Inductors

What you'll learn in Module 3.

Section 3.1 Electromagnetic Induction.

- Magnetic Fields around Conductors.
- The Solenoid.

Section 3.2 Inductance & Back e.m.f.

- The Unit of Inductance.
- Factors affecting Inductance.
- Voltage and e.m.f.
- Back e.m.f.
- Self Induction.

Section 3.3 Practical Inductors.

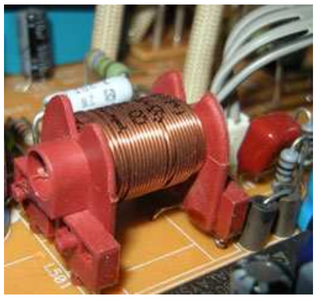
- The Solenoid.
- Practical Inductors.
- Inductor schematic symbols.

Section 3.4 Inductor Colour Codes.

- Colour codes for Inductors.

Section 3.5 Inductors Quiz.

Introduction



Inductors are components that are simple in their construction, consisting of coils of insulated copper wire wound around a former that will have some type of core at its centre. This core might be a metal such as iron that can be easily magnetised; or in high frequency inductors, it will more likely to be just air.

Inductors depend for their action on the magnetic field that is present around any conductor when it is carrying a current. If the wire coil is wound around a core made of a material that is easily magnetised, such as iron, then the magnetic field around the coil is concentrated within the core; this greatly increases the efficiency of the inductor.

Inductors in AC Circuits.

Inductors are extensively used in alternating current (AC) applications such as radio, TV and communications equipment, and in these systems, how inductors react to AC signals of different frequencies is very useful

Chokes.

Another name used for an inductor is a "Choke". Inductors, being just coils of copper wire, will allow DC to pass easily, but when AC is applied, inductors create an opposition to current flow that increases, as the frequency of the alternating current increases. Therefore AC is prevented from flowing or is "Choked off" while DC is allowed to pass. This effect is used in power supply circuits where the public AC mains (line) supply has to be converted to a DC supply suitable for powering electronic circuits.

Energy Storage in a DC circuit.

When a DC voltage is connected across an inductor, a current is made to flow through the inductor. As this current increases at switch on, an increasing magnetic field is created around the coils of wire. The electrical energy used in creating the magnetic field is therefore being stored as magnetic energy. Also when the energy in a magnetic field is changing, this will induce a voltage into those same coils that are setting up the magnetic field.

However the induced voltage, called an 'electromagnetic force of self induction' will be in the opposite polarity to the applied voltage that is setting up the magnetic field; therefore this induced e.m.f. is also commonly called a 'back e.m.f.' and its effect is to slow down the otherwise rapid change of current that takes place at switch on.

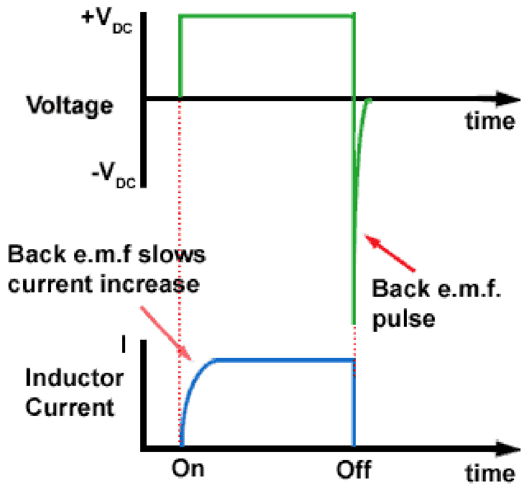


Fig. 3.0.1 Back e.m.f. in a DC Circuit

As the current through the inductor builds up, the rate of change of current has reduced, due to the back emf, and so has the back emf due to the reduced rate of change of the current. The electrical energy applied to the inductor has now been converted into magnetic energy and is stored in the magnetic field set up around the inductor.

If the voltage applied to the inductor is now switched off, the energy stored in the magnetic field is released back into the coils of the inductor, this time there is no opposing supply voltage applied so the entire magnetic field collapses instantly, and the stored energy, now in the form of a voltage across the inductor, but with opposite polarity to the original applied voltage.

This voltage will however now be much larger than the original supply voltage; this is because the amplitude of a voltage induced into a conductor is proportional to (among other factors) the rate of change of the magnetic field. At switch on, because there were two opposing voltages changing, the supply increasing and the back e.m.f. decreasing, the rate of change was slowed down. However at switch off there is no supply voltage so the magnetic field collapses extremely quickly causing a very rapid rate of change and therefore producing a very large voltage pulse.

This pulse can be tens, hundred or thousands of volts in amplitude, which can be very useful, e.g. in producing an ignition spark in a petrol engine, or very dangerous e.g. not good to touch! It can also very easily destroy other components such as semiconductors, and can be a source of serious radio interference. Learn more about back e.m.f. in Module 3.2

Inductors of many types.

The physical size of inductors varies greatly, depending on the power being handled, and on the frequency of the AC being used; from huge power transformers in power stations and the electricity supply grid, to tiny inductors in radio equipment consisting of a few turns of wire and only a few millimetres across. See also Module 3.3.

Module 3.1 Electromagnetic Induction.

Magnetic Field Around a Conductor.

A conductor carrying an electric current will produce a magnetic field around the conductor as shown in Fig.3.1.1. This field has a circular shape and exists along the whole length of the conductor. Because of its circular shape, the magnetic field does not have specific north or south poles, but is considered to flow in a continuous circular loop towards an undefined north pole.

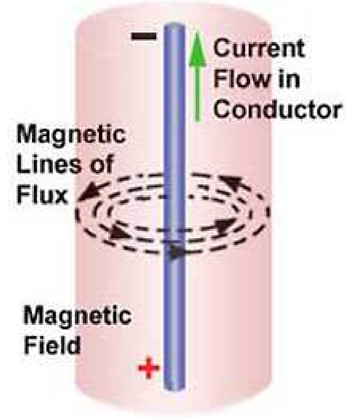


Fig. 3.1.1 Magnetic Field Around a Conductor.

Right Hand Grip Rule.

The direction of a magnetic field around a conductor can be remembered using the right hand grip rule shown in Fig 3.1.2. Imagine grasping a conductor in the right hand as shown, with the thumb indicating the direction of conventional current flow from positive to negative. The fingers of the right hand, curled around the conductor indicate the direction of flow of magnetic flux.

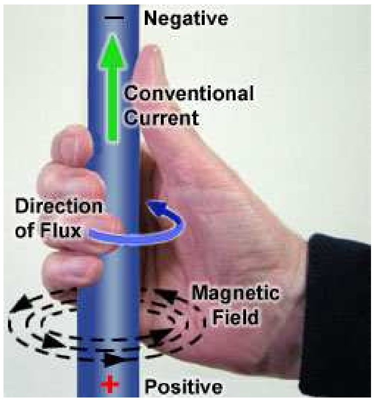


Fig. 3.1.2 Right Hand Grip Rule.

Magnetic Fields Around Parallel Conductors.

If two parallel conductors carry the same current, the direction of the magnetic fields around each conductor will interlink and oppose each other between the conductors as shown in Fig. 3.1.3 forming an area of zero magnetic flux (no flow) between the conductors, this happens between adjacent conductors around the axis of a coil.

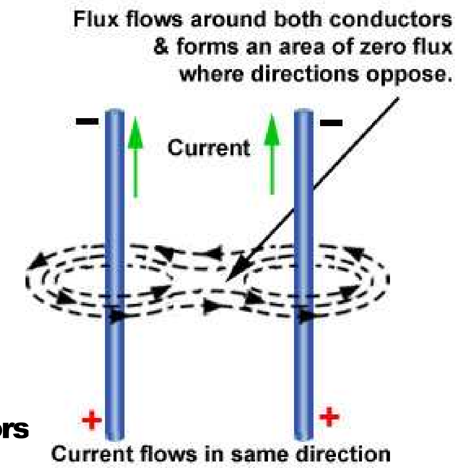


Fig. 3.1.3 Magnetic Field Around Parallel Conductors

Magnetic Fields Around Coils.

When the conductor is bent into a loop or coil however, the direction of the magnetic fields inside the coil coincide, concentrating the magnetic flux within the coil as shown in Fig 3.1.4.

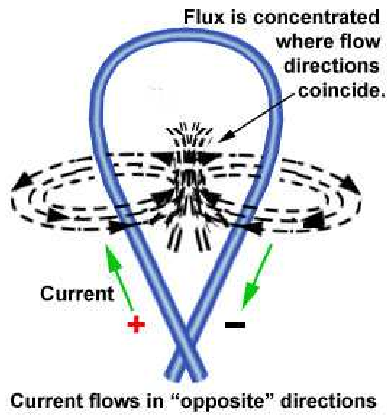


Fig. 3.1.4 Magnetic Field Around Looped Conductors.

The Solenoid.

When wire coils are formed into a series of continuous loops called a solenoid, the effects described above produce a magnetic field pattern that is similar to that around a bar magnet, as shown in Fig 3.1.5. Increasing or decreasing the current through the inductor increases or decreases the strength of the magnetic field, giving the effect of a bar magnet, but with a variable field strength.

This changing magnetic field can have several effects. It can be used to produce movement, for example in electric motors, or it can be used produce electrical effects in other conductors affected by the field.

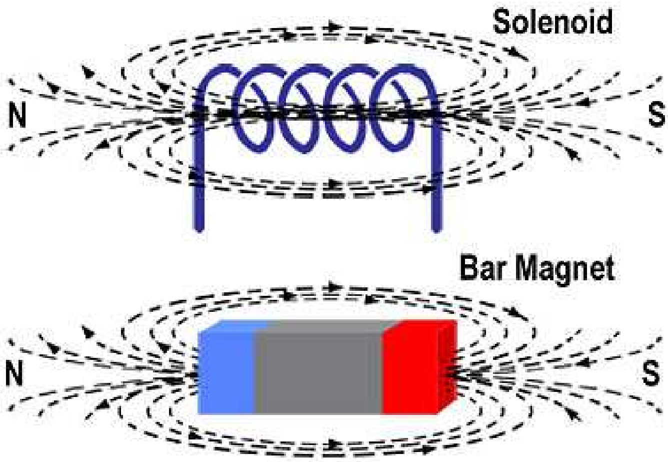


Fig. 3.1.5 Magnetic Field Around a Solenoid and a Bar Magnet.

As this module deals with AC signals in static components such as inductors and transformers, (rather than moving machines such as motors or generators) the effects described relate changes in the magnetic fields around static inductors, to changes in current through the those inductors.

Terms used in electromagnetism.

Magnetic Flux is the name given to the magnetic equivalent of electric current. It is the flow of magnetism from the north to the south pole of a magnet. Magnetic Flux flows along lines of **magnetic force** that make up a **magnetic field.**

Just like electric current, it is easier for magnetic flux to flow through some materials than others, soft iron for example has a very high **permeability.** That means, it is very easy for magnetic flux to flow through it. High permeability can also be described as a very low **reluctance** to the flow of magnetic flux (the magnetic equivalent of resistance).

Air has more reluctance and so is less permeable than iron. It is therefore easier for a flux to flow through iron than through air, and many electromagnetic devices use materials such as iron to concentrate magnetic flux into a small area and so increase the effectiveness of devices such as transformers, motors and electromagnets.

Module 3.2 Inductance

A current generated in a conductor by a changing magnetic field is proportional to the rate of change of the magnetic field. This effect is called INDUCTANCE and is given the symbol L. It is measured in units called the henry (H) named after the American Physicist Joseph Henry (1797-1878). One henry is the amount of inductance required to produce an e.m.f. of 1 volt in a conductor when the current in the conductor changes at the rate of 1 Ampere per second. The Henry is a rather large unit for use in electronics, with the milli-henry (mH) and micro-henry (µH) being more common. These units describe one thousandth and one millionth of a henry respectively.

Although the henry is given the symbol (capital) H, the name henry, applied to the unit of inductance uses a lower case h. The plural form of the henry may be henries or henrys; the American National Institute of Standards and Technology recommends that in US publications henries is used.

Factors Affecting Inductance.

The amount of inductance in an inductor is dependant on:

- a. The number of turns of wire in the inductor.
- b. The material of the core.
- c. The shape and size of the core.
- d. The shape, size and arrangement of the wire making up the coils.

Because inductance (in henries) depends on so many variable quantities, it is quite difficult to calculate accurately; numerous formulae have been developed to take different design features into account. Also these formulae often need to use special constants and tables of conversion data to work with the required degree of accuracy. The use of computer programs and computer-aided design has eased the situation somewhat. However, external effects caused by other components and wiring near the inductor, can also affect its value of inductance once it is assembled in a circuit, so when an accurate value of inductance is required, one approach is to calculate an approximate value, and design the inductor so that it is adjustable.

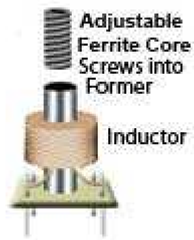


Fig. 3.2.1 Variable Inductor.

A typical formula for approximating the inductance value of an inductor is given below. This particular version is designed to calculate the inductance of "A solenoid wound with a single layer of turns of infinitely thin tape rather than wire, and with the turns evenly and closely spaced."

$$L = \frac{(d^2 n^2)}{l + 0.45d}$$

Where:

- L is the inductance in henries.
- *d* is the diameter of the coil in metres.
- *n* is the number of turns in the coil.
- *l* is the length of the coil in metres.

For coils not conforming exactly to the above specification extra factors must be incorporated.

Voltage and e.m.f.

A voltage **induced** into a conductor is called an e.m.f. (electro motive force) because its source is the changing magnetic field around and external to the conductor. Any externally produced voltage (including those produced by an external battery or power supply) is called an e.m.f., whilst a voltage (a potential difference or p.d.) across an internal component in a circuit is called a voltage.

Back e.m.f.

A back e.m.f.(also called a Counter e.m.f.) is an e.m.f. created across an inductor by the changing magnetic flux around the conductor, produced by a change in current in the inductor. Its value can be calculated using the formula:

$$E = -L\frac{\Delta I}{\Delta t}$$

Where:

- E is the induced back e.m.f. in volts
- L is the inductance of the coil in henries.
- ΔI is the change in current, in amperes.
- Δt is the time taken for the change in current, in seconds.

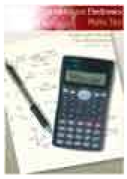
Notes:

Δ (Greek D – Delta) denotes a difference or change in a property.

So the formula describes the back e.m.f. as depending on the inductance (in henries) multiplied by the rate of change in current (in amperes per second).

The minus sign before L indicates that the polarity of the induced back e.m.f. will be reversed compared with the changing voltage across the conductor that originally caused the changing current and consequent changing magnetic field.

Remember that when working in practical values of milli or micro henries that all values used in the formula must be converted to the standard values of henries amperes and seconds as described in our Maths Tips booklet.



Example

Because the value of back e.m.f. depends on the rate of change of the current, it will be greatest when the fastest change occurs. For example, the rate of change is extremely fast whenever the current through an inductor is switched off; then the change can be from maximum to zero in just a few milliseconds.

Imagine that an inductor of 200mH connected across a supply of 9V is passing a current of 2amperes. When the current is switched off, it collapses to zero in 10ms, what would be the back e.m.f. generated across the coil?

E = 200mH x 2A / 10ms

or

$$E = 200 \times 10^{-3} \times 2/10 \times 10^{-3}$$

= 40volts

So the back e.m.f. generated at switch off is more than 4 times higher than the supply voltage!

These high voltage pulses that occur when an inductive component such as a motor or relay coil is switched off, can potentially cause damage to the output transistor or integrated circuit switching the device. Therefore essential protection is provided by including a diode in the output stage as shown in Figs. 3.2.2 and 3.2.3

Back e.m.f. Protection

The protection diode in Fig 3.2.2 connected across the inductor is normally reverse biased, as the voltage on its cathode, connected to the +V supply rail, will be more positive than its anode on the collector of the transistor. At switch off however, a large voltage spike of opposite polarity appears across the inductor, due to the collapsing magnetic field. For the duration of this voltage spike, the collector of the transistor could be at a higher potential than the supply, except that if this happens, the diode will become forward biased and prevent the collector voltage rising any higher than the supply rail.

Fig 3.2.3 shows a popular I.C. (ULN2803) for switching inductive loads. The outputs of the eight inverting amplifiers are each protected by a diode, having their common cathodes connected to the positive supply rail +V on pin 10.

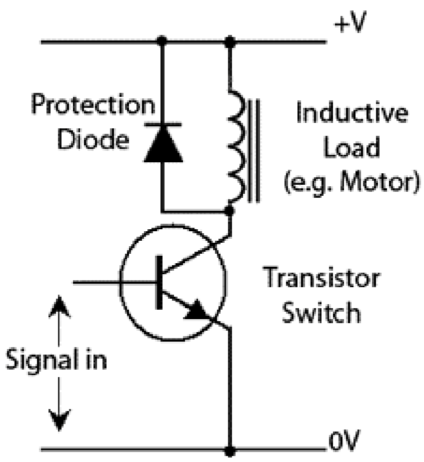


Fig. 3.2.2 Back e.m.f. Protection

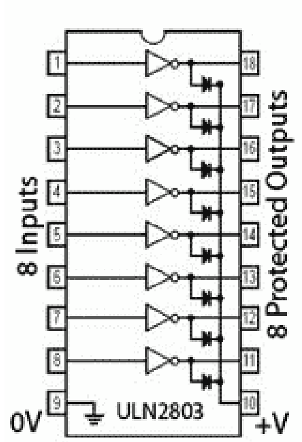


Fig. 3.2.3 Protection Diodes in the

Self-induction

The effect of an inductor inducing an e.m.f. into itself is called Self Induction (but often referred to simply as Induction). When an inductor induces an e.m.f. into a separate nearby inductor, this is called Mutual Induction and is a property used by transformers.

The way self-induction works depends on two interlinked actions occurring simultaneously, and on each of these actions depending on the other.

Action 1.

Any conductor, in which the current is changing, will produce a changing magnetic field around it.

Action 2.

Any conductor within a CHANGING magnetic field will have a changing e.m.f. induced into it. The value of this induced e.m.f. and the amount of induced current it produces in the conductor will depend on the rate of change of the magnetic field; the faster the flux of the field changes, the greater will be the induced e.m.f. and its consequent current.

The changing magnetic field created around a conductor by the changing current in the conductor causes a varying e.m.f. to be set up across that conductor. This varying e.m.f. in turn produces a varying current flowing in the opposite direction to the original current. The changes in this current therefore oppose the changes in the original current.

The effect of Action 2 is therefore to limit the changes occurring because of Action 1. If the original current is increasing, the induced current will slow the rate of increase. Similarly, if the original current is decreasing, the induced current will slow the rate of decrease. The overall result of this is to decrease the amplitude of the AC current through the inductor and so also reduce the amplitude of the AC voltage across the inductor.

Because the strength of the magnetic field set up by the original current is dependent on the rate (speed) of change of current, an inductor reduces the flow of alternating current (AC) more at high frequencies than at low. This limiting effect produced by the induced e.m.f. will be greater at higher frequencies because at high frequencies, the current and therefore the flux is changing more rapidly. The name given to this effect is Inductive Reactance.

Inductive Reactance.

Reactance produces an opposition to the flow of alternating current. Like resistance, it is measured in Ohms, but because resistance has the same value at any frequency and the opposition to AC found in inductors varies with frequency, it cannot be called resistance. Instead, it is called Reactance (X). Capacitors also have the property of reactance but they respond to frequency in a different way, therefore there are two types of reactance; inductors have Inductive Reactance (X_L), and capacitors have Capacitive Reactance (X_C).

Module 3.3 Practical Inductors

The Right Hand Curl Rule for a Solenoid.

Many practical inductors are based on the solenoid. Because of its shape, the lines of magnetic flux are concentrated along the centre line of the coil and this produces a magnetic field with a north and a south pole. To find out which end of the solenoid is the north pole, imagine grasping the solenoid in the right hand as shown in Fig 3.3.1 with the fingers curled around the solenoid in the direction of CONVENTIONAL CURRENT FLOW, from positive to negative around the solenoid, the right thumb is laid along the side of the solenoid and will be pointing towards the solenoid's north pole.

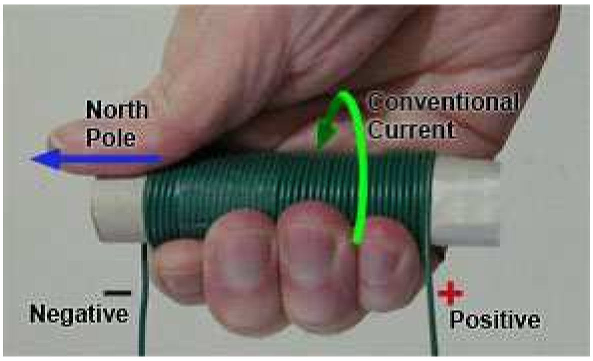
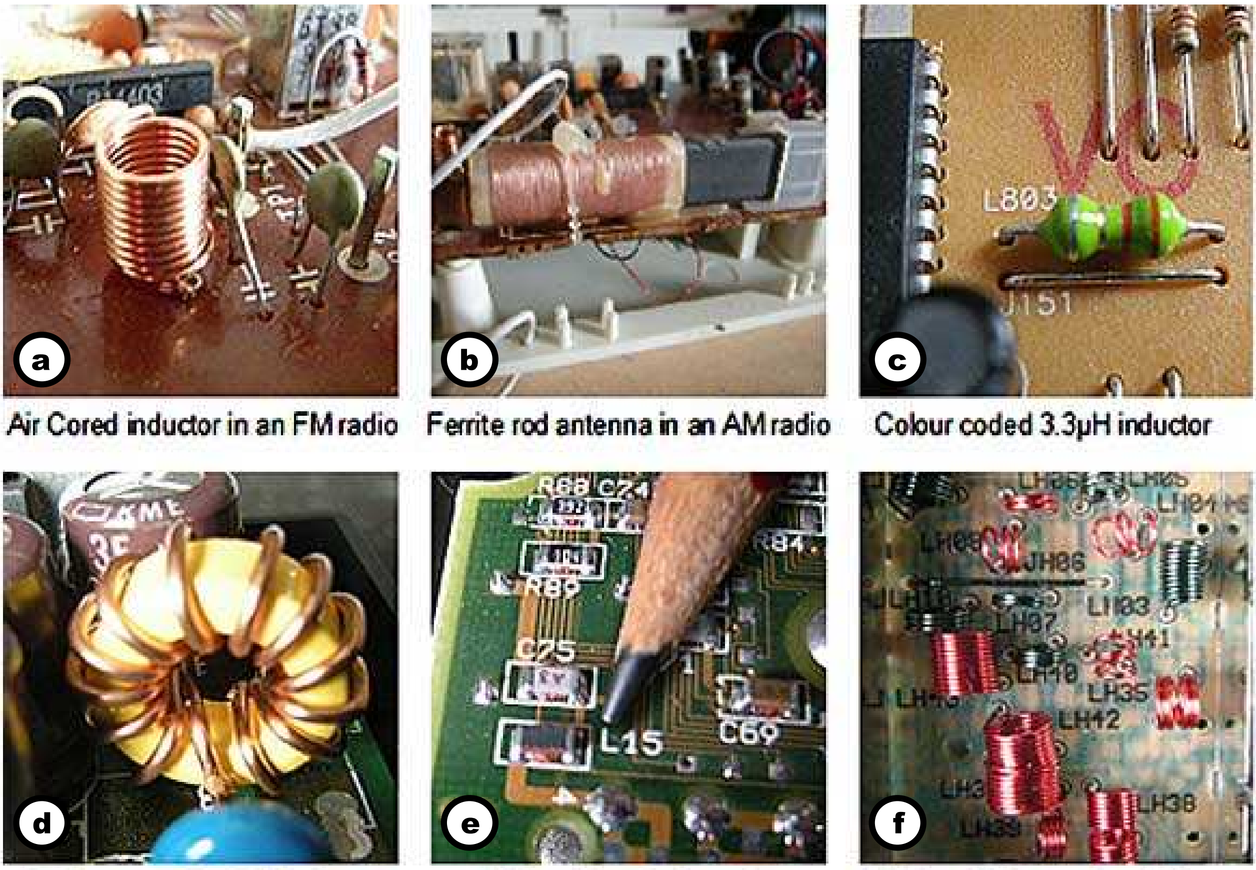


Fig. 3.3.1 The Right Hand Curl Rule.

Fig. 3.3.2 Practical Inductors.



a: Air Cored inductor in an FM radio

b: Ferrite rod antenna in an AM radio

c: Colour coded 3.3μH inductor

d: High current Toroidal Inductor in a power supply

e: Surface Mount inductor in a Hard Disk Drive. Typical values can be 0.1nH – 220nH

f: Air Cored inductors in a TV tuner working at UHF may have very few turns

(a) Air Cored Inductors

Simple air cored inductors are used in many circuits operating in the 1MHz to several hundred MHz range, including radio and TV receivers.

(b) AM Radio Antennas

AM radio receivers use internal antennas that have a number of inductors wound around a ferrite rod. These are combined with fixed and variable capacitors to enable the radio to be tuned to the various station frequencies.

(c) Colour Coded Axial Lead-out Inductors

Looking very similar to resistors, colour coded inductors have typical values from 0.1µH to 1mH. The value given by the colour bands are given by a standard EIA 4 band code for commercial inductors, and by a Military Standard 5 band code for military types On which the first band is always silver (denoting a military component) and the fifth band has an extended range of tolerances to indicate close tolerance types of +/- 1% to 4%

(d) Toroidal Inductors

Toroidal (ring shaped) cores are very efficient at concentrating the magnetic flux within the coil and are often used for large current inductors and transformers, such as those used in power supplies.

(e) SMD Chip Inductors

Surface mounted multi-layer chip inductors are tiny; often only 3 or 4mm across. Although this physical size limits the values of inductance that can be achieved, typical values of less than 1µH up to a few hundred µH are useful for many radio frequency and communications applications. The example shown is part of a hard disk drive control circuit.

(f) Inductors at UHF

Air cored inductors for UHF applications may consist of only one or two turns of wire. In some cases even a straight-line conductor, a few millimetres long can have enough inductance to form a useful inductor or transformer. In these situations the exact positioning of inductors relative to other components or metal casing, such as screening cans, is vitally important. During construction individual inductances may have had their inductance fine-tuned by slightly altering their positions, or the spacing between turns.

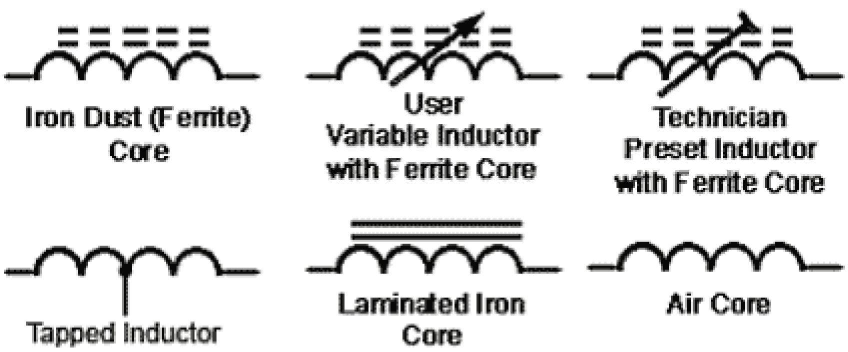
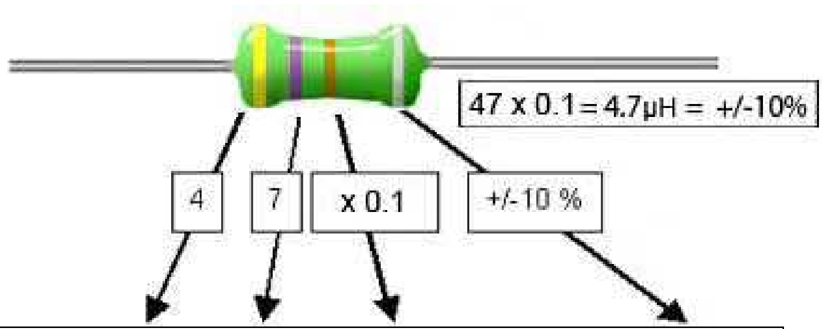


Fig. 3.3.3 Inductor (Schematic) Circuit Symbols.

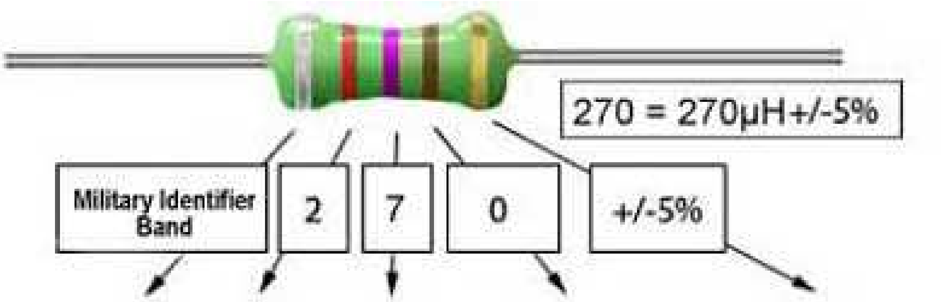
Module 3.4 Inductor Colour Codes

Fig 3.4.1 Four Band Standard E I A Colour Code For Inductors.



Band	1	2	3	4
Meaning	1st Digit	2nd Digit	(No. of zeros)	Tolerance %
Gold			.0 (divide by 10)	+/-5%
Silver			.00 (divide by 100)	+/-10%
Black	0	0	No Zeros	+/-20%
Brown	1	1	0	
Red	2	2	00	
Orange	3	3	,000	
Yellow	4	4	0,000	
Green	5	5		
Blue	6	6		
Violet	7	7		
Grey	8	8		
White	9	9		

Fig 3.4.2 Five Band Military Standard Inductor Colour Code



Band	1	2	3	4	5
Meaning (See Notes)	Mil. Spec.	Digit or Dec. point	Digit or Dec. point	Digit (or Multiplier)	Tolerance %
Gold		Decimal point	Decimal point		+/-5%
Silver	Always Silver double width				+/-10%
Black		0	0	0 (or x 1)	+/-20%
Brown		1	1	1 (or x 10)	+/-1%
Red		2	2	2 (or x 100)	+/-2%
Orange		3	3	3 (or x 1,000)	+/-3%
Yellow		4	4	4 (or x 10,000)	+/-4%
Green		5	5	5	
Blue		6	6	6	
Violet		7	7	7	
Grey		8	8	8	
White		9	9	9	

See notes on next page:

Notes:

The military standard for cylindrical inductors specifies 5 coloured bands The same colours are used as in the EIA 4 band code, but:

For band 1, a **double width** sliver band is used to signify Military Standard.

For values less than 10µH:

Bands 2, 3 and 4 indicate the value of inductance in µH

A gold band might be used in either band 2 or band 3. In either of these two bands, gold indicates a decimal point and band 4 is used as a digit instead of a multiplier band.

When no gold band is present in bands 2 or 3, band 4 is a multiplier band.

For example:

If bands 2,3 and 4 were red, gold, red the value would be 2.2 µH

If bands 2,3 and 4 were gold, yellow, violet the value would be 0.47 µH (470nH)

Band 5 indicates the tolerance between 1% and 20%

For values of 10µH or more:

Bands 2 and 3 represent basic value, and band 4 gives the number of zeros.

For example:

If bands 2, 3 and 4 were red, violet, orange the value would be 27000 µH

Chip (SMD) Inductors

For inductors of a very small physical size, coloured dots may be used instead of bands. In such cases, The silver dot indicating a Military (Mil) specification will be larger than the other dots and will be placed a the beginning of the dot sequence.

In some cases only a single coloured dot is used, and for their meaning it is necessary to refer to individual manufacturers data for accurate interpretation.

Dot code examples from Coilcraft Inc. http://www.coilcraft.com/colrcode.cfm

Dot code examples from Viking Tech Corporation. http://www.vikingamerica.com/ftp/NL.pdf

Module 3.5 Inductors Quiz

Try our quiz, based on the information you can find in Module 2. Check your answers on line at http://www.learnabout-electronics.org/ac_theory/inductors05.php

What you should know.

After studying Module 3, you should:

- Be able to describe electromagnetic effects in static conductors.
- Be able to describe inductors, units of inductance and circuit symbols.
- Be able to describe Self Induction and the effects of Back (counter) e.m.f. .
- Be able to describe frequency effects in inductors.
- Be able to describe constructional features and typical applications of inductors.

1.

What type of is inductor illustrated in Fig 3.5.1 ?

a) A laminated iron cored inductor.

b) A ferrite cored inductor.

c) A preset inductor.

d) An air cored inductor.

Fig 3.5.1

2.

The inductance of an inductor will be affected by which property or properties of the inductor's core?

a) The material of the core.

b) The material and size of the core.

c) The shape and size of the core.

d) The shape, size and material of the core.

3.

Which of the following ranges of inductance values would be most commonly encountered in electronic circuits?

a) henrys.

b) milli-henrys.

c) henrys and milli-henrys.

d) milli-henrys and micro-henrys.

4.

Which of the following properties of an inductor change with the applied frequency:

a) Reactance

b) Inductance

c) Reluctance

d) Resistance

5.

What is the value of the inductor shown in Fig 3.5.2?

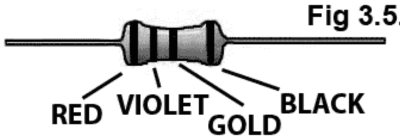
a) 27µH +/-10%

b) 2.7µH +/-20%

c) 270µH +/-10%

d) 27µH +/-5%

Fig 3.5.2



6.

Which of the following describes what happens to a non-moving conductor within a changing magnetic field?

a) The conductor will have a changing e.m.f. induced into it.

b) An e.m.f. will be induced into the conductor, proportional to conductor's reactance.

c) The conductor will have a steady current induced into it.

d) A current will be induced into the conductor, inversely proportional to conductor's reluctance.

7.

Which of the formulae shown in Fig 3.5.3 would be used for calculating back e.m.f. ?

a)

b)

c)

d)

Fig 3.5.3

a $E = -L\frac{\Delta t}{I}$

b $E = -L\frac{\Delta\Phi}{t}$

c $E = -L\frac{\Delta I}{\Delta t}$

d $E = -L\frac{I}{t}$

8.

Complete the following statement:
The magnetic field produced by a solenoid shaped inductor is:

a) Concentrated within, and along the axis of the coil.

b) Less likely to produce a back e.m.f. effect than in other coil shapes.

c) Most effective at very low frequencies.

d) More likely to produce a back e.m.f. effect than in other coil shapes.

9.

When using the right hand curl rule for a solenoid, what do the fingers of the right hand indicate?

a) The direction of conventional current flow.

b) The direction of the solenoid's north pole.

c) The direction of the solenoid's south pole.

d) The negative terminal of the solenoid.

10.

What would be the value of back e.m.f. induced at switch off, in a 3.3mH inductor passing a current of 250mA, assuming the time for the current to decay to zero was 50µs?

a) 10V b) 16.5V c) 22V d) 32.7V

