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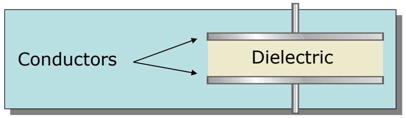
3. CAPACITORS

The Basic Capacitor

Capacitors are one of the fundamental passive components.

In its most basic form, it is composed of two conductive plates separated by an insulating dielectric.

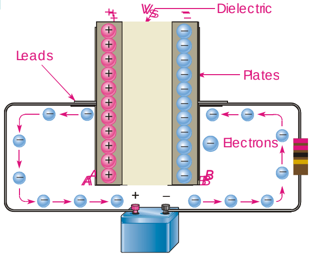
The ability to store charge is the definition of **capacitance**.



The Basic Capacitor

The charging process…

Initially uncharged
Charging
Fully charged
Source removed



A capacitor with stored charge can act as a temporary battery.

Capacitance

Capacitance is the ratio of charge to voltage

$$C = \frac{Q}{V}$$

Rearranging, the amount of charge on a capacitor is determined by the size of the capacitor (C) and the voltage (V).

$$Q = CV$$

Example

If a 22 μF capacitor is connected to a 10 V source, the charge is 220 μC

Capacitance

A capacitor stores energy in the form of an electric field that is established by the opposite charges on the two plates.
The energy of a charged capacitor is given by the equation

$$W = \frac{1}{2}CV^2$$

where

W = the energy in joules
C = the capacitance in farads
V = the voltage in volts

Capacitance

The capacitance of a capacitor depends on three physical characteristics.

$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{\varepsilon_r A}{d}\right)$$

C is directly proportional to
the **relative dielectric constant**
and the **plate area**.
C is inversely proportional to
the **distance** between the plates

Capacitance

Example

Find the capacitance of a circular 4.0 cm diameter sensor immersed in oil if the plates are separated by 0.25 mm.

$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{\varepsilon_r A}{d}\right) \qquad (\varepsilon_r = 4.0 \text{ for oil})$$

The plate area is $A = \pi r^2 = \pi\left(0.02\ \text{m}^2\right) = 1.26\times10^{-3}\ \text{m}^2$

The distance between the plates is $0.25\times10^{-3}\ \text{m}$

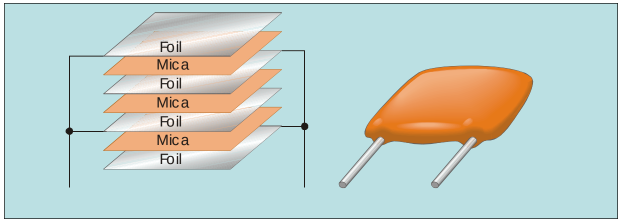
$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{(4.0)\left(1.26\times10^{-3}\ \text{m}^2\right)}{0.25\times10^{-3}\ \text{m}}\right) = 178 \text{ pF}$$

Capacitor types

Mica

Mica capacitors are small with high working voltage.

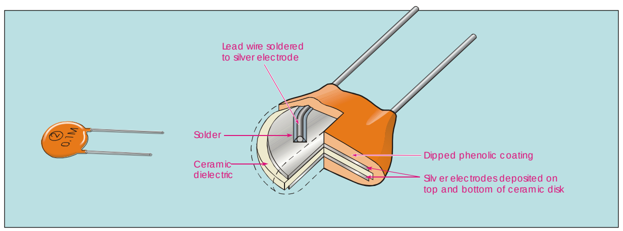
The **working voltage** is the voltage limit that cannot be exceeded.



Capacitor types

Ceramic disk

Ceramic disks are small nonpolarized capacitors
They have relatively high capacitance due to high ε_r.



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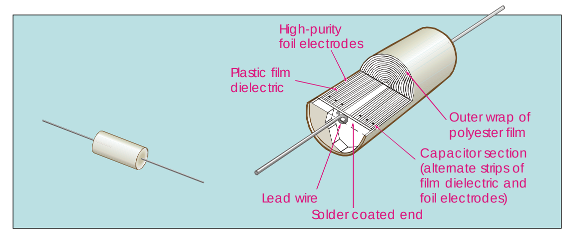
Capacitor types

Plastic Film

Plastic film capacitors are small and nonpolarized.

They have relatively high capacitance due to larger plate area.



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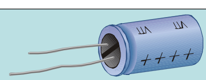
Capacitor types

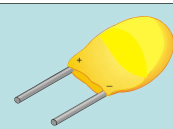
Electrolytic (two types)

Electrolytic capacitors have very high capacitance but they are not as precise as other types and tend to have more leakage current.

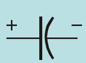
Electrolytic types are polarized.



Al electrolytic



Ta electrolytic



Symbol for any electrolytic capacitor

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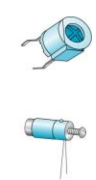
Capacitor types: Variable

Variable

Variable capacitors typically have small capacitance values and are usually adjusted manually.

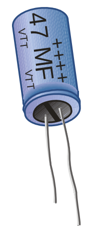
A solid-state device that is used as a variable capacitor is the varactor diode; it is adjusted with an electrical signal.



Capacitor labeling

Capacitors use several labeling methods. Small capacitors values are frequently stamped on them such as .001 or .01, which have implied units of microfarads.

Electrolytic capacitors have larger values, so are read as μF. The unit is usually stamped as μF, but some older ones may be shown as MF or MMF).



Capacitor labeling

A label such as 103 or 104 is read as 10×10^3 (10,000 pF) or 10×10^4 (100,000 pF) respectively. (Third digit is the multiplier.)

When values are marked as 330 or 6800, the units are picofarads.

Example

What is the value of each capacitor? Both are 2200 pF.

Problem

(a) What quantity of electric charge will produce a p.d. of 200 V between the plates of a capacitor of 5 F?

(b) Compare the magnitude of two capacitors, one having two circular plates of diameter 40 mm and placed 0.5 mm apart, the other having two square plates of side 50 mm and placed 0.75 mm apart. It may be assumed that the same dielectric material is used between the plates in each case.

[1 mC, 1.33]

Series capacitors

When capacitors are connected in series, the total capacitance is smaller than the smallest one.

The general equation for capacitors in series is

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots + \frac{1}{C_T}}$$

The total capacitance of two capacitors is

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$$

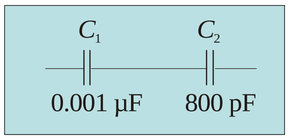
…or you can use the product-over-sum rule

$$C_T = \frac{C_1 \cdot C_2}{C_1 + C_2}$$

Series capacitors

Example

If a 0.001 μF capacitor is connected in series with an 800 pF capacitor, the total capacitance is 444 pF



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Parallel capacitors

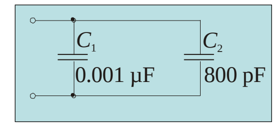
When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors.

The general equation for capacitors in parallel is

$$C_T = C_1 + C_2 + C_3 + \ldots C_n$$

Example

If a 0.001 μF capacitor is connected in parallel with an 800 pF capacitor, the total capacitance is 1800 pF



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Capacitive reactance

Capacitive reactance is the opposition to ac by a capacitor. The equation for capacitive reactance is

$$X_C = \frac{1}{2\pi f C}$$

Example

The reactance of a 0.047 μF capacitor when a frequency of 15 kHz is applied is

226 Ω

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Capacitive reactance : Series

When capacitors are in series, the total reactance is the sum of the individual reactances. That is,

$$X_{C(tot)} = X_{C1} + X_{C2} + X_{C3} + \cdots + X_{Cn}$$

Example

Assume three 0.033 μF capacitors are in series with a 2.5 kHz ac source. What is the total reactance?

Solution:

The reactance of each capacitor is

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(2.5\text{ kHz})(0.033\text{ μF})} = 1.93\text{ k}\Omega$$

$$X_{C(tot)} = X_{C1} + X_{C2} + X_{C3}$$

$$= 1.93\text{ k}\Omega + 1.93\text{ k}\Omega + 1.93\text{ k}\Omega = 5.79\text{ k}\Omega$$

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Capacitive reactance: Parallel

When capacitors are in parallel, the total reactance is the reciprocal of the sum of the reciprocals of the individual reactances. That is,

$$X_{C(tot)} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}} + \cdots + \frac{1}{X_{Cn}}}$$

Example

If the three 0.033 μF capacitors from the last example are placed in parallel with the 2.5 kHz ac source, what is the total reactance?

Solution:

The reactance of each capacitor is 1.93 kΩ

$$X_{C(tot)} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}}} = \frac{1}{\frac{1}{1.93\ \text{k}\Omega} + \frac{1}{1.93\ \text{k}\Omega} + \frac{1}{1.93\ \text{k}\Omega}} = 643\ \Omega$$

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Capacitive Voltage Divider

Two capacitors in series are commonly used as a capacitive voltage divider. The capacitors split the output voltage in proportion to their reactance (and inversely proportional to their capacitance).

Example

What is the output voltage for the capacitive voltage divider?

Solution:

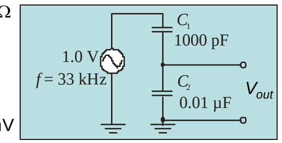
$$X_{C1} = \frac{1}{2\pi f C_1} = \frac{1}{2\pi(33\ \text{kHz})(1000\ \text{pF})} = 4.82\ \text{k}\Omega$$

$$X_{C2} = \frac{1}{2\pi f C_2} = \frac{1}{2\pi(33\ \text{kHz})(0.01\ \mu\text{F})} = 482\ \Omega$$

$$X_{C(tot)} = X_{C1} + X_{C2}$$

$$= 4.82\ \text{k}\Omega + 482\ \Omega = 5.30\ \text{k}\Omega$$

$$V_{out} = \left(\frac{X_{C2}}{X_{C(tot)}}\right) V_s = \left(\frac{482\ \Omega}{5.30\ \text{k}\Omega}\right) 1.0\ \text{V} = 91\ \text{mV}$$



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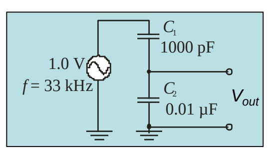
Capacitive Voltage Divider

Instead of using a ratio of reactances in the capacitor voltage divider equation, you can use a ratio of the total series capacitance to the output capacitance (multiplied by the input voltage). The result is the same. For the problem presented in the last slide,

$$C_{(tot)} = \frac{C_1 C_2}{C_1 + C_2} = \frac{(1000\ \text{pF})(0.01\ \mu\text{F})}{1000\ \text{pF} + 0.01\ \mu\text{F}} = 909\ \text{pF}$$

$$V_{out} = \left(\frac{C_{(tot)}}{C_2}\right) V_s = \left(\frac{909\ \text{pF}}{0.01\ \mu\text{F}}\right) 1.0\ \text{V} = 91\ \text{mV}$$



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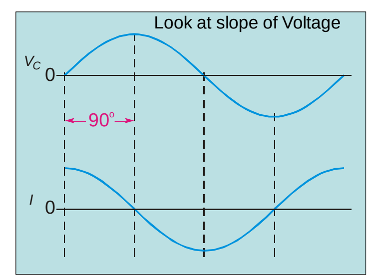
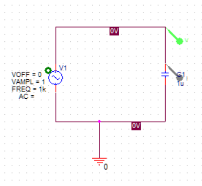
Capacitive phase shift

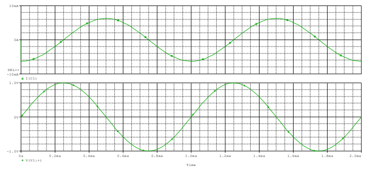
$$I = \frac{Q}{t} \qquad i = \frac{dQ}{dt} = C\frac{dV}{dt} = C\frac{d(V_0 \cdot sin(t))}{dt} = CV_0\cos(t)$$

When a sine wave is applied to a capacitor, there is a phase shift between voltage and current such that current always leads the voltage by 90°.



Capacitive phase shift PSPICE





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Power in a capacitor

Energy is stored by the capacitor during a portion of the ac cycle and returned to the source during another portion of the cycle.

Voltage and current are always 90º out of phase. For this reason, no true power is dissipated by a capacitor, because stored energy is returned to the circuit.

The rate at which a capacitor stores or returns energy is called **reactive power**.

The unit for reactive power is the VAR (volt-ampere reactive).

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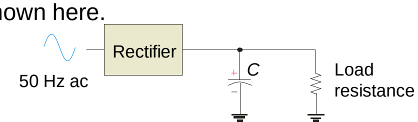
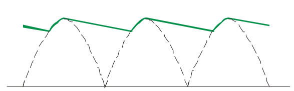
Power supply filtering

There are many applications for capacitors. One is in filters, such as the power supply filter shown here.



The filter smoothes the pulsating dc from the rectifier.



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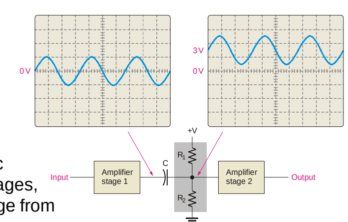
Coupling capacitors

Coupling capacitors are used to pass an ac signal from one stage to another while blocking dc.



The capacitor isolates dc between the amplifier stages, preventing dc in one stage from affecting the other stage.

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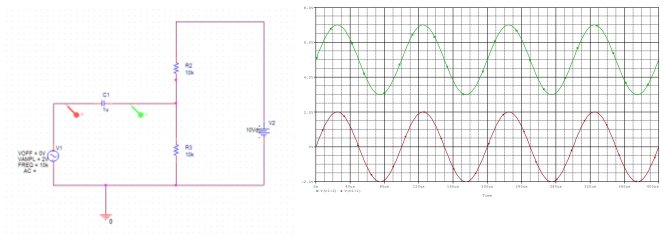
Coupling capacitor PSPICE



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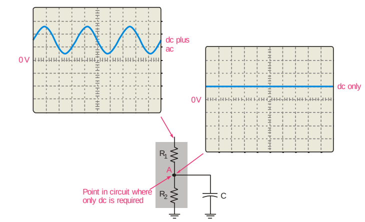
Bypass capacitors

Another application is to **bypass** an ac signal to ground but retain a dc value.

This is widely done to affect gain in amplifiers.

The bypass capacitor places point *A* at ac ground, keeping only a dc value at point *A*.



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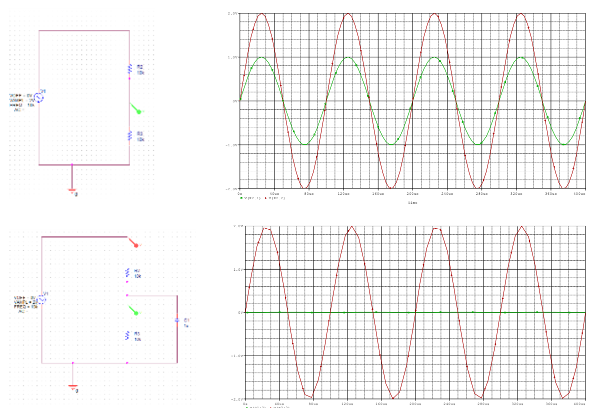
Bypass capacitors



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INDUCTORS

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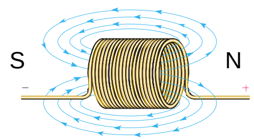
The Basic Inductor

When a length of wire is formed into a coil., it becomes a basic inductor. When there is current in the inductor, a three-dimensional magnetic field is created.

A change in current causes the magnetic field to change.

This in turn induces a voltage across the inductor that opposes the original change in current.



An inductor stores energy in the magnetic field created by the current.

$$W = \frac{1}{2} L I^2$$

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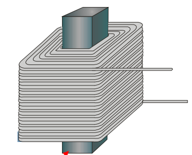
The Basic Inductor

One henry is the inductance of a coil when a current, changing at a rate of one ampere per second, induces one volt across the coil. Most coils are much smaller than 1 H.

The effect of inductance is greatly magnified by adding turns and winding them on a magnetic material. Large inductors and transformers are wound on a core to increase the inductance.



Magnetic core

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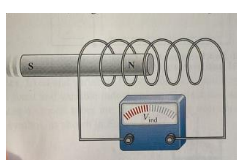
Faraday's law

Faraday's law was introduced in Chapter 7 and repeated here because of its importance to inductors.

The amount of voltage induced in a coil is directly proportional to the rate of change of the magnetic field with respect to the coil.



Move magnet faster => more voltage

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Lenz's law

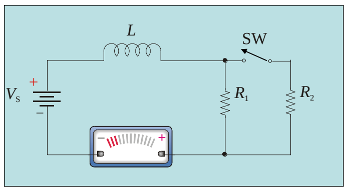
When the current through a coil changes and an induced voltage is created as a result of the changing magnetic field, the direction of the induced voltage is such that it always opposes the change in the current.

Lenz's law

When the current through a coil changes and an induced voltage is created as a result of the changing magnetic field, the direction of the induced voltage is such that it always opposes the change in the current.

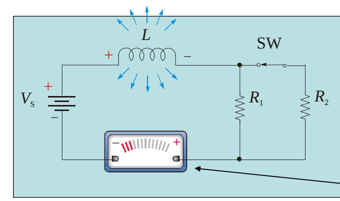
A basic circuit to demonstrate Lenz's law is shown.

Initially, the SW is open and there is a small current in the circuit through L and R_1.



Lenz's law

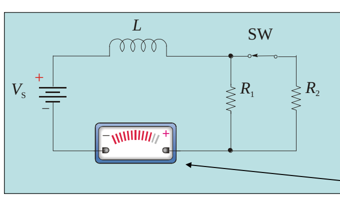
SW closes and immediately a voltage appears across L that tends to oppose any *change* in current.



Initially, the meter reads same current as before the switch was closed.

Lenz's law

After a time, the current stabilizes at a higher level (due to I_2) as the voltage decays across the coil.

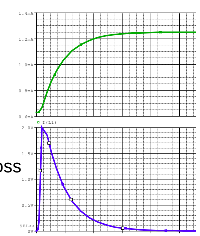


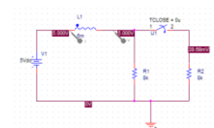
Later, the meter reads a higher current because of the load change.

Inductor Circuit PSPICE

Current

5-V = Voltage across the Inductor



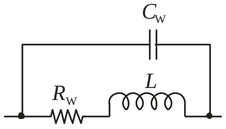


Practical inductors

In addition to inductance, actual inductors have winding resistance (R_W) due to the resistance of the wire and winding capacitance (C_W) between turns.

An equivalent circuit for a practical inductor including these effects is shown:

Notice that the winding resistance is in series with the coil and the winding capacitance is in parallel with both.



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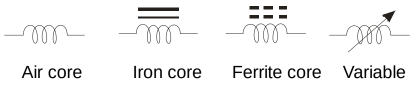
Types of inductors

There are a variety of inductors, depending on the amount of inductance required and the application.

Some, with fine wires, are encapsulated and may appear like a resistor.

Common symbols for inductors (coils) are



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Factors affecting inductance

Four factors affect the amount of inductance for a coil.

The equation for the inductance of a coil is

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

where

- L = inductance in Henries
- N = number of turns of wire
- μ = permeability in H/m (same as Wb/At-m)
- l = coil length on meters

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Inductance calculation

Example

What is the inductance of a 2 cm long, 150 turn coil wrapped on an low carbon steel core that is 0.5 cm diameter?

The permeability of low carbon steel is 2.5 x10^{-4} H/m

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

$l = 2\,cm = 2\times10^{-2}\,m$

$N = 150$

$A = \pi r^2$

$= \pi\left(\frac{0.5\times10^{-2}}{2}\right)^2 m^2$

$= 1.96\times10^{-5}\,m^2$

$\mu = 2.5\times10^{-4}\,H/m$

$$\Rightarrow L = \frac{150^2(2.5\times10^{-4})\,1.96\times10^{-5}}{2\times10^{-2}}$$

$= 0.0055\,H$

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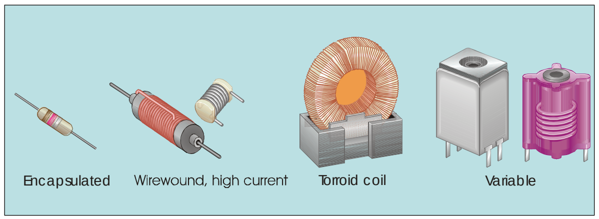
Practical inductors

Inductors come in a variety of sizes.

A few common ones are shown here.



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Series inductors

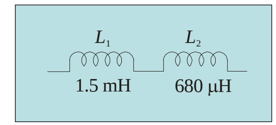
When inductors are connected in series, the total inductance is the sum of the individual inductors. The general equation for inductors in series is

$$L_T = L_1 + L_2 + L_3 + \ldots L_n$$

Example

If a 1.5 mH inductor is connected in series with an 680 μH inductor, the total inductance is

2.18 mH



SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Parallel inductors

When inductors are connected in parallel, the total inductance is smaller than the smallest one.

The general equation for inductors in parallel is

$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots + \frac{1}{L_T}}$$

The total inductance of two inductors is

$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2}}$$

…or you can use the product-over-sum rule.

$$L_T = \frac{L_1 \cdot L_2}{L_1 + L_2}$$

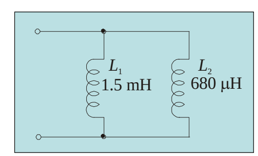
SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Parallel inductors

Example

If a 1.5 mH inductor is connected in parallel with an 680 μH inductor, the total inductance is

468 μH



Inductive reactance

Inductive reactance is the opposition to ac by an inductor.

The equation for inductive reactance is

$$X_L = 2\pi f L$$

Example

The reactance of a 33 μH inductor when a frequency of 550 kHz is applied is 114 Ω

Inductive reactance : Series

When inductors are in series, the total reactance is the sum of the individual reactances. That is,

$$X_{L(tot)} = X_{L1} + X_{L2} + X_{L3} + \cdots + X_{Ln}$$

Example Assume three 220 μH inductors are in series with a 455 kHz ac source. What is the total reactance?

Solution: The reactance of each inductor is

$$X_L = 2\pi f L = 2\pi(455\text{ kHz})(220\ \mu\text{H}) = 629\ \Omega$$

$$X_{L(tot)} = X_{L1} + X_{L2} + X_{L3}$$
$$= 629\ \Omega + 629\ \Omega + 629\ \Omega = 1.89\text{ k}\Omega$$

Inductive reactance: Parallel

When inductors are in parallel, the total reactance is the reciprocal of the sum of the reciprocals of the individual reactances. That is,

$$X_{L(tot)} = \frac{1}{\frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}} + \cdots + \frac{1}{X_{Ln}}}$$

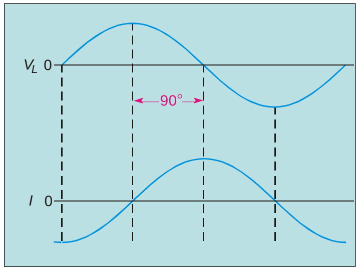
Example If the three 220 μH inductors from the last example are placed in parallel with the 455 kHz ac source, what is the total reactance?

Solution: The reactance of each inductor is 629 Ω

$$X_{L(tot)} = \frac{1}{\frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}}} = \frac{1}{\frac{1}{629\ \Omega} + \frac{1}{629\ \Omega} + \frac{1}{629\ \Omega}} = 210\ \Omega$$

Inductive phase shift

When a sine wave is applied to an inductor, there is a phase shift between voltage and current such that voltage always leads the current by 90º.



Power in an inductor

True Power: Ideally, inductors do not dissipate power. However, a small amount of power is dissipated in winding resistance given by the equation:

$$P_{true} = (I_{rms})^2 R_W$$

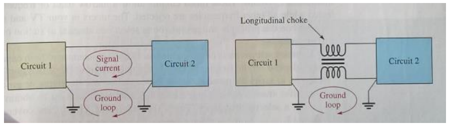
Reactive Power: Reactive power is a measure of the rate at which the inductor stores and returns energy. One form of the reactive power equation is:

$$P_r = V_{rms} I_{rms}$$

The unit for reactive power is the VAR.

Application of Inductors

Consider the case of two circuits connected with common lines as shown in Figure (a). A path for high frequency noise exists though the common grounds, creating a ground loop.
The current in the ground can affect the signal.
A special inductor, called a longitudinal choke is installed in the signal line
The ground loop sees a high impedance path, thus reducing the noise, while the low-frequency signal is coupled through the choke



Q of a coil - Figure of merit

In real Inductors the winding resistance appears as a resistance in series with the ideal inductor; it is referred to as DCR (DC resistance) or R_W.
This resistance dissipates some of the reactive energy.

The **quality factor** (***Q***) of a coil is given by the ratio of reactive power to true power.

$$Q = \frac{I^2 X_L}{I^2 R_W}$$

For a series circuit, *I* cancels, leaving

$$Q = \frac{2\pi f L}{R_W}$$