Basic electrical engineering

Assignment

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Submitted to

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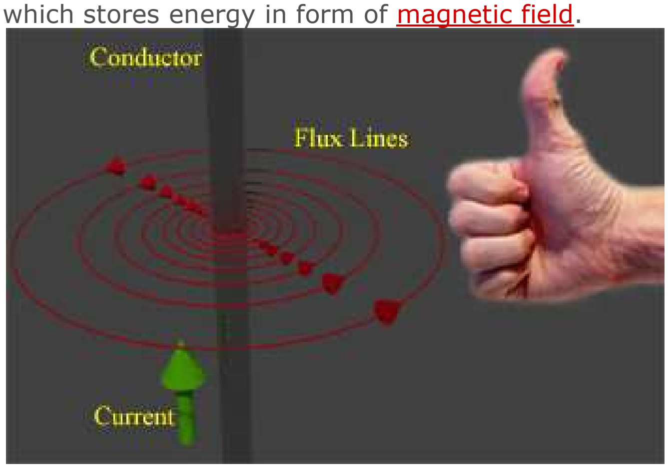
What is Inductor?

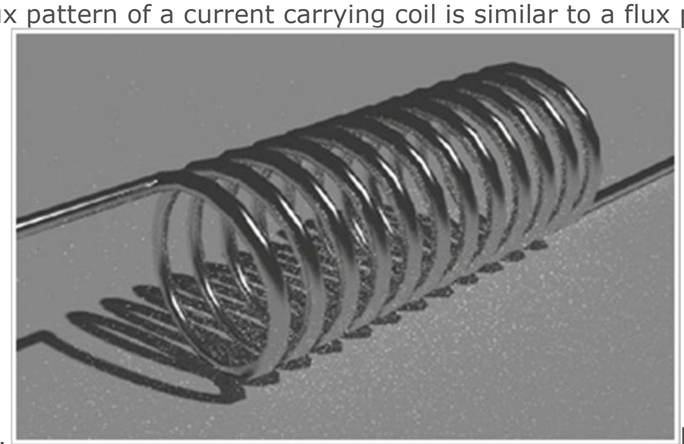
Before knowing **what is inductor** we should first know the **definition of inductance**.

Definition of Inductance

If a changing flux is linked with a coil of a conductor there would be an emf induced in it. The property of the coil of inducing emf due to the changing flux linked with it is known as **inductance of the coil**. Due to this property all electrical coil can be referred as **inductor**. In other way, an inductor can be defined as an energy storage device which stores energy in form of magnetic field.



Theory of Inductor

A current through a conductor produces a magnetic field surround it. The strength of this field depends upon the value of current passing through the conductor. The direction of the magnetic field is found using the right hand grip rule, which shown. The flux pattern for this magnetic field would be number of concentric circle perpendicular to the detection of current.
Now if we wound the conductor in form of a coil or solenoid, it can be assumed that there will be concentric circular flux lines for each individual turn of the coil as shown. But it is not possible practically, as if concentric circular flux lines for each individual turn exist, they will intersect each other. However, since lines of flux cannot intersect, the flux lines for individual turn will distort to form complete flux loops around the whole coil as shown. This flux pattern of a current carrying coil is similar to a flux pattern of a bar magnet as shown.  Now if the current through the coil is changed, the magnetic flux produced by it will also be changed at same rate. As the flux is already surrounds the coil, this changing flux obviously links the coil. Now according to Faraday's law of electromagnetic induction, if changing flux links with a coil, there would be an induced emf in it. Again as per Lenz's law this induced emf opposes every cause of producing it. Hence, the induced emf is in opposite of the applied voltage across the coil.

Definition of Self Inductance

Whenever, current flows through a circuit or coil, flux is produced surround it and this flux also links with the coil itself. Self induced emf in a coil is produced due to its own changing flux and changing flux is caused by changing current in the coil. So, it can be concluded that self-induced emf is ultimately due to changing current in the coil itself. And self inductance is the property of a coil or solenoid, which causes a self-induced emf to be produced, when the current through it changes.

Explanation of Self Inductance of a Coil

Whenever changing flux, links with a circuit, an emf is induced in the circuit. This is Faraday's laws of electromagnetic induction. According to this law,

$$e = -N\frac{d\phi}{dt} \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

Where, e is the induced emf. N is the number of turns. (dφ/dt) is the rate of change of flux leakage with respect to time. The negative sign of the equation indicates that the induced emf opposes the change flux linkage. This is according to Len'z law of induction. The flux is changing due to change in current of the circuit itself. The produced flux due to a current, in a circuit, always proportional to that current. That means, $\phi = Ki$ Where, i is the current in the circuit and K is the proportional constant.

$$Now,\ \frac{d\phi}{dt} = K\frac{di}{dt} \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

Now, from equation (1) and (2) we get,

$$e = -NK\frac{di}{dt}$$

The above equation can also be rewritten as

$$-e = L\frac{di}{dt} \cdots\cdots\cdots\cdots (3)$$

Where, L (= NK) is the constant of proportionality and this L is defined as the self inductance of the coil or solenoid. This L determines how much emf will be induced in a coil for a specific rate of change of current through it.

Now, from equation (1) and (3), we get,

$$L\frac{di}{dt} = N\frac{d\phi}{dt} \Rightarrow Ldi = Nd\phi$$

Integrating, both sides we get,

$$\int Ldi = \int Nd\phi \Rightarrow Li = N\phi \Rightarrow L = \frac{N\phi}{i} \cdots\cdots\cdots\cdots (4)$$

From the above expression, inductance can be also be defined as, "If the current I through an N turn coil produces a flux of Ø Weber, then its self-inductance would be L".

A coil can be designed to have a specific value of self-inductance (L). In the view of self-inductance, a coil or solenoid is referred as an inductor. Now, if cross-sectional area of the core of the inductor(coil) is A and flux density in the core is B, then total flux inside the core of inductor is AB.

Therefore, equation (4) can be written as

$$L = \frac{NAB}{i}$$

Now, B = $\mu_o\mu_r H$ Where, H is magnetic field strength, μ_o and μ_r are permeability of free space and relative permeability of the core respectively. Now, H = mmf/unit length = Ni/l Where l is the length of the coil.

Therefore,

$$L = \frac{NA\mu_o\mu_r Ni}{li} = \frac{A\mu_o\mu_r N^2}{l}$$

Self Inductance Formula

$$L = \frac{A\mu_o\mu_r N^2}{l}$$

Video presentation on theory of Inductor

Unit of Inductance

$$e = -L\frac{di}{dt}$$

Which we derived at equation (3). Where, L is known is the self induction of the circuit. In the above **equation of inductance**, if e = 1 Volt and (di / dt) is one ampere per second, then L = 1 and its unit is Henry. That means, if a circuit, produces emf of 1 Volt, due to the rate of change of current through it, one ampere per second then the circuit is said to have one henry self-inductance. This henry is **unit of inductance**.

Mutual Inductance

Inductance due to the current, through the circuit itself is called self inductance. But when a current flows through a circuit nearer to another circuit, then flux due to first circuit links to secondary circuit. If this flux linkage changes with respect to time, there will be an induced emf in the second circuit. Similarly, if current flows through second circuit, it will produced flux, and if this current changes, the flux will also change. This changing flux will link with first coil. Due to this phenomenon emf will be induced in the first coil. This phenomenon is known as mutual inductance. If current i_1 flows through circuit 1 then emf $e_2$is induced in the nearby circuit is given by, $e_2 = -M\frac{di_1}{dt}\ Volt$
Where, M is the mutual inductance.
If current i_2 flows through circuit 2, then emf e_1 is induced in the nearby circuit 1 is given by, $e_1 = -M\frac{di_2}{dt}\ Volt$

Defination of Mutual Inductance

Mutual inductance may be defined as the ability of one circuit to produce an emf in a nearby circuit by induction when current in the first circuit changes. In reverse way second circuit can also induce emf in the first circuit if current in the second circuit changes.

Coefficient of Mutual Inductance

Let's consider two nearby coils of turns N_1 and N_2 respectively. Let us again consider, current i_1 flowing through first coil produces φ_1. If this whole of the flux links with second coil, the weber-turn in the second coil would be $N_2\varphi_1$ due to current i_1 in the first coil. From this, it can be said, $(N_2\varphi_1)/i_1$ is the weber-turn of the second coil due to unit current in the first coil. This term is defined as co-efficient of mutual inductance. That means, mutual inductance between two coils or circuits is defined as the weber-turns in one coil or circuit due to 1 A current in the other coil or circuit.

Formula or Equation of Mutual Inductance

Now we have already found that, mutual inductance due to current in first coil is,

$$M = \frac{N_2\phi_1}{i_1}$$

Again, if self inductance of first coil or circuit is L_1, then,

$$L_1 i_1 = N_1\phi_1 \Rightarrow \frac{L_1}{N_1} = \frac{\phi_1}{i_1}$$

$$M = \frac{N_2 L_1}{N_1} \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

Similarly, coefficient of mutual inductance due to current i_2 in the second coil is, $M = \frac{N_1\phi_2}{i_2}$ Now, if self inductance of the second coil or circuit is, L_2,

$$L_2 i_2 = N_2\phi_2$$

$$\Rightarrow \frac{L_2}{N_2} = \frac{\phi_2}{i_2}$$

$$Therefore,\ M = \frac{N_1 L_2}{N_2} \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

Now, multiplying (5)

$$M \times M = \frac{N_2 L_1}{N_1} \times \frac{N_1 L_2}{N_2}$$

and (6), we get, $\Rightarrow M^2 = L_1 L_2 \Rightarrow M = \sqrt{L_1 L_2}$ This is an ideal case, when the whole changing flux of one coil, links to another coil. The value of M practically not equal to $\sqrt{(L_1 L_2)}$ as because the whole flux of one coil does not link with other, rather, a part of the flux of one coil, links with another coil. Hence practically,

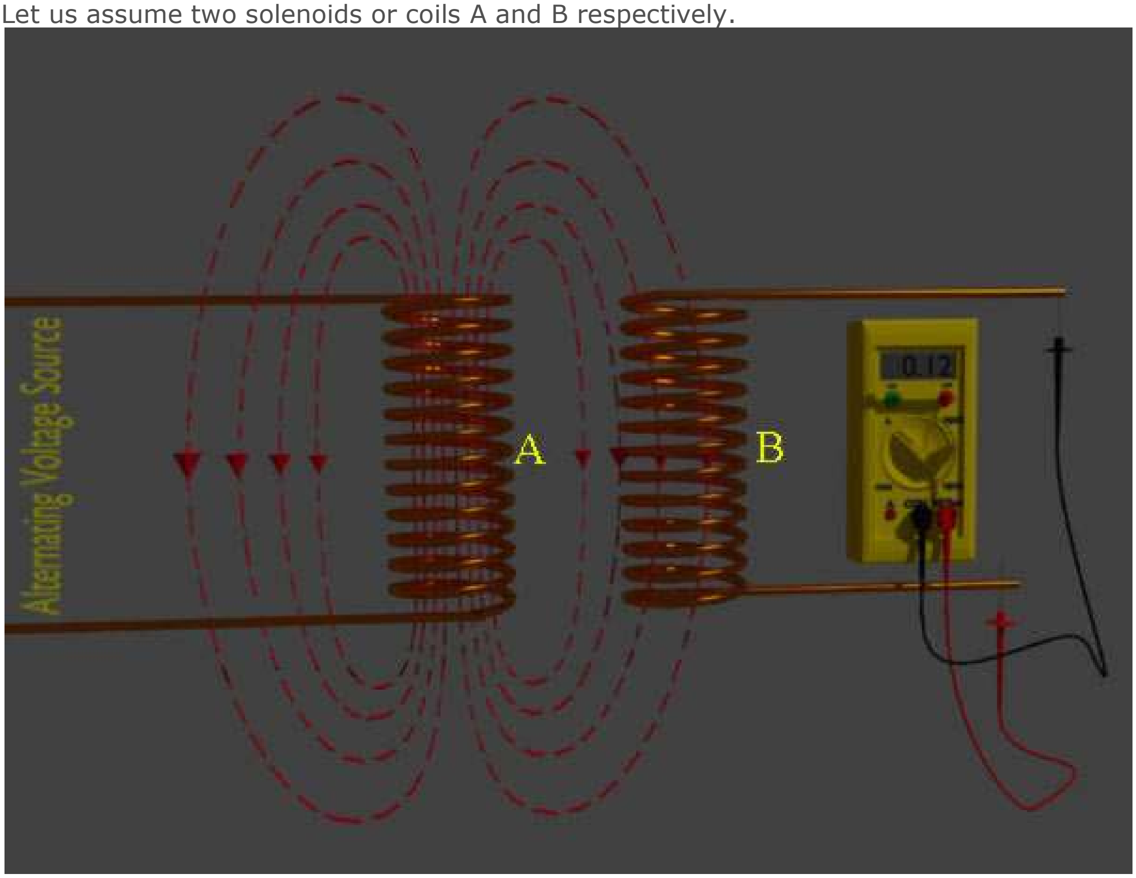
$$M \neq \sqrt{L_1 L_2}$$

$$and \ \frac{M}{\sqrt{L_1 L_2}} = K \ (\neq 1)$$

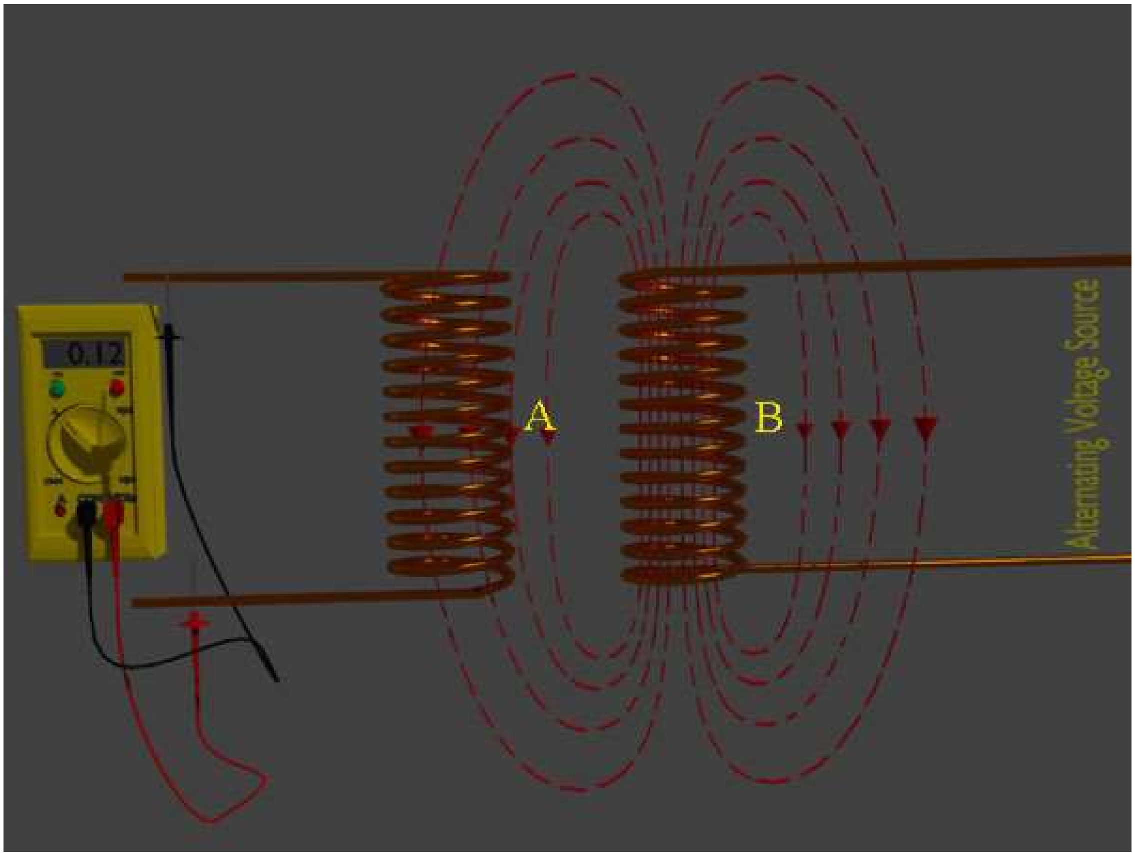
This k is known as coefficient of coupling and this is the ratio of actual coefficient of mutual inductance to ideal (maximum) coefficient of mutual inductance. If flux of one coil is entirely links with other, then value of K will be one. This is an ideal case. This is not possible, but when K nearly equal to unity, that means, maximum flux of one coil links to other, the coils are said to be tightly coupled or closely coupled. But when no flux of one coil links with other, the value of K becomes zero (K = 0), then the coils are said to be very loosely coupled or isolated.

Mutual Inductance of two Solenoids or Coils

Let us assume two solenoids or coils A and B respectively.



Coil A is connected with an alternating voltage source, V. Due to alternating source connected to coil A, it will produce an alternating flux as shown. Now, if we connect on sensitive voltmeter across coil B, we will find a non zero reading on it. That means, some emf is induced in the coil B. This is because, apportion of flux produced by coil A, links with coil B and as the flux changes in respect of time, there will be an induced emf in the coil B according to Faraday’s law of electromagnetic induction. This phenomenon is called mutual induction. That means, induction of emf in one coil due to flux of other coil is mutual induction.



Similarly, if the alternating voltage source was connected to coil B and induced voltage is measured by connecting voltmeter across coil A, the voltmeter gives a non-zero reading. That means, in this case the emf will be induced in coil A due to flux linkage from coil B. Let us consider coil A and B have turns N_1 and N_2. If the entire flux of coil A links with coil B, then weber-turns of the coil B due to unit current of coil A, would be $(N_2\varphi_1)/i_1$, where, $\varphi_1$and i_1 is flux and current of coil A. As per definition this is nothing but mutual inductance of coil A and B, M. That is, $M = \frac{N_2\phi_1}{i_1}$ Similarly, if the current and flux of the coil B are i_2 and φ_2. $Then,\ M = \frac{N_1\phi_2}{i_2}$

Inductances in Series

Let's coil or inductance A and B are connected in series. The self inductance of coil A , is $L_A$and that of coil B is L_B. Now again consider, M is the mutual inductance between them. There may be two conditions.

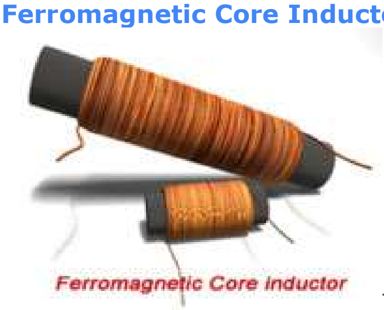
1. The direction of flux produced by both coil will be in same direction. In that case, the flux of coil B links will be coil A, will be in same direction with the flux produced by coil A, itself. Hence, the effective inductance of coil A will be $L_A + M$. At the same time, the flux of coil A, links with coil B will be in the same direction with the self flux of coil B. Hence, the effective inductance of coil B will be $L_B + M$. Hence total effective inductance of the series connected inductors A and B will be nothing but, $L_A + M + L_B + M = L_A + L_B + 2M$
2. Now, if the direction of instantaneous flux at coil A and B are in opposite, then flux of coil B linking with coil A, will be in opposite direction of flux produced by coil A itself. So, effective inductance of coil A will be $L_A - M$. In the same way, the flux of coil A which links with coil B will be in opposite direction of the self flux of coil B. Hence, effective inductance of coil B will be, $L_B - M$.

So, total inductance in series in this case will be, $L_A - M + L_B - M = L_A + L_B - 2M$ So, general form of equivalent inductance of two inductors in series in, $L_A + L_B \pm 2M$

Types of Inductor

There are many types of inductors; all differ in size, core material, type of windings, etc. so they are used in wide range of applications. The maximum capacity of the inductor gets specified by the type of core material and the number of turns on coil.
Depending on the value, **inductors** typically exist in two forms, fixed and variable. The number of turns of the fixed coil remains the same. This type is like resistors in shape and they can be distinguished by the fact that the first color band in fixed inductor is always silver. They are usually used in electronic equipment as in radios, communication apparatus, electronic testing instruments, etc.
The number of turns of the coil in variable inductors, changes depending on the design of the inductor. Some of them are designed to have taps to change the number of turns. The other design is fabricated to have a many fixed inductors for which, it can be switched into parallel or series combinations. They often get used in modern electronic equipment. Core or heart of inductor is the main part of the inductor. Some types of inductor depending on the material of the core will be discussed.

Ferromagnetic Core Inductor or Iron-core Inductors



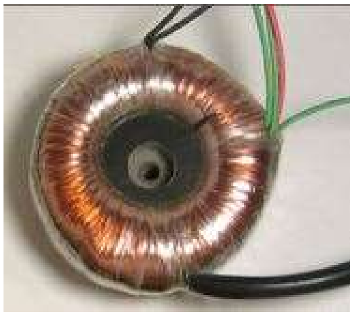
This type uses ferromagnetic materials such as ferrite or iron in manufacturing the inductor for increasing the inductance. Due to the high magnetic permeability of these materials, inductance can be increased in response of increasing the magnetic field.
At high frequencies it suffers from core loses, energy loses, that happens in ferromagnetic cores.

Air Core Inductor

Air cored inductor is the type where no solid core exists inside the coils. In addition, the coils that wound on nonmagnetic materials such as

ceramic and plastic, are also considered as air cored. This type does not use magnetic materials in its construction.
The main advantage of this form of **inductors** is that, at high magnetic field strength, they have a minimal signal loss. On the other hand, they need a bigger number of turns to get the same inductance that the solid cored inductors would produce. They are free of core losses because they are not depending on a solid core.

Toroidal Core Inductor



Toroidal Inductor constructs of a circular ring-formed magnetic core that characterized by it is magnetic with high permeability material like iron powder, for which the wire wounded to get inductor. It works pretty well in AC electronic circuits' application.
The advantage of this type is that, due to its symmetry, it has a minimum loss in magnetic flux; therefore it radiates less electromagnetic interference near circuits or devices. Electromagnetic interference is very important in electronics that require high frequency and low power.

Laminated Core Inductor

This form gets typified by its stacks made with thin steel sheets, on top of each other designed to be parallel to the magnetic field covered with insulating paint on the surface; commonly on oxide finish. It aims to block the eddy currents between steel sheets of stacks so the current keeps flowing through its sheet and minimizing loop area for which it leads to great decrease in the loss of energy. Laminated core inductor is also a low frequency inductor. It is more suitable and used in transformer applications.

Powdered Iron Core

Its core gets constructed by using magnetic materials that get characterized by its distributed air gaps. This gives the advantage to the core to store a high level of energy comparing to other types. In addition, very good inductance stability is gained with low losses in eddy current and hysteresis. Moreover, it has the lowest cost alternative.

Another Classification of Inductor

Coupled Inductor

It happens when inductors are related to each other by electromagnetic induction. Generally it gets used in applications as transformers and where the mutual inductance is required.

RF Inductor

Another name is radio frequency of RF inductors. This type operates at high frequency ranges. It is characterized by low current rating and high electrical resistance. However, it suffers from a proximity effect, where the wire resistance increases at high frequencies. Skin effect, where the wire resistance to high frequency is greater than the electrical resistance of current direct.

Multi-Layer Inductor

Here the wounded wire is coiled into layers. By increasing the number of layers, the inductance increases, but with increasing of the capacitance between layers.

Molded Inductor

The material for which it stands from is molded on ceramic or plastic. Molded inductors are typically available in bar and cylindrical shapes with a variety option of windings.

Choke

The main purpose of it is to block high frequencies and pass low frequencies. It exists in two types; RF chokes and power chokes.

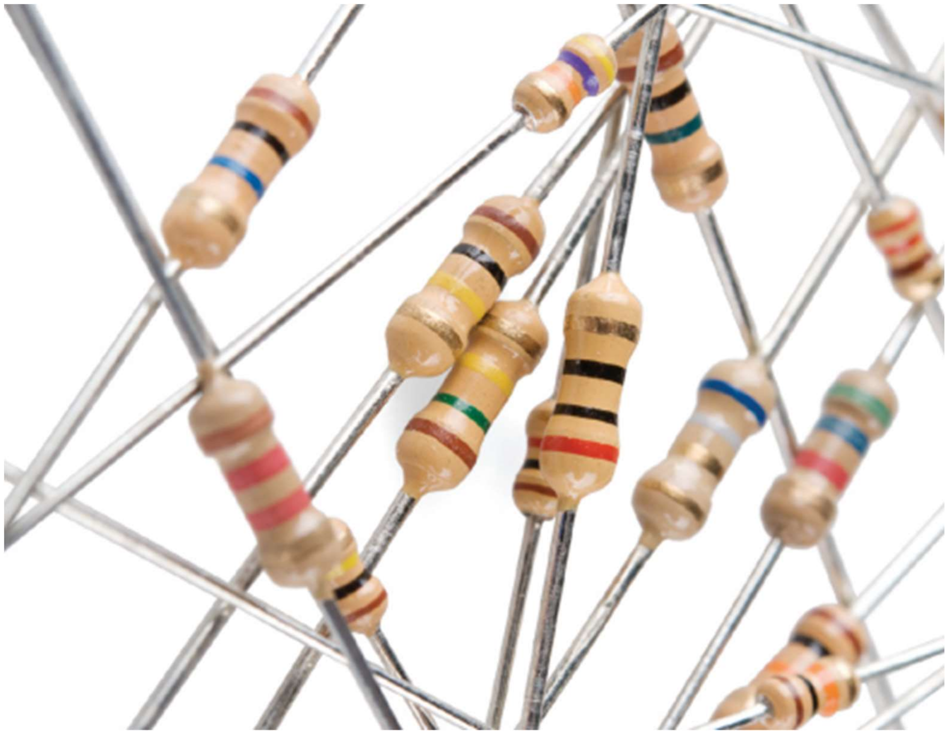
Applications of Inductors

In general there are a lot of applications due to a big variety of inductors. Here are some of them. Generally the inductors are very suitable for radio frequency, suppressing noise, signals, isolation and for high power applications. More applications summarized here:

1. Energy Storage
2. Sensors
3. Transformers
4. Filters
5. Motors

The use of inductors somehow is restricted due to its ability of radiation of electromagnetic interference. In addition, it is a side effect which makes **inductor** deviate a little bit from it is real behavior.

Resistors - the most ubiquitous of electronic components. They are a critical piece in just about every circuit. And they play a major role in our favorite equation, Ohm's Law.



In this, our pièce de *résistance*, we'll cover:

- What is a resistor?!
- Resistor units
- Resistor circuit symbol(s)
- Resistors in series and parallel
- Different variations of resistors
- Color coding decoding
- Surface mount resistor decoding
- Example resistor applications

Consider reading…

Some of the concepts in this tutorial build on previous electronics knowledge. Before jumping into this tutorial, consider reading (at least skimming) these first:

- What is Electricity?
- Voltage, Current, Resistance, and Ohm's Law
- What is a Circuit
- Series vs. Parallel Circuits
- How to Use A Multimeter - Specifically check out the measuring resistance section.
- Metric Prefixes

Resistor Basics

Resistors are electronic components which have a specific, never-changing electrical resistance. The resistor's resistance **limits the flow of electrons** through a circuit.

They are **passive** components, meaning they only consume power (and can't generate it). Resistors are usually added to circuits where they complement **active** components like op-amps, microcontrollers, and other integrated circuits. Commonly resistors are used to limit current, divide voltages, and pull-up I/O lines.

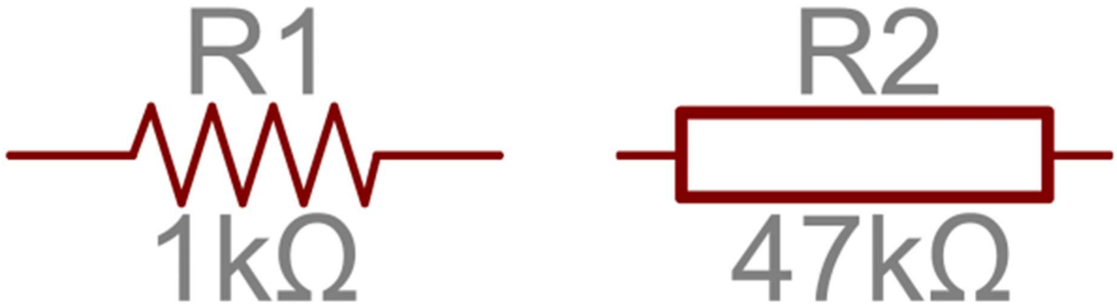
Resistor units

The electrical resistance of a resistor is measured in **ohms**. The symbol for an ohm is the greek capital-omega: Ω. The (somewhat roundabout) definition of 1Ω is the resistance between two points where 1 volt (1V) of applied potential energy will push 1 ampere (1A) of current.

As SI units go, larger or smaller values of ohms can be matched with a prefix like kilo-, mega-, or giga-, to make large values easier to read. It's very common to see resistors in the kilohm (kΩ) and megaohm (MΩ) range (much less common to see miliohm (mΩ) resistors). For example, a 4,700Ω resistor is equivalent to a 4.7kΩ resistor, and a 5,600,000Ω resistor can be written as 5,600kΩ or (more commonly as) 5.6MΩ.

Schematic symbol

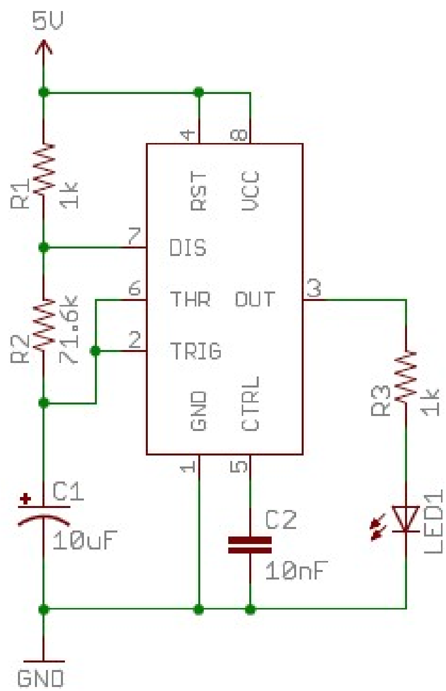
All resistors have **two terminals**, one connection on each end of the resistor. When modeled on a schematic, a resistor will show up as one of these two symbols:



Two common resistor schematic symbols. R1 is an American-style 1kΩ resistor, and R2 is an international-style 47kΩ resistor.

The terminals of the resistor are each of the lines extending from the squiggle (or rectangle). Those are what connect to the rest of the circuit.

The resistor circuit symbols are usually enhanced with both a resistance value and a name. The value, displayed in ohms, is obviously critical for both evaluating and actually constructing the circuit. The name of the resistor is usually an *R* preceding a number. Each resistor in a circuit should have a unique name/number. For example, here's a few resistors in action on a 555 timer circuit:



In this circuit, resistors play a key role in setting the frequency of the 555 timer's output. Another resistor (R3) limits the current through an LED.

Types of Resistors

Resistors come in a variety of shapes and sizes. They might be through-hole or surface-mount. They might be a standard, static resistor, a pack of resistors, or a special variable resistor.

Termination and mounting

Resistors will come in one of two termination-types: through-hole or surface-mount. These types of resistors are usually abbreviated as either PTH (plated through-hole) or SMD/SMT (surface-mount technology or device).

Through-hole resistors come with long, pliable leads which can be stuck into a breadboard or hand-soldered into a prototyping board or printed circuit board (PCB). These resistors are usually more useful in breadboarding, prototyping, or in any case where you'd rather not solder tiny, little 0.6mm-long SMD resistors. The long leads usually require trimming, and these resistors are bound to take up much more space than their surface-mount counterparts.

The most common through-hole resistors come in an axial package. The size of an axial resistor is relative to its power rating. A common ½W resistor measures about 9.2mm across, while a smaller ¼W resistor is about 6.3mm long.

A half-watt (½W) resistor (above) sized up to a quarter-watt (¼W).

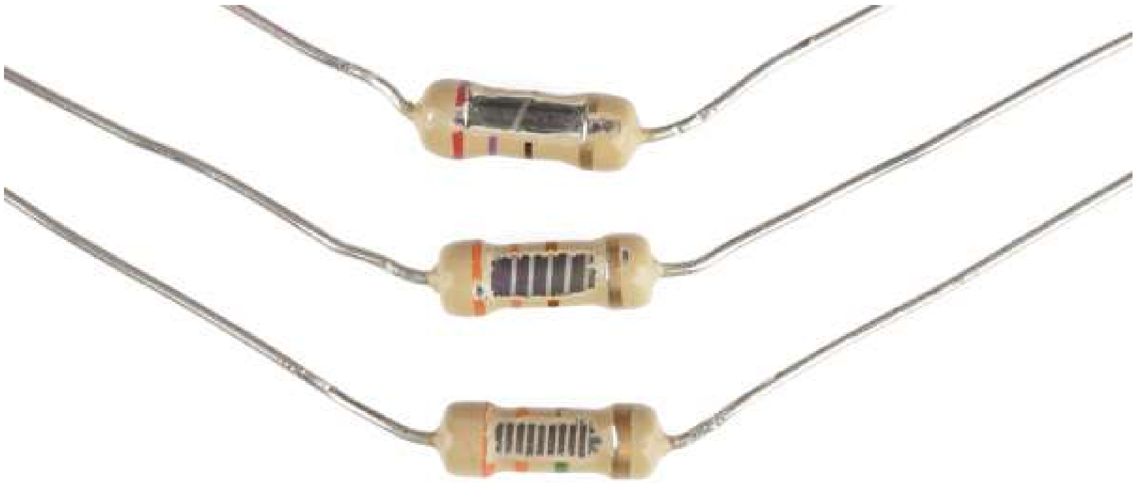
Surface-mount resistors are usually tiny black rectangles, terminated on either side with even smaller, shiny, silver, conductive edges. These resistors are intended to sit on top of PCBs, where they're soldered onto mating landing pads. Because these resistors are so small, they're usually set into place by a robot, and sent through an oven where solder melts and holds them in place.

A tiny 0603 330Ω resistor hovering over shiny George Washington's nose on top of a U.S. quarter.

SMD resistors come in standardized sizes; usually either 0805 (0.8mm long by 0.5mm wide), 0603, or 0402. They're great for mass circuit-board-production, or in designs where space is a precious commodity. They take a steady, precise hand to manually solder, though!

Resistor composition

Resistors can be constructed out of a variety of materials. Most common, modern resistors are made out of either a **carbon, metal, or metal-oxide film**. In these resistors, a thin film of conductive (though still resistive) material is wrapped in a helix around and covered by an insulating material. Most of the standard, no-frills, through-hole resistors will come in a carbon-film or metal-film composition.



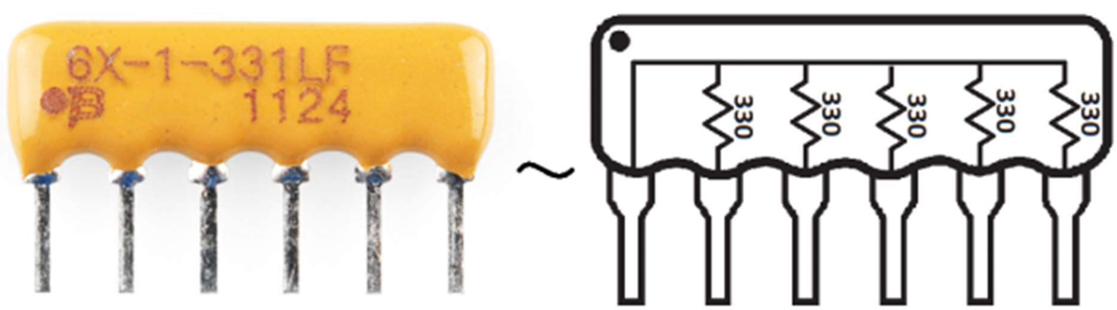
Peek inside the guts of a few carbon-film resistors. Resistance values from top to bottom: 27Ω, 330Ω and a 3.3MΩ. Inside the resistor, a carbon film is wrapped around an insulator. More wraps means a higher resistance. Pretty neat!

Other through-hole resistors might be wirewound or made of super-thin metallic foil. These resistors are usually more expensive, higher-end components specifically chosen for their unique characteristics like a higher power-rating, or maximum temperature range.

Surface-mount resistors are usually either **thick or thin-film** variety. Thick-film is usually cheaper but less precise than thin. In both resistor types, a small film of resistive metal alloy is sandwiched between a ceramic base and glass/epoxy coating, and then connected to the terminating conductive edges.

Special resistor packages

There are a variety of other, special-purpose resistors out there. Resistors may come in pre-wired packs of five-or-so resistor arrays. Resistors in these arrays may share a common pin, or be set up as voltage dividers.



An array of five 330Ω resistors, all tied together at one end.

Resistors don't have to be static either. Variable resistors, known as **rheostats**, are resistors which can be adjusted between a specific range of values. Similar to the rheostat is the **potentiometer**. Pots connect two resistors internally, in series, and adjust a center tap between them creating an adjustable voltage divider. These variable resistors are often used for inputs, like volume knobs, which need to be adjustable.

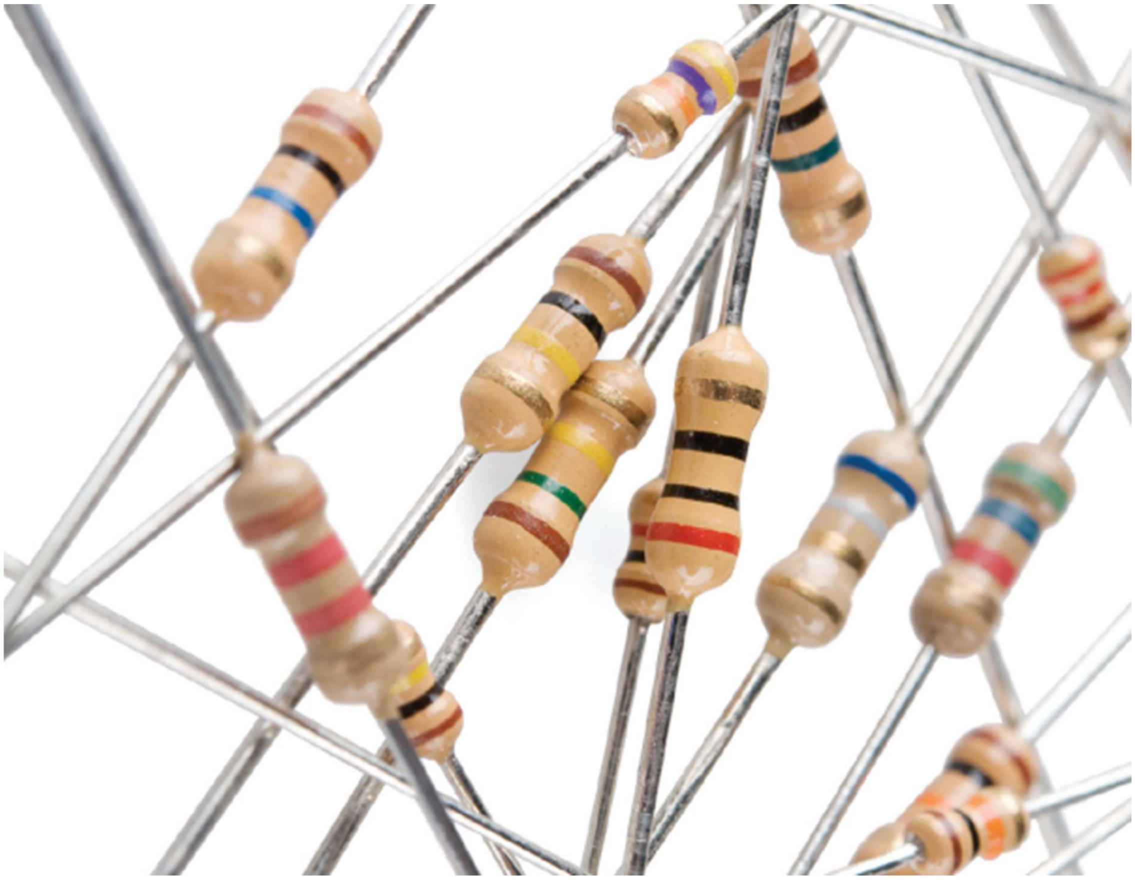
A smattering of potentiometers. From top-left, clockwise: a standard 10k trimpot, 2-axis joystick, softpot, slide pot, classic right-angle, and a breadboard friendly 10k trimpot.

Decoding Resistor Markings

Though they may not display their value outright, most resistors are marked to show what their resistance is. PTH resistors use a color-coding system (which really adds some flair to circuits), and SMD resistors have their own value-marking system.

Decoding the color bands

Through-hole, axial resistors usually use the color-band system to display their value. Most of these resistors will have four bands of color circling the resistor.



The first two bands indicate the **two most-significant digits** of the resistor's value. The third band is a weight value, which **multiplies** the two significant digits by a power of ten.

The final band indicates the **tolerance** of the resistor. The tolerance explains how much more or less the *actual*resistance of the resistor can be compared to what its nominal value is. No resistor is made to perfection, and different manufacturing processes will result in better or worse tolerances. For example, a 1kΩ resistor with 5% tolerance could actually be anywhere between 0.95kΩ and 1.05kΩ.

How do you tell which band is first and last? The last, tolerance band is often clearly separated from the value bands, and usually it'll either be silver or gold.

Here's a table of each of the colors and which value, multiplier or tolerance they represent:

Color	Digit value	Multiplier	Multiplied Out	Tolerance
Black	0	10^0	1	
Brown	1	10^1	10	
Red	2	10^2	100	
Orange	3	10^3	1,000	
Yellow	4	10^4	10000	
Green	5	10^5	100,000	
Blue	6	10^6	1,000,000	
Violet	7	10^7	10,000,000	
Gray	8	10^8	100,000,000	
White	9	10^9	1,000,000,000	
Gold				±5%
Silver				±10%

Here's an example of a 4.7kΩ resistor with four color bands:

When decoding the resistor color bands, consult a resistor color code table like the one above. For the first two bands, find that color's corresponding digit value. The 4.7kΩ resistor has color bands of yellow and violet to begin - which have digit values of 4 and 7 (47). The third band of the 4.7kΩ is red, which indicates that the 47 should be multiplied by 10^2 (or 100). 47 times 100 is 4,700!

If you're trying to commit the color band code to memory, a mnemonic device might help. There are a handful of(sometimes unsavory) mnemonics out there, to help remember the resistor color code. A good one, which spells out the difference between *b*lack and *b*rown is:

"**B**ig **b**rown **r**abbits **o**ften **y**ield **g**reat **b**ig **v**ocal **g**roans **w**hen **g**ingerly **s**napped."

Or, if you remember "ROY G. BIV", subtract the *indigo* (poor indigo, no one remembers indigo), and add black and brown to the front and gray and white to the back of the classic rainbow color-order.

Color Code Calculator

If you'd rather skip the math (we won't judge :), and just use a handy calculator, give this a try!

Band 1 Value 1 (MSV)	Band 2 Value 2	Band 3 Weight	Band 4 Tolerance
Brown (1)	Black (0)	Red (100)	

Resistance: 1,000 Ω ±5%

Decoding surface-mount markings

SMD resistors, like those in 0603 or 0805 packages, have their own way of displaying their value. There are a few common marking methods you'll see on these resistors. They'll usually have three to four characters – numbers or letters – printed on top of the case.

If the three characters you're seeing are *all numbers*, you're probably looking at an **E24** marked resistor. These markings actually share some similarity with the color-band system used on the PTH resistors. The first two numbers represent the first two most-significant digits of the value, the last number represents a magnitude.

In the above example picture, resistors are marked *104*, *105*, *205*, *751*, and *754*. The resistor marked with *104* should be 100kΩ (10×10^4), *105* would be 1MΩ (10×10^5), and *205* is 2MΩ (20×10^5). *751* is 750Ω (75×10^1), and *754* is 750kΩ (75×10^4).

Another common coding system is **E96**, and it's the most cryptic of the bunch. E96 resistors will be marked with three characters – two numbers at the beginning and a letter at the end. The two numbers tell you the first *three* digits of the value, by corresponding to one of the not-so-obvious values on this lookup table.

Code	Value	Code	Value	Code	Value	Code	Value	Code	Value	Code	Value
01	100	17	147	33	215	49	316	65	464	81	681
02	102	18	150	34	221	50	324	66	475	82	698
03	105	19	154	35	226	51	332	67	487	83	715
04	107	20	158	36	232	52	340	68	499	84	732
05	110	21	162	37	237	53	348	69	511	85	750
06	113	22	165	38	243	54	357	70	523	86	768
07	115	23	169	39	249	55	365	71	536	87	787
08	118	24	174	40	255	56	374	72	549	88	806
09	121	25	178	41	261	57	383	73	562	89	825
10	124	26	182	42	267	58	392	74	576	90	845
11	127	27	187	43	274	59	402	75	590	91	866
12	130	28	191	44	280	60	412	76	604	92	887
13	133	29	196	45	287	61	422	77	619	93	909
14	137	30	200	46	294	62	432	78	634	94	931
15	140	31	205	47	301	63	442	79	649	95	953
16	143	32	210	48	309	64	453	80	665	96	976

The letter at the end represents a multiplier, matching up to something on this table:

Letter	Multiplier	Letter	Multiplier	Letter	Multiplier
Z	0.001	A	1	D	1000
Y or R	0.01	B or H	10	E	10000
X or S	0.1	C	100	F	100000

So a *01C* resistor is our good friend, 10kΩ (100x100), *01B* is 1kΩ (100x10), and *01D* is 100kΩ. Those are easy, other codes may not be. *85A* from the picture above is 750Ω (750x1) and *30C* is actually 20kΩ.

Power Rating

The power rating of a resistor is one of the more hidden values. Nevertheless it can be important, and it's a topic that'll come up when selecting a resistor type.

Power is the rate at which energy is transformed into something else. It's calculated by multiplying the voltage difference across two points by the current running between them, and is measured in units of a watt (W). Light bulbs, for example, power electricity into light. But a resistor can only turn electrical energy running through it into **heat**. Heat isn't usually a nice playmate with electronics; too much heat leads to smoke, sparks, and fire!

Every resistor has a specific maximum power rating. In order to keep the resistor from heating up too much, it's important to make sure the power across a resistor is kept under it's maximum rating. The power rating of a resistor is measured in watts, and it's usually somewhere between ⅛W (0.125W) and 1W. Resistors with power ratings of more than 1W are usually referred to as power resistors, and are used specifically for their power dissipating abilities.

Finding a resistor's power rating

A resistor's power rating can usually be deduced by observing its package size. Standard through-hole resistors usually come with ¼W or ½W ratings. More special purpose, power resistors might actually list their power rating on the resistor.

These power resistors can handle a lot more power before they blow. From top-right to bottom-left there are examples of 25W, 5W and 3W resistors, with values of 2Ω, 3Ω 0.1Ω and 22kΩ. Smaller power-resistors are often used to sense current.

The power ratings of surface mount resistors can usually be judged by their size as well. Both 0402 and 0603-size resistors are usually rated for 1/16W, and 0805's can take 1/10W.

Measuring power across a resistor

Power is usually calculated by multiplying voltage and current (P = IV). But, by applying Ohm's law, we can also use the resistance value in calculating power. If we know the current running through a resistor, we can calculate the power as:

$$P = I^2 \cdot R$$

Or, if we know the voltage across a resistor, the power can be calculated as:

$$P = \frac{V^2}{R}$$

Series and Parallel Resistors

Resistors are paired together all the time in electronics, usually in either a series or parallel circuit. When resistors are combined in series or parallel, they create a **total resistance**, which can be calculated using one of two equations. Knowing how resistor values combine comes in handy if you need to create a specific resistor value.

Series resistors

When connected in series resistor values simply add up.

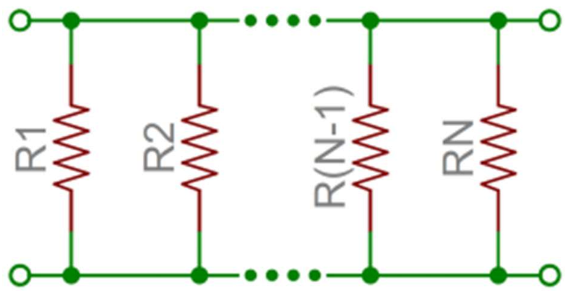
$$R_{tot} = R_1 + R_2 + ... + R_{N-1} + R_N$$

N resistors in series. The total resistance is the sum of all series resistors.

So, for example, if you just *have to have* a 12.33kΩ resistor, seek out some of the more common resistor values of 12kΩ and 330Ω, and butt them up together in series.

Parallel resistors

Finding the resistance of resistors in parallel isn't quite so easy. The total resistance of *N* resistors in parallel is the inverse of the sum of all inverse resistances. This equation might make more sense than that last sentence:



$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_{N-1}} + \frac{1}{R_N}$$

N resistors in parallel. To find the total resistance, invert each resistance value, add them up, and then invert that.

(The inverse of resistance is actually called **conductance**, so put more succinctly: the *conductance* of parallel resistors is the sum of each of their conductances).

As a special case of this equation: if you have **just two** resistors in parallel, their total resistance can be calculated with this slightly-less-inverted equation:

$$R_{tot} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

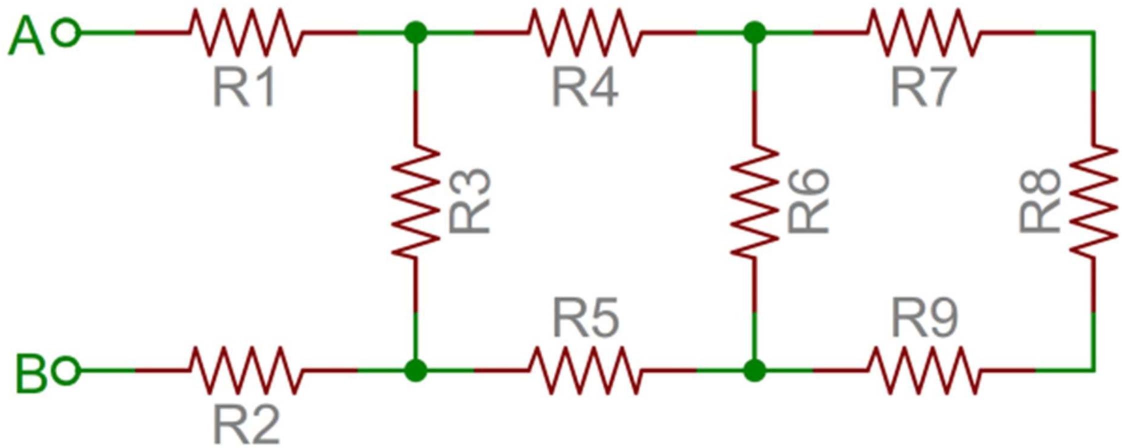
As an even *more special* case of that equation, if you have two parallel resistors of **equal value** the total resistance is half of their value. For example, if two 10kΩ resistors are in parallel, their total resistance is 5kΩ.

A shorthand way of saying two resistors are in parallel is by using the parallel operator: **||**. For example, if R_1 is in parallel with R_2, the conceptual equation could be written as $R_1||R_2$. Much cleaner, and hides all those nasty fractions!

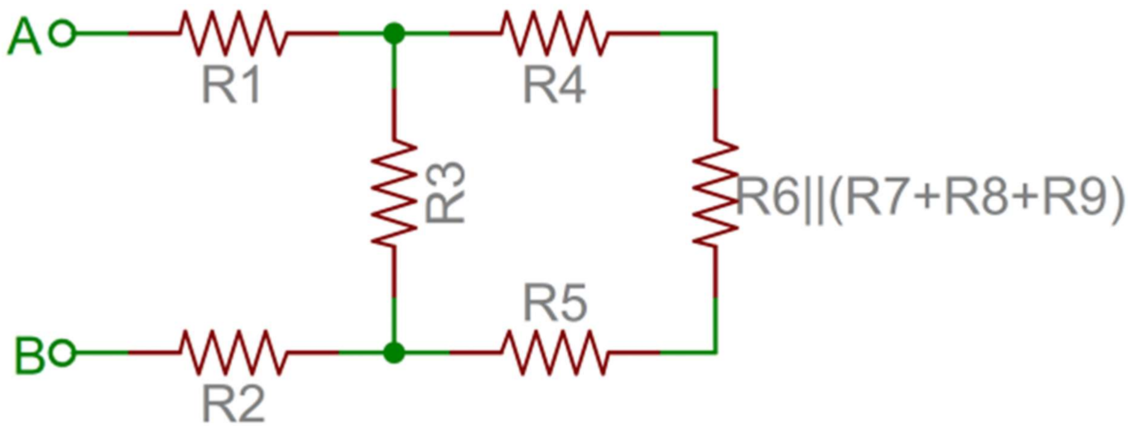
Resistor networks

As a special introduction to calculating total resistances, electronics teachers just *love* to subject their students to finding that of crazy, convoluted resistor networks.

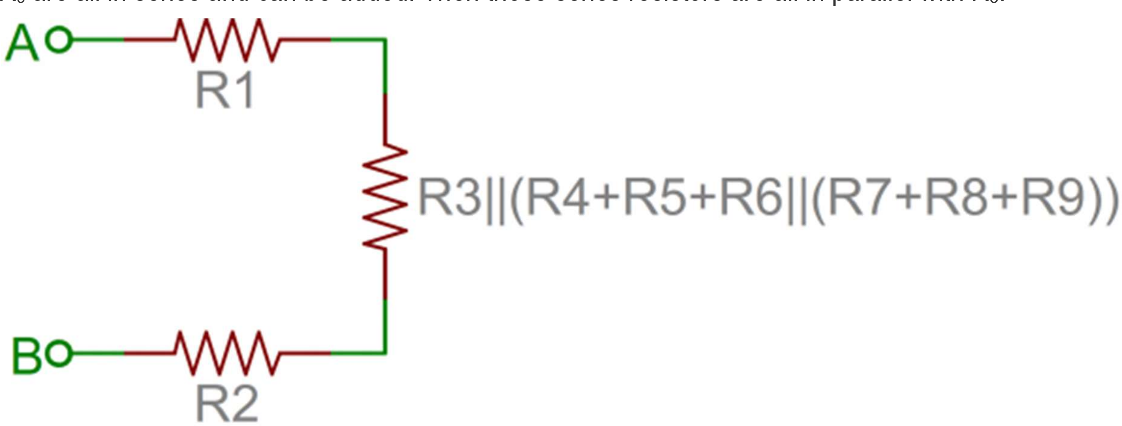
A tame resistor network question might be something like: "what's the resistance from terminals *A* to *B* in this circuit?"



To solve such a problem, start at the back-end of the circuit and simplify towards the two terminals. In this case R_7, $R_8$and R_9 are all in series and can be added together. Those three resistors are in parallel with R_6, so those four resistors could be turned into one with a resistance of $R_6||(R_7+R_8+R_9)$. Making our circuit:



Now the four right-most resistors can be simplified even further. R_4, R_5 and our conglomeration of R_6 - R_9 are all in series and can be added. Then those series resistors are all in parallel with R_3.



And that's just three series resistors between the *A* and *B* terminals. Add 'em on up! So the total resistance of that circuit is: $R_1+R_2+R_3||(R_4+R_5+R_6||(R_7+R_8+R_9))$.

Resistors exist in just about every electronic circuit ever. Here are a few examples of circuits, which heavily depend on our resistor friends.

Resistance standards

The primary standard for resistance, the "mercury ohm" was initially defined in 1884 in as a column of mercury 106.3 cm long and 1 square millimeter in cross-section, at 0 degrees Celsius. Difficulties in precisely measuring the physical constants to replicate this standard result in variations of as much as 30 ppm. From 1900 the mercury ohm was replaced with a precision machined plate of manganin.[20] Since 1990 the international resistance standard has been based on the quantized Hall effect discovered by Klaus von Klitzing, for which he won the Nobel Prize in Physics in 1985.[21]

Resistors of extremely high precision are manufactured for calibration and laboratory use. They may have four terminals, using one pair to carry an operating current and the other pair to measure the voltage drop; this eliminates errors caused by voltage drops across the lead resistances, because no charge flows through voltage sensing leads. It is important in small value resistors (100–0.0001 ohm) where lead resistance is significant or even comparable with respect to resistance standard value.[22]

CAPACITOR

Introduction

A capacitor is a two-terminal, electrical component. Along with resistors and inductors, they are one of the most fundamental **passive** components we use. You would have to look very hard to find a circuit which *didn't* have a capacitor in it.

Capacitor Theory

How a Capacitor Is Made

The schematic symbol for a capacitor actually closely resembles how it's made. A capacitor is created out of two metal plates and an insulating material called a **dielectric**. The metal plates are placed very close to each other, in parallel, but the dielectric sits between them to make sure they don't touch.

The dielectric can be made out of all sorts of insulating materials: paper, glass, rubber, ceramic, plastic, or anything that will impede the flow of current.

The plates are made of a conductive material: aluminum, tantalum, silver, or other metals. They're each connected to a terminal wire, which is what eventually connects to the rest of the circuit.

The capacitance of a capacitor – how many farads it has – depends on how it's constructed. More capacitance requires a larger capacitor. Plates with more overlapping surface area provide more capacitance, while more distance between the plates means less capacitance. The material of the dielectric even has an effect on how many farads a cap has. The total capacitance of a capacitor can be calculated with the equation:

$$C = \varepsilon_r \frac{A}{4\pi d}$$

Where ε_r is the dielectric's relative permittivity (a constant value determined by the dielectric material), *A* is the amount of area the plates overlap each other, and *d* is the distance between the plates.

How a Capacitor Works

Electric current is the flow of electric charge, which is what electrical components harness to light up, or spin, or do whatever they do. When current flows into a capacitor, the charges get "stuck" on the plates because they can't get past the insulating dielectric. Electrons – negatively charged particles – are sucked into one of the plates, and it becomes overall negatively charged. The large mass of negative charges on one plate pushes away like charges on the other plate, making it positively charged.

The positive and negative charges on each of these plates attract each other, because that's what opposite charges do. But, with the dielectric sitting between them, as much as they want to come together, the charges will forever be stuck on the plate (until they have somewhere else to go). The stationary charges on these plates create an electric field, which influence electric potential energy and voltage. When charges group together on a capacitor like this, the cap is storing electric energy just as a battery might store chemical energy.

Charging and Discharging

When positive and negative charges coalesce on the capacitor plates, the capacitor becomes **charged**. A capacitor can retain its electric field – hold its charge – because the positive and negative charges on each of the plates attract each other but never reach each other.

At some point the capacitor plates will be so full of charges that they just can't accept any more. There are enough negative charges on one plate that they can repel any others that try to join. This is where the **capacitance** (farads) of a capacitor comes into play, which tells you the maximum amount of charge the cap can store.

If a path in the circuit is created, which allows the charges to find another path to each other, they'll leave the capacitor, and it will **discharge**.

For example, in the circuit below, a battery can be used to induce an electric potential across the capacitor. This will cause equal but opposite charges to build up on each of the plates, until they're so full they repel any more current from flowing. An LED placed in series with the cap could provide a path for the current, and the energy stored in the capacitor could be used to briefly illuminate the LED.

Types of Capacitors

There are all sorts of capacitor types out there, each with certain features and drawbacks which make it better for some applications than others.

When deciding on capacitor types there are a handful of factors to consider:

- **Size** - Size both in terms of physical volume and capacitance. It's not uncommon for a capacitor to be the largest component in a circuit. They can also be very tiny. More capacitance typically requires a larger capacitor.
- **Maximum voltage** - Each capacitor is rated for a maximum voltage that can be dropped across it. Some capacitors might be rated for 1.5V, others might be rated for 100V. Exceeding the maximum voltage will usually result in destroying the capacitor.
- **Leakage current** - Capacitors aren't perfect. Every cap is prone to leaking some tiny amount of current through the dielectric, from one terminal to the other. This tiny current loss (usually nanoamps or less) is called leakage. Leakage causes energy stored in the capacitor to slowly, but surely drain away.
- **Equivalent series resistance (ESR)** - The terminals of a capacitor aren't 100% conductive, they'll always have a tiny amount of resistance (usually less than 0.01Ω) to them. This resistance becomes a problem when a lot of current runs through the cap, producing heat and power loss.
- **Tolerance** - Capacitors also can't be made to have an exact, precise capacitance. Each cap will be rated for their nominal capacitance, but, depending on the type, the exact value might vary anywhere from ±1% to ±20% of the desired value.

Ceramic Capacitors

The most commonly used and produced capacitor out there is the ceramic capacitor. The name comes from the material from which their dielectric is made.

Ceramic capacitors are usually both physically and capacitance-wise **small**. It's hard to find a ceramic capacitor much larger than 10µF. A surface-mount ceramic cap is commonly found in a tiny 0402 (0.4mm x 0.2mm), 0603 (0.6mm x 0.3mm) or 0805 package. Through-hole ceramic caps usually look like small (commonly yellow or red) bulbs, with two protruding terminals.

Compared to the equally popular electrolytic caps, ceramics are a more near-ideal capacitor (much lower ESR and leakage currents), but their small capacitance can be limiting. They are usually the least expensive option too. These caps are well-suited for high-frequency coupling and decoupling applications.

Aluminum and Tantalum Electrolytic

Electrolytics are great because they can pack *a lot* of capacitance into a relatively small volume. If you need a capacitor in the range of 1µF-1mF, you're most likely to find it in an electrolytic form. They're especially well suited to high-voltage applications because of their relatively high maximum voltage ratings.

Aluminum electrolytic capacitors, the most popular of the electrolytic family, usually look like little tin cans, with both leads extending from the bottom.

Unfortunately, electrolytic caps are usually **polarized**. They have a positive pin – the anode – and a negative pin called the cathode. When voltage is applied to an electrolytic cap, the anode must be at a higher voltage than the cathode. The cathode of an electrolytic capacitor is usually identified with a '-' marking, and a colored strip on the case. The leg of the anode might also be slightly longer as another indication. If voltage is applied in reverse on an electrolytic cap, they'll fail spectacularly (making a *pop* and bursting open), and permanently. After popping an electrolytic will behave like a short circuit.

These caps also notorious for **leakage** – allowing small amounts of current (on the order of nA) to run through the dielectric from one terminal to the other. This makes electrolytic caps less-than-ideal for energy storage, which is unfortunate given their high capacity and voltage rating.

Supercapacitors

If you're looking for a capacitor made to store energy, look no further than supercapacitors. These caps are uniquely designed to have *very* high capacitances, in the range of farads.

While they can store a huge amount of charge, supercaps can't deal with very high voltages. This 10F supercap is only rated for 2.5V max. Any more than that will destroy it. Super caps are commonly placed in series to achieve a higher voltage rating (while reducing total capacitance).

The main application for supercapacitors is in **storing and releasing energy**, like batteries, which are their main competition. While supercaps can't hold as much energy as an equally sized battery, they can release it much faster, and they usually have a much longer lifespan.

Others

Electrolytic and ceramic caps cover about 80% of the capacitor types out there (and supercaps only about 2%, but they're super!). Another common capacitor type is the **film capacitor**, which features very low parasitic losses (ESR), making them great for dealing with very high currents.

There's plenty of other less common capacitors. **Variable capacitors** can produce a range of capacitances, which makes them a good alternative to variable resistors in tuning circuits. Twisted wires or PCBs can create capacitance (sometimes undesired) because each consists of two conductors separated by an insulator. Leyden Jars – a glass jar filled with and surrounded by conductors – are the O.G. of the capacitor family. Finally, of course, flux capacitors (a strange combination of inductor and capacitor) are critical if you ever plan on traveling back to the glory days.

Energy Storage and Supply

It seems obvious that if a capacitor stores energy, one of it's many applications would be supplying that energy to a circuit, just like a battery. The problem is capacitors have a much lower **energy density** than batteries; they just can't pack as much energy as an equally sized chemical battery (but that gap is narrowing!).

The upside of capacitors is they usually lead longer lives than batteries, which makes them a better choice environmentally. They're also capable of delivering energy much faster than a battery, which makes them good for applications which need a short, but high burst of power. A camera flash might get its power from a capacitor (which, in turn, was probably charged by a battery).

Battery or Capacitor?

	Battery	**Capacitor**
Capacity	✓	
Energy Density	✓	
Charge/Discharge Rate		✓
Life Span		✓

Signal Filtering

Capacitors have a unique response to signals of varying frequencies. They can block out low-frequency or DC signal-components while allowing higher frequencies to pass right through. They're like a bouncer at a very exclusive club for high frequencies only.

Filtering signals can be useful in all sorts of signal processing applications. Radio receivers might use a capacitor (among other components) to tune out undesired frequencies.

Another example of capacitor signal filtering is passive **crossover** circuits inside speakers, which separate a single audio signal into many. A series capacitor will block out low frequencies, so the remaining high-frequency parts of the signal can go to the speaker's tweeter. In the low-frequency passing, subwoofer circuit, high-frequencies can mostly be shunted to ground through the parallel capacitor.

Hydraulic analogy

In the hydraulic analogy, a capacitor is analogous to a rubber membrane sealed inside a pipe. This animation illustrates a membrane being repeatedly stretched and un-stretched by the flow of water, which is analogous to a capacitor being repeatedly charged and discharged by the flow of charge.

In the hydraulic analogy, charge carriers flowing through a wire are analogous to water flowing through a pipe. A capacitor is like a rubber membrane sealed inside a pipe. Water molecules cannot pass through the membrane, but some water can move by stretching the membrane. The analogy clarifies a few aspects of capacitors:

- *The current alters the charge on a capacitor*, just as the flow of water changes the position of the membrane. More specifically, the effect of an electric current is to increase the charge of one plate of the capacitor, and decrease the charge of the other plate by an equal amount. This is just as when water flow moves the rubber membrane, it increases the amount of water on one side of the membrane, and decreases the amount of water on the other side.

- *The more a capacitor is charged, the larger its voltage drop*; i.e., the more it "pushes back" against the charging current. This is analogous to the fact that the more a membrane is stretched, the more it pushes back on the water.
- *Charge can flow "through" a capacitor even though no individual electron can get from one side to the other.* This is analogous to water flowing through the pipe even though no water molecule can pass through the rubber membrane. The flow cannot continue in the same direction forever; the capacitor experiences dielectric breakdown, and analogously the membrane will eventually break.
- The *capacitance* describes how much charge can be stored on one plate of a capacitor for a given "push" (voltage drop). A very stretchy, flexible membrane corresponds to a higher capacitance than a stiff membrane.
- A charged-up capacitor is storing potential energy, analogously to a stretched membrane.

Energy of electric field

Work must be done by an external influence to "move" charge between the conductors in a capacitor. When the external influence is removed, the charge separation persists in the electric field and energy is stored to be released when the charge is allowed to return to its equilibrium position. The work done in establishing the electric field, and hence the amount of energy stored.

Here Q is the charge stored in the capacitor, V is the voltage across the capacitor, and C is the capacitance.

In the case of a fluctuating voltage $V(t)$, the stored energy also fluctuates and hence power must flow into or out of the capacitor. This power can be found by taking the time derivative of the stored energy:

A real capacitor with loss may be modeled as an ideal capacitor that has an equivalent series resistance (ESR) which dissipates power as the capacitor is charged or discharged. For a sinusoidal input voltage the power dissipated due to the ESR is given as:

Current–voltage relation

The current $I(t)$ through any component in an electric circuit is defined as the rate of flow of a charge $Q(t)$ passing through it, but actual charges—electrons—

cannot pass through the dielectric layer of a capacitor. Rather, one electron accumulates on the negative plate for each one that leaves the positive plate, resulting in an electron depletion and consequent positive charge on one electrode that is equal and opposite to the accumulated negative charge on the other. Thus the charge on the electrodes is equal to the integral of the current as well as proportional to the voltage, as discussed above. As with any antiderivative, a constant of integration is added to represent the initial voltage $V(t_0)$.

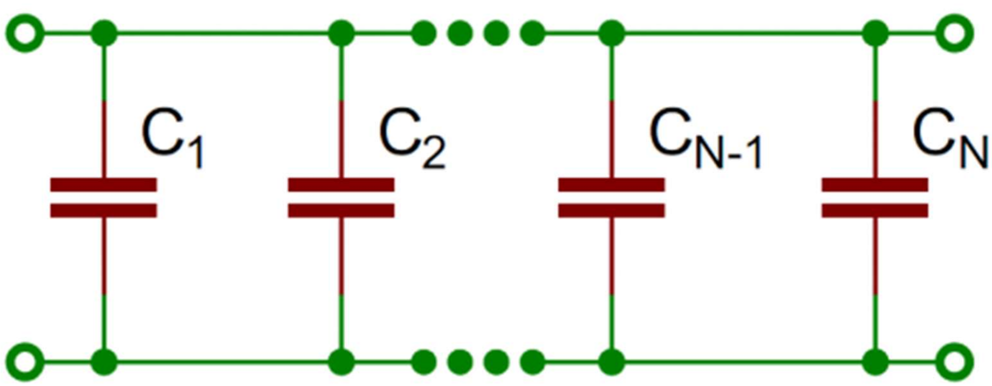
The dual of the capacitor is the inductor, which stores energy in a magnetic field rather than an electric field. Its current-voltage relation is obtained by exchanging current and voltage in the capacitor equations and replacing *C* with the inductance *L*.

Capacitors in Series/Parallel

Much like resistors, multiple capacitors can be combined in series or parallel to create a combined equivalent capacitance. Capacitors, however, add together in a way that's **completely the opposite** of resistors.

Capacitors in Parallel

When capacitors are placed in parallel with one another the total capacitance is simply the **sum of all capacitances**. This is analogous to the way resistors add when in series.



$$C_{Tot} = C_1 + C_2 + \ldots + C_{N-1} + C_N$$

So, for example, if you had three capacitors of values 10µF, 1µF, and 0.1µF in parallel, the total capacitance would be 11.1µF (10+1+0.1).

Capacitors in Series

Much like resistors are a pain to add in parallel, capacitors get funky when placed in *series*. The total capacitance of *N* capacitors in series is the inverse of the sum of all inverse capacitances.

$$\frac{1}{C_{Tot}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_{N-1}} + \frac{1}{C_N}$$

If you only have **two** capacitors in series, you can use the “product-over-sum” method to calculate the total capacitance:

$$C_{Tot} = \frac{C_1 C_2}{C_1 + C_2}$$

Taking that equation even further, if you have **two equal-valued capacitors in series**, the total capacitance is half of their value. For example two [10F supercapacitors] in series will produce a total capacitance of 5F (it’ll also have the benefit of doubling the voltage rating of the total capacitor, from 2.5V to 5V).

Application Examples

There are tons of applications for this nifty little (actually they’re usually pretty large) passive component. To give you an idea of their wide range of uses, here are a few examples:

Decoupling (Bypass) Capacitors

A lot of the capacitors you see in circuits, especially those featuring an integrated circuit, are decoupling. A decoupling capacitor's job is to supress high-frequency noise in power supply signals. They take tiny voltage ripples, which could otherwise be harmful to delicate ICs, out of the voltage supply.

In a way, decoupling capacitors act as a very small, local power supply for ICs (almost like an uninterupptable power supply is to computers). If the power supply very temporarily drops its voltage (which is actually pretty common, especially when the circuit it's powering is constantly switching its load requirements), a decoupling capacitor can briefly supply power at the correct voltage. This is why these capacitors are also called **bypass** caps; they can temporarily act as a power source, *bypassing* the power supply.

Decoupling capacitors connect between the power source (5V, 3.3V, etc.) and ground. It's not uncommon to use two or more different-valued, even different types of capacitors to bypass the power supply, because some capacitor values will be better than others at filtering out certain frequencies of noise.

Non-ideal behavior

Capacitors deviate from the ideal capacitor equation in a number of ways. Some of these, such as leakage current and parasitic effects are linear, or can be analyzed as nearly linear, and can be dealt with by adding virtual components to the equivalent circuit of an ideal capacitor. The usual methods of network analysis can then be applied. In other cases, such as with breakdown voltage, the effect is non-linear and ordinary (normal, e.g., linear) network analysis cannot be used, the effect must be dealt with separately. There is yet another group, which may be linear but invalidate the assumption in the analysis that capacitance is a constant. Such an example is temperature dependence. Finally, combined parasitic effects such as inherent inductance, resistance, or dielectric losses can exhibit non-uniform behavior at variable frequencies of operation.

Breakdown voltage

Above a particular electric field, known as the dielectric strength E_{ds}, the dielectric in a capacitor becomes conductive. The voltage at which this occurs is called the breakdown voltage of the device, and is given by the product of the dielectric strength and the separation between the conductors,[25] The maximum energy that can be stored safely in a capacitor is limited by the breakdown voltage. Due to the scaling of capacitance and breakdown voltage with dielectric thickness, all capacitors made with a particular dielectric have approximately equal maximum energy density, to the extent that the dielectric dominates their volume.[26]

For air dielectric capacitors the breakdown field strength is of the order 2 to 5 MV/m; for mica the breakdown is 100 to 300 MV/m; for oil, 15 to 25 MV/m; it can be much less when other materials are used for the dielectric.[27] The dielectric is used in very thin layers and so absolute breakdown voltage of capacitors is limited. Typical ratings for capacitors used for general electronics applications range from a few volts to 1 kV. As the voltage increases, the dielectric must be thicker, making high-voltage capacitors larger per capacitance than those rated for lower voltages. The breakdown voltage is critically affected by factors such as the geometry of the capacitor conductive parts; sharp edges or points increase the electric field strength at that point and can lead to a local breakdown. Once this starts to happen, the breakdown quickly tracks through the dielectric until it reaches the opposite plate, leaving carbon behind and causing a short (or relatively low resistance) circuit. The results can be explosive as the short in the capacitor draws current from the surrounding circuitry and dissipates the energy. However, in capacitors with particular dielectrics and thin metal electrodes shorts are not formed after breakdown. It happens because a metal melts or evaporates in a breakdown vicinity, isolating it from the rest of the capacitor.

The usual breakdown route is that the field strength becomes large enough to pull electrons in the dielectric from their atoms thus causing conduction. Other scenarios are possible, such as impurities in the dielectric, and, if the dielectric is of a crystalline nature, imperfections in the crystal structure can result in an avalanche breakdown as seen in semi-conductor devices. Breakdown voltage is also affected by pressure, humidity and temperature.

Q factor

The quality factor (or *Q*) of a capacitor is the ratio of its reactance to its resistance at a given frequency, and is a measure of its efficiency. The higher the Q factor of the capacitor, the closer it approaches the behavior of an ideal, lossless, capacitor.

Ripple current

Ripple current is the AC component of an applied source (often a switched-mode power supply) whose frequency may be constant or varying. Ripple current causes heat to be generated within the capacitor due to the dielectric losses caused by the changing field strength together with the current flow across the slightly resistive supply lines or the electrolyte in the capacitor. The equivalent series resistance (ESR) is the amount of internal series resistance one would add to a perfect capacitor to model this.

Some types of capacitors, primarily tantalum and aluminum electrolytic capacitors, as well as some film capacitors have a specified rating value for maximum ripple current.

Tantalum electrolytic capacitors with solid manganese dioxide electrolyte are limited by ripple current and generally have the highest ESR ratings in the capacitor family. Exceeding their ripple limits can lead to shorts and burning.

Film capacitors have very low ESR ratings but exceeding rated ripple current may cause degradation failures.

The capacitance of certain capacitors decreases as the component ages. In ceramic capacitors, this is caused by degradation of the dielectric. The type of dielectric, ambient operating and storage temperatures are the most significant aging factors, while the operating voltage has a smaller effect. The aging process may be reversed by heating the component above the Curie point. Aging is fastest near the beginning of life of the component, and the device stabilizes over time.[34] Electrolytic capacitors age as the electrolyte evaporates. In contrast with ceramic capacitors, this occurs towards the end of life of the component.

Temperature dependence of capacitance is usually expressed in parts per million (ppm) per °C. It can usually be taken as a broadly linear function but can be noticeably non-linear at the temperature extremes. The temperature coefficient can be either positive or negative, sometimes even amongst different samples of the same type. In other words, the spread in the range of temperature coefficients can encompass zero.

Capacitors, especially ceramic capacitors, and older designs such as paper capacitors, can absorb sound waves resulting in a microphonic effect. Vibration moves the plates, causing the capacitance to vary, in turn inducing AC current. Some dielectrics also generate piezoelectricity. The resulting interference is especially problematic in audio applications, potentially causing feedback or unintended recording. In the reverse microphonic effect, the varying electric field between the capacitor plates exerts a physical force, moving them as a speaker.

This can generate audible sound, but drains energy and stresses the dielectric and the electrolyte, if any.

Current and voltage reversal

Current reversal occurs when the current changes direction. Voltage reversal is the change of polarity in a circuit. Reversal is generally described as the percentage of the maximum rated voltage that reverses polarity. In DC circuits, this is usually less than 100%, often in the range of 0 to 90%, whereas AC circuits experience 100% reversal.

In DC circuits and pulsed circuits, current and voltage reversal are affected by the damping of the system. Voltage reversal is encountered in RLC circuits that are underdamped. The current and voltage reverse direction, forming a harmonic oscillator between the inductance and capacitance. The current and voltage tends to oscillate and may reverse direction several times, with each peak being lower than the previous, until the system reaches an equilibrium. This is often referred to as ringing. In comparison, critically damped or overdamped systems usually do not experience a voltage reversal. Reversal is also encountered in AC circuits, where the peak current is equal in each direction.

For maximum life, capacitors usually need to be able to handle the maximum amount of reversal that a system may experience. An AC circuit experiences 100% voltage reversal, while underdamped DC circuits experience less than 100%. Reversal creates excess electric fields in the dielectric, causes excess heating of both the dielectric and the conductors, and can dramatically shorten the life expectancy of the capacitor. Reversal ratings often affect the design considerations for the capacitor, from the choice of dielectric materials and voltage ratings to the types of internal connections used.[35]

Dielectric absorption

Capacitors made with any type of dielectric material show some level of "dielectric absorption" or "soakage". On discharging a capacitor and disconnecting it, after a short time it may develop a voltage due to hysteresis in the dielectric. This effect is objectionable in applications such as precision sample and hold circuits or timing circuits. The level of absorption depends on many factors, from design considerations to charging time, since the absorption is a time-dependent process. However, the primary factor is the type of dielectric material. Capacitors such as tantalum electrolytic or polysulfone film exhibit relatively high absorption, while polystyrene or Teflon allow very small levels of absorption.[36]In some capacitors where dangerous voltages and energies exist, such as in flashtubes, television sets, and defibrillators, the dielectric absorption can recharge the capacitor to hazardous voltages after it has been shorted or discharged. Any capacitor containing over 10 joules of energy is generally considered hazardous, while 50 joules or higher is potentially lethal. A capacitor may regain anywhere from 0.01 to 20% of its original charge over a period of several minutes, allowing a seemingly safe capacitor to become surprisingly dangerous.

Leakage

Leakage is equivalent to a resistor in parallel with the capacitor. Constant exposure to heat can cause dielectric breakdown and excessive leakage, a problem often seen in older vacuum tube circuits, particularly where oiled paper and foil capacitors were used. In many vacuum tube circuits, interstage coupling capacitors are used to conduct a varying signal from the plate of one tube to the grid circuit of the next stage. A leaky capacitor can cause the grid circuit voltage to be raised from its normal bias setting, causing excessive current or signal distortion in the downstream tube. In power amplifiers this can cause the plates to glow red, or current limiting resistors to overheat, even fail. Similar considerations apply to component fabricated solid-state (transistor) amplifiers, but owing to lower heat production and the use of modern polyester dielectric barriers this once-common problem has become relatively rare.

Electrolytic failure from disuse

Aluminum electrolytic capacitors are *conditioned* when manufactured by applying a voltage sufficient to initiate the proper internal chemical state. This state is maintained by regular use of the equipment. If a system using electrolytic capacitors is unused for a long period of time it can lose its conditioning. Sometimes they fail with a short circuit when next operated.

Voltage-dependent capacitors

The dielectric constant for a number of very useful dielectrics changes as a function of the applied electrical field, for example ferroelectric materials, so the capacitance for these devices is more complex. For example, in charging such a capacitor the differential increase in voltage with charge is governed by

where the voltage dependence of capacitance, $C(V)$, suggests that the capacitance is a function of the electric field strength, which in a large area parallel plate device is given by $\mathcal{E} = V/d$. This field polarizes the dielectric, which polarization, in the case of a ferroelectric, is a nonlinear S-shaped function of the electric field, which, in the case of a large area parallel plate device, translates into a capacitance that is a nonlinear function of the voltage.

Corresponding to the voltage-dependent capacitance, to charge the capacitor to voltage V an integral relation is found

which agrees with $Q = CV$ only when C does not depend on voltage V.

By the same token, the energy stored in the capacitor now is given by

The nonlinear capacitance of a microscope probe scanned along a ferroelectric surface is used to study the domain structure of ferroelectric materials.[45]

Another example of voltage dependent capacitance occurs in semiconductor devices such as semiconductor diodes, where the voltage dependence stems not from a change in dielectric constant but in a voltage dependence of the spacing between the charges on the two sides of the capacitor.[46] This effect is intentionally exploited in diode-like devices known as varicaps.

Frequency-dependent capacitors

If a capacitor is driven with a time-varying voltage that changes rapidly enough, at some frequency the polarization of the dielectric cannot follow the voltage. As an example of the origin of this mechanism, the internal microscopic dipoles contributing to the dielectric constant cannot move instantly, and so as frequency of an applied alternating voltage increases, the dipole response is limited and the dielectric constant diminishes. A changing dielectric constant with frequency is referred to as dielectric dispersion, and is governed by dielectric relaxation processes, such as Debye relaxation.

> At optical frequencies, in semiconductors the dielectric constant exhibits structure related to the band structure of the solid. Sophisticated modulation spectroscopy measurement methods based upon modulating the crystal structure by pressure or by other stresses and observing the related changes in absorption or reflection of light have advanced our knowledge of these materials.[56]

Capacitor markings

Most capacitors have numbers printed on their bodies to indicate their electrical characteristics. Larger capacitors like electrolytics usually display the actual capacitance together with the unit, for example, *220 μF*. Smaller capacitors like ceramics, however, use a shorthand-notation consisting of three digits and a letter, where the digits indicate the capacitance in pF, calculated as XY × 10^Z for digits XYZ, and the letter indicates the tolerance. Common tolerance indications are J, K, and M for ±5%, ±10%, and ±20%, respectively.

Additionally, the capacitor may be labeled with its working voltage, temperature and other relevant characteristics.

For typographical reasons, some manufacturers print *MF* on capacitors to indicate microfarads (μF).

Example

A capacitor labeled or designated as *473K 330V* has a capacitance of 47 × 10^3 pF = 47 nF (±10%) with a maximum working voltage of 330 V. The working voltage of a capacitor is nominally the highest voltage that may be applied across it without undue risk of breaking down the dielectric layer.

Letter and digit code

The notation to state a capacitor's value in a circuit diagram varies. The letter and digit code for capacitance values following IEC 60062 and BS 1852 avoids using a decimal separator and replaces the decimal separator with the SI prefix symbol for the particular value (and the letter `F` for weight 1). Example: `4n7` for 4.7 nF or `2F2` for 2.2 F.

Noise suppression, spikes, and snubber

When an inductive circuit is opened, the current through the inductance collapses quickly, creating a large voltage across the open circuit of the switch or relay. If the inductance is large enough, the energy may generate a spark, causing the contact points to oxidize, deteriorate, or sometimes weld together, or destroying a solid-state switch. A snubber capacitor across the newly opened circuit creates a path for this impulse to bypass the contact points, thereby preserving their life; these were commonly found in contact breakerignition systems, for instance. Similarly, in smaller scale circuits, the spark may not be enough to damage the switch but may still radiate undesirable radio frequency interference (RFI), which a filter capacitor absorbs. Snubber capacitors are usually employed with a low-value resistor in series, to dissipate energy and minimize RFI. Such resistor-capacitor combinations are available in a single package.

Capacitors are also used in parallel to interrupt units of a high-voltage circuit breaker in order to equally distribute the voltage between these units. In this case they are called grading capacitors.

In schematic diagrams, a capacitor used primarily for DC charge storage is often drawn vertically in circuit diagrams with the lower, more negative, plate drawn as an arc. The straight plate indicates the positive terminal of the device, if it is polarized .

Motor starters

In single phase squirrel cage motors, the primary winding within the motor housing is not capable of starting a rotational motion on the rotor, but is capable of sustaining one. To start the motor, a secondary "start" winding has a series non-polarized *starting capacitor* to introduce a lead in the sinusoidal current. When the secondary (start) winding is placed at an angle with respect to the primary (run) winding, a rotating electric field is created. The force of the rotational field is not constant, but is sufficient to start the rotor spinning. When the rotor comes close to operating speed, a centrifugal switch (or current-sensitive relay in series with the main winding) disconnects the capacitor. The start capacitor is typically mounted to the side of the motor housing. These are called capacitor-start motors, that have relatively high starting torque. Typically they can have up-to four times as much starting torque than a split-phase motor and are used on applications such as compressors, pressure washers and any small device requiring high starting torques.

Capacitor-run induction motors have a permanently connected phase-shifting capacitor in series with a second winding. The motor is much like a two-phase induction motor.

Motor-starting capacitors are typically non-polarized electrolytic types, while running capacitors are conventional paper or plastic film dielectric types.

Signal processing

The energy stored in a capacitor can be used to represent information, either in binary form, as in DRAMs, or in analogue form, as in analog sampled filters and CCDs. Capacitors can be used in analog circuits as components of integrators or more complex filters and in negative feedback loop stabilization. Signal processing circuits also use capacitors to integrate a current signal.

An inductor is a passive electronic component that stores energy in the form of a magnetic field. In its simplest form, an inductor consists of a wire loop or coil. The inductance is directly proportional to the number of turns in the coil. Inductance also depends on the radius of the coil and on the type of material around which the coil is wound.

For a given coil radius and number of turns, air core result in the least inductance. Materials such as wood, glass, and plastic - known as dielectric materials - are essentially the same as air for the purposes of inductor winding. Ferromagnetic substances such as iron, laminated iron, and powdered iron increase the inductance obtainable with a coil having a given number of turns. In some cases, this increase is on the order of thousands of times. The shape of the core is also significant. Toroidal (donut-shaped) cores provide more inductance, for a given core material and number of turns, than solenoidal (rod-shaped) cores.

The standard unit of inductance is the henry, abbreviated H. This is a large unit. More common units are the microhenry, abbreviated µH (1 µH =10^{-6}H) and the millihenry, abbreviated mH (1 mH =10^{-3} H). Occasionally, the nanohenry (nH) is used (1 nH = 10^{-9} H).

It is difficult to fabricate inductors onto integrated circuit (IC) chips. Fortunately, resistors can be substituted for inductors in most microcircuit applications. In some cases, inductance can be simulated by simple electronic circuits using transistors, resistors, and capacitors fabricated onto IC

chips.

Inductors are used with capacitors in various wireless

communications applications. An inductor connected in series or parallel with a capacitor can provide discrimination against unwanted signals. Large inductors are used in the power supplies of electronic equipment of all types, including computers and their peripherals. In these systems, the inductors help to smooth out the rectified utility AC, providing pure, battery-like DC.

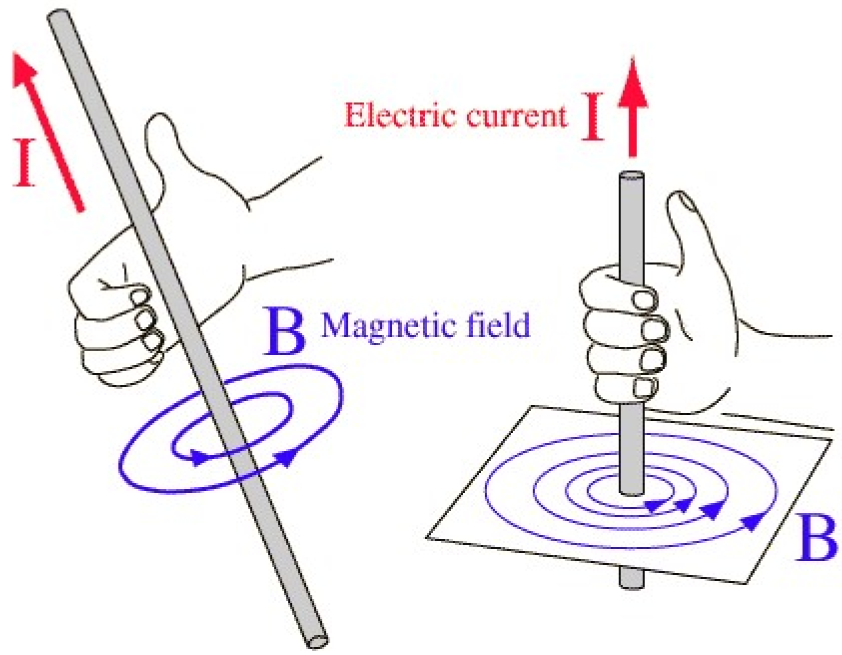
Description

An electric current flowing through a conductor generates a magnetic field surrounding it. Any changes of current and therefore in the magnetic flux through the cross-section of the inductor creates an opposing electromotive force in the conductor.

The inductance of a circuit depends on the geometry of the current path as well as the magnetic permeability of nearby materials. An inductor is a component consisting of a wire or other conductor shaped to increase the magnetic flux through the circuit, usually in the shape of a coil or helix. Winding the wire into a coil increases the number of times the magnetic flux lines link the circuit, increasing the field and thus the inductance. The more turns, the higher the inductance. The inductance also depends on the shape of the coil, separation of the turns, and many other factors. By adding a "magnetic core" made of a ferromagnetic material like iron inside the coil, the magnetizing field from the coil will induce magnetization in the material, increasing the magnetic flux. The high permeability of a ferromagnetic core can increase the inductance of a coil by a factor of several thousand over what it would be without it.

Lenz's law

Lenz's law **states that the current induced in a circuit due to a change or a motion in a magnetic field is so directed as to oppose the change in flux and to exert a mechanical force opposing the motion.**



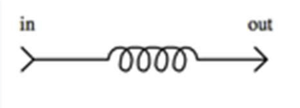
Lenz**'** law **is a manifestation of the conservation of energy. The induced EMF produces a current that opposes the change in flux, because a change in flux means a change in energy. ...** Lenz**'** law **is a consequence. As the change begins, the** law **says induction opposes and, thus, slows the change**.

Ideal and real inductors

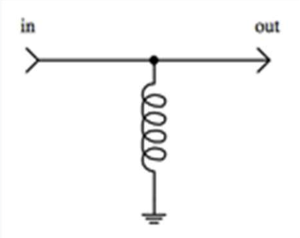
In circuit theory, inductors are idealized as obeying the mathematical relation (2) above precisely. An "ideal inductor" has inductance, but no resistance or capacitance, and does not dissipate or radiate energy. However real inductors have side effects which cause their behavior to depart from this simple model. They have resistance (due to the resistance of the wire and energy losses in core material), and parasitic capacitance (due to the electric field between the turns of wire which are at slightly different potentials). At high frequencies the capacitance begins to affect the inductor's behavior; at some frequency, real inductors behave as resonant circuits, becoming self-resonant. Above the resonant frequency the capacitive reactance becomes the dominant part of the impedance. At higher frequencies, resistive losses in the windings increase due to skin effect and proximity effect.

Inductors with ferromagnetic cores have additional energy losses due to hysteresis and eddy currents in the core, which increase with frequency. At high currents, iron core inductors also show gradual departure from ideal behavior due to nonlinearity caused by magnetic saturation of the core. An inductor may radiate electromagnetic energy into surrounding space and circuits, and may absorb electromagnetic emissions from other circuits, causing electromagnetic interference (EMI). For real-world inductor applications, these parasitic parameters may be as important as the inductance.

Applications



Example of signal filtering. In this configuration, the inductor blocks AC current, while allowing DC current to pass.



Example of signal filtering. In this configuration, the inductor decouples DC current, while allowing AC current to pass.

- Large 50 MVAR three-phase iron-core loading inductor at an Austrian utility substation

- A ferrite "bead" choke, consisting of an encircling ferrite cylinder, suppresses electronic noise in a computer power cord.

Inductors are used extensively in analog circuits and signal processing. Applications range from the use of large inductors in power supplies, which in conjunction with filter capacitors remove residual hums known as the mains hum or other fluctuations from the direct current output, to the small inductance of the ferrite bead or torus installed around a cable to prevent radio frequency interference from being transmitted down the wire. Inductors are used as the energy storage device in many switched-mode power supplies to produce DC current. The inductor supplies energy to the circuit to keep current flowing during the "off" switching periods.

An inductor connected to a capacitor forms a tuned circuit, which acts as a resonator for oscillating current. Tuned circuits are widely used in radio frequency equipment such as radio transmitters and receivers, as narrow bandpass filters to select a single frequency from a composite signal, and in electronic oscillators to generate sinusoidal signals.

Two (or more) inductors in proximity that have coupled magnetic flux (mutual inductance) form a transformer, which is a fundamental component of every electric utility power grid. The efficiency of a transformer may decrease as the frequency increases due to eddy currents in the core material and skin effect on the windings. The size of the core can be decreased at higher frequencies. For this reason, aircraft use 400 hertz alternating current rather than the usual 50 or 60 hertz, allowing a great saving in weight from the use of smaller transformers.

Inductors are also employed in electrical transmission systems, where they are used to limit switching currents and fault currents. In this field, they are more commonly referred to as reactors.

Because inductors have complicated side effects (detailed below) which cause them to depart from ideal behavior, because they can radiate electromagnetic interference (EMI), and most of all because of their bulk which prevents them from being integrated on semiconductor chips, the use of inductors is declining in modern electronic devices, particularly compact portable devices. Real inductors are increasingly being replaced by active circuits such as the gyrator which can synthesize inductance using capacitors.

Inductor construction

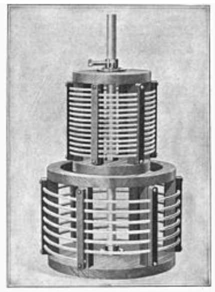
Small inductors can be etched directly onto a printed circuit board by laying out the trace in a spiral pattern. Some such planar inductors use a planar core.

Small value inductors can also be built on integrated circuits using the same processes that are used to make transistors. Aluminium interconnect is typically used, laid out in a spiral coil pattern. However, the small dimensions limit the inductance, and it is far more common to use a circuit called a "gyrator" that uses a capacitor and active components to behave similarly to an inductor.

An inductor usually consists of a coil of conducting material, typically insulated copper wire, wrapped around a core either of plastic or of a ferromagnetic (or ferrimagnetic) material; the latter is called an "iron core" inductor. Since power inductors require high induction levels, high permeability and low saturation points in the core materials are not ideal.[8] The high permeability of the ferromagnetic core increases the magnetic field and confines it closely to the inductor, thereby increasing the inductance. Low frequency inductors are constructed like transformers, with cores of electrical steel laminated to prevent eddy currents.
'Soft' ferrites are widely used for cores above audio frequencies, since they do not cause the large energy losses at high frequencies that ordinary iron alloys do. Inductors come in many shapes. Most are constructed as enamel coated wire (magnet wire) wrapped around a ferrite bobbin with wire exposed on the outside, while some enclose the wire completely in ferrite and are referred to as "shielded". Some inductors have an adjustable core, which enables changing of the inductance. Inductors used to block very high frequencies are sometimes made by stringing a ferrite bead on a wire.

Types of inductor

1. Air core inductor



Resonant oscillation transformer from a spark gap transmitter. Coupling can be adjusted by moving the top coil on the support rod. Shows high-Q construction with spaced turns of large-diameter tubing.

The term *air core coil* describes an inductor that does not use a magnetic core made of a ferromagnetic material. The term refers to coils wound on plastic, ceramic, or other nonmagnetic forms, as well as those that have only air inside the windings. Air core coils have lower inductance than ferromagnetic core coils, but are often used at high frequencies because they are free from energy losses called core losses that occur in ferromagnetic cores, which increase with frequency. A side effect that can occur in air core coils in which the winding is not rigidly supported on a form is 'microphony': mechanical vibration of the windings can cause variations in the inductance.

2. Radio frequency inductor

Collection of RF inductors, showing techniques to reduce losses. The three top left and the ferrite loop stick or rod antenna, bottom, have basket windings.

At high frequencies, particularly radio frequencies (RF), inductors have higher resistance and other losses. In addition to causing power loss, in resonant circuits this can reduce the Q factor of the circuit, broadening the bandwidth. In RF inductors, which are mostly air core types, specialized construction techniques are used to minimize these losses. The losses are due to these effects:

- **Skin effect**
- **Proximity effect**
- **Dielectric losses**
- **Parasitic capacitance**
- **Basket-weave coils**
- **Spider web coils**
- **Litz wire**

3. Ferromagnetic core inductor

Ferromagnetic-core or iron-core inductors use a magnetic core made of a ferromagnetic or ferrimagnetic material such as iron or ferrite to increase the inductance. A magnetic core can increase the inductance of a coil by a factor of several thousand, by increasing the magnetic field due to its higher magnetic permeability. However the magnetic properties of the core material cause several side effects which alter the behavior of the inductor and require special construction:

- Core losses: A time-varying current in a ferromagnetic inductor, which causes a time-varying magnetic field in its core, causes energy losses in the core material that are dissipated as heat, due to two processes:
    - Eddy currents: From Faraday's law of induction, the changing magnetic field can induce circulating loops of electric current in the conductive metal core. The energy in these currents is dissipated as heat in the resistance of the core material. The amount of energy lost increases with the area inside the loop of current.

- Hysteresis: Changing or reversing the magnetic field in the core also causes losses due to the motion of the tiny magnetic domains it is composed of. The energy loss is proportional to the area of the hysteresis loop in the BH graph of the core material. Materials with low coercivity have narrow hysteresis loops and so low hysteresis losses.

4. Laminated core inductor

Laminated iron core ballast inductor for a metal halide lamp

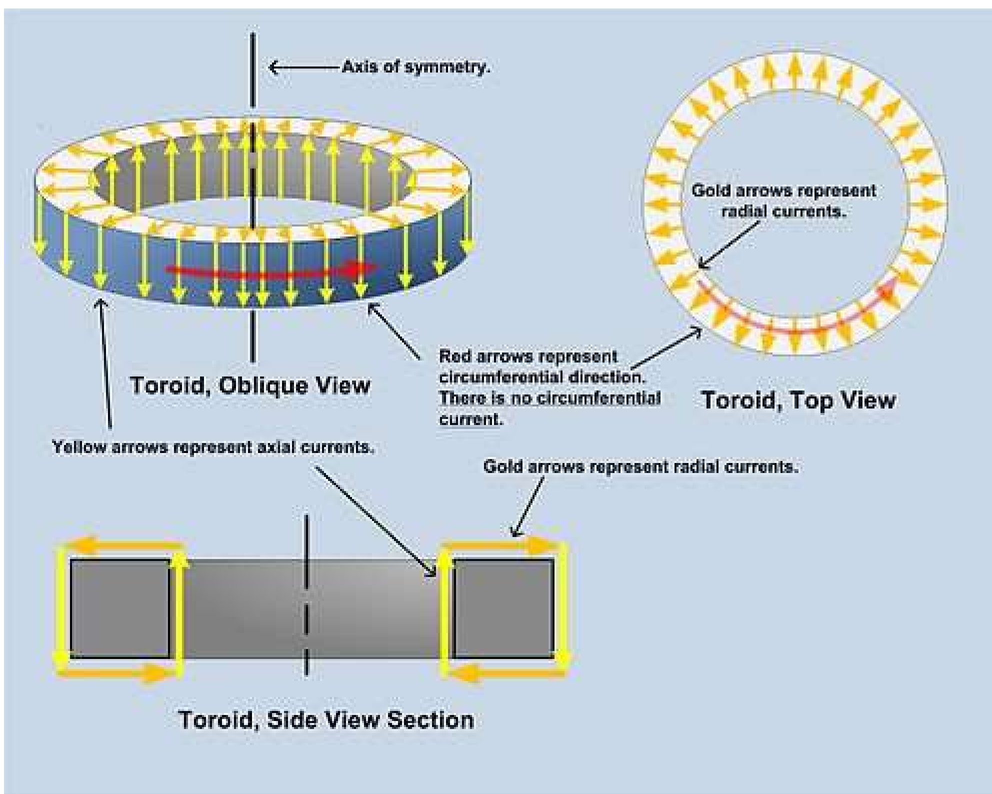
Low-frequency inductors are often made with laminated cores to prevent eddy currents, using construction similar to transformers. The core is made of stacks of thin steel sheets or laminations oriented parallel to the field, with an insulating coating on the surface. The insulation prevents eddy currents between the sheets, so any remaining currents must be within the cross sectional area of the individual laminations, reducing the area of the loop and thus reducing the energy losses greatly. The laminations are made of low-coercivity silicon steel, to further reduce hysteresis losses.

5. Ferrite-core inductor

For higher frequencies, inductors are made with cores of ferrite. Ferrite is a ceramic ferrimagnetic material that is nonconductive, so eddy currents cannot flow within it. The formulation of ferrite is $xxFe_2O_4$ where xx represents various metals. For inductor cores soft ferrites are used, which have low coercivity and thus low hysteresis losses. Another similar material is powdered iron cemented with a binder.

6. Toroidal core inductor

In an inductor wound on a straight rod-shaped core, the magnetic field lines emerging from one end of the core must pass through the air to re-enter the core at the other end. This reduces the field, because much of the magnetic field path is in air rather than the higher permeability core material. A higher magnetic field and inductance can be achieved by forming the core in a closed magnetic circuit.



Applications of Inductor

Like resistors and capacitors, inductors are also passive elements which are used to store the electric energy in the form of magnetic field. Simply an inductor is a wire or coil of a good electric conducting material with few turns (twists) in it.

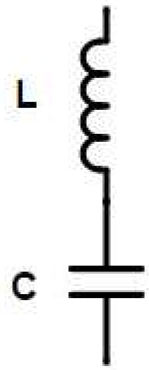
They will produce the magnetic flux (field) around them by the flow of an alternating current through it. An ideal inductor has no inductive reactance, so it acts as short circuit. In practical, every inductor has some resistance internally which we call as 'Inductive reactance'.

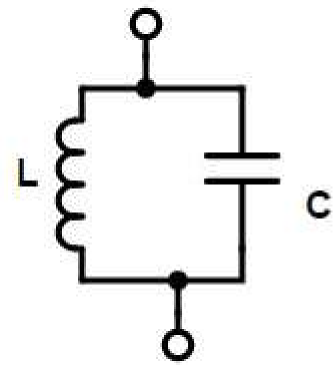
It is measured in ohms. When the inductive reactance of a coil is very high then the circuit acts as an open circuit and allows maximum current through it. Inductance is the phenomenon of an inductor that opposes the flow of current in the circuit, by generating the back EMF. This inductance is measured in Henry.

Inductors are of many types like air cored, iron cored, coupled or differential type and many more. Based on the requirement, inductors have many applications in electrical transmission.

Inductors in Tuned Circuits

Inductors are used in tuning circuits which are used to select the desired frequency. In a tuned circuit, we have capacitor connected along with the inductor, either in parallel or series. The frequency of the tuning circuit at which the capacitive reactance is equal to the inductive reactance (XC = XL) is called 'Resonant Frequency'.





The series resonance circuits are used in many electronic circuits like television , radio tuning circuits and filters to vary the frequency and selecting the various frequency channels.

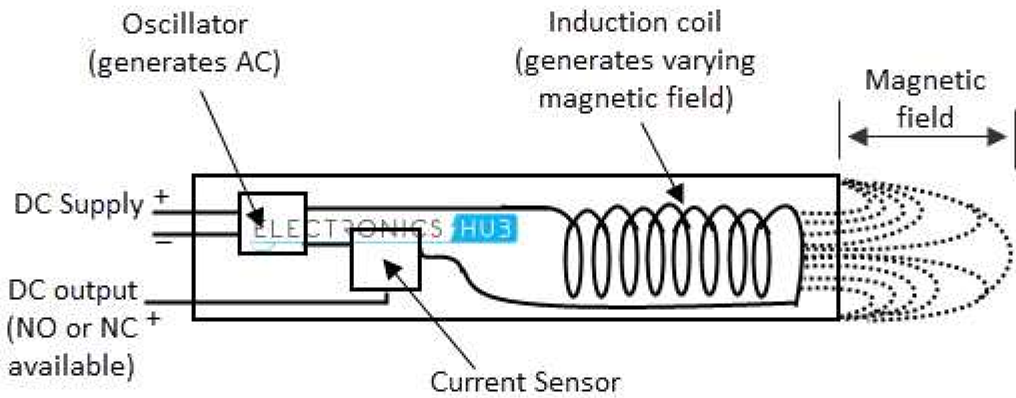
Inductive sensors

Inductors are used in proximity sensors which work on the principle of inductance. We know that inductance is the phenomenon in which , the magnetic field produced in the coil , will oppose the flow of current in it. So thus the inductance will restrict the current flow and reduces the circuit performance.

For better performances we need to amplify the current in the circuit. We use proximity sensors to find the level of amplification factor at which we need to amplify the current.

The manufacturers design the sensors by twisting the wire into a tight coil. There are 4 components in the inductive proximity sensor; they are an inductor or coil, an oscillator, a detection circuit and an output circuit.

In the inductive proximity sensor, a fluctuating magnetic field is generated by oscillator around the winding of coil, which locates in the sensing face of the device.



When an object moves in the field of inductive proximity area of detection, eddy currents starts building up in the metal object which will reduce the inductive sensor's magnetic field.

Strength of the oscillator is monitored by the detection circuit and an output is triggered from the output circuitry , when the oscillations are below the sufficient level.

The inductive proximity sensor is a contactless sensor and is very reliable in operation. The inductive sensors are used at traffic lights to detect the traffic density.

Energy Storage Devices

We can store the energy in passive elements like capacitor and inductors. Inductors can store energy for a limited time. As the inductors store the energy in the form of magnetic field, it will collapse when we remove the power supply.

The inductors functions as energy storage devices in switch mode power supplies (generally we use in our computers). In these type of power supplies, the output voltage ratio depends upon the charging time of the inductor.

Induction Motors

The well known and wide range application of inductors is Induction motors. In these induction motors or asynchronous motors, the inductors are in fixed position and they did not allowed to move in nearby magnetic field.

Induction motors converts the electrical energy into mechanical energy. The shaft in the motors will rotate because of the magnetic field produced by the alternating current.

The speed of the motor is fixed as it depends on the frequency of the power supplied from source. So we use inductors in these motors to control the speed by connecting them in series or parallel to shaft. These induction motors are very reliable and robust.

Transformers

Transformer is another popular application of inductors. By combining the inductors of shared magnetic field, we can design a transformer. Transformer is the basic and fundamental component of the power transmission system.

These are used to increase or decrease the power in transmission lines to required level, as step up and step down transformers respectively. In the transformers, the inductor (wire) is wounded to the core as primary and secondary windings.

The impedance of the inductor increases with increase in the frequency of supply. The impedance produced in the inductor will limit the effectiveness of transformer. In general, the inductance based transformers are limited to very low operational values.

Inductive Filters

Inductors and capacitors are combinely used to form filters. The filters are the electronic devices which are used to limit the frequency of the input signal entering to a circuit. There are many types of filters like low pass filter, high pass filter, band pass filter, notch filter etc which are designed by using inductors.

As the frequency increases, the impedance of the inductor also increases. Then the properties of filter will change according to the impedance value. There are many number of filter topologies we can create by using inductors.

Chokes

Inductors are also used as chokes. We know that the inductors will create an opposite current flow, when the alternating current flows through it. This means the inductors will choke the AC current and allows DC current to pass. This property of inductors is used in power supply circuits, where AC supply need to be converted to DC supply.

Ferrite beds

Generally we see the ferrite beds in computer cables and mobile chargers etc. these ferrite beds use inductors to reduce the radio frequency interference created by the cables.

Relays

A relay is like an electrical switch. It uses inductor coil to control the current flow in it. When the AC current flows through the inductor of the relay, it produces a magnetic field which effects the switch contacts.