ISTANBUL COMMERCE UNIVERSITY

Electrical-Electronics Engineering
EEE202 Electro-technic Laboratory

Theory

Part 1

Contents

List of Figures

1 DEFINITIONS

1.1 Atom

The smallest component of an element having the chemical properties of the element. Its structure is like in the following Figure 1.

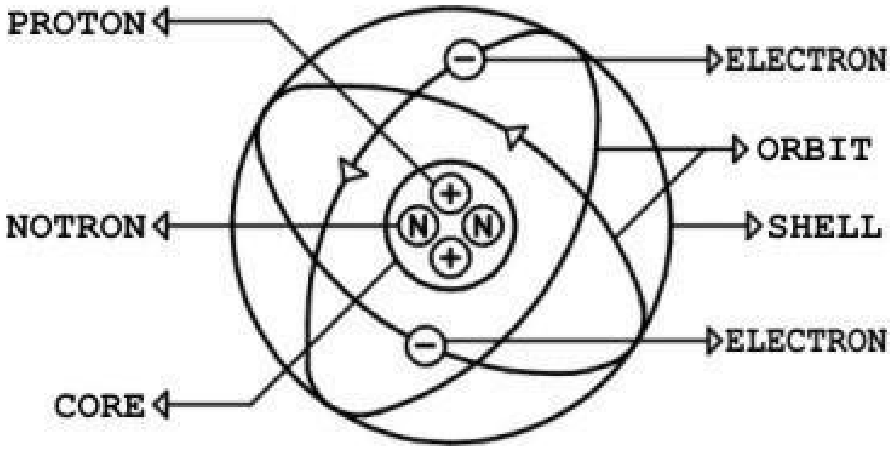


Figure 1: Model of atom.

The number of positive charges (protons) is equal to the negative charges (electron) in the core of an atom. Atom is electrically not charged (neutral). Because positive and negative charges are equal for every atom. The core and the shell are positioned like spheres with the same center but with different diameters. There may be more than one shell in an atom. Electrons turn around the core in their own orbit. Shells are imaginary spheres on which the orbits of the electrons are positioned. The electron that is on the most outer shell of an atom is called "free electron" or "valance electron". Free electrons can pass through one atom to another easily. This process is called electron flow.

1.2 Electric

It is a type of energy. Electrical energy is generated by two different points having different number of electrons in any condition. The number of electrons that a point has is called the electrical charge or the electrical potential of that point. The thunderbolt which comes into being between the earth and the clouds can be given as an example to electrical energy.

1.2.1 Coulomb

The unit showing the number of electrons. $1\,\text{Coulomb} = 625 \times 10^{16}\,\text{Electrons}$.

1.3 Electric Current

It is the flow of electron between two different points. "Amper" is its unit. Amper is the speed of the flow of 1 coulomb electrons in 1 second between any two different points. The point that has more electrons is electrically negative. The point to where the electrons move is positive. Those points are called "poles". So, the electron flow is from negative to positive. Electric current is just the flow of electrons. The direction of the electric current is assumed as from positive to negative (opposite to the direction of electron flow) in order to avoid showing negative sign in mathematical operation. Measurement devices of electrics and electronics are produced in compliance with the direction of circuit.

1.3.1 Direct Current

The current of which the direction does not change. Direct current is symbolized by "DC". Some DC types are shown in Figure 2.

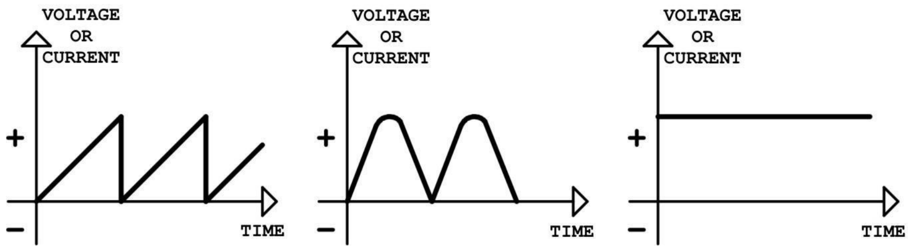


Figure 2: Direct current examples.

The change in the magnitude of voltage or current in the direct current supply does not affect the working of some electrical devices. However, direct current is required to be constant in electronic devices. The supplies in the direct current circuits are used as voltage supply, adjustable voltage supply, current supply or adjustable current supply. Output voltage of the adjustable voltage supply and the current that is given by the adjustable current supply can be adjusted. DC supply symbols are shown in Figure 3.

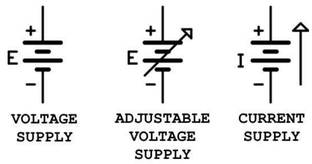


Figure 3: Direct Current supply symbols.

The units which the electric energy makes work is called load. In Figure 4, a load is connected to the terminals of a DC supply. During the work time, the direction of the current passing through the load does not change.

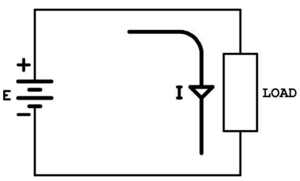


Figure 4: Simple circuit is supplied from DC source.

Also, the magnitude of DC does not change in the supplies that we use in daily life. DC is generally generated by using chemical ways. For example, batteries or accumulators.

1.3.2 Alternate Current

Electrical current which periodically reverses direction and magnitude. It is symbolized by "AC" (Alternating Current). Pendulum swing is an example of periodical move. Pendulum swing is from the midpoint and at equal distance to both sides. Half of the pendulum move is called "Alternation". A complete move of the pendulum consisting of two alternations is called a "period." A period is shown in Figure 5.

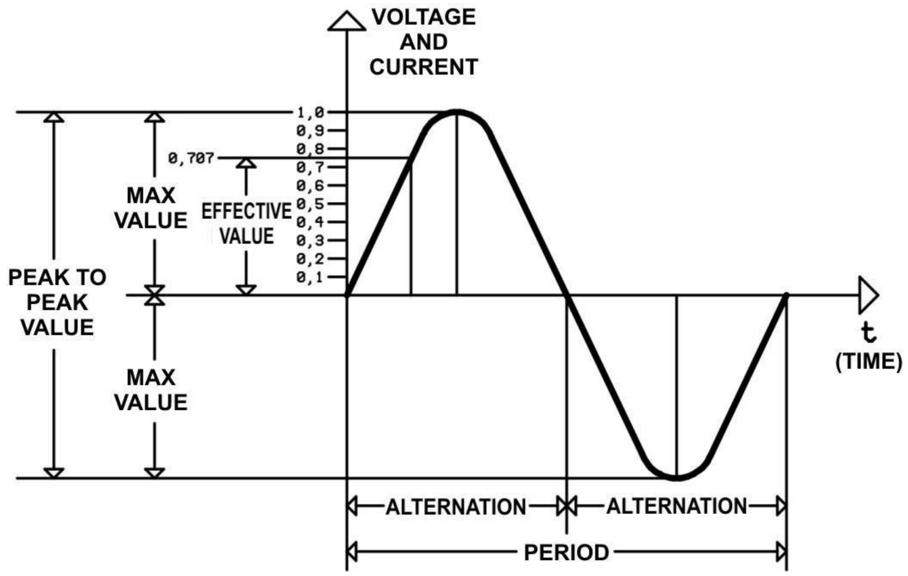


Figure 5: Parameters of Alternate Current is shown.

City network, generators are the sources of alternating current. Magnitude of the alternating current also varies during the work time. The magnitude of AC at any moment is called "instantaneous value." Instantaneous value is shown by "e" for voltage and by "i" for current. Measurement devices measure the effective value of the AC. Effective value is also called RMS (Root-Mean-Square). Effective value is the one we use in daily life. Effective value is shown by "E" for voltage and by "I" for current. The maximum value of an alternation is called "maximum value." Maximum value appears twice in a period: one in negative alternation and one in positive alternation. Maximum value is shown by E_{max} for voltage and by I_{max} for current. In the experiments of this book, mostly, the oscilloscope will be used. Oscilloscopes are the devices by which we can see and measure the electrical wave forms. "Peak to peak value" is the AC value which is the easiest one to measure by oscilloscope. Peak to peak value is the sum of two maximum values in a period. It is shown by E_{pp} for voltage and by I_{pp} for current. *pp* means peak to peak. Commonly used values for AC is shown in Figure 5.

The number of period in a second is called "frequency." Its unit is Hertz (Hz). Commonly used values of frequency are the Kilohertz (KHz) and Megahertz (MHz). Mathematical relations of these units are shown in Figure 6.

UPPER MULTIPLES	(MHz) MEGAHERTZ	1M= 1000 000 Hz
	(KHz) KILOHERTZ	1KHz= 1000 Hz
MAIN UNIT	(Hz) HERTZ	
LOWER MULTIPLES		

Figure 6: Mathematical relations of unit Hertz.

AC supplies are used as voltage and current sources. Ac supply symbols are shown in Figure 7.

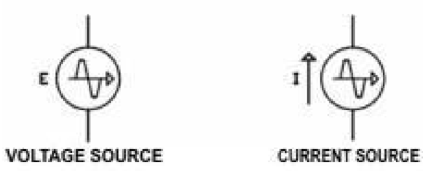


Figure 7: Alternate Current Source Symbols.

In Figure 8, a load is connected to the terminals of an AC supply. The direction of the current passing through the load varies during the work time depending on the change of the supply poles.

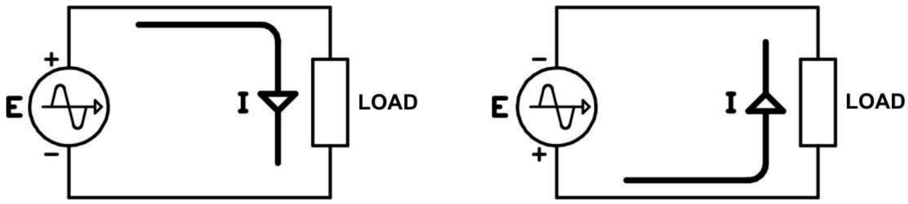


Figure 8: Simple circuits are supplied with AC sources.

AC is the electrical energy which is used in domestic electrical and electronical devices, industry and almost in every aspect of life. AC can be converted to DC by basic methods. Supply is also called “generator”.

1.4 Electric Voltage

Voltage is a representation of the electric potential energy per unit charge. It is shown by “E” and its unit is “Volt”.

1.5 Electric Materials

1.5.1 Conductor

The materials that allow electric current to pass through. Gold, silver and copper are good conductors.

1.5.2 Non-Conductor

The materials that does not allow electric current to pass through. Air, plastic and mica are non-conductors.

1.5.3 Semiconductor

A semiconductor is a solid whose electrical conductivity can be controlled over a wide range, either permanently or dynamically. Semiconductors are tremendously important.

1.6 Passive Components

Component of a circuit should be learned well in order to accommodate electrical circuits. Circuit arrangements and fault determination processes will be eased if the structures and properties of components are learned well. The component which doesn't do amplification is called "passive circuit components". Commonly used passive components are resistors, inductors and capacitors.

2 RESISTORS

The opposition presented to the electric current is called "resistance". Electric current is presented a small opposition while passing through the conductors. The resistors in electric circuits are produced in order to present opposition to the current. Main unit of the resistance is Ohm. Ohm is symbolized by (R) or (Ω). Upper multiples of Ohm is mostly used. Lower multiples are not commonly used. Upper and lower multiples of Ohm and the mathematical relation between them are shown in Figure 9.

UPPER MULTIPLES	(M) MEGA OHM	1M=1000 000 R
	(K) KILO OHM	1K=1000 R
MAIN UNIT	(R) OHM	
LOWER MULTIPLES	(m) MILI OHM	1000 m = 1R
	(μ) MIKCO OHM	1000 000 μ = 1R

Figure 9: Mathematical relations of unit Ohm.

Resistors are used to limit the current or adjust the voltage to a specific value in a point. Resistors are connected serial, parallel or mixed. Connection types will be explained later while the "Kirchhoff's Laws" are being examined.

There are three types of resistors depending on the material they are made of. These are carbon, metal film and wire-wound resistors. Carbon and metal film resistors are used in low current circuits while wire-wound resistors are used in high current circuits.

Resistors are divided into three according to the work they will do in the electric circuit. These are fixed resistors, adjustable resistors and thermistors.

2.1 Fixed Resistors

These are the resistors which are used to fix the voltage or current to a specific value at a specific point. Fixed resistor has two pins and they are connected to the circuit from the pins. Fixed resistor symbol is shown in Figure 10.

Figure 10: Fixed resistor symbol.

Devices produced with modern technology are very small in size. For these devices, small sized resistors are used. Those resistors consist of several very small resistors. There are serial or integrated resistors. In Figure 11, electrical connections of inner structures of serial and integrated resistors are shown. Pictures of commonly used fixed resistors are seen in Figure 12.

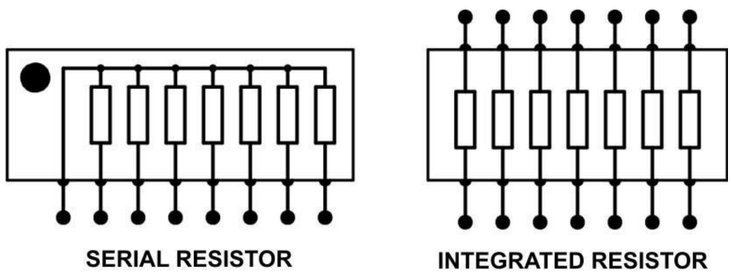


Figure 11: Some fixed resistors are shown according to inner structures.

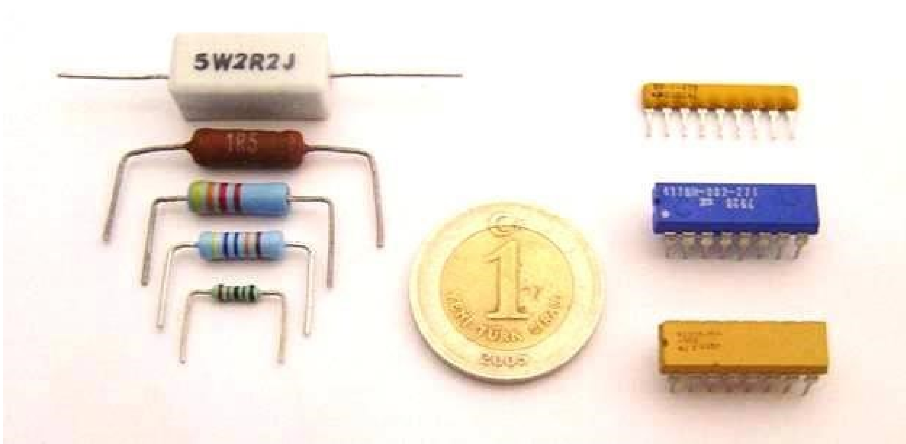


Figure 12: Commonly used resistors in real life are shown as example.

2.2 Adjustable Resistors

These are the resistors of which the value of resistance can be adjusted between zero and a specific value. In electric circuits, voltage or current at a specific point can be adjusted. Three types of adjustable resistors are produced: trimpots, potentiometers and rheostats.

2.2.1 Trimpots

These resistors are adjusted only once and placed in the inner structure of electrical device. Adjustment is made by the help of a screwdriver. Their mechanical structure is not suitable for multiple adjustments. Trimpots have three terminals: two terminals on the edge with fixed resistance and a moveable in the middle. The symbol and the structure of trimpot are shown in Figure 13.

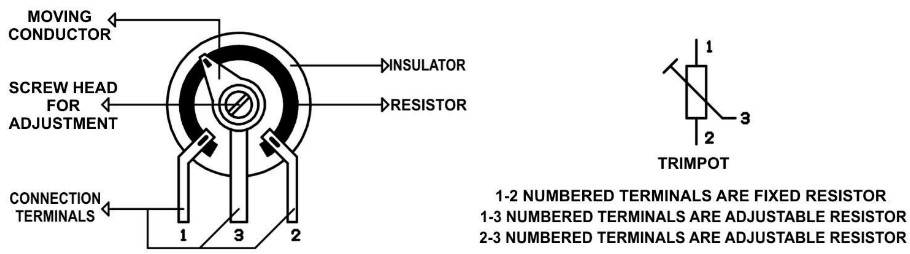


Figure 13: Inside and legs of trimpots are shown.

2.2.2 Potentiometers

These devices are the ones we can adjust any time during the work time. Adjustment shaft is connected to a button outside the device. The common example for the potentiometer is the adjustable resistor used for adjusting the sound of a radio. The structure of potentiometer is similar to the trimpot. The only difference is that potentiometer is lasting (strong) enough for multiple adjustments. They have also three terminals: two terminals on the edge with fixed resistance and a move-able in the middle. The resistors of commonly used standard trimpots and potentiometers are generally adjusted by rotating a shaft approximately 270^o. The adjustment process of these kinds of potentiometers and trimpots are completed at ten turn. The symbols of two types (slide-in and rotational types) of potentiometers are shown in Figure 14.

There are two types of relations between the rotating angle of mid-terminal and resistance presented. These are linear or logarithmic changes. If the resistance between the mid-terminal and edges changes linearly then it is a "linear potentiometer". If the shaft of a linear potentiometer is rotated until the mid-point of the rotating angle, the resistances between mid-terminal and each edge terminals are equal. If the resistance between the mid-terminal and edge terminals does not change linearly then it is a "logarithmic potentiometer". The resistance change percentages of logarithmic and linear potentiometers according to rotating angle are shown in Figure 15.

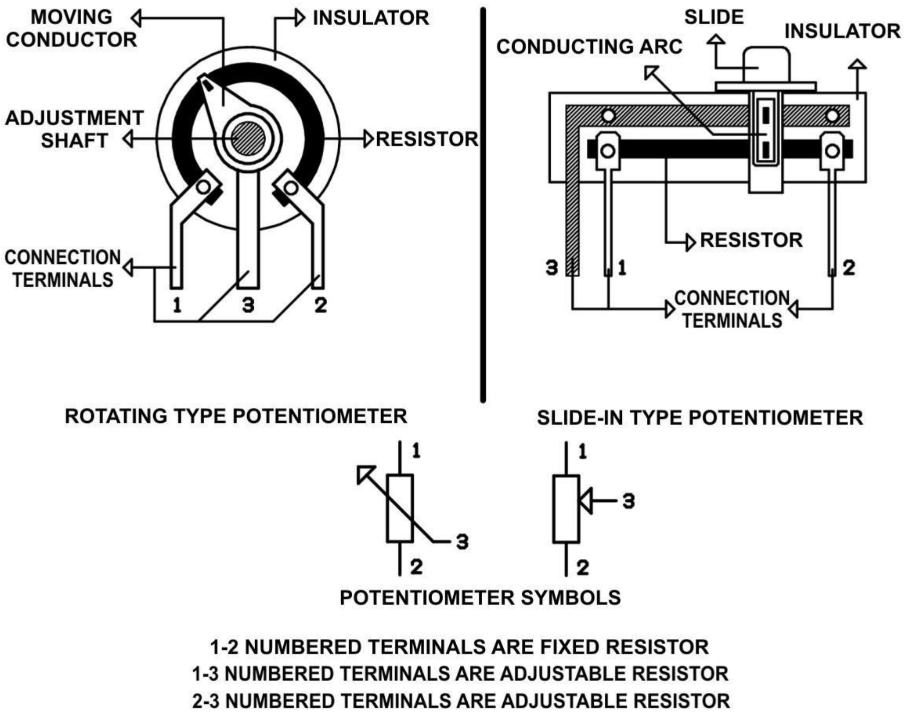


Figure 14: Inside and legs of potentiometer are shown.

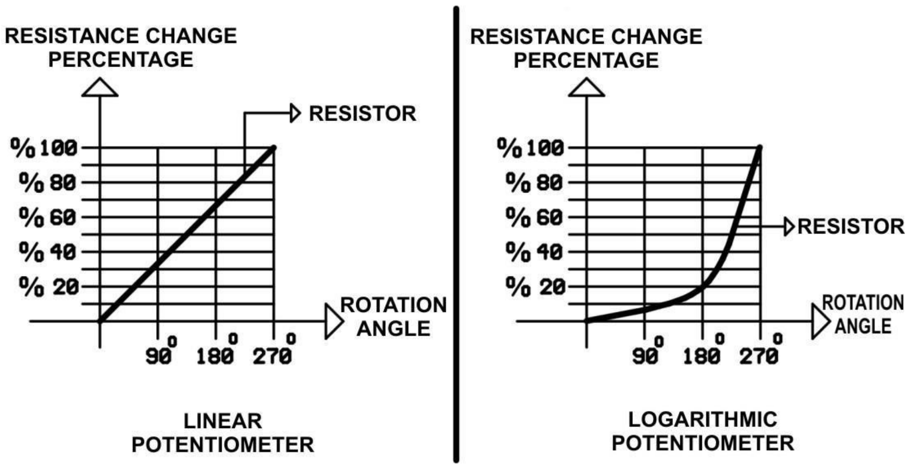


Figure 15: Resistance change percentage according to rotating angle.

Potentiometers should be chosen as suitable for the circuit properties. For example in sound amplifiers, sound level adjustment should be made with logarithmic potentiometers, while treble, bass and balance adjustments should be made by linear potentiometers. There are also twin potentiometers produced; they consist of two independent potentiometers sharing the same shaft or slide. These are called “stereo potentiometer”. Various types of trimpots and potentiometers are shown in Figure 16.

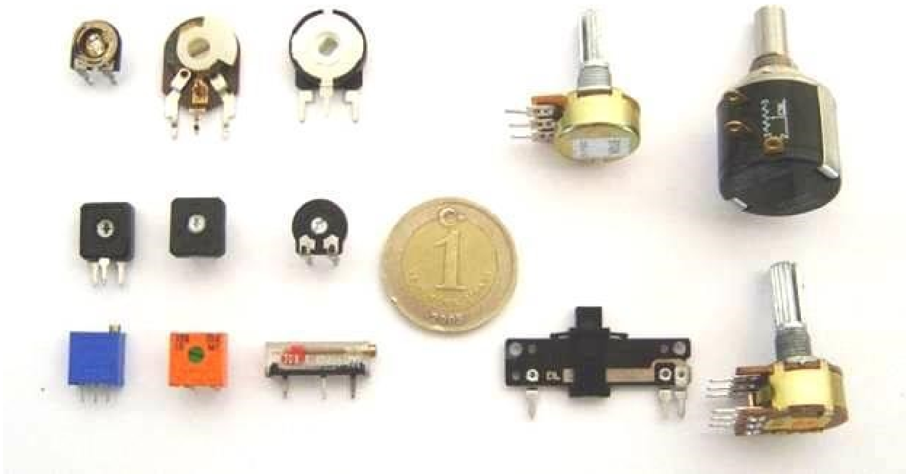


Figure 16: Commonly used trimpots and potentiometers in real life are shown as example.

2.2.3 Rheostat

The resistances made of chrome nickel wires to control high levels of current are called “rheostat”. Their structure and working principles are similar to potentiometers. Slide-in rheostats are commonly used in industry. The size of rheostats is far greater than potentiometers. Trimpots and potentiometers are used in electronical circuits while rheostats are used in electric circuits.

2.3 Thermistors

The production materials (carbon or metal) of resistors are affected from the environmental heat. Resistance of carbon changes inversely proportionate to the heat while resistance of metal changes directly proportionate to heat. This change is very small in the fixed and adjustable resistors. The change of resistance due to the environmental heat is far greater in resistors which are made of suitable metal oxides or metal crystals. These resistors are called “thermistors”. The resistances decreases or increases due to the effect of heat.

2.3.1 Negative Temperature Coefficient

Resistance of some metal oxides or metal crystals decreases if they are heated. Resistors with NTC are produced using this property. Symbol and heat-resistance change graphic of NTC is shown in Figure 17. The resistance of NTC at room temperature (18^oC - 20^oC) is called “cold resistance”. If a current passes through NTC, it behaves like carbon resistor. Due to the current passing through, it warms a little and its resistance decreases a little. With heating from outside, its resistance reaches greater values. Because of it’s this property, it is used as heat sensor.

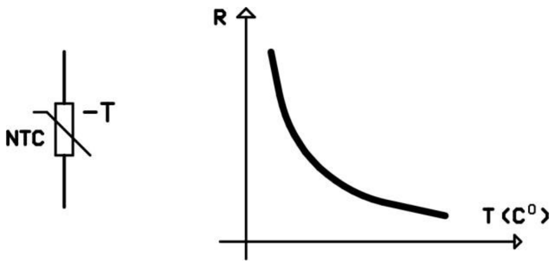


Figure 17: Symbol and heat resistance change graphic of NTC.

2.3.2 Positive Temperature Coefficient

Resistance of some metal oxides or some iron alloyed semiconductors increases if they are heated. Resistors with PTC are produced using this property. Symbol and heat-resistance change graphic of PTC is shown in Figure 18.

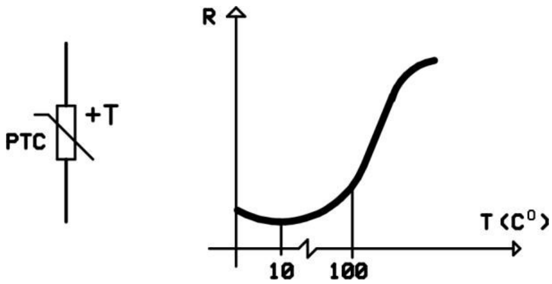


Figure 18: Symbol and heat resistance change graphic of PTC.

Initially, PTC behaves like NTC if it is heated starting from the low temperatures. At that moment, resistance decreases. Later, the resistance of PTC increases slowly until 100^{o}C and fatly after 100^{o}C. Because of it's this property, it is used as heat sensor. The resistance of NTC at room temperature (18^{o}C-20^{o}C) is called "cold resistance".

There are also some special resistors of which resistance decreases due to the light of environment.

2.3.3 Light Dependent Resistor

LDR is the circuit component of which resistance decreases under light. It is made of a semiconductor and covered with glass or transparent plastic. They are usually made of cadmium sulphide, cadmium selenite or lead sulphide. Conductance of LDR increases under light. So, the resistance decreases due to the increase of conductance. The symbol of LDR is shown in Figure 19. Resistances of LDR under light and in dark changes depending on the production material. There are LDR's produced to have 200 MOhm of resistance under complete darkness and 100 Ohm (or below) of resistance under complete light.

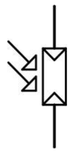
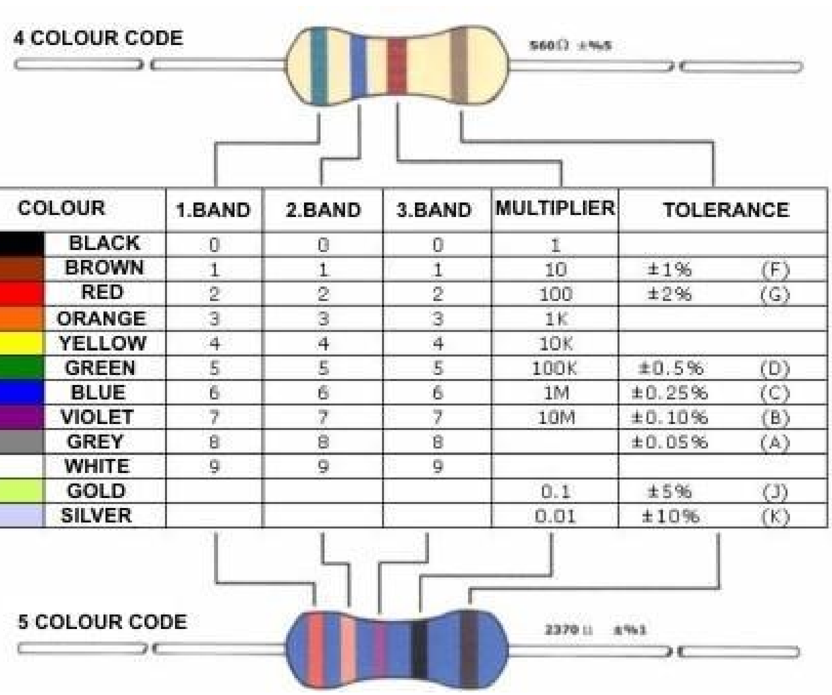


Figure 19: Symbol of LDR.

2.4 Colour Codes of Resistors

The values of fixed resistors are denoted by the producer firms through two methods. First method is to write the resistance value over the resistor using numbers (like 100 R, 180 K, 1.5 M). This method is not commonly used because the alphabets of all languages are not the same. The second method is to denote the resistance values with color scales. This method is usable for all countries. Every color denotes a number in that method. So, the color codes of resistors should be learned well. There are four colors in the color scales on the carbon resistors while there are five colors in the color scales on the metal film resistors. Colors, their numerical values and how to read them is shown in Figure 20.



COLOUR	1.BAND	2.BAND	3.BAND	MULTIPLIER	TOLERANCE	
BLACK	0	0	0	1		
BROWN	1	1	1	10	±1%	(F)
RED	2	2	2	100	±2%	(G)
ORANGE	3	3	3	1K		
YELLOW	4	4	4	10K		
GREEN	5	5	5	100K	±0.5%	(D)
BLUE	6	6	6	1M	±0.25%	(C)
VIOLET	7	7	7	10M	±0.10%	(B)
GREY	8	8	8		±0.05%	(A)
WHITE	9	9	9			
GOLD				0.1	±5%	(J)
SILVER				0.01	±10%	(K)

Figure 20: Colour diagram of resistor.

As we see, the last color shows the tolerance. Tolerance determines the maximum and minimum values of resistance. Carbon resistors have higher tolerances than metal film resistors. Because of that, metal film resistors are used in precision-bored (delicate) circuits while carbon resistors are used in circuits which are not precision-bored.

Example: Let's calculate the value of resistance and limits of resistance values according to the tolerance of a four band resistor on which there are colors of brown, black, red and gold.

Table 1: Coefficients of example resistance according to colour order.

1. Colour	2. Colour	3. Colour	Value (Ohm)	Tolerance (%)
1	0	00	1000R	5

According to example, $\% \pm 5 tolerance = 1000\frac{5}{100} = \frac{5000}{100} = 50R$. This means that the resistance is between $950R$ $(1000 - 50)$ and $1050R$ $(1000 + 50)$.

Example: Let's calculate the value of resistance and limits of resistance values according to the tolerance of a five band resistor on which there are colors of red, red, black, brown and purple.

Table 2: Coefficients of example resistance according to colour order.

1. Colour	2. Colour	3. Colour	4. Colour	Value (Ohm)	Tolerance (%)
2	2	0	0	2200R	0,1

According to example, $\% \pm 0,1 tolerance = 2200\frac{0,1}{100} = \frac{220}{100} = 2,2R$. This means that the resistance is between $2197,8$R $(2200 - 2,2)$ and 2202R $(2200 + 2,2)$. Better resistor is that have smaller tolerance limits.

In delicate electronic circuits, tolerances of some resistors are specifically shown on a schema. If these kinds of circuits are being applied, attention must be paid to the tolerance value.

Another point to pay attention is the power of resistor. Power of resistors is determined as Watt (W). If too great currents pass through the resistors and if the resistors do not have enough power they may be heatened and deformed. Because of that, you should use the resistors which have enough power suitable for the structure of the circuit. Resistors present the same opposition to the direct current (DC) and alternating current (AC). This opposition is called "ohmic resistance".

2.5 Measurement of Resistances

Resistances are measured by "Ohmmeter". The resistance that ohmmeters measure is ohmic resistance. Ohmmeters are devices that contain a DC (direct current) in themselves. A small current passes through the resistor during the measurement; ohmmeter examines this current and makes the measurement. The direction of this current does not affect the measurement. Ohmmeters are produced in two types: analog and digital (or numerical) types. It is difficult to measure delicate values with analog ohmmeters because their quadrants are not linear and they need selection of applicable level and caliber adjustment. There is also room for delusions of eye while reading the values. So, their production is very limited. Digital devices are commonly used by electricians. They can measure electric current (Amper), electric voltage (volt) and resistance (ohm). These devices are also called “avometer” (Amper-Volt-Ohm). Delicate values can be read by digital avometers and they are easy to use. A typical avometer can be seen in Figure 21.

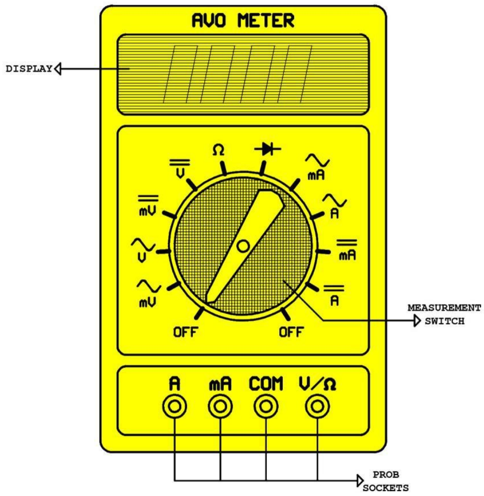


Figure 21: Avometer.

The cables that are used to connect the terminals of the measured component to the avometer are called “probes”. Probes have special plugs on both sides. The part of the probe that we grab by the hand is made of good insulators and the parts (terminals) that are used for measurement are made of good conductors. The conducting parts are also called “live terminals”. In order to prevent problems of usage, probes are produced as black and red. Black probe is called (-) negative probe and red probe is called (+) positive probe. Resistance measurement with avometer is shown in Figure 22.

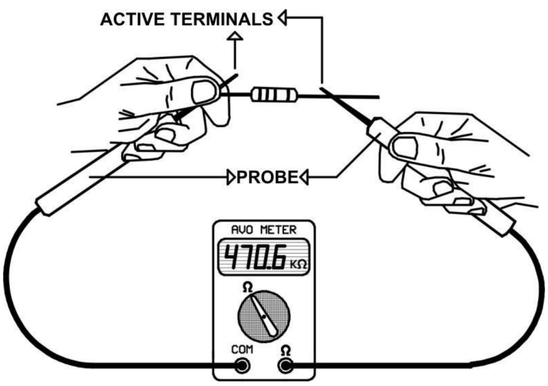


Figure 22: Connection of avometer to measure resistance.

Black probe will be plugged to "com" socket in all measurements. Red probe will be plugged to the socket of related measurement unit. In resistance measurement, the red probe will be plugged to ohm socket. The switch will be adjusted to "ohm. If the resistance is connected to a circuit, it should be disconnected from the circuit before measurement. Otherwise, supply of the circuit will damage the ohmmeter. If there is not a supply connected to the circuit, even so, the resistance should be disconnected from the circuit because the other components cause miss-measurement. The second point to pay attention is that if the measured resistance has a big value, you should not touch the terminals of the probe. Otherwise, resistance of your body will also be measured and the result will be wrong.

3 MEASUREMENT OF CURRENT, VOLTAGE AND POWER IN DC

As we know, electric is a type of energy. "Electric circuit" is required to benefit from this energy. The most basic electric circuit is shown in Figure 23.

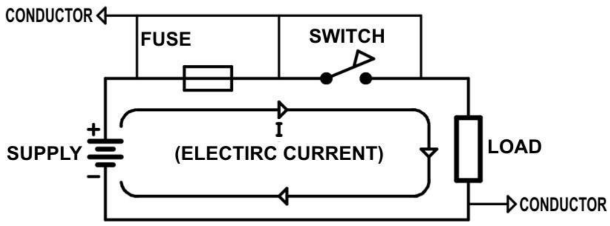


Figure 23: Basic electric circuit.

It is seen on Figure 23 that the most components: basic circuit consist of five supply, fuse, switch, load and these components are as in conductor. The definition of the following.

- **Supply**: It is the store of electrical energy. For example, batteries, accumulators, dynamos and generators are types of supplies.
- **Fuse:** It is the component of the circuit which protects the circuit and the environment in case of a breakdown of the electrical circuit.
- **Switch:**It is the component which controls the electrical energy.
- **Load:**It is the component by which the electrical energy is transformed to work. Lamps, irons, ovens, electric motors, radio and TV are examples of load. So, the electrical energy is an indispensable kind of energy which we use in every aspect of our life.
- **Conductor:** They are the wires which carry electrical energy from one point to one another. They are generally made of copper. Their shapes are usually circular.

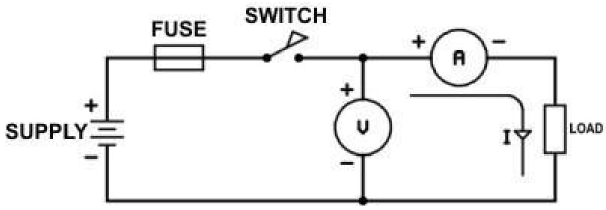


Figure 24: Basic electric circuit with switch.

In Figure 24, current passes through the circuit when the S switch is closed. Electric current is symbolized by I. Its unit is "Amper" and symbolized by (A). Upper and lower multiples of Amper, and the mathematical relation between them are shown in Figure 25.

UPPER MULTIPLES	(MA) MEGA AMPER	1MA=1000000 A
	(KA) KILO AMPER	1KA=1000 A
MAIN UNIT	(A) AMPER	
LOWER MULTIPLES	(mA) MILI AMPER	1000 mA =1A
	(μA) MICRO AMPER	1000 000 μA =1A

Figure 25: Mathematical relations of unit Amper.

Current is measured with "Ampermeter". Inner resistances of ampermeter are very slow and they are connected to the circuit serially. Voltage is symbolized by (E). Unit of voltage (potential) is volt and symbolized by (V). Upper and lower multiples of volt, and the mathematical relation between them are shown in Figure 26.

UPPER MULTIPLES	(MV) MEGA VOLT	1MV=1000 000 V
	(KV) KILO VOLT	1KV=1000 V
MAIN UNIT	(V) VOLT	
LOWER MULTIPLES	(mV) MILI VOLT	1000 mV =1V
	(μV) MICRO VOLT	1000 000 μV =1V

Figure 26: Mathematical relations of unit Volt.

Voltage is measured by the "Voltmeter". Internal resistances of Voltmeter are very large and parallel connected to the circuit. Measurement devices must be in appropriate scope for the magnitude to be measured. Otherwise, the measurement devices might breakdown or be damaged. Voltmeters and amper-meters are in two types. These are analog and digital measurement devices.

Analog Measurement Devices: These are the devices on which we read the electrical values written on a scale by the help of a moving needle. Analog devices must be connected to the direct current (DC) circuits by paying attention to its poles except for some very special types of devices. If the analog devices are connected to inversely to the electric circuit, the needle will move to the opposite direction and again the device will breakdown or be damaged. Analog devices are used rarely in our time. The reason why they are used (though rarely) is that they do not need another circuit or supply when measuring.

Digital Measurement Devices: These are the devices that writes the value of electric measured in normal (daily used) numbers. Because of that these devices are also called "numerical measurement devices". If pole symbol is opposite when the numerical devices are connected to the electric circuit, there is a symbol of negative (-) before the value it shows. These devices can not be damaged. They are widely used because of the easiness of their usage and because it is easy to read the values they show. The only problem is that they surely need a supply when using

3.1 Power in Direct Current

"Work" is what the electrical energy performed in the circuit. Shortly, power is the pace of work. Electric current is actually the flow of electrons. Electrons perform a work by leaving their energy while passing through the load. The value of the work is calculated as power. In direct current Power equals $Volt \times Amper$ and symbolized by w (watt).

Example: 8 Ampers of current passes through the load which is connected between the poles of an accumulator which is in 12 Volts of voltage.

$$P = E \times I$$
$$P = 12 \times 8$$
$$P = 96 Watt$$

4 OHM'S LAW

Ohm's law examines the mathematical relation between voltage, current and resistance in electric circuits.

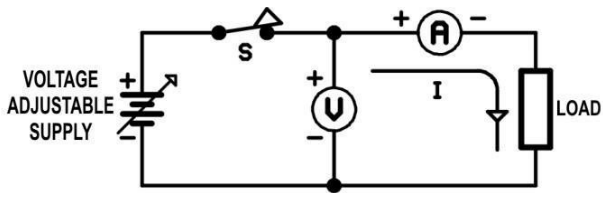


Figure 27: Basic electric circuit that Volt-meter and Amper-meter is used.

In Figure 27, the S switch is closed. If the voltage of adjustable generator is increased it will be observed that the current also increases. If voltage is decreased then the current also decreases. This means that voltage is directly proportionate to the current. If any value of voltage is divided by the current at the same moment, the result will be the same. This constant value equals the circuit resistance (R). Mathematically, resistance in circuit:

$$R = \frac{E}{I} \tag{1}$$

In equation 1, R is circuit resistance that unit is Ohm, E is circuit voltage that unit is Volt and I is circuit current that unit is Amper. Equation can be written as following equations.

$$I = \frac{E}{R} \text{ or } E = I \times R \tag{2}$$

The mathematical relation between the voltage, current and resistance can be memorized easily by "Ohm triangle" as shown Figure 28.

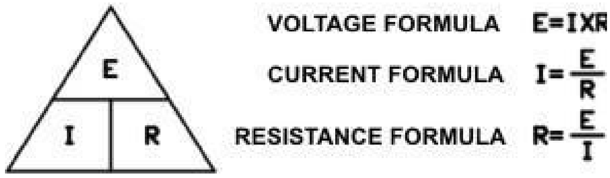


Figure 28: Ohm Triangle Diagram

5 KIRCHHOFF'S LAWS

One of the most important laws examining the relations between current, voltage and resistance is Kirchhoff's Laws for the situations when there are multiple resistors in a circuit. There are two laws of Kirchhoff.

- Kirchhoff's voltage law
- Kirchhoff's current law

5.1 Kirchhoff's Voltage Laws

Kirchhoff's voltage law examines the relations between current, voltage and resistance when the resistors are serially connected as shown Figure 29.

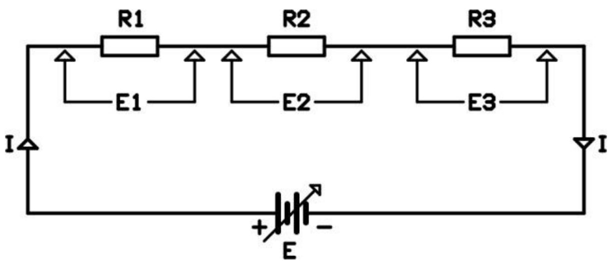


Figure 29: Basic electric circuit whose resistors are connected serially.

In Figure 29, circuit load consists of three serially connected resistors. The sum of voltages per resistors is equal to the supply voltage. According to that;

$$E = E_1 + E_2 + E_3 \tag{3}$$

Let's calculate the total resistance of serially connected resistors. As seen in Figure 29, circuit current (I) passes through all the resistors. Following equation is used in order to calculate the voltage per resistors according to Ohm's Law.

$$\begin{aligned} E1 =& I.R_1 \\ E2 =& I.R_2 \\ E3 =& I.R_3 \end{aligned} \tag{4}$$

If we symbolize the total resistance by (R_{tot}), supply voltage can be calculated as following equation.

$$E = I \times R_{tot} \tag{5}$$

Let's combine these equations with Kirchhoff's Law;

$$\begin{aligned} I \times R_{tot} &= E_1 + E_2 + E_3 \\ &= I.R_1 + I.R_2 + I.R_3 \\ R_{tot} &= R_1 + R_2 + R_3 \end{aligned} \tag{6}$$

If we assume that n pieces (numbers) of resistors are serially connected, then total resistance will be written as following equation.

$$R_{tot} = R_1 + R_2 + R_3 + \cdots + R_n \tag{7}$$

Example: : In the circuit at Figure 29, $R_1 = 2R$, $R_2 = 4R$, $R_3 = 6R$. If $E = 12V$ applied to the circuit, find following subsentence.

(a) The total resistance,

(b) The circuit current,

(c) Voltages per resistor,

(d) Are results same with the results of Kirchhoff's Voltage Laws.

Solution :

(a) Total resistance;

$$\begin{aligned} R =& R_1 + R_2 + R_3 \\ R =& 2 + 4 + 6 \\ R =& 12R \end{aligned}$$

(b) Circuit current;

$$I = \frac{E}{R} = \frac{12}{12} = 1A$$

(c) Voltages per resistors;

$$\begin{aligned} E_1 =& I.R_1 = 1.2 = 2V \\ E_2 =& I.R_2 = 1.4 = 4V \\ E_3 =& I.R_3 = 1.6 = 6V \end{aligned}$$

(d) Kirchhoff's Voltage Laws equation for the circuit;

$$E = E_1 + E_2 + E_3$$

If the resulting values are placed Kirchhoff's Voltage Laws equation;

$$\begin{aligned} E =& 2 + 4 + 6 = 1.2 \\ =& 12 \end{aligned}$$

Results of the Ohm's law and Kirchhoff's Voltage Laws are the same. In circuits that contain serially connected multiple resistors, voltages per resistors can be calculated using less mathematical processes by some applications of Ohm's and Kirchhoff's Laws. As we know, circuit current (I) passes through every resistors then following equation is calculated.

$$I = \frac{E}{R} = \frac{E_1}{R_1} = \frac{E_2}{R_2} = \frac{E_3}{R_3}$$

If we calculate the voltage on the R_1 resistor at the example problem:

$$\begin{aligned} \frac{E}{R} =& \frac{E_1}{R_1} \\ R \times E_1 =& R_1 \times E \\ E_1 =& \frac{R_1 \times E}{R} = \frac{R_1}{R} \times E \end{aligned}$$

If we place the values in the equation;

$$\begin{aligned} E_1 =& \frac{R_1}{R} \times E \\ =& \frac{2}{12} \times 12 = 2Volt \end{aligned}$$

To generalize the formula for the other resistors in the circuit;

$$\begin{aligned} E_2 =& \frac{R_2}{R} \times E = \frac{4}{12} \times 12 = 4\ Volt \\ E_3 =& \frac{R_3}{R} \times E = \frac{6}{12} \times 12 = 6\ Volt \end{aligned}$$

It is observable that circuit current is not used in the solution. This method is called "Voltage Division Method".

5.2 Kirchhoff's Current Laws

Kirchhoff's current law examines the relations between current, voltage and resistance when the resistors are parallelly connected.

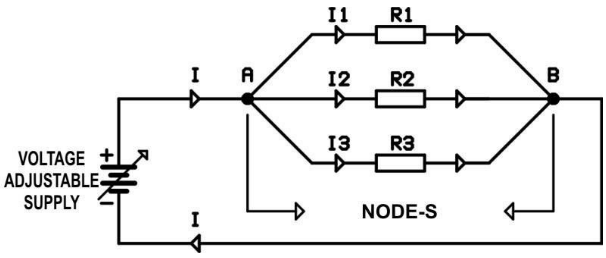


Figure 30: Basic electric circuit whose resistors are connected parallelly.

In Figure 30, circuit load consists of three parallelly connected resistors. In the circuit, the total current flowing into a node must be the same as the total current flowing out of the node. So, at node A;

$$I = I_1 + I_2 + I_3 \tag{8}$$

Let's calculate the total resistance of parallel resistors from this equation. It is observable on Figure 30 that there is circuit voltage (E) on every resistor. If we calculate the current passing through every resistor;

$$\begin{aligned} I_1 &= \frac{E}{R_1} \\ I_2 &= \frac{E}{R_2} \\ I_3 &= \frac{E}{R_3} \end{aligned} \tag{9}$$

If we symbolize the total circuit resistance by (R) then the circuit current will be written as $I = \frac{E}{R}$. Let's place these equations at the current equation at node A.

$$\begin{aligned} \frac{E}{R} &= \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3} \\ E \times \frac{1}{R} &= E \times \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) \\ \frac{1}{R} &= \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \end{aligned} \tag{10}$$

If we assume that n pieces (numbers) of resistors are parallelly connected, then total resistance can be calculated as following equation 11.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n} \tag{11}$$

Example: In the circuit at Figure 30, $R_1 = 6R$, $R_2 = 12R$, $R_3 = 4R$. If $E = 12V$ applied to the circuit;

(a) Find the current passing through every resistor.

(b) Calculate the total resistance.

(c) Calculate the circuit current with Ohm's and Kirchhoff's Laws.

Solution:

(a)

$$\begin{aligned} I_1 &= \frac{E}{R_1} = \frac{12}{6} = 2A \\ I_2 &= \frac{E}{R_2} = \frac{12}{12} = 1A \\ I_3 &= \frac{E}{R_3} = \frac{12}{4} = 3A \end{aligned}$$

(b)

$$\begin{aligned} \frac{1}{R_{tot}} &= \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \\ &= \frac{1}{6} + \frac{1}{12} + \frac{1}{4} \\ &= \frac{2}{12} + \frac{1}{12} + \frac{3}{12} \\ &= \frac{6}{12} \\ 6.R_{tot} &= 12 \\ R_{tot} &= \frac{12}{6} = 2R \end{aligned}$$

(c) Circuit current from Ohm's Law;

$$I = \frac{E}{R} = \frac{12}{2} = 6A$$

Circuit current from Kirchhoff's Law;

$$\begin{aligned} I &= I_1 + I_2 + I_3 \\ &= 2 + 1 + 3 = 6A \end{aligned}$$

Circuit current is found $6A$ in both ways. This proves the correctness of the calculations.

If two resistors are parallelly connected, a more practical formula can be used by an application of the total resistance formula.

$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} \tag{12}$$

To equate the denominators;

$$\begin{aligned} \frac{1}{R_{tot}} &= \frac{R_2}{R_1.R_2} + \frac{R_1}{R_2.R_1} \\ &= \frac{R_2 + R_1}{R_1.R_2} \end{aligned} \tag{13}$$

With the multiplication of interiors and exteriors;

$$\begin{aligned} R_{tot}(R_1 + R_2) &= R_1.R_2 \\ R_{tot} &= \frac{R_1.R_2}{R_1 + R_2} \end{aligned} \tag{14}$$

This means that if the resistors are parallelly connected, total resistance is equal to the division of multiplication of resistances to the sum of resistances.

Example: Two resistors are connected parallelly. $R_1 = 60R$ and $R_2 = 90R$. Calculate the total resistance.

$$\begin{aligned} R_{tot} &= \frac{R_1.R_2}{R_1 + R_2} \\ &= \frac{60.90}{60 + 90} = \frac{5400}{150} \\ &= 36R \end{aligned}$$

5.3 Resistance Power Calculation

The maximum value of current that can pass through all the resistors of circuit depends on the power of resistors. If there are two resistors with the same value and different powers, small current passes through the resistor with small power and big current passes through the resistor with greater power. Sizes of resistors increases directly proportionate to their power. The minimum required power for a resistor to be used in a circuit is calculated by the power formula that we used in direct current.

$$P = E.I \tag{15}$$

In equation 15, P is power that unit is Watt, E is Voltage that unit is Volt and I is Current that unit is Amper. As seen in the formula, we should know the voltage on the terminals of resistor and the current passing through the resistor in order to calculate the power of resistor. If we know the resistance value of resistor, power formula can be made more basic. Voltage in power formula can be extracted using the Ohm's Law.

$$\begin{aligned} P =& E.I \\ E =& I.R \\ P =& I.R.I \\ P =& I^2.R \end{aligned} \tag{16}$$

In the electrical circuit structures, the circuit components are so close that there is no air flow. Because of that, in practice, the resistors that have twice the power of the calculated value should be chosen. The current passing through the resistor causes it to heaten. When the resistors are degenerated due to any reason (heat, high current, etc..) they usually become open circuit.

5.4 Resistor Connections

If the resistor which will be used in the circuit is not easy to find (in terms of resistance value or power), the problem can be fixed by using serial, parallel or mixed connection of multiple resistors.

5.4.1 Serial Connection

If a required value of resistor could not be provided then multiple resistors can be connected serially and the problem can be fixed. Resistors are connected straightly in serial connection regardless of their number. The serial connection of three resistors are shown in Figure

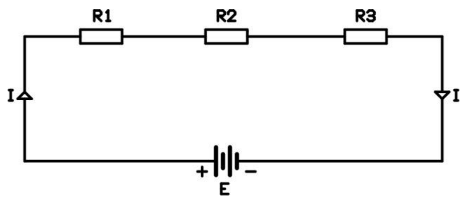


Figure 31: Basic electric circuit that resistors are connected serially.

Circuit current passes through all the resistors. If we symbolize the total resistance by with "R":

$$R = R_1 + R_2 + R_3 \tag{17}$$

Circuit current:

$$I = \frac{E}{R} \tag{18}$$

Circuit current (I) passes through all the resistors. Minimum power of each resistor (P_1, P_2, P_3) should be:

$$\begin{aligned} P_1 =& I_2.R_1 \\ P_2 =& I_2.R_2 \\ P_3 =& I_2.R_3 \end{aligned} \tag{19}$$

The power exerted by the supply (P) is the sum of powers spared on the resistors.

$$P = P_1 + P_2 + P_3 \text{ or } P = I^2.R \tag{20}$$

If we call the group of serially connected resistors as "system", the power of the system is equal to the power of the smallest resistor. In other words, the first resistor to be degenerated is the one with smallest power in serially connected resistors. Degenerated resistors make the circuit open and current does not pass.

Example: $R_1 = 3R$, $R_2 = 5R$ in the circuit at Figure 32. $E = 16V$ is applied to the circuit.

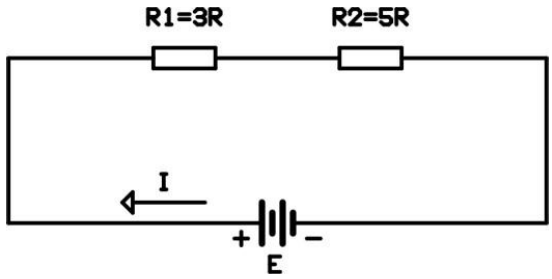


Figure 32: Basic electric circuit.

(a) Calculate the total resistance of circuit.

(b) Calculate the circuit current.

(c) Calculate the minimum power values required for each resistor.

(d) Calculate the power exerted by the supply.

Solution:

(a)

$$R_{tot} = R_1 + R_2 = 3 + 5 = 8R$$

(b)

$$I = \frac{E}{R} = \frac{16}{8} = 2A$$

(c)

$$\begin{aligned} P_1 =& I^2.R = 2^2.3 = 4.3 = 12W \\ P_2 =& I^2.R = 2^2.5 = 4.5 = 20W \end{aligned}$$

(d)

$$\begin{aligned} P_{tot} =& P_1 + P_2 = 12 + 20 = 32W \\ P_{tot} =& I^2.R = 2^2.8 = 4.8 = 32W \end{aligned}$$

5.4.2 Parallel Connection

If a required power value of resistor could not be provided then multiple resistors can be connected parallelly and the problem can be fixed. In parallel connection, the total resistance is smaller than the smallest resistor. Resistors are connected as in figure 4.10 in parallel connection regardless of their number. The parallel connection of three resistors are shown in Figure 33.

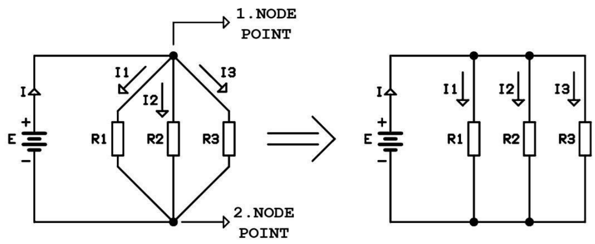


Figure 33: Basic electric circuit that resistors are connected parallelly.

In Figure 33 , there is no electrical difference between the two diagrams of “A” and “B”. There is circuit voltage on every resistor. The total resistance is R_{tot} can be found with following equation.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \tag{21}$$

Therefore circuit current can be calculated with R_{tot} as following equations.

$$I = \frac{E}{R} \text{ or } I = I_1 + I_2 + I_3 \tag{22}$$

Then, minimum required powers (P_1, P_2 and P_3) of resistors can be calculated with current values as following equations.

$$\begin{aligned} P_1 &= I_1^2.R_1 \\ P_2 &= I_2^2.R_2 \\ P_3 &= I_2^2.R_3 \end{aligned} \tag{23}$$

The total power exerted by the supply (P_{tot}) is the sum of powers spared on parallelly connected resistors so can be calculated by adding all powers on resistors.

$$P_{tot} = P_1 + P_2 + P_3 \text{ or } P_{tot} = I^2.R \tag{24}$$

If we call the group of parallelly connected resistors as “system”, the power of system is equal to the sum of resistances of resistors. If one of the resistors is degenerated, the current continues to pass through the other resistors. In that situation, the power exerted from the supply decreases. For example, if one of the heaters of an electrical stove collapses, then the other heaters continue to work. In that situation, the current coming from city network decreases and the level of heating decreases.

Example: In the circuit at Figure 34, R_1 and R_2 are equal to 6 R and 9 R sequentially. If 18 V is applied to the circuit, calculate following questions.

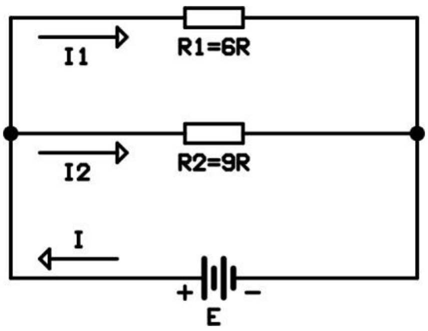


Figure 34: Basic electric circuit that resistors are connected parallelly.

(a) Calculate the total resistance of circuit.

(b) Find the current passing through every resistor and total current.

(c) Find the minimum required power of resistors.

(d) Find the power exerted from the supply.

Solutition : First of all, total resistance is calculated. Then, current, power and total power is calculated as following sentences.

(a)

$$R = \frac{R_1.R_2}{R_1 + R_2} = \frac{6.9}{6+9} = 3,6R$$

(b)

$$I_1 = \frac{E}{R_1} = \frac{18}{6} = 3A$$
$$I_2 = \frac{E}{R_2} = \frac{18}{9} = 2A$$

$$I_{tot} = I_1 + I_2 = 3 + 2 = 5A$$
Or
$$I_{tot} = \frac{E}{R} = \frac{18}{3,6} = 5A$$

(c)

$$P_1 = I_1^2.R_1 = 3^2.6 = 54W$$
$$P_2 = I_2^2.R_2 = 2^2.9 = 36W$$

(d)

$$P_{tot} = P_1 + P_2 = 54 + 36 = 90W$$
Or
$$P_{tot} = I_{tot}^2.R_{tot} = 5^2.3,6 = 90W$$

5.4.3 Mixed Connection

If it is not possible to reach resistance and/or power values for a resistor with only serial or parallel connection, multiple resistors can be connected serial and parallel at the same time and the problem can be fixed. This type of connection is called mixed connection. Mixed connection of three resistors is shown in Figure 35.

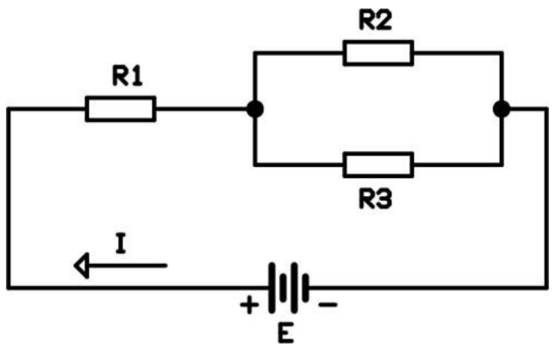


Figure 35: Basic electric circuit that resistors are connected parallelly and serially.

In Figure 35, R_2 and R_3 resistors are connected parallel and the R_1 resistor is serial to them. In problem solutions, first the parallel connections will be solved and converted to a single resistor. So, the circuit will be in serial connection. Then, total resistance, circuit current, voltage per resistor, and current per resistor will be calculated respectively. The minimum required power for resistors is calculated by using power formula. The power exerted from the supply is equal to the sum of powers spared on resistors.

Example: In the circuit at Figure 35, $R_1 = 5R$, $R_2 = 3R$ and $R_3 = 6R$. $E = 21V$ is applied to the circuit. Calculate following subsentence.

(a) Total resistance of circuit.

(b) Circuit current.

(c) Voltages per resistors.

(d) Current passing through every resistor.

(e) Minimum required power for resistors.

(f) The power exerted from the supply.

Solution: Let's re-draw the circuit shape and show the current passing through every resistor and voltage per resistor.

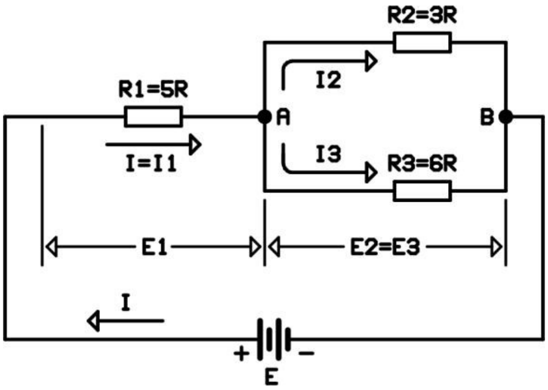


Figure 36: Values of current and resistor is written on mixed circuit.

(a) R_2 and R_3 resistors are connected parallelly. If we call the total resistance of these two as R_A:

$$R_A = \frac{R_2.R_3}{R_2 + R_3} = \frac{3.6}{3+6} = \frac{18}{9} = 2R$$

Therefore, R_A and R_1 resistors are serially connected as following Figure 37. Sum of these two is the total resistance of the circuit.

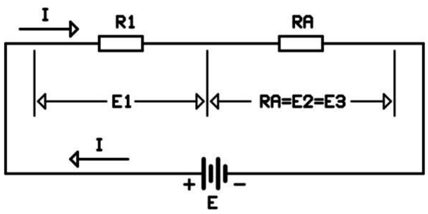


Figure 37: Resistors of circuit are transformed to serial from mixed.

$$R_{tot} = R_A + R_1 = 2 + 5 = 7R$$

(b)

$$I = \frac{E}{R} = \frac{21}{7} = 3A$$

(c) As we see in Figure **??**, Circuit current passes through R_1 and R_A resistors. Voltages for each of them is calculated.

$$E_1 = I.R_1 = 3.5 = 15V$$

R_A resistor is the total resistance of the parallelly connected R_2 and R_3 resistors. Because of the fact that voltage is equal on the terminals of parallel resistors:

$$E_A = E_2 = E_3 = I.R_A = 3.2 = 6V$$

There will be circuit voltage on R_1 and R_A resistors. If this is correct than it means that the previous processes are also correct.

$$\begin{aligned} E =& E_1 + E_A \\ 21 =& 15 + 6 \\ 21 =& 21 \end{aligned}$$

(d) As we see from Figure 36, circuit current passes through the R_1resistor. So:

$$\begin{aligned} I_1 =& I = 3A \\ &\text{Or} \\ I_1 =& \frac{E_1}{R_1} = \frac{15}{5} = 3A \end{aligned}$$

Circuit current is divided into two at node A after it passes through the R_1 resistor. These currents are I_2 and I_3 currents. From the Kirchhoff's current law $I = I_2 + I_3$. The voltages on the R_2 and R_3 resistors are known. So:

$$\begin{aligned} I_2 =& \frac{E_2}{R_2} = \frac{6}{3} = 2A \\ I_3 =& \frac{E_3}{R_3} = \frac{6}{6} = 1A \end{aligned}$$

(e) As we know the currents passing through every resistor and the values of resistors, minimum required power for each resistor will be:

$$\begin{aligned} P_1 =& I_1^2.R_1 = 3^2.5 = 9.5 = 45W \\ P_2 =& I_2^2.R_2 = 2^2.3 = 4.3 = 12W \\ P_3 =& I_3^2.R_3 = 1^2.6 = 1.6 = 6W \end{aligned}$$

(f) The power exerted from the supply is equal to the sum of powers spared on all resistors.

$$\begin{aligned} P_{tot} =& P_1 + P_2 + P_3 \\ P_{tot} =& 45 + 12 + 6 \\ P_{tot} =& 64 \end{aligned}$$