of non-linearity. Figure 1 shows the characteristic curves of a MOV (high \( \alpha \)) and SiC varistor (low \( \alpha \)).
Important selection parameters are the clamping voltage, peak current, maximum pulse energy, rated AC/DC voltage and standby current. When used on communications lines, the stray capacitance is also an important parameter. A high capacitance can act as a filter for high frequency signals or induce crosstalk, limiting the available bandwidth of the communications line.

Varistors are useful for short duration protection in case of high transient voltage surges in the order of 1-1000 microseconds. They are however not suited to handle sustained surges. If transient pulse energy in joules (J) is too high and significantly exceeds the absolute maximum ratings, they can melt, burn or explode.

MOVs degrade when exposed to repeated surges. After each surge the MOVs clamping voltage moves a little lower, how much depends on the joule rating of the MOV in relation to the pulse. As the clamping voltage falls lower and lower, a possible failure mode is a partial or complete short circuit, when the clamping voltage falls
below the protected line voltage. This situation could lead to a fire hazard. To prevent fire hazards, they are often connected in series with a thermal fuse which disconnects the MOV in case of overheating. To limit the degradation, it is advisable to use an as high clamping-voltage as the protected circuit allows, to limit the amount of exposure to surges.

3.2.6.3. APPLICATIONS

The nonlinear characteristic of the varistor make them ideal for use as surge protector devices. Sources of high voltage transients can for example be lightning strikes, electrostatic discharges or inductive discharge from motors or transformers. They are for example often used in surge protector power strips. Special types with a low capacitance protect communication lines. These VDRs are useful for a wide variety of applications that can include:

- Telephone and other communication line protection
- Radio communication equipment transient suppression
- Surge protector power strips
- Cable TV system surge protectors
- Power supply protection
- Microprocessor protection
- Electronics equipment protection
- Low voltage board level protection
- Transient voltage surge suppressor (TVSS)
- Car electronics protection
- Industrial high energy AC protection
3.2.6.4. TYPES

The most important types are:

- Metal oxide varistor – Described before, the MOV is a nonlinear transient suppressor composed of zinc oxide (ZnO)
- Silicon carbide varistor – At one time this was the most common type before the MOV came into the market. These components utilize silicon carbide (SiC). They have been intensively used in high power, high voltage applications. The disadvantage of these devices is that they draw a significant standby current; therefore a series gap is required to limit the standby power consumption.

Alternative types of surge suppressing devices include:

- Selenium cells – These suppressors use selenium rectifiers allowing a high-energy reverse breakdown current. Some selenium cells have seal-healing properties that allow them to withstand high-energy discharges. They however do not have the clamping ability of modern MOVs.
- Zener diodes – A transient suppression device that utilizes silicon rectifier technology. They have a very constant voltage clamp ability. The major drawback of these components is that they have a limited energy dissipation capability.
- Crowbar devices – A crowbar device short-circuits a surge to ground, this short-circuit will continue until the current is below a certain very low level. Creating a lagging or power-follow effect. Examples of crowbar devices are:
  - Gas discharge tube (GDT) or spark gap – These devices conduct after a conducting spark is
created, the disadvantage is that they take a relative long time to trigger, the advantage is the large current carrying capabilities.

- Thyristor surge protection device (TSPD) – has similar characteristics as a GDT, but can act much faster.

### 3.2.6.5. VARIStOR SYMBOL

The following symbol is used for a varistor. It is depicted as a variable resistor which is dependent on voltage, $U$.

![Varistor symbol IEC standard](image)

### 3.2.7. MAGNETO RESISTOR

Magneto resistors have a variable resistance which is dependent on the magnetic field strength. A Magneto resistor can be used to measure magnetic field presence, strength and direction. They are also known as magnetic dependent resistors (MDR). A magneto resistor is a subfamily of magnetic field sensors or magnetometers.

A magneto resistor is a resistor of which the electrical resistance changes when an external magnetic field is applied.
3.2.7.1. MAGNETO RESISTOR CHARACTERISTICS

Magneto resistors make use of the magnetoresistance effect. This effect was first discovered in 1856 by William Thomson, also known as Lord Kelvin. The effect is noticed in ferromagnetic materials and dependent on the magnetic field strength and angle between the direction of electric current and the magnetic field. This effect is therefore known as anisotropic magnetoresistance (AMR). Other, more recently discovered magnetoresistance effects are the giant magnetoresistance effect (GMR), collosal magnetoresistance effect (CMR) and tunnel magnetoresistance effect (TMR). Because most conventional magneto resistors utilize the AMR effect, the other effects will not be discussed in this article.

Permalloy, an alloy consisting of 81% nickel (Ni) and 19% iron (Fe) has a high anisotropic magneto resistance as well as a low magnetostriction (change in size due to magnetic fields) and therefore is a favorite material for magneto resistors.

Magneto resistors are often constructed of long thin films of permalloy. To increase the sensitivity of a permalloy magneto resistor, shorting bars of aluminium or gold are placed on the thin permalloy films under an angle of 45 degrees. This forces the current to flow in a direction of 45 degrees relative to the length of the film. This is called a barber pole configuration.

Permalloy film magnetoresistor using barber pole pattern of shorting bars
A typical AMR magnetoresistive sensor is constructed of a combination of 4 permalloy thin film magnetoresistors, connected in a wheatstone measurement bridge.

### 3.2.7.2. MAGNETO RESISTOR APPLICATIONS

Various applications are possible as magnetic field sensing devices, applications include for example:

- Electronic compass
- Magnetometry, measurement of magnetic field intensity and direction
- Position sensors
  - Angle position sensors
  - Rotary position sensors
  - Linear position sensors
- Ferrous metal detection
  - Vehicle and traffic detection

### 3.2.7.3. MAGNETO RESISTOR SYMBOL

The following symbol is used for a magneto resistor. It is shown as a variable resistor which is dependent on magnetic flux, indicated by ‘x’.

![Magneto resistor symbol IEC standard](image)
3.2.8. PHOTO RESISTOR

Photo resistors, also known as light dependent resistors (LDR), are light sensitive devices most often used to indicate the presence or absence of light, or to measure the light intensity. In the dark, their resistance is very high, sometimes up to 1MΩ, but when the LDR sensor is exposed to light, the resistance drops dramatically, even down to a few ohms, depending on the light intensity. LDRs have a sensitivity that varies with the wavelength of the light applied and are nonlinear devices. They are used in many applications but are sometimes made obsolete by other devices such as photodiodes and phototransistors. Some countries have banned LDRs made of lead or cadmium over environmental safety concerns.

Photo resistors are light sensitive resistors whose resistance decreases as the intensity of light they are exposed to increases.

3.2.8.1. TYPES OF PHOTO RESISTORS AND WORKING MECHANISMS

Based on the materials used, photo resistors can be divided into two types: intrinsic and extrinsic. Intrinsic photo resistors use undoped materials such as silicon or germanium. Photons that fall on the device excite electrons from the valence band to the conduction band, and the result of this process are more free electrons in the material, which can carry current, and therefore less resistance. Extrinsic photo resistors are made of materials
doped with impurities, also called dopants. The dopants create a new energy band above the existing valence band, populated by electrons. These electrons need less energy to make the transition to the conduction band thanks to the smaller energy gap. The result is a device sensitive to different wavelengths of light. Regardless, both types will exhibit a decrease in resistance when illuminated. The higher the light intensity, the larger the resistance drop is. Therefore, the resistance of LDRs is an inverse, nonlinear function of light intensity.

3.2.8.2. **WAVELENGTH DEPENDENCY**

The sensitivity of a photo resistor varies with the light wavelength. If the wavelength is outside a certain range, it will not affect the resistance of the device at all. It can be said that the LDR is not sensitive in that light wavelength range. Different materials have different unique spectral response curves of wavelength versus sensitivity. Extrinsic light dependent resistors are generally designed for longer wavelengths of light, with a tendency towards the infrared (IR). When working in the IR range, care must be taken to avoid heat buildup, which could affect measurements by changing the resistance of the device due to thermal effects. The figure shown here represents the spectral response of photoconductive detectors made of different materials, with the operating temperature expressed in K and written in the parentheses.
3.2.8.3. SENSITIVITY

Light dependent resistors have a lower sensitivity than photo diodes and photo transistors. Photo diodes and photo transistors are true semiconductor devices which use light to control the flow of electrons and holes across PN-junctions, while light dependent resistors are passive components, lacking a PN-junction. If the light intensity is kept constant, the resistance may still vary significantly due to temperature changes, so they are sensitive to temperature changes as well. This property makes LDRs unsuitable for precise light intensity measurements.

3.2.8.4. LATENCY

Another interesting property of photo resistors is that there is time latency between changes in illumination and changes in resistance. This phenomenon is called the resistance recovery rate. It takes usually about 10 ms for the resistance to drop completely when light is applied after total darkness, while it can take up to 1 second for the resistance to rise back to the starting value after the
complete removal of light. For this reason the LDR cannot be used where rapid fluctuations of light are to be recorded or used to actuate control equipment, but this same property is exploited in some other devices, such as audio compressors, where the function of the light dependent resistor is to smooth the response.

### 3.2.8.5. CONSTRUCTION AND PROPERTIES OF PHOTORESISTORS

Since the discovery of selenium photoconductivity, many materials have been found with similar characteristics. In the 1930s and 1940s PbS, PbSe and PbTe were studied following the development of photoconductors made of silicon and germanium. Modern light dependent resistors are made of lead sulfide, lead selenide, indium antimonide, and most commonly cadmium sulfide and cadmium selenide. The popular cadmium sulfide types are often indicated as CdS photoresistors. To manufacture a cadmium sulfide LDR, highly purified cadmium sulfide powder and inert binding materials are mixed. This mixture is then pressed and sintered. Electrodes are vacuum evaporated onto the surface of one side to form interleaving combs and connection leads are connected. The disc is then mounted in a glass envelope or encapsulated in transparent plastic to prevent surface contamination. The spectral response curve of cadmium sulfide matches that of the human eye. The peak sensitivity wavelength is about 560-600 nm which is in the visible part of the spectrum. It should be noted that devices containing lead or cadmium are not RoHS compliant and are banned for use in countries that adhere to RoHS laws.
3.2.8.6. TYPICAL APPLICATIONS FOR PHOTORESISTORS

Photo resistors are most often used as light sensors. They are often utilized when it is required to detect the presence and absence of light or measure the light intensity. Examples are night lights and photography light meters. An interesting hobbyist application for light dependent resistors is the line following robot, which uses a light source and two or more LDRs to determine the needed change of course. Sometimes, they are used outside sensing applications, for example in audio compressors, because their reaction to light is not instantaneous, and so the function of LDR is to introduce a delayed response.

3.2.8.7. LIGHT SENSOR

If a basic light sensor is needed, an LDR circuit such as the one in the figure can be used. The LED lights up when the intensity of the light reaching the LDR resistor is sufficient. The 10K variable resistor is used to set the threshold at which the LED will turn on. If the LDR light is below the threshold intensity, the LED will remain in the off state. In real-world applications, the LED would be replaced with a
relay or the output could be wired to a microcontroller or some other device. If a darkness sensor was needed, where the LED would light in the absence of light, the LDR and the two 10K resistors should be swapped.

3.2.8.8. AUDIO COMPRESSORS

Audio compressors are devices which reduce the gain of the audio amplifier when the amplitude of the signal is above a set value. This is done to amplify soft sounds while preventing the loud sounds from clipping. Some compressors use an LDR and a small lamp (LED or electroluminescent panel) connected to the signal source to create changes in signal gain. This technique is believed by some to add smoother characteristics to the signal because the response times of the light and the resistor soften the attack and release. The delay in the response time in these applications is on the order of 0.1s.

3.2.8.9. LIGHT DEPENDENT RESISTOR SYMBOL

The following symbol is used to depict light dependent or photo resistors according to the IEC standard. Sometime the resistor symbol is circled, with the arrows outside the circle.

Photo resistor symbol IEC standard
3.3. WIREWOUND RESISTOR

A wire wound resistor is an electrical passive component that limits current. The resistive element exists out of an insulated metallic wire that is wound around a core of non-conductive material. The wire material has a high resistivity, and is usually made of an alloy such as Nickel-chromium (Nichrome) or a copper-nickel-manganese alloy called Manganin. Common core materials include ceramic, plastic and glass. Wire wound resistors are the oldest type of resistors that are still manufactured today. They can be produced very accurate, and have excellent properties for low resistance values and high power ratings.

A wire wound resistor is a resistor where a wire with a high resistivity is wrapped around an insulating core to provide the resistance.

Schematic view of a wirewound resistor

3.3.1. CONSTRUCTION

Wire wound resistor construction varies widely. The manufacturing and choice of materials used is dependent on the way the resistor will be used in a circuit. All are made by winding a wire around a core. The resistance value is dependent on the resistivity of the wire, the cross section and the length. Since these parameters can be accurately controlled, a high precision can be achieved. For high
tolerance requirements, the resistance value is measured to determine exactly the cut to length of the wire. To create a high resistance, the wire diameter needs to be very small, and the length needs to be very long. Therefore wire wound resistors are mainly produced for lower resistance values. For low power ratings, very thin wire is used. The handling of the wire is for this matter critical. Any damage may sever contact. After winding the wire is well protected from access of moisture to prevent electrolytic corrosion. Next to precision, there are also wire wound resistors with high power rating for 50W or more. These resistors have a quite different construction. Compared to other resistor types as the metal film, the wire diameter is relatively big and therefore more robust.

3.3.2. RESISTOR WIRE MATERIAL

Wirewound resistors are mainly produced with alloys, since pure metals have a high temperature coefficient of resistance. However, for high temperatures pure metals are used such as Tungsten. The temperature coefficient is a sign of how much the resistance will change as the temperature changes. TCR is measured in units of ppm/°C. If a manufacturer rates a resistor at 50ppm/°C, the resistor will not change more than 50Ω in resistance for each 1MΩ of the resistors given value, for a temperature change of 1°C. Typical alloys that are used as resistor wire are:

- Copper alloys
- Silver alloys
- Nickel Chromium alloys
- Iron Chromium alloys
- Iron Chromium Aluminum alloys
In the following table the properties of the most common alloys are given.

<table>
<thead>
<tr>
<th>Alloy Group</th>
<th>Material</th>
<th>Composition (in %)</th>
<th>Resistivity 10^-6 Ω/m</th>
<th>TCR (10^-3 Ω/°)</th>
<th>Max operating temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Constantan</td>
<td>54Cu - 45Ni - 1Mn</td>
<td>0.485</td>
<td>0.2</td>
<td>400</td>
</tr>
<tr>
<td>Copper</td>
<td>Nickelin</td>
<td>67Cu - 30Ni - 3Mn</td>
<td>0.4</td>
<td>0.11</td>
<td>300</td>
</tr>
<tr>
<td>Copper</td>
<td>Manganin</td>
<td>86Cu - 2Ni - 12Mn</td>
<td>0.442</td>
<td>0.02</td>
<td>300</td>
</tr>
<tr>
<td>Silver</td>
<td>N.B.W. 109</td>
<td>82Ag - 10Mn - 8Sn</td>
<td>0.55</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>N.B.W. 139</td>
<td>78Ag - 13Mn - 9Sn</td>
<td>0.61</td>
<td>0.08</td>
<td>0-150</td>
</tr>
<tr>
<td>Silver</td>
<td>N.B.W. 173</td>
<td>80Ag - 17Mn - 3Sn</td>
<td>0.58</td>
<td>0.105</td>
<td>0-200</td>
</tr>
<tr>
<td>Nickel Chromium</td>
<td>Nichrome</td>
<td>20Cr - 77/80Ni - 0/2Mn</td>
<td>1.105</td>
<td>0.17</td>
<td>1100/1150</td>
</tr>
<tr>
<td>Iron Chromium</td>
<td>CrNiFe 1</td>
<td>70Ni - 20Cr - 8Fe - 2Mn</td>
<td>1.11</td>
<td>0.9</td>
<td>1050/1100</td>
</tr>
<tr>
<td>Iron Chromium</td>
<td>CrNiFe 2</td>
<td>63Ni - 15Cr - 20Fe - 2Mn</td>
<td>1.12</td>
<td>0.89</td>
<td>1050/1100</td>
</tr>
<tr>
<td>Iron Chromium</td>
<td>Kanthal A</td>
<td>72Fe - 20Cr - 5Al - 3Co</td>
<td>1.45</td>
<td>0.06</td>
<td>1300</td>
</tr>
<tr>
<td>Iron Chromium Aluminium</td>
<td>Cekas</td>
<td>75Fe - 20Cr - 5Al</td>
<td>1.4</td>
<td>0.04</td>
<td>1300</td>
</tr>
<tr>
<td>Iron Chromium Aluminium</td>
<td>Megapyr</td>
<td>65Fe - 30Cr - 5Al</td>
<td>1.4</td>
<td>0.025</td>
<td>1350</td>
</tr>
<tr>
<td>Pure Metals</td>
<td>Tungsten</td>
<td>100 W (sintered)</td>
<td>0.0553</td>
<td>4.5</td>
<td>1500/1700</td>
</tr>
</tbody>
</table>

### 3.3.3. HIGH FREQUENCY EFFECTS; INDUCTION AND CAPACITANCE

Wire wound resistors naturally have some capacitance and inductance. Because of this, they influence the current flow in an alternating current circuit. This effect is usually not wanted. Because of the design principle of the wirewound resistor, which is
basically an inductor, these resistors have the worst high frequency properties of all resistor types.

There are several ways to apply the winding, depending on the application of the resistor. With a DC current fewer problems with the winding arise than with an AC current, because of the parasitic capacity and self-induction. To reduce these effects, several winding types are existing:

- **Bifilar winding**
- **Winding on a flat former**
- **Ayrton-Perry winding**

These types of winding are applied for measurement devices and decade banks. The drawback of these methods is the difficulty of the manufacturing process.

- **Bifilar winding**
  A bifilar winding is a type of winding where the wire is folded double, and from this double wire a capacitor is made as in the picture below. This type of winding results
in very low self-induction, but the parasitic capacity between the wires is large.

- **Simple winding on a flat former**
  Another way to reduce the capacity that arises with a bifilar winding is the simple winding on a flat former. The thinner the card, the closer the wires of front and back are together. They cancel each other’s field and thus reduce the inductance.

- **Ayrton Perry winding**
  Resistors with Ayrton Perry winding are used for the most demanding circuits. This type of winding is similar to the simple winding on a flat former, but in this case two opposite windings are applied. The wires with opposite direction of current are close together, so that the winding is free of self-induction. The intersections are on the same potential to have a minor effect on the capacity.

### 3.3.4. TYPES OF WIRE WOUND RESISTORS

Wire wound resistors can roughly be classified in two types: precision and power. They can be modified for use in current and temperature sensors and potentiometers. These versatile resistors can be used in a wide range of applications.

**Precision wirewound**

High precision wire wound resistors typically used in precision AF attenuators, measuring bridges and calibration equipment. A typical value for the tolerance of the resistance value is 0.1% or better. The temperature coefficient of resistance lies around 5 ppm/°C, which is considerably better than most metal film resistors (around 25
ppm/°C). The stability is fairly good, with values like 35 ppm change for a year of operation at full power rating. The temperature rise of these resistors is usually below 30°C. Therefore they can be coated by epoxy resin materials. In practice, a designer might decide that a resistor needs to be within ±0.05% of the design value for a particular circuit application. To account for aging, TCR and other parameters, the designer might then specify a tolerance of ±0.01%. This ensures that the resistor stays within the required resistance range over time and varying circuit conditions.

**Power wirewound**

Wire wound resistors exist for very high power applications. The range varies from 0.5 watts till more than 1000 watts. Power wirewound resistors can be divided in types according to the coating type. Silicone resins are used for the lowest dissipation levels. They are compact resistors that can withstand temperature rises up to 300°C above the ambient temperature. Another type of coating is vitreous enamel. This traditional coating has good insulating properties at low temperatures, but at full rated temperature the insulation is considerably less. This property makes it less and less common. The maximum working surface temperature is up to 400°C. TCR varies from 75 till 200 ppm/°C. Typical resistance values are in the range from 1Ω till 10 kΩ. The majority of the power wirewound resistors have a ceramic core and a ceramic coating to protect the winding. The ceramic coating combines a high insulation and physical protection with good heat dissipation. Typical power ratings are between 4 and 17 watts. The maximum surface temperature is around 300°C and the TCR varies from 250 till 400 ppm/°C. The resistance values are between 10kΩ and 22kΩ. Usually they are manufactured with leads that allow for vertical or horizontal mounting.
For the highest dissipation values the resistor has an aluminum case with fins. These fins give a larger surface area from which to dissipate heat, letting the resistor handle more power without being damaged. These resistors have a ceramic core and a silicone resin coating, encased in an aluminum extrusion. The surface is anodized to maintain a good insulation resistance. These resistors have a typical power rating of 25 to 50 watts. This assumes that the resistor will be mounted on a metal surface, so that the heat can dissipate better. The maximum surface temperature is around 300°C and the TCR is low with around 25 ppm/°C for the ohmic values above 50Ω. Usually the TCR is higher for lower resistance values.

**Potentiometer wirewound**

Potentiometers are often wire wound resistors. A potentiometer is a resistor that has three terminals. One of these is attached to a movable contact that varies the amount of resistance. Wire wound resistors are suitable as potentiometer, because of the durable construction.

### 3.3.5. WIRE WOUND RESISTOR APPLICATIONS

Wire wound resistors are often used in circuit breakers or as fuses. To make a fusible resistor, the manufacturer attaches a small spring to one end of the resistor. A small amount of solder will hold this spring in place. If current and heat through the resistor gets high enough, the solder will melt and the spring will pop up and open the circuit. Because of their high power capabilities, wire wound resistors are common in circuit breaker applications. The may be
used as components in a large circuit breaker device, or may act as circuit breakers themselves.

When fusible wire wound resistors are sold for use in high power applications, they are often labeled as circuit breakers. Wire wound resistor potentiometers can be made to offer both high power and high precision. These potentiometers are often used in stereo systems for their precision and in high power applications like transducers and televisions. Wire wound resistors can also be used as temperature sensors. In this case, metal that has a positive temperature coefficient is used. This means that as the temperature of the metal rises, the resistance rises. This varying resistance can be measured and converted back to a temperature value.

Enhancing the inductive effect that is natural to wire wound resistors can let these resistors be used as current sensors. Inductive reactance is determined by the inductance of the device and the current flowing through it. Current sensing devices measure the reactance and convert it to a current reading. These are used in situations where a high current condition may occur, and it is desirable to correct it before tripping a breaker. Large cooling water pumps and freezer units are examples of this type of application.
3.4. CARBON COMPOSITION RESISTOR

Carbon composition resistors (CCR) are fixed form resistors. They are made out of fine carbon particles mixed with a binder (for example clay). After baking it has a solid form. Although carbon composition resistors are widely applied in circuits, the majority of resistors are nowadays made by deposition of a metal or carbon film over a ceramic carrier.

3.4.1. ADVANTAGES AND DISADVANTAGES

The big advantage of carbon composition resistors is their ability to withstand high energy pulses. When current flows through the resistor, the entire carbon composition body conducts the energy. The wirewound resistor for example, has a much smaller volume of the wire to conduct. So the thermal mass of the carbon composition resistor is much higher, resulting in a higher energy capability. Carbon resistors can be made with a higher resistance than wirewound resistors, and are considerably cheaper. However, the properties are less good in terms of temperature coefficient, noise, voltage dependence and load.
Fifty years ago, carbon composition resistors were widely used in consumer electronics. Because of the low stability of the resistance value, this type of resistor is not suitable for any modern high precision application. For example, the resistance value can change up to 5% over a shelf life of one year. With heavy use the value changes even more: up to 15% for a 2000h test at full rating with 70°C. Soldering can cause a 2% change. The reason for this instability is inherent to the design of the resistor. The carbon composition contains materials with different heat expansion properties. When the conducting carbon particles and the non-conducting binder heat up or cool down, stresses arise in the resistor body. The mechanical contact between the conducting particles will change, and this leads to a change in resistance value. Also noise properties are not good due to the mixture of different materials. The noise level increases when current flows. Resistors of 0.25W and 0.5W, have a maximum voltage of respectively 150V and 500V. Insulation resistance is poor with approximately $10^9 \, \Omega$ (order of magnitude worse than other types). One more reason for the decrease in the use of this type of resistor is the high temperature coefficient of around 1200 ppm/° C. The operating temperature range is between around -40 to 150 ° C. However, the resistor derates above 70 ° C.

### 3.4.2. APPLICATIONS

Carbon composition resistors are suitable to withstand high energy pulses, while having a relatively small size. For this reason the carbon composition resistor is still used in many applications today. Applications include the protection of circuits (surge or discharge protection), current limiting, high voltage power supplies, high power or strobe lighting, and welding.
An example of an application is a medical defibrillator. The sensitive measurement equipment attached to the patient needs to be protected against the high energy pulses of around 30 Joule. Carbon composition resistors are applied in the equipment or the leads and have to withstand all pulse energy.

3.4.3. MANUFACTURING

The resistive material for the carbon composition resistor is a blend of graphite, ceramic dust and resin. The mixture is pressed into sticks under high pressure and temperature. The connecting wires are centrally pressed in both ends of the resistor. Alternatively, metal caps are fitted on both rod ends, which form the attachment for the wire leads. After the baking process a massive resistance body is created. Drawback of this process is the difficulty to predetermine the resistance value. The resistor body is porous and therefore a coating is required. In the past some resistors were made without coating. The resistance value is established by varying the length of the carbon composition body, to create an adequate path for current. To vary the dissipation, resistors are made with different diameters to provide a large enough surface to dissipate heat. Commercial available carbon composition resistors have dissipation values between 1/8W and 1/4W, while in the 1980’s resistors where available up to 5W. Although many suppliers switched to producing other types of resistor, some suppliers are specialized in carbon composition resistors.

In the table below the electrical resistivity is shown for the resistor material.
3.4.4. HISTORY OF THE CARBON COMPOSITION RESISTOR

The carbon composition resistor exists over hundred years. In the beginning of the twentieth century, the resistors were produced without coating. The lead wires were directly soldered onto the resistor body. The only available resistor types until the 1960s were wirewound and carbon composition. In the 1960s and 70s there was a shift in use of carbon composition resistors to other types like the carbon or metal film resistor.

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity Ω / m</th>
</tr>
</thead>
<tbody>
<tr>
<td>graphite</td>
<td>4×10^-6 - 11×10^-6</td>
</tr>
<tr>
<td>amorphous carbon</td>
<td>35×10^-6 – 50×10^-6</td>
</tr>
</tbody>
</table>
3.5. **CARBON FILM RESISTOR**

Carbon film resistors are a fixed form type resistor. They are constructed out of a ceramic carrier with a thin pure carbon film around it, which functions as resistive material.

Larger pitch means shorter resistance path, thus lower resistance value.

3.5.1. **ADVANTAGES AND DRAWBACKS**

Carbon film resistors are a significant improvement on carbon composition. However, in comparison to metal film and metal oxide film, the commercially available range steadily decreases. Metal and oxide film are not more expensive to produce, and have overall better properties.
3.5.2. APPLICATIONS

Typical use for carbon film resistors is in high voltage and temperature applications. Operating temperatures are up to 15kV with a nominal temperature of 350°C. Examples are high voltage power supplies, radar, x-rays and laser.

3.5.3. MANUFACTURING

Carbon film resistors are made with a deposition process. At high temperature and under a high pressure, a ceramic carrier is held in hydrocarbon gas. The gas (methane or benzene) is cracked at a temperature of 1000°C. The crystalline carbon is pyrolytically deposited on the ceramic substrate. Because of the precise distribution of the pure graphite without binding, these carbon resistors have a low noise. The desired resistance value can be obtained by choosing the right layer thickness, and by cutting a spiral shape in the carbon layer. The helical cut in the film increases the length of the current path. By decreasing the pitch of the helix, the length of the resistive path increases, and there with the resistance value increases. Furthermore, by fine tuning the cutting of the spiral the resistor can have a higher accuracy of resistance value. Typical tolerance values for carbon film resistors are 2, 5, 10 and 20%.

Because of the use of pure carbon, the carbon film resistor has a higher negative temperature coefficient than carbon composition. The resistive temperature coefficient lies between $2.5 \times 10^{-4} \, \Omega/°C$ and $-8 \times 10^{-4} \, \Omega/°C$. Also this type of resistor is protected against chemical influences with a silicone coating. This type of resistor is widely used in electronics. Therefore it is important to note that the
small resistors have a capacity of approximately 0.5 pF. Self-induction is around 0.01 μH for uncut resistors and up to several μH for spiral cut resistors. These resistors are available in values between 1Ω – 10’000 MΩ and have a power rating of 1/16, ⅛, ¼, ½, 1 or 2 watt.

3.6. METAL FILM RESISTOR

Metal film resistors have a thin metal layer as resistive element on a non-conducting body. They are amongst the most common types of axial resistors. Other film type resistors are carbon film and thick and thin film resistors. In most literature referrals to metal film, usually it is a cylindrical axial resistor. However, thin film chip resistors use the same manufacturing principle for the metal layer. The appearance of metal film resistors is similar to carbon film resistors, but their properties for stability, accuracy and reliability are considerably better.

Metal film resistors are axial resistors with a thin metal film as resistive element. The thin film is deposited on usually a ceramic body.
3.6.1. CONSTRUCTION

The resistive element is a thin metal layer that is usually sputtered (vacuum deposition) on a cylindrical high purity ceramic core. Sometimes other techniques than sputtering are used. The deposited metal is artificially aged by keeping it for a long period at a low temperature. This results in a better accuracy of the resistor. The resistance material is often nickel chromium (NiCr), but for special applications also other alloys are used such as tin and antimony, gold with platinum and tantalum nitride. The stability and resistance are strongly dependent on the thickness of the metal film (50-250 nm). A larger thickness of the layer results in a better stability and a lower resistance value. On both ends a metal cover is pressed with the connection leads. After this, the desired resistance is achieved by cutting a spiral shaped slot in the thin metal layer. This is usually done by lasers, while in the past sandblasting and grinding techniques were used. Carbon film resistors use the same technique to trim the resistance. The resistor is covered with several coating layers that are baked individually. The coating protects against moisture and mechanical stresses and preferably has a high dielectric strength. The resistor value is marked by color code bands or with text. The metal film resistors are available with tolerances of 0.1, 0.25, 0.5, 1 and 2%. The Temperature Coefficient of Resistance is usually between 50 and 100 ppm/K.

3.6.2. TYPICAL APPLICATIONS

Metal film resistors have good characteristics for tolerance, stability and TCR. Furthermore, the resistors feature low noise properties and a high linearity because of a low voltage coefficient. Therefore,
in circuits where tight tolerance, low temperature coefficient and low noise properties are important, often metal film resistors are used. Examples of applications are active filters or bridge circuits.

### 3.6.3. RELIABILITY

For a good reliability, metal film resistors are normally operated between 20 and 80 percent of their specified power rating. Reliability is generally increased by derating 50%. However, in very specific situations, at lower than 20% of the power rating in a humid environment the reliability decreases. Compared to wirewound or carbon composition resistors, these resistors are easier damaged by voltage surges and power overloads.
3.7. METAL OXIDE FILM RESISTOR

Metal-oxide film resistors are fixed form, axial resistors. They are made of ceramic rod that is coated with a thin film of metal oxides, such as tin oxide. Metal oxide film resistors must not be confused with metal oxide varistors, made of zinc oxide or silicon carbide.

3.7.1. PROPERTIES

Metal oxide film resistors exceed the performance of metal film and carbon film for the following properties: power rating, voltage rating, overload capabilities, surges and high temperatures. Designers choose often the metal oxide film resistor for high endurance applications. For an overview of resistor types with their properties, look here. Stability properties are less good than for the metal film resistor. The metal oxide film resistors have poor properties for low values and tolerance. The temperature coefficient is around 300 ppm/°C, which is higher than for metal film types.

<table>
<thead>
<tr>
<th>Material</th>
<th>Carbon film</th>
<th>Metal film</th>
<th>Metal oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>200 °C / 390 °F</td>
<td>250-300 °C / 480-570 °F</td>
<td>450 °C / 840 °F</td>
</tr>
</tbody>
</table>

The resistance material for metal oxide resistors is tin oxide that is contaminated with antimony oxide; this is to increase the resistivity. Metal oxide resistors can withstand higher temperatures than carbon or metal film resistors. The noise properties are similar to carbon resistors.
3.7.2. TYPICAL APPLICATIONS

Many properties of metal oxide film resistors are similar to metal film resistors. For basic use, metal film and metal oxide film are currently the predominant resistor types. Compared to carbon film, the prices are just as low. Only for dissipation values above 1 watt combined with reasonable stability, the carbon film resistors are still more cost efficient.

3.7.3. CONSTRUCTION

The metal oxide film is mostly produced with chemical deposition methods. Almost always a ceramic carrier is used as substrate. The deposition process involves the reaction of a pure metal with a gas at high temperature and at a low pressure. A very common metal oxide film is tin oxide. The film is established by heating the resistor body in a tin chloride vapor. Other metal oxide films have usually a different deposition process. Firstly a thin metal film is applied, which is afterwards reacted with oxygen. The desired composition is achieved by measuring the resistance of a test piece.

After the film is applied to the resistor body, the final resistance value is achieved by applying a helical cut. This is usually done by laser cutting, while in the past it was done by grinding or sandblasting. The spiral cut makes the resistance path longer and of smaller cross section, and can increase the resistance value up to thousand times greater than before the cut. The resistance value can be accurately controlled by the cutting. During the cutting process, the resistance is measured to allow for small corrections.
3.7.4. HISTORY

Metal oxide film resistors were the first alternatives to carbon composition resistors. They were in the past easier to manufacture than metal film resistors. Nowadays however, their numbers decrease and they are less and less available.

3.8. THIN AND THICK FILM

Thin and thick film resistors are the most common types in the market. They are characterized by a resistive layer on a ceramic base. Although their appearance might be very similar, their properties and manufacturing process are very different. The naming originates from the different layer thicknesses. Thin film has a thickness in the order of 0.1 micrometer or smaller, while thick film is around thousands time thicker. However, the main difference is method the resistive film is applied onto the substrate. Thin film resistors have a metallic film that is vacuum deposited on an insulating substrate. Thick film resistors are produced by firing a special paste onto the substrate. The paste is a mixture of glass and metal oxides. Thin film is more accurate, has a better temperature coefficient and is more stable. It therefore competes with other technologies that feature high precision, such as wirewound or bulk metal foil. On the other hand, thick film is preferred for applications where these high requirements are not critical since prices are much lower.
3.8.1. THIN FILM TECHNOLOGY

The resistive layer is sputtered (vacuum deposition) onto a ceramic base. This creates a uniform metallic film of around 0.1 micrometer thick. Often an alloy of Nickel and Chromium is used (Nichrome). They are produced with different layer thicknesses to accommodate a range of resistance values. The layer is dense and uniform, which makes it suitable to trim the resistance value by a subtractive process. With photo etching or by laser trimming patterns are created to increase the resistive path and to calibrate the resistance value. The base is often alumina ceramic, silicon or glass. Usually thin film is produced as a chip or smd resistor, but the film can also be applied onto a cylindrical base with axial leads. In this case, more often the term metal film resistor is used.

Thin film is usually used for precision applications. They feature relatively high tolerances, low temperature coefficients and low noise. Also for high frequency applications thin film performs better than thick film. Inductance and capacitance are generally lower. The parasitic inductance of thin film can be higher if it is executed as a cylindrical helix (metal film resistor). This higher performance
comes with a cost, which can be factors higher than the price of thick film resistors. Typical examples where thin film is used are medical equipment, audio installations, precision controls and measurement devices.

### 3.8.2. THICK FILM TECHNOLOGY

In the 1970s thick film started to gain popularity. Today, these are by far the most used resistors in electrical and electronic devices. They come usually as chip resistor (SMD), and have the lowest cost compared to any other technology.

![Diagram of thick film resistor](image)

The resistive material is a special paste with a mixture of a binder, a carrier, and the metal oxides to be deposited. The binder is a glassy frit and the carrier exists of organic solvent systems and plasticizers. Modern resistor pastes are based on oxides of ruthenium, iridium and rhenium. This is also referred to as a cermet (Ceramic – Metallic). The resistive layer is printed onto a substrate at 850°C. The substrate is often 95% alumina ceramic. After the firing of the paste on the carrier, the film becomes glasslike, which makes it well protected against moisture. The complete firing process is schematically depicted in the graph below. The thickness is in the order of 100 micrometer. This is approximately 1000 times more
than thin film. Unlike thin film, this process is additive. This means that the resistive layers are added sequentially to the substrate to create the conducting patterns and resistance values.

The temperature coefficient typically ranges from 50 ppm to 200 ppm/K. Tolerances are between 1% and 5%. Because costs are low, thick film is generally preferred in case no high tolerances, low TCR or high stability is required. Therefore, these resistors can be found in almost any device with an AC plug or a battery. Advantages of thick over thin technology are not only lower cost, but also the ability to handle more power, provide a wider range of resistance values and withstand high surge conditions.

### 3.8.3. THIN VERSUS THICK FILM; WHAT ARE THE DIFFERENCES?

In the table below the main differences between the two technologies are listed. The components may look the same, but the way of producing and the electrical properties are definitely different.
### Characteristic

<table>
<thead>
<tr>
<th>Thin Film</th>
<th>Thick Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example</td>
<td>While the manufacturing process and properties are very different, the chip resistors for thin and thick film often have a similar appearance.</td>
</tr>
</tbody>
</table>

### Construction

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Thin Film</th>
<th>Thick Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film thickness (µm)</td>
<td>±0.1</td>
<td>±100</td>
</tr>
<tr>
<td>Manufacturing process</td>
<td>Sputtering (Vacuum Deposition)</td>
<td>Screen and stencil printing</td>
</tr>
<tr>
<td>Trimming</td>
<td>Abrasive or Laser, for complex patterns photo etching</td>
<td>Abrasive or Laser</td>
</tr>
<tr>
<td>Resistive Material</td>
<td>Uniform metallic film, usually Nichrome</td>
<td>Paste of Ruthenium Oxide or other alloy.</td>
</tr>
</tbody>
</table>

### Properties

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Thin Film</th>
<th>Thick Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance Values (Ω)</td>
<td>0.2 – 20M</td>
<td>1 – 100M</td>
</tr>
<tr>
<td>Tolerance (%)</td>
<td>±0.1 – ±2</td>
<td>±1 – ±5</td>
</tr>
<tr>
<td>Temperature Coefficient (ppm/K)</td>
<td>±5 – ±50</td>
<td>±50 – ±200</td>
</tr>
<tr>
<td>Maximum Operating Temperature (°C)</td>
<td>155</td>
<td>155</td>
</tr>
<tr>
<td>Maximum Operating Voltage Umax (V)</td>
<td>50 – 500</td>
<td>50 – 200</td>
</tr>
<tr>
<td>Non-linearity (dB)</td>
<td>&gt;110</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Current Noise (µV/V)</td>
<td>&lt;0.1</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Power Rating P72 (W)</td>
<td>1/16 – 1</td>
<td>1/16 – 1/4</td>
</tr>
<tr>
<td>Stability at P72 (1000h) ∆R/R %</td>
<td>±0.15 – ±0.5</td>
<td>±1 – ±3</td>
</tr>
<tr>
<td>Moisture resistance</td>
<td>Thin film is more resistant to moisture, since they are glass like.</td>
<td></td>
</tr>
<tr>
<td>High frequency behavior</td>
<td>Thin film features lower parasitic inductance and capacitance. However, inductance may be high if thin film is executed with a cylindrical shape that is spiral cut.</td>
<td></td>
</tr>
</tbody>
</table>

### Applications

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Thin Film</th>
<th>Thick Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical areas of use</td>
<td>High precision: Measuring or monitoring equipment, medical or audio applications, precision controls.</td>
<td>Very wide, almost any electrical device with battery or AC connection. The average PC contains well over 1000 thick film chip resistors.</td>
</tr>
</tbody>
</table>

### Market share

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Thin Film</th>
<th>Thick Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>More expensive than thick film.</td>
<td>Lowest cost resistor type on the market. Preferred solution if performance requirements are low.</td>
</tr>
</tbody>
</table>

### Estimated use in analogue circuits

<table>
<thead>
<tr>
<th>Thin Film</th>
<th>Thick Film</th>
</tr>
</thead>
</table>

www.resistorguide.com | Resistor Types 111
4. RESISTOR STANDARDS

Standardization is a key element in the design of electronic components. A huge amount of effort and money is saved by having standards for resistor sizes, values, markings, symbols and measurement methods. Although international standards like the IEC (International Electrical Commission) and national standards such as ANSI (American National Standards Institute) are widely accepted, resistor manufacturers often use their own definitions. Therefore it is always important to carefully check the manufacturers’ documentation.

4.1. RESISTOR COLOR CODE

Resistor values are often indicated with color codes. Practically all leaded resistors with a power rating up to one watt are marked with color bands. The coding is defined in the international standard IEC 60062. This standard describes the marking codes for resistors and capacitors. It includes also numerical codes, as for example often used for SMD resistors. The color code is given by several bands. Together they specify the resistance value, the tolerance and sometimes the reliability or failure rate. The number of bands varies from three till six. As a minimum, two bands indicate the resistance value and one band serves as multiplier. The resistance values are standardized; these values are called preferred value.
# RESISTOR COLOR CODE CHART

The chart below shows how to determine the resistance and tolerance for resistors. The table can also be used to specify the color of the bands when the values are known.

An [online automatic resistor calculator](https://www.resistorguide.com) can be used to quickly find the resistor values.

<table>
<thead>
<tr>
<th>Color</th>
<th>Significant figures</th>
<th>Multiply</th>
<th>Tolerance (%)</th>
<th>Temp. Coeff. (ppm/K)</th>
<th>Fail Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad</td>
<td>black</td>
<td>0 0 0</td>
<td>x 1</td>
<td>1</td>
<td>250 (U)</td>
</tr>
<tr>
<td>Beer</td>
<td>brown</td>
<td>1 1 1</td>
<td>x 10</td>
<td>1 (F)</td>
<td>100 (S)</td>
</tr>
<tr>
<td>Rots</td>
<td>red</td>
<td>2 2 2</td>
<td>x 100</td>
<td>2 (G)</td>
<td>50 (R)</td>
</tr>
<tr>
<td>Our</td>
<td>orange</td>
<td>3 3 3</td>
<td>x 1K</td>
<td>3</td>
<td>15 (P)</td>
</tr>
<tr>
<td>Young</td>
<td>yellow</td>
<td>4 4 4</td>
<td>x 10K</td>
<td>4</td>
<td>25 (Q)</td>
</tr>
<tr>
<td>Guts</td>
<td>green</td>
<td>5 5 5</td>
<td>x 100K</td>
<td>5</td>
<td>20 (Z)</td>
</tr>
<tr>
<td>But</td>
<td>blue</td>
<td>6 6 6</td>
<td>x 1M</td>
<td>6</td>
<td>0.25 (C)</td>
</tr>
<tr>
<td>Vodka</td>
<td>violet</td>
<td>7 7 7</td>
<td>x 10M</td>
<td>7</td>
<td>5 (M)</td>
</tr>
<tr>
<td>Goes</td>
<td>grey</td>
<td>8 8 8</td>
<td>x 100M</td>
<td>8</td>
<td>0.05 (A)</td>
</tr>
<tr>
<td>Well</td>
<td>white</td>
<td>9 9 9</td>
<td>x 1G</td>
<td>9</td>
<td>1 (K)</td>
</tr>
<tr>
<td>Get</td>
<td>gold</td>
<td>3th digit only for 5 and 6 bands</td>
<td>x 0.1 5 (J)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Some</td>
<td>silver</td>
<td>0.01 10 (K)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Now!</td>
<td>none</td>
<td>20 (M)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Image of resistor color code chart](chart.png)

- 6 band: 3.21kΩ 1% 50ppm/K
- 5 band: 521Ω 1%
- 4 band: 82kΩ 5%
- 3 band: 330Ω 20%

*gap between band 3 and 4 indicates reading direction*
4.1.2. **TIPS FOR READING RESISTOR CODES**

In the sections below examples are given for different numbers of bands, but first some tips are given to read the color code:

The reading direction might not always be clear. Sometimes the increased space between band 3 and 4 give away the reading direction. Also, the first band is usually the closest to a lead. A gold or silver band (the tolerance) is always the last band.

It is a good practice to check the manufacturer’s documentation to be sure about the used coding system. Even better is to measure the resistance with a multi-meter. In some cases this might even be the only way to figure out the resistance; for example when the color bands are burnt off.

4.1.3. **FOUR BAND RESISTOR**

The four band color code is the most common variation. These resistors have two bands for the resistance value, one multiplier and one tolerance band. In the example on the left these bands are green, blue, red and gold. By using the color code chart, one finds
that green stands for 5 and blue for 6. The value is thus $56 \cdot 100 = 5600 \, \Omega$. The golden band means that the resistor has a tolerance of 5%. The resistance value lies therefore between 5320 and 5880 \, \Omega.

If the tolerance band would be left blank, the result is a 3 band resistor. This means that the resistance value remains the same, but the tolerance is 20%.

### 4.1.4. FIVE BAND RESISTOR

Resistors with high precision have an extra band to indicate a third significant digit. Therefore, the first three bands indicate the significant digits, the fourth band is the multiply factor and the fifth band represents the tolerance. There are exceptions to this. For example, sometimes the extra band indicates failure rate (military specification) or temperature coefficient (older or specialized resistors). Please read the section “Color code exceptions” for more information.

Shown example: brown (1), yellow (4), purple (7), black (x1), green (0.5%): $147 \, \Omega$ 0.5%.
Resistors with 6 bands are usually for high precision resistors that have an additional band to specify the temperature coefficient (ppm/K). The most common color for the sixth band is brown (100 ppm/K). This means that for a temperature change of 10 °C, the resistance value can change 0.1%. For special applications where temperature coefficient is critical other colors

Shown example: orange (3), red (2), brown (1), green (x10), brown (1%), red (50 ppm/K): 3.21 kΩ 1% 50 ppm/K.
four band resistors. More information about the reliability can be found in the US military handbook MIL-HDBK-199.

- **Single black band or zero-ohm resistor**
  A resistor with a single black band is called a zero-ohm resistor. Principally it is a wire link with only function of connecting traces on a PCB. Using the resistor package has the advantage of being able to use the same automated machines to place components on a circuit board.

- **5 band resistor with a 4th band of gold or silver**
  Five band resistors with a fourth band of gold or silver form an exception, and are used on specialized and older resistors. The first two bands represent the significant digits, the 3th the multiply factor, the 4th the tolerance and the 5th the temperature coefficient (ppm/K).

- **Deviating colors**
  For high voltage resistors often the colors gold and silver are replaced with yellow and gray. This is to prevent having metal particles in the coating.

### 4.2. PREFERRED VALUES

In 1952 the IEC (International Electrotechnical Commission) decided to define the resistance and tolerance values into a norm, to ease the mass manufacturing of resistors. These are referred to as preferred values or E-series, and they are published in standard IEC 60063:1963. These standard values are also valid for other components like capacitors, inductors and Zener diodes. The
preferred values for resistors were established in 1952, but the concept of the geometric series was already introduced by army engineer Renard in the 1870s.

The E12 series of resistor values, including their color codes.

The standardization of resistor values serves several important purposes. When manufacturers produce resistors with different resistance values, these end up approximately equally spaced on a logarithmic scale. This helps the supplier to limit the number of different values that have to be produced or kept in stock. By using standard values, resistors of different manufacturers are compatible for the same design, which is favorable for the electrical engineer.

Aside from the preferred values, many other standards related to resistors exist. An example is standard sizes for resistors, or the marking of resistors with color codes or numerical codes. Power ratings of resistors are not defined in a norm, therefore often is deviated from the above described series.
4.2.1. E-SERIES

As basis the E12 has been developed. E12 means that every decade (0.1-1, 1-10, 10-100 etc.) is divided in 12 steps. The size of every step is equal to:

\[ 10^{\left(\frac{1}{12}\right)} = 1.21 \]

One could also say every value is 120% higher than the last, rounded to whole numbers. Because of this, all resistors with a tolerance of 10% overlap. The series looks as follows: 1 – 1.2 – 1.5 – 1.8 – 2.2 – 2.7 – 3.3 – 3.9 – 4.7 – 5.6 – 6.8 – 8.2 – 10 etc. All these values can be powers of ten (1.2 – 12 – 120 etc.).

Next to the E12 series, other series are existing. It is a good practice to specify resistors from a low series when tolerance requirements are not high. The most common series are:

- E6 20%
- E12 10%
- E24 5% (also available with 1%)
- E48 2%
- E96 1%
- E192 0.5% (also used for resistors with 0.25% and 0.1%).

The E6 series has six values in each decade. The Tolerance is 20%.
The E12 series is probably the most common series and exist for almost every resistor. The tolerance is ±10%.

### E12 series (tolerance 10%)

<table>
<thead>
<tr>
<th>10</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>22</th>
<th>27</th>
<th>33</th>
<th>39</th>
<th>47</th>
<th>56</th>
<th>68</th>
<th>82</th>
</tr>
</thead>
</table>

Each decade is divided in 48 values. A third significant digit is added (just as for the E96 and E192 series).
### E96 series (tolerance 1%)

<table>
<thead>
<tr>
<th>Value</th>
<th>100</th>
<th>102</th>
<th>105</th>
<th>107</th>
<th>110</th>
<th>113</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>118</td>
<td>121</td>
<td>124</td>
<td>127</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>133</td>
<td>137</td>
<td>140</td>
<td>143</td>
<td>147</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>164</td>
<td>158</td>
<td>162</td>
<td>165</td>
<td>169</td>
<td>174</td>
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<td>178</td>
<td>182</td>
<td>187</td>
<td>191</td>
<td>196</td>
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<td></td>
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<td>205</td>
<td>210</td>
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<td>221</td>
<td>236</td>
<td>232</td>
<td></td>
</tr>
<tr>
<td>237</td>
<td>243</td>
<td>249</td>
<td>255</td>
<td>261</td>
<td>267</td>
<td></td>
</tr>
<tr>
<td>274</td>
<td>280</td>
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<td>294</td>
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<td>309</td>
<td></td>
</tr>
<tr>
<td>316</td>
<td>324</td>
<td>332</td>
<td>340</td>
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<td>487</td>
<td>491</td>
<td>511</td>
<td>523</td>
<td>536</td>
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<tr>
<td>562</td>
<td>576</td>
<td>590</td>
<td>604</td>
<td>619</td>
<td>634</td>
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</tr>
<tr>
<td>649</td>
<td>665</td>
<td>681</td>
<td>698</td>
<td>715</td>
<td>732</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>768</td>
<td>787</td>
<td>806</td>
<td>825</td>
<td>845</td>
<td></td>
</tr>
<tr>
<td>866</td>
<td>887</td>
<td>909</td>
<td>931</td>
<td>953</td>
<td>976</td>
<td></td>
</tr>
</tbody>
</table>

### E192 series (tolerance 0.5%, 0.25% and 0.1%)

<table>
<thead>
<tr>
<th>Value</th>
<th>101</th>
<th>102</th>
<th>104</th>
<th>105</th>
<th>106</th>
<th>107</th>
<th>109</th>
<th>110</th>
<th>111</th>
<th>113</th>
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<td>316</td>
<td>320</td>
<td>324</td>
<td>328</td>
<td>332</td>
<td>336</td>
<td>340</td>
<td>344</td>
<td>348</td>
<td>352</td>
<td>357</td>
<td>361</td>
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<td>365</td>
<td>370</td>
<td>374</td>
<td>379</td>
<td>383</td>
<td>388</td>
<td>392</td>
<td>397</td>
<td>402</td>
<td>407</td>
<td>412</td>
<td>417</td>
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<tr>
<td>422</td>
<td>427</td>
<td>432</td>
<td>437</td>
<td>442</td>
<td>448</td>
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<td>464</td>
<td>470</td>
<td>475</td>
<td>481</td>
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<td>487</td>
<td>493</td>
<td>499</td>
<td>505</td>
<td>511</td>
<td>517</td>
<td>523</td>
<td>530</td>
<td>536</td>
<td>542</td>
<td>549</td>
<td>556</td>
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<tr>
<td>562</td>
<td>569</td>
<td>576</td>
<td>583</td>
<td>590</td>
<td>597</td>
<td>604</td>
<td>612</td>
<td>619</td>
<td>626</td>
<td>634</td>
<td>642</td>
</tr>
<tr>
<td>649</td>
<td>657</td>
<td>665</td>
<td>673</td>
<td>681</td>
<td>690</td>
<td>698</td>
<td>706</td>
<td>715</td>
<td>723</td>
<td>732</td>
<td>741</td>
</tr>
<tr>
<td>750</td>
<td>759</td>
<td>768</td>
<td>777</td>
<td>787</td>
<td>796</td>
<td>806</td>
<td>816</td>
<td>825</td>
<td>835</td>
<td>845</td>
<td>856</td>
</tr>
<tr>
<td>866</td>
<td>876</td>
<td>887</td>
<td>898</td>
<td>909</td>
<td>920</td>
<td>931</td>
<td>942</td>
<td>953</td>
<td>965</td>
<td>976</td>
<td>988</td>
</tr>
</tbody>
</table>
4.3. **SMD RESISTORS**

SMD stands for Surface Mounted Device. An SMD is any electronic component that is made to use with SMT, or Surface Mount Technology. SMT was developed to meet the ongoing desire for printed circuit board manufacture to use smaller components and be faster, more efficient, and cheaper.

SMDs are smaller than their traditional counterparts. They are often square, rectangular or oval in shape, with very low profiles. Instead of wire leads that go through the PCB, SMD’s have small leads or pins that are soldered to pads on the surface of the board. This eliminates the need for holes in the board, and lets both sides of the board be more fully used.

The manufacture of PCBs using SMT is similar to that for components with leads. Small pads of silver or gold plate or tin-lead are placed on the board for attaching the components. Solder paste, a mixture of flux and small balls of solder, is then applied to the mounting pads by a machine similar to a computer printer. Once the PCB is prepared, SMDs are placed on it using a machine called a pick-and-place machine. The components are fed to the machine in long tubes, on rolls of tape or in trays. These machines can attach thousands of components per hour; one manufacturer advertises a rate as high as 60,000cph. The board is then sent through a reflow soldering oven. In this oven, the board is slowly brought up to a temperature that will melt the SMD resistors on a circuit board from a USB memory stick
solder. Once cooled, the board is cleaned to remove solder flux residue and stray solder particles. A visual inspection checks for missing or out-of-position parts and that the board is clean.

### 4.3.1. SMD RESISTOR PACKAGES

The term package refers to the size, shape and/or lead configuration of an electronic component. For instance, an IC chip that is has leads in two rows down opposite sides of the chip is called a Dual Inline Package (DIP) chip. In SMD resistors, resistor package designators tell the length and width of the resistor. SMD packages may be given in inches as well as in millimeters. It is therefore important to check the manufacturer’s documentation. In the table below the most common packages are given in imperial units with the metric equivalent. Furthermore an approximation is given for the typical power ratings.

### 4.3.2. RESISTOR SMD CODE

Because of the small size of SMD resistors, there is often not room for the traditional color band code to be printed on them. Therefore, new resistor SMD codes were developed. The most commonly seen codes are the three and four digit system and an Electronic Industries Alliance (EIA) system called EIA-96.

### 4.3.3. THE THREE AND FOUR DIGIT SYSTEM

In this system the first two or three digits indicate the numerical resistance value of the resistor and the last digit gives a multiplier.
The number of the last digit indicates the power of ten by which to multiply the given resistor value. Here are some examples of values under this system:

- $450 = 45\Omega \times 10^0$ is $45\Omega$
- $273 = 27\Omega \times 10^3$ is $27,000\Omega$ ($27\k\Omega$)
- $7992 = 799\Omega \times 10^2$ is $79,900\Omega$ ($79.9\k\Omega$)
- $1733 = 173\Omega \times 10^3$ is $173,000\Omega$ ($173\k\Omega$)

The letter “R” is used to indicate the position of a decimal point for resistance values lower than 10 ohms. Thus, $0R5$ would be $0.5\Omega$ and $0R01$ would be $0.01\Omega$.

### 4.3.4. THE EIA-96 SYSTEM

Higher precision resistors, combined with the decreasing sizes of resistors, have created the need to have a new, more compact marking for SMD resistors. Therefore the EIA-96 marking system has been created. It is based on the E96-series, thus aimed at resistors with 1% tolerance.

In this system, the marking exists out of three digits: 2 numbers to indicate the resistor value and 1 letter for the multiplier. The two first numbers represent a code that indicates a resistance value with three significant digits. In the table below the values for each code is given, which are basically the values from the E96 series. For example, the code 04 means 107 ohms, and 60 means 412 ohms. The multiplying factor gives the final value of the resistor, for example:

- $01A = 100\ \Omega \pm1\%$
- $38C = 24300\ \Omega \pm1\%$
92Z = 0.887 Ω ±1%

The usage of a letter prevents the confusion with other marking systems. However, pay attention because the letter R is used in both systems. For resistors with tolerances other than 1%, different letter tables exist.

As with package codes, these resistance value codes are common, but a manufacturer may use a variation on these or even something completely different. It is therefore always important to verify the manufacturer’s marking system.

<table>
<thead>
<tr>
<th>Code</th>
<th>Multiply factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>0.001</td>
</tr>
<tr>
<td>Y/R</td>
<td>0.01</td>
</tr>
<tr>
<td>X/S</td>
<td>0.1</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>B/H</td>
<td>10</td>
</tr>
<tr>
<td>C</td>
<td>100</td>
</tr>
<tr>
<td>D</td>
<td>1000</td>
</tr>
<tr>
<td>E</td>
<td>10000</td>
</tr>
<tr>
<td>F</td>
<td>10000</td>
</tr>
</tbody>
</table>
4.4. RESISTOR SIZES AND PACKAGES

Resistors are available in a large amount of different packages. Nowadays the most used are the rectangular surface mount resistors, but also the good old axial resistor is still used extensively in through-hole designs. This page will inform you about the dimensions of SMD, axial and MELF packages and about the required land patterns for SMD components.

### 4.4.1. SMD RESISTOR SIZES

The shape and size of surface mount resistors are standardized; most manufacturers use the JEDEC standards. The size of SMD resistors is indicated by a numerical code, such as 0603. This code
contains the width and height of the package. So in the example of 0603 Imperial code, this indicates a length of 0.060” and a width of 0.030”. This code can be given in Imperial or Metric units, in general the Imperial code is used more often to indicate the package size. On the contrary in modern PCB design metric units (mm) are more often used, this can be confusing. In general you can assume the code is in imperial units, but the dimensions used are in mm. The SMD resistor size depends mainly on the required power rating. The following table lists the dimensions and specifications of commonly used surface mount packages.

<table>
<thead>
<tr>
<th>Code</th>
<th>Length (l)</th>
<th>Width (w)</th>
<th>Height (h)</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inch</td>
<td>mm</td>
<td>Inch</td>
<td>mm</td>
</tr>
<tr>
<td>Imperial</td>
<td>Metric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0201</td>
<td>0603</td>
<td>0.024</td>
<td>0.6</td>
<td>0.012</td>
</tr>
<tr>
<td>0402</td>
<td>1005</td>
<td>0.04</td>
<td>1.0</td>
<td>0.02</td>
</tr>
<tr>
<td>0603</td>
<td>1608</td>
<td>0.06</td>
<td>1.55</td>
<td>0.03</td>
</tr>
<tr>
<td>0805</td>
<td>2012</td>
<td>0.08</td>
<td>2.0</td>
<td>0.05</td>
</tr>
<tr>
<td>1206</td>
<td>3216</td>
<td>0.12</td>
<td>3.2</td>
<td>0.06</td>
</tr>
<tr>
<td>1210</td>
<td>3225</td>
<td>0.12</td>
<td>3.2</td>
<td>0.10</td>
</tr>
<tr>
<td>1218</td>
<td>3246</td>
<td>0.12</td>
<td>3.2</td>
<td>0.18</td>
</tr>
<tr>
<td>2010</td>
<td>5025</td>
<td>0.20</td>
<td>5.0</td>
<td>0.10</td>
</tr>
<tr>
<td>2512</td>
<td>6332</td>
<td>0.25</td>
<td>6.3</td>
<td>0.12</td>
</tr>
</tbody>
</table>

### 4.4.2. SOLDER PAD AND LAND PATTERN

When designing with surface mount components the right solder pad size and land pattern should be used. The following table shows
an indication of the land pattern for common surface mount packages. The table lists the dimensions for reflow soldering, for wave soldering smaller pads are used.

![Land Pattern Diagram](image)

<table>
<thead>
<tr>
<th>Code</th>
<th>Pad length (a)</th>
<th>Pad width (b)</th>
<th>Gap (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Imperial</td>
<td>Metric</td>
<td></td>
</tr>
<tr>
<td>0201</td>
<td>0.012 inch</td>
<td>0.3 mm</td>
<td>0.012 inch</td>
</tr>
<tr>
<td>0402</td>
<td>0.024 inch</td>
<td>0.6 mm</td>
<td>0.020 inch</td>
</tr>
<tr>
<td>0603</td>
<td>0.035 inch</td>
<td>0.9 mm</td>
<td>0.024 inch</td>
</tr>
<tr>
<td>0805</td>
<td>0.051 inch</td>
<td>1.3 mm</td>
<td>0.028 inch</td>
</tr>
<tr>
<td>1206</td>
<td>0.063 inch</td>
<td>1.6 mm</td>
<td>0.035 inch</td>
</tr>
<tr>
<td>1218</td>
<td>0.19 inch</td>
<td>4.8 mm</td>
<td>0.035 inch</td>
</tr>
<tr>
<td>2010</td>
<td>0.11 inch</td>
<td>2.8 mm</td>
<td>0.059 inch</td>
</tr>
<tr>
<td>2512</td>
<td>0.14 inch</td>
<td>3.5 mm</td>
<td>0.063 inch</td>
</tr>
</tbody>
</table>

### 4.4.3. AXIAL RESISTOR SIZE

The size of axial resistors is not as standardized as the SMD resistors and different manufacturers often use slightly different dimensions. Furthermore the size of an axial resistor depends on the power rating and the type of resistor such as carbon composition, wirewound, carbon or metal film. The following drawing and table give an indication of the dimensions of common carbon film and metal film axial resistors. Whenever the exact size needs to be
known, always check the manufacturer datasheet of the component.

### MELF RESISTOR PACKAGE SIZES

Sometimes surface mount resistors are also used as MELF packages (Metal Electrode Leadless Face). The main advantage of using MELF instead of standard SMD packages is the lower thermal coefficient and better stability. The TCR of thin film MELF resistors is often between 25-50 ppm/K while standard thick film SMD resistors often have a TCR of > 200 ppm/K. This is possible due to the cylindrical construction of MELF resistors. This cylindrical construction also gives the package distinct disadvantages, mainly when the components have to be placed using pick and place machines. Because of their round shape a special suction cup and more vacuum is required. There are three common MELF package sizes: MicroMELF, MiniMELF and MELF. The following table lists the characteristics of these types.
<table>
<thead>
<tr>
<th>Name</th>
<th>Abbr.</th>
<th>Code</th>
<th>Length</th>
<th>Diameter</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>MicroMELF</td>
<td>MMU</td>
<td>0102</td>
<td>2.2</td>
<td>1.1</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>MiniMELF</td>
<td>MMA</td>
<td>0204</td>
<td>3.6</td>
<td>1.4</td>
<td>0.25 – 0.4</td>
</tr>
<tr>
<td>MELF</td>
<td>MMB</td>
<td>0207</td>
<td>5.8</td>
<td>2.2</td>
<td>0.4 – 1.0</td>
</tr>
</tbody>
</table>

### 4.5. RESISTOR SYMBOLS

Several standards exist, which describe how the different components should be displayed. In the past a lot of countries or even industries used their own standards, which can be confusing. Nowadays the IEC 60617 standard is international standard for these electronic symbols. However the local standards are still used from time to time. In general, the ANSI standard is still common in the United States. Some examples of standards which describe resistor symbols:

- IEC 60617 (International)
- ANSI Y32 / IEEE 315 (US) – old
- DIN 40900 (Germany) – old
- AS 1102 (Australia) – old

Sometimes the symbol for a particular device is different when it is used in another field of application. Other symbols are used in
electronics then for example in architecture and buildings. On top of this, many local deviations from the international standards exist. The following table shows the most common resistor symbols for electronics design.
<table>
<thead>
<tr>
<th>Type</th>
<th>Abbr.</th>
<th>IEC (International)</th>
<th>ANSI (US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed resistor</td>
<td>R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating resistor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potentiometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trimming potentiometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rheostat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preset resistor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photo resistor or Light dependent resistor</td>
<td>LDR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Varistor or Voltage dependent resistor</td>
<td>VDR</td>
<td></td>
<td>RV MOV</td>
</tr>
<tr>
<td>NTC thermistor</td>
<td>NTC</td>
<td></td>
<td>RT</td>
</tr>
<tr>
<td>PTC thermistor</td>
<td>PTC</td>
<td></td>
<td>RT</td>
</tr>
<tr>
<td>Magneto resistor or Magnetic dependent resistor</td>
<td>MDR</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>
In many electrical circuits resistors are connected in series or parallel. A designer might for example combine several resistors with standard values (E-series) to reach a specific resistance value. For series connection, the current through each resistor is equal. There is only one path for the current to follow. The voltage drop however, is proportional to the resistance of each individual resistor. The equivalent resistance of several resistors in series is given by:

$$R_{eq} = \sum_{i=1}^{n} R_i = R_1 + R_2 + \ldots + R_n$$

The voltage across each resistor is calculated with Ohm’s law:

$$V_i = I \cdot R_i$$
Example

Consider a circuit as shown in the picture below. Two resistors $R_1$ and $R_2$ connected in series are subject to a constant current $I$. How can we calculate the voltage drop for each resistor and how can we determine the equivalent resistance value for the two resistors? The current through each resistor is equal. Knowing this, and using Ohm’s law we get the voltage drop for $R_1$ and $R_2$:

\[ V_{resistor1} = I \cdot R_1 = 5 \cdot 2 = 10V \]
\[ V_{resistor2} = I \cdot R_2 = 5 \cdot 3 = 15V \]
\[ V_{eq} = V_{resistor1} + V_{resistor2} = 10 + 15 = 25V \]

The equivalent resistance is equal to the sum of $R_1$ and $R_2$:

\[ R_{eq} = R_1 + R_2 = 2 + 3 = 5\Omega \]

This corresponds with the voltage drops that we calculated:

\[ V_{eq} = I \cdot R_{eq} = 5 \cdot 5 = 25V \]
5.2. RESISTORS IN PARALLEL

Resistors are often connected in series or parallel to create more complex networks. An example of 3 resistors in parallel is shown in the picture above. The voltage across resistors in parallel is the same for each resistor. The current however, is in proportion to the resistance of each individual resistor. The equivalent resistance of several resistors in parallel is given by:

\[
\frac{1}{R_{eq}} = \sum_{i=1}^{n} \frac{1}{R_i} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}
\]

The current through each resistor is given by:

\[
I = \frac{V}{R_i}
\]

Example

A circuit designer needs to install a resistor with 9 ohms and can choose from the E-12 series of preferred values (.., 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, ..). The value of 9 ohms is
unfortunately not available in this series. He decides to connect to standard values in parallel with an equivalent resistance of 9 ohms. The equivalent resistance value for 2 resistors in parallel is calculated with these steps:

\[
\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}
\]

\[
\frac{1}{R_{eq}} = \frac{R_2}{R_1R_2} + \frac{R_1}{R_1R_2}
\]

\[
\frac{1}{R_{eq}} = \frac{R_1 + R_2}{R_1R_2}
\]

\[
R_{eq} = \frac{R_1R_2}{R_1 + R_2}
\]

The above equation shows that if \( R_1 \) is equal to \( R_2 \), \( R_{eq} \) is half of the value of one of the two resistors. For a \( R_{eq} \) of 9 ohms, \( R_1 \) and \( R_2 \) should therefore have a value of \( 2 \times 9 = 18 \) ohms. This happens to be a standard value from the E-series.

\[
R_{eq} = \frac{R_1R_2}{R_1 + R_2} = \frac{18 \cdot 18}{18 + 18} = 9\Omega
\]

As a solution finally, the designer connects two resistors of 18 ohms in parallel as shown in the figure right.

![Resistor circuit diagram](image-url)
## 5.3. Resistors in Parallel and Series

A more complex resistor network can be solved by systematic grouping of resistors. In the picture below three resistors are connected. Resistors R2 and R3 are connected in series. They are in parallel with resistor R1. To solve the network, the resistors are separated in two groups. Group 1 consists of only R1. Group 2 consists of R2 and R3.

The equivalent resistance of group 2 is easily calculated by the sum of R2 and R3:

$$R_{\text{group2}} = R_2 + R_3$$

This leads to the simplified circuit with two resistors in parallel. The equivalent resistance value of this circuit is easily calculated:

$$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_{\text{group2}}}$$

$$R_{\text{eq}} = \frac{R_1 \cdot R_{\text{group2}}}{R_1 + R_{\text{group2}}}$$

$$R_{\text{eq}} = \frac{R_1 \cdot (R_2 + R_3)}{R_1 + R_2 + R_3}$$
5.4. WHAT ARE HEATER RESISTORS?

Heater resistors are used whenever an electronic device needs to generate heat for some reason. They are designed as a special type of power resistor to provide a reliable and controllable source of heat. A heating resistor can produce convective heat, meaning it heats up the surrounding air, or radiant heat, meaning it heats other objects directly through a phenomenon called infrared radiation. Radiant heating requires the heater resistor to be placed within line of sight of the object that is to be heated, while convective heating sometimes utilizes fans to blow air over heater resistors in order to increase the heating effectiveness.

Heater resistors are a special type of power resistors whose main purpose is to convert electrical energy into heat.

5.4.1. RADIANT HEATING

5.4.1.1. WIREWOUND RADIANT HEATER

Wire-wound radiant heaters are essentially wire-wound power resistors.
The heated object receives heat by absorbing infrared rays emitted by the glowing-hot wire. Some of the energy is given off as light in the visible spectrum as well. A reflector is often added behind the resistance heating element in order to direct as much heat as possible in the desired direction. The wire can be exposed or enclosed in a tube to protect it from damage. This is especially useful if there is a risk of water drops falling on the element, which could cause thermal stress damage. Wire-wound radiant heaters are often used in bathrooms or outdoor uses where the intent is to heat a person without having to heat up the surrounding air first.

5.4.1.2. HALOGEN RADIANT HEATER

Halogen radiant heaters, often called quartz heaters, are similar in design to halogen light bulbs. They are most often made of a quartz tube with a tungsten resistive filament inside of it. The air from the tube is evacuated and replaced with an inert gas such as argon or nitrogen, and a small amount of halogen gas is added to prolong the heater lifespan by protecting and cleaning the filament in a chemical process called a halogen cycle. A reflector is added behind the heating element to direct the heat energy in the desired direction. They are often equipped with safety mechanisms which turn off the heater if it is tipped over, to prevent fires. Halogen heaters are often used in technological processes requiring contactless heating, such as chemical processes, paint drying, food
processing and thawing, as well as incubators and heating augmentation in cold rooms.

5.4.2. CONVECTION AND FAN-POWERED AIR HEATING

5.4.2.1. ELECTRIC CONVECTION HEATER

Electric convection heaters have a heating element which is exposed to air. Once the air is in contact with a hot object it heats up and, due to the fact that hot air is lighter than cold air, rises up, leaving space for more cool air to come in contact with the heater from below. This process is called air convection. Electric convection heaters sometimes do not heat the air directly, as is the case in oil radiators. In such devices, the heater element is in direct contact with special oil which spreads the heat throughout the radiator. The heat is then transferred to the surroundings by air convection. A special subtype of convection heaters is floor heating, which uses resistive wires to heat the entire surface of a floor in a room. The heat is then transferred to the air by convection, but the heat difference between the floor and the air is kept under a few degrees to avoid unpleasant air convection currents.
5.4.2.2. **FAN HEATER**

Fan heaters are similar to electric convection heaters, except air is forced over the heating element by means of an electrical fan. These heaters are used to heat up closed spaces such as rooms or vehicle interiors while the engine is still warming up to operating temperature. The downside to using fan heaters is that they are noisy compared to traditional convection heaters, although recent advances in technology have reduced the amount of noise generated by fans. The heater element is often constructed of a PTC thermistor.

5.4.3. **LIQUID HEATING**

5.4.3.1. **SUBMERSIBLE HEATER**

Submersible heater elements are resistive heaters used to heat up liquids. They are electrically insulated to maintain safety and prevent electrolysis of the liquid that is being heated up. Many applications call for the use of immersion water heaters, such as water heaters, water boilers and aquarium heaters, which are equipped with a thermostat to maintain constant temperature. If a submersible heater element is constantly in contact with hard water, as is the case in household water heaters, limescale (calcium
carbonate deposits) eventually builds up on the heater element. As the element is cycled on and off, the thermal expansion and contraction of the element breaks the limescale and it falls to the bottom of the container, a process which over time can significantly reduce the liquid capacity of the heater.

5.4.3.2. INDUSTRIAL LIQUID HEATING

Industrial liquid heaters are custom designed and built for the application. Examples of industrial applications that call for electrical heating are asphalt heating/melting, bio-diesel processing, clean steam generation, food processing, textiles, pharmaceutical processing and many more.

5.4.4. OTHER TYPES OF HEATER RESISTORS

The number of interesting applications for heating resistance wire is overwhelming, and only some of them will be listed here. For example, heater resistors can be used in heated motorcycle hand grips for driving in cold weather. or special heating resistors embedded in, or sometimes applied to, the surface of a car window which are used for de-fogging and de-frosting, most often seen on the rear window in the form of resistive tracks on the glass.
Another useful application is surveillance cameras. A heater resistor is placed close to the glass cover and the lens. The heat from the resistor keeps the glass temperature above the dew point, which prevents fogging and snow buildup, which keeps the camera useful in all weather conditions.

In order to accurately develop photographic films, a very precise and constant temperature is required, otherwise colors will degrade. In a similar way, many chemical processes need a constant temperature and heating might be required. Some medical equipment, such as blood analyzers, also needs constant temperature to operate correctly.

5.5. RESISTORS IN LED CIRCUITS

An LED (Light Emitting Diode) emits light when an electric current passes through it. The simplest circuit to power an LED is a voltage source with a resistor and an LED in series. Such a resistor is often called a ballast resistor. The ballast resistor is used to limit the current through the LED and to prevent that it burns. If the voltage source is equal to the voltage drop of the LED, no resistor is required. The resistance of the ballast resistor is easy to calculate with Ohm’s law and Kirchhoff’s circuit laws. The rated LED voltage is subtracted from the voltage source, and then divided by the desired LED operating current:
The Resistor Guide

\[ R = \frac{V - V_{LED}}{I} \]

Where \( V \) is the voltage source, \( V_{LED} \) is the LED voltage and \( I \) the LED current. This way you can find the right resistor for LED.

LEDs are also available in an integrated package with the correct resistor for LED operation. This simple circuit might be used as a power-on indicator for a DVD player or a computer monitor. Although this simple circuit is widely used in consumer electronics, it is not very efficient since the surplus of energy of the voltage source is dissipated by the ballast resistor. Therefore, sometimes more complex circuits are applied with better energy efficiency.

**Example of simple LED circuit**
In the following example an LED with a voltage of 2 volts and an amperage of 20 mili-amperes must be connected to a 12 volts supply. The ballast resistor can be calculated using the formula:

\[
R = \frac{V - V_{LED}}{I}
\]

\[
R = \frac{12 - 2}{0.03} = 333
\]

The resistor must have a resistance of 333 ohm. If the precise value is not available, choose the next value that is higher.

### 5.5.1. LED IN A SERIES CIRCUIT

Often multiple LEDs are connected to a single voltage source with a series connection. In this way multiple resistors can share the same current. Because the current through all LEDs in series is equal, they should be of the same type. Note that lighting one LED in this circuit uses just as much power as multiple LEDs in series. The voltage source must provide a large enough voltage for the sum of voltage drops of the LEDs plus the resistor. Typically the voltage source is 50 percent higher than the sum of LED voltages. In contradiction, sometimes is chosen to have a lower voltage source. In this strategy, the lower brightness is compensated by the larger number of LEDs. Furthermore, there is less thermal loss and the LEDs have a higher lifespan due to the lower load.
Example of LEDs in series

In this example two LEDs are connected in series. One red LED with a voltage of 2V and a blue LED with 4.5 volts. Both have a rated amperage of 30 mA. Kirchhoff’s circuit laws tell that the sum of voltage drops across the circuit is zero. Therefore the resistor voltage must be equal to the voltage source minus the sum of the voltage drops of the LEDs. With Ohm’s law we calculate the resistance value of the ballast resistor:

\[ R = \frac{V - V_{LED1} - V_{LED2}}{I} \]

\[ R = \frac{12 - 2 - 4.5}{0.03} = 183.3 \]

The resistor must have a value of at least 183.3 ohms. Note that the voltage drop is 5.5 volts. It would have been possible to connect additional LEDs in the circuit.
5.5.2. LED IN A PARALLEL CIRCUIT

It is possible to connect LEDs in parallel, but it gives more problems than series circuits. The forward voltages of the LEDs must closely match, otherwise only the lowest voltage LED lights up and possibly burn by the larger current. Even if the LEDs have the same specification, they can have bad matching I-V characteristics due to variations in the production process. This causes the LEDs to pass a different current. To minimize the difference in current, LEDs in parallel normally have a ballast resistor for each branch.

5.5.3. HOW DOES AN LED WORK?

An LED (Light Emitting Diode) is semiconductor device; it is essentially a P-N junction with a lead attached to each side. An ideal diode has zero resistance when forward biased and infinite resistance when reversed biased. In real diodes however, a small amount of voltage must be present across the diode to make it conduct. This voltage along with other characteristics is determined by the materials and construction of the diode. When the forward bias voltage becomes large enough, excess electrons from one side of the junction start to combine with holes from the other side. When this occurs, the electrons fall into a less energetic state and
release energy. In LEDs this energy is released in the form of photons. The materials from which the LED is made determine the wavelength, and therefore the color of the emitted light. The first LEDs were made with gallium arsenide and gave off a red light. Today an LED can be made from a variety of materials and can emit a range of colors. Voltages vary from about 1.6 volts for red LEDs to about 4.4 volts for ultraviolet ones. Knowing the correct voltage is important because applying too much voltage across the diode can cause more current than the LED can safely handle.

LEDs today are available in low and high power. LEDs typically give off less heat and use less power than in incandescent bulb of equal brightness. They last longer than equivalent light bulbs. LEDs are used in a wide range of lighting and light sensing applications.

5.5.4. USING LEDS AS PHOTODIODES

LEDs can be used as photodiodes. Photodiodes are semiconductors that behave in the opposite manner from LEDs. Whereas an LED will
emit light as it conducts, a photodiode will generate current when exposed to the correct wavelength of light. An LED will act exhibit this characteristic when exposed to light at a wavelength below its normal operational wavelength. This allows LEDs to be used in circuits like light sensors and fiber optic communication circuits.

5.5.5. LED SYMBOL

5.6. POWER RESISTORS

Power resistors are designed to withstand and dissipate large amounts of power. In general they have a power rating of at least 5 Watt. They are made from materials with a high thermal conductivity, allowing efficient cooling. They are often designed to be coupled with heat sinks to be able to dissipate the high amount of power. Some might even need forced air or liquid cooling while under maximum load. Some are wire wound, some are made from wire grids for ease of cooling, but the common thing for all power resistors is that they are built to dissipate the most power while keeping their size as small as possible. An example use for power resistors are load banks used to dissipate power generated during engine braking in vehicles using electrical motors, such as locomotives or trams.
A power resistor is a resistor designed and manufactured to dissipate large amounts of power in a compact physical package.

5.6.1. TYPES AND CONSTRUCTION

5.6.1.1. WIREWOUND RESISTORS

Wire wound resistors are made by winding a metal wire around a solid form, often made of ceramic, fiberglass or plastic. Metal caps are attached to the end of the winding and metallic leads are attached to the ends. The end product is often coated with a non-conductive paint or enamel to offer some protection from the environment. Wire wound resistors can be built to withstand high temperatures, sometimes up to 450 °C. These resistors are often built to tight tolerances thanks to the material used, an alloy of nickel and chrome called Nichrome. The body of the device is then coated with a non-conductive paint, enamel or plastic.

![An edge wound resistor.](image)

There are several winding methods. Some of them are: helical winding, edge-winding and bifilar winding. The helical type is the ordinary winding in which a wire is wound in a helix around a cylindrical core. Since the wire is coil-shaped, this type of resistor also has a certain inductance. To avoid the potential interference
with other devices and the generation of unwanted magnetic fields, wire wound resistors can be made using a bifilar winding, which is wound in two directions, reducing the electromagnetic fields created by the resistor. Edge-wound resistors are made by winding a strip of metal by its wider edge. These are usually coreless, air-cooled and can dissipate more power than the helical type.

5.6.1.2. GRID RESISTOR

Grid resistors are large matrices of metal strips connected between two electrodes. They vary in size, but can be as large as a refrigerator. It is not uncommon to see grid resistors valued at under 0.04Ω and can withstand currents of over 500 amperes. They are used as brake resistors and load banks for railroad vehicles, neutral grounding resistors, load testing of generators and harmonic filtering for electric substations.

5.6.1.3. CHIP/SMD RESISTORS

Chip resistors are resistors which look like integrated circuit chips. Surface mount power resistors are made from many different materials, such as pressed carbon, ceramics and metal (cermet resistors) or metal foil. Wire wound chip resistors are also available.
SMD resistors are actually smaller form, surface mounted chip resistors. The resistor itself consists of a metal oxide film deposited onto a ceramic substrate. The thickness and length of film determines the resistance. They have power dissipation ratings much lower than those of grid resistors or water resistors and can usually dissipate no more than a few watts, provided they have appropriate cooling.

### 5.6.1.4. WATER RESISTORS

Water resistors are consisted of tubes filled with a saline solution with an electrode at both ends. The concentration of salt in the solution controls the resistance of the resistor. Water in the tube provides a large heat capacity which allows high power dissipation. Some high power water resistors used in pulsed modes utilize copper sulfate solutions instead of saline.

### 5.6.1.5. LIQUID RHEOSTATS

Liquid rheostats, or salt water rheostats, are a type of variable resistors in which the resistance is controlled by submerging the electrodes into a saline solution. The resistance may be may be raised or lowered by adjusting the electrode position inside the liquid. The mixture must not be allowed to boil in order to stabilize the load. Liquid rheostats are slightly outdated, but are still constructed for use in some diesel generators.
### 5.6.1.6. TYPICAL APPLICATIONS

Power resistors are used when there is a need to safely convert large amounts of energy into heat using electrical energy as a medium. They are used as controllable power dissipation devices, protective devices and devices that simulate real world loads.

### 5.6.1.7. ENGINE BRAKING

High power resistors are used in locomotives and trams to safely convert kinetic energy of the vehicle to heat. Since the energies involved in stopping heavy vehicles moving at high speeds, classic disc brakes would wear out too fast and their maintenance would be too expensive. Because of that, regenerative braking tends to be used. In regenerative braking, kinetic energy is transformed to electrical energy and fed back into the supply network. However, when regenerative braking is not available, power resistors are used. Resistance brakes offer controlled braking power without introducing wear to the parts. It is often necessary to dissipate many kilowatts for extended periods of time.

<table>
<thead>
<tr>
<th>Type</th>
<th>Typical power dissipation</th>
<th>Size</th>
<th>Vibration resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helical wound</td>
<td>&lt;50 W</td>
<td>Small-medium</td>
<td>Low</td>
</tr>
<tr>
<td>Edge wound</td>
<td>&lt;3.5 kW</td>
<td>Small-medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Grid</td>
<td>&lt;100 kW</td>
<td>Medium-large</td>
<td>High</td>
</tr>
<tr>
<td>Chip/SMD</td>
<td>&lt;5W</td>
<td>Small-very small</td>
<td>High</td>
</tr>
<tr>
<td>Water</td>
<td>&lt;500 MW (30s)</td>
<td>Medium-large</td>
<td>Medium</td>
</tr>
</tbody>
</table>
5.6.1.8. LOAD BANKS

Load bank resistors are devices used to safely simulate a real-world load. They are used to load-test generators, turbines and battery UPS systems. Resistive load banks provide a known adjustable resistance value in a compact package as opposed to real loads which can be dispersed over a large area, random in value and are usually not exclusively resistive, but may have an inductive or capacitive component as well. AC load banks can withstand and dissipate as much as 6 megawatts of power, which is quite a lot, but such large load banks can be the size of a room, and they are equipped with active cooling to prevent thermal damage.

5.6.1.9. NEUTRAL GROUNDING RESISTORS

Neutral grounding resistors are power resistors used in power grounding of Y-connected generators. They are used to limit the fault current as well as transient over-voltages and allow protective relays to be used in such applications. Neutral grounding resistors are rated at up to 8 kilo amperes and are mostly used in medium-voltage AC distribution systems. When these resistors are used, even if a grounding fault occurs, it is much easier to locate because of a limited number of possible fault locations.

5.7. PULL-UP RESISTORS

Pull-up resistors are resistors used in logic circuits to ensure a well-defined logical level at a pin under all conditions. As a reminder,
digital logic circuits have three logic states: high, low and floating (or high impedance). The high-impedance state occurs when the pin is not pulled to a high or low logic level, but is left “floating” instead. A good illustration of this is an unconnected input pin of a microcontroller. It is neither in a high or low logic state, and a microcontroller might unpredictably interpret the input value as either a logical high or logical low. Pull-up resistors are used to solve the dilemma for the microcontroller by pulling the value to a logical high state, as seen in the figure. If there weren’t for the pull-up resistor, the MCU’s input would be floating when the switch is open and brought down only when the switch is closed.

Pull-up resistors are not a special kind of resistors; they are simple fixed-value resistors connected between the voltage supply (usually +5V) and the appropriate pin, which results in defining the input or output voltage in the absence of a driving signal. A typical pull-up resistor value is 4.7kΩ, but can vary depending on the application.

Pull-up resistors are resistors which are used to ensure that a wire is pulled to a high logical level in the absence of an input signal.
5.7.1. HOW DO PULL-DOWN RESISTORS WORK?

Pull-down resistor

Pull-down resistors work in the same manner as pull-up resistors, except that they pull the pin to a logical low value. They are connected between ground and the appropriate pin on a device. An example of a pull-down resistor in a digital circuit can be seen in the figure. A pushbutton switch is connected between the supply voltage and a microcontroller pin. In such a circuit, when the switch is closed, the micro-controller input is at a logical high value, but when the switch is open, the pull-down resistor pulls the input voltage down to ground (logical zero value), preventing an undefined state at the input. The pull-down resistor must have a larger resistance than the impedance of the logic circuit, or else it might be able to pull the voltage down by too much and the input voltage at the pin would remain at a constant logical low value – regardless of the switch position.
5.7.2. PULL-UP RESISTOR VALUE

The appropriate value for the pull-up resistor is limited by two factors. The first factor is power dissipation. If the resistance value is too low, a high current will flow through the pull-up resistor, heating the device and using up an unnecessary amount of power when the switch is closed. This condition is called a strong pull-up and is avoided when low power consumption is a requirement. The second factor is the pin voltage when the switch is open. If the pull-up resistance value is too high, combined with a large leakage current of the input pin, the input voltage can become insufficient when the switch is open. This condition is called having a weak pull-up. The actual value of the pull-up’s resistance depends on the impedance of the input pin, which is closely related to the pin’s leakage current.

A rule of thumb is to use a resistor that is at least 10 times smaller than the value of the input pin impedance. In bipolar logic families which operate at operating at 5V, the typical pull-up resistor value is 1-5 kΩ. For switch and resistive sensor applications, the typical pull-up resistor value is 1-10 kΩ. If in doubt, a good starting point when using a switch is 4.7 kΩ. Some digital circuits, such as CMOS families, have a small input leakage current, allowing much higher resistance values, from around 10kΩ up to 1MΩ. The disadvantage when using a larger resistance value is that the input pin responses to voltage changes slower. This is the result of the coupling between the pull-up resistor and the line capacitance of the wire which forms an RC circuit. The larger the product of R and C, the more time is needed for the capacitance to charge and discharge, and consequently the slower the circuit. In high-speed circuits, a large pull-up resistor can sometimes limit the speed at which the pin can reliably change state.
5.7.3. TYPICAL APPLICATIONS FOR PULL-UP AND PULL-DOWN RESISTORS

Pull-up and pull-down resistors are often used when interfacing a switch or some other input with a microcontroller or other digital gates. Most microcontrollers have in-built programmable pull up/down resistors so fewer external components are needed. It is possible to interface a switch with such microcontrollers directly. Pull-up resistors are in general used more often than pull-down resistors, although some microcontroller families have both pull-up and pull-downs available. They are often used in analog to digital converters to provide a controlled current flow into a resistive sensor. Another application is the I2C protocol bus, where pull-up resistors are used to enable a single pin to act as an input or an output. When not connected to a bus, the pin floats in a high-impedance state. Pull-down resistors are also used on outputs to provide a known output impedance.

5.8. BLOWER RESISTORS

Blower resistors are resistors which are used to control the fan speed of automotive blowers. The fan speed can be changed either by switching the blower resistor resistance mechanically, using a rotating lever, or electronically by the air conditioning system. The change in resistance then limits the current through the motor, which dictates the speed at which the blower fan works. Blower resistors, being a mechanical component, are prone to wear and are the most common point of failure in a car’s heating system. This
The article will focus on mechanical blower resistors, their construction and troubleshooting.

## 5.8.1. CONSTRUCTION

A blower fan is connected to the negative battery terminal (also called ground) on one end and to the positive battery terminal through a blower resistor on the other end. The blower resistor is connected in series with the blower fan. This means that the current running through the blower motor, and thus is speed is controlled by the resistor value. The user chooses a suitable fan speed by using a selector to connect one of the resistors in the blower resistor pack. Blower resistors are made of several resistors with different resistances. There are also two additional circuits used for the off state and the highest fan speed state. In the off state, the blower motor is disconnected from the power supply. In the highest speed state, the blower resistor is bypassed completely and the fan is connected directly to the car’s battery, which allows maximum current through the motor. The lower the resistance of the selected resistor in a pack, the higher the current that flows through the blower fan, and the faster the fan will turn.
5.8.2. TROUBLESHOOTING

The individual resistors inside the pack are usually wire wound and they may fail by burning out from use, and may also fail due to mechanical stresses and vibrations typically found in an automotive environment. When a blower resistor is faulty, the fan will usually operate at one speed only, usually the highest speed setting possible. Sometimes, only some of the speed settings will be faulty while others might work.

5.8.3. IDENTIFYING THE FAULT

When trying to diagnose a blower fan motor, the following steps should be followed:

- If a car’s blower motor doesn’t work at all, there are several components to be checked in the system:
  
  - Check the fuse for power on both ends using a multimeter. If there is power on one end of the blower fan fuse but not the other, then the fuse needs to be replaced.
  
  - Check the fan relay, if the car is equipped with one. Such relays can be tested by placing a finger on them and switching the fan’s control on and off. Clicking from the relay is an indication that the relay is almost certainly working correctly.
  
  - Check the fan itself for power presence by turning on the fan control and checking the fan itself for +12V at its terminals. To do this, switch your multimeter to voltage measuring mode and verify that the voltage
difference between the fan’s terminals is 12V. If there is no power present at the fan, suspect a wiring fault. In this case, it’s best to take the car to a certified auto electrician. If power is present on the fan’s terminals and the fan is not working, the blower fan is defective.

If the fan operates at some speed settings, but doesn’t work at some other speed settings, this means that the blower resistor is faulty and should be replaced.

Find the blower resistor and detach it from the rest of the circuit. For the precise location, consult the repair manual for your car’s make and model. Some common locations are near the blower fan motor, under or behind the dashboard, around the passenger footwell etc.

Once the resistor is located and detached, it is often possible to say whether the resistor has burned out or not judging by the physical appearance only. A burned out resistor should be replaced by the appropriate replacement from your car manufacturer.

If the appearance is normal, it is necessary to measure the resistance across each individual resistor. The resistors are all connected to a common point. Switch the multimeter to the resistance measuring mode, attach one probe of the multimeter to the common point and use the other probe to measure resistances at other points. If any of these resistances show an open circuit (infinite resistance), then the blower resistor needs to be replaced.
A word of caution: the blower resistor gets very hot during normal operation, so care must be taken to avoid burns and other injuries.

5.9. **SHUNT RESISTOR**

A shunt resistor is used to measure electric current, alternating or direct. This is done by measuring the voltage drop across the resistor.

5.9.1. **SHUNT RESISTOR FOR CURRENT MEASURING**

A device to measure electric current is called an ammeter. Most modern ammeters measure the voltage drop over a precision resistor with a known resistance. The current flow is calculated by using Ohm’s law:

\[ I = \frac{V}{R} \]

Most ammeters have an inbuilt resistor to measure the current. However, when the current is too high for the ammeter, a different setup is required. The solution is to place the ammeter in parallel with an accurate shunt resistor. Another term that is sometimes used for this type of resistor is ammeter shunt.

Usually this is a high precision manganin resistor with a low resistance value. The current is divided over the shunt and the ammeter, such that only a small (known) percentage flows through
the ammeter. In this way, large currents can still be measured. By correctly scaling the ammeter, the actual amperage can be directly measured. Using this configuration, in theory the maximum amperage that can be measured is endless. However, the voltage rating of the measurement device must not be exceeded. This means that the maximum current multiplied by the resistance value, cannot be higher than the voltage rating. Also, the resistance value should be as low as possible to limit the interference with the circuit. On the contrary, the resolution gets smaller the smaller the resistance and thus the voltage drop is.

**Example**

As an example a shunt resistor is used with a resistance of 1 mOhm. The resistor is placed in a circuit, and a voltage drop of 30 millivolts is measured across the resistor. This means that the current is equal to the voltage divided over the resistance, or: $I = V / R = 0.030 / 0.001 = 30$ A. The same calculation could be made, but now with the resistance value unknown and the voltage and current known. This is used to calibrate shunt resistance.
5.9.2. POSITION OF THE SHUNT IN THE CIRCUIT FOR CURRENT MEASURING

A. Often the shunt is placed in the grounded side to eliminate the common mode voltage. However, other disadvantages exist.

B. In this configuration, the common mode voltage could be too high for the ammeter.

It is important to carefully choose the position of the shunt in the circuit. When the circuit shares a common ground with the measurement device, often is chosen to place the shunt as close to the ground as possible. The reason is to protect the ammeter from the common mode voltage that might be too high and damage the device or give erroneous results. A disadvantage from this set up is that leakages that bypass the shunt might not be detected. In case the shunt is placed in the ungrounded leg, it must be isolated from the ground or include a voltage divider or an isolation amplifier to protect the instrument. Other ways are possible to not connect the measurement instrument directly with the high voltage circuit, such as using the Hall Effect. However, current shunts are commonly more affordable and cheaper.
5.9.3. SPECIFYING A SHUNT RESISTOR

Several parameters are important to specify a shunt resistor. Shunt resistors have a maximum current rating. The resistance value is given by the voltage drop at the maximum current rating. For example, a shunt resistor rated with 100A and 50mV has a resistance of $\frac{50}{100} = 0.5$ mOhm. The voltage drop at maximum current is typically rated 50, 75 or 100 mV.

Other important parameters include the resistance tolerance, the temperature coefficient of resistance and the power rating. The power rating indicates the amount of electric power that the resistor can dissipate at a given ambient temperature without damaging or changing the resistor parameters. The produced power can be calculated with Joules law. Shunt resistors have usually a derating factor of 66 percent for continuous operation. This is defined for a run time longer than two minutes. High temperatures negatively influence the accuracy of the shunt. From 80 degrees Celsius thermal drift starts. This gets worse with rising temperature, and from 140 degrees the resistor will damage and the resistance value be permanently changed.

5.9.4. WHAT IS A SHUNT IN ELECTRONICS?

In this article is focused on shunt resistors, with the primary purpose to measure current. However, the meaning of the term shunt in electronics is broader than that. A shunt is an element that is used in a circuit to redirect current around another part. The areas of application vary widely. For some applications, electrical devices other than resistors can be used. A few examples are given to illustrate the diversity of shunts.
- **Protecting a circuit against overvoltage**
  A method to protect a circuit from a too high voltage is using a crowbar circuit. When the voltage gets too high, a device will short circuit. This results in the current flowing parallel to the circuit. This causes immediately a voltage drop in the circuit. The high current through the shunt should trigger a circuit breaker or a fuse.

- **Bypassing a defective device**
  When one element in a series circuit fails, it will break the complete circuit. A shunt can be used to overcome this problem. The higher voltage that exists due to the failure will cause the shunt to short out. The electricity will pass around the defective element. A good example of this is Christmas lighting.

- **Bypass electrical noise**
  Shunts with a capacitor are sometimes applied in circuits where high-frequency noise is a problem. Before the undesired signal reaches the circuit elements, the capacitor redirect the noise to the ground.
### Safety Checks when making a resistance measurement

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Before connection the ohmmeter leads, turn off the power in the circuit.</td>
</tr>
<tr>
<td>2.</td>
<td>When connecting the leads to a DC current or voltage, make sure the plus and minus are chosen correctly.</td>
</tr>
<tr>
<td>3.</td>
<td>Adjust the meter to the right settings (AC, DC, ohms etc.)</td>
</tr>
<tr>
<td>4</td>
<td>Is the range of the meter high enough for the test circuit?</td>
</tr>
<tr>
<td>5a.</td>
<td>If measuring current or voltage, turn on power and inspect the meter value.</td>
</tr>
<tr>
<td>5b.</td>
<td>Don’t switch on power if you are measuring resistance.</td>
</tr>
<tr>
<td>6.</td>
<td>Switch off the power and then remove the test leads from the circuit.</td>
</tr>
<tr>
<td>7.</td>
<td>In case you measured current, reconnect the circuit as appropriate.</td>
</tr>
</tbody>
</table>
6. APPENDIX

RESISTOR FORMULA’S AND LAWS

Ohm’s Law

\[ R = \frac{V}{I} \]
\[ \rho = \frac{E}{I} \]

Wire resistance

\[ R = \rho \frac{l}{A} \]

Sheet resistance

\[ R = \rho \frac{l}{A} = \rho \frac{l}{t \cdot w} \]

Resistors in parallel

\[ \frac{1}{R_{eq}} = \sum_{i=1}^{n} \frac{1}{R_i} = \frac{1}{R_1} + \ldots + \frac{1}{R_n} \]

Current through each resistor:

\[ I = \frac{V}{R_i} \]

Voltage across each resistor:

\[ V_i = I \cdot R_i \]

1\textsuperscript{st} law or current law: In 1 node, the sum of all entering or leaving currents is zero.

2\textsuperscript{nd} law or voltage law: In a closed loop, the sum of voltage rises or drops is zero.
RESISTOR COLOR CODE

<table>
<thead>
<tr>
<th>Color</th>
<th>Significant figures</th>
<th>Multiply</th>
<th>Tolerance</th>
<th>TCR (ppm/K)</th>
<th>Fail rate (%)</th>
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</thead>
<tbody>
<tr>
<td>Black</td>
<td>0</td>
<td>10^0</td>
<td></td>
<td>250</td>
<td></td>
</tr>
<tr>
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<td>1</td>
<td>10^1</td>
<td>1</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Red</td>
<td>2</td>
<td>10^2</td>
<td>2</td>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>Orange</td>
<td>3</td>
<td>10^3</td>
<td>15</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td>4</td>
<td>10^4</td>
<td>25</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
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<td></td>
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</tr>
<tr>
<td>Blue</td>
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<td>10^6</td>
<td>0.25</td>
<td>10</td>
<td></td>
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<td>7</td>
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RESISTOR SMD CODE

Three digit code

3 digit Code: A B C

Value = AB · 10^C

Example: 450 = 45 · 10^0 = 45Ω

Four digit code

4 digit code: A B C D

Value = ABC · 10^D

Example: 7992 = 799 · 10^2 = 79.9kΩ

EIA-96 system

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<thead>
<tr>
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<tr>
<td>Y/R</td>
<td>0.01</td>
</tr>
<tr>
<td>X/S</td>
<td>0.1</td>
</tr>
<tr>
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</tr>
<tr>
<td>B/H</td>
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<tr>
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<tr>
<td>F</td>
<td>10000</td>
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</table>

Example

01A = 100 Ω ±1%
38C = 24300 Ω ±1%
**RESISTOR SYMBOLS**

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<th>Abbr.</th>
<th>IEC (International)</th>
<th>ANSI (US)</th>
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<td>Fixed resistor</td>
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<td>Potentiometer</td>
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<td>Rheostat</td>
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<tr>
<td>Preset resistor</td>
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<tr>
<td>Photo resistor or LDR</td>
<td>LDR</td>
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<tr>
<td>Light dependent resistor</td>
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<tr>
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<td>RV</td>
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<td>MOV</td>
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<td></td>
<td>RT</td>
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<td>Magnetic dependent resistor</td>
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# RESISTOR SIZES AND PACKAGES

## SMD Resistor

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<th>Imperial Length</th>
<th>Imperial Width</th>
<th>Imperial Height</th>
<th>Metric Length (mm)</th>
<th>Metric Width (mm)</th>
<th>Metric Height (mm)</th>
<th>Power (Watt)</th>
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</thead>
<tbody>
<tr>
<td>0201</td>
<td>0.024</td>
<td>0.012</td>
<td>0.012</td>
<td>0.6</td>
<td>0.3</td>
<td>0.1</td>
<td>1/20 (0.05)</td>
</tr>
<tr>
<td>0402</td>
<td>0.04</td>
<td>0.02</td>
<td>0.004</td>
<td>1.0</td>
<td>0.5</td>
<td>0.014</td>
<td>1/16 (0.062)</td>
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<tr>
<td>0603</td>
<td>0.06</td>
<td>0.03</td>
<td>0.035</td>
<td>1.55</td>
<td>0.85</td>
<td>0.018</td>
<td>1/10 (0.10)</td>
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<td>2.0</td>
<td>1.2</td>
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<td>1/8 (0.125)</td>
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<td>0.12</td>
<td>0.06</td>
<td>0.022</td>
<td>3.2</td>
<td>1.6</td>
<td>0.022</td>
<td>1/4 (0.25)</td>
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<td>0.10</td>
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<td>2.5</td>
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<td>1.0</td>
<td>0.024</td>
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## Melf Resistor

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<th>Abbr.</th>
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<th>Diameter (mm)</th>
<th>Power (Watt)</th>
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<tr>
<td>MicroMELF</td>
<td>MMU</td>
<td>0102</td>
<td>2.2</td>
<td>1.1</td>
<td>0.2 – 0.3</td>
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<tr>
<td>MiniMELF</td>
<td>MMA</td>
<td>0204</td>
<td>3.6</td>
<td>1.4</td>
<td>0.25 – 0.4</td>
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<td>MM8</td>
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<td>0.4 – 1.0</td>
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## Solder path and land pattern

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<th>Gap (c)</th>
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## Axial Resistor

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<th>Body length (l)</th>
<th>Body diameter (d)</th>
<th>Lead length (a)</th>
<th>Lead diameter (da)</th>
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<tr>
<td>1/8 (0.125)</td>
<td>3.0 ± 0.3</td>
<td>1.8 ± 0.3</td>
<td>28 ± 3</td>
<td>0.45 ± 0.05</td>
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<tr>
<td>1/4 (0.25)</td>
<td>6.5 ± 0.5</td>
<td>2.5 ± 0.3</td>
<td>28 ± 3</td>
<td>0.6 ± 0.05</td>
</tr>
<tr>
<td>1/2 (0.5)</td>
<td>8.5 ± 0.5</td>
<td>3.2 ± 0.3</td>
<td>28 ± 3</td>
<td>0.6 ± 0.05</td>
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<tr>
<td>1</td>
<td>11 ± 1</td>
<td>5 ± 0.5</td>
<td>28 ± 3</td>
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### PREFERRED VALUES

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<table>
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<table>
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<table>
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8. ABOUT THE AUTHORS

The main authors of the Resistor Guide are M.Sc. J.W. Pustjens and M.Sc. P.F. Van Oorschot. Confronted with the problem that there is little unbiased quality information available in one reference, both on the internet as in book form, over several years they consolidated the most important educational topics. Van Oorschot has worked in the research to study the feasibility of electric vehicles. Pustjens has worked in machine specifications for packaging machinery.

For any feedback or questions, please contact us via info@resistorguide.com.
The resistor guide will guide you in the world of resistors. This book is designed as an educational reference. The selected topics cover the questions of most electrical engineers, students and hobbyists.

In Fundamentals, an introduction in the physical background of resistor theory is given. Also the main mathematical laws and main resistor properties are explained. Then, a broad overview is given of all popular resistor types, constructions and materials. The next chapter includes all relevant resistor standards, such as the color code, the SMD code, preferred values and packaging. Finally examples are given of resistor applications. Interactive applications for the calculations can be found at www.resistorguide.com.