Amateur Wireless Station Operators License Exam

Study material 2017

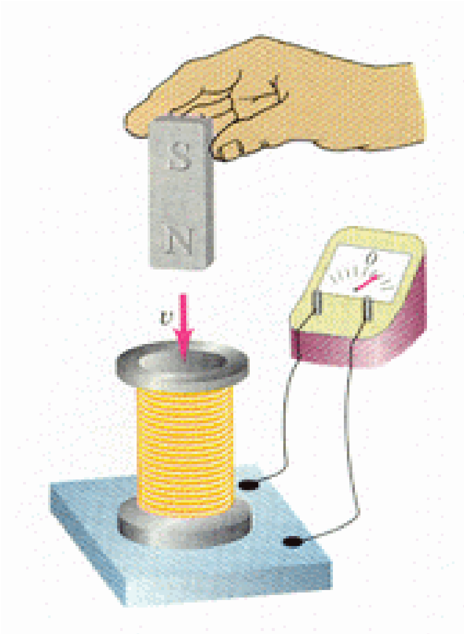
CHAPTER 7

Faraday's Law of Electromagnetic Induction

In 1831, Michael Faraday, an English physicist gave one of most basic law of electromagnetism called Faraday’s law of electromagnetic induction. This law explains the working principle of most of electrical motors, generators, electrical transformers and inductors. This law shows the relationship between electric circuit and magnetic field. Faraday performed an experiment with a magnet and coil. During that experiment he found how emf(electro motive force) is induced in the coil when flux linked with it changes.

Faraday’s Experiment -relationship between induced emf and flux

In this experiment Faraday used a magnet and a coil and connects a galvanometer across the coil. At starting the magnet is at rest so there is no deflection in the galvanometer i.e needle of galvanometer is at center or zero position. When the magnet is moved toward the coil, the needle of galvanometer deflects in one direction. When the magnet is held stationary at that position, the needle of galvanometer returns to zero position. Now when the magnet is moved away from the coil , there is some deflection in the needle but in opposite direction and again when the magnet become stationary at that point with respect to coil , the needle of galvanometer return to zero position. Similarly if magnet is held stationary and the coil is moved away and towards the magnet, the galvanometer shows deflection in similar manner. It is also seen that the faster the change in the magnetic field, the greater will be the induced emf or voltage in the coil.



Position of magnet	*Deflection in galvanometer*
Magnet at rest	No deflection in galvanometer
Magnet moves towards the coil	Deflection in galvanometer in one direction
Magnet is held stationary at same position (near the coil)	No deflection in galvanometer
Magnet moves away from the coil	Deflection in galvanometer but in opposite direction
Magnet is held stationary at same position (away from the coil)	No deflection in galvanometer

From the above experiment Faraday concluded that ***whenever there is relative motion between conductor and a magnetic field, the flux linkage with a coil changes and this change in flux induces a voltage across a coil.***

Michael Faraday formulated two laws on the basis of above experiments. These laws are called Faraday’s laws of electromagnetic induction.

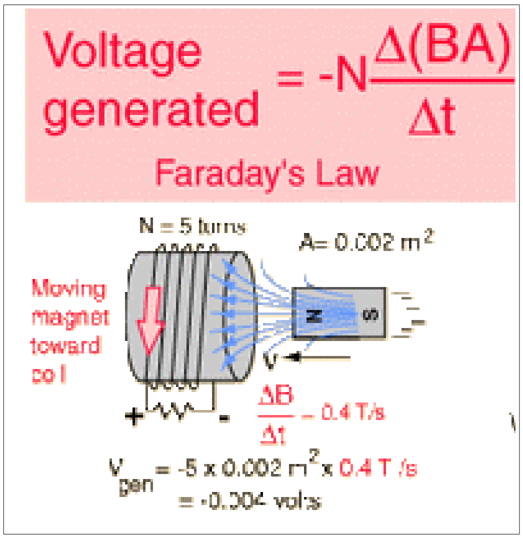
Faraday’s First Law
Any change in the magnetic field of a coil of wire will cause an emf to be induced in the coil. This emf induced is called induced emf and if the conductor circuit is closed, the current will also circulate through the circuit and this current is called induced current.

Method to change magnetic field:

1. By moving a magnet toward or away from the coil
2. By moving the coil into or out of the magnetic field.
3. By changing area of a coil placed in the magnetic field
4. By rotating the coil relative to the magnet.

Faraday's Second Law

It states that the magnitude of emf induced in the coil is equal to the rate of change of flux linkages with the coil. The flux linkages of the coil is the product of number of turns in the coil and flux associated with the coil.



Lenz's Law

The minus sign in Faraday's law refers to the direction, or polarity, of the induced voltage. In 1833, the Russian physicist Heinrich Lenz discovered the directional relationships among the forces, voltages, and currents of electromagnetic induction. Lenz's law states:

An induced electromotive force generates a current that induces a counter magnetic field that opposes the magnetic field generating the current.

For example, when an external magnetic field approaches a ring shaped conductor, the current that is produced in the ring will induce its own magnetic field in opposition to the approaching external magnetic field. On the other hand, when the external magnetic field moves away from the ring, the induced magnetic field in the ring reverses direction and opposes the change in the direction of the external magnetic field.

How to increase emf induced in a coil ?

- By increasing the number of turns in the coil i.e N- From the formula derived above it is easily seen that if number of turns of coil is increased, the induced emf is also increased.

- By increasing magnetic field strength i.e B surrounding the coil- Mathematically if magnetic field increases, flux increases and if flux increases emf induced will also increased Theoretically if the coil is passed through a stronger magnetic field, there will be more lines of force for coil to cut and hence there will be more emf induced.

- By increasing the speed of the relative motion between the coil and the magnet. – If the relative speed between the coil and magnet is increased from its previous value, the coil will cut the lines of flux at a faster rate so more induced emf would be produced.

Applications of Faraday Law

Faraday law is one of the most basic and important law of electromagnetism. This law finds its application in most of electrical machines, industries and medical field etc.

•Electrical Transformers
It is a static ac device which is used to either step up or step down voltage or current. It is used in generating station, transmission and distribution system. The transformer works on Faraday's law.

•Electrical Generators
The basic working principle of electrical generator is Faraday's law of mutual induction.Electric generator is used to convert mechanical energy into electrical energy.

•Induction Cookers
The Induction cooker, is the fastest way of cooking. It also works on principle of mutual induction. When current flows through the coil of copper wire placed below a cooking container, it produces a changing magnetic field. This alternating or changing magnetic field induces an emf and hence the current in the conductive container and we know that flow of current always produces heat in it.

•Electromagnetic Flow Meters
It is used to measure velocity of blood and certain fluids. When a magnetic field is applied to electrically insulating pipe in which conducting fluids are flowing then according to Faraday's law an electromotive force is induced in it. This induced emf is proportional to velocity of fluid flowing.

Self-Inductance

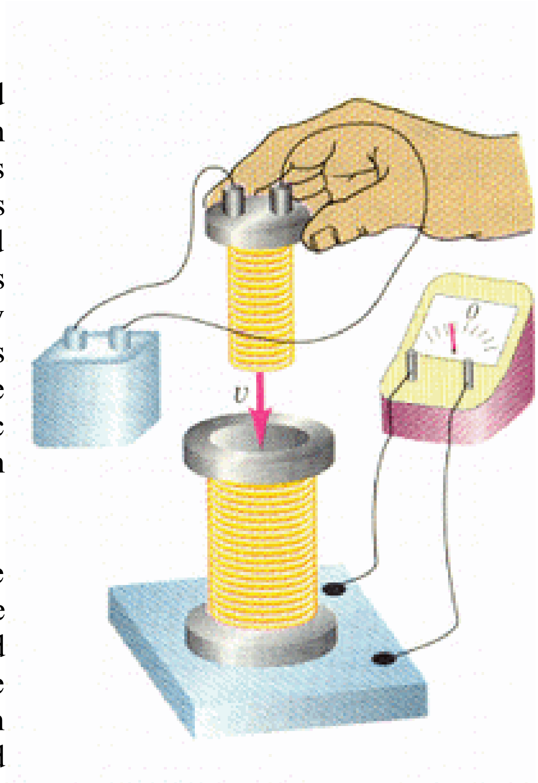
We know that current flow in a conductor produces a magnetic field around the conductor. When the current is increasing, decreasing, or changing direction, the magnetic field changes. The magnetic field expands, contracts, or changes direction in response to the changes in current flow. **A changing magnetic field induces an additional electromotive force, or voltage in the conductor. The induction of this additional voltage is called self-induction, because it is induced within the conductor itself.** The direction of the self-induced electromotive force, or voltage, is in the opposite direction of the current flow that generated it. This is consistent with Lenz's law. The effect of self-induction in a circuit is to oppose any change in current flow in the circuit. For example, when voltage is applied to a circuit, current begins to flow in all parts of the circuit. This current induces a magnetic field around it. As the field is expanding, a counter voltage, sometimes called back voltage, is generated in the circuit. This back voltage causes a current flow in the opposite direction of the main current flow. Inductance at this stage acts to oppose the buildup of current. When the induced magnetic field becomes steady, it ceases to induce back voltage.

When the current in a circuit is switched off, the induced magnetic field begins to collapse. As the field is collapsing, it generates voltage in the direction that momentarily prolongs the main current flow. When the induced magnetic field is fully collapsed, the induced voltage and current flow cease. Again, self-induction opposes changes in current flow. It opposes the buildup, and delays the breakdown, of current.

Mutual Inductance
In Faraday's experiment with two coils on a conducting iron ring, he discovered that a changing magnetic field in one coil induces an electromotive force, or voltage, in the second coil. This phenomenon is called **mutual inductance. Mutual inductance occurs when a changing magnetic**

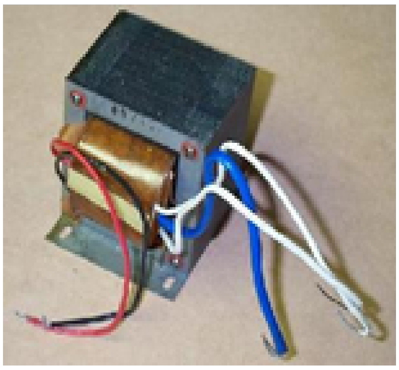
field in one circuit induces voltage in a nearby circuit.

Consistent with Lenz's law, the direction of the induced electromotive force, or voltage, is in the opposite direction of the current flow that generated it. Looking at Faraday's experiment again below, we find that when voltage is applied to the coil on the right, a magnetic field is induced in the iron ring. As the field is expanding, a voltage is generated in the second coil on the left. This secondary voltage causes a current flow in the second coil. This secondary current flow is in the opposite direction of the current flow of the first coil. When the induced magnetic field in the ring becomes steady, current ceases to flow in the second coil.



When the current in the first coil is switched off, the induced magnetic field in the ring begins to collapse. As the field is collapsing, it again generates voltage in the second coil. The resulting current flow in the second coil is in the opposite direction of the previously induced current. When the magnetic field in the ring is fully collapsed, the induced voltage and current flow in the secondary coil ceases.

Transformer



The transformer is one of the simplest of electrical devices. Its basic design, materials, and principles have changed little over the last one hundred years, yet transformer designs and materials continue to be improved. Transformers are essential in high voltage power transmission providing an economical means of transmitting power over large distances. In electronic circuitry, new methods of circuit design have replaced some of the applications of transformers, but electronic technology has also developed new transformer designs and applications.

Transformers come in a range of sizes from a thumbnail-sized coupling transformer hidden inside a stage microphone to gigawatt units used to interconnect large portions of national power grids, all operating with the same basic principles and with many similarities in their parts.

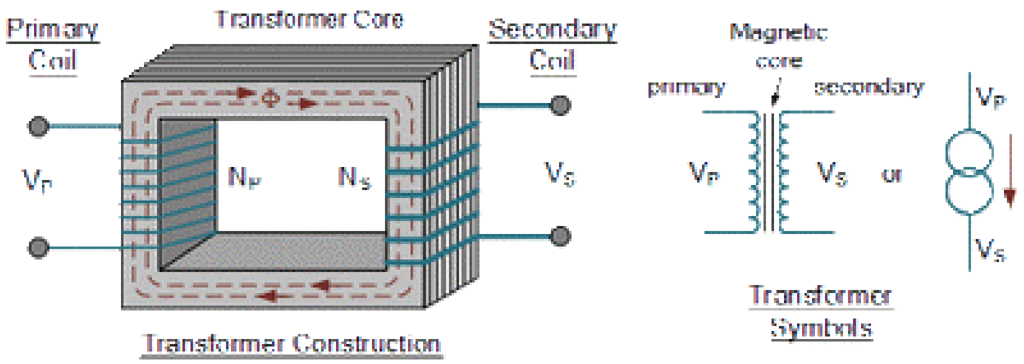
Transformers are the main components of the systems that performs.

- Convert DC to AC or vice versa
- Change the voltage or current of DC
- Change the AC supply frequency.

Transformer – Working Principle

A transformer can be defined as a static device which helps in the transformation of electric power in one circuit to electric power of the same frequency in another circuit. The voltage can be raised or lowered in a circuit, but with a proportional increase or decrease in the current ratings.

The main principle of operation of a transformer is mutual inductance between two circuits which is linked by a common magnetic flux. A basic transformer consists of two coils that are electrically separate and inductive, but are magnetically linked through a path of reluctance. The working principle of the transformer can be understood from the figure below.



Where:

VP - is the Primary Voltage

VS - is the Secondary Voltage

NP - is the Number of Primary Windings

NS - is the Number of Secondary Windings

Φ (phi) - is the Flux Linkage

As shown above the transformer has primary and secondary windings. The core laminations are joined in the form of strips in between the strips you can see that there are some narrow gaps right through the cross-section of the core. These staggered joints are said to be 'imbricated'. Both the coils have high mutual inductance. A mutual electro-motive force is induced in the transformer from the alternating flux that is set up in the laminated core, due to the coil that is connected to a source of alternating voltage. Most of the alternating flux developed by this coil is linked with the other coil and thus produces the mutual induced electro-motive force. The so produced electro-motive force can be explained with the help of Faraday's laws of Electromagnetic Induction

If the second coil circuit is closed, a current flows in it and thus electrical energy is transferred magnetically from the first to the second coil.

The alternating current supply is given to the first coil and hence it can be called as the primary winding. The energy is drawn out from the second coil and thus can be called as the secondary winding.

In short, a transformer carries the operations shown below:

- Transfer of electric power from one circuit to another.
- Transfer of electric power without any change in frequency.
- Transfer with the principle of electromagnetic induction.
- The two electrical circuits are linked by mutual induction.

For the simple construction of a transformer, you must need two coils having mutual inductance and a laminated steel core. The two coils are insulated from each other and from the steel core. The device will also need some suitable container for the assembled core and windings, a medium with which the core and its windings from its container can be insulated. In order to insulate and to bring out the terminals of the winding from the tank, apt bushings that are made from either porcelain or capacitor type must be used.

In all transformers that are used commercially, the core is made out of transformer sheet steel laminations assembled to provide a continuous magnetic path with minimum of air-gap included. The steel should have high permeability and low hysteresis loss (discussed below). For this to happen, the steel should be made of high silicon content and must also be heat treated. By effectively laminating the core, the eddy-current losses can be reduced. The lamination can be done with the help of a light coat of core plate varnish or lay an oxide layer on the surface. For a frequency of 50 Hertz, the thickness of the lamination varies from 0.35mm to 0.5mm for a frequency of 25 Hertz.

A Transformers Turns Ratio

The difference in voltage between the primary and the secondary windings is achieved by changing the number of coil turns in the primary winding (NP) compared to the number of coil turns on the secondary winding (NS). As the transformer is a linear device, a ratio now exists between the number of turns of the primary coil divided by the number of turns of the secondary coil. This ratio, called the ratio of transformation, more commonly known as a transformer "turns ratio", (TR). This turns ratio value dictates the operation of the transformer and the corresponding voltage available on the secondary winding.

It is necessary to know the ratio of the number of turns of wire on the primary winding compared to the secondary winding. The turns ratio, which has no units, compares the two windings in order and is written with a colon, such as 3:1 (3-to-1). This means in this example, that if there are 3 volts on the primary winding there will be 1 volt on the secondary winding, 3-to-1. Then we can see that if the ratio between the number of turns changes the resulting voltages must also change by the same ratio, and this is true.

A transformer is all about "ratios", and the turns ratio of a given transformer will be the same as its voltage ratio. In other words for a transformer: "turns ratio = voltage ratio". The actual number of turns of wire on any winding is generally not important, just the turns ratio and this relationship is given as:

$$\frac{N_P}{N_S} = \frac{V_P}{V_S} = n = \text{Turns Ratio}$$

Example No 1

A voltage transformer has 1500 turns of wire on its primary coil and 500 turns of wire for its secondary coil. What will be the turns ratio (TR) of the transformer.

$$\text{T.R.} = \frac{N_P}{N_S} = \frac{\#\text{Pri.Coils}}{\#\text{Sec.Coils}} = \frac{1500}{500} = \frac{3}{1} = 3:1$$

This ratio of 3:1 (3-to-1) simply means that there are three primary windings for every one secondary winding. As the ratio moves from a larger number on the left to a smaller number on the right, the primary voltage is therefore stepped down in value as shown.

Example No 2

If 240 volts are applied to the primary winding of the same transformer, what will be the resulting secondary no load voltage.

$$T.R. = 3:1 = \frac{3}{1} = \frac{V_P}{V_S} = \frac{\#Pri.\ Volts}{\#Sec.\ Volts} = \frac{240}{V_S}$$

$$\therefore Sec\ Volts,\ V_S = \frac{V_P}{3} = \frac{240}{3} = 80\ volts$$

Again confirming that the transformer is a “step-down transformer” as the primary voltage is 240 volts and the corresponding secondary voltage is lower at 80 volts.

Transformer Core Losses

The ability of iron or steel to carry magnetic flux is much greater than it is in air, and this ability to allow magnetic flux to flow is called ***permeability.*** Most transformer cores are constructed from low carbon steels which can have permeabilities in the order of 1500 compared with just 1.0 for air. This means that a steel laminated core can carry a magnetic flux 1500 times better than that of air. However, when a magnetic flux flows in a transformers steel core, two types of losses occur in the steel. One termed “eddy current losses” and the other termed “hysteresis losses”.

Hysteresis Losses

Transformer Hysteresis Losses are caused because of the friction of the molecules against the flow of the magnetic lines of force required to magnetize the core, which are constantly changing in value and direction first in one direction and then the other due to the influence of the sinusoidal supply voltage. This molecular friction causes heat to be developed which represents an energy loss to the transformer. Excessive heat loss can overtime shorten the life of the insulating materials used in the manufacture of the windings and structures. Therefore, cooling of a transformer is important.

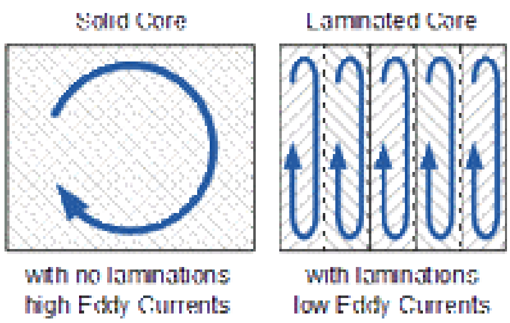
Also, transformers are designed to operate at a particular supply frequency. Lowering the frequency of the supply will result in increased hysteresis and higher temperature in the iron core. So reducing the supply frequency from 60 Hertz to 50 Hertz will raise the amount of hysteresis present, decreased the VA capacity of the transformer.

Eddy Current Losses

Transformer Eddy Current Losses on the other hand are caused by the flow of circulating currents induced into the steel caused by the flow of the magnetic flux around the core. These circulating currents are generated because to the magnetic flux the core is acting like a single loop of wire. Since the iron core is a good conductor, the eddy currents induced by a solid iron core will be large. Eddy currents do not contribute anything towards the usefulness of the transformer but instead they oppose the flow of the induced current by acting like a negative force generating resistive heating and power loss within the core.

Laminating the Core

Eddy current losses within a transformer core can not be eliminated completely, but they can be greatly reduced and controlled by reducing the thickness of the steel core. Instead of having one big solid iron core as the magnetic core material of the transformer or coil, the magnetic path is split up into many thin pressed steel shapes called "laminations".



The laminations used in a transformer construction are very thin strips of insulated metal joined together to produce a solid but laminated core as we saw above. These laminations are insulated from each other by a coat of varnish or paper to increase the effective resistivity of the core thereby increasing the overall resistance to limit the flow of the eddy currents. The result of all this insulation is that the unwanted induced eddy current power-loss in the core is greatly reduced, and it is for this reason why the magnetic iron circuit of every transformer and other electro-magnetic machines are all laminated. Using laminations in a transformer construction reduces eddy current losses.

The losses of energy, which appears as heat due both to hysteresis and to eddy currents in the magnetic path, is known commonly as “transformer core losses”. Since these losses occur in all magnetic materials as a result of alternating magnetic fields. Transformer core losses are always present in a transformer whenever the primary is energized, even if no load is connected to the secondary winding. Also this hysteresis and the eddy current losses are sometimes referred to as “transformer iron losses”, as the magnetic flux causing these losses is constant at all loads.

Eddy Current Losses

But there is also another type of energy loss associated with transformers called “copper losses”. Transformer Copper Losses are mainly due to the electrical resistance of the primary and secondary windings. Most transformer coils are made from copper wire which has resistance in several hundred Ohms, (Ω). This resistance opposes the magnetizing currents flowing through them.

When a load is connected to the transformers secondary winding, large electrical currents flow in both the primary and the secondary windings, electrical energy and power (or the I^2R) losses occur as heat. Generally copper losses vary with the load current, being almost zero at no-load, and at a maximum at full-load when current flow is at maximum. Transformers with high voltage and current ratings require conductors of large cross-section to help minimize their copper losses.

Then we can define an ideal transformer as having:

1. No Hysteresis loops or Hysteresis losses $\rightarrow 0$
2. Infinite Resistivity of core material giving zero Eddy current losses $\rightarrow 0$
3. Zero winding resistance giving zero I2R copper losses $\rightarrow 0$

But this wont happen in reality, losses will be there always. Advances in the area of modern transformer designs are being in reducing these losses marginally.

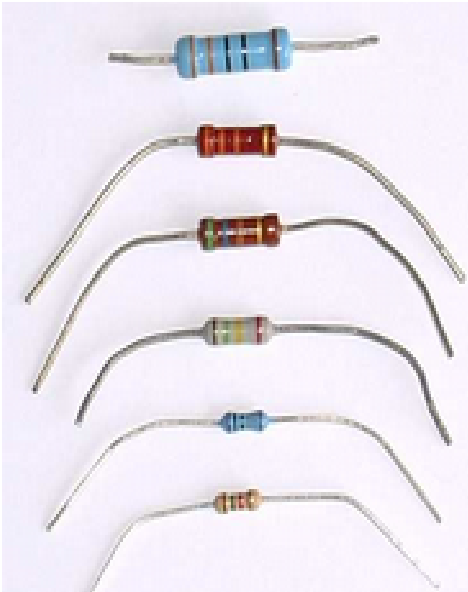
Applications

Transformers are adapted to numerous engineering applications and may be classified in many ways:

- By power level (from fraction of a watt to many megawatts),
- By application (power supply, impedance matching, circuit isolation),
- By frequency range (power, audio, RF)
- By voltage class (a few volts to about 750 kilovolts)
- By cooling type (air cooled, oil filled, fan cooled, water cooled, etc.)
- By purpose (rectifier, arc furnace, amplifier output, etc.).
- By ratio of the number of turns in the coils

Step-up
The secondary has more turns than the primary. Used to boost the given voltage
Step-down
The secondary has fewer turns than the primary. Used for lowering voltage, Eg a radio power-plug adapter.
Isolating
Intended to transform from one voltage to the same voltage. The two coils have approximately equal numbers of turns, although often there is a slight difference in the number of turns, in order to compensate for losses (otherwise the output voltage would be a little less than, rather than the same as, the input voltage).
Variable
The primary and secondary have an adjustable number of turns which can be selected without reconnecting the transformer.

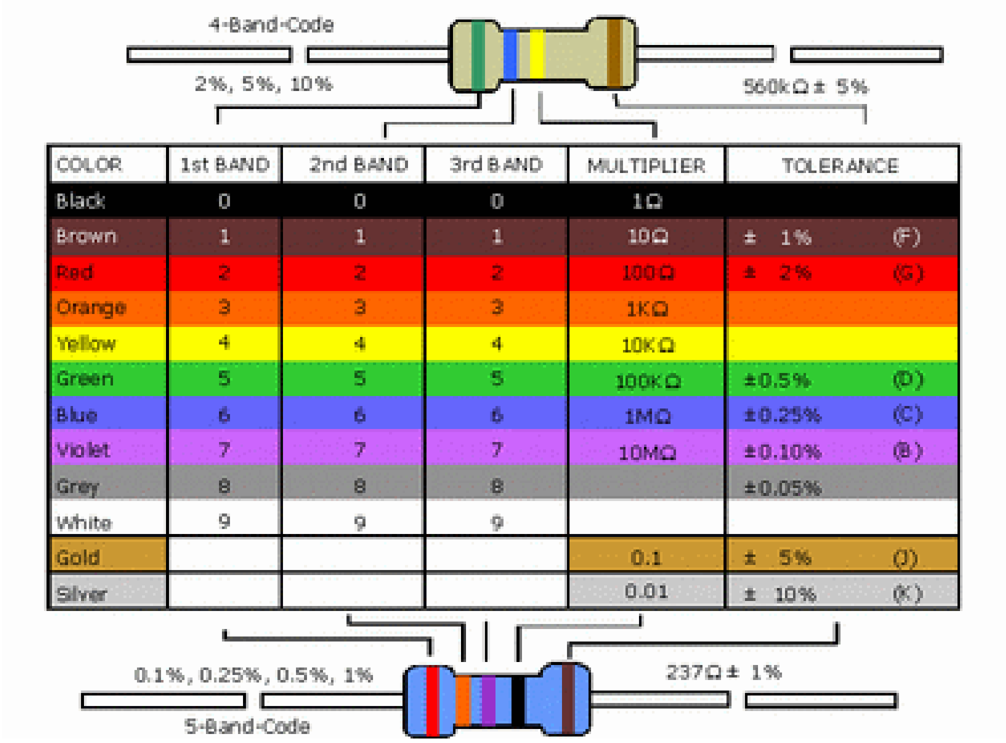
Electronic color code



The electronic color code is used to indicate the values or ratings of electronic components, very commonly for resistors, but also for capacitors, inductors, and others. A separate code, the 25-pair color code, is used to identify wires in some telecommunications cables. The electronic color code was developed in the early 1920s by the Radio Manufacturer's Association. Color bands were commonly used (especially on resistors) because they were easily printed on tiny components, decreasing construction costs. However, there were drawbacks, especially for color blind people. Overheating of a component, or dirt accumulation, may make it impossible to distinguish brown from red from orange. Advances in printing technology have made printed numbers practical for small components, which are often found in modern electronics.

Resistance color code

Resistors are color-coded for easy reading. Here's the color code, there is a 4 band code and a 5 band code. 5-band code is usually used with low tolerance metal film resistors.



COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1% (F)
Red	2	2	2	100Ω	± 2% (G)
Orange	3	3	3	1KΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	±0.5% (D)
Blue	6	6	6	1MΩ	±0.25% (C)
Violet	7	7	7	10MΩ	±0.10% (B)
Grey	8	8	8		±0.05%
White	9	9	9		
Gold				0.1	± 5% (J)
Silver				0.01	± 10% (K)

How to Read the Code

To determine the value of a given resistor look for the gold or silver tolerance band and rotate the resistor as in the chart. (Tolerance band on the right-hand end of the colors -- refer to the tolerance chart below for exact values). The Gold or Silver band is always set to the right, then you read from left to right. Sometimes there will be no tolerance band,then simply find the side that has a band closest to a lead and make that the first band.

Look at the first color band and determine its color. Now look at the chart and match the "first and second color band" color to the "digit it represents". Write down this number.

Now look at the second color band and match that color to the same chart. Write this number next to the first digit.

The third (or the fourth for the 5 band code) color band is the number you will multiply the result by. Match this third color band with the chart -- this time looking at the row of multiplier numbers. This is the number you will multiply the other two digits by. Write it next to the other two digits, with a multiplication sign before it.

Example: 1 (brown) 0 (black) x 100 (red) = 1,000 ohms

To get the value of the resistor, simply multiply the first two numbers (first number in the tens column, and the second number in the ones column) by the Multiplier.

Tolerance

Resistors are never the exact value that the color codes indicate. Therefore manufacturers place a tolerance color band on the resistor to tell you just how accurate this resistor is made. This band is on the right-hand end of the bands. It is simply shows a measurement of the imperfections.

Tolerance Rating Red = 2% Gold = 5% Silver = 10% No band = 20%

As the chart indicates, Red means the resistor is within 2%; Gold means the resistor is within 5% of rated value. Silver being within 10% and no color band being within 20%. To determine the exact range that the resistor may be, take the value of the resistor and multiply it by 5%, 10%, or 20%, as per the color band

Example: A 1,000-Ohm resistor with a gold band maybe with any value between 950 to 1050 Ohms.

Example: A 22,000-Ohm resistor with a silver band maybe with any value between 19,800 and 24,200 Ohms.

Remember the color codes with the following sentence to recollect the color sequence

B.B ROY from **G**reat **B**ritain has a **V**ery **G**ood **Wife** named **G**iji **S**imon**.**

MULTIPLE-CHOICE QUESTIONS AND ANSWERS

1. Which of the following does not change in a transformer ?
(a) Current
(b) Voltage
(c) Frequency
(d) All the above
Ans: c

2. In a transformer the energy is conveyed from primary to secondary
(a) through cooling coil
(b) through air
(c) by the flux
(d) none of the above
Ans: c

3. A transformer core is laminated to
(a) reduce hysteresis loss
(b) reduce eddy current losses
(c) reduce copper losses
(d) reduce all above losses
Ans: b

4. The degree of mechanical vibrations produced by the laminations of a transformer depends on
(a) tightness of clamping
(b) gauge of laminations
(c) size of laminations
(d) all the above

5. The purpose of providing an iron core in a transformer is to
(a) provide support to windings
(b) reduce hysteresis loss
(c) decrease the reluctance of the magnetic path
(d) reduce eddy current losses
Ans: c

6.A transformer cannot raise or lower the voltage of a D.C. supply because
(a) there is no need to change the D.C. voltage
(b) a D.C. circuit has more losses
(c) Faraday's laws of electromagnetic induction are not valid since the rate of change of flux is zero
(d) none of the above
Ans: c

7. Primary winding of a transformer
(a)is always a low voltage winding
(b)is always a high voltage winding
(c)could either be a low voltage or high voltage winding
(d)none of the above
Ans: c

8.An ideal transformer is one which has
(a)no losses and magnetic leakage
(b)interleaved primary and secondary windings
(c)a common core for its primary and secondary windings
(d)core of stainless steel and winding of pure copper metal
(e)none of the above
Ans: a

9.The transformer laminations are insulated from each other by
(a)mica strip
(b)thin coat of varnish
(c)paper
(d)any of the above
Ans: b

10.The size of a transformer core will depend on
(a)frequency
(b)area of the core
(c)flux density of the core material
(d)(a) and (b) both
Ans: d

11. When the turns ratio of a transformer is 20 and the primary ac voltage is 12 V, the secondary voltage is
(a)120v
(b)12v
(c)240v
(d)440v
Ans C

12.The primary and secondary winding of a transformer are
(a) conductively linked.
(b)inductively linked.
(c)electrically linked.
(d)mechanically linked.
Ans b