Passive Elements: Resistors, Inductors, Capacitors

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EE*241* - Electric Circuits *I*

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Contents

1 Abstract

This report aims to discuss the passive components, resistors, inductors and capacitors. Specifically, passive compenents construction, types, sizes, practical values, applications, safe usage and their recycling.

We also investigate 2^{nd} order circuit simulation of RLC circuits, and show the different types of dampings caused by changing components values as well as graph the waveforms using Multisim^{TM}.

2 Passive Elements

2.1 Resistors

Resistors are essential components in electrical and electronic circuits which are used in different electronic devices. There are different types of resistors available but based on the type, their properties may vary. These properties will assist you while selecting the right type of resistor for designing any circuit. Different types of resistors are used in different applications based on the requirement. So it is compulsory to identify the type of resistor as well, in which the type of resistor is used. Most of the circuits can be designed with these components, so it is impossible to design the circuit without using these components. This article discusses an overview of a resistor

Figure 1: Resistor Symbols, (Right is Variable)

2.1.1 Construction

Carbon film resistor is taken to give details of the construction of a resistor. The construction of a resistor is shown in the below diagram. This resistor consists of two terminals like a normal resistor. The construction of a carbon film resistor can be done by placing the carbon layer on a substrate of a ceramic. The carbon film is a resistive material toward the flow of current in this resistor. However, it blocks some amount of current.

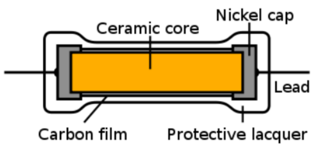

Figure 2: Carbon Resistor Construction

The substrate of the ceramic performs like the insulating material toward the current. So it doesn't let the heat through the ceramic. Thus, these resistors can resist high temperatures without any harm. The end caps on the resistor are metallic that are placed at both ends of the terminals. The two terminals are connected at the two metallic end caps on the resistor.

2.1.2 Types

There are numerous resistor technologies out there, with new technologies springing up all the time. The major technologies include carbon film, metal film, thick film, thin film, carbon composition, wirewound, and metal oxide. When selecting resistors for an application, you generally specify whether the resistor is to be a precision resis- tor, semiprecision resistor, general- purpose resistor, or power resistor.

Precision resistors have low voltage and power coefficients and excellent tempera- ture and time stabilities, along with low noise and very low reactance. These resis- tors are available in metal- film or wire constructions and are typically designed for circuits having very close resistance tolerances on values. Semiprecision resistors are smaller than precision resistors and are used primarily for current- limiting or voltage- dropping functions. They have long- term tempera- ture stability.

General-purpose resistors are used in circuits that do not require tight resistance tol- erances or long-term stability. For general- purpose resistors, initial resistance varia- tions may be in the neighborhood of 5 percent, and the variation in resistance under full- rated power may approach 20 percent. Typically, general-purpose resistors have a high coefficient of resistance and high noise levels. However, good-quality metal film resistors are low cost and often used as general-purpose resistors.

Power resistors are used for power supplies, control circuits, and voltage dividers where operational stability of 5 percent is acceptable. Power resistors are available in wirewound and film construction. Film-type power resistors have the advantage of stability at high frequencies and have higher resistance values than wirewound resis- tors for a given size [1].

The following provides finer details highlighting the differences between the var- ious available resistors.

(a) **Precision Wirewound**

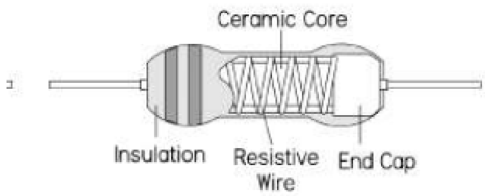

Figure 3: Precision Wirewound Resistor

Precision wirewound resistors are very stable resistors manufactured with high tolerances. They are made by winding wire of nickel-chromium alloy onto a ceramic tube covered with a vitreous coating. They are designed to have a very low temperature coefficient of resistance (as low as 3 ppm/°C) and can achieve accuracies up to 0.005 percent. They are usually expected to operate in a temperature range from -55 to 200°C, with a maximum operating temperature of 145°C. Life is generally rated at 10,000 hours at rated temperature and load, though this can increase if operated below rated temperature. The allowable change in resistance under these conditions is about 0.10 percent. In terms of noise, there is little—only contact noise. The power-handling capability is generally low, but high-power versions are available with heat sinks.

Because of the wire-winding nature, these resistors have a component of inductances as well as capacitance associated with them. They tend to be inductive at lower frequencies and somewhat capacitive at higher frequencies, regardless of resistance value. They also have a resonant frequency—with a very low Q value. For this reason, they are unsuitable for operation above 50 kHz—forget about RF applications. Precision wire-wounds are not to be used for general- purpose work, but are reserved for high-accuracy dc applications such as high- precision dc measuring equipment and as reference resistors for voltage regulators and decoding networks. (Note: There are certain precision wirewounds listed in manufacturers' catalogs as "type HS" wirewounds. These resistors have a special winding pattern that can greatly cut down on the inductance of the winds. There are two different types of HS wirewounds: one type has almost zero inductance but greatly increased interwinding capacitance; the other type has low inductance and low capacitance and is well suited for fast-settling amplifiers.)

Once considered the best and most stable resistors, precision wirewounds now have a competitor, precision film resistors, which can match them in most every regard [1].

(b) **Power Wirewound**
Power wirewound resistors are similar to their precision counterparts but are designed to handle a lot more power. They will handle more power per unit vol- ume than any other resistor. Some of the most powerful are wound similar to heater elements and require some form of cooling (e.g., fans or immersion in liquids such as mineral oil or high-density silicone liquids). These resistors are wound on a winding form, such as a ceramic tube, rod, heavily anodized aluminum, or fiberglass mandrel. The cores on which the windings are made have high heat conductivity (Steatite, Alumina, beryllium oxide, etc.). They come in various shapes—oval, flat, cylindrical—most shapes designed for heat dissipation. Chassis-mount wirewounds are generally cylindrical power resistors wound on a ceramic core molded and pressed into an aluminum heat sink and usually with heat- radiating fins. These are designed to be mounted to metal plates or a chassis to further con- duct heat, which results in a rating about five times the normal power rating. Power wirewounds come in a variety of different accuracy and TCR ratings.

(c) **Metal Film**
In applications that involve fast rise times (microseconds) or high frequencies (mega-hertz), metal-film resistors are usually the best. They are also quite cheap and come in small sizes (e.g., surface-mount).

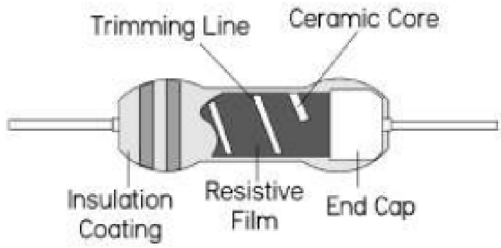

Figure 4: Metal Film Resistor

Metal-film resistors are often considered the best compromise of all resistors. Once considered less accurate and stable than wire- wounds, the technology has greatly improved, with special precision metal-film resistors reaching TC values as low as 20, 10, 5, and even 2 ppm/°C, with accuracies as good as 0.01 percent. They also have much less inductance than wirewounds and are smaller in size and less expensive. When compared to carbon-film resistors, they have lower TCs, lower noise, linearity, and better frequency characteristics and accuracy. They also surpass carbon- film resistors in terms of high-frequency characteristics. Carbon- film resistors do, however, come with higher maximum resistance values.

A metal-film resistor is made from a base metal that is vaporized in a vacuum and deposited on a ceramic rod or wafer. The resistance value is then controlled by careful adjustment of the width, length, and depth of the film. The process is very exacting, resulting in resistors with very tight tolerance values. Metal-film resistors are used extensively in surface- mount technology.

Carbon-film resistors are the most common resistor around. They are made by coating (dipping, rolling, printing, or spraying) a ceramic substrate with a special carbon-film mixture. The thickness and percentage of the carbon mixture roughly determine the resistance. To tailor resistances to precise values the ceramic pieces can be cut to a spe- cific length. Further refinement is accomplished by cutting a spiral trimming groove. An alternative method of producing carbon film is to mechanically apply carbon dust dispersed in a curable polymeric binder. The material is painted on the substrate in a spiral pattern and cured at a moderately elevated temperature.

Carbon-film resistors, with 1 percent tolerances, are normally manufactured with spiral cuts and have the same kind of voltage-overload limitations as metal-film types. Though these resistors are very popular, they are drifty (TC values around 500 to 800 ppm/°C) and should not be used in circuits where metal-film resistors are intended. In other words, don't confuse the two when building or replacing blown components. Carbon-film resistors have many of the same characteristics as carbon composition resistors such as being noisy and having a voltage coefficient; they outperform carbon composition resistors in terms of lower TCR ratings and tighter tolerances. Resistor types include general purpose, through-hole, and surface-mount devices. They also come in specialty types, such as high- power, high- voltage, and fusible. Tolerances of 1 percent or even better can be achieved; however, caution must be used in getting tight tolerances for this type of resistor because the TC, voltage coefficient, and stability may mean that it is good only for that tolerance at the time it was installed. The TC of carbon-film resistors is in the neighborhood of 100 to 200 ppm and is generally negative. Frequency response of carbon-film resistors is among the best, far better than wirewounds, and much better than carbon composition.

(d) **Carbon Composition**
Carbon composition resistors, though not as popular as they once were, still find use in noncritical applications. They are composed of carbon particles mixed with a binder. The resistance value is varied by controlling the carbon concentration. This mixture is molded into a cylindrical shape and hardened by baking. Leads are attached axially to each end, and the assembly is encapsulated in a protective coating. Composition resistors are economical and exhibit low noise levels for resistances of about 1 MΩ. Composition resistors are usually rated for temperatures in the neigh borhood of 70°C for power ranging from 1/8 to 2 W. They have end-to-end shunted capacitance that may be noticed at frequencies in the neighborhood of 100 kHz, espe- cially for resistance values above 0.3 MΩ.

However, due to poor tolerances—from 5% to 20% carbon-composition resistors should not be used in critical applications. Due to their construction, they generate considerable noise that varies depending on resistance value and the package size (though above 1 MΩ they exhibit low noise).

Though composition resistors have many poor characteristics, they do quite well in overvoltage conditions. Where a metal- film resistor's spiral gap would be zapped (breakdown causing it to short and destroy itself) during a severe overvoltage condition, a carbon-composition resistor wouldn't be so wimpy. A carbon-composition resistor uses a large chunk of resistive material that can handle large overloads for a short time without any flashover effects (shorting). So if you're planning to discharge a high-voltage capacitor through a series resistor where tolerances and such aren't important, carbon composition isn't a bad choice. Power- handling capability in relation to physical size is greater than with precision wirewounds but less than with power wirewounds [1].

(e) **Thin- and Thick-Film Resistors**
Thin-film resistors are made by depositing an extremely thin layer of NiCr resistive film (less than 1

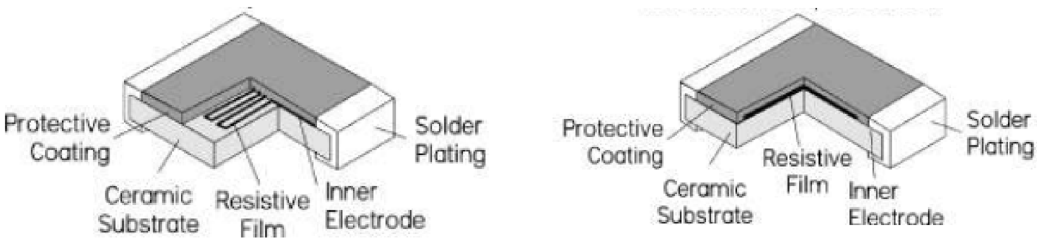

Figure 5: Thick and Thin Film Resistor (Left-to-Right)

µm) on an aluminum oxide substrate, while using NiCu materials as conducting electrodes. Thin- film technology offers extreme precision and stability (tight tolerances and low TCR values). However, these resistors have relatively limited surge capabilities due to the low mass of the resistive material. Thin-film resistors are designed as small surface-mount devices used in PCB designs and are frequently used as microwave passive and active power components such as microwave power resistors, microwave power terminations, microwave resistive power dividers, and microwave attenuators.

Thick-film resistors, in contrast to thin-film resistors, use a thicker film of RuO_2, and have PdAg electrodes. These materials are also mixed with glass-based material to form a paste for printing on the substrate. The thickness of the printing material is usually 12 µm. Thick-film resistors also exhibit decent precision and stability, perhaps approaching those of thin-film resistors; however, they far exceed thin films in terms of maximum surge capacity—one to two orders of magnitude difference. Thick-film resistors come in two-lead packages and in surface- mount form. Some thick- film resistors are designed as power resistors.

Both thin-film and thick- film technologies are constantly improving, and it is difficult to specify all characteristics. Your best bet is to consult manufacturers' data sheets for more details.

(f) **Power Film Resistors**
Power-film resistors are similar in manufacture to their respective metal- film or carbon-film resistors. They are manufactured and rated as power resistors, with power rating being the most important characteristic. Power-film resistors are available in higher maximum values than power wirewound resistors and have a very good fre- quency response. They are generally used in applications requiring good frequency response and/or higher maximum values. Generally, they are used for power appli- cations, where tolerances are wider, and the temperature ratings are changed so that under full load the resistor will not exceed the maximum design temperature. Also, the physical size of the resistor is larger, and in some cases the core is made from a heat- conductive material attached to a heat sink to dissipate heat more efficiently [1].

(g) **Metal Oxide**
Metal-oxide resistors contain a resistance element formed by the oxidation reaction of a vapor or spray of tin-chloride solution on the heated surface of a glass or ceramic rod. The resulting tin-oxide film is adjusted to value by cutting a helix path through the film. These resistors can sustain high temperatures and electrical overloads, and have moderate-to- precision characteristics. Resistor types in this class include high-power and flameproof axial through hole and surface-mount types. Axial versions are either blue in color or white. The outer shell of these resistors, which is flameproof like the interior, is also resistant to external heat and humidity. Metal oxide resistors can be used to replace carbon-composition components in some applications. They are ideal for pulse-power applications. Small-sized power- type metal- oxide resistors come in a 0.5 to 5W range, with standard tolerances of ± 1 to ± 5 percent and TCRs around ± 300 ppm/°C. Metal-oxide resistors are used in general purpose voltage dividers, RC timing circuits, and as pullup and pulldown resistor surge applications (e.g., RC snubber circuits, current-limiting circuits, and overload ground lines). They also come with maximum resistance values exceeding those of wirewound resistors. In general, they have decent electrical and mechanical stability and high reliability.

(h) **Fuse Resistors**

Figure 6: Fuse Resistor

A fuse resistor acts as both a resistor and a fuse. Fuse resistors are designed to open-circuit (fuse) when subjected to a large surge current or fault condition. They are spe-cially spiraled to provide the fusible function with flame-retardant coating. The fusing current is calculated based on the amount of energy required to melt the resistive material (the melt temperature plus the amount of energy required to vaporize the resistive material). These resistors will typically run hotter than a normal precision or power resistor, so that a momentary surge will bring the resistive element up to fusing temperature. Some designs create a hot spot inside the resistor to assist in this fusing. The major unknown when using fuse resistors is the heat transfer of the materials, which can be quite significant for pulses of long duration and is very difficult to calcu-late. Mounting fuse resistors is critical, since this will affect the fusing current. Many fuse resistors are made to mount in fuse clips for more accurate fusing characteristics. They come in a variety of types, including carbon film, metal film, thin film, and wire-wound fusible. Fuse resistors are widely used in constant voltage and overload pro-tection circuits found in battery chargers, TV sets, cordless phones, PC/CPU coolers,

(i) **Chip Resistor Arrays**

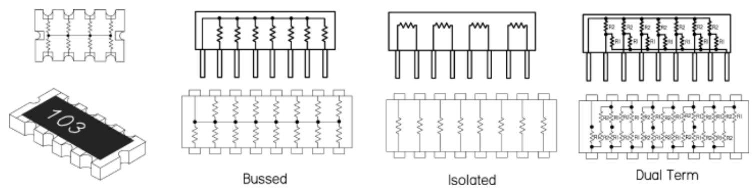

Figure 7: Chip Resistor Arrays

Resistor arrays contain any combination of two or more resistive elements produced on a single substrate. The resistive elements can be constructed using thick-film or thin- film technologies. These arrays come in SIP and DIP packages as well as leadless surface-mountable packages with solderable terminations. Various circuit schematics are available, including isolated resistors, single common and dual common bused resistors. Resistor arrays are used for a wide range of applications where economy of space and weight and placement costs are at a premium. Tolerances are 1 percent and 5 percent, temperature coefficients range from 50 ppm to 200 ppm, and power capabilities compare to individual resistors of similar size.

(j) **Cement Resistors**
These resistors are designed as power resistors with the added provision of being heat and flame resistant. Typical power ratings range from 1 W to 20 W or more. Tolerances are around 5 percent, with TCR ratings of around 300 ppm/°C.

(k) **Zero-Ohm Resistors**

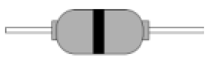

Figure 8: Zero-Ohm Resistor

These are really nothing more than a piece of wire used for crossovers, permanent jumpers, or program jumpers (manual switch circuitry) in PCB design. They look like a signal diode with a single black stripe in the center—not to be confused with a diode that has its stripe nearer to one end. The single black stripe is meant to signify a 0-Ω value. Advantages to using these zero- ohm resistors over simple wires include ease of handling for mechanized PCB placement machinery, very low jumper-to- jumper capacitance (suitable for high-speed data lines), small footprint, and

(l) **Potentiometers**

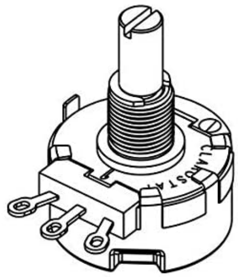

Figure 9: A Typical Potentiometer

When a voltage is applied across a potentiometer, it can deliver a variable fraction of that voltage. It is often used to adjust sensitivity, balance, input, or output, especially in audio equipment and sensors such as motion detectors.

A potentiometer can also be used to insert a variable resistance in a circuit, in which case it should really be referred to as a variable resistor, although most people will still call it a potentiometer [2].

(m) **Thermistors**
A small NTC thermistor Thermistors are resistors of which the resistance changes significantly when the temperature changes. NTC thermistors decrease in resistance when the temperature rises, while PTC thermistors increase in resistance when the temperature rises. Thermistors are often used as temperature sensors or thermal protection devices.

(n) **Light Dependent Resistor**
Light dependent resistors or photoresistors show a decrease in resistance when light intensity increases. They are often used to identify light or dark situations; for example, to switch on street lights in the evening

2.1.3 Sizes

Resistors are available in a large number of different package styles and sizes. The most commonly used today are the rectangular surface mount (SMD) resistors, but also the good old axial resistor is still used extensively in through-hole designs. This page provides information on the dimensions of SMD, axial, and MELF packages. It also provides some recommended land patterns for SMD components for solder attach to PCBs

2.1.3.1 SMD Resistors Sizes

The shape and size of surface mount resistors are standardized, with most manufacturers using the JEDEC standards. The size of SMD resistors is indicated by a numerical code, such as 0603. This code contains the width and height of the package. So, the imperial code 0603 indicates a length of 0.060" and a width of 0.030".

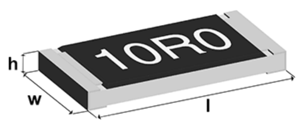

Figure 10: SMD Resistor

The SMD package code can be given in either imperial or metric units. In general, the imperial code is used more often to indicate the package size. Confusingly, even when the imperial naming convention is used, the metric dimensions are often used during the design of the printed circuit boards (PCBs). In general, you can assume the code is in imperial units, but the dimensions used are in mm. The SMD resistor size used depends primarily on the required power rating, the minimum feature size of the PCB manufacturing, and the limitations of the pick-and-place equipment. Table: 1 lists the dimensions and specifications of commonly used surface mount packages [3].

Code		Length (L)		Width (W)		Height (H)		Power
Imperial	Metric	inch	mm	inch	mm	inch	mm	Watt
0201	0603	0.024	0.6	0.012	0.3	0.01	0.25	1/20 (0.05)
0402	1005	0.04	1.0	0.02	0.5	0.014	0.35	1/16 (0.062)
0603	1608	0.06	1.55	0.03	0.85	0.018	0.45	1/10 (0.10)
0805	2012	0.08	2.0	0.05	1.2	0.018	0.45	1/8 (0.125)
1206	3216	0.12	3.2	0.06	1.6	0.022	0.55	1/4 (0.25)
1210	3225	0.12	3.2	0.10	2.5	0.022	0.55	1/2 (0.50)
1812	3246	0.12	3.2	0.18	4.6	0.022	0.55	1
2010	5025	0.20	5.0	0.10	2.5	0.024	0.6	3/4 (0.75)
2512	6332	0.25	6.3	0.12	3.2	0.024	0.6	1

Table 1: SMD Resistors sizes [3]

2.1.3.2 Axial Resistor Sizes

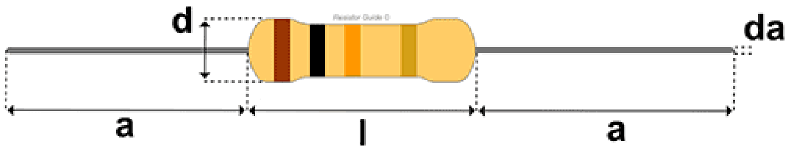

Figure 11: Axial Resistor

The size of axial resistors is not as standardized as the SMD resistors, and different manufacturers often use slightly different dimensions. Furthermore, the size of an axial resistor depends on the power rating and the type of resistor such as carbon composition, wirewound, carbon film, or metal film. The following drawing and table give an indication of the dimensions of common carbon film and metal film axial resistors. Whenever the exact size needs to be known, always check the manufacturer datasheet of the component [3].

Power rating	Body length (l)	Body diameter (d)	Lead length (a)	Lead diameter (da)
Watt	mm	mm	mm	mm
1/8 (0.125)	3.0± 0.3	1.8 ± 0.3	28± 3	0.45± 0.05
1/4 (0.25)	6.5 ± 0.5	2.5± 0.3	28± 3	0.6± 0.05
1/2 (0.5)	8.5 ± 0.5	3.2± 0.3	28± 3	0.6± 0.05
1	11± 1	5± 0.5	28± 3	0.8± 0.05

Table 2: Axial Resistors sizes [3]

2.1.4 Values

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

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

Aside from the preferred values, many other standards related to resistors exist. Example include the standard sizes for resistors and the marking of resistors with color codes or numerical codes. Power ratings of resistors are not defined in a norm, and, therefore, often deviate from the above described series

Given that an resistor has tolerence of $\pm 20\%$, a 1Ω inductor could have an actual resistance as high as 1.2Ω, therfore it would be pointless to have any value between 1Ω and 1.2Ω [4].

The E series of preferred numbers were chosen such that when a component is manufactured it will end up in a range of roughly equally spaced values on a logarithmic scale, to solve this problem.

Where the fomula for each value is determined by the n-th root:

$$V_n = round(\sqrt[m]{10^n}) \quad (1)$$

Where each of the following variables is multiplied by 10^0, 10^1, 10^2, 10^3, 10^4, 10^5 and 10^6 (1Ω to $20M\Omega$).

(a) **E3 values** (40% tolerance) (rarely used)
1.0, 2.2, 4.7

(b) **E6 values** (20% tolerance)
1.0, 1.5, 2.2, 3.3, 4.7, 6.8

(c) **E12 values** (10% tolerance)
1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2

(d) **E24 values** (5% tolerance)
1.0, 1.1, 1.2, 1.3, 1.5, 1.6, 1.8, 2.0, 2.2, 2.4, 2.7, 3.0, 3.3, 3.6, 3.9, 4.3, 4.7, 5.1, 5.6, 6.2, 6.8, 7.5, 8.2, 9.1

(e) **E48 values** (2% tolerance)
1.00, 1.05, 1.10, 1.15, 1.21, 1.27, 1.33, 1.40, 1.47, 1.54, 1.62, 1.69, 1.78, 1.87, 1.96, 2.05, 2.15, 2.26, 2.37, 2.49, 2.61, 2.74, 2.87, 3.01, 3.16, 3.32, 3.48, 3.65, 3.83, 4.02, 4.22, 4.42, 4.64, 4.87, 5.11, 5.36, 5.62, 5.90, 6.19, 6.49, 6.81, 7.15, 7.50, 7.87, 8.25, 8.66, 9.09, 9.53

(f) **E96 values** (1% tolerance)
1.00, 1.02, 1.05, 1.07, 1.10, 1.13, 1.15, 1.18, 1.21, 1.24, 1.27, 1.30, 1.33, 1.37, 1.40, 1.43, 1.47, 1.50, 1.54, 1.58, 1.62, 1.65, 1.69, 1.74, 1.78, 1.82, 1.87, 1.91, 1.96, 2.00, 2.05, 2.10, 2.15, 2.21, 2.26, 2.32, 2.37, 2.43, 2.49, 2.55, 2.61, 2.67, 2.74, 2.80, 2.87, 2.94, 3.01, 3.09, 3.16, 3.24, 3.32, 3.40, 3.48, 3.57, 3.65, 3.74, 3.83, 3.92, 4.02, 4.12, 4.22, 4.32, 4.42, 4.53, 4.64, 4.75, 4.87, 4.99, 5.11, 5.23, 5.36, 5.49, 5.62, 5.76, 5.90, 6.04, 6.19, 6.34, 6.49, 6.65, 6.81, 6.98, 7.15, 7.32, 7.50, 7.68, 7.87, 8.06, 8.25, 8.45, 8.66, 8.87, 9.09, 9.31, 9.53, 9.76

(g) **E192 values** (0.5% and lower tolerance)
1.00, 1.01, 1.02, 1.04, 1.05, 1.06, 1.07, 1.09, 1.10, 1.11, 1.13, 1.14, 1.15, 1.17, 1.18, 1.20, 1.21, 1.23, 1.24, 1.26, 1.27, 1.29, 1.30, 1.32, 1.33, 1.35, 1.37, 1.38, 1.40, 1.42, 1.43, 1.45, 1.47, 1.49, 1.50, 1.52, 1.54, 1.56, 1.58, 1.60, 1.62, 1.64, 1.65, 1.67, 1.69, 1.72, 1.74, 1.76, 1.78, 1.80, 1.82, 1.84, 1.87, 1.89, 1.91, 1.93, 1.96, 1.98, 2.00, 2.03, 2.05, 2.08, 2.10, 2.13, 2.15, 2.18, 2.21, 2.23, 2.26, 2.29, 2.32, 2.34, 2.37, 2.40, 2.43, 2.46, 2.49, 2.52, 2.55, 2.58, 2.61, 2.64, 2.67, 2.71, 2.74, 2.77, 2.80, 2.84, 2.87, 2.91, 2.94, 2.98, 3.01, 3.05, 3.09, 3.12, 3.16, 3.20, 3.24, 3.28, 3.32, 3.36, 3.40, 3.44, 3.48, 3.52, 3.57, 3.61, 3.65, 3.70, 3.74, 3.79, 3.83, 3.88, 3.92, 3.97, 4.02, 4.07, 4.12, 4.17, 4.22, 4.27, 4.32, 4.37, 4.42, 4.48, 4.53, 4.59, 4.64, 4.70, 4.75, 4.81, 4.87, 4.93, 4.99, 5.05, 5.11, 5.17, 5.23, 5.30, 5.36, 5.42, 5.49, 5.56, 5.62, 5.69, 5.76, 5.83, 5.90, 5.97, 6.04, 6.12, 6.19, 6.26, 6.34, 6.42, 6.49, 6.57, 6.65, 6.73, 6.81, 6.90, 6.98, 7.06, 7.15, 7.23, 7.32, 7.41, 7.50, 7.59, 7.68, 7.77, 7.87, 7.96, 8.06, 8.16, 8.25, 8.35, 8.45, 8.56, 8.66, 8.76, 8.87, 8.98, 9.09, 9.20, 9.31, 9.42, 9.53, 9.65, 9.76, 9.88

2.1.5 Effect Of Temprature And Other Parameters

Since the flow of electrons through any medium will develop heat, all resistors will be subject to changes in temperature. The effect of these temperature variations will depend upon the type of construction and is known as the Temperature Coefficient.

Temperature coefficient indicates how temperature changes affect the resistor's value and may be either positive or negative. In general, composition resistors have a negative temperature coefficient and metallic or wire wound resistors have a positive coefficient. This means that composition resistors will decrease in resistance with an increase in temperature, while metallic types will increase in resistance with an increase in the temperature. A low temperature coefficient indicates that the change in resistance per degree of temperature change is slight. High quality resistors have a low temperature coefficient; some even zero. These, of course, are most desirable, especially in precision work [5].

2.1.6 Applications And Safe Usage

2.1.6.1 Limiting Current

To protect a device from damage caused by excessive current, a series resistor is chosen to allow a current that does not exceed the manufacturer's specification. In the case of a single through- hole LED (often referred to as an indicator), the forward current is often limited to around 20mA, and the value of the resistor will depend on the voltage being used [2].

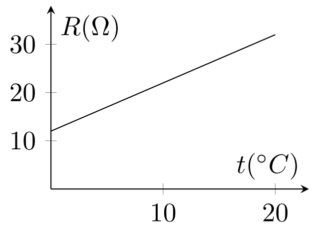

Figure 12: Change of resistance with increase in temprature

2.1.6.2 Pullup and Pulldown Resistors

When a mechanical switch or pushbutton is attached to the input of a logic chip or microcontroller, a pullup or pulldown resistor is used, applying positive voltage or grounding the pin, respectively, to prevent it from "floating" in an indeterminate state when the switch is open. In Figure 10-17, the upper schematic shows a pulldown resistor, whereas the lower schematic shows a pullup resistor. A common value for either of them is 10K. When the pushbutton is pressed, its direct connection to positive voltage or to ground easily overwhelms the effect of the resistor. The choice of pullup or pulldown resistor may depend on the type of chip being used [2].

2.1.6.3 RC Network

A resistor will adjust the charge/discharge time when placed in series with a capacitor. When the switch closes, the resistor limits the rate at which the capacitor will charge itself from the power supply. Because a capacitor has an ideally infinite resistance to DC current, the voltage measured at point A will rise until it is close to the supply voltage. For Capacitors, see Section: 2.2

2.1.6.4 Voltage Divider

Two resistors may be used to create a voltage divider If V_{in} is the supply voltage, the output voltage, V_{out}, measured at point A, is found by the formula:

$$V_{out} = V_{in} \times (\frac{R_2}{R_1 + R_2}) \tag{2}$$

In reality, the actual value of V_{out} is likely to be affected by how heavily the output is loaded.

If the output node has a high impedance, such as the input to a logic chip or comparator, it will be more susceptible to electrical noise, and lower-value resistors may be needed in the voltage divider to maintain a higher current flow and maintain stability in the attached device.

2.1.6.5 Safe Usage

One should always use the right type of resistor for the circuit, taking into consderation the power rating of the resistor. Going to a higher power rating than needed will make the circuit more robust, while maintaining equivalence.

Some fuses are *fusable*, designed to burn out harmlessly like a fuse, one should not replace this type of resistor with any normal one. In case where fire would be a hazard, a *non-flammable* should be used [2].

2.1.7 Recycling

Some people form the resistors in beautiful shapes to make them a beautiful shape for decoration, and this is a matter of recycling.

There are some factories that melt the resistors with the intention of recycling them and separating each component separately

Electrical resistors can be recycled by placing them in the places designated for them, such as metal waste.

2.2 Capacitors

2.2.1 Construction

The capacitor is a passive component and it stores the electrical energy into an electrical field. The effect of the capacitor is known as a capacitance. It is made up of two close conductors and separated by the dielectric material. If the plates are connected to the power then the plates accumulate the electric charge. One plate accumulates the positive charge and another plate accumulates the negative charge. The electric symbol of the capacitor is shown in Figure: 14.

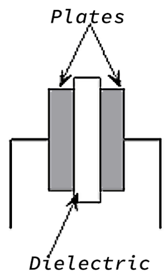

Figure 13: Capacitor Construction

Figure 14: Capacitor Symbols, (left is Polar)

2.2.2 Types

(a) **Electrolytic Capacitors**

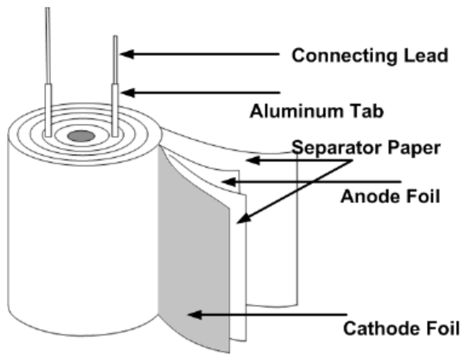

Figure 15: Electrolytic Capacitor

Generally, the electrolyte capacitors are used when the large capacitor values are required. The thin metal film layer is used for one electrode and for the second electrode (cathode) a semi-liquid electrolyte solution which is in jelly or paste is used. The dielectric plate is a thin layer of oxide, it is developed electrochemically in production with the thickness of the film and it is less than the ten microns.

This insulating layer is very thin, it is possible to make capacitors with a large value of capacitance for a physical size, which is in small and the distance between the two plates is very small. The types of capacitors in the majority of electrolytic are polarized, which is DC voltage is applied to the capacitor terminal and they must be correct polarity.

If the positive to the positive terminal and the negative to the negative terminal as an incorrect polarization will break the insulating oxide layer and there will be permanent damage. All the polarized electrolytic capacitors have polarity clearly with the negative sign to show the negative terminal and the polarity should be followed. The uses of electrolytic capacitors are generally in the DC power supply circuit because they are large in capacitance and small in reducing the ripple voltage. The applications of this electrolytic capacitors are coupling and decoupling. The disadvantage of the electrolytic capacitors is their relatively low voltage rating because of the polarization of electrolytic capacitor

(b) **Mica Capacitors**
This capacitor is a group of natural minerals and the silver mica capacitors use the dielectric. There are two types of mica capacitors which are clamped capacitors & silver mica capacitor. Clamped mica capacitors are considered as an obsolete because of their inferior characteristic. The silver mica capacitors are prepared by sandwiching mica sheet coated with metal on both sides and this assembly is then encased in epoxy to protect the environment. The mica capacitors are used in the design calls for stable, reliable capacitor of relatively small.

Figure 16: Mica Capacitor

The mica capacitors are the low loss capacitors, used at high frequencies and this capacitor is very stable chemically, electrically, and mechanically, because of its specific crystalline structure binding & it is a typically layered structure. The most common used are Muscovite and phlogopite mica. The Muscovite mica is better in the electrical properties and the other Mica has a high-temperature resistance.

(c) **Paper Capacitor**

Figure 17: Paper Capacitor

In the initial stage if the capacitors the paper was used in between the two foils of the capacitor, but these days the other materials like plastics are used, therefore it is called as a paper capacitor. The capacitance range of the paper capacitor is from 0.001 to 2.000micro farad and the voltage is very high which is up to 2000V.

(d) **Film Capacitor**

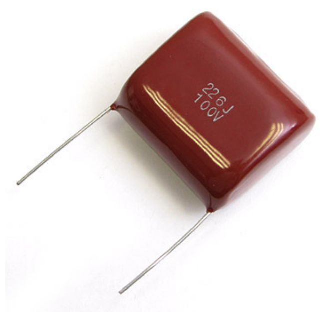

Figure 18: Film Capacitor

There are different types of film capacitors are available like polyester film, metallized film, polypropylene film, PTE film and polystyrene film. The core difference between these capacitors types is the material used as a dielectric and dielectric should be chosen properly according to their properties. The applications of the film capacitors are stability, low inductance, and low cost.

The PTE film capacitance is a heat resistance and it is used in the aerospace and military technology. The metalized polyester film capacitor is used in the applications are it requires long stability at a relatively low.

(e) **Plastic Foil Capacitor**
The plastic foil capacitor is non-polarized by nature and the electrolytic capacitors are generally two capacitors in the series, which are in the back to back hence the result is in the non-polarized with half capacitance. The nonpolarized capacitor requires the AC applications in the series or in parallel with the signal or power supply.

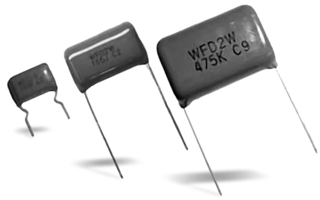

Figure 19: Plastic Foil Capacitor

The examples are the speaker crossover filters and power factor correction network. In these two applications, a large AC voltage signal is applied across the capacitor.

(f) **Ceramic Capacitors**
The ceramic capacitors are the capacitors and use the ceramic material as a dielectric. The ceramics are

Figure 20: Ceramic Capacitor

one of the first materials to use in the production of capacitors as an insulator.

There are many geometries are used in the ceramic capacitors and some of them are the ceramic tubular capacitor, barrier layer capacitors are obsolete because of their size, parasitic effects or electrical characteristics. The two common types of ceramic capacitors are multilayer ceramic capacitor (MLCC) and ceramic disc capacitor.

The multilayer ceramic capacitors are prepared by using the surface mounted (SMD) technology and they are smaller in size, therefore, it is used widely. The values of the ceramic capacitors are typically between the 1nF and 1µF and the values are up to 100µF are possible.

The ceramic disc capacitors are manufactured by coating a ceramic disc with silver contacts on both sides and to achieve with the larger capacitance, these devices are made from multiple layers. The ceramic capacitors will a have high-frequency responses due to the parasitic effects like resistance and inductance.

(g) **Air Core (Variable)**

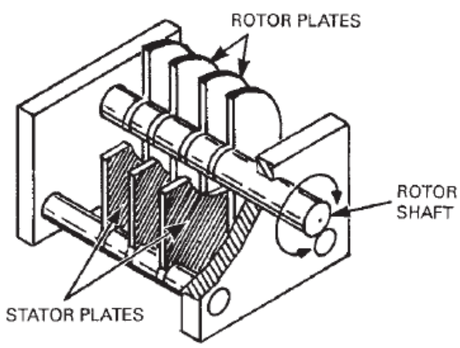

Figure 21: Air Core (Variable) Capacitor

This is an air-spaced capacitor dielectric that is the best approximation to the ideal picture. These capacitors are large when compared to those of the same value using other dielectrics. Their capacitance is very stable over a wide temperature range. Leakage losses are low, and therefore a very high Q can be obtained. To vary the capacitance, the effective surface area of an array of parallel plates is altered via a mechanical turn-knob. Tuning capacitors are used

(h) **Super Capacitors**

These devices store extremely large amounts of charge (from 0.022 to 50 F)—much more than a typical

Figure 22: Super Capacitors

capacitor. This level of energy storage approaches around 1/10 that of a low-density battery. However, unlike a battery, the power output can be 10 times greater—a useful feature in high-current pulse applications.

Supercapacitors consist of two nonreactive porous plates suspended within an electrolyte. A voltage applied to the positive plate attracts the negative ions in the electrolyte, while the voltage on the negative plate attracts the positive ions. This effectively creates two layers of capacitive storage, one where the charges are separated at the positive plate and another where the charges are separated at the negative plate. Conductive rubber membranes contain the electrode and electrolyte material and make contact with a cell. Several cells are stacked in series to achieve the desired

(i) **Oil-Filled Capacitors**

This type is used in high-voltage, high-current applications that generate a lot of heat, the oil cools

Figure 23: Oil-Filled Capacitor

the capacitor. Applications include induction heating, high-energy pulsing, commutation, equipment bypassing, ignitions, frequency conversion, high-voltage rip ple filtering, snubbing, coupling, and spark generation. Voltages range from 1 to 300 kV, capacitance from around 100 pF to 5000 µF. Typically, they come in large packages [1].

2.2.3 Sizes

2.2.3.1 SMD capacitor package sizes

Table: 3 shows the typical capacitor sizes.

SMD Package type	Dimensionsmm	Dimensionsinches
2920	7.4 x 5.1	0.29 x 0.20
2725	6.9 x 6.3	0.27 x 0.25
2512	6.3 x 3.2	0.25 x 0.125
2010	5.0 x 2.5	0.20 x 0.10
1825	4.5 x 6.4	0.18 x 0.25
1812	4.6 x 3.0	0.18 x 0.125
1806	4.5 x 1.6	0.18 x 0.06
1210	3.2 x 2.5	0.125 x 0.10
1206	3.0 x 1.5	0.12 x 0.06
1008	2.5 x 2.0	0.10 x 0.08
0805	2.0 x 1.3	0.08 x 0.05
0603	1.5 x 0.8	0.06 x 0.03
0402	1.0 x 0.5	0.04 x 0.02
0201	0.6 x 0.3	0.02 x 0.01
01005	0.4 x 0.2	0.016 x 0.008

Table 3: SMD Capacitor Package sizes

2.2.3.2 THT inductor package sizes

Table: 4 shows the typical capacitor sizes.

Body length (l)	Body diameter (d)	Lead length (a)	Lead diameter (da)
mm	mm	mm	mm
3.0± 0.3	1.8 ± 0.3	28± 3	0.45± 0.05
6.5 ± 0.5	2.5± 0.3	28± 3	0.6± 0.05
8.5 ± 0.5	3.2± 0.3	28± 3	0.6± 0.05
11± 1	5± 0.5	28± 3	0.8± 0.05

Table 4: THT Capacitor Package sizes

2.2.4 Values

Table: 5 shows the typical capacitor sizes.

2.2.5 Effect Of Temprature And Other Parameters

Temperature changes have significant effects on the capacitance of an aluminum electrolytic capacitor. As the temperature of the electrolyte decreases, its viscosity increases, resulting in a reduced electrical conductivity. Therefore, the capacitance of an aluminum electrolytic capacitor reduces with a decrease in temperature. At low frequencies, the relationship between temperature and the capacitance of an aluminum electrolytic capacitor is nearly linear.When operating at -40°C, low voltage aluminum electrolytic capacitors with a low temperature rating of -55°C exhibit a capacitance loss of between -10% and -20%. Capacitance loss for high voltage capacitors can be up to 40%.

Like all capacitors, an aluminum electrolytic capacitor comprises two layers of a conductive material separated by a layer of dielectric material. An aluminum foil of extremely high purity is used as the anode, while a conductive liquid (electrolyte) is used as the cathode. The two aluminum foils of an aluminum electrolytic capacitor provide the large contact area required to allow current to pass to the conductive operating electrolyte. To achieve high capacitance values, the effective contact area of the anode is typically enlarged by electrochemical etching. The types and degree of etching is determined by the desired effective contact area. Etching of foils allows for the production of miniaturized devices, and the technology is widely used in the production of today's aluminum electrolytic capacitors.

pF	pF	pF	pF	µF	µF	µF	µF	µF	µF	µF
1.0	10	100	1000	0.01	0.1	1.0	10	100	1000	10,000
1.1	11	110	1100							
1.2	12	120	1200							
1.3	13	130	1300							
1.5	15	150	1500	0.015	0.15	1.5	15	150	1500	
1.6	16	160	1600							
1.8	18	180	1800							
2.0	20	200	2000							
2.2	22	220	2200	0.022	0.22	2.2	22	220	2200	
2.4	24	240	2400							
2.7	27	270	2700							
3.0	30	300	3000							
3.3	33	330	3300	0.033	0.33	3.3	33	330	3300	
3.6	36	360	3600							
3.9	39	390	3900							
4.3	43	430	4300							
4.7	47	470	4700	0.047	0.47	4.7	47	470	4700	
5.1	51	510	5100							
5.6	56	560	5600							
6.2	62	620	6200							
6.8	68	680	6800	0.068	0.68	6.8	68	680	6800	
7.5	75	750	7500							
8.2	82	820	8200							
9.1	91	910	9100							

Table 5: Capacitor Sizes [6]

2.2.6 Applications And Safe Usage

Capacitor have many uses in electronic and electrical systems. Some of the most important ones are listed below.

2.2.6.1 Bypassing

Bypass capacitors are often used to bypass undesired alternating signals (supply ripple, noise, etc.) around a component or group of components to ground. Often the ac is removed (or greatly attenuated) from the ac/dc mixture, leaving the dc free to feed the bypassed component.

2.2.6.2 Energy Storage

A capacitor can store electric energy when it is connected to its charging circuit. And when it is disconnected from its charging circuit, it can dissipate that stored energy, so it can be used like a temporary battery.

2.2.6.3 Power Conditioning

Reservoir capacitors are used in power supplies where they smooth the output of a full or half wave rectifier. They can also be used in charge pump circuits as the energy storage element in the generation of higher voltages than the input voltage.

2.2.6.4 Power factor Correction

In electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phase Electrical load.

In high-voltage direct current transmission systems, power factor correction capacitors may have tuning inductors to suppress harmonic currents that would otherwise be injected into the AC power system.

2.2.6.5 Motor Starter

There are also capacitor-run induction motors which 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.

2.2.7 Recycling

A capacitor is a unit that receives electricity and then funnels it out to the device that needs power. A capacitor stores an electrical charge and then regulates the voltage that's released, ensuring that too much voltage isn't discharged. It can also remove noise associated with high frequency.

Capacitors generally contain a lot of metal. This is where recycling your capacitor comes in. Depending on the type of metal in your capacitor, you can find a way to recycle the item. The best way to recycle your capacitor is to take it to an electronics recycling facility and see if they'll accept it.

You should be able to find a metal recycler in your area that accepts capacitors. Not all metal recyclers will take capacitors, but those that do are generally set up to check for oil contamination. There are also many household items that use capacitors that don't contain oil. These include clothes dryers, fans, refrigerators, stoves, TVs, washing machines and other electronic equipment

2.3 Inductors

The basic role of an inductor is to prevent any sudden changes in current from flowing through it.

Figure 24: Inductor Symbols, (Right is Variable)

2.3.1 Construction

The basic inductor is a coil, which may be just a loop with one or more turns of wire; or it may be a coil with some length, known as a solenoid. Variations include coils wound on various core materials, the most popular being iron (or iron alloys, laminations, or powder) and ferrite (a gray, nonconductive, brittle magnetic material). These are all ploys to multiply the inductance of a given coil by the 'permeability' of the core material. The core may be in the shape of a rod, a toroid (Figure: 33), or even more bizarre shapes, such as a 'pot core' (Figure: 34) [7].

Diffrenct inductor constructions can and their values can be found below.

(a) **Air Coil Inductor**

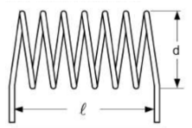

Figure 25: Air Coil Inductor

$$L(\mu H) = \frac{d^2 N^2}{18d + 40l} \tag{3}$$

Where:

$$L = \text{Inductance in } \mu H \tag{4}$$
$$d = \text{coil diameter in inches} \tag{5}$$
$$l = \text{coil length in inches} \tag{6}$$
$$N = \text{total Number of turns} \tag{7}$$

(b) **Multilayer Air Coil Inductor**

$$L(\mu H) = \frac{0.8 \times (N \times r)^2}{6r + 9l + 10b} \tag{8}$$

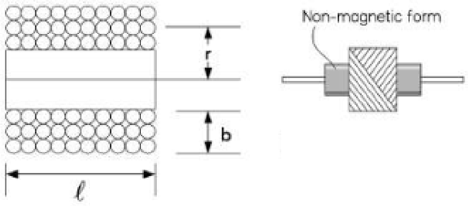

Figure 26: Multilayer Air Coil Inductor

Where:

$$L = \text{Inductance in } \mu H \quad (9)$$
$$r = \text{radius of coil} \quad (10)$$
$$b = \text{coil length in inches} \quad (11)$$
$$l = \text{coil length in inches} \quad (12)$$
$$N = \text{total Number of turns} \quad (13)$$

(c) **Spiral Coil Inductor**

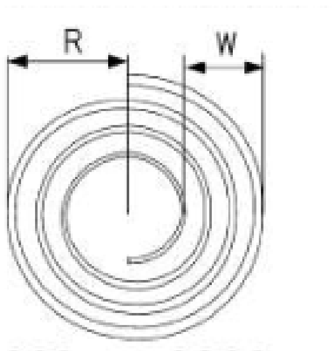

Figure 27: Spiral Coil Inductor

$$L(\mu H) = \frac{(N \times R)^2}{8R + 11w} \quad (14)$$

Where:

$$L = \text{Inductance in } \mu H \quad (15)$$
$$R = \text{average radius of coil in inches} \quad (16)$$
$$W = \text{width of coil in inches} \quad (17)$$
$$N = \text{total Number of turns} \quad (18)$$

2.3.2 Varients

Inductors can be divided into two varients based on whether the core is magnatic or not.

(a) **Magnetic Core** A magnetic core may be made from solid iron, plates of iron or steel separated by thin insulating material, powdered iron mixed with a binder, or a ferrite compound derived from nickel, zinc, manganese, or a combination. An iron core has at least 1,000 times the permeability of air, while some ferrites are 10,000 times as permeable.

One major disadvantage of a magnetic core is *hysteresis*, which in this context refers to the tendency of the core to retain some magnetic 'memory' as a cycle of alternating current changes from positive to negative. This residual magnetism must be overcome by the next positive pulse of AC. The tendency of the core to retain magnetic polarity is known as its retentivity. Iron cores are especially retentive.

Another disadvantage of some magnetic cores is that they may host eddy currents induced by the magnetic field of the coil. These electrical currents tend to circulate through the core, reducing efficiency by generating waste heat, especially if coil currents are high. Forming a core from iron or steel plates, separated by thin layers of insulation, will inhibit these currents. Powdered iron inhibits eddy currents because the particles have limited contact. Ferrites are nonconductive, and are therefore immune to eddy currents. They are widely used.

Hysteresis and eddy currents both incur energy losses with each AC cycle. Therefore, the losses increase linearly as the AC frequency increases. Consequently, inductor cores that suffer either of these problems are not well-suited to high frequencies [2].

(b) **Non-Magnetic Core** The problems associated with magnetic cores may be avoided by winding the coil around a nonmagnetic core that may be hollow, ceramic, or plastic. A hollow core is referred to as an *air core*. The permeability of ceramic and plastic cores is close to that of air. An inductor with a nonmagnetic core will be immune to eddy currents and retentivity, but will have to be significantly larger than a magnetic cored coil with comparable inductance. In the case of a very primitive radio receiver, such as a crystal set, the air-cored coil that selects a radio frequency may be several inches in diameter [2].

2.3.3 Types

There are many different inductors out there of both varients, magnetic and non-magnetic cores. Some inductors are designed for general-purpose filtering, others for RF/EMI filtering, others for high-current choking, and still others for energy storage (in switching power supplies)[1].

(a) **Multilayer chip Inductors**

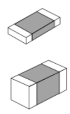

Figure 28: Multilayer chip Inductors

Description: Used predominantly in high- density PCB surface- mount circuits where size, interboard magnetic coupling, and vibration are major concerns. They have fewer para- sitic characteristics and less resis- tive loss when compared to most other leaded inductors. Come with excellent Q values, and high-frequency performance, while generating very little noise. Smaller boards and shorter traces also reduce EMI emissions and signal cross- coupling. Come in various current ratings.

Application Used for EMI/RFI attenuation and suppression, as well as reactive elements in LC resonant oscilla- tors and impedance- matching networks, and other choke- coil type applications. They are found in A/D converters, bandpass filters, pulse generators, RF amplifiers, signal generators, switching power supplies, and telecom.

(b) **Molded Inductors**

Figure 29: Molded Inductor

Description: Small with axial leads for PC board mounting. Outer coating protects coil from the environment. Comes in a shielded version as well. Frequency range is typically greater than 50khz.

Application: Used in filters, AD converters, AM/ FM radio, pulse generators, signal generators, switching power supplies, and telecom [1].

(c) **Shielded Inductor**

Description: The magnetic shield is designed to prevent magnetic coupling and RF/EMI interference issues especially important in densely packed boards where signal corruption is a major concern. Come in surface- mount, axial lead, and other configurations and a variety of current-handling ratings.

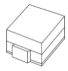

Figure 30: Shielded Inductor

Applications: Used in high- reliability applications where magnetic coupling is to be avoided. Used for dc/dc converters, computers, telecom equipment, filters, LDC displays,

(d) **Conformal Coated Inductors**

Figure 31: Conformal Coated Inductor

Description: An inexpensive inductor that comes with axial or radial leads similar to molded inductors. Outer coating protects inductor from environments.
Application: Typically used in less harsh environments than molded inductors. Usually used in less critical RFI/EMI applications. Higher-Q versions can be used in many of the same applications of molded inductors [1].

(e) **Chokes**

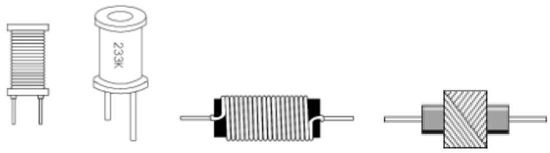

Figure 32: Left to Right: High Current Choke, Hash Choke, RF Choke

Description: These devices utilize ferrite or powdered iron cores to achieve large inductance values for low coil count and small volume. Fewer turns translates into lower dc resistance, an important feature for higher current applications.
Application: High- current hash chokes are used for home appliances, communications systems, computer add-ons, dc-fc, switching power supplies, transmitters, and uninterrupted power supplies. Power line chokes are used for filters, power supplies, RFI suppression, power amps, switching regulators, SCR and Triac controls, and speaker crossover networks [1].

(f) **Toroids**

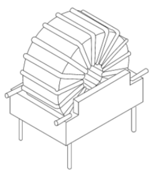

Figure 33: Toroid Inductor

Description: The magnetic circuit created by a rod-shaped core must be completed by the lines of force traveling back around from one end of the rod to the other, through the surrounding air. Since air has low permeability, this is a major source of inefficiency, By comparison, a torus (a geometrical shape resembling a donut) completes the entire magnetic circuit inside its core. This significantly increases its efficiency. Also, because its field is better contained, a toroidal inductor needs little or no shielding to protect other components from stray magnetic effects [2].

Application: Toroids are used in a variety of different applications. They are used as chokes in ac power lines and to reduce EMI. Also used in home appliances, audio generators, auto electronics, bandpass filters, audiovisual equipment, dc-fc, I/O boards, impedance match transformers, oscillators, pulse generators, switching power supplies, telecom equipment, transmitters, tuned amplifiers, uninterrupted power supplies, etc. [1]

(g) **Pot Cores**

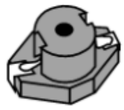

Figure 34: Pot Core Inductor

Description: Provide ultra-high inductance values and high dc current ratings while maintaining a stable inductance due to high saturation currents and self-shielding. Excellent Q values in a small size.
Application: Commonly used in telecom, audio, and automotive applications. Used as dc chokes, differential mode chokes, filters, and in switching circuits.

(h) **Balun Chokes**

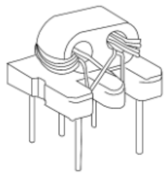

Figure 35: Balun Choke Inductor

Description: Typically used in impedance-matching applications. "Balun" refers to a balanced-unbalanced transformation of impedance levels.
Application: Used in AM/FM radio, television and communications systems, I/O boards, impedance matching, pulse generators, transmitters, and walkie-talkies [1].

(i) **Air Core Inductor**

Figure 36: Air Core Inductor

Description: Air core inductors have non-magnetic core such as plastic, ceramic or just air as suggested by its obvious name.

Air core inductor uses any non-magnetic material as core to reduce the core losses i.e. eddy current and stray losses, especially when the operating frequency is very high. But the use of non-magnetic core also decreases its inductance. **Applications:** They are widely used in RF applications because of their low losses at high operating frequencies [8]. It is also used for constructing RF tuning coils and filter circuits [9].

(j) **Variable Inductor**

Description: Solenoidal, or cylindrical, coils can be made to have variable inductance by sliding ferromagnetic cores in and out of them [10]. In this form they're available with inductances ranging from microhenrys to henrys, typically with a 2:1 tuning range for any given inductor. Also available are rotary inductors (coreless coils with a rolling contact) [7].

Applications: Typically used at frequencies above 50 kHz. Used in LC resonant tank circuits in AM/FM radio [1], This is a common practice in radio communications. The frequency of a radio circuit can be adjusted in this way [10].

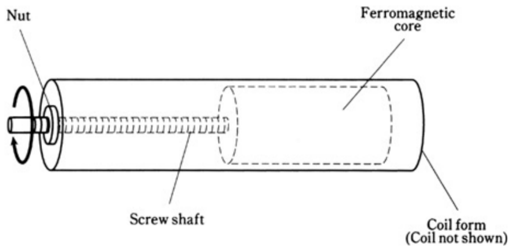

Figure 37: Variable Inductor

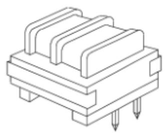

Figure 38: Common Mode Choke

(k) **Common-Mode Choke**

Description: Common- and differential-mode chokes are used to eliminate noise on a pair of conductors. Common-mode noise is defined as noise that is present in or common to both conductors, and can be the result of induced noise caused by the antenna effect on a conductor or PC trace. Used to prevent EMI and RF interference from power supply lines and for prevention of malfunctioning of electronic equipment. Common-mode chokes usually have ferrite core material well suited to attenuate common-mode current.
Application: Common-mode chokes are very useful devices found in many radio circuits. They may help nearly any interference problem, from cable TV to telephones to audio interference caused by RF picked up on speaker leads. Particularly well-suited for applications such as line filters in switch-mode power supplies, and are also commonly used in desktop computers, industrial electronics, office equipment, and consumer electronics such as TVs and audio equipment [1].

(l) **Ferrite Beads**

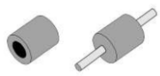

Figure 39: Ferrite Beads, Right: Hollow Version, Left: Leaded Version

Description: A ferrite bead inverts the design of a typical inductor by running a wire through a hole in the center of the bead, instead of coiling the wire around the core [2], the inductance range is rather limited to RF. Used for removing RF energy that exists within a transmission line structure (PCB trace) [1].
Application: Ferrite beads are placed on cables entering receiving equipment to prevent external RF from entering and contaminating signals in the cable runs [1], Computer cabling to external devices, lamp dimmers, and some types of motors can be sources of radio frequency [2].

(m) **Ceramic Core Inductor**

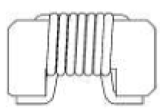

Figure 40: Ceramic Core Inductor

Description: These inductors use a special ceramic core that surpasses many ferrite core type inductors in terms of high frequency operation, low IDC, high SRF, high Q, and tight tolerances.

Application: Used in LC resonant circuits such as oscillators and signal generators. Used in impedance matching, circuit isolation, and RF filtration. Found in mobile phones, Bluetooth devices, wireless instruments, as well as audio, TV, and telecom devices [1].

(n) **Thin Film Inductor**

Figure 41: Thin Film Inductor

Description: Such type of inductor is designed on a substrate of thin ferrite or magnetic material. A conductive spiral shaped trace of copper is placed on top of the substrate. The design allows stability and resistant to vibrations [8].

Applications: Due to Its high accuracy, performance and compact size, it is used in mobile communication devices, wireless networks and power supplies, etc [8].

2.3.4 Sizes

Inductors sizes are semi-standarized, and can be divided into SMD (Surface Mount Device) and THT (Through Hole Technology).

2.3.4.1 SMD package sizes

SMD Package type	Dimensions mm	Dimensions inches
2920	7.4 x 5.1	0.29 x 0.20
2725	6.9 x 6.3	0.27 x 0.25
2512	6.3 x 3.2	0.25 x 0.125
2010	5.0 x 2.5	0.20 x 0.10
1825	4.5 x 6.4	0.18 x 0.25
1812	4.6 x 3.0	0.18 x 0.125
1806	4.5 x 1.6	0.18 x 0.06
1210	3.2 x 2.5	0.125 x 0.10
1206	3.0 x 1.5	0.12 x 0.06
1008	2.5 x 2.0	0.10 x 0.08
0805	2.0 x 1.3	0.08 x 0.05
0603	1.5 x 0.8	0.06 x 0.03
0402	1.0 x 0.5	0.04 x 0.02
0201	0.6 x 0.3	0.02 x 0.01
01005	0.4 x 0.2	0.016 x 0.008

2.3.4.2 THT inductor package sizes

Body length (l)	Body diameter (d)	Lead length (a)	Lead diameter (da)
mm	mm	mm	mm
3.0± 0.3	1.8 ± 0.3	28± 3	0.45± 0.05
6.5 ± 0.5	2.5± 0.3	28± 3	0.6± 0.05
8.5 ± 0.5	3.2± 0.3	28± 3	0.6± 0.05
11± 1	5± 0.5	28± 3	0.8± 0.05

Table 6: THT Inductor Package sizes

2.3.5 Values

Given that an inductor has tolerence of ±20%, a $1H$ inductor could have an actuall inductance as high as $1.2H$, therfore it would be pointless to have any value between $1H$ and $1.2H$ [11].

The E series of preferred numbers were chosen such that when a component is manufactured it will end up in a range of roughly equally spaced values on a logarithmic scale, to solve this problem.

Where the fomula for each value is determined by the n-th root:

$$V_n = round(\sqrt[m]{10^n}) \tag{19}$$

Where each of the following variables is multiplied by 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1} and 10^{-2} ($1\mu H$ to $\sim 20H$).

(a) **E3 values** (40% tolerance) (rarely used)
1.0, 2.2, 4.7

(b) **E6 values** (20% tolerance)
1.0, 1.5, 2.2, 3.3, 4.7, 6.8

(c) **E12 values** (10% tolerance)
1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2

(d) **E24 values** (5% tolerance)
1.0, 1.1, 1.2, 1.3, 1.5, 1.6, 1.8, 2.0, 2.2, 2.4, 2.7, 3.0, 3.3, 3.6, 3.9, 4.3, 4.7, 5.1, 5.6, 6.2, 6.8, 7.5, 8.2, 9.1

(e) **E48 values** (2% tolerance)
1.00, 1.05, 1.10, 1.15, 1.21, 1.27, 1.33, 1.40, 1.47, 1.54, 1.62, 1.69, 1.78, 1.87, 1.96, 2.05, 2.15, 2.26, 2.37, 2.49, 2.61, 2.74, 2.87, 3.01, 3.16, 3.32, 3.48, 3.65, 3.83, 4.02, 4.22, 4.42, 4.64, 4.87, 5.11, 5.36, 5.62, 5.90, 6.19, 6.49, 6.81, 7.15, 7.50, 7.87, 8.25, 8.66, 9.09, 9.53

(f) **E96 values** (1% tolerance)
1.00, 1.02, 1.05, 1.07, 1.10, 1.13, 1.15, 1.18, 1.21, 1.24, 1.27, 1.30, 1.33, 1.37, 1.40, 1.43, 1.47, 1.50, 1.54, 1.58, 1.62, 1.65, 1.69, 1.74, 1.78, 1.82, 1.87, 1.91, 1.96, 2.00, 2.05, 2.10, 2.15, 2.21, 2.26, 2.32, 2.37, 2.43, 2.49, 2.55, 2.61, 2.67, 2.74, 2.80, 2.87, 2.94, 3.01, 3.09, 3.16, 3.24, 3.32, 3.40, 3.48, 3.57, 3.65, 3.74, 3.83, 3.92, 4.02, 4.12, 4.22, 4.32, 4.42, 4.53, 4.64, 4.75, 4.87, 4.99, 5.11, 5.23, 5.36, 5.49, 5.62, 5.76, 5.90, 6.04, 6.19, 6.34, 6.49, 6.65, 6.81, 6.98, 7.15, 7.32, 7.50, 7.68, 7.87, 8.06, 8.25, 8.45, 8.66, 8.87, 9.09, 9.31, 9.53, 9.76

(g) **E192 values** (0.5% and lower tolerance)
1.00, 1.01, 1.02, 1.04, 1.05, 1.06, 1.07, 1.09, 1.10, 1.11, 1.13, 1.14, 1.15, 1.17, 1.18, 1.20, 1.21, 1.23, 1.24, 1.26, 1.27, 1.29, 1.30, 1.32, 1.33, 1.35, 1.37, 1.38, 1.40, 1.42, 1.43, 1.45, 1.47, 1.49, 1.50, 1.52, 1.54, 1.56, 1.58, 1.60, 1.62, 1.64, 1.65, 1.67, 1.69, 1.72, 1.74, 1.76, 1.78, 1.80, 1.82, 1.84, 1.87, 1.89, 1.91, 1.93, 1.96, 1.98, 2.00, 2.03, 2.05, 2.08, 2.10, 2.13, 2.15, 2.18, 2.21, 2.23, 2.26, 2.29, 2.32, 2.34, 2.37, 2.40, 2.43, 2.46, 2.49, 2.52, 2.55, 2.58, 2.61, 2.64, 2.67, 2.71, 2.74, 2.77, 2.80, 2.84, 2.87, 2.91, 2.94, 2.98, 3.01, 3.05, 3.09, 3.12, 3.16, 3.20, 3.24, 3.28, 3.32, 3.36, 3.40, 3.44, 3.48, 3.52, 3.57, 3.61, 3.65, 3.70, 3.74, 3.79, 3.83, 3.88, 3.92, 3.97, 4.02, 4.07, 4.12, 4.17, 4.22, 4.27, 4.32, 4.37, 4.42, 4.48, 4.53, 4.59, 4.64, 4.70, 4.75, 4.81, 4.87, 4.93, 4.99, 5.05, 5.11, 5.17, 5.23, 5.30, 5.36, 5.42, 5.49, 5.56, 5.62, 5.69, 5.76, 5.83, 5.90, 5.97, 6.04, 6.12, 6.19, 6.26, 6.34, 6.42, 6.49, 6.57, 6.65, 6.73, 6.81, 6.90, 6.98, 7.06, 7.15, 7.23, 7.32, 7.41, 7.50, 7.59, 7.68, 7.77, 7.87, 7.96, 8.06, 8.16, 8.25, 8.35, 8.45, 8.56, 8.66, 8.76, 8.87, 8.98, 9.09, 9.20, 9.31, 9.42, 9.53, 9.65, 9.76, 9.88

2.3.6 Effect Of Temprature And Other Parameters

2.3.6.1 Inductance Temprature Coeffcient

The change in inductance per unit temperature change. Measured under zero bias condition and expressed in parts per million (ppm) [1]. The temperature coefficient of inductance of a coil of inductance L is determined by the relative variation of L which corresponds to the temperature variation of one degree centigrade [12].

$$\lambda' \frac{1}{L}(\frac{\Delta l}{\Delta t}) \tag{20}$$

2.3.6.2 Self-resonant frequency

Self-resonant frequency (SRF or f_0): The frequency at which the inductor's distributed capacitance resonates with the inductance. At this frequency, the inductance is equal to the capacitance and they cancel each other. As a consequence, at SRF, the inductor acts as a purely resistive high-impedance element. Also at this frequency, the Q value of the inductor is zero. Distributed capacitance is caused by the turns of wire layered on top of each other and around the core. This capacitance is in parallel to the inductance. At frequencies above SRF, the capacitive reactance of the parallel combination will become the dominant component [1].

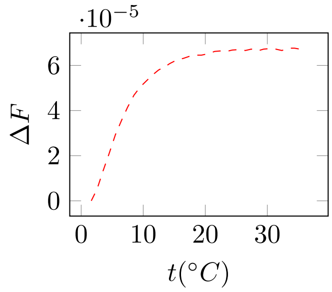

Figure 42: Change of Inductance with increase in temprature [13]

2.3.6.3 Resistance temperature coefficient

Resistance temperature coefficient: The change in dc wire resistance per unit temperature change. Measured low dc bias (< 1 VDC) and expressed in parts per million [1].

2.3.6.4 Curie temperature (TC)

The temperature beyond which the core material loses its magnetic properties [1].

2.3.7 Applications And Safe Usage

Inductor have many applications, some of which are listed below.

2.3.7.1 Low-Pass Filter

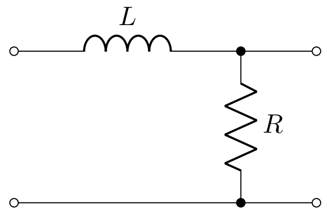

Figure 43: Low Pass Filter

Filters offer little opposition to certain frequencies while blocking others. In a low-pass filter is constructed using a resistor and inductor. The inductor's impedance increases with frequency, thus preventing high-frequency signals from passing.

2.3.7.2 High-Pass Filter

In a high-pass filter blocks low frequencies the inductor acts as a low-impedance path to ground for low-frequency

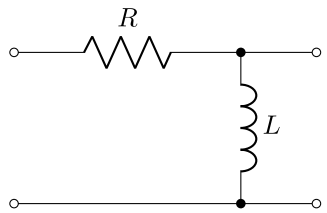

Figure 44: High Pass Filter

signals.

2.3.7.3 Buck Converter

In switching regulator applications, an inductor is used as an energy storage device, when the semiconductor switch is on, the current in the inductor ramps up and energy is stored. When the switch is turned off, the stored energy is released into the load. Output voltages have a ripple that must be minimized by selecting appropriate inductance and output capacitor values.

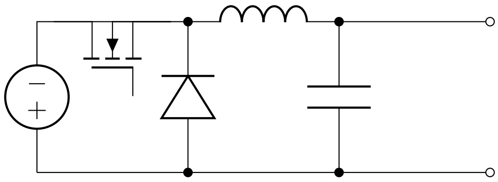

Figure 45: Buck Converer

2.3.8 Recycling

Inductors are fairly easy to recycle, especially those made from iron(or any metal) based core.

Inductor wires are usually made from Copper which can be easily recycled after burning the insulation layer.The Copper scraps are usually transferred to pyrometallurgical recovery sites. [14]

3 Second Order Circuit Simulation

3.1 Series Circuit Simulation

The series RCL circuit in Figure: 46 was simulated in Multisim^{TM} to observe damping and how different component values affect it.

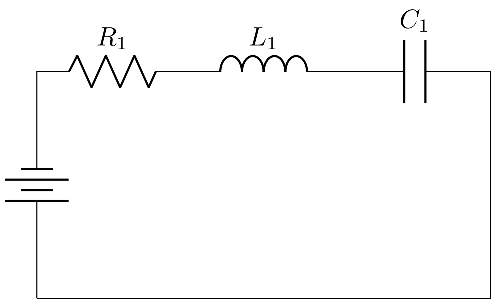

Figure 46: Series RCL Circuit used in Multisim^{TM} Simulation

The circuit was then drawn in Multisim^{TM} ,as seen in Figure: 47, and different values of Resistor R_1 were used.

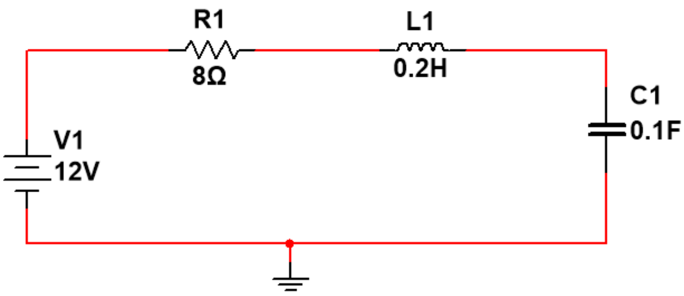

Figure 47: Series circuit drawn in Multisim^{TM}

3.1.1 Types of Damping

(a) **Over damping Case** ($\alpha < W$)

$$i(t) = C_1 e^{s_1 t} + C_2 e^{s_2 t} \tag{21}$$

(b) **Critically damped Case** ($\alpha = W$)

$$i(t) = (C_1 + C_2)e^{-\alpha t} \tag{22}$$

(c) **Underdamped Case** ($\alpha > W$)

$$i(t) = e^{-\alpha t}(C_1 \cos Wt + C_2 \sin Wt) \tag{23}$$

[15]

3.1.2 Simulation

3.1.2.1 Critical Damping

When the value of R_1 was set to 8Ω, and a graph of Current vs Time was plotted, Critical damping was observed as seen in Figure: 48

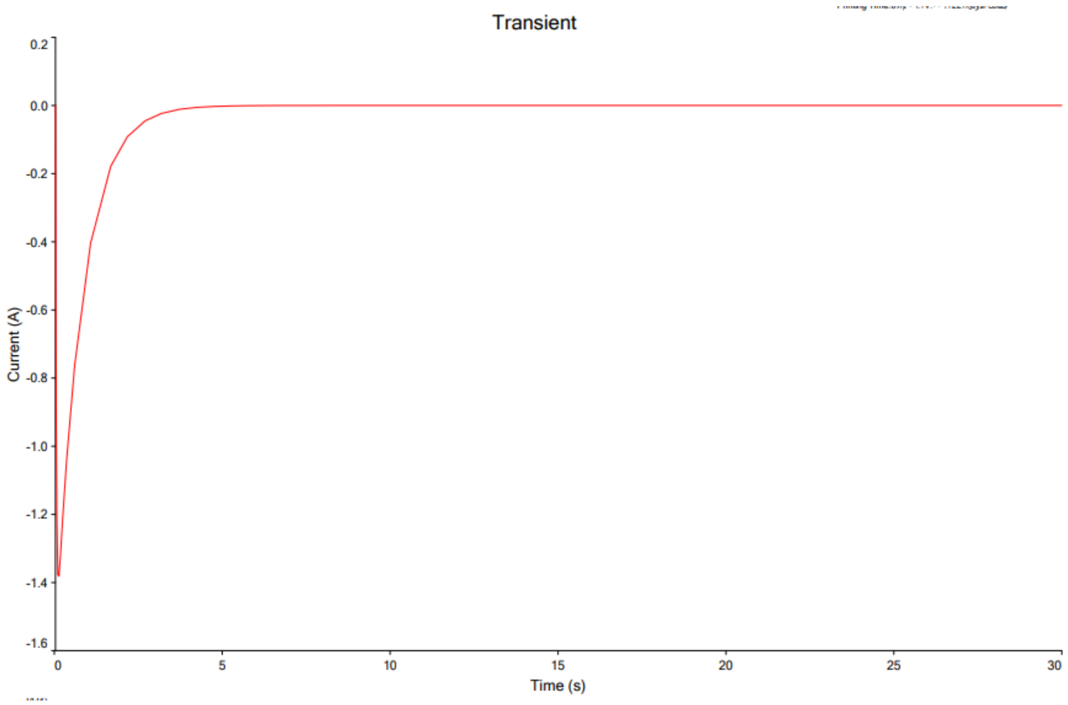

Figure 48: Multisim^{TM} series circuit critically damped current graph

3.1.2.2 Over Damping

When the value of R_1 was set to 40Ω, and a graph of Current vs Time was plotted, Over damping was observed as seen in Figure: 49

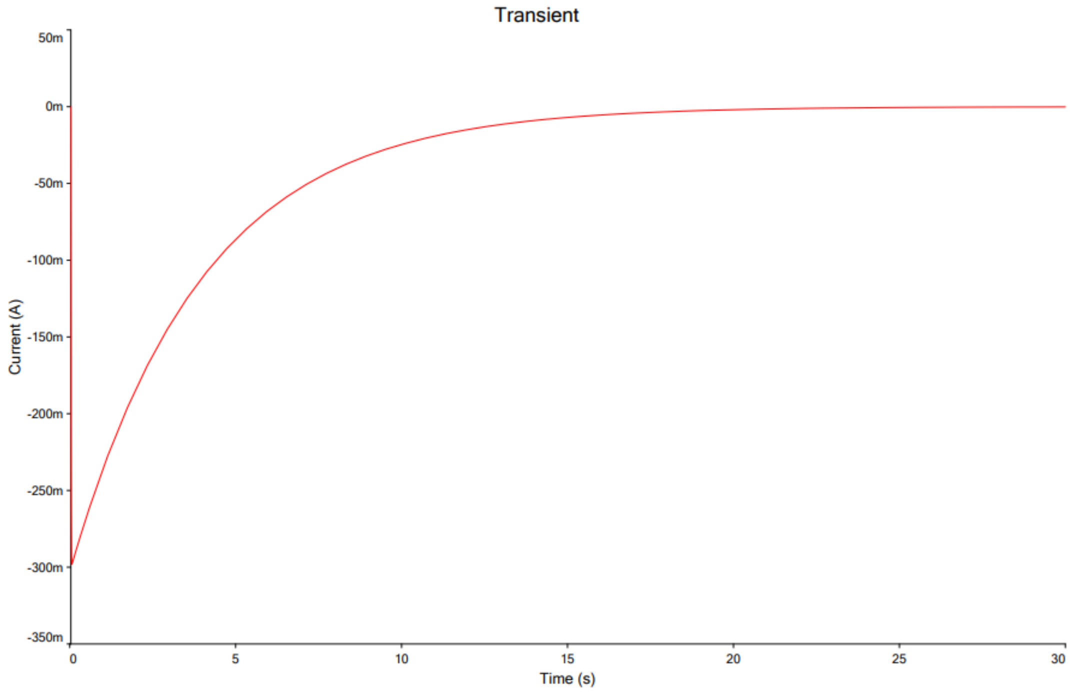

Figure 49: Multisim^{TM} series circuit over damping current graph

3.1.2.3 Under Damping

When the value of R_1 was set to 0.5Ω, and a graph of Current vs Time was plotted, under damping was observed as seen in Figure: 50

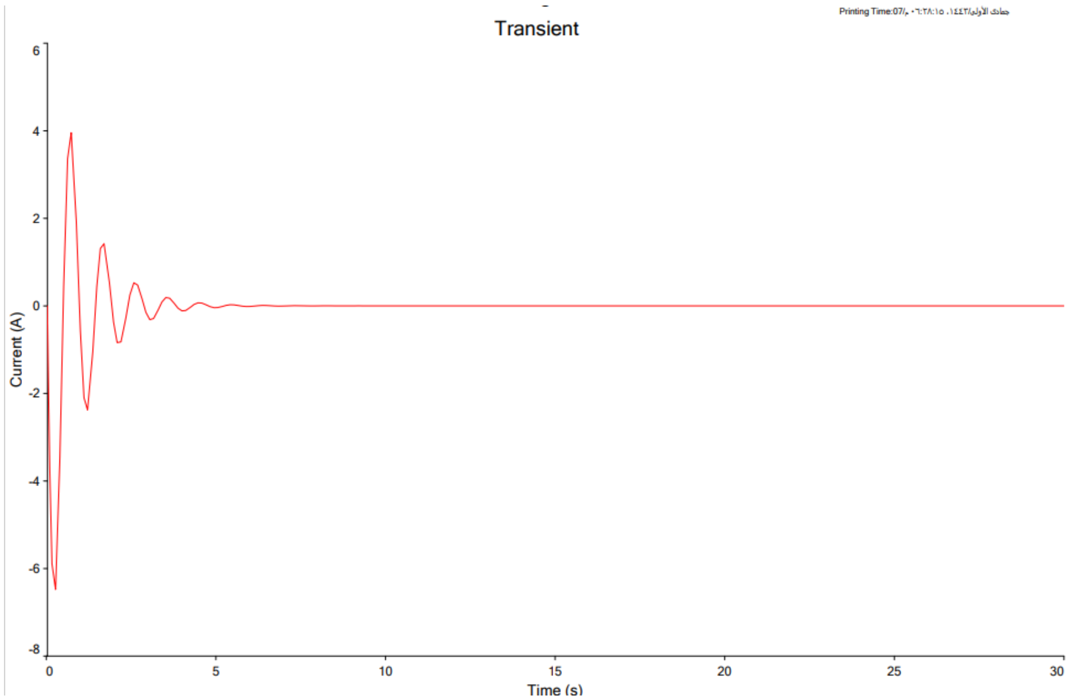

Figure 50: Multisim^{TM} series circuit under damping current graph

3.1.2.4 Results Observation

We notice that by increasing the value of the resistance R_1, the degree of damping decreases.

3.2 Parallel Circuit Simulation

The parallel RCL circuit in Figure: 46 was simulated in Multisim^{TM} to observe damping and how different component values affect it.

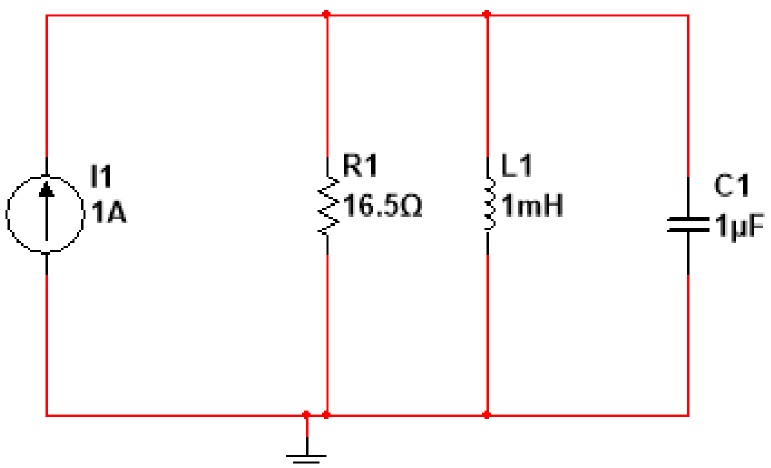

Figure 51: Parallel circuit drawn in Multisim^{TM}

The circuit was then drawn in Multisim^{TM} ,as seen in Figure: 51, and different values of Resistor R_1 were used.

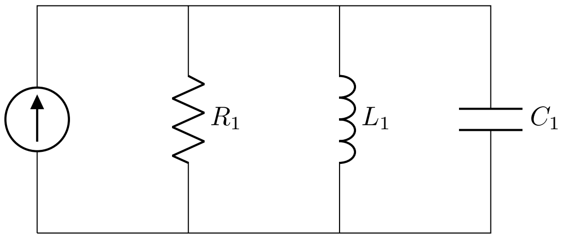

Figure 52: Parallel RCL Circuit used in Multisim^{TM} Simulation

3.2.1 Types of Damping

(a) **Overdamping Case** ($\alpha < W$)

$$i(t) = C_1 e^{s_1 t} + C_2 e^{s_2 t} \tag{24}$$

(b) **Critically damped Case** ($\alpha = W$)

$$i(t) = (C_1 + C_2)e^{-\alpha t} \tag{25}$$

(c) **Underdamped Case** ($\alpha > W$)

$$i(t) = e^{-\alpha t}(C_1 \cos Wt + C_2 \sin Wt) \tag{26}$$

[15]

3.2.2 Simulation

3.2.2.1 Critical Damping

When the value of R_1 was set to 16.5Ω, and a graph of Current vs Time was plotted, Critical damping was observed as seen in Figure: 53

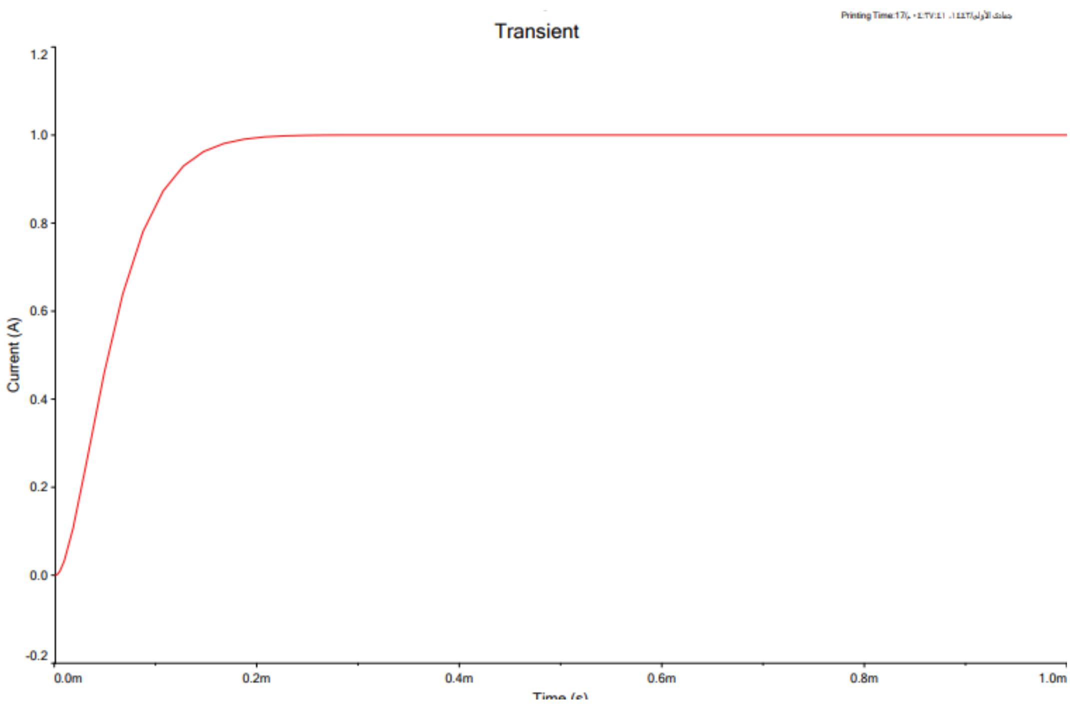

Figure 53: Multisim^{TM} parallel circuit Critically damped current graph

3.2.2.2 Over Damping

When the value of R_1 was set to 1Ω, and a graph of Current vs Time was plotted, Over damping was observed as seen in Figure: 54

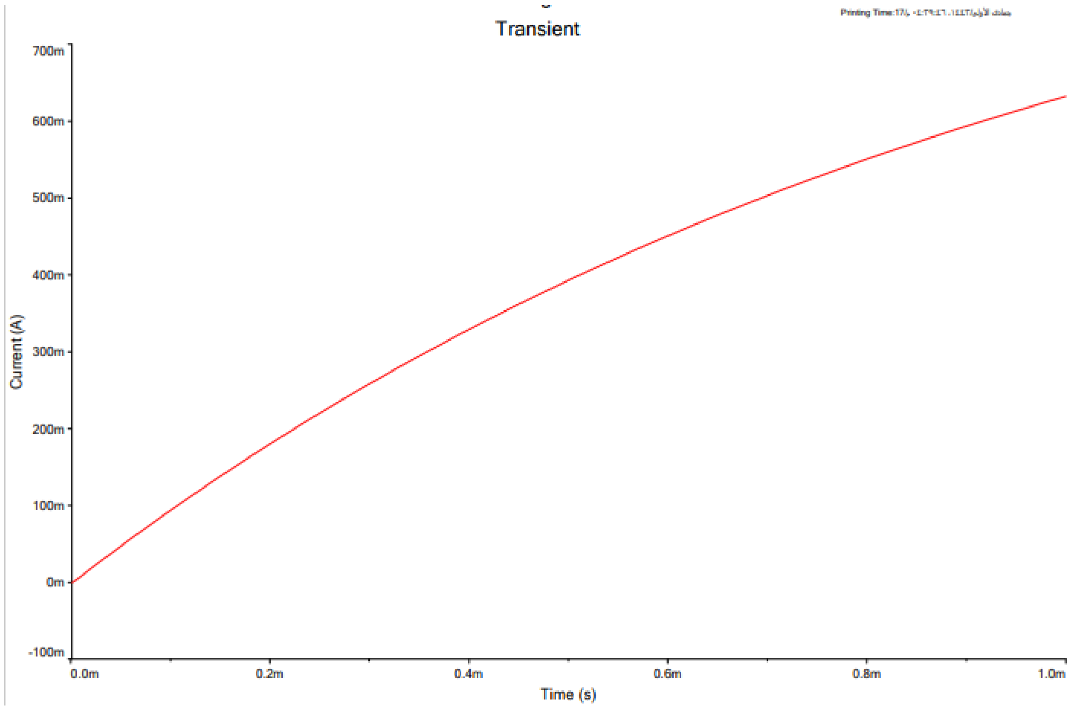

Figure 54: Multisim^{TM} parallel circuit over damping current graph

3.2.2.3 Under Damping

When the value of R_1 was set to 100Ω, and a graph of Current vs Time was plotted, under damping was observed as seen in Figure: 55

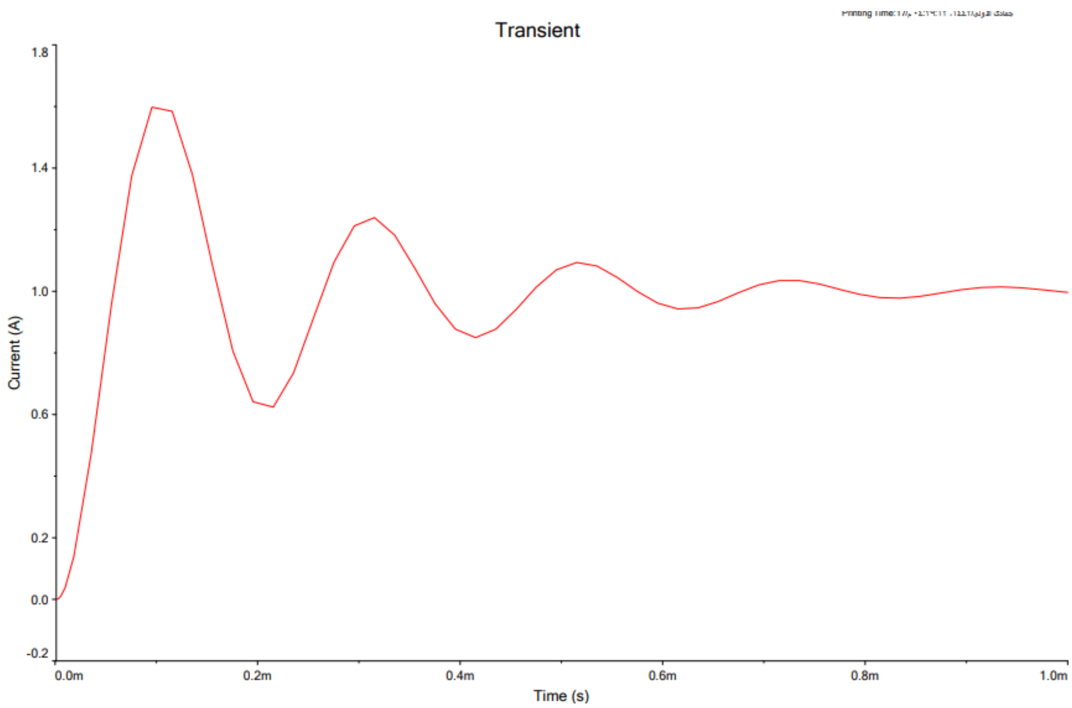

Figure 55: Multisim^{TM} parallel circuit under damping current graph

3.2.2.4 Results Observation

We notice that by increasing the value of the resistance R_1, the degree of damping increases.

List of Figures

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