Resistors

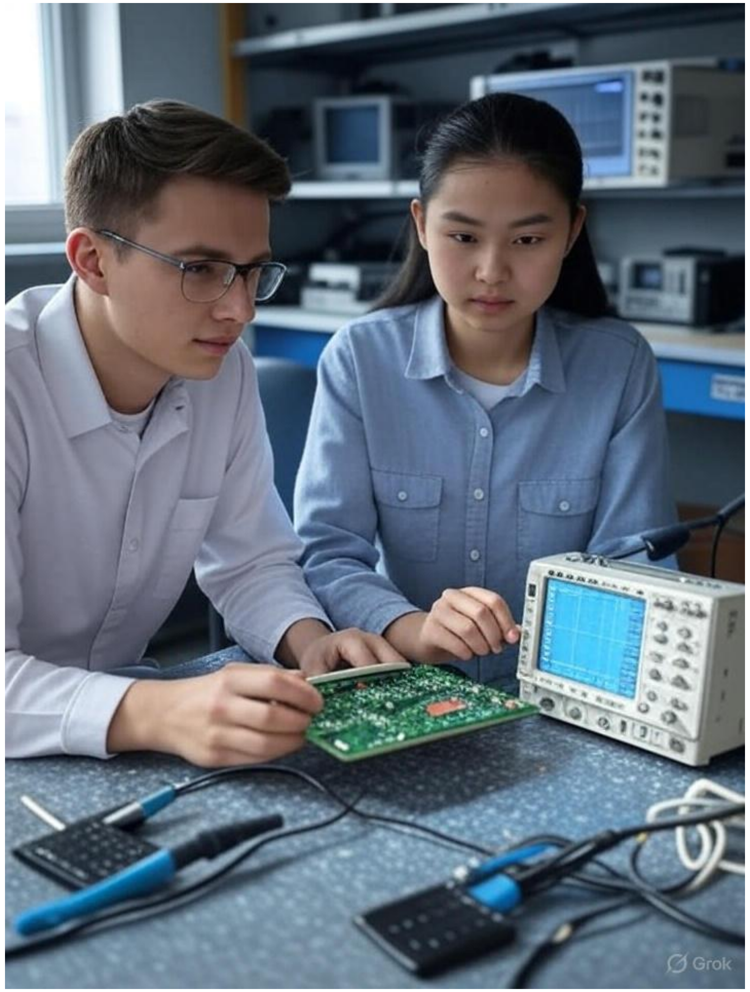
Purpose of this content

- To support engineers to gain a solid foundational knowledge on electrical and electronic components.
- Why?. Because, for every product design, components are the foundational elements.
  - **Passives :** Resistors, Inductors, Capacitors
  - **Semiconductor Discrete devices :** Various types of Diodes, Transistors, FET/MOSFETs, IGBT, Thyristors etc.,
  - **Semiconductor ICs (Actives) :** Analog, Power management, Interface ICs, MCUs, MPU, FPGAs, Sensors etc.,
- Obvious, first step of a flawless design is to get a deeper knowledge on the components.
- Next step is designing circuits using components.
  - For simulating the behavior of circuits before the final board design, there are few free and many paid software tools available. https://www.analog.com/en/resources/design-tools-and-calculators/ltspice-simulator.html
  - https://www.ti.com/tool/PSPICE-FOR-TI

Audiences for this content

To whom this content can be useful?

- Professionals who are starting their career in embedded electronics, hardware design and system design.
- Undergraduate Engineering students from E&E, ECE, Instrumentation, Mechatronics, Computer Science or students.
- Postgraduate engineering students who wants to focus on electrical, electronics products design.
- Students who are in Arts college / Diploma studying electrical, electronics subjects



Details on content creator & Request to the learner

Content put together by

https://www.seekerssignpost.com/

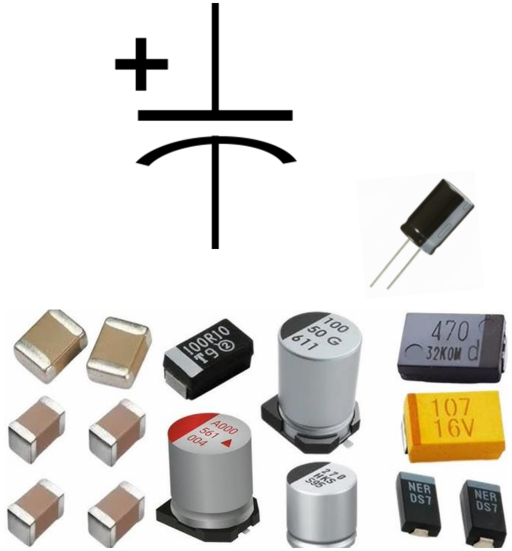
A Request to the Reader: If you like this content, and you want to share this to someone, *please share the weblink of this material.*

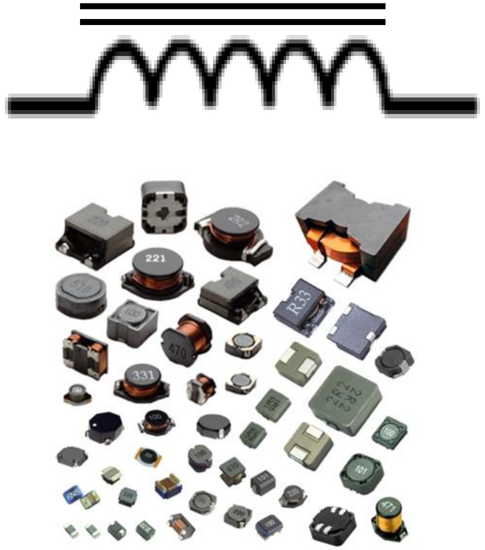
Note: This content uses references to some of the great materials out there on the internet from several component manufacturers and other websites etc., We humbly recognize and thank all of those efforts which brings clarity to engineers and help making the product development great.

In case if you are an owner of such content and for some reasons you do not want the references to be a part of these slides, please feel free to write an e-mail to us to remove those references. Also, you can send us your comments, feedback and nay new content requirement to our e-mail ID.

e-mail: seekerssignpost@gmail.com

Short Introduction to functions of R, C, L



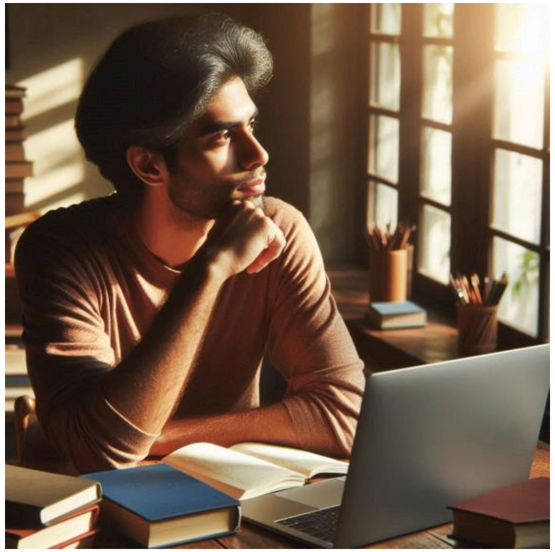


Resistor is a component that helps decide the magnitude of current flow in a circuit.

Capacitor is a component that can store energy, hold on to it and release it when demanded.

Inductor is a component which can store energy if current flows through it and release it when the current through it becomes zero. It cannot store for long like a capacitor.

Why is it essential to learn in depth about Resistors - 1



- Often, you may have gone through the data sheets of a discrete Semiconductor and ICs.
- But, how many times you have read the data sheet of a passive component like a Resistor?
- How many resistors and types are there on a PCB? Is it not wise to choose the resistors, right?
- When you create a new product, assume that you have made a wrong choice on a resistor that affects
  - a) the reliability of the PCB across the operating conditions, or
  - b) affects the accuracy of measurement across the operating temperature (for ex., -45 Deg C to +105 Deg C). what would be the impact on your product development timeline and cost?

Why is it essential to learn in depth about Resistors - 2

- **Ensure Design Precision:** Selecting correct resistor value, tolerance, TCR, and power rating are critical for accurate performance and preventing failures.
- **Manage Power and Heat:** Engineers need to calculate power dissipation to avoid overheating, ensure reliability and safety during entire product operating conditions (Design for wide range of operating temperature, altitude, humidity, overvoltage and surge conditions).
- **Mitigate Parasitic Effects:** Resistors exhibit parasitic inductance and capacitance, impacting high-frequency performance; engineers must account for these to ensure circuit stability in high frequency switching and RF applications

Content List – 1 of 3 (Hyperlinked)

Content List – 2 of 3 (Hyperlinked)

Content List – 3 of 3 (Hyperlinked)

Check out more learning materials

https://www.seekerssignpost.com

Seekers Signpost

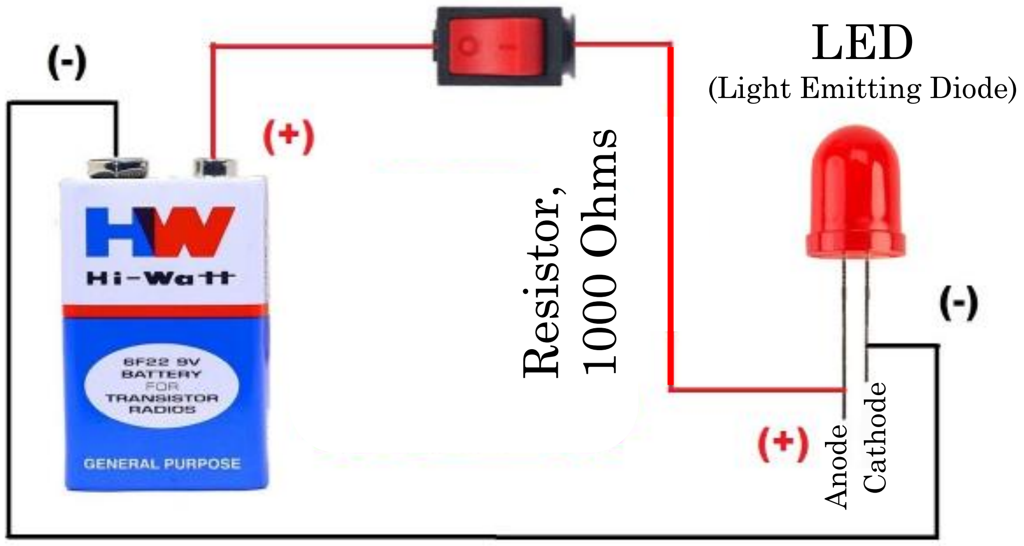
Knowledge with Compassion for life

We will be glad to hear your comments and feedback. E-mail us at seekerssignpost@gmail.com

“Resistance” (Electric current flow opposition in a material)
“Resistors” (A current limiting component)

Let’s imagine life without a Resistor !

What happens if an Indication LED is directly connected to a fresh new 9V battery, like shown below?!

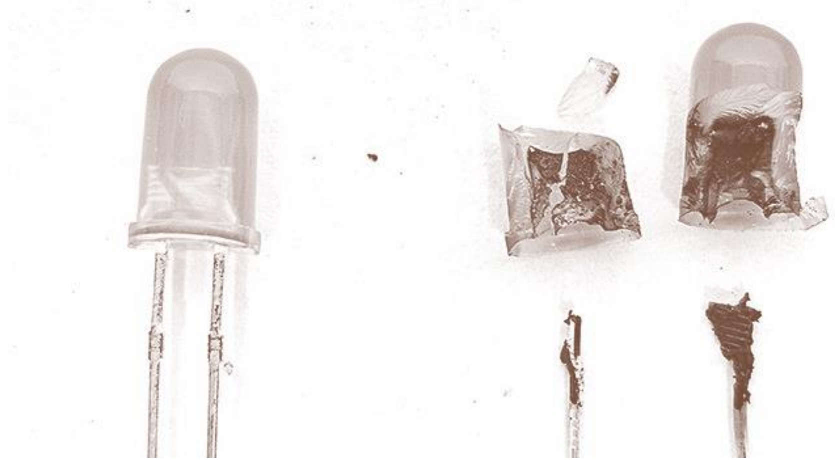


9V Battery

LED glows too brightly for a brief period followed by the destruction of the LED.

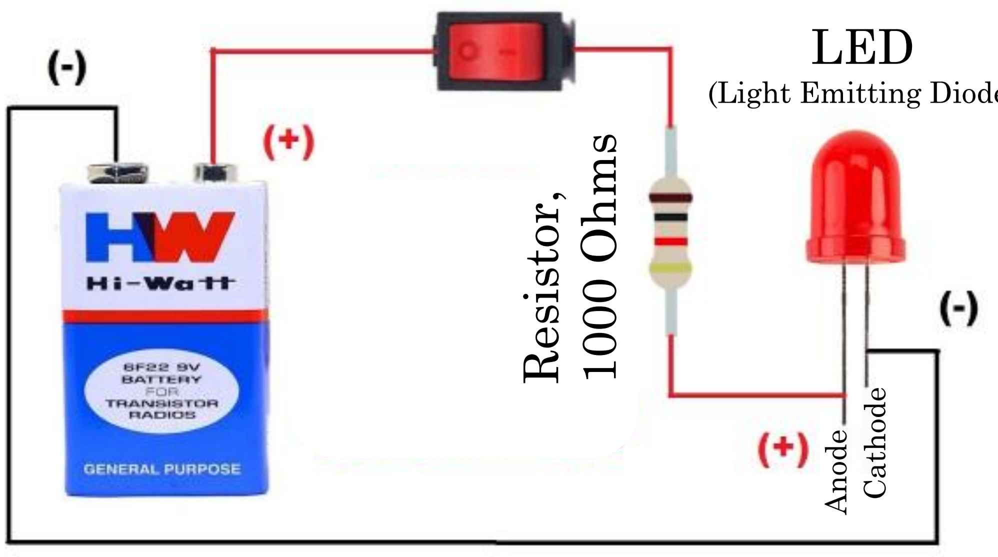
So, what happened?

We were supposed to limit the current through the LED to a safe operating value, using a component called “Resistor” and we didn’t do so…



What is “Resistance” and a “Resistor”

- **Resistance is a measure of how much a material opposes the flow of electric current through it.**
- **Higher the resistance, higher is the difficulty for electrons to move through the material when a voltage is applied across the material.**
- **The component “Resistor” is designed to offer a “certain resistance” in a circuit and designed to handle “certain power level” safely.**
- **Key Points:**
  - Resistance is denoted by symbol “R”.
  - Its unit is Ohms. Symbol of Ohms is : Ω
  - A higher resistance means less current will flow for a given voltage.



Here, the resistor helps to limit the current flowing through the Light Emitting Diode (LED) to a safe value.

Lower the resistance, higher the current and hence higher the brightness of LED and vice versa.

What causes electrical Resistance - #1

#1 - Collisions with Atoms (Lattice Scattering) :

- As electrons flow through a conductor (like a metal), they scatter off the vibrating atoms in the crystal lattice. The more frequent these collisions, the higher the resistance.
- **Increased temperature** of the conductor causes atoms to vibrate more, increasing resistance. (That means, resistance changes as the temperature changes)

#2 - Impurities and Defects:

- Real materials are never perfectly pure. Impurities, grain boundaries, or structural defects disrupt electron flow. These disruptions scatter electrons, increasing resistance.

What causes electrical Resistance - #2

#3 - Material Type: (Intrinsic Properties)

- Metals have low resistance because they have many free electrons (a “sea” of electrons). Insulators have very few free electrons, so resistance is extremely high. Semiconductors fall in between, with resistance that can be tuned.

#4 – Dimension of the material

- **Length**: Longer wires have more resistance (more opportunity for scattering).
- **Cross-sectional area**: Thicker wires have lower resistance because they provide more pathways for electrons.
- This relationship is captured by the formula:

$$R = \rho \ * \frac{L}{A}$$

Resistor

A **resistor** is a passive electronic component that provides a definite amount of **resistance** to control the current or divide the voltage in a circuit.

- **Function:** Controls / resists the flow of electric current by introducing resistance to it.
- **Characteristic:** *Dissipates the energy as heat. Resistance causes power loss of I^2R. Energy lost over time "t" seconds is $I^2R * t$*
- **Behavior:**
  - Obeys **Ohm's Law**: V=I * R or R = V/I
  - **Supposed to be Independent of frequency** (ideal resistor has no reactance).
- **Key Parameter:** Resistance R (in ohms, Ω)
- **Use Cases of resistors:**
  - Limiting current in a circuit.
  - Voltage / Potential dividers.
  - Pull-up or pull-down resistors etc.,


Resistor symbol (US and Japan)


Resistor symbol (Europe)

Back to content List

“Resistivity - ρ” (of a material)

“Temperature Co-efficient of Resistivity - α”

Introduction to Resistivity

What is common in this image is, both can be called as Roads, but one is a "Mud Road" the other one is a "Tar road".

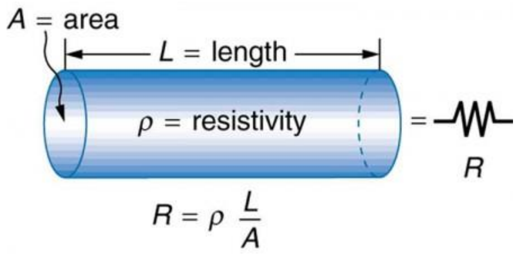
The speed at which one can drive a bike on these roads can be very different, due their surface property.

In the same way, **Resistivity (ρ)** is an inherent property of the conductor's material showing how much it naturally resists electron flow, no matter the conductor's shape or size. It's measured in ohm-meters (Ω·m).

e.g., copper (like a nice Tar Road), or iron (Like a mud road with ups and downs with sand)

Resistivity of a material

Resistance of a piece of conducting wire $R = \rho * \frac{L}{A}$



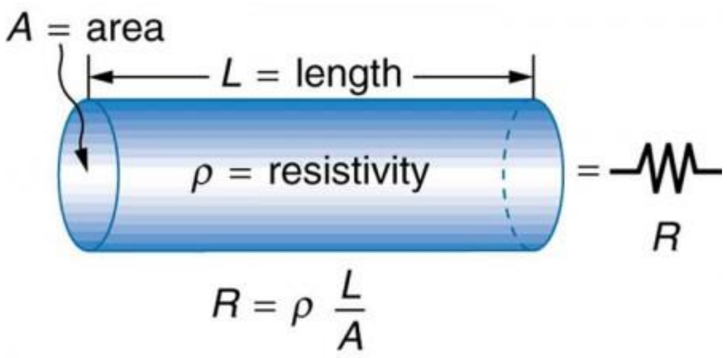
Where:

- ***ρ*** **(rho): Resistivity of the material (Ω·m).**
  - Resistivity is a measure of any material's inherent ability to resist the movement of charge carriers (like electrons) for a given dimension.
  - For example, copper has a low resistivity ($\rho \approx 1.68 \times 10^{-8}$ Ω·m), while rubber has a very high resistivity (10^{12} to 10^{15} Ω·m.)
- ***L***: Length of the conductor (in meters).
- ***A***: Cross-sectional area of the conductor (in square meters).
- So, to know the resistance of a piece of a copper, we need to its resistivity, it's length and its cross-sectional area.

Image Courtesy: https://courses.lumenlearning.com/suny-physics/chapter/20-3-resistance-and-resistivity/

Resistance of a wire

$$Resistance\ R = \rho * \frac{L}{A}$$



- So, to know the resistance of a piece of a copper, we need to its resistivity, it's length and its cross-sectional area.

- When we do electrical wiring at home, the dimensions of the wire is same. However, as the resistivity of a material doesn't stay constant at all temperatures, the resistance of a conductor and even the resistance of a Resistor component varies with temperature variation.

$$R \propto l$$

Longer the conductor, higher the resistance value.

$$R \propto 1/A$$

Bigger the conductor cross section, lower the resistance value.

Introduction to Temperature Coefficient of Resistivity



Like the level of rain fall could make a mud road or Tar road as "wet, flooded or dry", which would eventually have the impact on the riding quality on the road, besides the type of the road itself…

"*Resistivity* (ρ) has factor of heat sensitivity called Temperature co-efficient of Resistivity (α).

How is Resistivity specified?

- Since the Resistivity of any material "ρ"is not a constant value across varying temperatures, the question is, how do we specify the resistivity of a material? ANS: The resistivity value is generally specified at 20^0C.

- To specify the temperature dependance of resistivity, the "Temperature coefficient of Resistivity per ^{0}C (α)" for each material is also specified.

- Once we know Resistivity (ρ) and temperature co-efficient of Resistivity (α), we can find the Resistivity for any given Temperature "T" using formula.

Calculate Resistivity for a given temperature

- To find Resistivity at any given temperature

$$\rho_t = \rho_0 [1 + \alpha (T - T_0)]$$

- ρ_t is the resistivity at any given temperature T^0C . Unit is ohm-meters (Ω.m)
- T is the temperature at which we want to calculate the resistivity
- T_0 is the reference temperature at which ρ_0 is specified
- ρ_0 is the resistivity at a standard temperature (typ. 20^0C)
- α is the temperature coefficient of the resistivity of the material

ρ, α, of commonly used materials

Material	Type	Resistivity (ρ) at 20°C (Ω·m)	Temperature Coefficient of Resistivity (α) (1/°C)
Silver	Conductor	1.59×10^{-8}	0.0038
Copper	Conductor	1.68×10^{-8}	0.0039
Gold	Conductor	2.44×10^{-8}	0.0034
Aluminum	Conductor	2.82×10^{-8}	0.0039
Tungsten	Conductor	5.60×10^{-8}	0.0045
Iron	Conductor	9.71×10^{-8}	0.00651
Platinum	Conductor	10.6×10^{-8}	0.00392
Nichrome	Conductor	1.10×10^{-6}	0.0004
Manganin	Conductor	4.82×10^{-7}	0.00001
Constantan	Conductor	4.90×10^{-7}	0.000008
Silicon (pure)	Semiconductor	6.40×10^{2}	-0.075
Germanium (pure)	Semiconductor	4.60×10^{-1}	-0.048
Glass	Insulator	$10^{10} – 10^{14}$	Negative (varies, typically -0.01 to -0.1)
Rubber	Insulator	$10^{13} – 10^{15}$	Negative (varies, typically -0.01 to -0.1)
Mica	Insulator	$10^{11} – 10^{14}$	Negative (varies, typically -0.01 to -0.1)
Porcelain	Insulator	$10^{12} – 10^{14}$	Negative (varies, typically -0.01 to -0.1)
Dry Wood	Insulator	$10^{14} – 10^{16}$	Negative (varies, typically -0.01 to -0.1)
PTFE (Teflon)	Insulator	$10^{22} – 10^{24}$	Negative (varies, typically -0.01 to -0.1)

Back to content List

OHM's Law

Relation between Voltage, Resistance and Current

Assuming when a car gives same amount of acceleration, the effective speed is influenced by the road resistance.

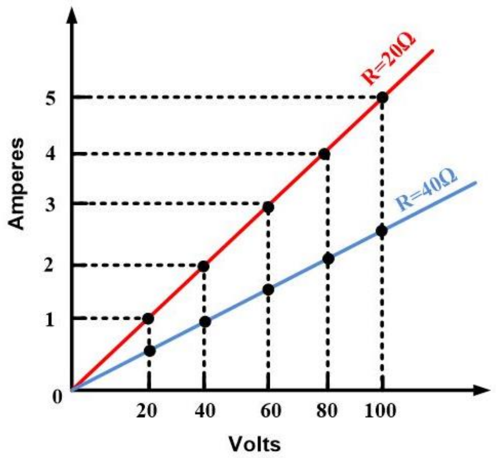
Acceleration → Applied Voltage V
Road Resistance → Resistance of the Resistor R
Effective Speed → Current I.

Effective speed is directly proportional to Acceleration and inversely proportional to the road resistance. Like wise Current is directly proportional to Voltage and inversely proportional to Resistance.

Ohm's law

Georg Simon Ohm;
16 March 1789;
German Mathematician & Physicist

Ohm's law states that the electric current through a conductor between two points is directly proportional to the voltage across the two points. Introducing the constant of proportionality, the resistance, one arrives at the three mathematical equations used to describe this relationship.



$$V = IR \quad \text{or} \quad I = \frac{V}{R} \quad \text{or} \quad R = \frac{V}{I}$$

V is in Volts; I is in Amps; R is in Ohms

Courtesy: https://en.wikipedia.org/wiki/Georg_Ohm

Can we do some mental Mathematics?

Keeping R Constant, say 1 Ohms

If V = 1 volts; then I = -- Amps
If V = 2 volts; then I = -- Amps
If V = 0.5 volts; then I = -- Amps

Keeping V Constant, say 1 Volts

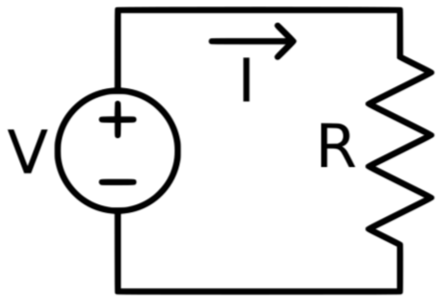
If R = 1 Ohms; then I = -- Amps
If R = 2 Ohms; then I = -- Amps
If R = 0.5 Ohms; then I = -- Amps

Keeping R Constant, say 1 Ohms

If V = 1 volts; then I = 1 Amps
If V = 2 volts; then I = 2 Amps
If V = 0.5 volts; then I = 0.5 Amps

Keeping V Constant, say 1 Volts

If R = 1 Ohms; then I = 1 Amps
If R = 2 Ohms; then I = 0.5 Amps
If R = 0.5 Ohms; then I = 2 Amps



$$V = IR \quad \text{or} \quad I = \frac{V}{R} \quad \text{or} \quad R = \frac{V}{I}$$

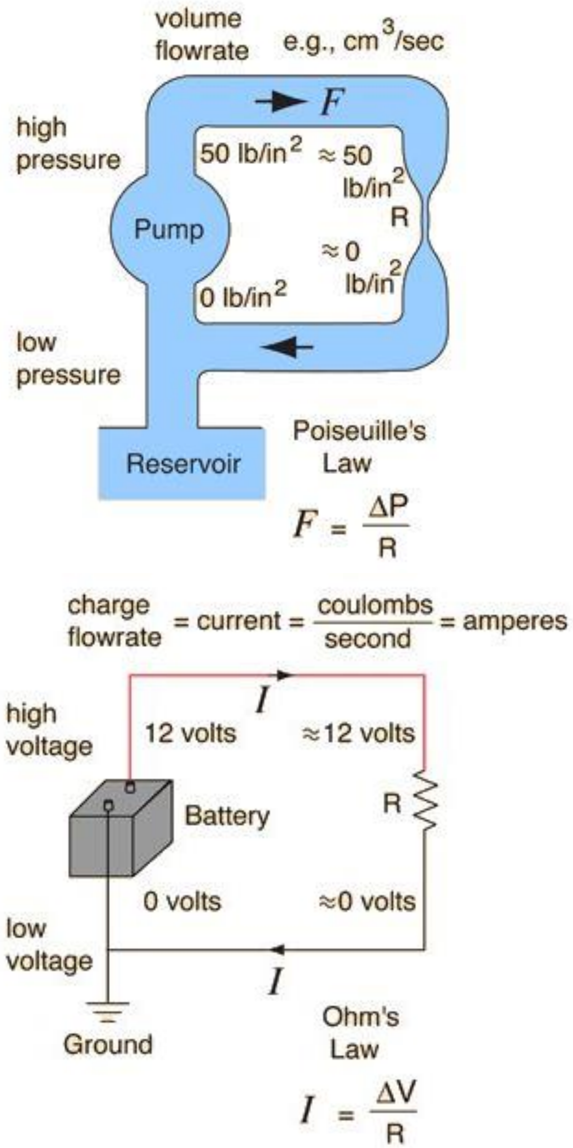
What is Voltage or Potential difference

Physical Intuition: The Water Analogy

To understand voltage, imagine a water system:
Voltage is like the **pressure difference** between two points in a water pipe. If one end of the pipe is at high pressure and the other at low pressure water flows from high to low pressure point due to this pressure difference.

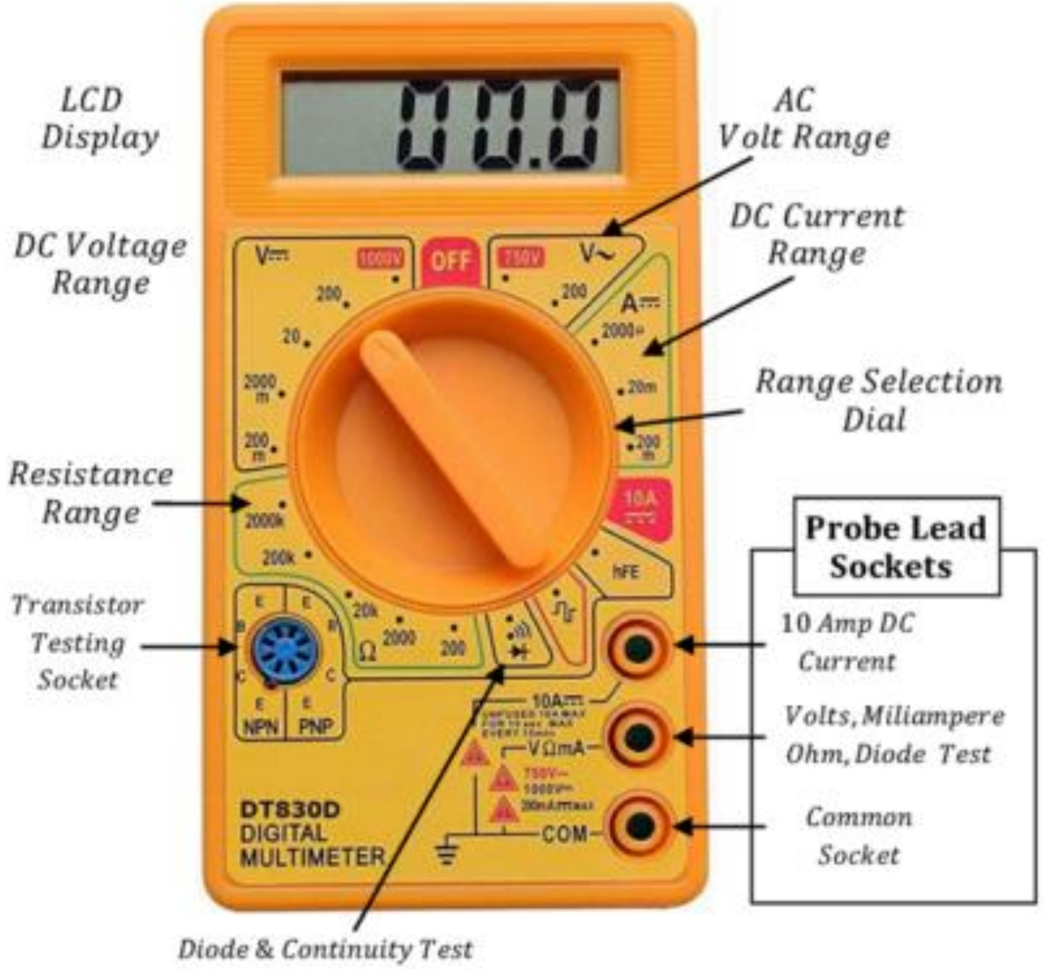
In electrical terms, the "pressure" is the potential difference, and the "flow" is the electric current (movement of electrons).

A battery, for example, creates a potential difference by maintaining a surplus of electrons at its negative terminal (like high pressure) and a deficit at its positive terminal (like low pressure). Other source of voltage are generators, solar cells.

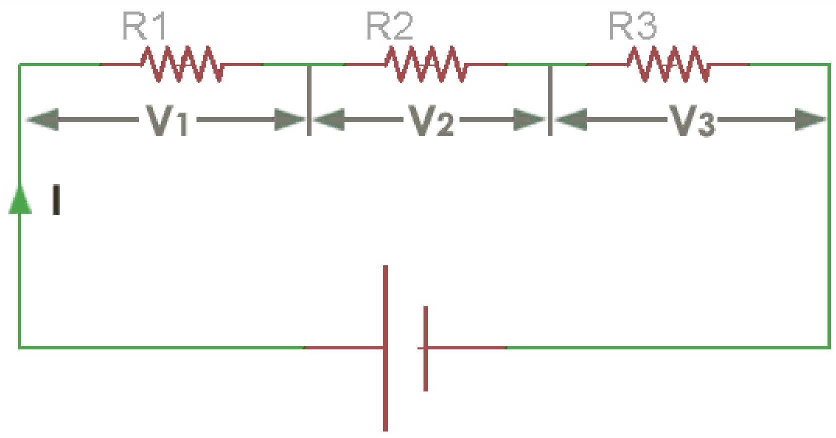


How to measure “R”, “V”, “I”

Ever wondered how we can measure V, I and R?
Digital Multimeters are available that can measure all these parameters



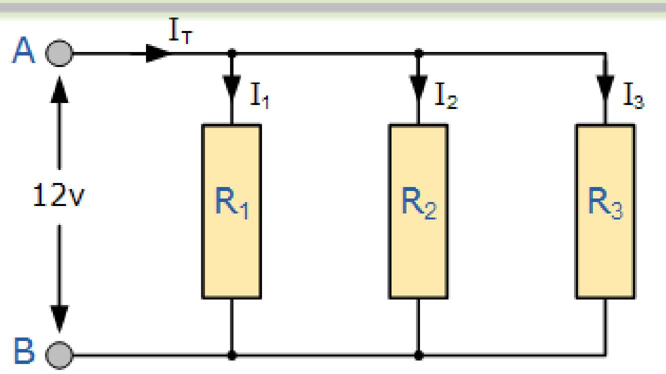
Resistors in Series



Typically used for:
Voltage Division: Multiple resistors in series to create required voltage, used in voltage divider network.
High-Voltage Handling: Series resistors distribute high voltages across multiple components to prevent breakdown, common in high-voltage power supplies or CRT circuits.

Same Current:
All resistors in a series circuit have the same current flowing through them.
Total Resistance:
The total resistance is the sum of all individual resistances: $R_{total} = R1 + R2 + ... + Rn$.
Voltage Division:
The voltage supplied to the circuit is divided across the resistors based on their individual resistances.
Series Circuit Behavior:
If one resistor in a series circuit fails, the entire circuit is interrupted, as there is only one path for the current.

Resistors in Parallel



Typically used for:
Increased Power Rating: Parallel resistors combine to handle higher power, used in applications like audio amplifiers or motor control circuits where distributing the heat dissipation is critical.

Voltage:
The voltage across each resistor in a parallel circuit is the same and equal to the source voltage.
Current:
The current through each resistor depends on its individual resistance. The total current is the sum of the currents through each branch.
Total Resistance:
The total resistance in a parallel circuit is calculated using the formula: 1/Req = 1/R1 + 1/R2 + ... + 1/Rn. Where Req is the equivalent resistance and R1, R2, ... are the individual resistances.
Impact of Adding Resistors:
Adding more resistors in parallel reduces the overall resistance, as it provides more paths for current to flow. (Adding two resistors of equal value results in half the value of the resistor)
Applications:
Parallel circuits are used in various applications, including power distribution in homes and circuits where multiple devices need to operate independently.

Simple formulas to remember

Formula Description	Resistor	Inductor	Capacitor
Defining Equation	$R = \frac{V}{I}$ (Ohm's Law)	$L = \frac{V}{\frac{di}{dt}}$	$C = \frac{Q}{V}$
Physical Property Formula	$R = \rho \frac{l}{A}$	$L = \frac{\mu N^2 A}{l}$ (solenoid)	$C = \epsilon \frac{A}{d}$
Series Connection	$R_{total} = R_1 + R_2 + R_3 + ...$	$L_{total} = L_1 + L_2 + L_3 + ...$	$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + ...$
Parallel Connection	$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ...$	$\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + ...$	$C_{total} = C_1 + C_2 + C_3 + ...$
Energy Stored	Not typically stored (dissipated as heat)	$E = \frac{1}{2} L I^2$	$E = \frac{1}{2} C V^2$
AC Reactance	None (constant resistance)	$X_L = 2\pi f L$	$X_C = \frac{1}{2\pi f C}$
Power Dissipation (DC)	$P = I^2 R$ or $P = \frac{V^2}{R}$	None (no power dissipation in ideal case)	None (no power dissipation in ideal case)
Time Constant	Involved in RC and RL circuits	$\tau = \frac{L}{R}$ (in RL circuit)	$\tau = RC$ (in RC circuit)

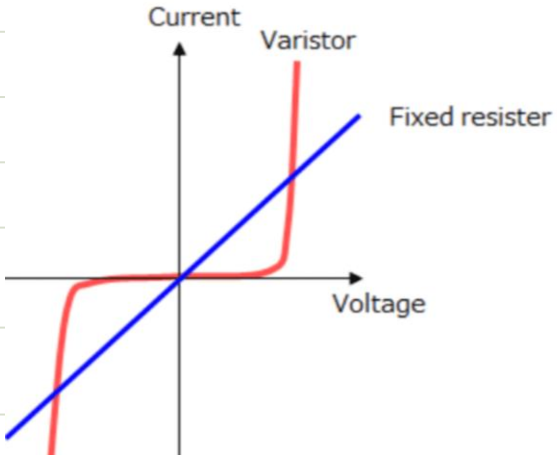
- "R = Resistance in Ohms, V = Voltage in Volts, I = Current in Amps"
- "ρ = resistivity in Ohm-metre, L = Length of the material in metre, A = Area of cross section in Square metre"
- P = Power in Watts

Back to content List

Linear, Non-linear Resistors

Linear and Non-Linear resistors

Linear	Fixed	Carbon
		Wire wound
		Thick film
		Thin Film
	Variable	Trimmer
		Potentiometer
		Rheostat
Non-Linear	Varistor (MOV)	
	NTC, PTC thermistor	
	LDR	

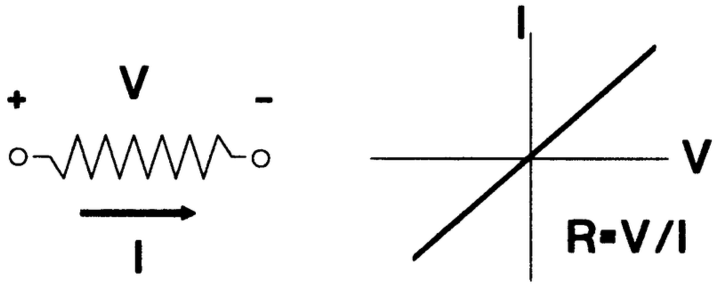


Linear Resistors

Definition:
A resistor whose resistance remains constant regardless of the voltage or current applied, following Ohm's Law (V = IR).

Characteristics:
Resistance does not vary with voltage, current, or frequency.
Voltage and current are directly proportional.

Examples:
Carbon film resistors, metal film resistors.



Used in:
Voltage dividers, current limiting, and basic circuit applications.

Non-linear Resistors

Definition:
A resistor whose resistance changes with applied voltage, current, or other factors like temperature or light, not strictly following Ohm's Law.

Characteristics:
Resistance varies non-linearly (e.g., with voltage, temperature, or light).

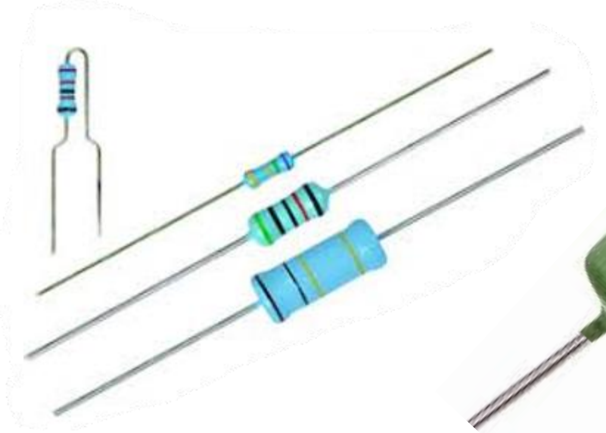
Examples:
Thermistors (temperature-dependent), LDRs (light-dependent resistors), varistors (voltage-dependent).

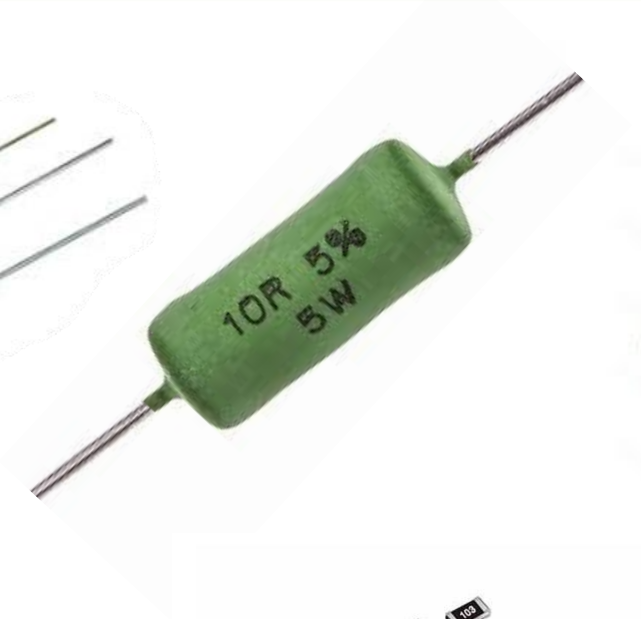
Used in:
Temperature sensors, light sensors, surge protectors, and specialized circuits.

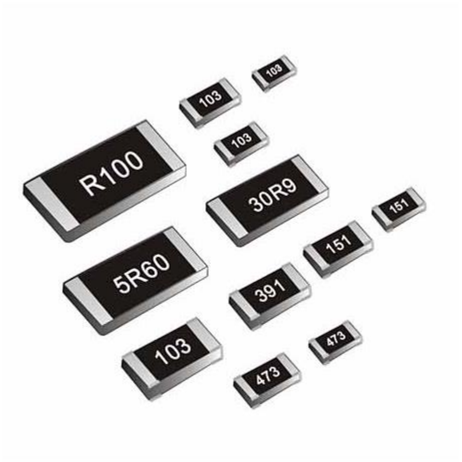
Back to content List

Fixed Value Resistors (Leaded, SMD components)

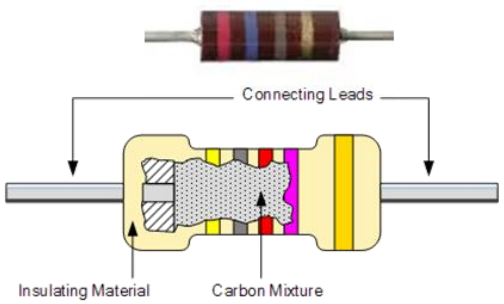
Fixed Value Resistors



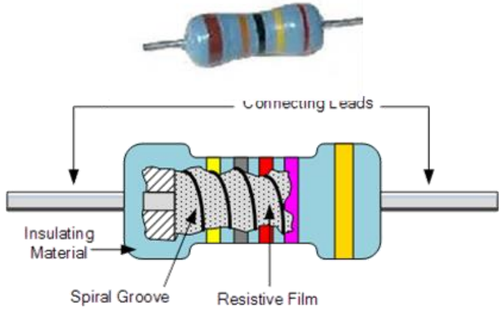




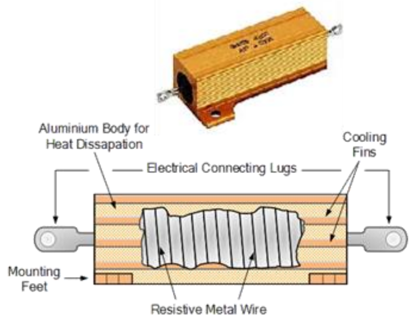
Fixed Resistor - Construction



Carbon resistor

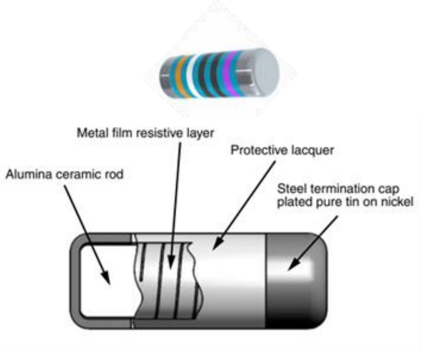


Metal film resistor

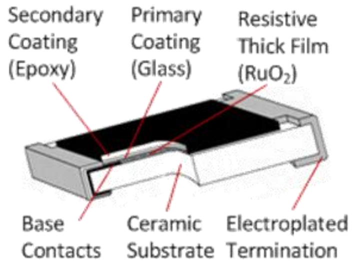


Wire wound resistor

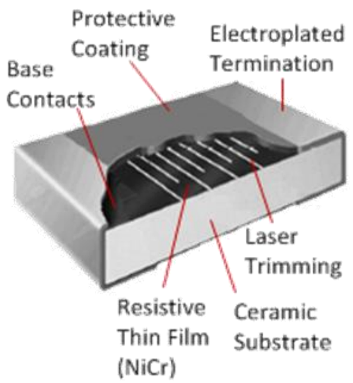
Wire wound resistor



Metal electrode leadless face (**MELF**)



Thick film resistor



Thin film resistor

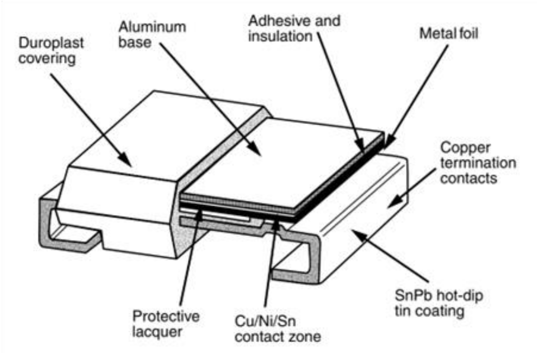


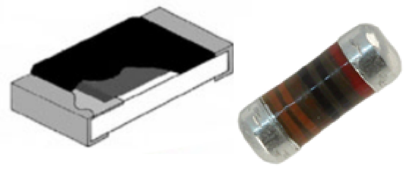
Fig. 7 - Metal foil resistor

Metal electrode leadless face (**MELF**)

*Image courtesy : Application Note - Vishay

SMD Resistor materials and characteristics

- **Thick Film** (Chip Resistors/Chip Arrays/Networks)
  - Specially built surface-mount film resistor that carries high power for the part size. For thick film resistors, the ruthenium oxide "film" is applied using traditional screen-printing technology onto the surface of a substrate.

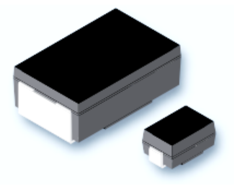


0.1 Ω to 50 GΩ
± 1 Tolerance
± 100 ppm

- **Thin Film** (Chip Resistors/Chip Arrays/Networks)
  - A type of surface-mount film resistor with a relatively thin resistive element, measured in angstroms (millionths of an inch). Thin film resistors are made by sputtering (also known vacuum deposition) a resistive material, such as nichrome or tantalum nitride, onto the surface of a substrate.

0.03 Ω to 3 GΩ
± 0.011 Tolerance
± 5 ppm

- **Metal Film** (Chip Resistors/Leaded/MELF)
  - A type of cylindrical resistors made by depositing a resistive element made of a thin conducting film of a metal or metal alloy, such as nichrome, onto a cylindrical ceramic or glass core. The resistance is controlled by cutting a helical groove through the conducting film.

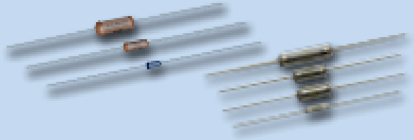
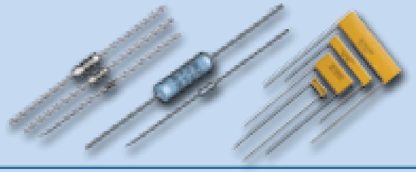
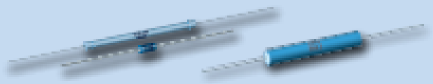
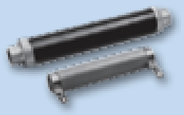


5 Ω to 100 KΩ
± 0.01 Tolerance
± 5 ppm

Courtesy: https://www.vishay.com/docs/49562/49562.pdf

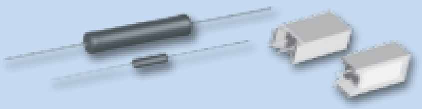
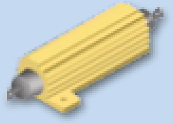
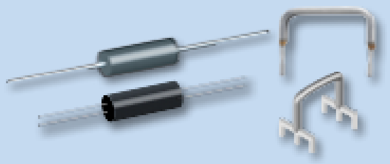
Leaded Resistors and characteristics: #1

0.1 Ω to 50 GΩ
± 1 Tolerance
± 100 ppm

Technology *	Examples of Vishay Models	Resistance Range	Best Tolerance (%)	Best TCR (ppm/°C)	Strengths
Metal Film 	CMF, PTF, CCF, ERL, ERC, GSR, HDN	0.1 Ω to 50 MΩ	± 0.01	± 5	• General purpose • Wide resistance range • Good high frequency characteristics
High Voltage, High Pulse Films 	CPF, FP, HVW, MVW, TR, TD, FHV	0.1 Ω to 3 TΩ	± 0.1	± 25	• Pulse resistant • Flameproof • Good high frequency characteristics • High power
Metal Oxide 	ROX, RNX, RJU	100 Ω to 3 GΩ	± 0.5	± 50	• High voltage • High resistance values
Carbon Film 	G, D, B, T, SPW	50 Ω to 500 MΩ	± 5	> ± 250	• High power • High wattages • High resistance values

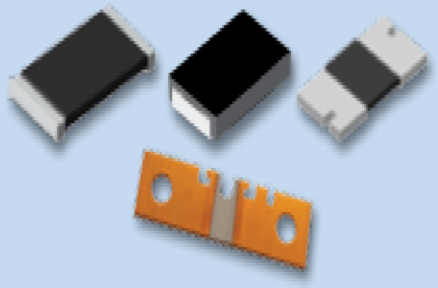
Courtesy: https://www.vishay.com/docs/49562/49562.pdf

Leaded Resistors and characteristics: #2

Technology *	Examples of Vishay Models	Resistance Range	Best Tolerance (%)	Best TCR (ppm/°C)	Strengths
Wirewound 	RW, RWR, G, RS, CW, CP, CA, CPR, CPL, CPCx, MR, MRA	0.01 Ω to 6 MΩ	± 0.005	± 2	• Wide power ranges • Wide resistance range • Excellent overload capabilities
Wirewound (Tubular) 	HL, HLW, HLZ, FxE, FxT, AxE, AxT, CMx, Fx	0.05 Ω to 645 kΩ	± 5	± 30	• Wide power ranges • Wide resistance range • Excellent overload capabilities
Wirewound (Housed) 	RH, RE, RER	0.01 Ω to 273 kΩ	± 0.05	± 20	• Wide power ranges • Wide resistance range • Excellent overload capabilities
Metal Element 	LVR, SR, SPU Open, SPU Molded	0.001 Ω to 0.8 Ω	± 0.1	± 30	• Wide power ranges • Excellent overload capabilities • Low ohmic values

Courtesy: https://www.vishay.com/docs/49562/49562.pdf

Current sense resistors

Technology *	Examples of Vishay Models	Resistance Range	Best Tolerance (%)	Best TCR (ppm/°C)	Strengths
Power Metal Strip® 	WSL, WSR, WSK, WSH, WSLP, WSLT, WSLS, WSBS, WSMS	0.00005 Ω to 1 Ω	± 0.1	± 30	• Current sensing • Ultra low values

Courtesy: https://www.vishay.com/docs/49562/49562.pdf

Thick film Vs Carbon film resistors

Characteristic	Thick Film Resistors	Carbon Film Resistors
Manufacturing	**Screen-printed resistive paste** on ceramic substrate, then fired	**Carbon film** deposited on a ceramic rod
Precision (Tolerance)	Moderate (±1% to ±10%)	Low (typically ±5% to ±20%)
Stability (TCR)	Moderate (±100 to ±300 ppm/°C)	Poor (±200 to ±1000 ppm/°C)
Noise Performance	Moderate to high (due to granular structure)	**High noise**, especially in sensitive circuits
Power Handling	Good for small size; widely used in SMT formats	Moderate to low
Cost	Very low (mass production SMT)	Very low, but older technology
Surge Handling	Can handle higher surge power in some variants	Moderate surge capacity
Applications	General-purpose: consumer electronics, automotive, appliances	Budget electronics, legacy designs, high-voltage dividers

Thin film Vs Metal film resistors

Characteristic	Thin Film Resistors	Metal Film Resistors
Manufacturing	Vacuum-deposited **ultra-thin** resistive layer on ceramic	**Sputtered or evaporated metal alloy** on substrate
Precision	Very high (tolerance ±0.01% to ±1%)	Moderate to high (tolerance ±0.1% to ±2%)
Stability (TCR)	Excellent (±5 to ±50 ppm/°C)	Good (±50 to ±100 ppm/°C)
Noise Performance	Very low (due to uniform structure)	Low, but usually not as low as thin film
Frequency Response	Better for **high-frequency / RF** applications	Not typically optimized for RF
Cost	More expensive	Less expensive than thin film
Applications	High-precision: medical, aerospace, RF, test equipment	Precision analog, audio, general industrial use

Available resistor values

How many standard resistor values are available for purchase? (From 0.1 Ohm to 10G Ohm)

- IEC (International Electrotechnical Commission) has defined 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.
- This helps the supplier to limit the number of different values that must be produced or kept in stock.
- By using standard values, resistors from different manufacturers are compatible for the same design, which is favorable for the electrical engineer

pico	10^{-12}
nano	10^{-9}
micro	10^{-6}
milli	10^{-3}
kilo	10^{+3}
mega	10^{+6}
giga	10^{+9}
tera	10^{+12}

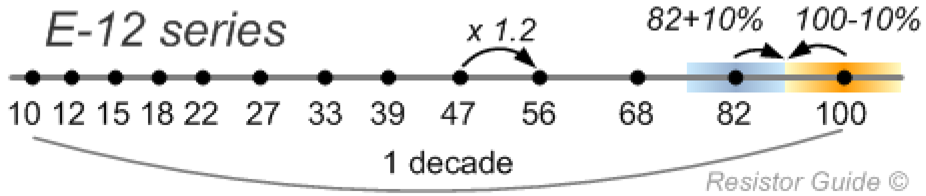
Resistors are available from few milli ohms to giga ohms

E-12 series of resistor values

- E12 means that every decade (0.1 to 1.0, 1 to 10, 10 to 100, etc.) is divided in 12 steps on a logarithmic scale. The size of every step is equal to $10^{\left(\frac{1}{12}\right)} = 1.21$

- Thus, every value is 1.21 times higher than the previous value in the series, 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 of these values can be powers of ten (1.2 – 12 – 120, etc.).

- While the E12 series is the most common, other series are also available. 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% tolerance; 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%).

Courtesy: https://eepower.com/resistor-guide/resistor-standards-and-codes/resistor-values/#

SMD "0 Ohm" / "Jumper" resistance

Often a "0 Ohm" / "Jumper" resistance becomes essential in PCB designs.
For example,

- Optional configuration like a pull up +5V or pull down to ground of an I/O pin,
- Provide a resistor in series with the power trace of an IC, using which during initial testing a known resistor can be populated (like 0.01 Ohm) to measure the current consumption and later use the zero-ohm resistor etc.,
- To connect two separate ground planes at the power source point,

These resistors exist both as rectangular thick film chips as well as metal film MELFs. Max resistance for the thick film chips usually is ≤50 mΩ at sizes between 0603 and 2010. Thin film MELFs in typical sizes of L x D ≈ 2 x 1.4 to 6 x 2.4 mm are specified for ≤10 mΩ.

As well as maximum resistance a maximum current is also specified for these components. This is important especially if the resistance is used power trace and need to carry a high current.

Leaded Resistor color coding

To remember the color sequence :

B (Black)

B (Brown)

ROY of (Red, Orange, Yellow)

Great (Green)

Britain had (Blue)

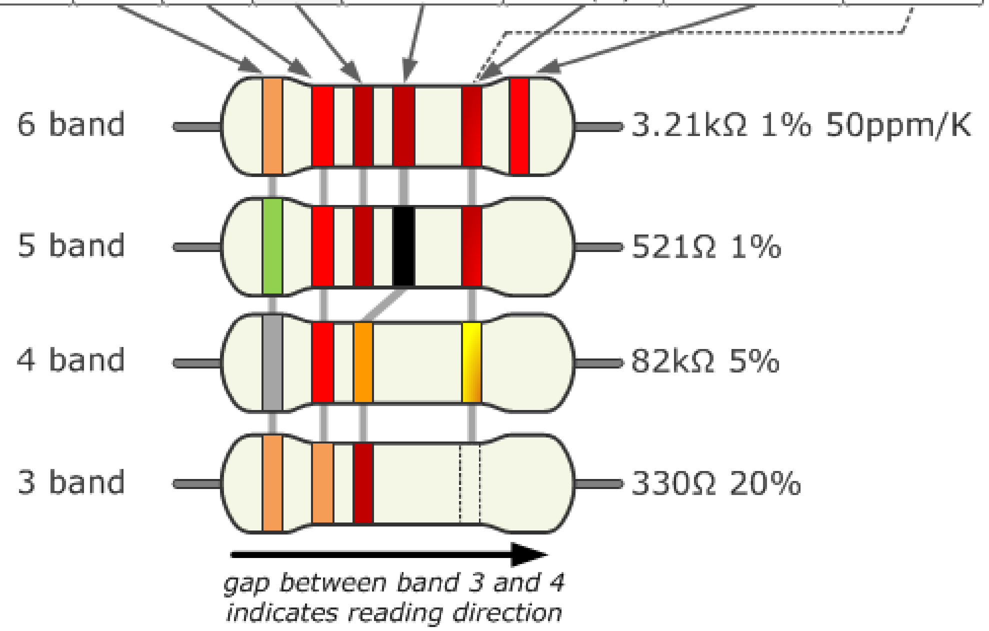
Very (Violet)

Good (Grey)

Wife (White)

BBROYGreatBritainVeryGoodWife

Color	Signficant figures			Multiply	Tolerance (%)	Temp. Coeff. (ppm/K)	Fail Rate (%)
black	0	0	0	x 1		250 (U)	
brown	1	1	1	x 10	1 (F)	100 (S)	1
red	2	2	2	x 100	2 (G)	50 (R)	0.1
orange	3	3	3	x 1K		15 (P)	0.01
yellow	4	4	4	x 10K		25 (Q)	0.001
green	5	5	5	x 100K	0.5 (D)	20 (Z)	
blue	6	6	6	x 1M	0.25 (C)	10 (Z)	
violet	7	7	7	x 10M	0.1 (B)	5 (M)	
grey	8	8	8	x 100M	0.05 (A)	1(K)	
white	9	9	9	x 1G			
gold			3th digit only for 5 and 6 bands	x 0.1	5 (J)		
silver				x 0.01	10 (K)		
none					20 (M)		

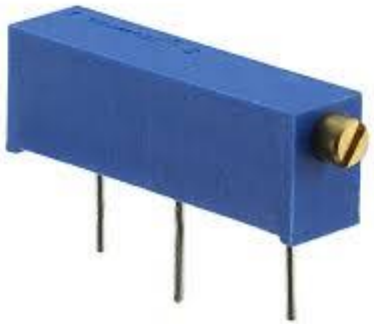


Back to content List

Variable Resistors (Potentiometer, Trimmers)

Variable Resistors

TRIMMERS / TRIM POTs



Potentiometers

Sliding Potentiometers

Linear and Logarithmic Potentiometers

Feature	Linear Potentiometer	Logarithmic Potentiometer
Resistance Change	Proportional to dial position	Changes logarithmically with dial position (exponential curve)
Application	Precise position sensing, linear control	Audio volume controls, applications requiring logarithmic scales

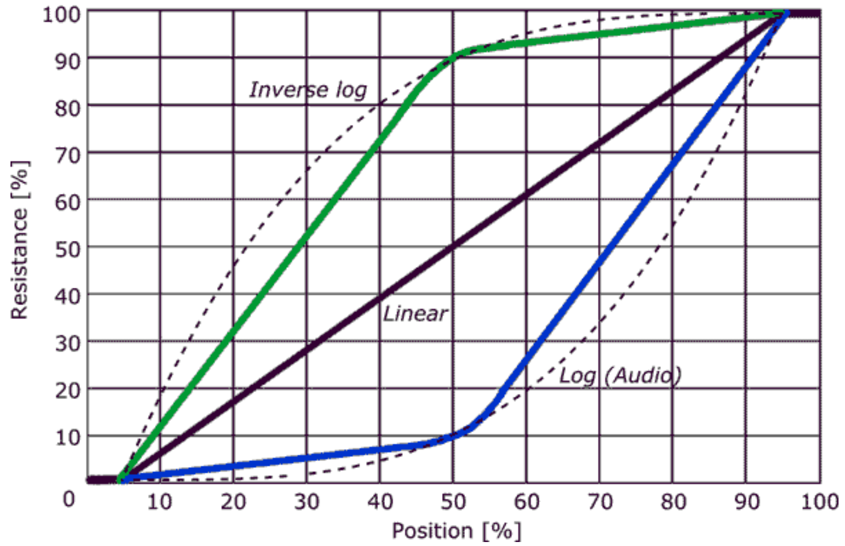
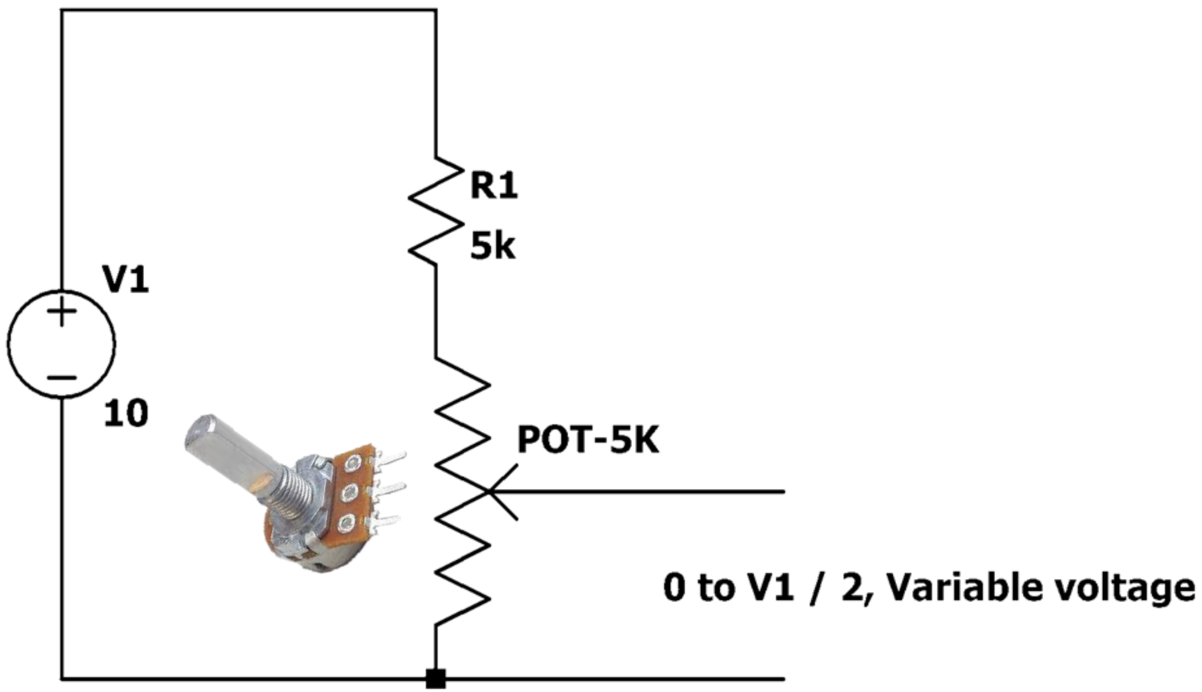


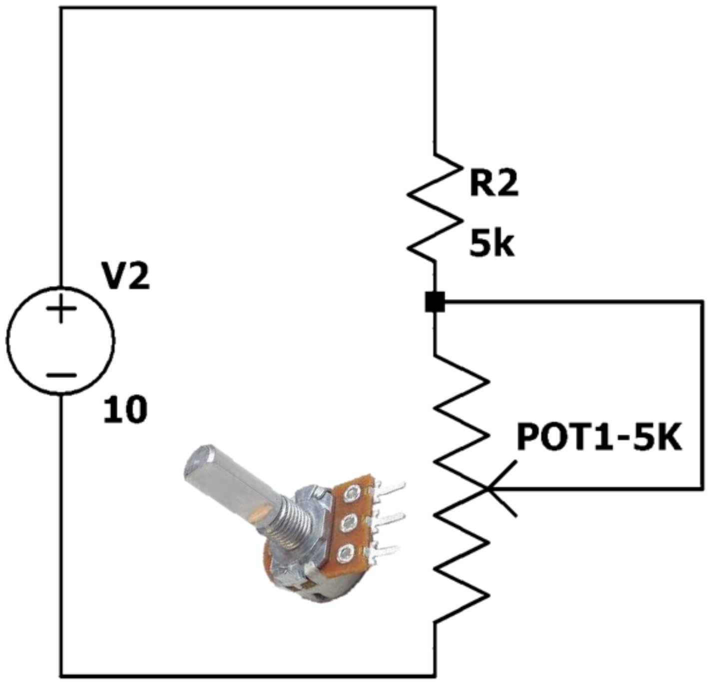
Image Courtesy: https://eepower.com/resistor-guide/resistor-types/potentiometer-taper/#

Applications of Variable Resistor

Potentiometer mode



Variable resistance mode



- "Potentiometer mode" is the common application, to create variable voltage inputs.
- Potentiometer change can be linear or Logarithmic. Logarithmic pots are used in audio applications as our ear response to sound is logarithmic in nature.
- The number of turn of potentiometer can be single or multi turn (ex: 10 turns)

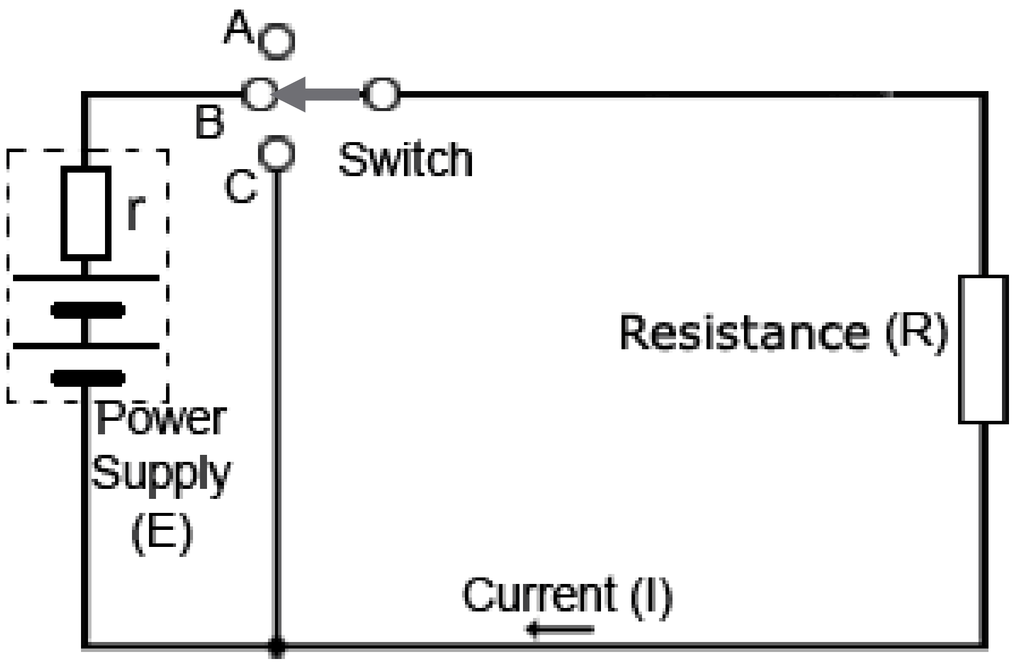
Back to content List

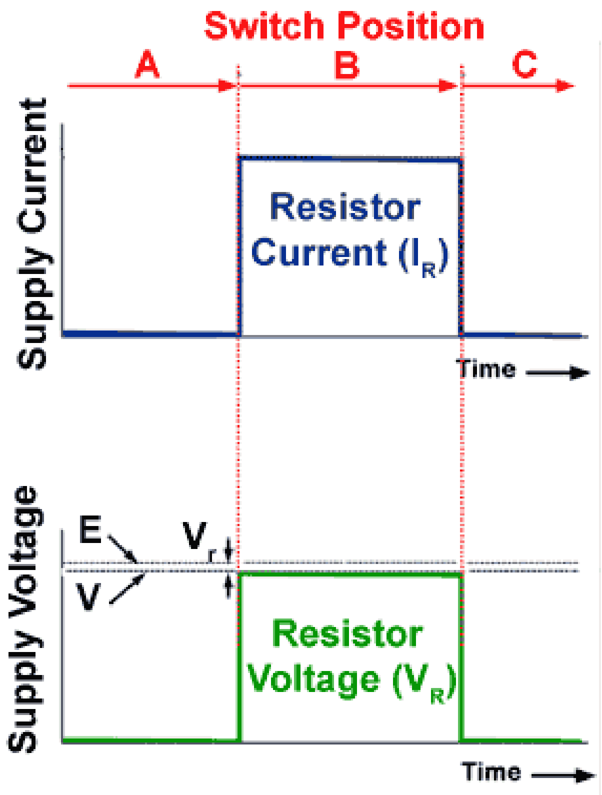
Voltage, Current waveforms

Waveforms in circuits with Resistors

Voltage and current waveforms of Resistor in DC

Both voltage and current waveforms are in phase. (i.e., There is no phase shift between the voltage and current waveform). Magnitude of current as per Ohm's law.

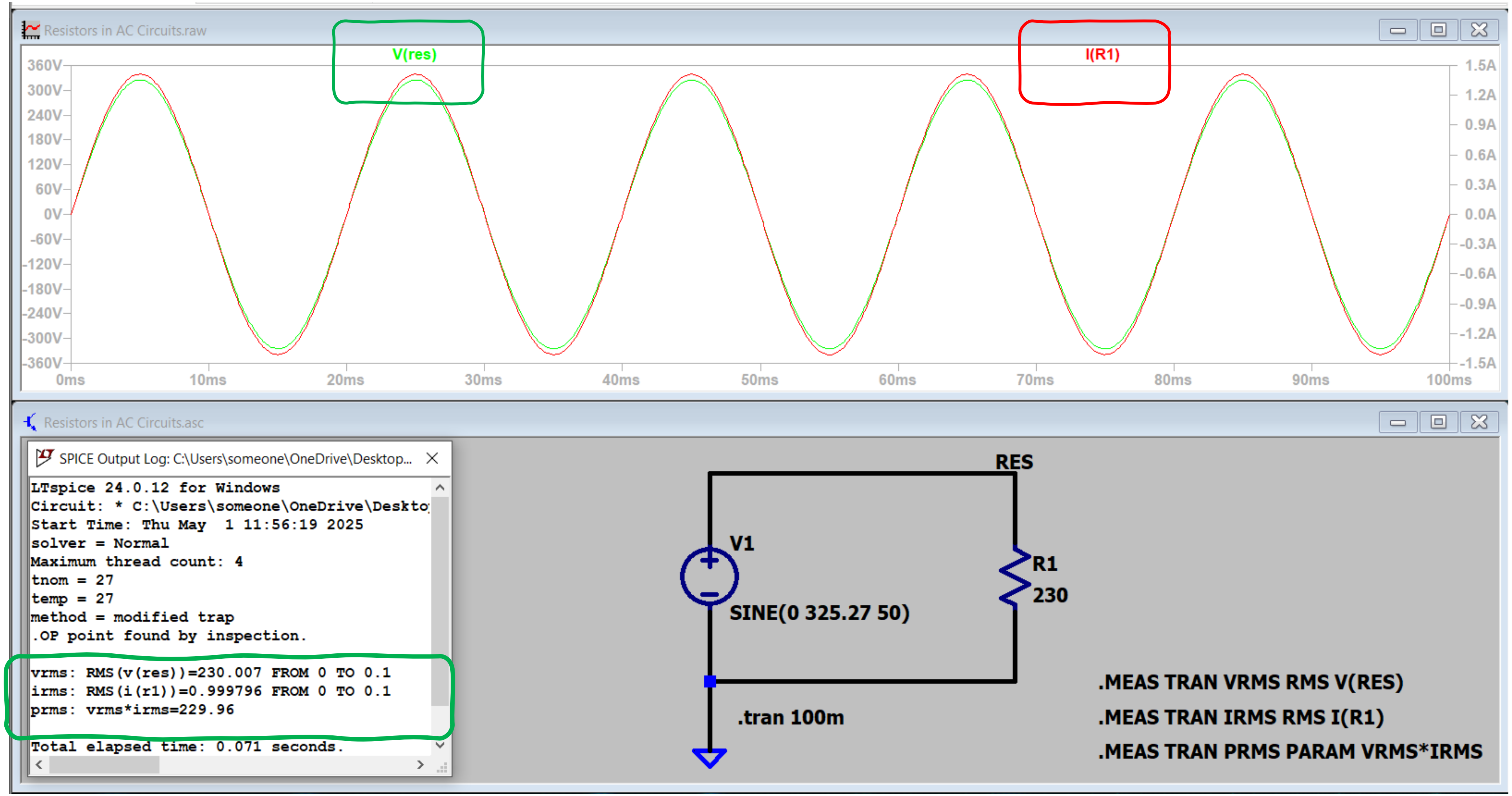




Courtesy: https://learnabout-electronics.org/ac_theory/dc_ccts41.php

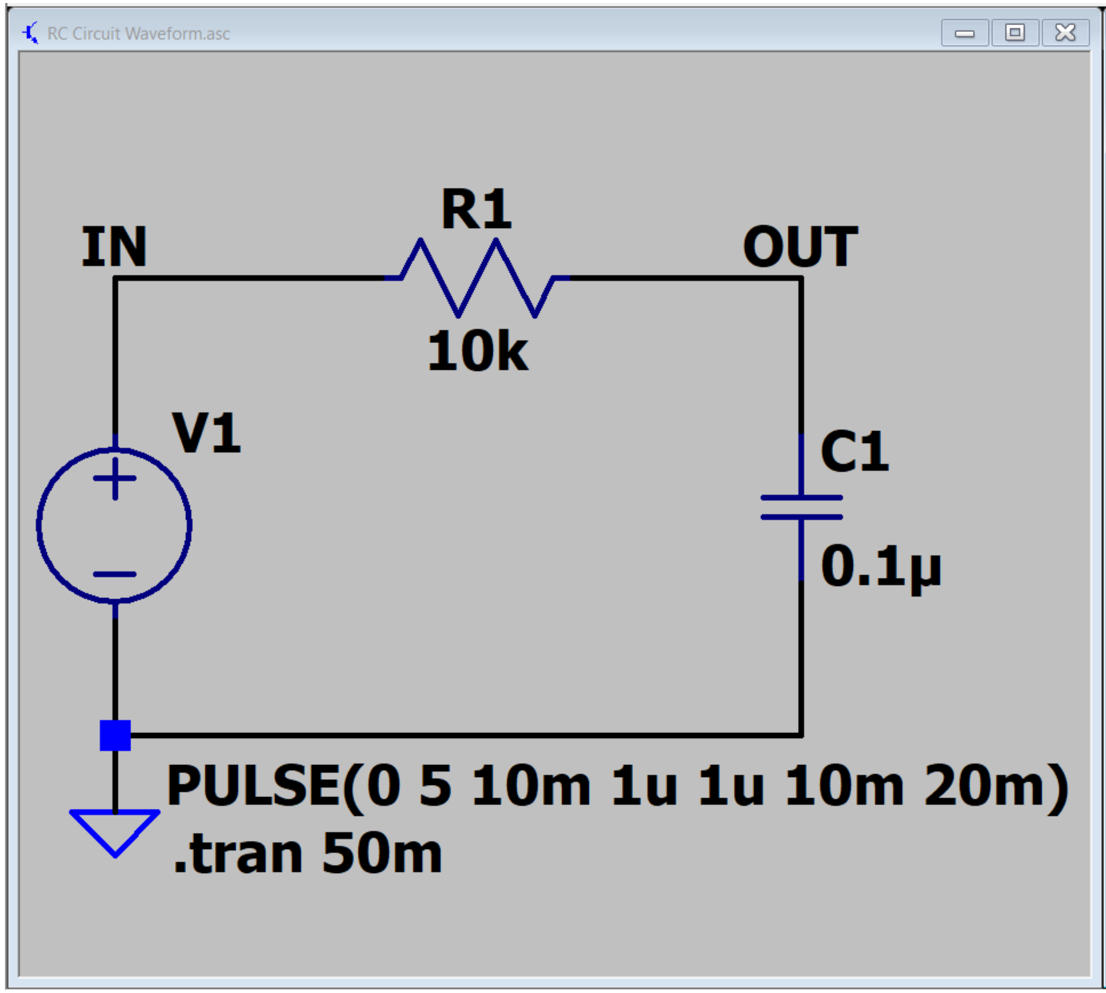
Waveforms in AC circuits with only Resistance

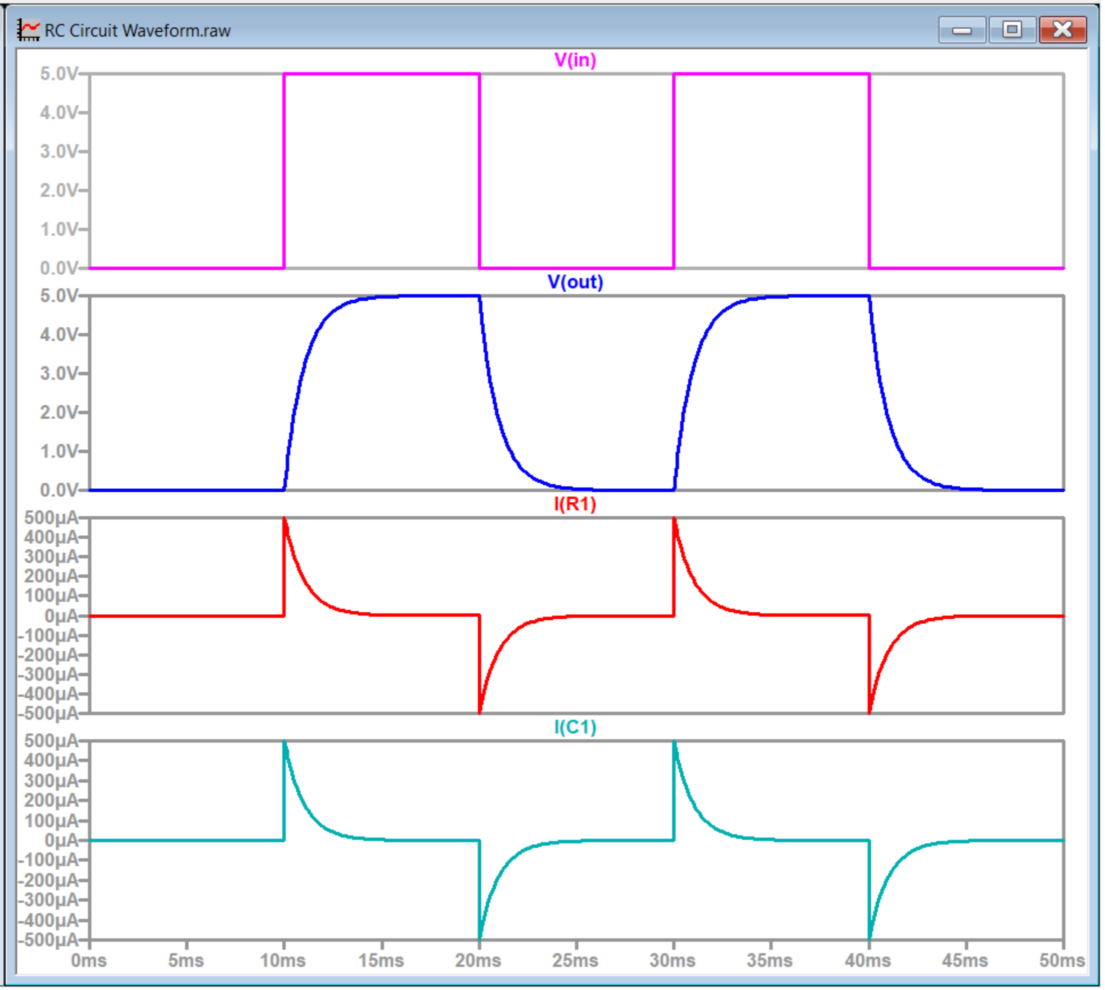
In case of AC, voltage and current waveforms are in phase. Hence power = $V_{RMS} * I_{RMS}$



RC circuit voltage and current waveforms

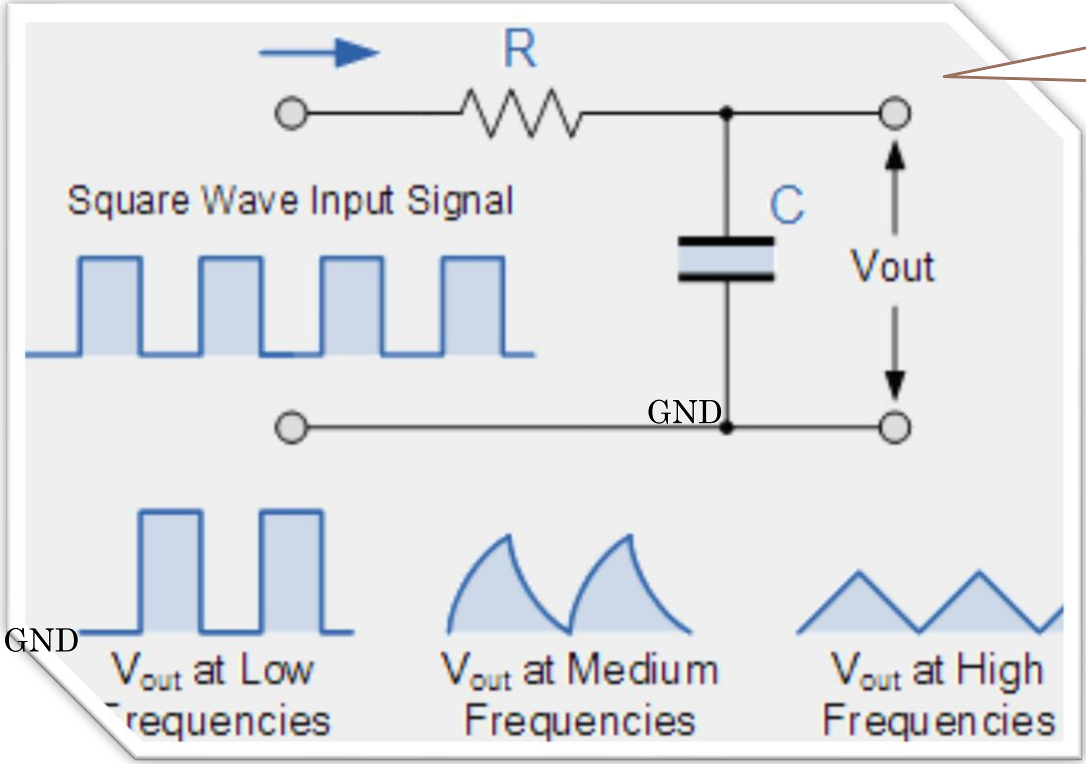
Waveforms for a DC PWM voltage to a capacitor (C) through a series resistor (R)



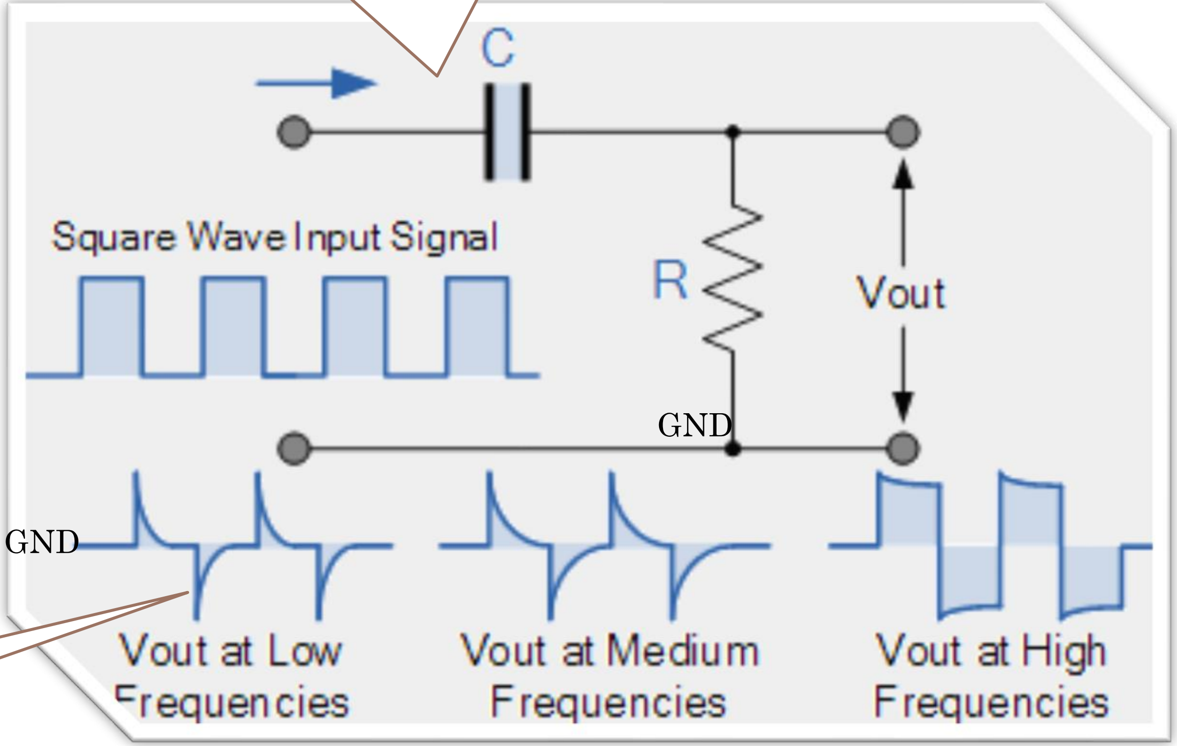


Waveforms in RC(Low pass), CR(High Pass) circuits

RC - Low Pass Filter
(LPF)



CR - High Pass Filter
(HPF)



Note: Vout across R
goes negative as well

Back to content List

Specification of Resistors

Specifications of a Resistors - 1

1. **Resistance Value (Ω)**:
    1. The nominal resistance, typically specified in ohms (Ω), ranging from fractions of an ohm to megaohms (e.g., 1 Ω to 10 MΩ).
    2. Tolerance: The acceptable deviation from the nominal value, expressed as a percentage (e.g., ±1%, ±5%, ±0.1% for precision resistors).

2. **Power Rating (W)**:
    1. The maximum power a resistor can dissipate without overheating, typically in watts (e.g., 1/8 W, 1/4 W, 1 W, up to 50 W for high-power resistors).
    2. Determined by the resistor's size, material, and cooling mechanism.

3. **Temperature Coefficient of Resistance (TCR)**:
    1. The change in resistance per degree Celsius, expressed in parts per million per °C (ppm/°C) or %/°C.
    2. Example: ±50 ppm/°C means resistance changes by 0.005% per °C.
    3. Low TCR (e.g., ±10 ppm/°C) is critical for precision applications.

Specifications of a Resistors - 2

4. Operating Temperature Range:
1. The temperature range in which the resistor operates reliably (e.g., -55°C to +155°C for standard resistors, wider for specialized types).

5. Voltage Rating:
1. The maximum continuous voltage a resistor can handle without breakdown, dependent on its physical size and construction.
2. Calculated as $\sqrt{(P \times R)}$, where P is power rating and R is resistance, unless otherwise specified.

6. Stability and Aging:
1. Long-term stability: Resistance drift over time (e.g., ±0.5% after 1000 hours at rated power).
2. Specified under load life tests (e.g., 70°C, rated power, 1000 hours).

7. Environmental Compliance:
1. RoHS compliance (lead-free) for environmental safety.
2. Halogen-free options for automotive and medical applications.

8. Frequency Response:
1. Relevant for high-frequency applications

Specifications of a Resistors - 3

Additional Specifications

1. **Physical Size and Package**:
   1. Surface-mount (e.g., 0402, 0603, 1206 chip sizes) or through-hole (e.g., axial, radial).
   2. Smaller sizes have lower power and voltage ratings but are suitable for compact circuits.

2. **Material and Construction**:
   1. **Carbon Film/Composition**: High noise, used for general-purpose or pulse applications.
   2. **Metal Film/Thin Film**: Low noise, high precision, used in audio and instrumentation.
   3. **Thick Film**: Cost-effective, used in automotive and general electronics.
   4. **Wirewound**: High power, used in industrial and high-current applications.
   5. **Metal Foil**: Ultra-precision, low TCR, used in metrology and high-end audio.

Automotive Qualification of Resistors

Resistors used in automotive applications must meet stringent reliability and performance standards due to harsh operating conditions.

1. **AEC-Q200 Qualification**:
   1. Standard for passive components in automotive applications, defined by the Automotive Electronics Council.
   2. Tests include:
      1. **Temperature Cycling**: -55°C to +150°C for 1000 cycles.
      2. **High Humidity**: 85°C/85% RH for 1000 hours.
      3. **High-Temperature Exposure**: Up to 175°C for 1000 hours.
      4. **Mechanical Shock and Vibration**: Simulates road conditions.
      5. **Pulse Load Testing**: For surge robustness in automotive transients.
2. **Operating Conditions**:
   1. Wide temperature range: -55°C to +175°C (or higher for under-hood applications).
   2. Resistance to moisture, chemicals, and thermal shock.
3. **Specific Requirements**:
   1. **Anti-Sulfur Protection**: Resistors (e.g., Vishay's CRA series) use special coatings to resist sulfur corrosion in high-sulfur environments (e.g., near exhaust systems).
   2. **High Reliability**: Zero-defect manufacturing for safety-critical systems (e.g., ABS, airbag circuits).
   3. **Low TCR**: Typically ±100 ppm/°C or better for stable performance across temperature swings.

Back to content List

Tolerance specification of Resistors and it’s impact on circuit design

Resistor Tolerance specification

What is Tolerance?

- **Tolerance** is the **maximum deviation** from the **nominal (marked) resistance** value.
- Expressed as a **percentage (%)**.
- Example: A 100 Ω resistor with ±5% tolerance can vary from **95 Ω to 105 Ω**.

Why Tolerance Matters?

- Affects **accuracy** of voltage dividers, filters, amplifiers
- Important in **precision analog, adjustable power supplies** and **timing circuits**
- Low-tolerance = **better performance**, but **higher cost**

What tolerances are available?

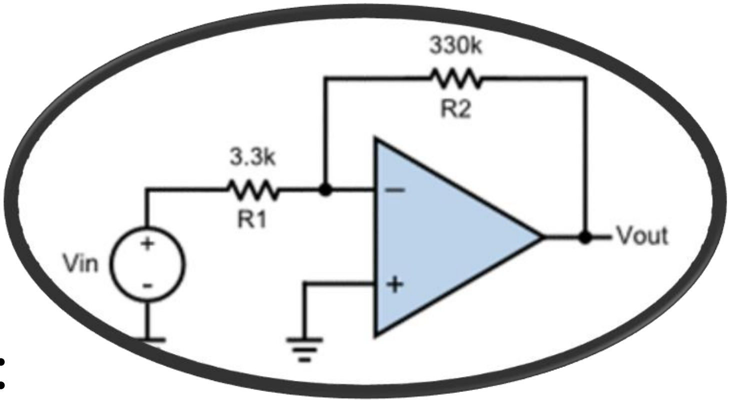
Tolerance	Typical Use
±20%	Old/low-cost general use
±10%	Basic applications
±5%	General-purpose
±1%	Precision analog, better accuracy
±0.1%–±0.5%	High-precision circuits

Example of Resistor tolerance and it's impact

Let's consider an example of a non-inverting amplifier circuit with a required gain of "100" and understand how tolerance can affect the "actual gain".

For example, a 1kΩ ±20% tolerance resistor may have a maximum and minimum resistive value of:

- Maximum Resistance Value 1kΩ or 1000Ω + 20% = 1,200Ω
- Minimum Resistance Value 1kΩ or 1000Ω – 20% = 800Ω



Gain = - R2 / R1

R_{in}	R_f	%tolerance(+/-)	Actual R_{in} min	Actual R_{in} max	Actual R_f min	Actual R_f max	Gain R_f/R_{in}
3,300	3,30,000	20%	2,640	3,960	2,64,000	3,96,000	150.00
3,300	3,30,000	10%	2,970	3,630	2,97,000	3,63,000	122.22
3,300	3,30,000	1%	3,267	3,333	3,26,700	3,33,300	102.02
3,300	3,30,000	0.1%	3,297	3,303	3,29,670	3,30,330	100.20
3,300	3,30,000	0.010%	3,300	3,300	3,29,967	3,30,033	100.02

So, with 0.1% / 10% tolerances, the gain can be 100.2 / 122.22 !

Hence, remember to choose low tolerance resistor for precision analog applications.

Selection consideration: Resistor Tolerance Vs Cost

- **Design aspect of Tolerance:** Higher tolerance of resistor can affect the gain of an amplifier; or affects the output voltage in case of an adjustable linear regulator or switching regulator etc.,
  - For ex: when we buy 5000 units of resistors, they are all not going to be of exact same value, due to the tolerance spec. Hence every board is going to have variation from the ideal value.
- **Cost aspect of Tolerance:** In general, resistors of lower tolerance value are costlier.
  - Hence, the designer needs to strike a balance between price and the circuit performance requirements

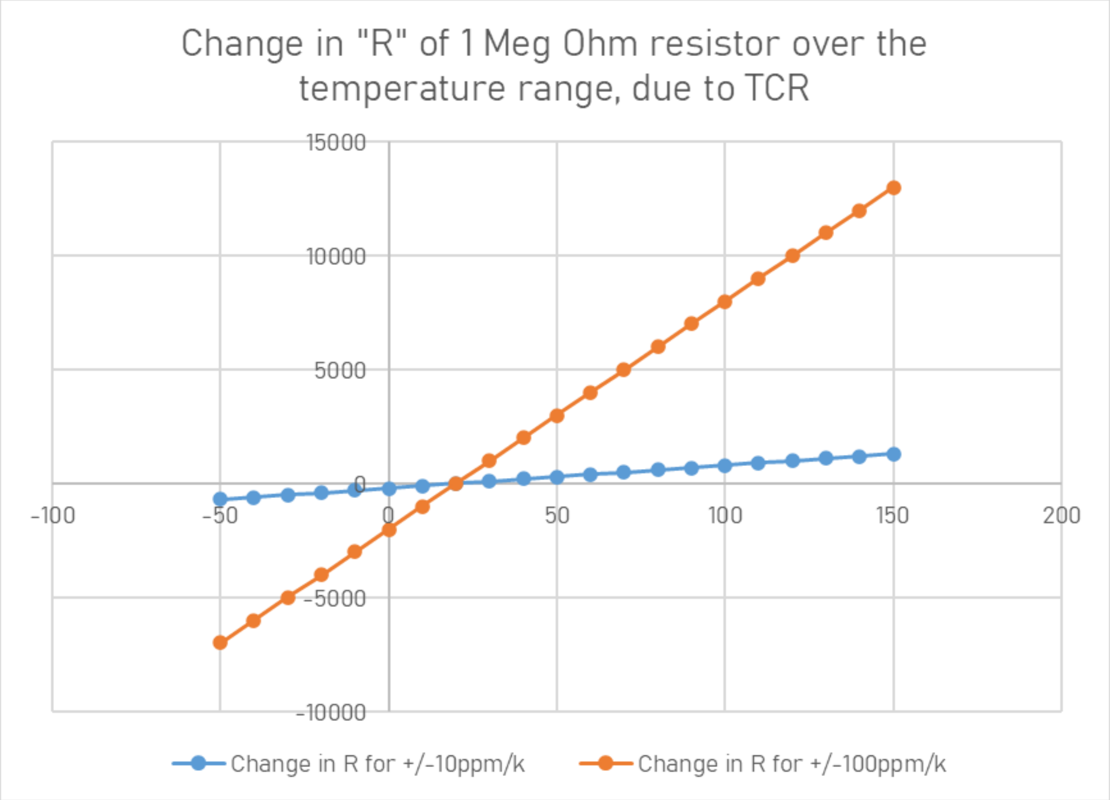
Go to https://www.digikey.in and https://www.mouser.in/ and go to section "Passives→ Resistors→ Through hole resistors" to experience what are all the difference tolerances are available and how are they priced

Back to content List

Temperature Coefficient specification of Resistors and it's impact on circuit design

Temperature Co-efficient of Resistor (TCR)

- Resistance value of a Resistor is not a fixed one and it varies as the resistivity of the resistor material is temperature dependent.
- TCR is a measure of how much a material's electrical resistance changes with temperature, typically expressed in **parts per million per degree Celsius (ppm/°C)**
- $TCR = \frac{\Delta R/R_0}{\Delta T} \times 10^6$ (in ppm/°C)
- ΔR = Change in resistance
- R_0 = Resistance at the reference temperature (for ex: at 25°C)
- ΔT = Change in temperature with respect to the reference temperature ($T-T_0$)



The product design may need to operate for commercial / Industrial / Automotive / Military temperature grades. So do the analysis on how the TCR of resistors selected can impact the circuit operation and choose the right component. Also remember, low TCR resistances can be costlier.

Example: Change in "R" due to TCR

Example Scenario:
Initial Resistance (R_0): **10,000** ohms (at a reference temperature of 25°C)
TCR: +200 ppm/°C (positive, meaning resistance increases with temperature)
Temperature Change (ΔT): The temperature rises from 25°C to 75°C, a change of 50°C.

Step-by-Step Calculation:
TCR of +200 ppm/°C = 200×10^{-6} °C^{-1} = 0.0002 °C^{-1}

Change in Resistance (ΔR):
The change in resistance is given by: $\Delta R = R_0 \times \text{TCR} \times \Delta T$
Plugging in the values: $\Delta R = 10{,}000 \times 0.0002 \times 50 = 100$ ohms

New Resistance (R):
The new resistance after the temperature change is: $R = R_0 + \Delta R = 10{,}000 + 100$ = **10,100** ohms
So the resistance has changed by +1%

Applications where low TCR is critical:

- High-precision instrumentation
- Precision Current sensing
- Laser Driver

Never forget to analyze, how the TCR can impact your circuit, then decide what is acceptable to your application requirements.

https://www.vishay.com/docs/60131/pltu.pdf

Impact of Resistor TCR on circuits

Why TCR Matters

- Resistance can **drift significantly** in circuits exposed to heat
- Affects **gain, bias points, reference voltages**, etc.
- **High TCR** → Large changes with change in environment temperature
- **Low TCR** → Stable performance

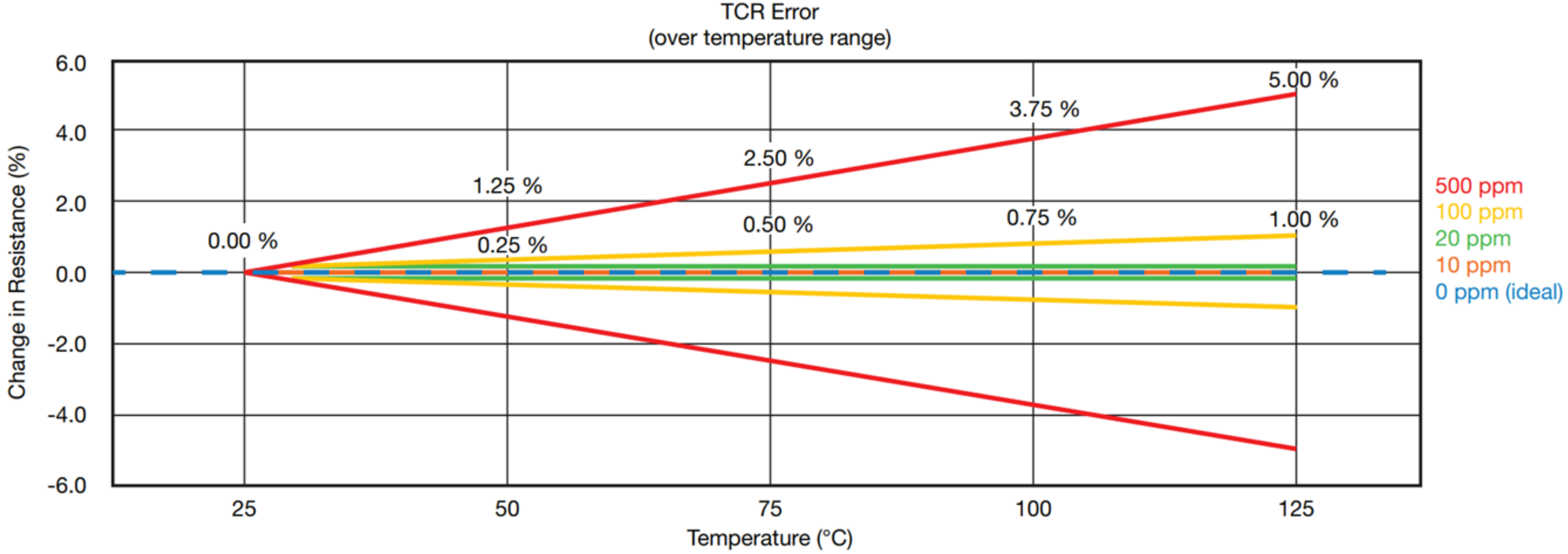
Applications Sensitive to TCR

- Precision analog (op-amps, ADCs, DACs)
- Oscillators and timing circuits
- RF and temperature-sensing electronics
- Measurement systems (e.g., multimeters)

TCR of different resistor materials

TCR, ppm/°C OF VARIOUS RESISTOR ELEMENT MATERIALS				
Temperature range	-55 °C to +25 °C	0 °C to +25 °C	+25 °C to +60 °C	+25 °C to +125 °C
Manganin	+50	+10	-5	-80
Zeranin	+20	± 2.5	± 5.0	+10
Evanohm	+5.0	+2.5	-2.5	-5.0
Foil	-1.0	-0.3	+0.3	+1.0
Thin film	-10	-5.0	+5.0	+10
Thick film	-100	-25	+50	+100

The following graph compares different TCR levels as a percentage change in resistance versus increasing temperature from 25 °C.



Back to content List

Power Rating specification of Resistors and it’s impact on circuit design

Power rating of a resistor

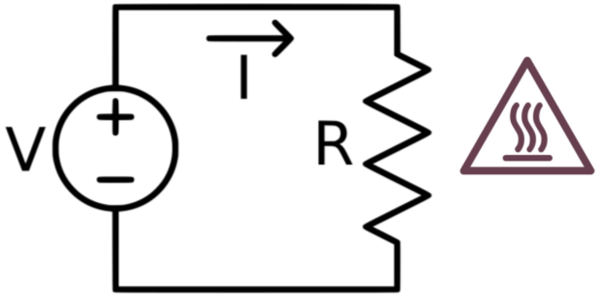
- Power rating of the resistor component dictates the maximum amount of power it can safely dissipate as heat without overheating or failing.
- Exceeding the power rating can cause the resistor to overheat, leading to failure or fire hazards. Staying within the rating ensures the resistor operates reliably over its intended lifespan.
- Choosing a resistor with a power rating at least double the expected power dissipation can ensure reliable operation and prevent premature failure. Alternately if there is heatsinking for the component, it can help to keep the component's temperature below it's safe limit.

Remember, the power loss and thereby the heat generated from a resistor won't be desirable as it increases the overall temperature of all the other components surrounding it as well.

Power Loss in a Resistor

Current through a Resistor causes power loss in it, which is a radiated as heat energy. Temperature of the Resistor also increases above the environment temperature.

Equation for power in DC circuits, P = V * I (V in volts, I in Amps, P in Watts)
In the given circuit, the voltage across the resistor is V, current through it is I, and hence the power loss is
P = V * I (in Watts)
or, substituting $I = \frac{V}{R}$ from Ohm's law
$P = V^2 / R$
or, substituting $V = I * R$ from Ohm's law
$P = I^2R$ (in Watts)



Keeping R Constant, say 1 Ohms
If I = 1 Amps; then P = 1 Watts
If I = 2 Amps; then P = 4 Watts
If I = 0.5 Amps; then P = 0.25 Watts

$$P \propto I^2$$

Question for thought: What would happen if a Resistor designed to safely handle 0.25W of power is made to dissipate 1W of power in the given circuit.

Understanding Resistor Power related specs - 1

https://www.vishay.com/docs/28730/ac_ac-at_ac-ni.pdf

Let's refer the datasheet of Vishay 3W resistor AC03-AT

TYPE	RATED DISSIPATION P_{40}	RATED DISSIPATION P_{70}
AC01, AC01-AT	1 W	0.9 W
AC03	3 W	2.5 W
AC03-AT	3 W	2.5 W

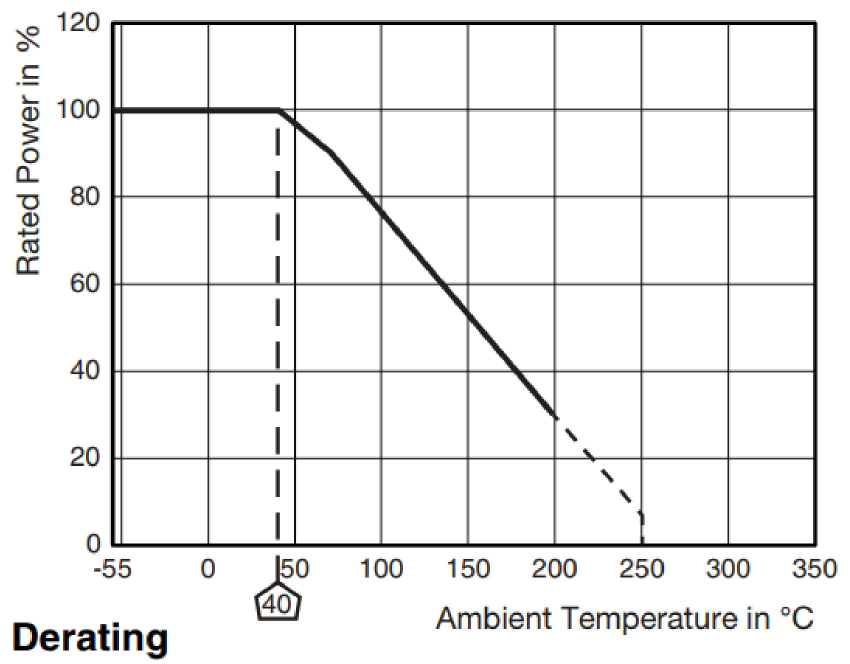
P_{40} and P_{70}:

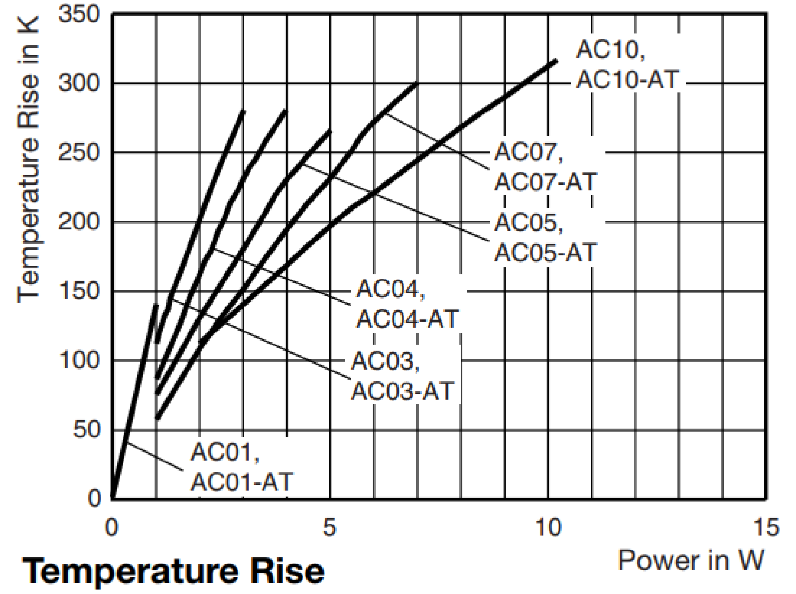
These values indicate the maximum power the resistor can handle at 40°C and 70°C, respectively. The temperature of the resistor's surroundings affects how much power it can dissipate. Higher temperatures mean the resistor needs to dissipate less power to avoid exceeding its maximum temperature limit.

Understanding Resistor Power related specs - 2

https://www.vishay.com/docs/28730/ac_ac-at_ac-ni.pdf

Let's refer the datasheet of Vishay 3W resistor AC03-AT





It is clear from the derating curve that, maximum power cannot be applied to a resistor, once the surrounding temperature of resistor exceeds 40 deg C.

Real life scenario examples of ambient temperature

https://www.vishay.com/docs/28730/ac_ac-at_ac-ni.pdf

Assumptions: External Ambient temperature is 25 deg C and RθJA (°C/W) of resistor selected is 90. Power being dissipated in the resistor is 3 Watts.

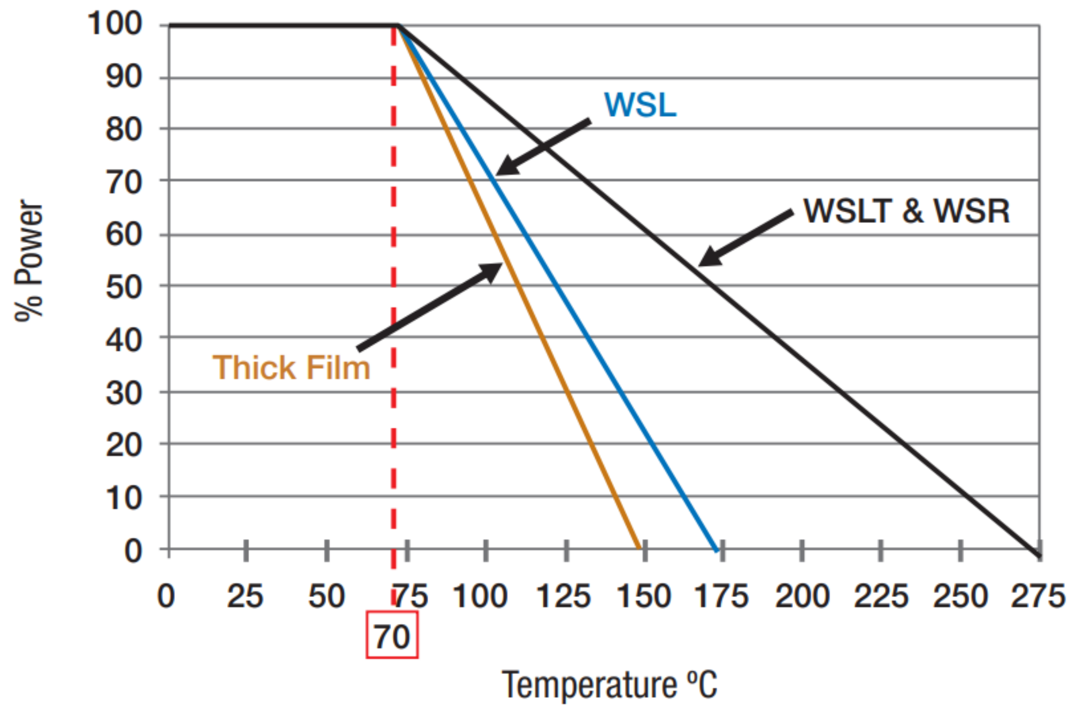
Case	Est. RθJA (°C/W)	ΔT @ 3W (°C)	Final Temp (°C)	Safe?
Open PCB, No Air	90	270	295	❌ (Close to failure)
Open PCB, With Airflow	30	90	115	⚠️ Maybe
Sealed Metal, No thermal contact	90–100	270–300	~295–325	❌
Sealed Metal, Good thermal Contact	15–20	45–60	70–85	✅
Sealed ABS Plastic Box	100–120	300–360	325–385	❌🔥

If a PCB with resistor having power loss is kept within an air tight casing, remember the heat released by the resistor gets trapped inside and rises the overall temperature of the environment within the casing even though external ambient temperature may be low !.

If a high power is dissipated in a resistor within an air tight enclosure, designer should ensure that, the heat from the resistor is transferred to a heatsink or metal casing.

Power resistor derating curves for various resistors

- Some of Vishay resistors can be operated at full rated power up to 70°C of ambient temperature. However, beyond this temperature, the part will need to be derated. (Derate linearly to 0 W at 150 °C (Thick film), at 175°C (WSL series), 275 °C (WSR series)
- Some of Vishay resistors can be operated up to 150deg C and some even up to 275 DegC



Assume you are using a thick film resistor at an ambient or environment temperature of 85°C, what will be your power derating factor?

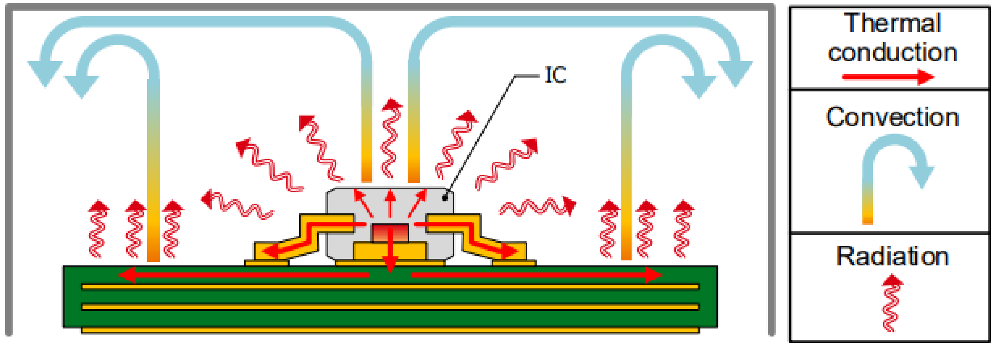
https://www.vishay.com/docs/30138/wslt2010.pdf

Temperature rise in a resistor

The temperature rise in a resistor depends on

1. The power loss and time (I^2R * T, WhereT is Time in seconds)
2. How much of the heat generated in the resistor is taken away through Conduction, convection and radiation.

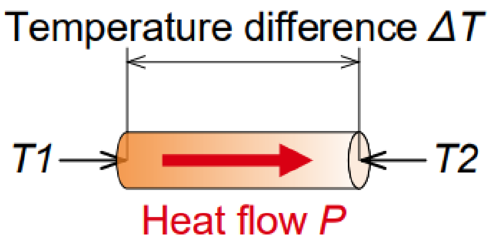
- **Conduction:** Spreading of the heat through the terminal of the component to the PCB. So larger the area of the PCB trace, higher the thickness of the trace, better is the heat transfer.
- **Convection:** Convection of the heat from the resistor to the fluid. Yes, the fluid here is "Air". So larger the surface area of the component, better will be the convection. Larger the flow of air around the component, better the heat transfer will be.
- **Radiation:** How much of heat is radiated from the component.



Overall, if more temperature is lost by conduction, convection and radiation, the absolute temperature of the component will be lesser. Component temperature = Ambient temperature in deg C + Heat rise in component in Deg C

What specs determines the temperature rise?

Thermal Resistance

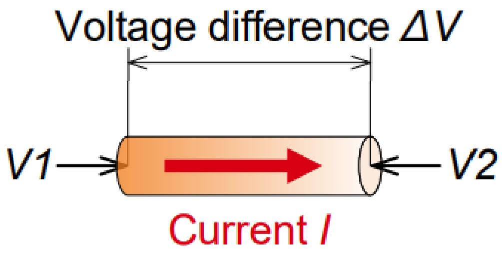


$$\text{Thermal resistance } Rth = \frac{T1 - T2}{\text{Heat flow } P}$$

$$= \frac{\text{Temperature difference } \Delta T}{\text{Heat flow } P} \quad [°C/W]$$

Electric	Voltage difference ΔV (V)	Electric resistance R (Ω)	Current I (A)
Thermal	Temperature difference ΔT (°C)	Thermal resistance Rth (°C/W)	Heat flow P (W)

Ohm's law analogy



$$\text{Electric resistance } R = \frac{V1 - V2}{\text{Current } I}$$

$$= \frac{\text{Voltage difference } \Delta V}{\text{Current } I} \quad [V/A]$$

Electric	$\Delta V = R \times I$	$R = \frac{\Delta V}{I}$	$I = \frac{\Delta V}{R}$
Thermal	$\Delta T = Rth \times P$	$Rth = \frac{\Delta T}{P}$	$P = \frac{\Delta T}{Rth}$

Courtesy: https://fscdn.rohm.com/en/products/databook/applinote/common/basics_of_thermal_resistance_and_heat_dissipation_an-e.pdf

How to calculate the temperature rise?

Change in temperature of the component can be found from

$$\Delta T = R_{thja} * P$$

ΔT = Change in temperature in deg C

R_{thja} = Thermal resistance from junction or heat source to ambient (Generally mentioned in the datasheet)

P = Power loss in the component

Absolute temperature of component = $\Delta T + T_{amb}$

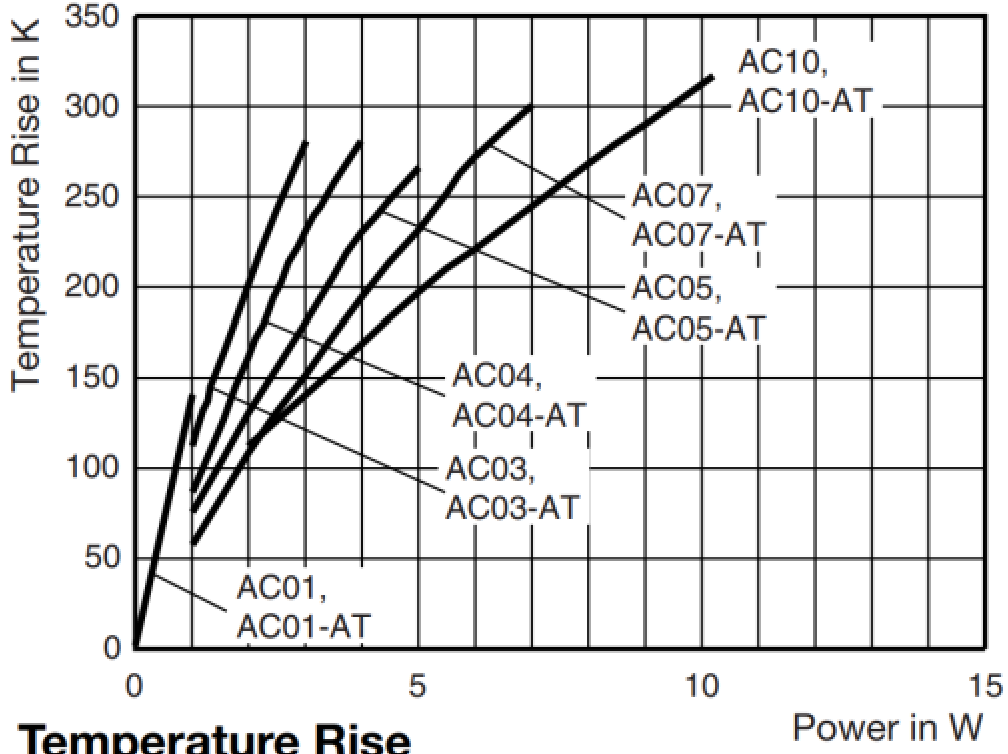
T_{amb} = The Max ambient temperature at which your end product is supposed to work

Consumer-grade : 0°C and 70°C.

industrial-grade: -40°C to +85°C.

Automotive-grade : -40°C to +105°C or even up to +125°C)

If is R_{thja} not available in the datasheet, look for this characteristics



Temperature Rise

https://www.vishay.com/docs/28730/ac_ac-at_ac-ni.pdf

Back to content List

Pulse Withstanding Resistors

Pulse withstanding Resistors

- ◆ What Are Pulse-Withstanding Resistors?
  - Designed to absorb short, high-energy pulses without damage—rated by pulse power, voltage & energy. For Ex: Resistor RP2512 supports up to 3000 W pulse power and 6 kV surge capability per IEC 60115-1
- ◆ Why They're Unique?
  - Untrimmed resistive layer (5 % tolerance) avoids fragility → strong surge handling.
  - Can withstand repeated 1.2/50 µs lightning pulses with <1 % shift.
  - Suitable for continuous pulses at rated power with high repeatability
- ◆ Example use cases of Pulse with standing

Stage	Pulse Resistor Role
AC Line Input	Surge suppression in series with MOVs to absorb part of surge energy
DC Output	Load dump resistor or protection against back EMF
Filter Bleeder	Safe discharge of input/output capacitors

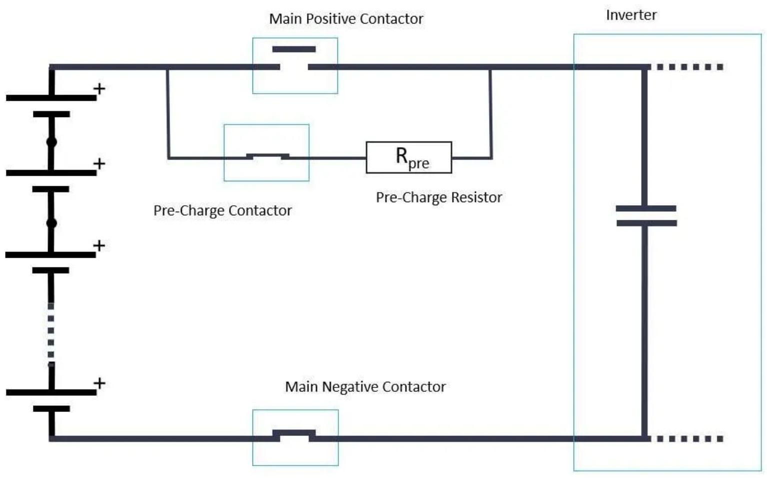
https://www.seielect.com/catalog/sei-rpc.pdf

Example use of Pulse withstanding Resistors

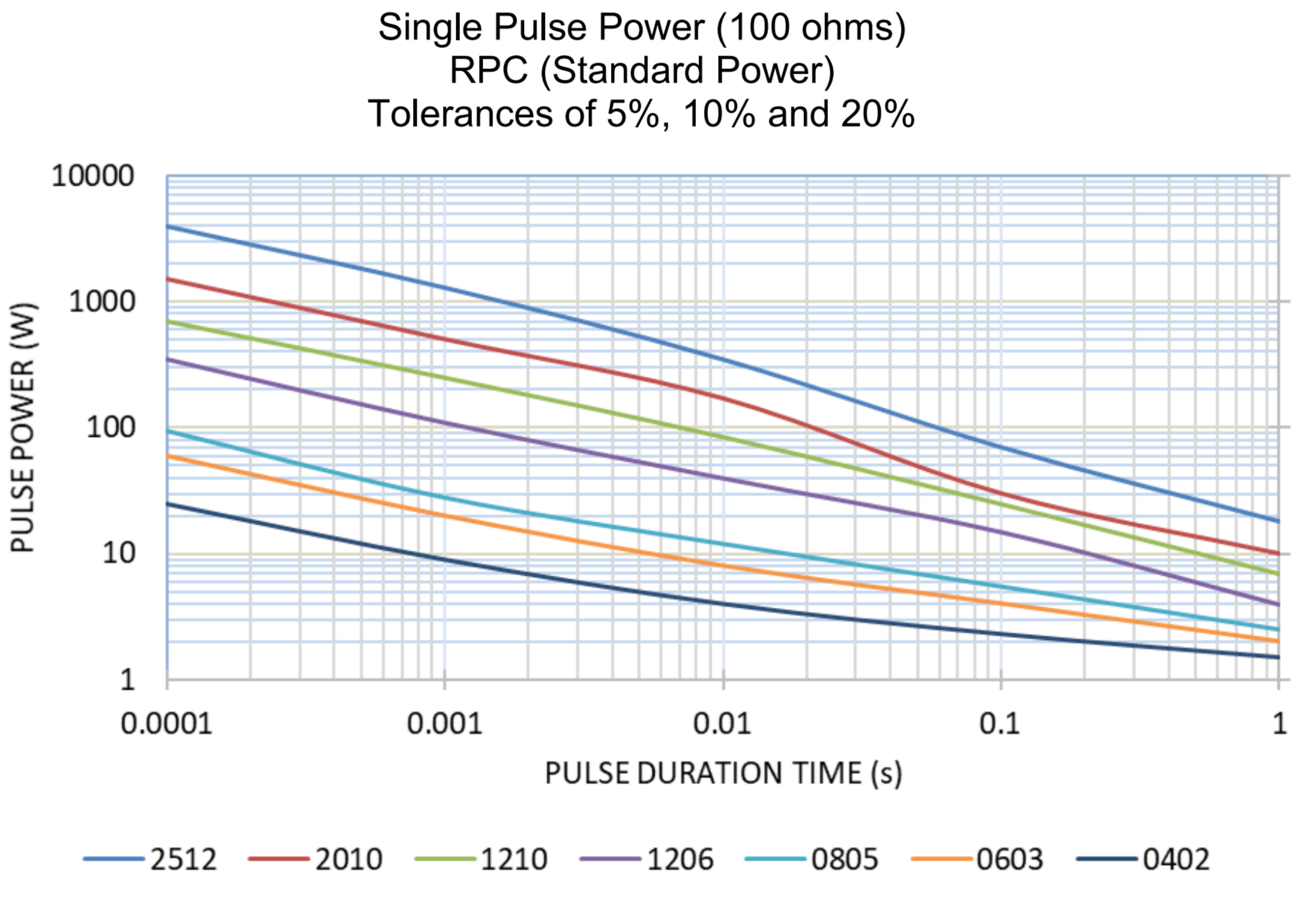
- When an automotive BMS needs to power the load, as the load may have a higher capacitance due to loads (10's of milli farads), we need to connect the load first through a pre-charge resistor and once the load voltage reaches a level, the main contactor can be closed bypassing the pre-charge resistor.

- Assuming a pre-charge resistor of 10 Ohms, and load capacitance of 30 milli Farads, At t = 0ms P = 230.4W; At t = 300ms P= 31.1W; At t = 600ms P=4.15W; At t = 900ms P = 0.58W; At t = 1500ms P = 0W.

- In this case, the peak power goes up to 230W and within a second, it comes down to 0.5W. So pulse withstanding resistor can be safely used here



Pulse withstanding Resistors - Specs



https://www.seielect.com/catalog/sei-rpc.pdf

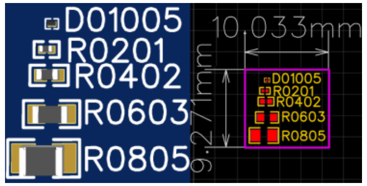
- As per the pulse withstanding graph from "Stackpole Electronics" either the 2010 or 2512 package SMD resistor can easily handle the requirement discussed for a BMS.
- The continuous power rating of RPC2512 is just 1.5W, however this resistor can safely handle the pulse power requirement
- Note: Do check the Power Derating Curve to ensure safe operation within your operating temperature condition.

But what if the load has a short circuit fault when the Pre-charge circuit is turned on ?!
Ans: If the power loss in the resistor exceeds it 's rated power for more than a hundred micro seconds, the resistor would fail. So, need to have faster sensing of load terminal voltage for protection.

Back to content List

Voltage Rating specification of Resistors and it's impact on circuit design

Voltage rating of SMD Resistors

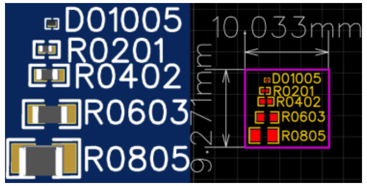


- ◆ **What Is Voltage Rating?**
- The maximum continuous voltage that can be safely applied across a resistor without breakdown, arcing, or damage. Exceeding this can lead to insulation failure, arcing, or resistor drift
- ◆ **Key factors affecting Voltage Rating**

Factor	**Impact**
Resistor Size	Larger SMD packages (e.g., 1206, 1210) have **higher voltage ratings**
Resistive Film Material	Different materials have different **dielectric strength**
Board Layout & Spacing	Creepage/clearance on PCB affects **actual safe voltage**
Pulse Conditions	Continuos vs. transient (pulse) conditions requires different considerations.

- 📌 **Note:** Always check manufacturer datasheets for exact voltage rating. Derating may be necessary for high-humidity or altitude environments

Voltage rating of SMD Resistors



Code		Length (l)		Width (w)		Height (h)		Power
Imperial	Metric	inch	mm	inch	mm	inch	mm	W
0201	0603	0.024	0.6	0.012	0.3	0.01	0.25	1/20
0402	1005	0.04	1.0	0.02	0.5	0.014	0.35	1/16
0603	1608	0.06	1.55	0.03	0.85	0.018	0.45	1/10
0805	2012	0.08	2.0	0.05	1.2	0.018	0.45	1/8
1206	3216	0.12	3.2	0.06	1.6	0.022	0.55	1/4
1210	3225	0.12	3.2	0.10	2.5	0.022	0.55	1/2
1812	3246	0.12	3.2	0.18	4.6	0.022	0.55	1
2010	5025	0.20	5.0	0.10	2.5	0.024	0.6	3/4
2512	6332	0.25	6.3	0.12	3.2	0.024	0.6	1

Max Working Voltage

(Unit: V)

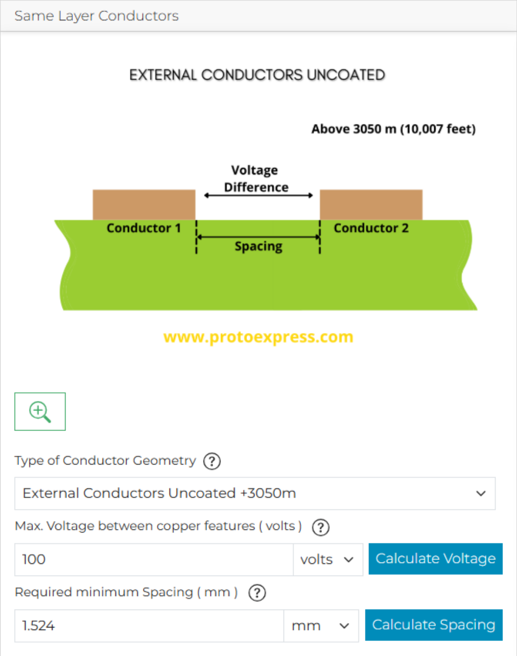
Dim / Item	0402 (01005)	0603 (0201)	1005 (0402)	1608 (0603)	2012 (0805)	3216 (1206)	3225 (1210)	5025 (2010)	6432 (2512)
Max Working	15	25	50	50	150	200	200	200	200

Assume 1000V DC needs to be measured by an ADC which can accept 5V max. Can we use just two resistors (100KOhm, 2K Ohm) to attenuate 1000V to 5V? Ans: A single 100K ohm resistor cannot safely handle the high voltage across it as it may exceed it's voltage rating.

Courtesy: https://www.samsungsem.com/resources/file/global/support/product_catalog/Chip_Resistor.pdf

Minimum trace spacing requirements in a PCB

Like resistor packages have a definite max working voltage, while doing PCB Layouts, for a given voltage between two adjacent traces, there must be a minimum spacing to be provided for safe operation. This distance value is influenced by whether the conductors are in the internal layer or external layer, if it is external layer, whether it has a protective coating on the components or not, what is the altitude of operation for the PCB etc.,(As per IPC2221 standard for creepage and clearance)



Geometry Table

Play Demo Video

Type of Conductor Geometry	IPC Standard Titles
Conductors on internal layers	B1 - Internal Conductors
External Conductors Uncoated	B2 - External Conductors Uncoated, Sea Level to 3050 m (10,007 feet)
External Conductors Uncoated, +3050 m	B3 - External Conductors Uncoated, over 3050 m (+10,007 feet)
External Conductors SM Coated	B4 - External Conductors with Permanent polymer(SM) coating (any elevation)
Extenal Conductors With Conformal Coating	A5 - External Conductors With conformal coating over assembly (any elevation)
Component Leads Uncoated	A6 - External Components lead/termination uncoated, Sea Level to 3050 m (10,007 feet)
Component Leads With Conformal Coating	A7 - External Components lead/termination , with conformal coating, (any elevation)

Try the online tool “PCB Conductor Spacing and Voltage Calculator” from Sierra Circuits

PCB Conductor Spacing and Voltage Calculator | Sierra Circuits

Courtesy: https://www.protoexpress.com/blog/importance-pcb-line-spacing-creepage-clearance/

Back to content List

High voltage resistors

High Voltage Resistors

◆ **What is a High Voltage Resistor?**

- A resistor built to safely operate at high voltages (typically ≥1 kV)
- Designed with materials and geometry to minimize leakage, arcing, and instability

◆ Applications:

- High-voltage power supplies (medical, X-ray)
- Precision voltage dividers
- CRTs, photomultiplier tubes
- Surge protection and ESD systems

Voltage Coefficient of Resistance (VCR)

- **Definition**: Percentage change in resistance per volt (ppm/V). A specification important for resistors used in high voltage circuits
- **Typical Values**: 0.1–20 ppm/V (precision resistors).
- **Factors**: Material, construction, voltage stress.
- **Formula**: $\Delta R/R = \text{VCR} \times \Delta V$.
- **Applications:** Energy storage systems, Automotive BMS

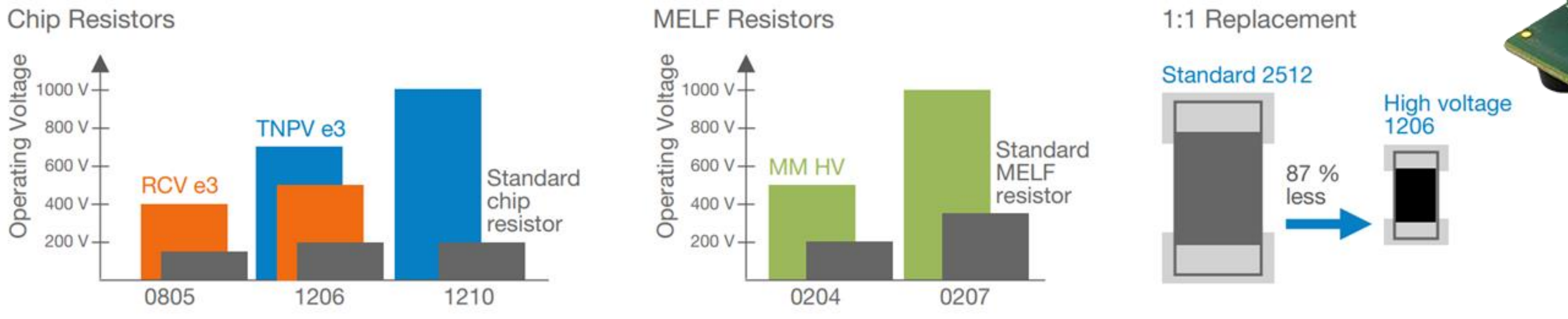
Example:
Resistor: 1 MΩ with VCR = 20 ppm/V Voltage change: 0 V to 500 V
Step 1: Calculate resistance change: $\Delta R/R = 20\ \text{ppm/V} \times 500\ \text{V} = 10000\ \text{ppm} = 1.0\%$
Step 2: Calculate new resistance: $R_{\text{new}} = 1{,}000{,}000\ \Omega \times (1 + 0.01) = 1{,}010{,}000\ \Omega$
Impact: This change in resistance introduces error in the measurement

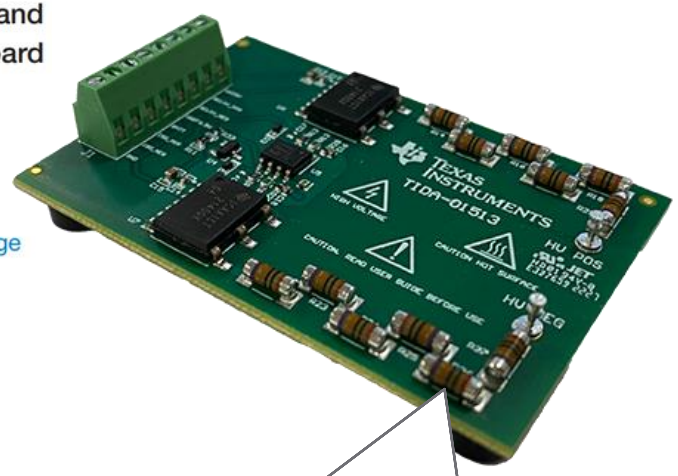
Notes:
- For high voltage measurement applications, use low-VCR resistors (e.g., metal film) for precision.
- Critical above 100 V; impacts measurement accuracy.

Compact High Voltage resistors

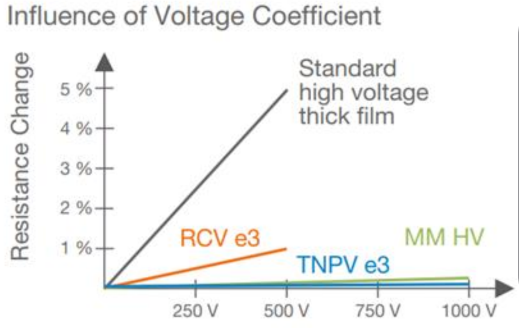
Today, various industrial and automotive applications operate at high voltages, which are significantly larger than the permissible operating voltage of a single SMD resistor. Thus, multiple resistors are typically used in series to distribute the voltage load. This workaround becomes unnecessary with the use of high voltage resistors, which combine a high operating voltage rating with a low voltage coefficient.

Operating Voltage — The significantly increased operating voltage allows up to five standard components to be replaced by a single high voltage resistor of the same case size. Besides component count reduction, board space will be saved and placement costs reduced. Since the voltage rating even exceeds that of standard components in the next case size, board space savings can also be achieved by 1:1 replacement with a smaller component.





Voltage Coefficient — The voltage coefficient of resistance (VCR) indicates the resistor's permissible change of resistance, depending on the operating voltage. Hence, using high voltage resistors at the allowed elevated voltage levels may cause a significant resistance change. Thus, high precision applications will benefit from thin film resistors, which feature an especially low VCR of ≤ 2 ppm/V.



Multiple MELF resistors in series. (Can be replaced by Single Vishay high voltage resistor)

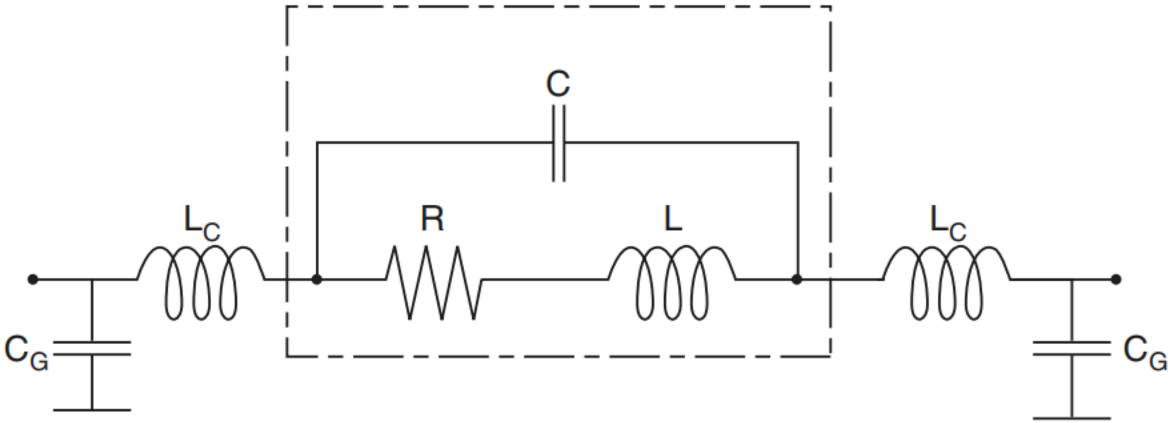
https://www.vishay.com/docs/48552/_ms11394929-1905-did_you_know-_smd_hv_resistors.pdf

Back to content List

Parasitic Inductance, Capacitance in Resistors and it’s impact on circuit design

Parasitic L and C in Resistors

- Resistor does possess a small amount of parasitic inductance and capacitance due it's construction. Although this does no harm at low frequency circuits, at high frequencies the impedances of these parasitic elements start dominating.



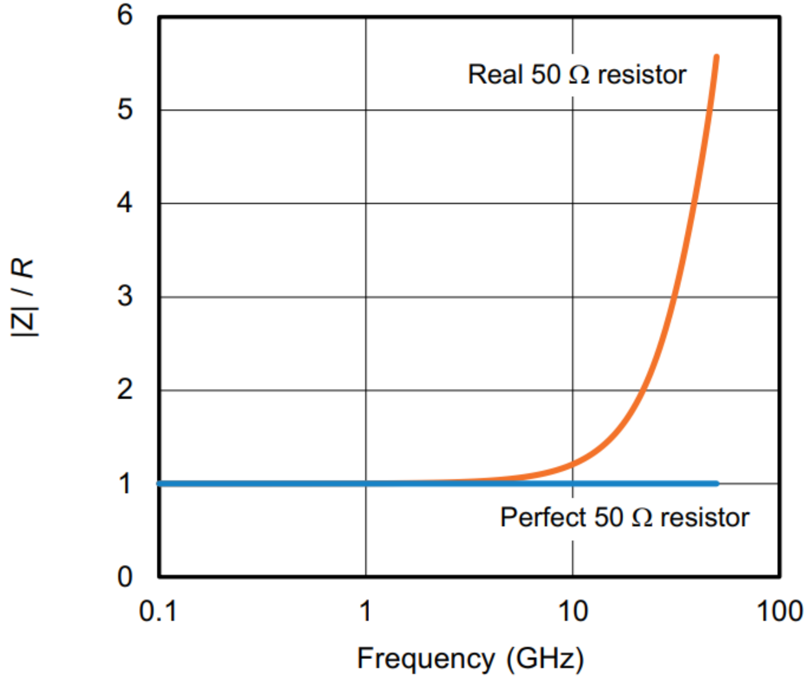
C: internal shunt capacitance

L: internal inductance

R: resistance

L_C: external connection inductance

C_G: external capacitance to ground

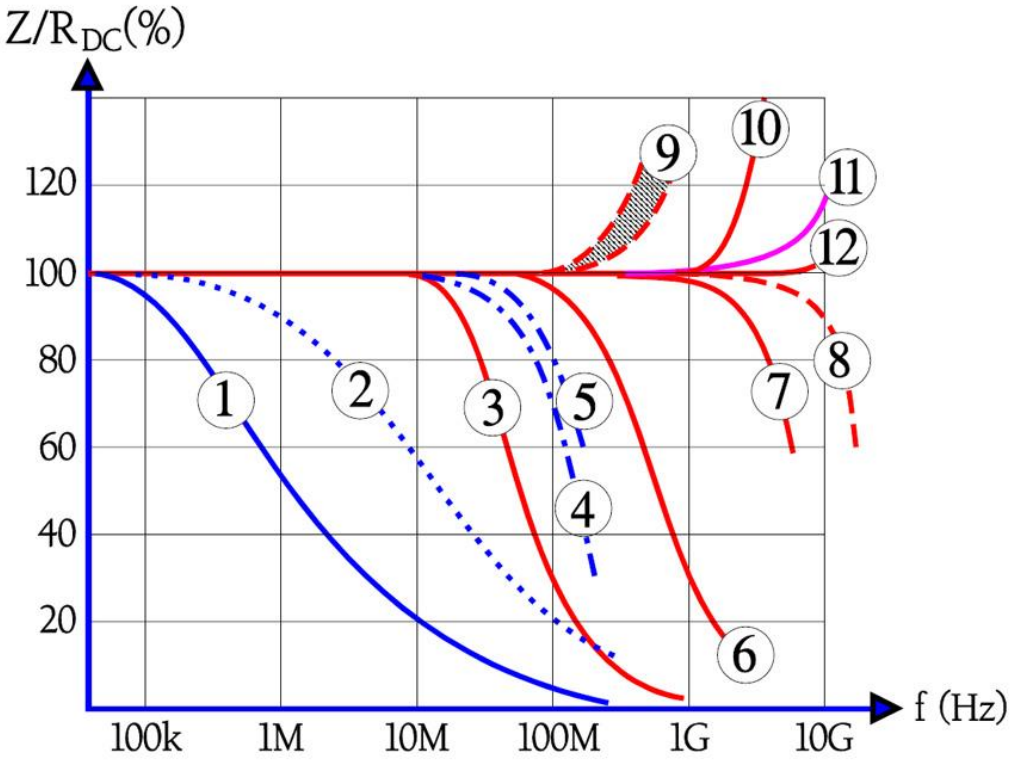


As the frequency increases, the impedance deviates from 50 Ω

Courtesy: https://www.vishay.com/docs/60107/freqresp.pdf

Courtesy: https://www.vishay.com/docs/53077/microwavethinfilmres.pdf

Z/R of characteristics of resistance

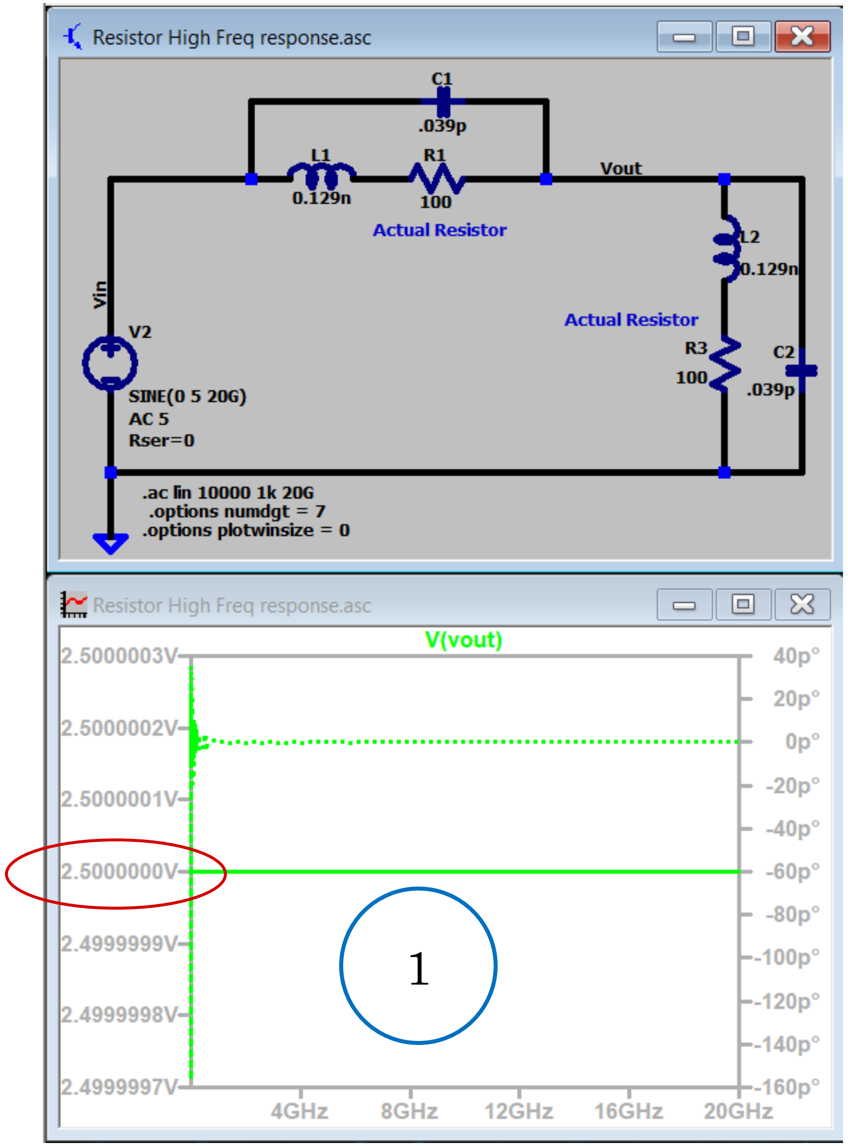


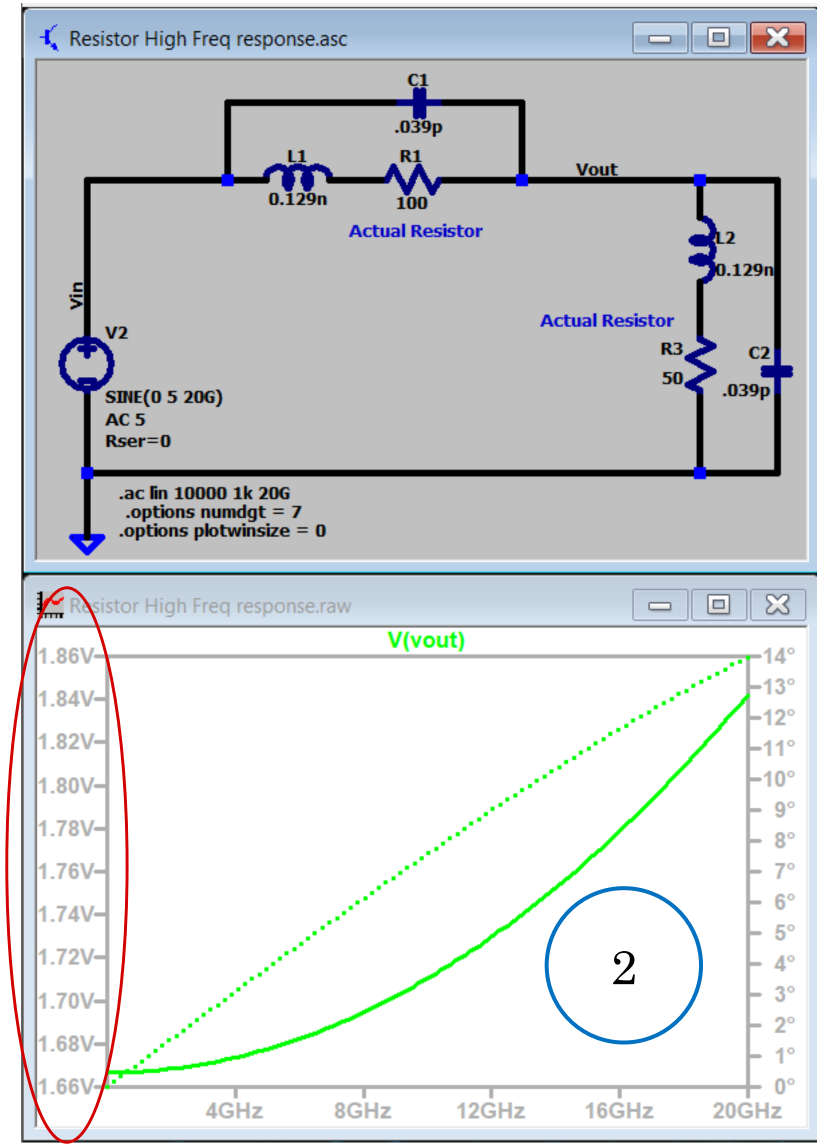
Examples of frequency dependence as the ratio of AC impedance through DC resistance for different resistor types:

1. Carbon composition, ¼ W, 1 MΩ .
2. Carbon composition, ¼ W, 100 kΩ .
3. Chip, thick film, EIA size 0603, 100 kΩ ; c » 0.05 pF; L » 0.4 nH.
4. Metal glaze or metal film, DIN size 0207, 100 kΩ ; c » 0.4 pF.
5. MELF, DIN size 0204, 10 kΩ .
6. Chip, thick film, EIA size 0603, 10 kΩ ; c » 0.05 pF; L » 0.4 nH.; Chip, metal foil, EIA size 1210, 10 kW.
7. Chip, thick film, EIA size 0603, 1 kΩ ; c » 0.05 pF; L » 0.4 nH.
8. MELF, DIN size 0102, high frequency design, 10 Ω ; c » 0.035 pF; L » 0.8 nH.
9. MELF, DIN size 0204, 10 Ω .
10. Chip, thick film, EIA size 0603, 10 Ω ; c » 0.05 pF; L » 0.4 nH.
11. Chip, thin film, EIA size 0603, 100 Ω ; c » 0.035 pF; L » 1.2 nH.
12. Chip, thick film, EIA size 0603, 100 Ω ; c » 0.05 pF; L » 0.4 nH.

Note: MELF resistors, known for their high precision and reliability, come in standard DIN sizes like 0102, 0204, and 0207. EIA (Electronic Industries Alliance) sizes are primarily used for surface mount resistors (SMD) and are characterized by numerical codes. Some common EIA sizes include 0603, 0805, and 1206

Frequency response of a Resistor





- 1) When both voltage divider resistors are of same value, say 100 Ohms, the voltage across them is equal for frequencies from 1KHz to 20GHz. The change in impedance in both resistors cancels each other. (Although current through the circuit will change).
- 2) When one of them is changed to say 50 Ohms, the voltage across them is no more balanced. This is due to different Z/R for each resistors. This is one example where parasitic in resistor can affect intended circuit response

Parasitic Inductance

Parasitics in Resistors
Parasitic effects are unintended electrical characteristics that affect resistor performance, especially at high frequencies or in precision circuits.

1. **Parasitic Inductance**:
    1. Caused by the physical structure of the resistor (e.g., wirewound resistors have coiled conductors, SMD Resistors have end metal caps for soldering).
    2. Typical values: 1–20 nH for surface-mount resistors, higher for wirewound (up to μH).
    3. Impact: Causes phase shifts or resonance in high-frequency circuits (e.g., RF or switching power supplies).
    4. Mitigation: Use non-inductive designs (e.g., thin-film, metal film) or special winding techniques (e.g., Ayrton-Perry winding).

Parasitic Capacitance

Parasitic Capacitance:

1. Arises from the resistor's body acting as a capacitor between terminals or to ground.
2. Typical values: 0.1–2 pF for surface-mount resistors.
3. Impact: Affects high-frequency performance, creating a low-pass filter effect.
4. Mitigation: Use low-capacitance designs or chip resistors with minimal surface area.

Criticality of Parasitic L, C

Applications Affected:

1. High-frequency circuits (e.g., RF amplifiers, oscillators).
2. Precision analog circuits where parasitics cause signal distortion.

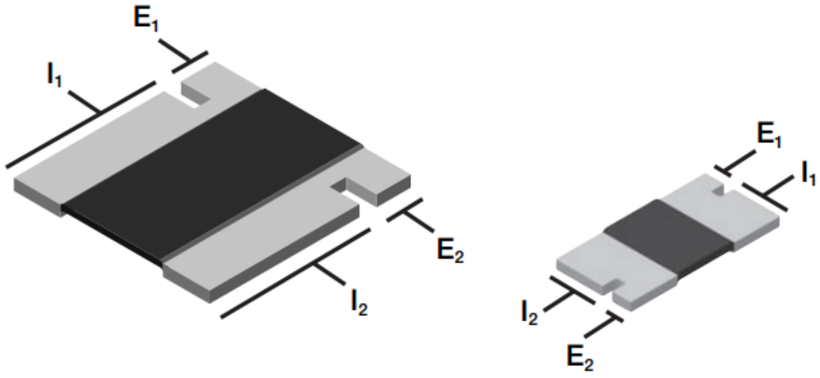
Measurement of parasitic L and C:

1. Parasitics are characterized using impedance analyzers or network analyzers at specific frequencies.
2. Specified in datasheets for high-frequency or precision resistors (e.g., Vishay's FC series for RF applications).

Back to content List

Current shunt resistors

Current Shunts / Shunt Resistors



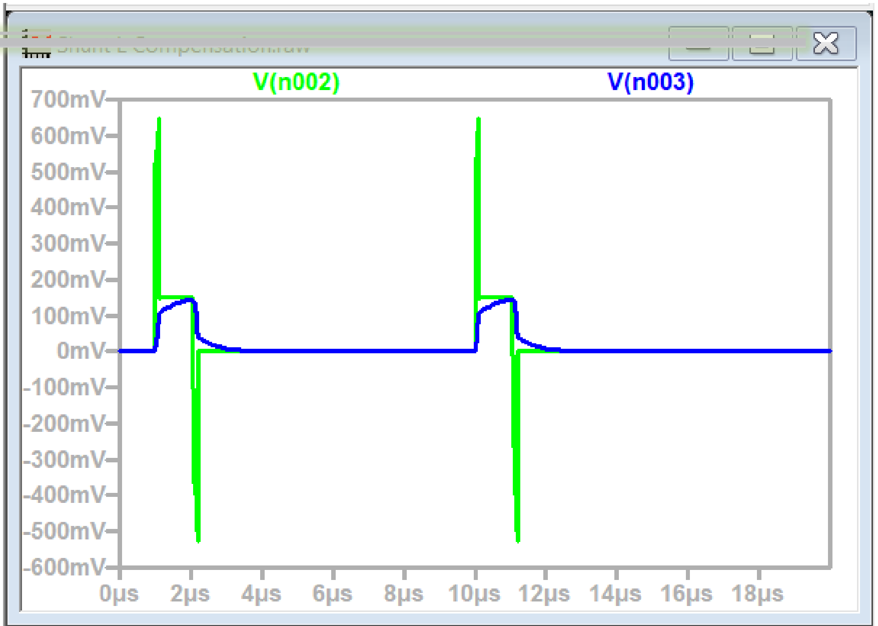
(E_1 & E_2 Voltage Connections, I_1 & I_2 Current Connections)

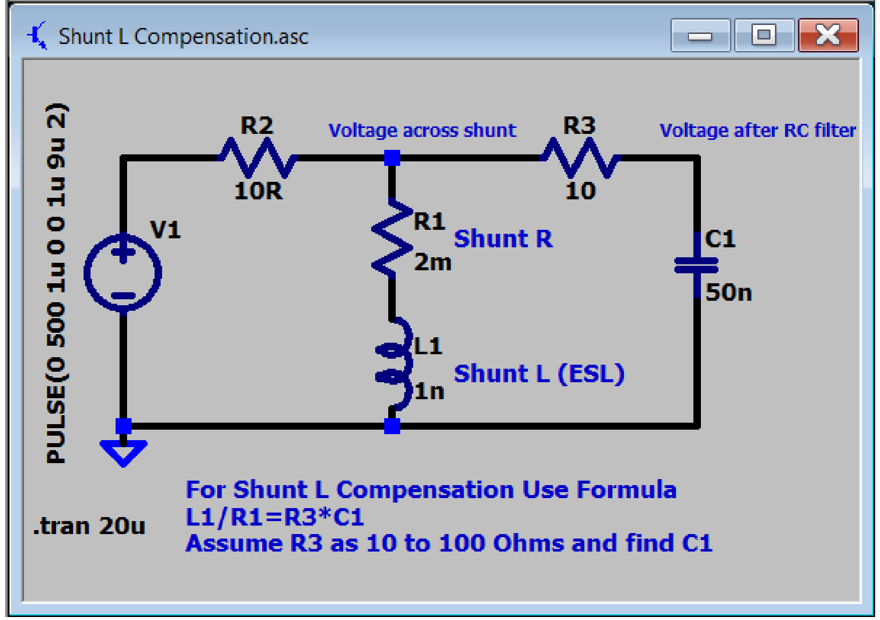
- Resistor used for current measurement. (Measure voltage drop and use I = V/R)
- Very low resistance value to keep the power loss minimal (0.1 milli ohms to 10's of milli Ohms), capable of carrying higher current.
- There are shunts with 4 terminals for "Kelvin Connection" to enable error free measurement.
- For high frequency switching applications, ESL should be low.

https://www.vishay.com/docs/30304/currentmeasurement.pdf

Effect of ESL in shunts due to fast switching currents

- Current shunts are used for current sensing in Motor inverters, Battery management systems, DC-DC Converters, etc.,
- High current shunts being metal, they inherently have parasitic inductance (ESL). This is typically around 1nH~5nH
- While this inductance may not be an issue in DC current measurements, in high frequency circuits with fast rise and fast fall of current, the ESL causes positive voltage spike while the current rises (to reduce the rise of current) and, negative spike when the current tries to become zero (to aid the current to continue flowing). (Counter emf = -L*di/dt)
- This needs to be eliminated to protect the ADC input, from excessive positive and negative voltage spikes.





Compensating the ESL of the shunt

- Effect of ESL can be compensated using the selection of R and C filter as shown in the circuit Diagram.
- The filter component values are computed using the following ratio.

$$\frac{ESL_{Shunt}}{R_{Shunt}} = R_{filter} * C_{Filter}$$

R_{Filter} can be assumed to be between 10 to 100 ohms and C_{Filter} can be calculated, knowing R_{Shunt} and ESL_{Shunt}

- Effect of ESL can be compensated using the selection of R and C filter as shown in the circuit Diagram.
- The filter component values are computed using the following ratio.

$$\frac{ESL_{Shunt}}{R_{Shunt}} = R_{filter} * C_{Filter}$$

R_{Filter} can be assumed to be between 10 to 100 ohms and C_{Filter} can be calculated, knowing R_{Shunt} and ESL_{Shunt}

https://www.planetanalog.com/current-shunt-resistor-inductance-it-matters/

Construction to reduce ESL in SMD shunt resistors

- **The long side electrode design** in current sense resistors minimizes the parasitic inductance (ESL).
- This is crucial for applications requiring accurate current sensing in high-frequency environments, such as DC/DC converters in power supplies or automotive applications.
- Long side electrode design also helps for better thermal relief due to the increased electrode area

Standard sense resistor

Resistor with long side electrode

Construction of Shunt for low ESL

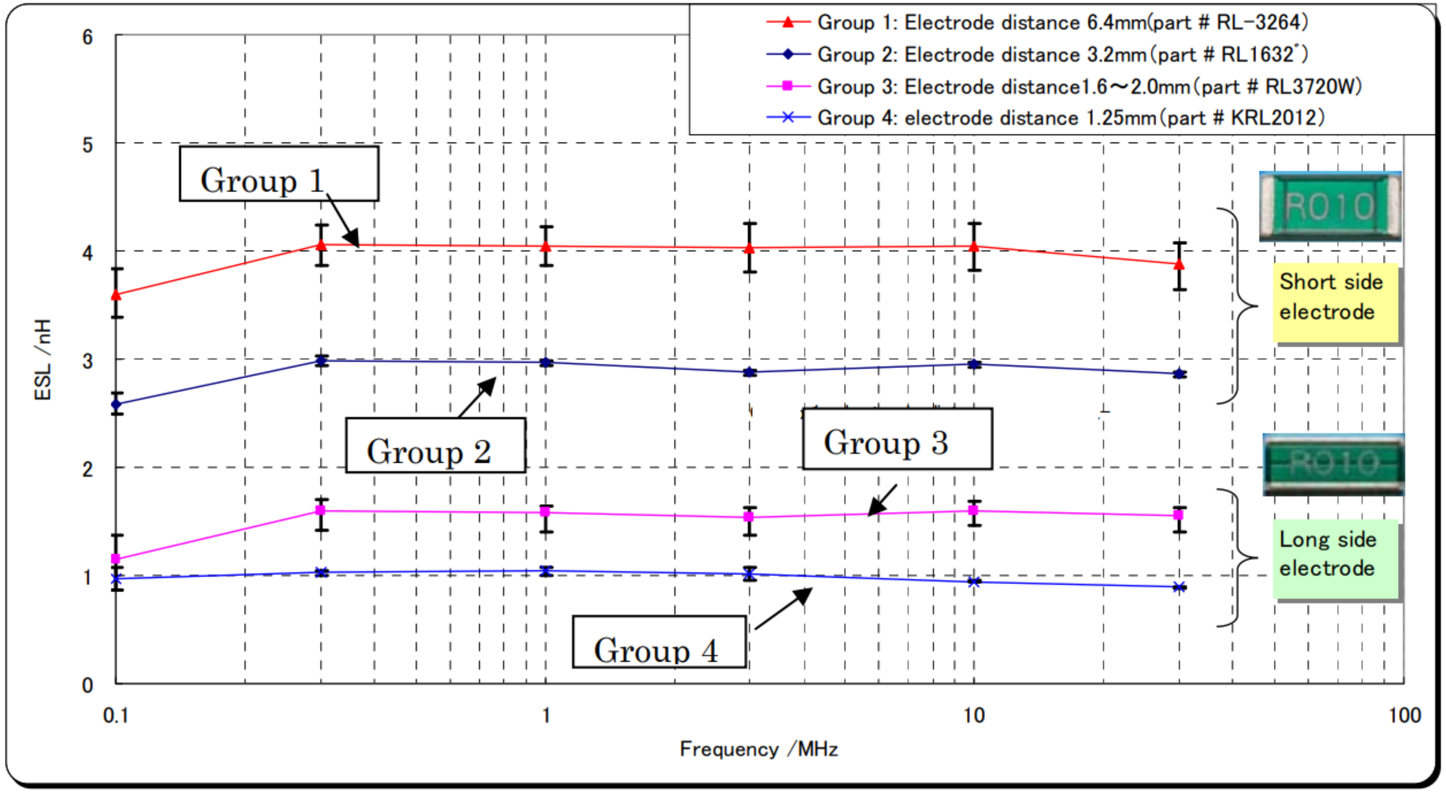
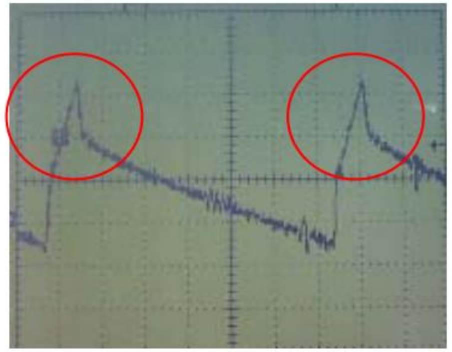


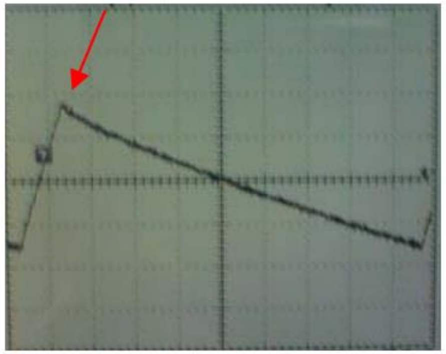
Figure 2 ESL comparison: long side terminal vs. short-side terminal

Actual measurement example



Picture 1 with short side terminal

Reduced noise



Picture2 with long side terminal

https://www.newark.com/pdfs/techarticles/susumu/LowESLCurrentSensingChipResistor.pdf

Back to content List

RF Resistors

RF Resistors

- RF Resistors are specifically designed for use in Radio Frequency (RF) circuits (typically >100 kHz up to GHz range).
- Unique Features Compared to Standard Resistors:
  - Low Parasitics : Designed to minimize parasitic inductance and capacitance, which affect performance at high frequencies.
  - Wide Frequency Range: Stable resistance across a broad frequency spectrum (up to many GHz).
  - Controlled Impedance : Precise impedance matching to ensure minimal signal reflection in RF paths.
  - Surface Mount or Thin-Film Construction: Often use thin-film, thick-film, or planar technology for better RF performance.
- Typical Applications: Attenuators; RF Terminations; Bias Tees; RF Filters & Matching Networks

Construction to reduce Parasitic L in Resistors

- Manufacturer utilise certain techniques to reduce the parasitic inductance and capacitance. For use in RF, high speed circuits, look for resistors specific for high frequency applications.

TABLE 1 - PARAMETERS FOR DIFFERENT CASE SIZES UTILIZED

CASE SIZE	LENGTH (inch/ mm)	WIDTH (inch/ mm)	RESISTOR AREA (inch²/ mm²)	MODEL INTERNAL COEFFICIENTS	
				C (pF)	L (nH)
0201	0.02/ 0.51	0.01/ 0.25	0.00004/ 0.02581	0.0206	1.73×10^{-5}
0402	0.04/ 1.02	0.02/ 0.51	0.000352/ 0.22710	0.0262	1.89×10^{-3}
0402 (wrap)	0.04/ 1.02	0.02/ 0.51	0.000352/ 0.22710	0.0392	0.1209
0603	0.064/ 1.626	0.032/ 0.813	0.000816/ 0.52645	0.0403	0.0267

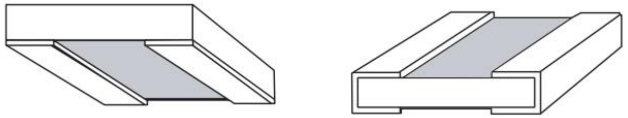


Fig. 1 - Termination styles:
Left - flip chip, resistor down
Right - wrap around, resistor up

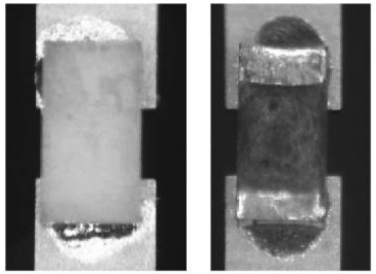
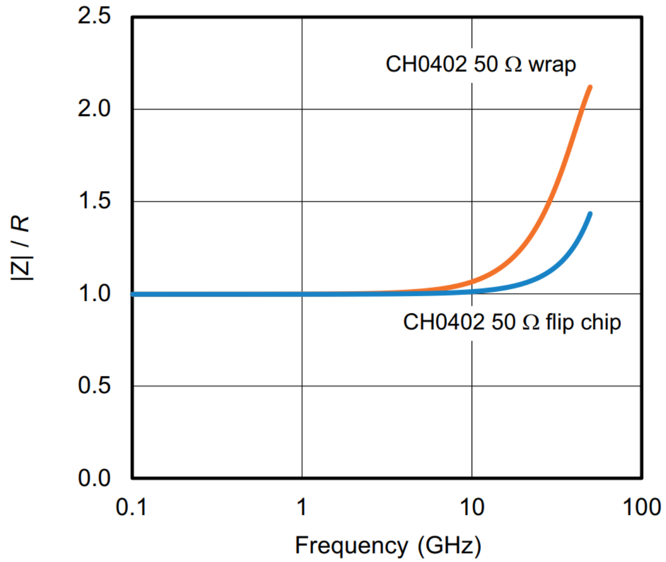
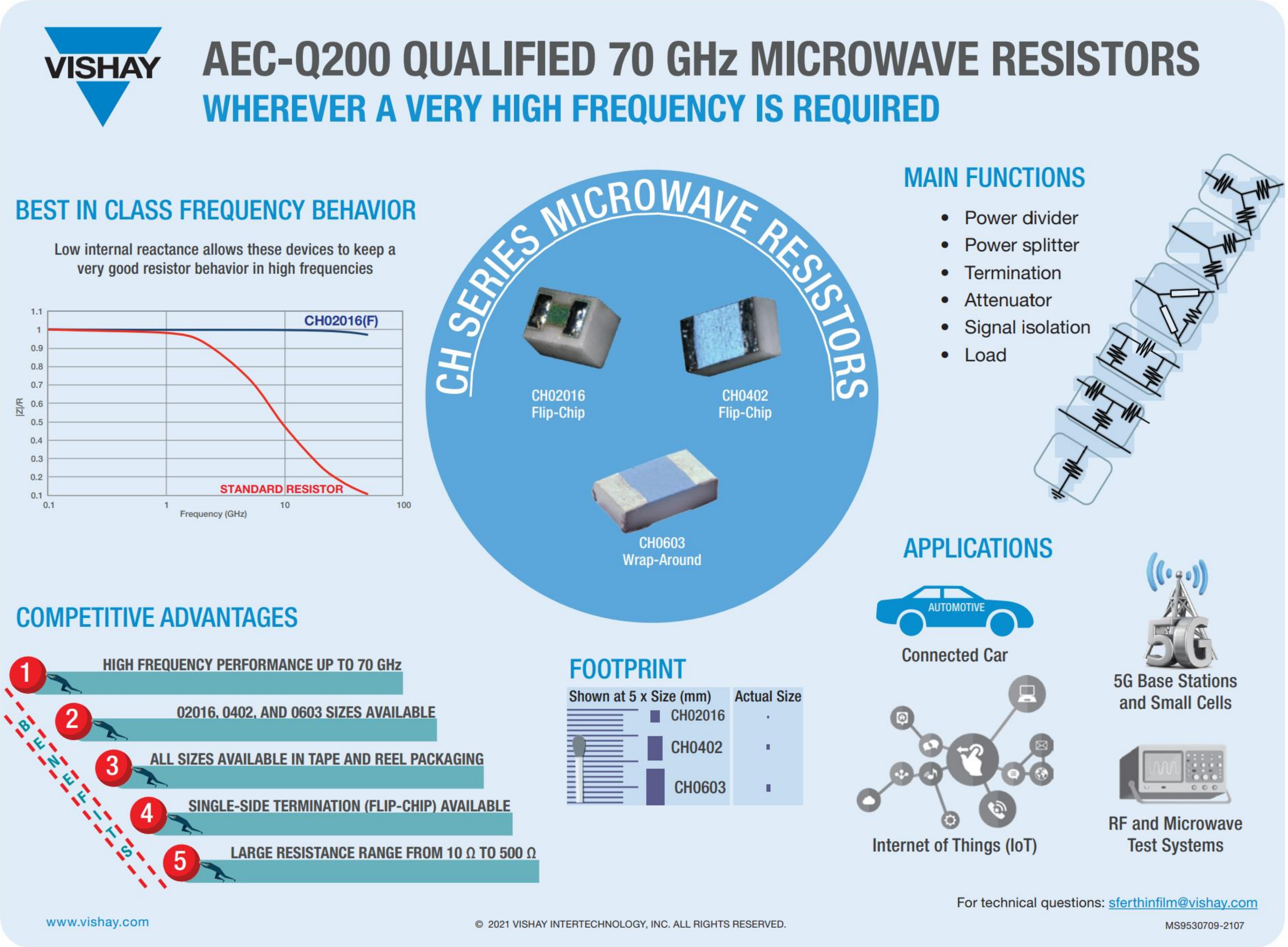


Fig. 2 - Mounting on resistors on RF grounded quartz substrates for testing
Left - flip chip, resistor down
Right - wrap around, resistor up



https://www.vishay.com/docs/53077/microwavethinfilmres.pdf

Courtesy: https://www.vishay.com/docs/60107/freqresp.pdf



Courtesy: https://www.vishay.com/docs/48510/_ms9530709-2106-infographic_ch.pdf

Back to content List

Noise specification of Resistors

Noise Specification of Resistors

- Noise in resistors arises from the physical processes within the resistive material and its interaction with the environment.

- Resistor noise has several components. The most relevant for audio, medical, high precision instrumentation applications, are "thermal noise" and "current noise".

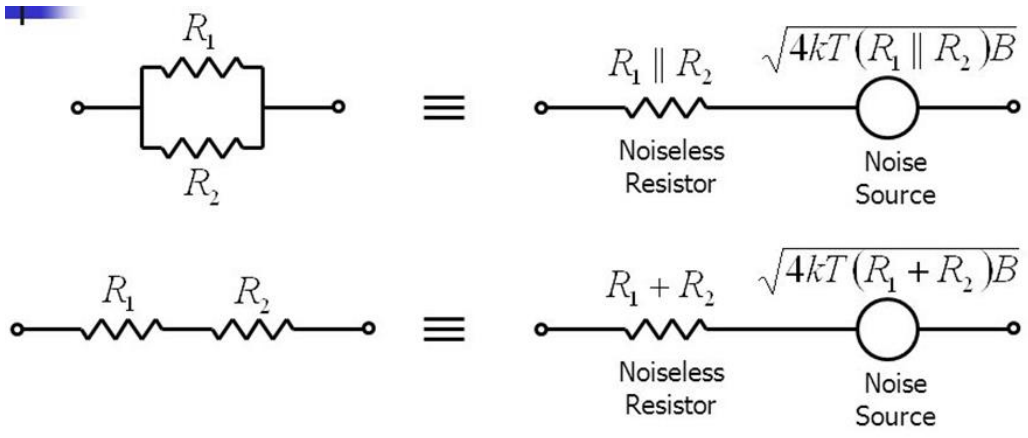
- Resistors, like other passive components, are noise sources to various degrees, depending upon resistance value, temperature, applied voltage, and resistor type.

Thermal / Johnson's noise

- The random thermal movement of charge carriers in a conductor always produces electrical noise of value

$$\sqrt{4kTBR}$$

- k is Boltzmann's Constant (1.38065 x 10^{-23} J/K),
- T is the absolute temperature in Kelvin,
- B is the bandwidth in Hz and
- R the resistance in Ohms.



NB. When adding noise sources, the result is the root of the sum of squares.

1/f or Current noise

- If we record a DC current through an electrical conductor, we would at a sufficiently high amplification be able to see small randomly occurring ripples on the "surface".
- Current noise, has a direct relationship to the type of resistive material. The spectral density of voltage of current noise S_E is found experimentally to be directly proportional to the square of DC voltage drop U across the resistor and inversely proportional to the frequency f
- $S_E = C * U2 / f$
- C is a constant that depends on material of the resistive element and its manufacturing process

Current, Thermal noise in resistors

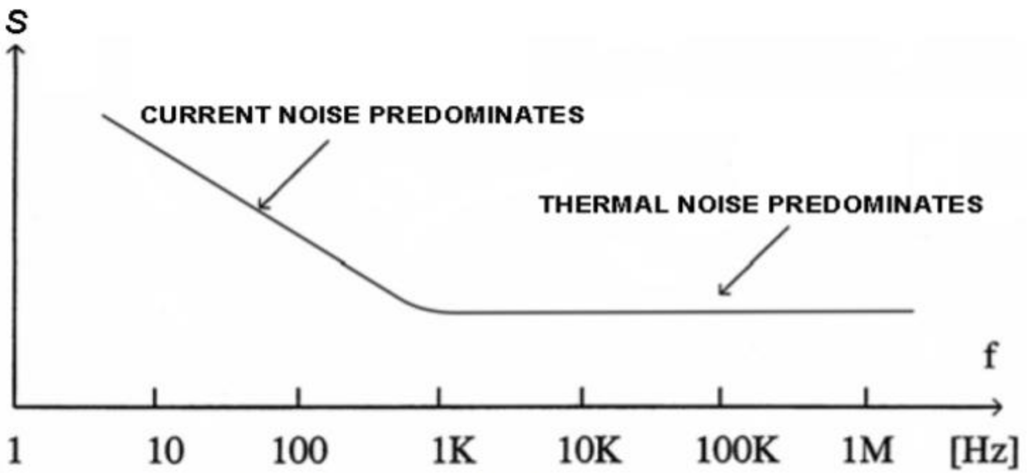
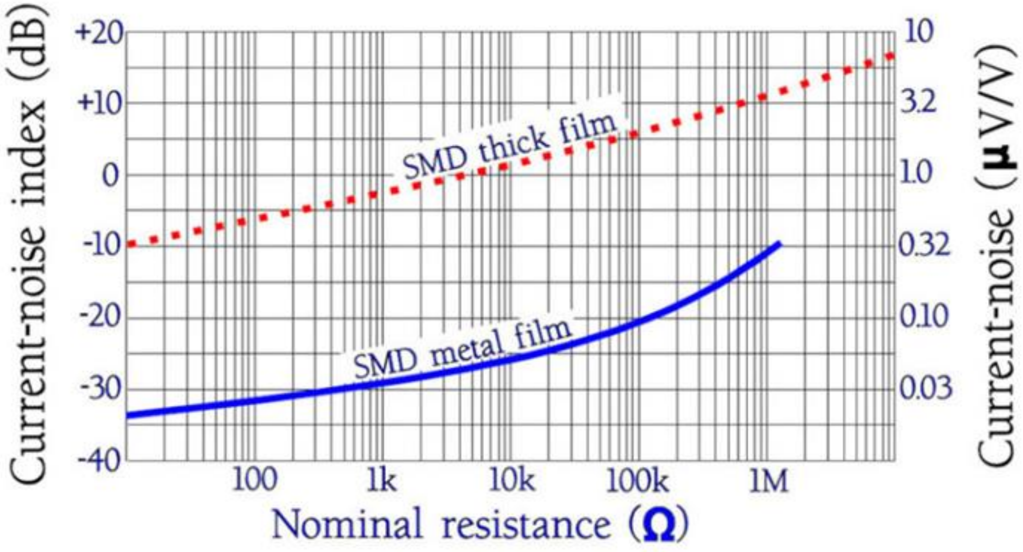


Fig.1: Spectral density of total noise voltage in resistor.

- RESISTOR NOISE EXAMPLE
- For a 100 kΩ resistor, let's find its power spectral density
- $S = 4\ k\ T\ R$
  $= 4 \times 1.38 \times 10^{-23} \times 300 \times 100k$
  $= 1.66 \times 10^{-15}$ (V2 / Hz)
- and voltage spectral density
- $N = S^{½}$
  $= (4\ k\ T\ R)^{½}$
  $= 40.7 \times 10^{-9}$ (V / Hz½)
- At first, 40 nV/Hz½ doesn't sound like much. But suppose you are designing a low-noise design amplifier using a quiet op amp with an input voltage noise of only 4 nV/Hz½ . You wouldn't want to kill the party by using a 100k boom box as a feedback resistor. Smaller R values around 1k would be a better choice.

Courtesy: http://www.ecircuitcenter.com/Circuits/Noise/Noise_Analysis/res_noise.htm

Noise of different resistor materials



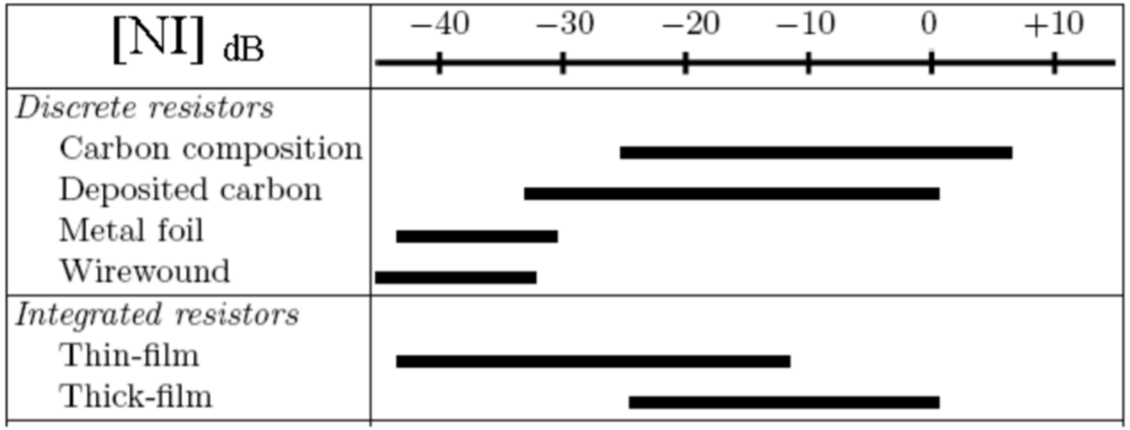


Fig.2: Average noise indexes of commercial resistors [2, p.168].

So which material types have lower Noise Index? (Good for precision circuits)
Ans: Wirewound, Metal foil, Thin film

Applications where Noise specifications matters

Factor	Effect
Resistance Value	Higher resistance → more noise
Material & Type	Carbon > Thick Film > Metal Film > Thin Film (lowest)
Current Flow	Excess noise increases with current

Applications Where Noise Matters

- Low-level analog signals (e.g., preamps, sensors)
- >14-bit resolution ADC circuits
- Audio circuits (high-fidelity audio, microphones)
- Medical electronics (ECG, EEG)
- Precision measurement instruments
- RF & communications (low-noise amplifiers)

Best Practices

- Use Thin Film or Metal Film resistors in low-noise applications
- Avoid carbon composition or high-value thick film in sensitive designs

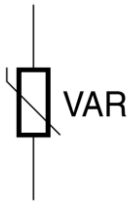
Back to content List

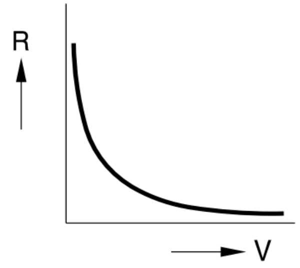
Varistors (Metal Oxide Varistors - MOV)

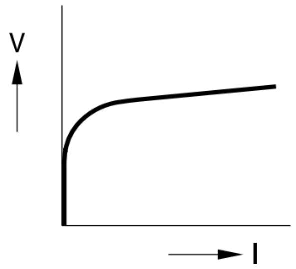
Metal Oxide Varistors (MOV)

- MOV (Metal Oxide Varistor) is a voltage-dependent resistor used for overvoltage protection.
- Exhibits nonlinear resistance: high resistance at normal voltage, low resistance during surges.
- Composed of zinc oxide (ZnO) grains with metal oxide additives, sintered into a ceramic disc.
- Operates by clamping excess voltage and diverting surge current to ground.
- Widely used in electronic circuits to safeguard against lightning, transients, and power surges.

- AC Power Lines: Surges from lightning strikes or switching operations can exceed 1KV, damaging equipment unless mitigated by MOVs or surge arresters.
- Across a Relay coil: Coil de-energization induces back-EMF surges (up to 10x operating voltage), risking relay or circuit damage without flyback diodes or MOVs.

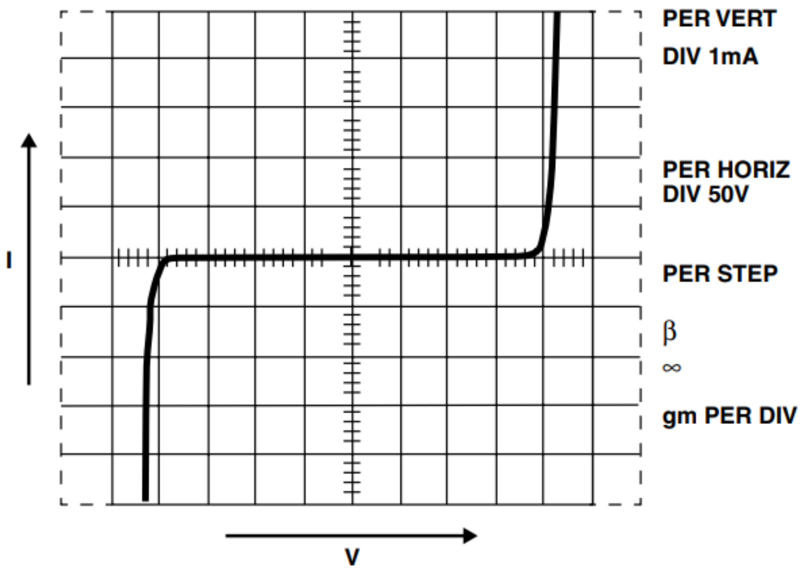




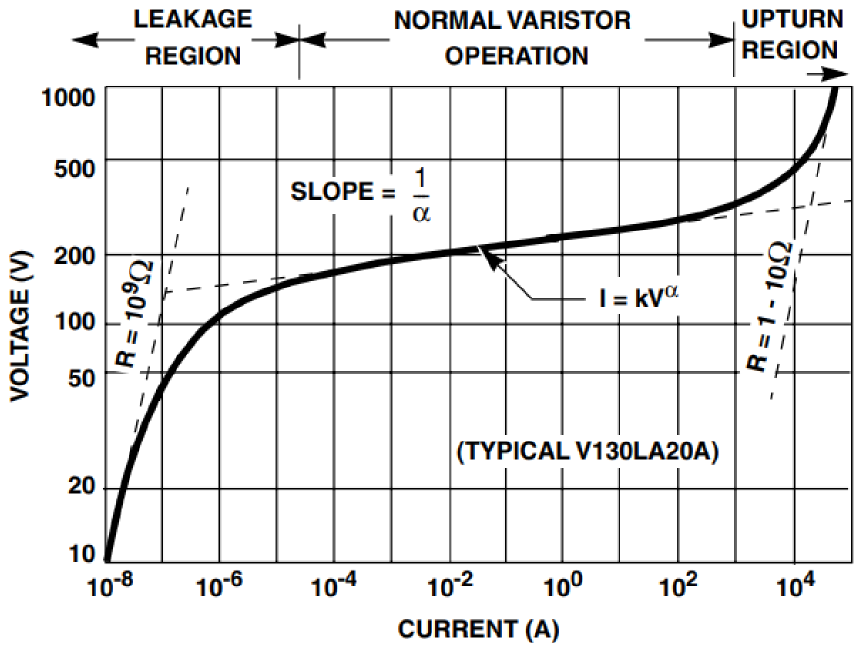


Characteristics of Varistor

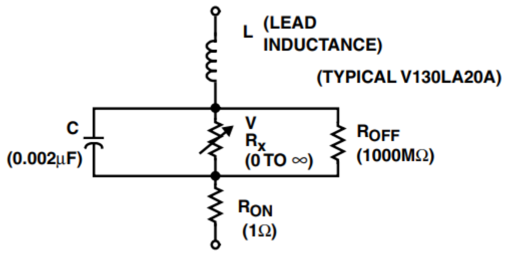
TYPICAL VARISTOR V-I CHARACTERISTIC



TYPICAL VARISTOR V-I CURVE



VARISTOR EQUIVALENT CIRCUIT MODEL



Varistors are voltage dependent, nonlinear devices which have an electrical behavior like a back-to-back Zener diodes. The potentially destructive energy of the incoming transient pulse is absorbed by the varistor, thereby protecting vulnerable circuit components.

Courtesy: http://educypedia.karadimov.info/library/an9767.pdf

MOV Specifications - 1

- **Maximum Continuous Operating Voltage (MCOV):** The maximum RMS or DC voltage the MOV can withstand continuously without degradation. Should exceed the normal operating voltage of the circuit (e.g., 130V MCOV for a 120V AC line).
- **Clamping Voltage (V_C):** The voltage at which the MOV starts conducting significant current to clamp the surge. Typically specified at a given current (e.g., 1mA or 1kA peak). Must be higher than the circuit's operating voltage but lower than the equipment's damage threshold.
- **Energy Absorption Capability (W_s or Joules):** The maximum energy (in joules) the MOV can absorb in a single surge event without failure. Depends on surge duration and waveform (e.g., 8/20µs pulse). Choose based on expected surge energy (e.g., 100J for small appliances, 1000J+ for industrial use).
- **Peak Pulse Current (I_TM):** The maximum surge current the MOV can handle for a specified duration (e.g., 8/20µs or 10/1000µs waveform). Must exceed the anticipated peak current (e.g., 10kA for lightning protection).
- **Response Time:** The time taken for the MOV to transition from a high-resistance to a low-resistance state (typically <25ns). Critical for fast transients like ESD or switching surges.

MOV Specifications - 2

- **Operating Temperature Range:** The temperature range over which the MOV maintains performance (e.g., -40°C to +85°C). Select based on the environmental conditions of the application.
- **Capacitance:** The parasitic capacitance of the MOV (e.g., 100pF to 5000pF), which can affect high-frequency circuits. Lower capacitance is preferred for data lines or RF applications.
- **Disc Diameter and Size:** Physical size (e.g., 7mm, 14mm, 20mm) impacts energy handling and current capacity. Larger discs handle higher surges but require more space.
- **Leakage Current:** The small current that flows through the MOV at normal operating voltage (e.g., <1μA). Lower leakage is better to avoid power loss or heating.
- **End-of-Life Degradation:** Indicates how the MOV's performance degrades after multiple surge events. Check manufacturer data for lifetime ratings (e.g., number of surges at a given energy level).
- **Standards Compliance:** Ensure the MOV meets relevant standards (e.g., UL 1449 for surge protective devices, IEC 61000-4-5 for surge immunity) for safety and reliability.

What is Power line Surge and what causes it

In AC power supply lines, a temporary increase in the supply voltage is called as "Surge".

Surges are caused by switching events and insulation faults in AC power distribution networks and also by the switching of reactive loads such as motors or power factor capacitor banks.

When a line fault occurs, the short circuit can be huge causing the circuit breaker or fuse to open the circuit. When the protective device opens the circuit, the high current together with line inductance causes a very high flyback voltage as surge.

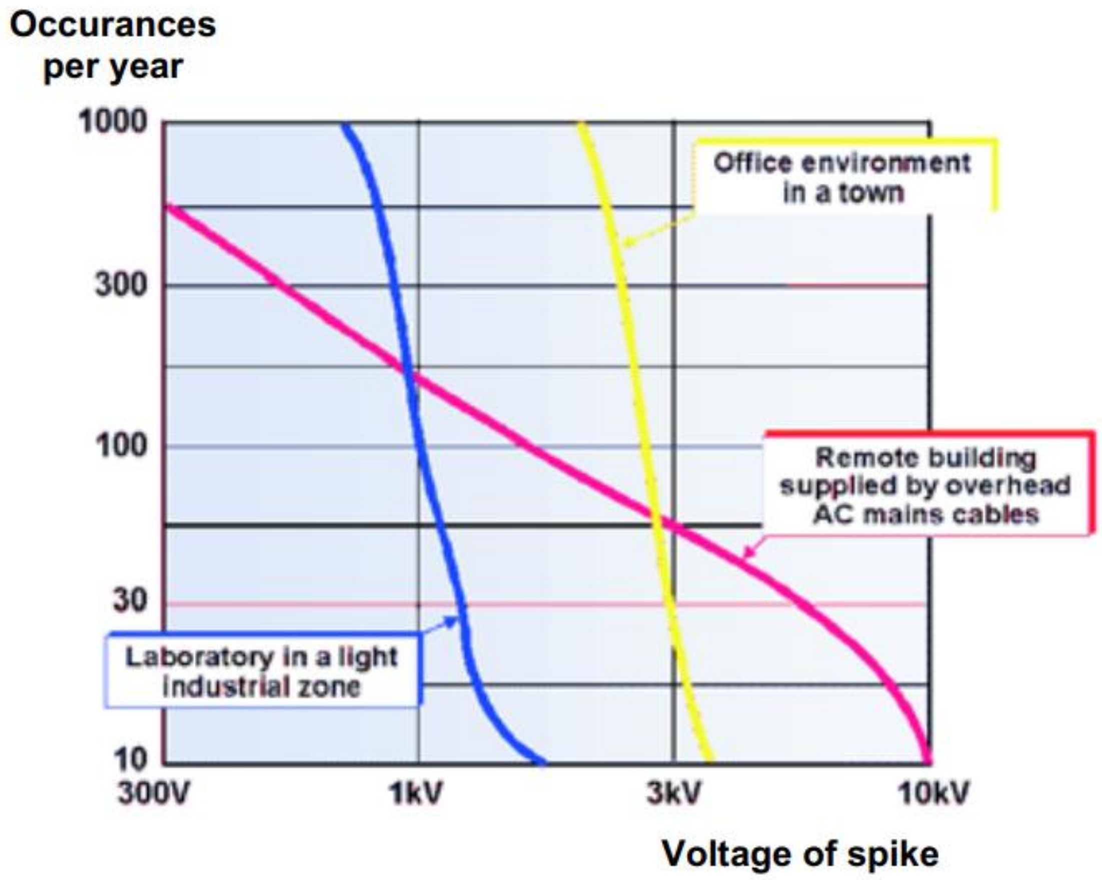
Surges are also created by lightning. Surge test standards such as ISO / EN 61000-4-5 only address the indirect effects of lightning which is due to the induction of voltages and currents or earth potential lift due to the impedance of earthing structure.

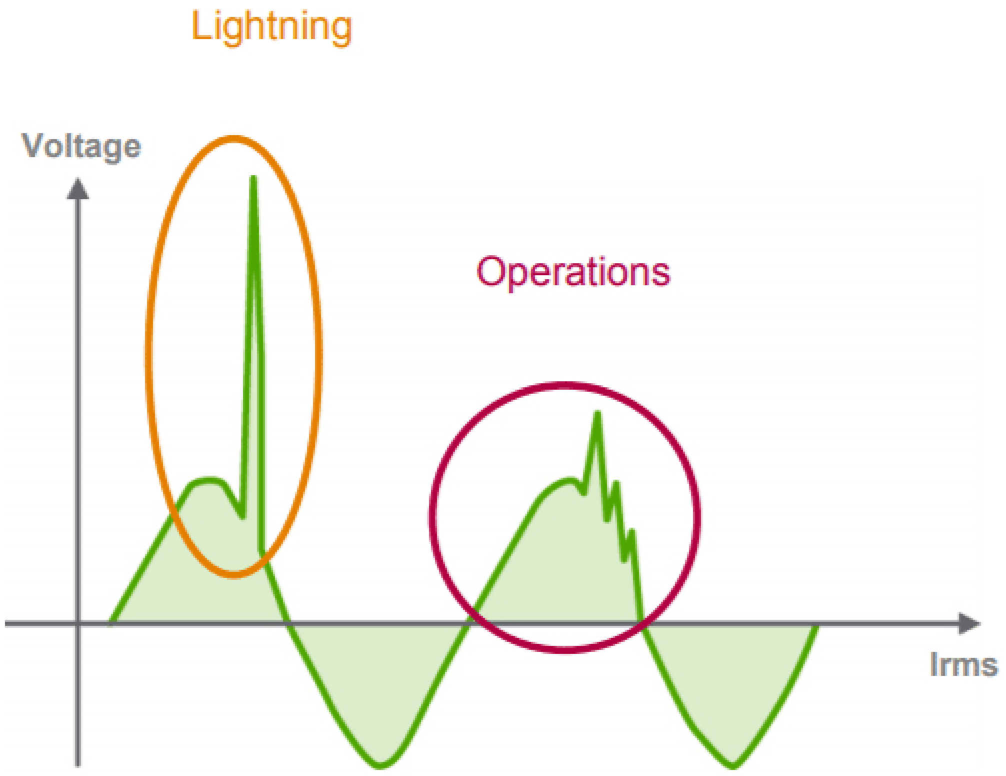
This high voltage surge can be destructive to electronic components used in consumer, Industrial equipments.

Similar surge events also happen in automotive applications (ICE Engines)due to a phenomenon called "Load dump".

Courtesy: https://cherryclough.com/media/file/REO%20Guidebooks/61000-4-5_immunity%20to%20surges.pdf

Surge magnitude and occurrences per year





Courtesy: https://cherryclough.com/media/file/REO%20Guidebooks/61000-4-5_immunity%20to%20surges.pdf

Surge protection compliance testing

Every electronic product needs to have necessary protection components to protect the equipment from surge.

To test and certify the equipment is passing the surge tests, the EMC standard ISO 61000-4-5 defines the surge voltage, current level and waveforms.

Equipment suppliers must get their equipment certified as per this standard from certified agencies like TUV.

One of the compliance test service provider in India and worldwide
Product Testing Service | TUV India

https://emcfastpass.com/wp-content/uploads/2017/04/surge_overview.pdf

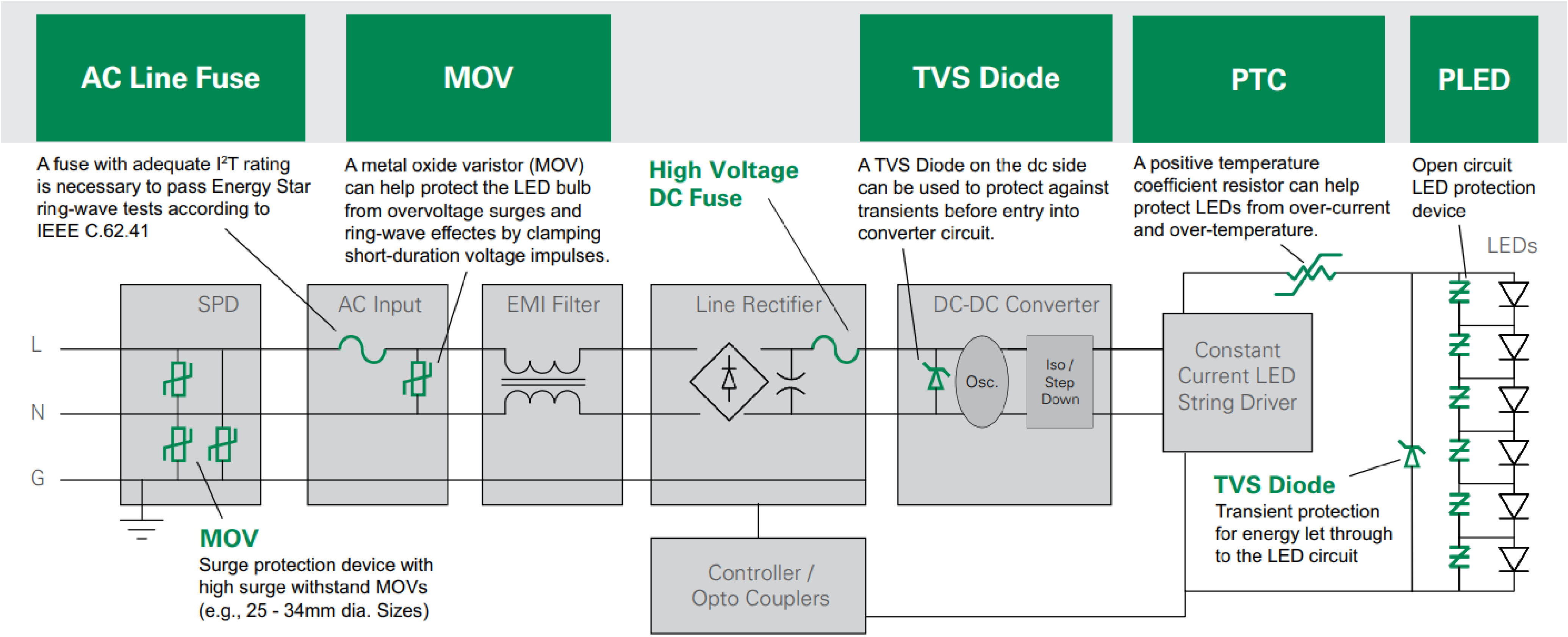
How to select Varistor for power line surge

To learn more about how to select the surge protection Varistor for a given mains operating voltage and surge level, check out these documents

Wurth Electronik : ANP015 | 1-Phase Line Filter Design

Littelfuse: LED Design Guide

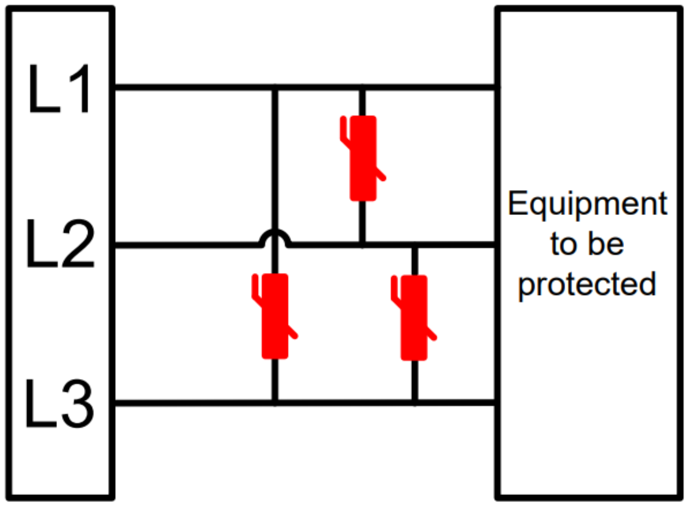
Surge protection for an Outdoor LED Luminaire

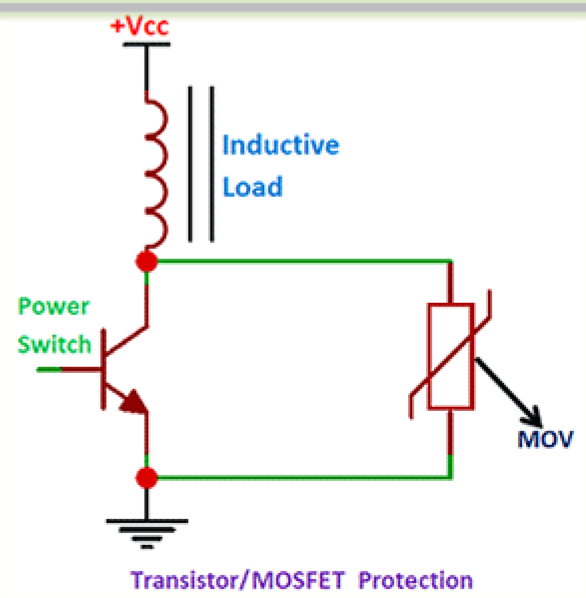


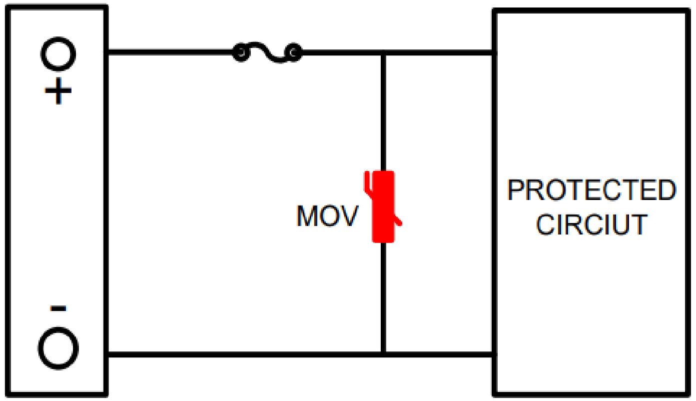
LED Street lamps are highly prone to failure due to high voltage surges induces due to Lightning and hence needs sufficient level of surge protection. MOVs are commonly used for the surge protection device.

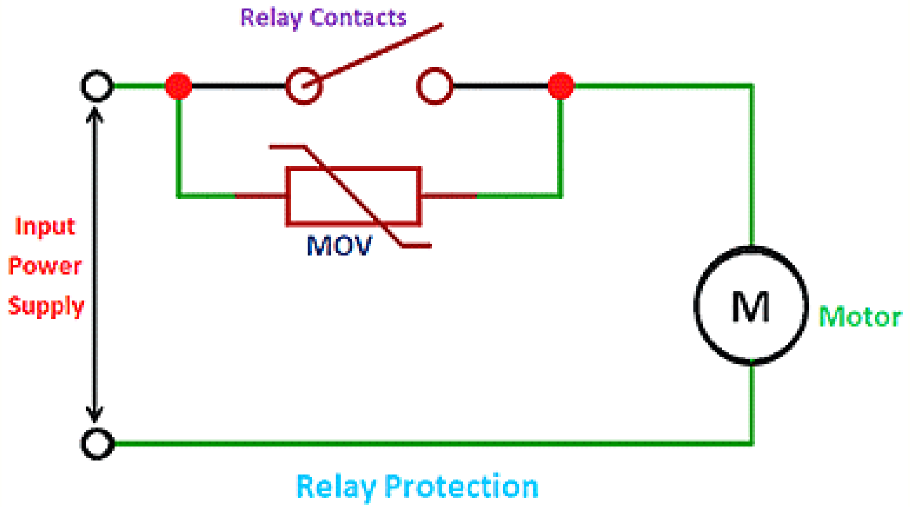
[Courtesy: https://electronicscatalogs.littelfuse.com/led/data/lid15flx/011/html/export.pdf](https://electronicscatalogs.littelfuse.com/led/data/lid15flx/011/html/export.pdf)

Example applications of MOV





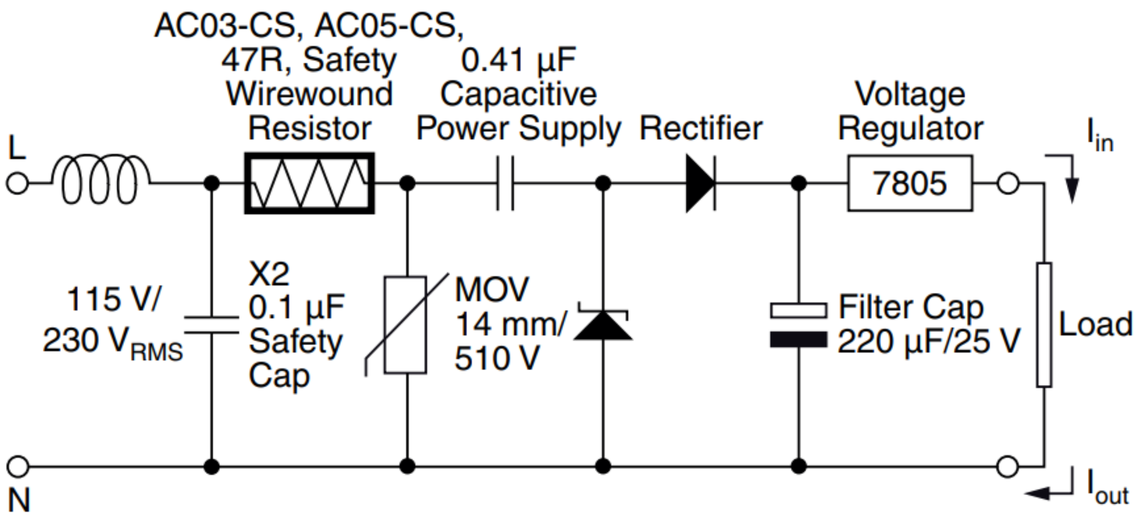




Combining Pulse withstanding Resistors and Varistors

Combining a pulse withstanding resistor along with Varistor helps in reducing the power rating and hence the size of MOV, as the pulse withstanding resistor can dissipate a significant portion of the surge energy, thereby increasing the number of safe operation of Varistor

Capacitive Power Supply for 1-Phase Energy Meter with AC03-CS, AC05-CS Safety Wirewound Resistor



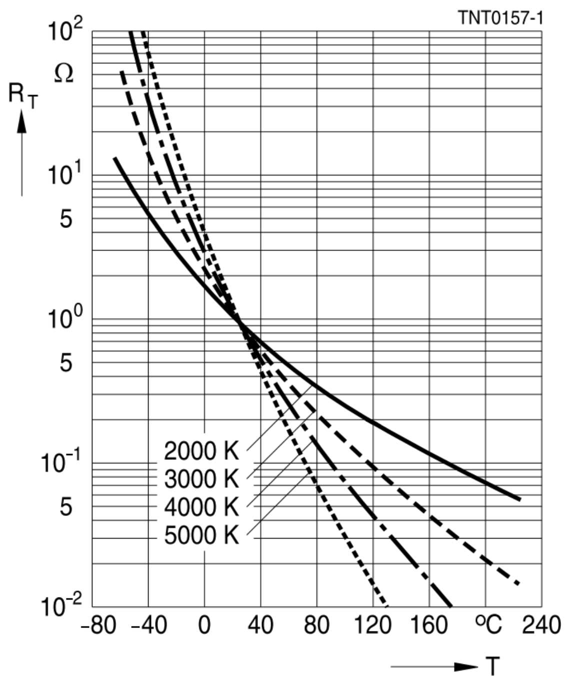
Courtesy: https://www.vishay.com/docs/28897/ac0xcsenrgymet.pdf

Back to content List

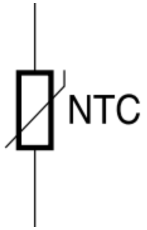
NTC Thermistors (Temperature sensors)

NTC Thermistors

- NTC Thermistor is a temperature-sensitive resistor with a negative temperature coefficient.
- Made from ceramic materials like manganese, nickel, and cobalt oxides, exhibiting decreased resistance as temperature rises.
- Operates based on the exponential relationship between resistance and temperature (R ∝ e^(β/T)).Offers high sensitivity and accuracy for temperature measurement and compensation.
- Widely used in circuits to detect, monitor, or stabilize temperature variations.



Resistance/temperature characteristics (parameter: B value)



$$R_T = R_R \cdot e^{B \cdot \left(\frac{1}{T} - \frac{1}{T_R}\right)}$$

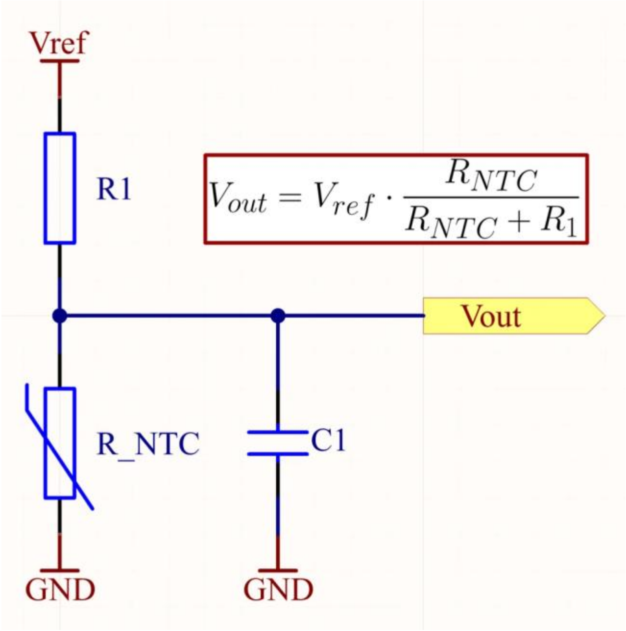
R_T	NTC resistance in Ω at temperature T in K
R_R	NTC resistance in Ω at rated temperature T_R in K
T	Temperature in K
T_R	Rated temperature in K
B	B value in K, material-specific constant of NTC thermistor
e	Euler number (e = 2.71828)

https://www.tdk-electronics.tdk.com/download/531116/19643b7ea798d7c4670141a88cd993f9/pdf-general-technical-information.pdf

Specifications of Thermistors

Parameter	Definition
Resistance Tolerance	Deviation range from nominal resistance at 25 °C (e.g., ±1%, ±3%, ±5%). Lower the better
B Value (B Term)	Defines temperature-resistance relationship, measured between two temps (e.g., 3435 K for 25/85 °C).
B Value Tolerance	Accuracy of the B value, typically ±1% to ±3%. Lower the better.
Max. Electric Power (at 25 °C)	Maximum power the thermistor can handle continuously at 25 °C (e.g., 100 mW)
Thermal Dissipation Constant	Power required to raise thermistor temperature by 1 °C (e.g., 1 mW/°C). Higher the better.

Errors in NTC Measurement



Below are the areas and specs that introduces error in temperature measurement using NTCs.

- NTC 's Resistance Tolerance, B-Term Tolerance. Thermal Dissipation Constant just in case more current passes through NTC.
- Initial Tolerance of the NTC Bias resistor (R1) and it's temperature coefficient of resistance in PPM
- Initial Tolerance of the Vref and it's temperature coefficient of change in PPM
- Error due to ADC specifications
- Error due to low input impedance of the ADC. This can be mitigated by using capacitor C1 as 0.1~1uF

Applications of NTC Thermistors

- **Temperature Sensing:** Monitors and controls temperatures in HVAC systems and thermostats.
- **Automotive:** Measures coolant or air temperature in engines and climate control units.
- **Medical Devices:** Ensures precise temperature regulation in incubators and patient monitoring equipment.
- **Consumer Electronics:** Protects batteries and circuits by detecting over-temperature conditions in smartphones and laptops.
- **Inrush Protection in SMPS Inputs:** Limits initial current surge in switched-mode power supplies during startup, preventing damage to components.

Thermistors Vs RTDs

Parameters	NTC Thermistors	PTC Thermistors	RTDs
Temperature Range	-80°C to +300°C	60°C to 120°C	-200°C to +850°C
Temperature Coefficient	Negative	Positive	Positive
Linearity	Exponential	Exponential	Near linear
Sensitivity	High	High	Low
Response Time	Fast	Fast	Slow
Excitation	Required	Required	Required
Self-Heating	Yes	Yes	Yes
Wiring Configuration	2-wire	2-wire	2-wire, 3-wire, 4-wire
Cost	Inexpensive to moderate	Inexpensive	Moderate to expensive
Size	Small	Small	Medium

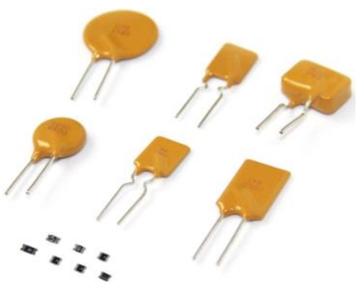
https://www.analog.com/en/resources/analog-dialogue/articles/thermistor-temperature-sensing-system-part-1.html
https://www.analog.com/en/resources/analog-dialogue/articles/thermistor-temperature-sensing-system-part-2.html

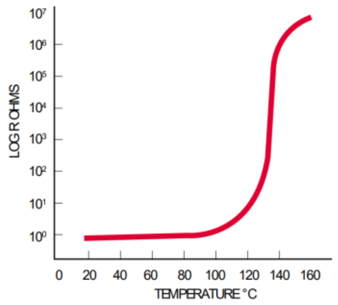
Back to content List

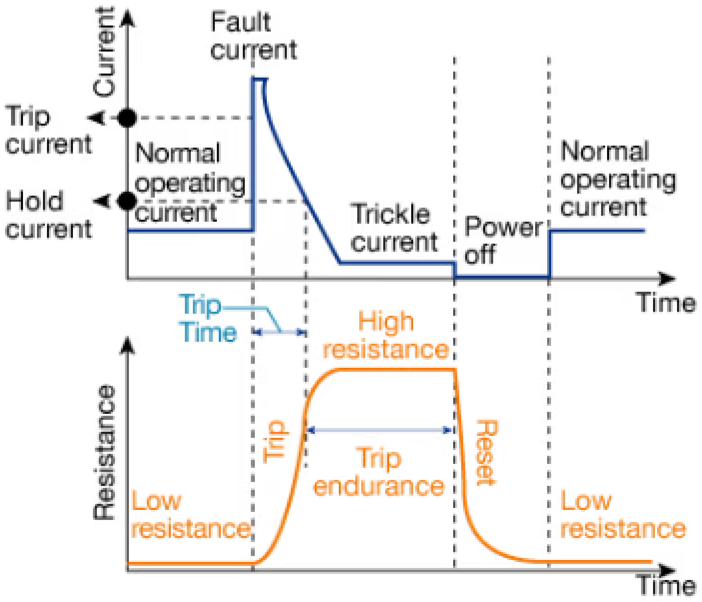
PTC (Resettable Fuse)

PTC Resettable Fuse (PPTC)

- A resettable fuse is a device that protects electronic circuits from damage caused by overcurrent conditions, overloads, overheating, or short circuits.
- There are two types of resettable fuses: traditional radial lead and SMD chip packages.
- Resettable fuse material has a **Positive Temperature Coefficient (PTC)**, which means that a rise in temperature is followed by an increase in resistance. When a rise in temperature occurs due to an overcurrent or similar fault state, resistance in the fuse increases, reducing the current.
- Once the fault is rectified, the PTC's core cools and contracts, allowing the current to flow normally. This ability to reset itself after fault removal, differentiates a resettable fuse from a regular fuse, which must be replaced after a fault condition.







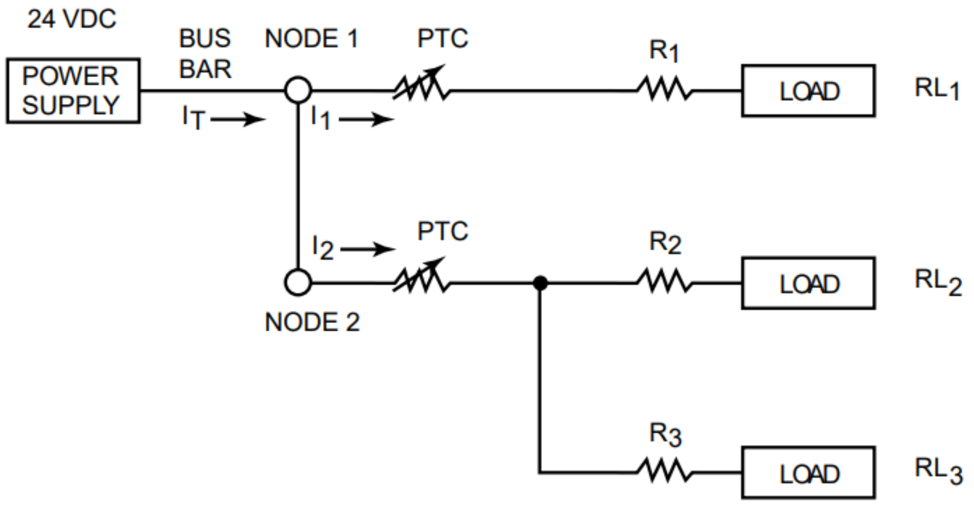
[Courtesy: https://community.element14.com/technologies/experts/b/comprehensive-guides/posts/a-comprehensive-guide-to-resettable-fuses](https://community.element14.com/technologies/experts/b/comprehensive-guides/posts/a-comprehensive-guide-to-resettable-fuses)

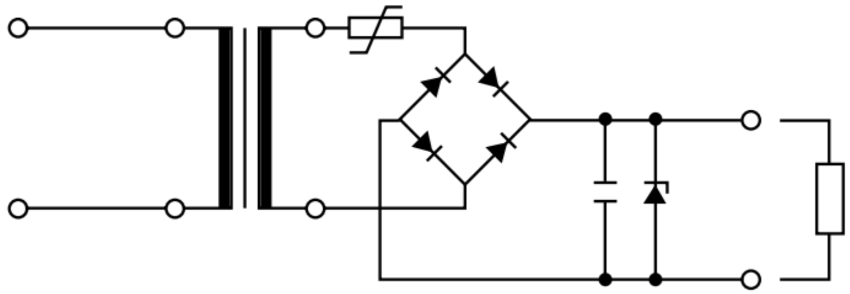
PTC Specifications

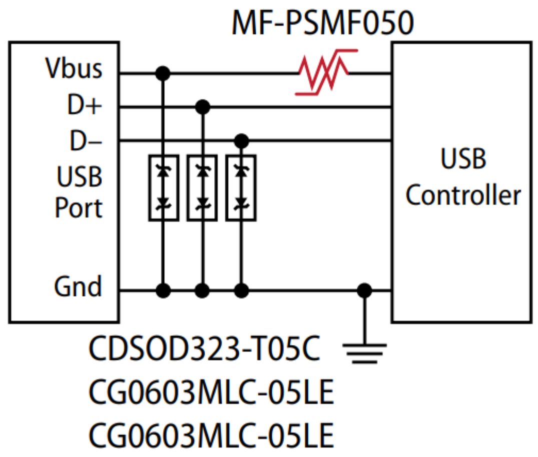
- **Holding Current:** the maximum amount of current a resettable fuse can tolerate before tripping and transitioning from a low-resistance state to a high-resistance state. The fuse's holding current higher than the maximum amount of electricity in a circuit, so that it doesn't trip during normal operation.
- **Trip Current:** the amount of current that will trip the fuse and open the circuit. Resettable fuses have a higher trip current than traditional fuses, and they are designed to trip quickly in response to overcurrent conditions. The trip current generally surpasses the holding current.
- **Rated Voltage:** the maximum voltage a fuse can safely operate without breaking down. The selected fuse's voltage rating must match or exceed the circuit voltage being used.
- **Maximum Current:** the largest amount of electricity that can pass through the fuse which would cause it to overheat, possibly causing damage. The maximum current rating is typically specified by the thermistor manufacturer and is based on the thermistor's size, materials, and design.
- **Max Time to Trip (MTT):** the maximum amount of time it takes for the device to switch from a low-resistance state to a high-resistance state when a fault current occurs. The time-to-trip of a PPTC device is defined as the time required to trip the device starting at the onset of a fault current. The time is dependent on the magnitude and duration of the fault current and the ambient temperature.
- **Typical Power:** the amount of power typically dissipated by the fuse when in tripped state, in a 23°C still air environment.

Courtesy: https://community.element14.com/technologies/experts/b/comprehensive-guides/posts/a-comprehensive-guide-to-resettable-fuses

PTC - few Application examples







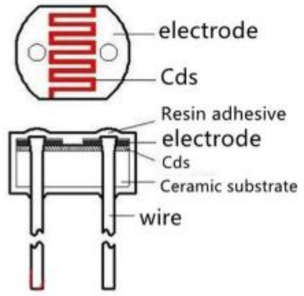
Courtesy: https://www.bourns.com/pdfs/mfsolgd.pdf

Back to content List

Light Dependent Resistor (LDR)

Light Dependent Resistor (LDR)

- ◆ **LDR:** Also known as a photoresistor. A passive component whose resistance decreases as light intensity increases. Made from photoconductive materials like cadmium sulfide (CdS)



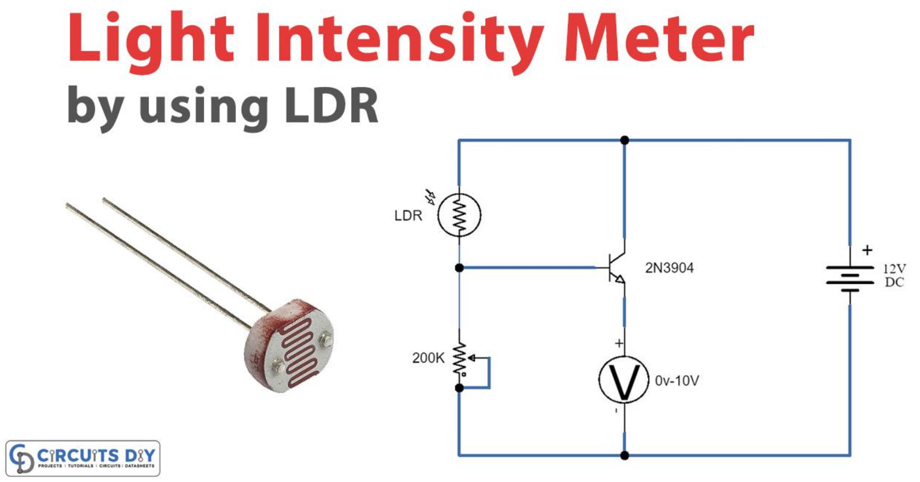
- ◆ Key Specifications of LDRs

Specification	**Description**
Dark Resistance	Resistance in **complete darkness** (can be >1 MΩ)
Light Resistance	Resistance under bright light (typically **few hundred ohms**)
Spectral Response	Most sensitive to **visible light (≈550–600 nm)**
Response Time	Time to react to changes in light (~**tens to hundreds of ms**)
Max Voltage	Maximum allowed across the device (commonly **100–200 V**)
Temperature Coefficient	Resistance varies with temperature as well as light

- ◆ Typical applications of LDRs: Automatic night lights; Light/dark detectors; Solar garden lights; Alarm systems; Display brightness control

Courtesy: https://community.element14.com/technologies/experts/b/comprehensive-guides/posts/a-comprehensive-guide-to-resettable-fuses

Example applications using LDR



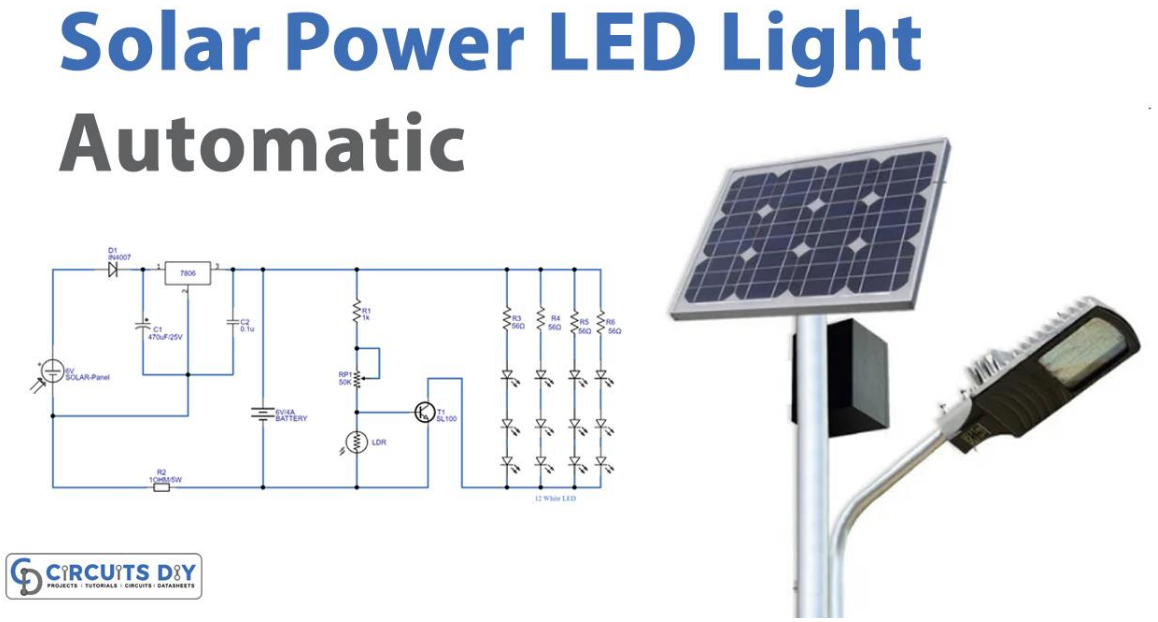


Image Courtesy: https://www.circuits-diy.com/light-intensity-meter-using-ldr/#google_vignette
Image Courtesy: https://www.circuits-diy.com/automatic-solar-power-led-light-circuit/#google_vignette

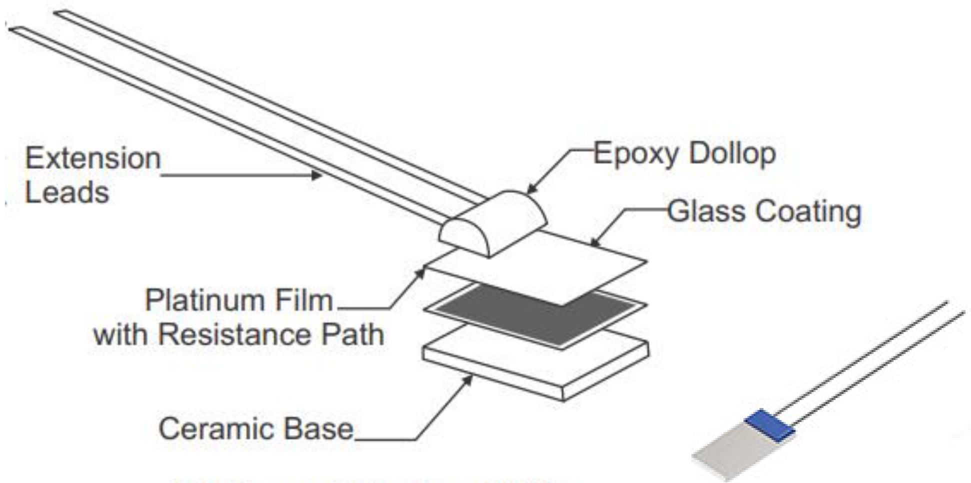
Back to content List

Resistance Temperature Detector (RTD - Temperature Sensor)

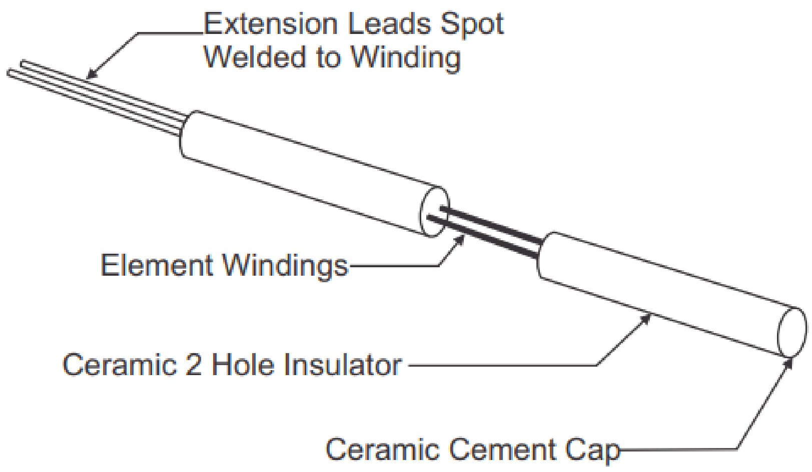
Resistance Temperature Detector (RTD)

What is an RTD?

An RTD is a temperature sensor that operates on the principle that the electrical resistance of certain metals (e.g., platinum, nickel, copper) changes predictably with temperature. Platinum RTDs (e.g., PT100, PT1000) are the most common due to their linearity, stability, and wide temperature range.



Platinum thin film RTD



Inner coil wire wound RTD

Image Courtesy: https://tempsens.com/wp-content/uploads/2024/12/Tempsens-Handbook-2025.pdf

RTD – Principle of operation

- RTDs rely on the temperature coefficient of resistance (TCR), where resistance increases nearly linearly with temperature for metals.
- The relationship is described by the equation:

$$R_t = R_0[1 + \alpha(T - T_0)]$$

  where:
  - R_t: Resistance at temperature T
  - R_0: Resistance at reference temperature T_0 (usually 0°C)
  - α: Temperature coefficient of resistivity (e.g., 0.00385/°C for platinum PT100)
  - T: Temperature being measured
- Platinum RTDs follow standards like IEC 60751, which defines the resistance-temperature relationship.

Temperature Range:

Wide operating range, typically -200°C to +850°C for platinum RTDs, though practical limits depend on construction (e.g., -50°C to +500°C for common industrial RTDs).

Nickel and copper RTDs have narrower ranges (e.g., -80°C to +260°C for nickel).

RTD – Accuracy and Linearity

Accuracy and Precision:

- RTDs offer high accuracy, typically ±0.1°C to ±0.5°C, depending on the class (e.g., Class A, Class B per IEC 60751).
- High repeatability and long-term stability (e.g., drift <0.05°C/year for platinum RTDs).

Linearity:

- RTDs, especially platinum-based, exhibit near-linear resistance change over a wide temperature range, making them easier to interface with measurement systems compared to non-linear sensors like thermistors.
- Non-linearity is minimal but corrected using the Callendar-Van Dusen equation for high precision:
  $R_t = R_0[1 + AT + BT^2 + C(T - 100)T^3]$ (for $T < 0°C$).

Specifications of RTD - 1

Resistance Value:

- Common nominal resistances at 0°C:
  - PT100: 100 Ω
  - PT1000: 1000 Ω
  - Nickel RTDs: 100 Ω or 500 Ω
  - Copper RTDs: 10 Ω or 100 Ω
- The resistance value determines the sensitivity (e.g., PT100 changes ~0.385 Ω/°C).

Temperature Coefficient of Resistance (TCR):

- Platinum: ~0.00385/°C (IEC 60751 standard for PT100/PT1000).
- Nickel: ~0.00618/°C.
- Copper: ~0.00428/°C.
- Higher TCR means greater resistance change per degree, improving sensitivity.

Specifications of RTD - 2

Accuracy Classes (IEC 60751 for Platinum RTDs):
- **Class AA**: ±(0.1 + 0.0017|T|)°C (highest accuracy, e.g., ±0.1°C at 0°C).
- **Class A**: ±(0.15 + 0.002|T|)°C.
- **Class B**: ±(0.3 + 0.005|T|)°C (most common).
- **Class 1/10 DIN**: ±0.03°C at 0°C (ultra-precision).

Construction Types:
- **Wire-Wound RTDs**:
  - Platinum wire wound around a ceramic or glass core.
  - High accuracy, suitable for wide temperature ranges (-200°C to +850°C).
  - Slower response, more robust for high-vibration environments.
- **Thin-Film RTDs**:
  - Platinum film deposited on a ceramic substrate.
  - Compact, faster response, cost-effective.
  - Common in industrial and automotive applications (up to ~500°C).

RTD Connection configurations

Connection Configurations:

2-Wire: Simple but lead resistance affects accuracy; used in low-precision applications.

3-Wire: Compensates for lead resistance; most common in industrial applications.

4-Wire: Highest accuracy, eliminates lead resistance; used in precision lab measurements.

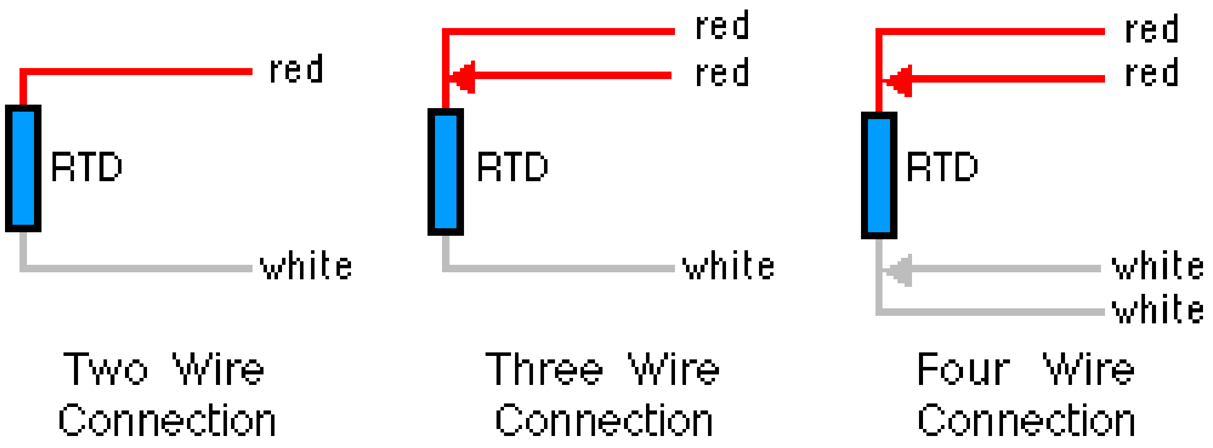


Image Courtesy: https://instrumentationtools.com/difference-between-2-3-and-4-wire-rtds/

Back to content List

Weblinks for Resistor Datasheet, Application Notes

Resistor datasheets

- Resistors have the datasheet. It is a must to read, understand each specification and the characteristics data curves for a reliable circuit design.
- https://www.digikey.in/en/products/category/resistors/2
- https://www.digikey.in/en/products/category/potentiometers-variable-resistors/5
- https://www.mouser.in/c/passive-components/resistors/
- https://www.mouser.in/c/rf-wireless/rf-resistors/
- https://www.vishay.com/en/resistors-fixed/
- https://www.vishay.com/en/trimmers/
- https://www.vishay.com/en/potentiometers/
- https://m.samsungsem.com/resources/file/global/support/product_catalog/Chip_Resistor.pdf

Resistor Application notes

- Vishay, Resistors 101 : https://www.vishay.com/docs/49873/49873_sg2113.pdf
- Vishay, Basics of Linear Fixed Resistors: https://www.vishay.com/docs/28771/basics.pdf
- Bourns, Pulse Withstanding Resistors : https://www.bourns.com/docs/technical-documents/technical-library/fixed-resistors/application-notes/bourns_high_pulse_resistor_appnote.pdf?
- Vishay, Resistors in pulse load applications: https://www.vishay.com/docs/48516/_ms9702509-2401-vishaychecklistpulseload.pdf
- Vishay, Safety fusible resistors: https://www.vishay.com/docs/28897/ac0xcsenrgymet.pdf

Back to content List