Contents - Part 1

1.0 Introduction to Part 1

Having looked at some of the alternative offerings on the web, I decided it was time to do a series on basic electronics. Most I have seen are either too simplistic, and do not explain each component well enough, or are so detailed that it is almost impossible to know what you *need* to know as opposed to what you are *told* you need. These are usually very different.

Basic components are not always as simple as they may appear at first look. This article is intended for the beginner to electronics, who will need to know a number of things before starting on even the simplest of projects. The more experienced hobbyist will probably learn some new things as well, since there is a good deal of information here that most non-professionals will be unaware of.

This is by no means an exhaustive list, and I shall attempt to keep a reasonable balance between full explanations and simplicity. I shall also introduce some new terminology as I go along, and it is important to read this the way it was written, or you will miss the explanation of each term as it is first encountered.

It must be noted that the US still retains some very antiquated terminology, and this often causes great confusion for the beginner (and sometimes the not-so-beginner as well). You will see some "beat-ups" of the US - citizens of same, please don't be offended, but rather complain bitterly to anyone you see using the old terminology.

Within The Audio Pages, I use predominantly European symbols and terminology - these are also the recommended (but not mandatory) symbols and terms for Australia, and I have been using them for so long that I won't be changing them.

2.0 Definitions

The basic electrical units and definitions are as shown below. This list is not exhaustive (also see the Glossary), but covers the terms you will encounter most of the time. Many of the terms are somewhat inter-related, so you need to read all of them to make sure that you understand the relationship between them.

Passive: Capable of operating without an external power source.

Typical passive components are resistors, capacitors, inductors and diodes (although the latter are a special case).

Active: Requiring a source of power to operate.

Includes transistors (all types), integrated circuits (all types), TRIACs, SCRs, LEDs, etc.

DC: Direct Current

The electrons flow in one direction only. Current flow is from negative to positive, although it is often more convenient to think of it as from positive to negative. This is sometimes referred to as "conventional" current as opposed to electron flow.

AC: Alternating Current

The electrons flow in both directions in a cyclic manner - first one way, then the other. The rate of change of direction determines the frequency, measured in Hertz (cycles per second).

Frequency: Unit is Hertz, Symbol is Hz, old symbol was cps (cycles per second)

A complete cycle is completed when the AC signal has gone from zero volts to one extreme, back through zero volts to the opposite extreme, and returned to zero. The accepted audio range is from 20Hz to 20,000Hz. The number of times the signal completes a complete cycle in one second is the frequency.

Voltage: Unit is Volts, Symbol is V or U, old symbol was E

Voltage is the "pressure" of electricity, or "electromotive force" (hence the old term E). A 9V battery has a voltage of 9V DC, and may be positive or negative depending on the terminal that is used as the reference. The mains has a voltage of 220, 240 or 110V depending where you live - this is AC, and alternates between positive and negative values. Voltage is also commonly measured in millivolts (mV), and 1,000 mV is 1V. Microvolts (uV) and nanovolts (nV) are also used.

Current: Unit is Amperes (Amps), Symbol is I

Current is the flow of electricity (electrons). No current flows between the terminals of a battery or other voltage supply unless a load is connected. The magnitude of the current is determined by the available voltage, and the resistance (or impedance) of the load and the power source. Current can be AC or DC, positive or negative, depending upon the reference. For electronics, current may also be measured in mA (milliamps) - 1,000 mA is 1A. Nanoamps (nA) are also used in some cases.

Resistance: Unit is Ohms, Symbol is R or Ω

Resistance is a measure of how easily (or with what difficulty) electrons will flow through the device. Copper wire has a very low resistance, so a small voltage will allow a large current to flow. Likewise, the plastic insulation has a very high resistance, and prevents current from flowing from one wire to those adjacent. Resistors have a defined resistance, so the current can be calculated for any voltage. Resistance in passive devices is always positive (i.e. > 0)

Capacitance: Unit is Farads, Symbol is C

Capacitance is a measure of stored charge. Unlike a battery, a capacitor stores a charge electrostatically rather than chemically, and reacts much faster. A capacitor passes AC, but will not pass DC (at least for all practical purposes). The reactance or AC resistance (called impedance) of a capacitor depends on its value and the frequency of the AC signal. Capacitance is always a positive value.

Inductance: Unit is Henrys, Symbol is H or L (depending on context)

Inductance occurs in any piece of conducting material, but is wound into a coil to be useful. An inductor stores a charge magnetically, and presents a low impedance to DC (theoretically zero), and a higher impedance to AC dependent on the value of inductance and the frequency. In this respect it is the electrical opposite of a capacitor. Inductance is always a positive value. The symbol "Hy" is sometimes used in (guess where :-) ... the US. There is no such symbol.

Impedance: Unit is Ohms, Symbol is Ω or Z

Unlike resistance, impedance is a frequency dependent value, and is specified for AC signals. Impedance is made up of a combination of resistance, capacitance, and/ or inductance. In many cases, impedance and resistance are the same (a resistor for example). Impedance is most commonly positive (like resistance), but can be negative with some components or circuit arrangements.

Decibels: Unit is Bel, but because this is large, deci-Bels (1/10th Bel) are used), Symbol is dB

Decibels are used in audio because they are a logarithmic measure of voltage, current or power, and correspond well to the response of the ear. A 3dB change is half or double the power (0.707 or 1.414 times voltage or current respectively). Decibels will be discussed more thoroughly in a separate section.

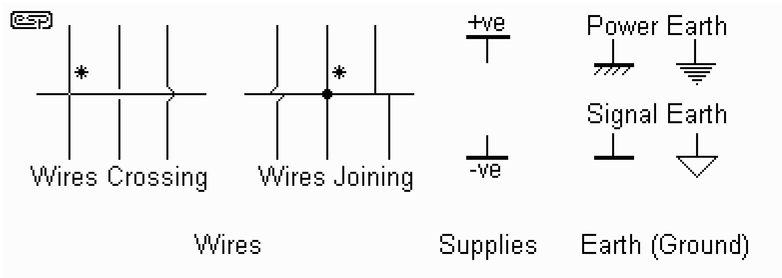
A few basic rules that electrical circuits always follow are useful before we start.

- A voltage of 1V across a resistance of 1 Ohm will cause a current flow of 1 Amp, and the resistor will dissipate 1 Watt (all as heat).
- The current entering any passive circuit equals the current leaving it, regardless of the component configuration.
- Electricity can kill you!
- The danger of electricity is current flowing through your body, not what is available from the source. A million volts at 1 microamp will make you jump, but 50V at 50mA can stop you dead - literally.
- An electric current flowing in a circuit does not cause vibrations at the physical level (good or bad), unless the circuit is a vibrator, loudspeaker, motor or some other electro-mechanical device. (i.e. components don't vibrate of their own accord unless designed to do so.)
- External vibrations do not affect the operation of 99.9% of electronic circuits, unless of a significant magnitude to cause physical damage, or the equipment is designed to detect such vibrations (for example, a microphone).
- Power is measured in Watts, and PMPO does not exist except in the minds of advertising writers.
- Large capacitors are not intrinsically "slower" than small ones (of the same type). Large values take longer to charge and discharge, but will pass AC just as well as small ones. They are better for low frequencies.
- Electricity can still kill you, even after reading this article.

Some of these are intended to forewarn you against some of the outrageous claims you will find as you research these topics further, and others are simple electrical rules that apply whether we like it or not.

3.0 Wiring Symbols

There are many different representations for basic wiring symbols, and these are the most common. Other symbols will be introduced as we progress.



Some Wiring Symbols

The conventions I use for wires crossing and joining are marked with a star (*) - the others are a small sample of those in common use, but are fairly representative. Many can be worked out from their position in the circuit diagram (schematic).

4.0 Units

The commonly accepted units in electronics are metric. In accordance with the SI (System Internationale) metric specifications, any basic unit (such as an Ohm or Farad) will be graded or sub-graded in units of 1,000 - this gives the following table.

Term	**Abbreviation**	**Value (Scientific)**	**Value (Normal)**
Tera	T	1×10^{12}	1,000,000,000,000
Giga	G	1×10^{9}	1,000,000,000
Mega	M	1×10^{6}	1,000,000
kilo	k (lower case)	1×10^{3}	1,000
Units	-	1	1
Milli	m	1×10^{-3}	1 / 1,000
Micro	µ or u	1×10^{-6}	1 / 1,000,000
Nano	n	1×10^{-9}	1 / 1,000,000,000

Pico	p	1 x 10^{-12}	1 / 1,000,000,000,000

Metric Multiplication Units

The abbreviations and case are important - "m" is quite clearly different from "M". In general, values smaller than unity use lower case, and those greater than unity use upper case. "k" is clearly an exception to this. There are others that go above and below those shown, but it is unlikely you will encounter them. Even Giga and Tera are unusual in electronics (except for determining the size hard drive needed to install a Microsoft application :-)

5.0 Resistors

The first and most common electronic component is the resistor. There is virtually no working circuit I know of that doesn't use them, and a small number of practical circuits can be built using nothing else. There are three main parameters for resistors, but only two of them are normally needed, especially for solid state electronics.

- Resistance - the value of resistance, measured in Ohms. This is the primary parameter, and determines the current flow for any applied voltage.
- Power - The amount of power the resistor can handle safely. Large resistors (physically) generally have a higher power rating than small ones, and this is always specified by the manufacturer. Excess power will cause the resistor to overheat and fail, often in a spectacular manner.
- Voltage - Rarely specified, but this is the maximum voltage that may appear across a resistor. It has nothing to do with power rating, which may be exceeded at rated voltage. It is a measure of the maximum voltage that may appear across any value of resistance for this style without breakdown.

The resistance value is specified in ohms, the standard symbol is "R" or Ω. Resistor values are often stated as "k" (kilo, or times 1,000) or "M", (meg, or times 1,000,000) for convenience. There are a few conventions that are followed, and these can cause problems for the beginner. To explain - a resistor has a value of 2,200 Ohms. This may be shown as any of these ...

- 2,200 Ohms
- 2,200 Ω
- 2,200R
- 2.2k
- 2.2k Ω

- 2k2

The use of the symbol for Ohms (Omega, Ω is optional, and is most commonly left off, since it is irksome to add from most keyboards. The letter "R" and the "2k2" conventions are European, and not commonly seen in the US and other backward countries :-) Other variants are 0R1, for example, which means 0.1 Ohm

The schematic symbols for resistors are either of those shown below. I use the Euro version of the symbol exclusively.

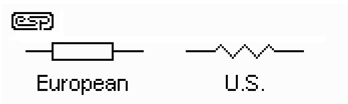


Figure 1.1 - Resistor Symbols

The basic formula for resistance is Ohm's law, which states that ...

1.1.1 $R = V / I$ Where V is voltage, I is current, and R is resistance

The other formula you need with resistance is Power (P)

1.1.2 $P = V^2 / R$
1.1.3 $P = I^2 * R$

The easiest way to transpose any formula is what I call the "Transposition Triangle" - which can (and will) be applied to other formulae. The resistance and power forms are shown below - just cover the value you want, and the correct formula is shown. In case anyone ever wondered why they had to do algebra at school, now you know - it is primarily for the manipulation of a formula - they just don't teach the simple ways. A blank between two values means they are multiplied, and the line means divide.

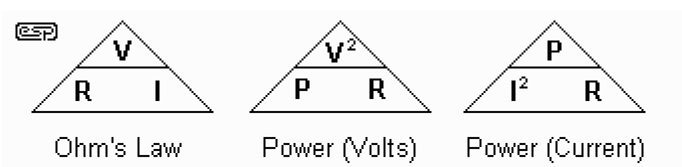


Figure 1.2 - Transposition Triangles for Resistance

Needless to say, if the value you want is squared, then you need to take the square root to get the actual value. For example, you have a 100 Ohm, 5W resistor, and want to know the maximum voltage that can be applied. $V^2 = P * R = 500$, and the square root of 500 is 22.36, or 22V. This is the maximum voltage across the resistor to remain within its power rating.

Resistors have the same value for AC and DC - they are not frequency dependent within the normal audio range. Even at radio frequencies, they will tend to provide the same value, but at very high frequencies other effects become influential. These characteristics will not be covered, as they are outside the scope of this article.

A useful thing to remember for a quick calculation is that 1V across a 1k resistor will have 1mA of current flow - therefore 10V across 1k will be 10mA (etc.).

5.1 Standard Values

There are a number of different standards, commonly known as E12, E24, E48 and E96, meaning that there are 12, 24, 48 or 96 individual values per decade (e.g. from 1k to 10k). The most common, and quite adequate for 99.9% of all projects, are the E12 and E24 series, and I shall not bother with the others at this time. The E12 and E24 series follow these sequences:

1		1.2		1.5		1.8		2.2		2.7		3.3		3.9		4.7		5.6		6.8		8.2		10

Table 1.2 - E12 Resistor Series

1		1.2		1.5		1.8		2.2		2.7		3.3		3.9		4.7		5.6		6.8		8.2		10
	1.1		1.3		1.6		2.0		2.4		3.0		3.6		4.3		5.1		6.2		7.5		9.1	

Table 1.3 - E24 Resistor Series

Generally, 5% resistors will follow the E12 sequence, and 1% or 2% resistors will be available in the E24 sequence. Wherever possible in my projects, I use E12 as these are commonly available almost everywhere.

Resistors are commonly available in values ranging from 0.1 Ohm (0R1) up to 10M Ohms (10,000,000 Ohms). Not all values are available in all types, and close tolerances are uncommon in very high and very low values.

5.2 Colour Codes

Low power (<= 2W) resistors are nearly always marked using the standard colour code. This comes in two variants - 4 band and 5 band. The 4 band code is most common with 5% and 10% tolerance, and the 5 band code is used with 1% and better.

Colour	**First Digit**	**Second Digit**	**Third Digit**	**Multiplier**	**Tolerance**
Black	0	0	0	1	
Brown	1	1	1	10	1%
Red	2	2	2	100	2%

Orange	3	3	3	1,000	
Yellow	4	4	4	10,000	
Green	5	5	5	100,000	
Blue	6	6	6	1,000,000	
Violet	7	7	7		
Grey	8	8	8		
White	9	9	9		
Gold				0.1	5%
Silver				0.01	10%

Table 1.1 - Resistor Colour Code

My apologies if the colours look wrong - blame the originators of the HTML colours, which are a little restricting, to say the least. With the 4 band code, the third digit column is not used, it is only used with the 5 band code. This is somewhat confusing, but we are unable to change it, so get used to it. Personally, I suggest the use of a multimeter when sorting resistors - I know it's cheating, but at least you don't get caught out by incorrectly marked components (and yes, this does happen).

5.3 Tolerance

The tolerance of resistors is mostly 1%, 2%, 5% and 10%. In the old days, 20% was also common, but these are now rare. Even 10% resistors are hard to get except in extremely high or low values (> 1M or < 1R), where they may be the only options available at a sensible price.

A 100R resistor with 5% tolerance may be anywhere between 95 and 105 ohms - in most circuits this is insignificant, but there will be occasions where very close tolerance is needed (e.g. 0.1% or better). This is fairly rare for audio, but there are a few instances where you may see such close tolerance components.

5.4 Power Ratings

Resistors are available with power ratings of 1/8th W (or less for surface mount devices), up to hundreds of watts. The most common are 1/4W (0.25W), 1/2W (0.5W), 1W, 5W and 10W. Very few projects require higher powers, and it is often much cheaper to use multiple 10W resistors than a single (say) 50W unit. They will also be very much easier to obtain.

Like all components, it is preferable to keep temperatures as low as possible, so no resistor should be operated at its full power rating for any extended time. I recommend a maximum of 0.5 of the power rating wherever possible. Wirewound resistors can tolerate severe overloads for a short period, but I prefer to keep the absolute maximum to somewhat less than 250% - even for very brief periods, since they may become open circuit from the stress, rather than temperature (this does happen, and I have experienced it during tests and repairs).

5.5 Resistance Materials

Resistors are made from a number of different materials. I shall only concentrate on the most common varieties, and the attributes I have described for each are typical - there will be variations from different makers, and specialised types that don't follow these (very) basic characteristics. All resistors are comparatively cheap.

- **Carbon Composition:** Low to medium power. Comparatively poor tolerance and stability. Noisier than most others.
- **Carbon Film:** Low power. Reasonable tolerance and stability. Reasonably quiet.
- **Metal Film:** Low to medium power. Very good tolerance and stability. Quiet.
- **Wirewound:** High to very high power. Acceptable to very good tolerance, good stability. Quiet. May have inductance.

A couple of points to ponder. Resistors make noise! Everything that is above 0K (zero Kelvin, absolute zero, or -273 degrees Celsius) makes noise, and resistors are no exception. Noise is proportional to temperature and voltage. Low noise circuits will always use low resistor values and low voltage wherever possible.

Resistors may also have inductance, and wirewound types are the worst for this. There are non-inductive wirewound resistors, but are not readily available, and usually not cheap.

6.0 Capacitors

Capacitors come in a bewildering variety of different types. The specific type may be critical in some applications, where in others, you can use anything you please. Capacitors are the second most common passive component, and there are few circuits that do not use at least one capacitor.

A capacitor is essentially two conductive plates, separated by an insulator (the dielectric). To conserve space, the assembly is commonly rolled up, or consists of many small plates in parallel for each terminal, each separated from the other by a thin plastic film. See below for more detailed information on the different constructional methods. A capacitor also exists whenever there is more than zero components in a circuit - any two pieces of wire will have some degree of capacitance between them, as will tracks on a PCB, and adjacent components. Capacitance also exists in semiconductors (diodes, transistors), and is an inescapable part of electronics.

There are two main symbols for capacitors, and one other that is common in the US, but rarely seen elsewhere. Caps (as they are commonly called) come in two primary versions - polarised and nonpolarised. Polarised capacitors must have DC present at all times, of the correct polarity and exceeding any AC that may be present on the DC polarising voltage. Reverse connection will result in the device failing, often in a spectacular fashion, and sometimes with the added excitement of flames, or high speed pieces of casing and electrolyte (an internal fluid in many polarised caps). This is not a good thing.

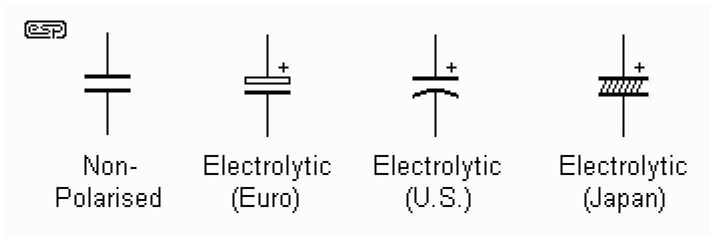


Figure 6.1 - Capacitor Symbols

Capacitors are rated in Farads, and the standard symbol is "C" or "F", depending upon the context. A Farad is so big that capacitors are most commonly rated in micro-Farads (uF). The Greek letter (lower case) Mu is the proper symbol, but "u" is available on keyboards, and is far more common. Because of the nature of capacitors, they are also rated in very much smaller units than the micro-Farad - the units used are ...

- mF: Milli-Farad, $1x10^{-3}$ Farad (1,000th of a Farad) - uncommon
- **uF**: Micro-Farad, $1x10^{-6}$ Farad (1,000,000th of a Farad)
- mF: Micro-Farad, a very, very old term, still sometimes used in the US (*True!*) - Causes much confusion.
- ufd: Micro-Farad, another very old term, still used in the US
- mfd (or MFD): Yet another antiquated term - US again!
- **nF**: Nano-Farad, $1x10^{-9}$ Farad (1,000,000,000th of a Farad) - Common everywhere *except* the US
- **pF**: Pico-Farad, $1x10^{-12}$ Farad (1,000,000,000,000th of a Farad)
- mmF: Micro-Micro-Farad, another extremely old term, also still used sometimes in the US

The items in bold are the ones I use in all articles and projects, and the others should be considered obsolete and not used - *at all, by anyone* ***!***

Milli-Farads (mF) ***should*** be used for large values, but are generally avoided because of the US's continued use of the ancient terminology. When I say ancient, I mean it - these terms date back to the late 1920s or so. Any time you see the term "mF", it *almost certainly* means uF - especially if the source is the US. You may need to determine the correct value from its usage in the circuit.

A capacitor with a value of 100nF may also be written as 0.1uF (especially in the US). A capacitor marked on a schematic as 2n2 has a value of 2.2nF, or 0.0022uF (mF ??). It may also be written (or marked) as 2,200pF. These are all equivalent, and although this may appear confusing (it is), it is important to understand the different terms that are applied.

A capacitor has an infinite (theoretically!) resistance at DC, and with AC, it has an impedance. Impedance is defined as a non-resistive (or only partially resistive) load, and is frequency dependent. This is a very useful characteristic, and is used to advantage in many circuits.

In the case of a capacitor, the impedance is called Capacitive Reactance generally shown as Xc. The formula for calculating Xc is shown below ...

6.1.1 $Xc = 1 / 2 \pi F C$ where π is 3.14159..., F is frequency in Hertz, and C is capacitance in Farads

The Transposition Triangle can be used here as well, and simplifies the extraction of the wanted value considerably.

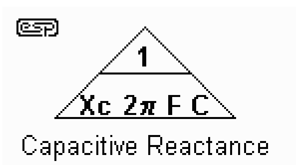


Figure 6.2 - Capacitance Triangle

As an example, what is the formula for finding the frequency where a 10uF capacitor has a reactance of 8 Ohms? Simply cover the term "F" (frequency), and the formula is

6.1.2 $F = 1 / 2 \pi C Xc$

In case you were wondering, the frequency is 1.989kHz (2kHz near enough). At this frequency, if the capacitor were feeding an 8 ohm loudspeaker, the frequency response will be 3dB down at 2kHz, and the signal going to the speaker will increase with increasing frequency. Since the values are the same (8 ohm speaker and 8 ohms reactance) you would expect that the signal should be 6dB down, but because of phase shift (more on this later), it is actually 3dB.

With capacitors, there is no power rating. A capacitor in theory dissipates no power, regardless of the voltage across it or the current through it. In reality, this is not quite true, but for all practical purposes it does apply.

All capacitors have a voltage rating, and this must not be exceeded. If a higher than rated voltage is applied, the insulation between the "plates" of the capacitor breaks down, and an arc will often weld the plates together, short circuiting the component. The "working voltage" is DC unless otherwise specified, and application of an equivalent AC signal will probably destroy the capacitor.

6.1 Standard Values

Capacitors generally follow the E12 sequence, but with some types, there are very few values available within the range. There are also a few oddities, especially with electrolytic caps (these are polarised types).

1	1.2	1.5	1.8	2.2	2.7	3.3	3.9	4.7	5.6	6.8	8.2	10

Table 6.1 - E12 Capacitor Series

Some electrolytic types have non-standard values, such as 4,000uF for example. These are easily recognised, and should cause no fear or panic :-)

6.2 Capacitor Markings

Unlike resistors, few capacitors are colour coded. Some years ago, various European makers used colour codes, but these have gone by the wayside for nearly all components available today. This is not to say that you won't find them, but I am not going to cover this.

The type of marking depends on the type of capacitor in some cases, and there are several different standards in common use. Because of this, each type shall be covered separately.

- **Ceramic:** These caps are usually used when extremely low values are needed. Ceramic caps typically range in value from 1pF up to 100nF, but in some cases and styles this will vary. They are commonly marked in pF (such as 100p), or a multiplier is used (such as 101, meaning 100pF - 10 plus one zero).

- **Plastic Film:** These are available in many different materials. Polyester is one of the most popular capacitor types, and these combine predictable size (especially the MKT types) and good performance. MKT caps use various different markings, and it takes some familiarity before you will feel completely comfortable. We will use a 47nF (0.047uF) MKT cap as an example. This could be marked as 473k, 473k63, or 47n. A 4.7nF cap may be marked 472k, 472k63, or 4n7. The third digit is a multiplier, and indicates the number of zeros to give the value in pF. 63 means that the working voltage is 63V, and this must not be exceeded.

- **Electrolytic:** Used where large values are needed, these caps are (nearly) always marked directly with the value in uF and the maximum voltage. Sometimes the maximum temperature is also indicated, but if not, 85 deg C should be assumed. Electros are polarised, and the negative terminal is marked clearly on the case. For "RB" style caps (printed circuit board mounting), the positive lead is usually the longer of the two.

- **Tantalum:** Another form of polarised capacitor. Theoretically unaffected by zero bias voltage, I (and many others) have found them to be unreliable regardless of usage. Some tantalum caps are colour coded - I do not propose to discuss these any further, so if you use them, you will have to figure out the markings for yourself.

6.3 Tolerance

The quoted tolerance of most polyester (or other plastic film types) capacitors is typically 10%, but in practice it is usually better than that. Close tolerance types (e.g. 1%) are available, but they are usually rather expensive. If you have a capacitance meter, it is far cheaper to buy more than you need, and select them yourself.

Electrolytic capacitors have a typical tolerance of +50/-20%, but this varies from one manufacturer to the next. Electrolytics are also affected by age, and as they get older, the capacitance falls. Modern electros are better than the old ones, but they are still potentially unreliable at elevated temperatures or with significant current flow (AC, of course).

6.4 Capacitance Materials

As you have no doubt discovered by now, the range is awesome. Although some of the types listed below are not especially common, these are the most popular of the capacitors available. There is a school of thought that the differences between various dielectrics are audible, and although this may be true in extreme cases, generally I do not believe this to be the case - provided of course that a reasonable comparison is made, using capacitors designed for the application.

Many of the capacitors listed are "metallised", meaning that instead of using aluminium or other metal plates, the film is coated with an extremely thin layer of vapourised metal. This makes the capacitor much smaller than would otherwise be the case.

- **Silvered Mica:** Probably the most linear low value capacitor, these are most commonly used in RF applications where the dielectric losses would preclude other types. They are physically large and comparatively expensive.

- **Polystyrene:** Very good electrical properties, including exceptionally high dielectric resistance. Very linear and stable, but physically large. Polystyrene is affected by many solvents, and is unsuitable for high temperatures.

- **Ceramic:** Excellent high frequency performance, but not stable with temperature (except NPO types). The temperature sensitivity is often used to stabilise RF oscillators. Very good bypass caps for high speed opamps. Not recommended for use in the audio path. Commonly available in voltages up to 3kV or more.

- **Monolithic Ceramic:** Designed as bypass capacitors, these are physically small, and have excellent HF performance. Stability is suspect, and they are not recommended for use in the audio path.

- **Polyester:** One of the most popular types, in the "MKT" package style. Stable and reliable, but generally only low voltage (up to 100V). Suitable for all audio applications, as well as bypass on power amplifiers and opamps.

- **Mylar:** Also known as "Greencaps" - another popular cap, suitable for all audio applications, as well as bypass for power amps and opamps. (Note that Greencaps may also be polyester).

- **Polypropylene:** Available in relatively large values, and excellent for passive loudspeaker crossover networks. Said by some to be audibly superior to other plastic film types (personally, I doubt this claim).
- **PET**: (Polyethylene Terephthalate) - the same stuff that plastic drink bottles are made from. Used in many different types of plastic film caps, often replacing polyester or mylar
- **Electrolytic:** Using plates of aluminium and an electrolyte to provide conductivity, these caps use an extremely thin layer of aluminium oxide (created by anodising) as the dielectric. This gives very high capacitance per unit volume, and electros are used as coupling capacitors, filter capacitors in power supplies, and anywhere where a close tolerance is not needed, but high capacitance is necessary. They have a maximum current rating which must not be exceeded, and are somewhat unreliable. There are no alternatives.
- **Low Leakage Electrolytic:** These are a "premium" version of standard electrolytic capacitors, and are used where relatively high capacitance is required, but leakage (DC current flow) is undesirable, even at very low values. These are (IMHO) a better alternative than ...
- **Tantalum:** Very high capacitance per unit volume, but probably the most unreliable capacitor ever made. I do not recommend their use unless there is no alternative (this is rare).
- **Bipolar Electrolytic:** Two polarised electrolytic capacitors in series, with the positive (or negative) terminals joined internally. These are often used in crossover networks, and offer low cost and small size. They are not especially reliable at any appreciable power, and I don't recommend them. They are sometimes useful in circuits where a high value cap is needed, but there is little or no polarising voltage. I have found no problems with them in this application, but distortion may be an issue in some cases.
- **Oil/ Paper:** These were used many years ago, and can still be found as motor start and power factor factor correction capacitors. They are extremely rugged, and are self-healing. They do not fail as a short circuit - any arc is extinguished by the oil, and the cap can continue to function normally after the excess voltage is removed.

This is only a basic listing, but gives the reader an idea of the variety available. The recommendations are mine, but there are many others in the electronics industry who will agree with me (as well as many who will not - such is life).

Apart from the desired quantity of capacitance, capacitors have some unwanted features as well. Many of them - especially electrolytics - have significant inductance, and they all posses some value of resistance (although generally small). The resistance is referred to as ESR (Equivalent Series Resistance), and this can have adverse effects at high currents (e.g. power supplies). Although it exists in all capacitors, ESR is generally quoted only for electrolytics.

7.0 Inductors

These are the last of the purely passive components. An inductor is most commonly a coil, but in reality, even a straight piece of wire has inductance. Winding it into a coil simply concentrates the magnetic field, and increases the inductance considerably for a given length of wire. Although there are some very common inductive components (such as transformers, which are a special case), they are not often used in audio. Small inductors are sometimes used in the output of power amplifiers to prevent instability with capacitive loads.

Note: Transformers are a special case of inductive components, and will be covered separately.

Even very short component leads have some inductance, and like capacitance, it is just a part of life. Mostly in audio, these stray inductances cause no problems, but they can make or break a radio frequency circuit, especially at the higher frequencies.

An inductor can be considered the opposite of a capacitor. It passes DC with little resistance, but becomes more of an obstacle to the signal as frequency increases.

There are a number of different symbols for inductors, and three of them are shown below. Somewhat perversely perhaps, I use the "standard" symbol most of the time, since this is what is supported best by my schematic drawing package.

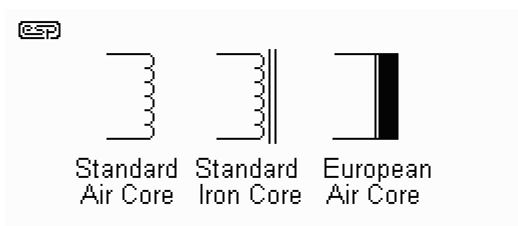


Figure 7.1 - Inductor Symbols

There are other core types not shown above. Dotted lines instead of solid mean that the core is ferrite or powdered iron, rather than steel laminations or a toroidal steel core. Note that pure iron is rarely (if ever) used, since there are various grades of steel with much better magnetic properties. The use of a magnetic core further concentrates the magnetic field, and increases inductance, but at the expense of linearity. Steel or ferrite cores should never be used in crossover networks for this reason (although many manufacturers do just that, and use bipolar electrolytic capacitors to save costs).

Inductance is measured in Henrys (H) and has the symbol "L" (yes, but ... Just accept it :-). The typical range is from a few micro-Henrys up to 10H or more. Although inductors are available as components, there are few (if any) conventions as to values or markings. Some of the available types may follow the E12 range, but then again they may not.

Like a capacitor, an inductor has reactance as well, but it works in the opposite direction. The formula for calculating the inductive reactance (X_L) is ...

7.1.1 $X_L = 2 \pi F L$ where L is inductance in Henrys

As before, the transposition triangle helps us to realise the wanted value without having to remember basic algebra.

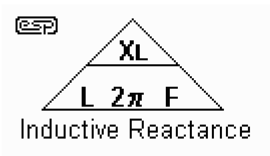


Figure 7.2 - Inductance Triangle

An inductor has a reactance of 8 ohms at 2Khz. What is the inductance? As before, cover the wanted value, in this case inductance. The formula becomes ...

7.1.2 $L = X_L / 2 \pi F$

The answer is 636uH. From this we could deduce that a 636uH inductor in series with an 8 ohm loudspeaker will reduce the level by 3dB at 2kHz. Like the capacitor, when inductive reactance equals resistance, the response is 3dB down, and not 6dB as would be the case with two equal resistances. What we have done in these last two examples is design a simple 2kHz passive crossover network, using a 10uF capacitor to feed the tweeter, and a 636uH inductor feeding the low frequency driver.

Like a capacitor, an inductor (in theory) dissipates no power, regardless of the voltage across it or the current passing through. In reality, all inductors have resistance, so there is a finite limit to the current before the wire gets so hot that the insulation melts.

7.1 Quality Factor

The resistance of a coil determines its Q, or Quality factor. An inductor with high resistance has a low Q, and vice versa. I do not propose to cover this in any more detail at this stage, and most commercially available inductors will have a sufficiently high Q for anything we will need in audio. If desired, the Q of any inductor may be reduced by wiring a resistor in series with the coil, but it cannot be increased because of its internal limitations.

7.2 Power Ratings

Because of the resistance, there is also a limit to the power that any given inductor can handle. In the case of any inductor with a magnetic core, a further (and usually overriding) limitation is the maximum magnetic flux density supported by the magnetic material before it saturates. Once saturated, any increase in current causes no additional magnetic field (since the core cannot support any more magnetism), and the inductance falls. This causes gross non-linearities, which can have severe repercussions in some circuits (such as a switchmode power supply).

7.3 Inductance Materials

The most common winding material is copper, and this may be supported on a plastic bobbin, or can be self-supporting with the aid of cable ties, lacquer, or epoxy potting compounds. Iron or ferrite cores may be toroidal (shaped like a ring), or can be in the traditional EI (ee-eye) format. In some cases for crossover networks and some other applications, a piece of magnetic material is inserted through the middle of the coil, but does not make a complete magnetic circuit. This reduces inductance compared to a full core, but reduces the effects of saturation, and allows much higher power ratings.

7.4 Core Types

Inductors may use a variety of materials for the core, ranging from air (lowest inductance, but highest linearity), through to various grades of steel or ferrite materials. Since inductors are nearly always used only for AC operation, the constantly changing magnetic flux will induce a current into any conductive core material in a similar manner to a transformer. This is called "eddy current" and represents a total loss in the circuit. Because the currents may be very high, this leads to the core becoming hot, and also reduces performance.

To combat this, steel cores are laminated, using thin sheets of steel insulated from each other. This prevents the circulating currents from becoming excessive, thereby reducing losses considerably. As the frequency increases, even the thin sheets will start to suffer from losses, so powdered iron (a misnomer, since it is more commonly powdered steel) cores are used. Small granules of magnetic material are mixed with a suitable bonding agent, and fired at high temperature to form a ceramic-like material that has excellent magnetic properties. The smaller the magnetic particles (and the less bonding agent used), the better the performance at high power and high frequencies. It is important that the individual granules are insulated from each other, or losses will increase.

These materials are available in a huge variety of different formulations, and are usually optimised for a particular operating frequency range. Some are designed for 20kHz up to 200kHz or so, and these are commonly used for switchmode power supplies, television "flyback" transformers and the like. Other materials are designed to operate at radio frequencies (RF), and these are most commonly classified as "ferrite" cores. In some cases, the terms "powdered iron" and "ferrite" are used interchangeably, but this is not correct - they are different materials with different properties.

These will be covered in more detail when transformers are discussed.

8.0 Components in Combination

Components in combination form most of the circuits we see. All passives can be arranged in series, parallel, and in any number of different ways to achieve the desired result. Amplification is not possible with passive components, since there is no means to do so. This does not mean that we are limited - there are still many combinations that are extremely useful, and they are often used around active devices (such as opamps) to provide the characteristics we need. Parallel operation is often used to obtain greater power, where a number of low power resistors are wired in parallel to get a lower resistance, but higher power. Series connections are sometimes used to obtain very high values (or to increase the voltage rating). There are endless possibilities, and I shall only concentrate on the most common.

8.1 Resistors

Resistors can be wired in parallel or in series, or any combination thereof, so that values greater or smaller than normal or with higher power or voltage can be obtained. This also allows us to create new values, not catered for in the standard values.

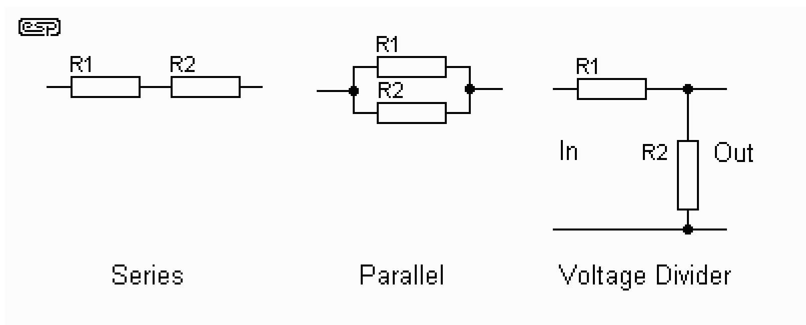


Figure 8.1 - Some Resistor Combinations

Series: When wired in series, the values simply add together. A 100 ohm and a 2k2 resistor in series will have a value of 2k3.

8.1.1 R = R1 + R2 (+ R3, etc.)

Parallel: In parallel, the value is lower than either of the resistors. A formula is needed to calculate the final value

8.1.2 1/R = 1/R1 + 1/R2 (+ 1/R3 etc.) Also written as ...
8.1.3 R = 1 / ((1 / R1) + (1 / R2)) An alternative for two resistors is ...
8.1.4 R = (R1 * R2) / (R1 + R2)

The same resistors as before in parallel will have a total resistance of 95.65 ohms (100 || 2,200). Either formula above may be used for the same result.

Four 100 ohm 10W resistors gives a final value of either 400 ohms 40W (series), 25 ohms 40W (parallel) or 100 ohms 50W (series/ parallel).

Voltage Dividers: One of the most useful and common applications for resistors. A voltage divider is used to reduce the voltage to something more suited to our needs. This connection provides no "transformation", but is used to match impedances or levels. The formula for a voltage divider is

8.1.5 Vd = (R1 + R2) / R2

With our standard resistors as used above, we can create a voltage divider of 23 (R1=2k2, R2=100R) or 1.045 (R1=100R, R2=2k2). Perhaps surprisingly, both of these are useful ***!***

8.2 Capacitors

Like resistors, capacitors can also be wired in series, parallel or a combination.

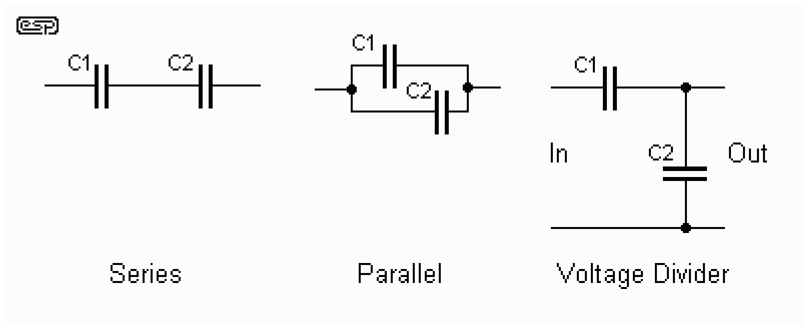


Figure 8.2 - Capacitor Combinations

The capacitive voltage divider may come as a surprise, but it is a useful circuit, and is common in RF oscillators and precision attenuators (the latter in conjunction with resistors). Despite what you may intuitively think, the capacitive divider is not frequency dependent, so long as the source impedance is low, and the load impedance is high compared to the capacitive reactance.

When using caps in series or parallel, exactly the opposite formulae are used from those for resistance. Caps in parallel have a value that is the sum of the individual capacitances. Here are the calculations ...

Parallel: A 12nF and a 100nF cap are wired in parallel. The total capacitance is 112nF

8.2.1 C = C1 + R2 (+ R3, etc.)

Series: In series, the value is lower than either of the caps. A formula is needed to calculate the final value

8.2.2 1 / C = 1 / C1 + 1 / C2 (+ 1 / C3 etc.) Also written as ...
8.2.3 C = 1 / ((1 / C1) + (1 / C2)) An alternative for two capacitors is ...
8.2.4 C = (C1 * C2) / (C1 + C2)

This should look fairly familiar by now. The same two caps in series will give a total value of 10n7 (10.7nF).

The voltage divider is calculated in the same way, except that the terms are reversed (the larger capacitor has a lower reactance).

8.3 Inductors

I shall leave it to the reader to determine the formulae, but suffice to say that they behave in the same way as resistors in series and parallel. The formulae are the same, except that "L" (for inductance) is substituted for "R".

An inductive voltage divider can also be made, but it is much more common to use a single winding, and connect a tapping to it for the output. This allows the windings to share a common magnetic field, and makes a thoroughly useful component. These inductors are called "autotransformers", and they behave very similarly to a conventional transformer, except that only one winding is used, so there is no isolation. As a suitable introduction to the transformer, I have shown the circuit for a variable voltage transformer, called a Variac (this is trademarked, but the term has become generic for such devices).

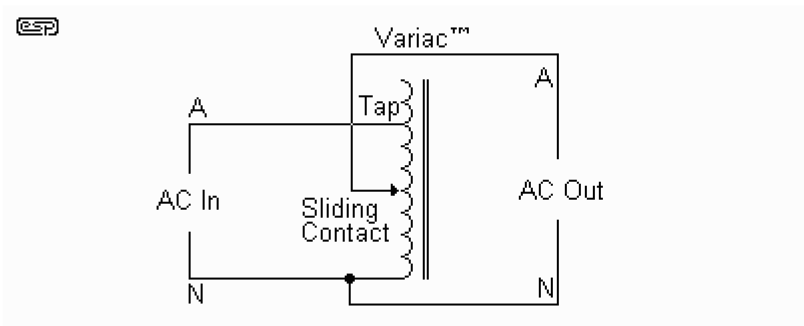


Figure 8.3 - The Schematic of a Variac

A Variac is nothing more than an iron cored inductor. The mains is applied to a tap about 10% from the end of the winding. The sliding contact allows the output voltage to be varied from 0V AC, up to about 260V (for a 240V version). As a testbench tool they are indispensable, and they make a fine example of a tapped inductance as well.

I stated before that passive components cannot amplify, yet I have said here that 240V input can become 260V output. Surely this is amplification? No, it is not. This process is "transformation", and is quite different. The term "amplifier" indicates that there will be a power gain in the circuit (as well as voltage gain in most amps), and this cannot be achieved with a transformer. Even assuming an "ideal" component (i.e. one having no losses), the output power can never exceed the input power, so no amplification has taken place.

9.0 Composite Circuits

When any or all of the above passive components are combined, we create real circuits that can perform functions that are not possible with a single component type. These "composite" circuits make up the vast majority of all electronics circuits in real life, and understanding how they fit together is very important to your understanding of electronics.

The response of various filters is critical to understanding the way many electronics circuits work. Figure 5.0 shows the two most common, and two others will be introduced as we progress further.

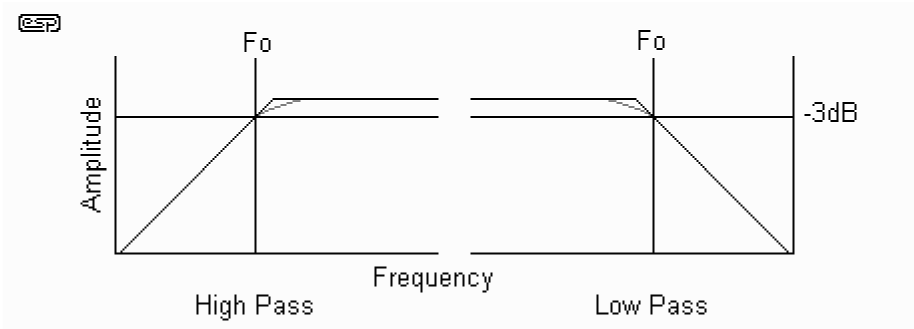


Figure 9.1 - High Pass and Low Pass Filter Response

The theoretical response is shown, and the actual response is in grey. Real circuits (almost) never have sharp transitions, and the curves shown are typical of most filters. The most common use of combined resistance and reactance (from a capacitor or inductor) is for filters. Fo is the frequency at which response is 3dB down in all such filters.

Within this article, only single pole (also known as 1st order) filters will be covered - the idea is to learn the basics, and not get bogged down in great detail with specific circuit topologies. A simple first order filter has a rolloff of 6dB per octave, meaning that the voltage (or current) of a low pass filter is halved each time the frequency is halved. In the case of a high pass filter, the signal is halved each time the frequency is doubled. These conditions only apply when the applied signal is at least one octave from the filter's "corner" frequency.

This slope is also referred to as 20dB per decade, so the signal is reduced by 20dB for each decade (e.g. from 100Hz to 1kHz) from the corner frequency.

9.1 Resistance / Capacitance Circuits

When resistance (R) and capacitance (C) are used together, we can start making some useful circuits. The combination of a non-reactive (resistor) and a reactive (capacitor) component creates a whole new set of circuits. Simple filters are easily made, and basic circuits such as integrators (low pass filters) and differentiators (high pass filters) will be a breeze after this section is completed.

The frequency of any filter is defined as that frequency where the signal is 3dB lower than in the pass band. A low pass filter is any filter that passes frequencies below the "turnover" point, and the relationship between R, C and F is shown below ...

9.1.1 $F = 1 / 2 \pi R C$ I shall leave it to you to fit this into the transposition triangle.

A 10k resistor and a 100nF capacitor will have a "transition" frequency (Fo) of 159Hz, and it does not matter if it is connected as high or low pass. Sometimes, the time constant is used instead - Time

Constant is defined as the time taken for the voltage to reach 68% of the supply voltage upon application of a DC signal, or discharge to 37% of the fully charged voltage upon removal of the DC. This depends on the circuit configuration.

9.1.2   T = R C   Where **T** is time constant

For the same values, the time constant is 1ms (1 millisecond, or 1/1,000 second). The time constant is used mainly where DC is applied to the circuit, and it is used as a simple timer, but is also used with AC in some instances. From this, it is obvious that the frequency is therefore equal to

9.1.3 $F = 1 / 2 \pi T$

This is not especially common, but you may need it sometime.

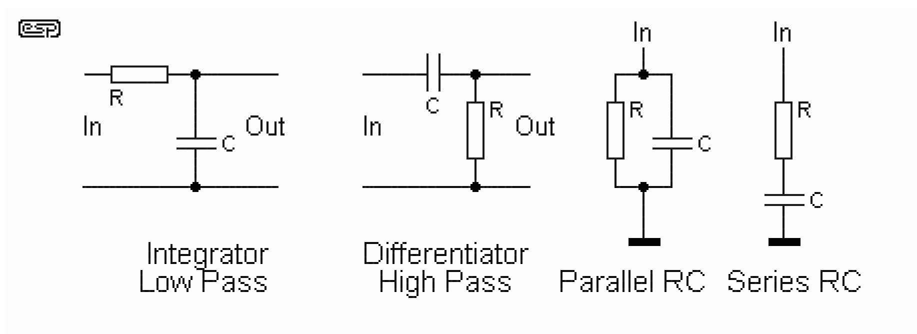


Figure 9.1 - Some RC Circuits

The above are only the most basic of the possibilities, and the formula (9.1.1) above covers them all. The differentiator (or high pass filter) and integrator (low pass filter) are quite possibly the most common circuits in existence, although most of the time you will be quite unaware that this is what you are looking at. The series and parallel circuits are shown with one end connected to Earth - again, although this is a common arrangement, it is by no means the only way these configurations are used. For the following, we shall assume the same resistance and capacitance as shown above - 10k and 100nF.

The parallel RC circuit will exhibit only the resistance at DC, and the impedance will fall as the frequency is increased. At high frequency, the impedance will approach zero Ohms. At some intermediate frequency determined by formula 9.1.1, the reactance of the capacitor will be equal to the resistance, so (logically, one might think), the impedance will be half the resistor value. In fact, this is not the case, and the impedance will be 7k07 Ohms. This needs some further investigation ...

The series RC circuit also exhibits frequency dependent behaviour, but at DC the impedance is infinite (for practical purposes), and at some high frequency it is approximately equal to the resistance value alone. It is the opposite of the parallel circuit. This circuit is seen at the output of almost every solid state amplifier ever made, and is intended to stabilise the amplifier at high frequencies in the presence of inductive loads (speaker cables and loudspeakers).

Because of a phenomenon called "phase shift" (see below) these RC circuits can only be calculated using vector mathematics (trigonometry) or "complex" arithmetic, neither is particularly straightforward, and I will look at a simple example only - otherwise they will not be covered here.

9.1.4 $Z = \sqrt{(1 / (1/R^2 + 1/Xc^2))}$ For parallel circuits, or ...
9.1.5 $Z = \sqrt{(R^2 + Xc^2)}$ For series circuits.

Simple !!! Actually, it is. In the case of the series circuit, we take the square root of the two values squared - those who still recall a little trigonometry will recognise the formula. It is a little more complex for the parallel circuit, just as it was for parallel resistors - the only difference is the units are squared before we add them, take the square root, and the reciprocal. If this is all too hard, there is a simple way, but it only works when the capacitive reactance equals resistance. Since this is the -3dB frequency (upon which nearly all filters and such are specified), it will suit you most of the time.

9.1.6 Z = 0.707 * R For parallel circuits, and ...
9.1.7 Z = 1.414 * R For series circuits.

If we work this out - having first calculated the frequency where Xc = R (159Hz), we can now apply the maths. Z is equal to 7k07 for the parallel circuit, and 14k1 for the series circuit. Remember, this simple formula ***only*** applies when Xc = R.

Figure 5.2 shows one of the effects of phase shift in a capacitor - the current (red trace) is out of phase with respect to the voltage. In fact, the current is leading the voltage by 90 degrees. It may seem impossible for the current through a device to occur before the voltage, and this situation only really applies to "steady state" signals. This is known in electrical engineering as a leading power factor.

It becomes more complex mathematically to calculate the transient (or varying signal) behaviour of the circuit, but interestingly, this has no effect on sound, and the performance with music will be in accordance with the steady state calculations.

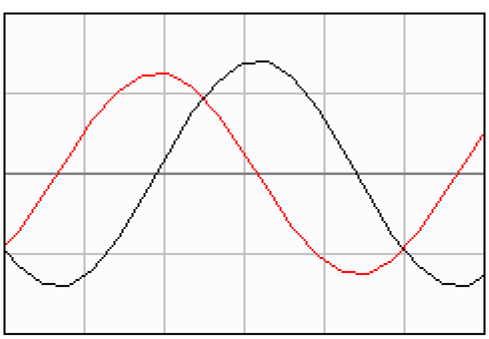


Figure 9.2 - Capacitive Phase Shift

The phase shift through any RC circuit varies with frequency, and at frequencies where Xc is low compared to the -3dB frequency, it is minimal. Phase shift is not audible in any normal audio circuit.

When the value of the integration or differentiation capacitor is large compared to the lowest operating frequency, it is more commonly called a coupling capacitor. The same formulae are used regardless of the nomenclature of the circuit.

9.2 Resistance / Inductance Circuits

The combination of resistance (R) and inductance (L) is much less common than RC circuits in modern electronics circuits. Many of the same circuit arrangements can be applied, but it uncommon to do so.

These days, the most common application of RL circuits is in passive crossover networks. The speaker is not pure resistance, but is often compensated with a "Zobel" network in an attempt to cancel the inductive component of the speaker.

The turnover frequency (-3dB) is determined by the formula below.

9.2.1 $F = R / 2 \pi L$ Again, I shall leave it to you to fit this into the transposition triangle

A couple of simple RL filters are shown in Figure 9.3 for reference. These are not uncommon circuits, and they may be seen in amplifiers and loudspeaker crossovers networks almost anywhere.

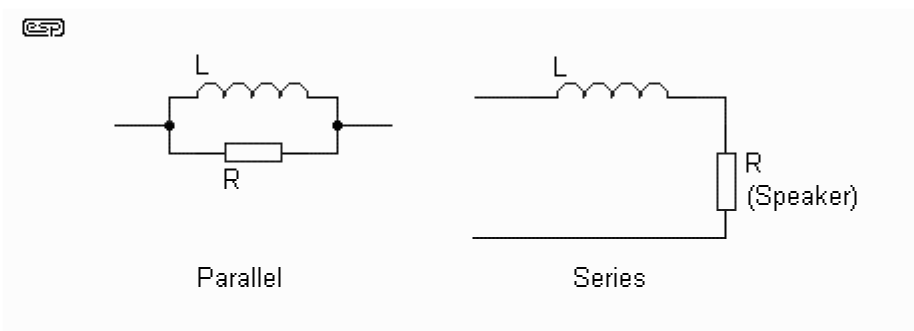


Figure 9.3 - Basic Resistance / Inductance Filters

The series circuit is typical of a simple crossover network to a woofer, and the "resistance" is the loudspeaker. The parallel circuit is seen on the output of many amplifier circuits, and is used to isolate the amplifier from capacitive loading effects at high frequencies. Because of the phase shift introduced by capacitance, some amplifiers become unstable at very high frequencies, and tend to oscillate. This affects sound quality and component life (especially the transistors), and is to be avoided.

Inductors (like capacitors) are reactive, and they cannot be calculated simply. To determine the impedance of a series or parallel circuit requires exactly the same processes as described for capacitors. Like capacitors, inductors cause phase shift, except the shift is the reverse - the current occurs after the voltage. In electrical engineering, this is referred to as as a lagging power factor. This is shown in Figure 9.4, and again, the red trace is current - it can be seen that the current occurs after the voltage.

Figure 9.4 - Inductive Phase Shift

Just as we did with capacitive reactance, if we work only with the -3dB frequency, this is where inductive reactance (X_L) and resistance are equal. Because the inductive reactance increases with increasing frequency (as opposed to capacitive reactance which falls as frequency increases), the configurations for low pass and high pass are reversed. We can still use the same simple formulae, and again, these ***only*** work when X_L is equal to R.

9.2.2 Z = 0.707 * R For parallel circuits, and ...
9.2.3 Z = 1.414 * R For series circuits.

Integrators and differentiators can also be made using RL circuits, but they are very uncommon in normal linear electronics circuits and will not be covered at this time.

9.3 Capacitance / Inductance Circuits

The combination of capacitance and inductance (at least in its "normal" form) is quite uncommon in audio or other low frequency circuits. Simulated inductors (using an opamp to create an artificial component with the properties of an inductor) are common, and they behave in a very similar manner in simple circuits.

The combination using real inductors has some fascinating properties, depending on the way they are connected. These will be covered only briefly here - they are much more commonly used in RF work, and in some cases for generation of very high voltages for experimental purposes (Tesla coils and car ignition coils spring to mind). A series resonant circuit can generate voltages that are many times the input voltage, and this interesting fact can be used to advantage (or to kill yourself!).

An inductor and capacitor in series presents a very low impedance at resonance, defined as the frequency where inductive and capacitive reactance are equal. With ideal (i.e. completely lossless) components, the impedance at resonance is zero, but in reality there will always be some resistance because of the resistance of the coil, and some small capacitive losses.

Resonance (Fo) is determined by the formula ...

9.3.1 Fo = 1 / 2 π √ L C

Yet again, the insertion of this into the transposition triangle is up to you, but you need a hint - to extract L or C, all other terms must be squared first. (For example, $1 = 4 \pi^2 F^2 L C$ - the triangle is very easy now!)

Parallel resonance uses the same formula, and at resonance the impedance is theoretically infinite with ideal components. Both of these combinations are used extensively in radio work, and parallel resonance circuits are used in many tape machines, for example.

It is somewhat beyond the scope of this article to describe this in detail, but tape machines use a high frequency bias oscillator to overcome the inherent distortion that occurs when a material is magnetised. The HF signal is at a very high amplitude, because the inductance of the tape heads causes their impedance to be very high at the bias frequency (typically between 50kHz and 150kHz). Should this high amplitude high frequency be fed into the record amplifier, the low impedance of the amp circuit will "steal" most of the bias, and the amplifier will probably be forced into distortion as well, and the circuit won't work. A parallel resonant circuit tuned to the bias frequency is used to isolate the bias from the amp. It has no effect on the audio signal, because the resonance is very sharp, and it presents a low impedance path for all signals other than the bias voltage.

A parallel or series resonant circuit can be indistinguishable from each other in some circuits, and in RF work these resonant systems are often referred to as a "tank". Energy is stored by both reactances, and is released into a load (such as an antenna). The energy storage allows an RF circuit to oscillate happily with only the occasional "nudge" from a transistor or other active device - this is usually done once each complete cycle.

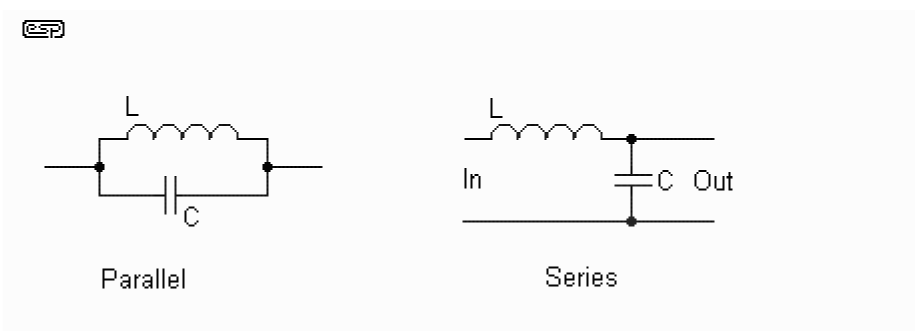


Figure 9.5 - Parallel and Series Resonance

I have shown the series circuit with an input and an output. If the inductance and capacitance were to be selected for resonance at the mains frequency, and a low voltage / high current transformer were used to supply a voltage at the input if the circuit, the voltage across the capacitor could easily reach several thousand volts. Exactly the same voltage would appear across the inductor, but the two voltages are exactly equal and opposite, so they cancel out.

Warning
Do not attempt to build this circuit for use with mains voltages and frequency, as serious injury or death

may occur. The circuit is potentially lethal, even with an input of only a few volts. The supply current will also be extremely high, as the series resonant circuit behaves like a short circuit at resonance. This is *not* in jest !

In all cases when the circuit is at resonance, the reactance of the capacitor and inductor cancel. For series resonance, they cancel such that the circuit appears electrically as almost a short circuit. Parallel resonance is almost an open circuit at resonance. Any "stray" impedance is pure resistance for a tank circuit at resonance.

The frequency response of an LC tuned circuit is either a frequency peak or dip as shown in Figure 5.6. Fo is now the resonant frequency (the term seems to have come from RF circuits, where Fo means frequency of oscillation).

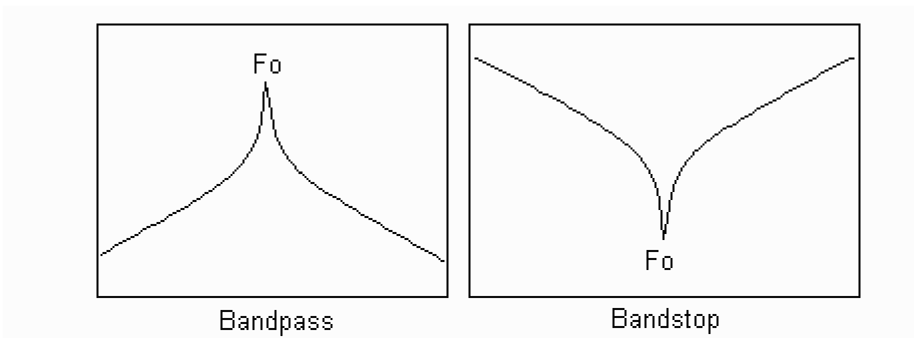


Figure 9.5 - Response of LC Resonant Circuits

The "Q" (or "Quality factor") of these circuits is very high, and the steep slopes leading to and from Fo are quite visible. Ultimately, a frequency is reached where either the inductance or capacitance becomes negligible compared to the other, and the slope becomes 6dB per octave, as with any other single pole filter. Multiple circuits can be cascaded to improve the ultimate rolloff.

Q is defined as the frequency divided by the bandwidth, measured from the 3dB points relative to the maximum or minimum response, F_L and F_H. For example, the bandpass filter shown above has a centre frequency (Fo) of 1.59kHz, and the 3dB frequencies are 1.58kHz and 1.6kHz. 1.59kHz divided by the difference (200Hz) gives a Q of 7.95 - there are no units for Q, it is a relative measurement only.

As a matter of interest, these figures were obtained using a 1uF capacitor, a 10mH inductor, and a 1 Ohm series resistance. In a simulation, I used an input voltage of 1V at 1590Hz, and the voltage across L and C is 97V. This is not amplification, since there is no power gain, but even at the low input voltage used, the circuit is potentially deadly. Needless to say, the capacitor must be rated for the voltage, and this rating is AC - a 100V DC capacitor will fail.

A bandpass filter of this type may be used to filter a specific frequency, and effectively removes all others. This is not strictly true of course, since the rolloff slopes are finite, but the other frequencies will be suppressed by 20dB at less than 100Hz either side of the centre frequency (74Hz on the low side and 85Hz on the high side to be exact).

Likewise, a bandstop filter will remove an offending frequency, and allows everything else through. Again, this is not as simple as that, but the principle is sufficiently sound that these circuits are used in radio and TV receivers to extract the wanted station and reject the others quite effectively (with some help from a lot of other circuitry as well, it must be admitted).