Inductor

Inductor is a passive component designed to resist changes in current and is often referred as" AC Resistors". The ability to resist changes in current and the ability to store energy in its magnetic field, account for the bulk of the useful properties of inductors. When current passes through an inductor, a magnetic field will produce. An alternately changing magnetic field produces an alternately changing electrical field, thus induces a voltage that opposes the field-producing current. The induced voltage across an inductor is calculated as follows:

$V = L\, di/dt$.

Thus, the induced voltage is proportional to the inductance value and the rate of current change.

By its nature, an Inductor is a low pass filter, having the properties of letting low frequency signals pass and high frequency signals be blocked. At high frequency, the inductor becomes a high impedance element that can be used for RF isolation.

An inductor is magnetic component of energy storage, it also operates in the circuits for energy conversion, the energy stored in an inductor can be calculated using the following formula:

$E = 1/2\, L{*}I^2$ (Joule).

An inductor is also used for impedance matching.

Coils and Chokes

Coils is another common name for inductors.
Chokes is another name for an inductor used in signal or power lines which is intended to filter or choke out signals

Molded Inductors

An inductor whose case has been formed via a molding process. Common molding processes include injection and transfer molding. Molded inductors typically have well defined body dimensions which consist of smooth surfaces and sharper corners as compared to other case types such as epoxy coated and shrink wrap coatings.

Multilayer Inductors

An inductor constructed by layering the coil between layers of core material. The coil typically consists of a bare metal material (no insulation). This technology is sometimes referred to as “non-wirewound”. The inductance value can be made larger by adding additional layers for a given spiral pattern.

Multilayer inductor is sometimes called Monolithic Inductor.

Ferrite Beads

Ferrite beads is a frequency dependent resistor and is used to help reduce noise. At low frequencies, inductive impedance is 10 ohm or less and the attenuation to the low frequency signal is limited. At higher frequencies, the impedance increases to over 100 ohms and becomes resistive above 100 MHz. The beads attenuates noise of unwanted frequencies through absorbing the noise signal and releasing in form of heat due to eddy current. The difference between beads and inductors：

(1) The raw material is different.
Low core loss ferrite is used to make inductors, while high core loss ferrite is used to make beads.

(2) Usage is different.

Inductor is used as a energy storage and signal filtering component, ferrite beads is used as energy assumption component to suppress noise signals.

Common Mode Chokes

Used to suppress noise or electrical interference that is common to both electrical lines in relation to earth ground.

Differential Mode Chokes

Also known as normal-mode chokes, used to suppress the electrical interference that is not common to both electrical lines but present between both electrical lines.

Inductance

Inductance L is a constant used to describe an inductor's capacity of energy storage. An inductor can operate together capacitors to realize the energy conversion between electrical field energy and magnetic field energy so as to realize the electrical signal conversion (Voltage transformation).

The Inductance for a given inductor is influenced by the core material, core shape and size, the turns count and the shape of coil. In extreme ideal conditions, for example, the inductance of a toroidal inductor can be theoretically calculated by the formula mentioned below, which is derived from Faraday's Law and Ampere's Law :

L= (μ Ae/Le) *N2
μ : core permeability
Ae:effective cross-sectional area
Le: effective magnetic path Length
N : winding turns

Inductance is the primary property parameter of an inductor that provides the desired circuit function and is the first parameter to be calculated in most design procedures based on the topology, electrical parameters (current, voltage) of input and output by converter design equations.

Inductance unit conversion:

1 millihenry (mH) = 10^{-3}H　　1H=10^{3}mH
1 microhenry (μH) =10^{-6} H　　1mH=10^{3}μH

The inductance of Inductors used in DC-DC converters is usually expressed in μH..

The inductance of Inductors in high frequency applications is usually expressed in nH.

The inductance of Power Chokes for low frequency filtering is usually expressed in mH

Inductance Tolerance Designation

Designation	Tolerance
W	±0.05nH
B	±0.1nH
C	±0.2nH
S	±0.3nH
D	±0.5nH

Designation	Tolerance
F	±1%
G	±2%
H	±3%
J	±5%
K	±10%

Designation	Tolerance
L	±15%
M	±20%
N	±25%
Y	±30%
P	±35%

DCR (DC Resistance)

This is a force that tends to resist the flow of direct current in copper wire, which can be calculated by the equation:
$DCR=\rho L/S$
*ρ：resistivity (**Ω**·cm)
(1.724 × 10-6Ω·cm for soft-annealed copper at room temperature)
* L：length of the copper wire wound (unit: mm)
* S：the wire bare cross-sectional area (unit:$m^{2)}$
The unit of DCR is ohm(**Ω**) and mohm (m**Ω**), $1\Omega=10^3$ mΩ

DCR(Direct Current Resistance) is a very important parameters for an inductor to contribute to the copper losses :
$Q=I^2 *R*t$

Irms（Temperature rise Current）

Irms is the amount of continuous DC current flowing through a magnetic component that causes the maximum allowable temperature rise.This heat rating current **Irms** is defined as the current at which the temperature rise is usally 40℃ from 20℃ ambient.

Isat（Saturation Current / DC Superposition Current）

Isat is the amount of continuous DC bias current flowing through a magnetic components which causes its inductance to drop by a specified amount from the initial zero DC bias inductance value due to magnetic core saturation.

This saturation rating current **Isat** is defined as the current at which the inductance usually decreases by 30% from its initial value at 20℃ ambient in energy storage applications. Saturation Current **Isat** is also called DC Superposition Current.

The cause of the inductance to drop due to the DC bias current is related to the magnetic properties of core.
The core and some of the space around the core, can only store a given amount of magnetic density.

Beyond the maximum flux density point, the permeability of the core is reduced.
Thus, the inductance is caused to drop. Core saturation does not apply to “air core”.

Idc (Rated Current)

Rated current is the level of continuous DC current that can be passed through a magnetic component,
Isat and Irms are used to decide rated current and the smaller one is specified as **Idc**.

The rated current is related to the inductor’s ability to minimize the power losses in the winding by having a low DC resistance.It is also related to the inductor’s ability to dissipate this power lost in the windings.Thus,Idc can be increased by reducing DCR or increasing the size of the component.

For beads and ceramic inductors, Idc is usually based on temperature rise current(Irms).

For ferrite inductors, Idc is determined both by temperature rise current (Irms) and saturation current(Isat).

Z (Impedance)

The impedance of a magnetic component is a sum of DC resistance and AC inductive reactance which can be calculated using the formula :

$Z_L=j\omega L$, $\omega=2\pi f$

L is the inductance value in Henry(H) and is AC frequency in Hz.
This equation indicates that higher impedance levels are achieved by higher inductance values or at higher frequencies. Skin effect and core losses also add to the impedance of an inductor.

Distributed Capacitance (Stray Capacitance)

The distributed capacitance is caused by the turns of wire layered on top of each other and around the core. This capacitance is in parallel to the inductance.

The unit of capacitance is usually in pF, $1pF=10^{-6}uF$

The AC impedance of a capacitor: $Z_C=1/j\omega C$

Matched Impedance

The condition that exists when two coupled circuits are adjusted so that the output impedance of one circuit equals the input impedance of the other circuit connected to the first. There is a minimum power loss between two circuits when their connecting impedances are equal.

SRF (Self-resonant Frequency)

SRF is the frequency at which the inductor’s winding distributed capacitance resonates naturally with the inductance. At this frequency, the inductor acts as an purely resistive with the highest impedance, and phase transition from INDUCTIVE to CAPACITIVE occurs.

Inductance and impedance rise sharply near an inductor’s SRF,the peak of inductor impedance occurs at SRF that can be calculated by the formula:,

SRF (in Hz)= $\dfrac{1}{2\pi\sqrt{LC}}$

Here L is the inductance and C is the distributed capacitance of the inductor.
For high order filter or impedance applications, it’s more important to have a relatively flat inductance curve near the required frequency, so an inductor with SRF well above (decade higher than) the required frequency is suggested to be selected.

SRF. depends on the inductance value and its winding structure that affect the distributed capacitance.
The higher the inductance value, the lower the SRF, due to the increased winding distributed capacitance.

Q (Quality factor)

The Q value of an inductor is a measure of the relative losses in an inductor. The Q is also known as the "quality factor" and is technically defined as the ratio of inductive reactance to effective resistance and is represented by,

$$Q=\frac{X_L}{R_e}=\frac{2\pi fL}{R_E}$$

Since XL and Re are functions of frequency, the test frequency must be given when specifying Q

XL typically increases with frequency at a faster rate than Re at lower frequencies, and vice versa at higher frequencies. This results in a bell shaped curve-for Q vs frequency.

Re is mainly comprised of the DC resistance of the wire, the core losses and skin effect of the wire. Based on the above formula, it can be shown that the Q is Zero at the self resonant frequency since the inductance is Zero at this point.

The magnitude of the peak impedance is related to the Quality Factor(Q) of the inductor.

Copper Loss

Copper loss is the power lost by current flowing through the windings. Copper loss is inherent losses associated with inductors including DC loss and AC loss:

(1) Copper Wire DC Loss
DC resistance of winding wire produces heat energy assumption calculated by **$Q=I^2 *R*t$**
(2) Copper Wire AC Loss (Skin Effect, Proximity Effect)
The skin and proximity effects lead to eddy currents in winding conductors, which increase copper loss under high current high frequency magnetic conditions.

The results of these losses are to lower efficiency and to transferred into heat, which further increases the losses in the inductor.

Core Loss

Core losses caused by an alternating magnetic field in the core material. The losses are a function of the operating frequency and the total magnetic flux swing. The total core losses are made up of three components: Hysteresis, Eddy current and the Residual losses. These losses vary considerably from one magnetic material to another. Applications such as higher power and higher frequency switching regulators and RF designs require careful core selection to yield highest inductor performance by keeping the core losses to a minimum. The results of these losses are to lower efficiency and to produce heat, which further increases the losses in the inductor.

Ferrite

Ferrite is a soft magnetic material which consists of a mixed oxide of iron and other elements that are made to have a crystalline molecular structure. The crystalline structure is created by firing the ferrite material at a very high temperature for a specified amount of time and profile. The general composition of ferrites is xxFe2O4 where xx represents one or several metals. The most popular metal combinations are manganese and zinc (MnZn) and nickel and zinc (NiZn). These metals can be easily magnetized

Ferrite has many properties: high magnetic permeability, high electrical resistivity, low core losses. Ferrite can be shaped in many ways so as to address specific applications. In EMI applications ferrite absorbs the signals of unwanted frequencies and releases in form of heat.

Ferrite is popularly used to manufacture inductors in power conversion, signal filtering and noise suppression.

Ceramic Cores

Ceramic is one of the common materials used for inductor cores. Its main purpose is to provide a form for the coil. In some designs it also provides the structure to hold the terminals in place. Ceramic has a very low thermal coefficient of expansion. This allows for relatively high inductance stability over the operating temperature ranges.

Ceramic has no magnetic properties. Thus, there is no increase in permeability due to the core material. Ceramic core inductors are often referred to as **"air core"** inductors. Ceramic core inductors are most often used in high frequency applications where low inductance values, very low core losses and high Q values are required

Kool MU® CORE

Kool Mu® is a magnetic soft material that has an inherent distributed air gap. The distributed air gap allows the core to store higher levels of magnetic flux when compared to other magnetic materials such as ferrites. This characteristic allows a higher DC current level to flow through the inductor before the inductor saturates.

Kool Mu® material is an alloy that is made up of basically nickel and iron powder (approx. 50% of each) and is available in several permeabilities. It has a higher permeability than powdered iron and also lower core losses. Kool Mu® is required to be pressed at a much higher pressure than powdered iron material. The manufacturing process includes an annealing step that relieves the pressure put onto the powdered metals which restores their desirable magnetic properties. Thus, the powdered particles require a high temperature insulation as compared to powdered iron.

Kool Mu® performs well in power switching applications. The relative cost is significantly higher than powdered iron.

Laminated Cores

Cores constructed by stacking multiple laminations on top of each other. The laminations are offered in a variety of materials and thicknesses. Some laminations are made to have the grains oriented to minimize the core losses and give higher permeabilities. Each lamination has an insulated surface which is commonly an oxide finish. Laminated cores are used in some inductor designs but are more common in a wide variety of transformer applications.

MPP cores

MPP is an acronym for molypermalloy powder. It is a magnetic material that has an inherent distributed air gap. The distributed air gap allows the core to store higher levels of magnetic flux when compared to other magnetic materials such as ferrites. This characteristic allows a higher DC current level to flow through the inductor before the inductor saturates.

The basic raw materials are nickel, iron and molybdenum. The ratios are: approximately 80% nickel, 2% - 3% molybdenum, and the remaining is iron. The manufacturing process includes an annealing step as discussed in the Kool Mu® definition. MPP stores higher amounts of energy and has a higher permeability than Kool Mu®.

Cores are offered in 10 or more permeability selections. The core characteristics allow inductors to perform very well in switching power applications. Since higher energy can be stored by the core, more DC current can be passed through the inductor before the core saturates. The cost of MPP is significantly higher than Kool Mu®, powdered irons and most ferrite cores with similar sizes.

PERMEABILITY (CORE)

The permeability of a magnetic core is the characteristic that gives the core the ability to concentrate lines of magnetic flux. The core material, as well as the core geometry, affect the core's "effective permeability". For a given core shape, size and material, and a given winding, higher permeabilitymagnetic materials result in higher inductance values as opposed to lower permeability materials.

MAGNETIC WIRE

Wire used to create a magnetic field such as those in magnetic components(inductors and transformers). Magnet wire is nearly 100% copper and must be made from virgin copper. It is offered with a number of different organic polymer film coatings.

LITZ WIRE

Wire consisting of a number of separately insulated strands that are woven or bunched together such that each strand tends to take all possible positions in the cross section of the wire as a whole. The current through each individual strand is divided equally since this wire design equalizes the flux linkages and reactance of the individual strands. In other words, a Litz conductor has lower AC losses than comparable solid wire conductors which becomes important as the operating frequency increases.

Curie Temperature

The temperature above which a ferrite core loses its magnetic properties. The core's permeability typically increases dramatically as the core temperature approaches the curie temperature which causes the inductance to increase. The permeability drops to near unity at the curie temperature which causes the inductance to drop dramatically. The curie point is the temperature at which the initial permeability has dropped to 10 % of its original value at room temperature.

OPERATING TEMPERATURE RANGE

Range of ambient temperatures over which a component can be operated safely. The operating temperature is different from the storage temperature in that it accounts for the component's self temperature rise caused by the winding loss from a given DC bias current. This power loss is referred to as the “copper” loss and is equal to:

$$\text{Power Loss} = DCR * I^2$$

This power loss results in an increase to the component temperature above the given ambient temperature. Thus, the maximum operating temperature will be less than the maximum storage temperature:

Maximum Operating Temperature = Storage Temperature - Self Temperature Rise

Skin Effect

Skin effect is the tendency for alternating current to flow near the surface of the conductor in lieu of flowing in a manner as to utilize the entire cross-sectional area of the conductor. This phenomenon causes the resistance of the conductor to increase. the magnetic field associated with the current in
the conductor causes eddy current near the center of the conductor which opposes the flow of the main current near the center of the conductor. The main current flow is forced further to the surface as the frequency of the alternating current increases.

Litz wire is usually used to avoid Skin Effect.

Shielded Inductor

An inductor designed for its core to contain a majority of its magnetic field. Some inductor designs, for example, the core shape of toroid, pot and EE, EP which have a closed magnetic path are self shielding.

It should be noted that magnetic shielding is a matter of degree. A certain percentage of the magnetic field will escape the core material. This is even applicable for toroidal cores as lower core permeabilities will have higher fringing filelde than will high permeability toroidal cores.

Closed Magnetic Path

Magnetic core shapes designed to contain all of the magnetic flux generated from an excited winding(s). Inductors made with these core types are considered to be shielded inductors. Shielding, however, is a matter of degree.

Common core shapes that are considered to have closed magnetic paths are toroid, EE, EP-cores and most pot cores. Shielded bobbins also offer a high degree of shielding and may be considered to have closed magnetic paths for most practical purposes. Common core shapes that are considered to have open magnetic flux paths are rod cores and unshielded bobbin cores.

DC-DC converter

A circuit or device that converts a DC input voltage to a regulated output voltage. The output voltage may be lower, higher or the same as the input voltage. Switching regulator DC-DC circuits most often require an inductor or transformer to achieve the regulated output voltage. Switching regulator circuits can achieve a higher level of power efficiency when compared to non-switching techniques.

NOISE

Unwanted electrical energy in a circuit that is unrelated to the desired signal. Sources of noise are most often generated by some type of switching circuit. Common sources include switching voltage regulators and clocked signals such as digital circuits.

EMI (Electro-Magnetic Interference)

EMI is unintended high frequency electromagnetic radiation, which is generated in digital and analog systems. EMI can adversely affect the performance of a circuit internally and that of other associated equipment in close proximity or even far field.

EMC (Electromagnetic Compatibility)

EMC means the ability of equipment or system to function satisfactorily in an electromagnetic environment without introducing intolerable electromagnetic disturbance to anything in that environment.

Common Mode Signal

Common mode signal appears equally (with respect to local circuit common) on both lines of a 2-wire cable not connected to earth, shield, or local common. Usually but not always, it is an unwanted signal that should be rejected by the receiving circuit. Common-mode voltage (VCM) is expressed mathematically as the average of the two signal voltages with respect to local ground

Normal Mode Signal / Differential Mode Signal

Normal mode signal is any type (other than common mode) that appears between a pair of wires, or on a single wire referenced to (or returned via) the earth, chassis, or shield. Normal-mode signals are read between two wires in a balanced or unbalanced transmission path. For a balanced 2-wire path, one wire is driven positive while the other is driven negative an equal amount, both with respect to a static or no-signal condition in which both lines assume the same voltage level relative to circuit common.

Differential mode signal appears differentially on a pair of wires in an ungrounded cable configuration. In some circles, differential mode noise has been given the title of "Normal Mode Noise".