Inductor Reference Guide

Common Terms, Types, Materials and Applications

Power & Energy Engineering Team
Abracon, LLC

08/28/2020

Abstract: This application notes defines and reviews common inductor terminology, various inductor construction typologies, associated materials, familiar applications, and technical performance factors that electronics engineers, from novices to the experienced magnetics specialists, will find useful and insightful when selecting their next inductor.

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Inductor Common Terms

Inductors are essential components in circuit designs. These passive electrical components store and supply energy. Inductors are used for a wide variety of applications, such as DC-to-DC buck and boost power conversions, impedance matching, and filtering high frequency noise in electrical circuits. There are many factors to consider when selecting the optimal inductor for an application, including the current rating, the DC resistance, and the inductor's temperature rating of the inductor. Use this glossary of commonly used inductor terms as a reference guide when selecting an inductor.

Inductor

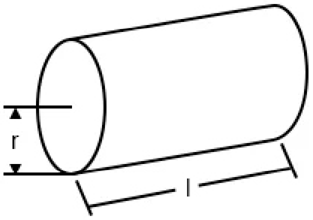
An inductor is a passive electrical component used to store energy in the form of a magnetic field. When induced by current, the component creates a magnetic field proportional to the applied current. These properties are often used for current regulation, current resistance and signal balancing, depending on the inductance value. Inductance values greater than 1mH are generally used for high frequency blocking. Inductance values from 0.1uH to 1mH are generally used for current regulation of peripheral loads. Inductance values below 0.1uH are generally used for high frequency signal balancing.

Inductance

Inductance is the scale of an electrical conductor/component to induce an electromotive force by a variation of current, described as V=L(di/dt). Aside from describing electromagnetic relationships, inductance is quantified by the cross-sectional area of a coil, the number of wire turns, the permeability and the coil length.

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

$$\mu = \mu_r \mu_0$$



Where,

L = Inductance of coil in Henrys
N = Number of turns in wire coil(straight wire = 1)
μ = Permeability of core material(absolute, not relative)
μ_r = Relative permeability, dimensionless (μ_0= 1 for air)
μ_0 = 1.26 x 10^{-6} T-m/At permeability of free space
A = Area of coil in square meters = πr^2
l = Average length of coil in meters

[1]

Impedance

The impedance of an inductor is composed of resistive and reactive elements:

$$Z=RL+XL$$

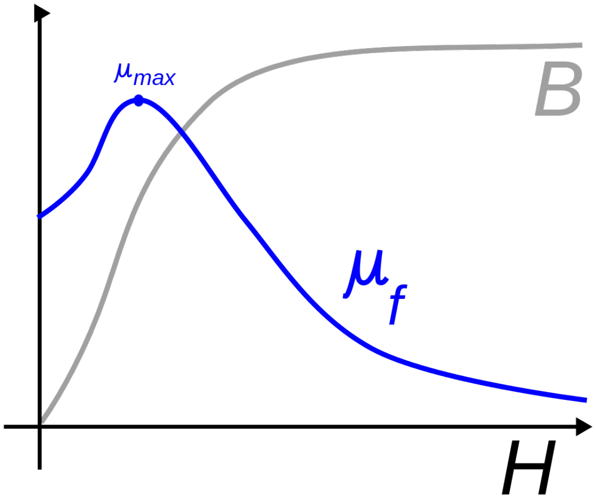
Each value represents the resistance to current for both direct current (DC) and alternating current (AC), respectively. RL is the resistance of a DC current as a result of the resistance of the coil. Disregarding core losses and assuming sinusoidal AC signals, ideal inductors have AC impedances of $XL=2\pi fL$. The greater the inductance, the larger the impedance to respective frequencies. In applications, it is important to note the losses accumulated from skin affect, hysteresis and eddy currents.

DC Resistance (DCR)

DCR is the measured resistance of the inductor without alternating current. In most cases, this value is specified as a maximum rating. The DCR is inversely proportional to the package size and proportional to the inductance value due to the cross section and the coil turns. For RF inductors, the DCR can measure up to 10KΩ. The DCR can measure down to 0.25mΩ for Abracon power inductors.

Saturation Current (Isat)

When an inductor is induced by current, the magnetic properties begin to decline exponentially at certain boundaries. As current is applied, the magnetic field intensity, H, increases to a point where the magnetic flux density, B, reaches a limit and permeability decreases.



[2]

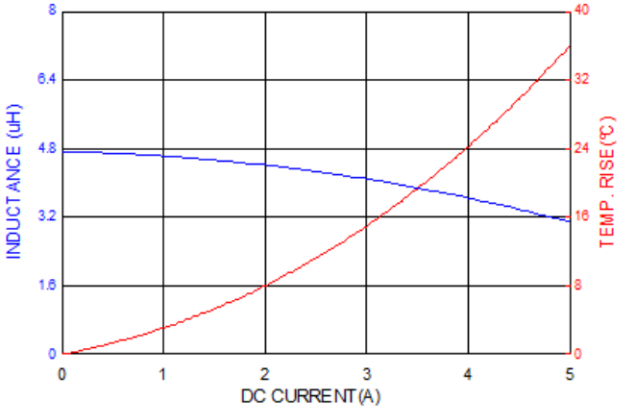
The linear region of the curve, as illustrated above, when the inductance is unaffected and remains at its nominal inductance. As the B field saturates, the inductance begins to decline at a proportional rate. The saturation current specifies the current at which the inductance drops a specific amount of the nominal inductance as a result of applied DC current and saturated magnetic flux density. The most common saturation options are as follows:

Δ5%
Δ10%
Δ20%
Δ30%
Δ50%

RF inductors generally utilize between 30%-50%. Chokes, such as drum core inductors and high inductance devices, utilize between 5%-10%. DC-DC converter inductors, such as molded and SMD wire wound inductors, utilize between 10%-30%.

Temperature Rise Current (Irms)

Each inductor is composed of conductive elements, whether in the form of photolytic layers or coiled copper wire. As a result, each inductor carries resistance inversely proportional to the cross-sectional area of the wire. This resistance produces heat accumulation when current is applied and increases non-linearly as current increases. The temperature rise current specified in Abracon datasheets is the DC current at which the case temperature of the inductor increases by the specified industry standard test criteria of Δ40°C.

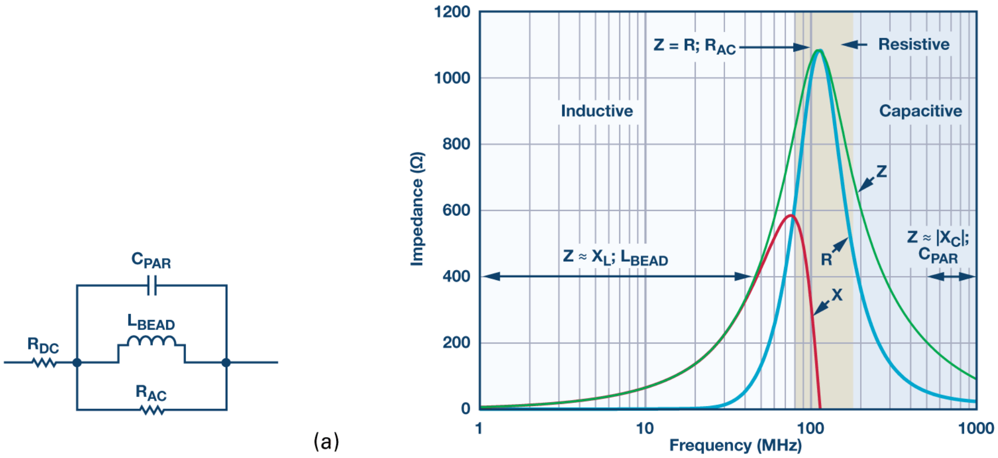


Rated Current (Idc)

Rated current is specified as the lower value of the Isat and the Irms because, in application, the inductor is not expected to operate beyond either of the testing criteria, i.e., -30% change of inductance or Δ40°C.

SRF

Self-resonate frequency (SRF) is the frequency at which the reactance of the parasitic capacitance from the overlapping coils and electrodes is equal to the reactance of the inductor. At this point, the net reactance is zero, and the impedance is extremely high and completely resistive.



(a)

(b)

[3]

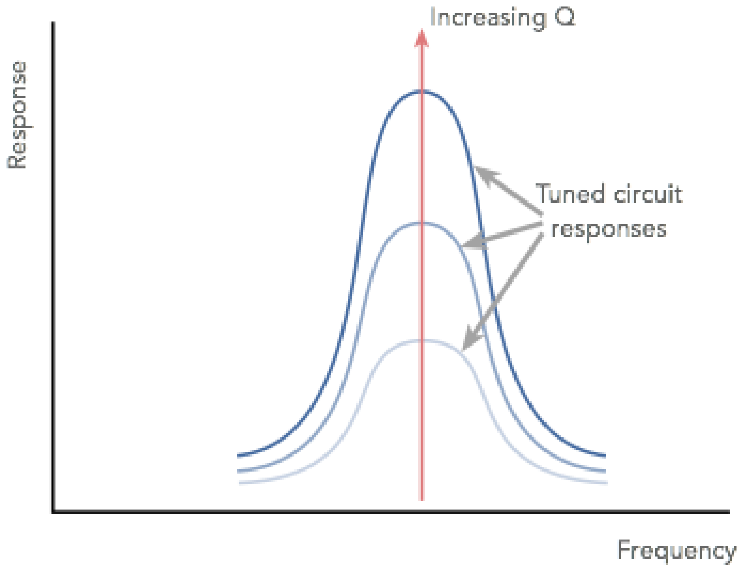
Since the capacitance is related to the coil parasitics, higher SRFs can be achieved by reducing the number of wire turns and increasing the permeability for the same inductance value.

Q

The quality factory is a numeric value reflecting the proportionality between inductor reactance and resistance:

$$Q=(2\pi fL)/R$$

At lower frequencies, inductors' reactance increases faster than resistance, resulting in a Q increase. As the frequencies get higher, resistivity begins to increase at a faster rate due to skin effect, AC losses and hysteresis. Over this span of frequency, the Q curve results in a bell-curve shaped plot.



[4]

The relationship between Q and SRF is the change in the inductor's net reactance. At the SRF, the reactance is zero, and therefore, the Q is zero.

Operating Temperature

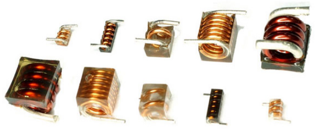
Operating temperature is simply the temperature range in which an inductor can withstand. There are two ways the operating temperature can be specified, 1) not including temperature rise or 2) including temperature rise. When current is applied to an inductor, the case temperature will increase in temperature. Generally, manufacturer datasheets specify the heating of an inductor by the current which causes a 40°C rise above ambient. Most manufacturers will specify the operating temperature to reflect the worst-case scenario, also specified as Irms. For example, if the temperature rise current is 30A and the operating temperature -40°C ~ 125°C is inclusive of Irms, then the ambient temperature must be 85°C at 30A since the component's case temperature will measure 125°C.

Inductor Types

Inductors are available in a variety of package sizes and construction types. The materials and processes used in the construction of an inductor can give the component certain properties, such as package size, electrical performance or cost, that can be advantageous or required for certain applications. Abracon's available inductor types are outlined below. Inductor type is an essential consideration when selecting the appropriate component for an application.

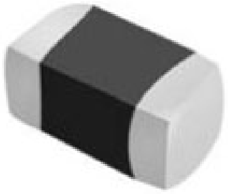
Air Core

Most inductors utilize magnetic material to increase inductance value per winding by increasing magnetic flux densities. The drawback to magnetic material is the saturation of flux density over current due to the decrease in permeability. Since RF applications require low inductance values for high frequencies, magnetic flux is not always necessary. Air coils have no magnetic core. Therefore, this type handles higher current than other RF inductors, like the multilayer and wire wound types. Since the current is not dependent on the magnetic saturation, the rated current is based on the heating of the wire alone. The nature of the coil is thick wire with spaced out windings, creating low DCR and low capacitance parasitic values. This results in a high Q product for RF applications requiring high current.



Multilayer

The name multilayer implies the build of the ML chip inductor. Depending on the base material, layers of conductive and ferrite/metal/ceramic materials are laminated together. Lamination, terminal finish and conductive patterns can vary greatly to optimize for SRF, Q and DCR specifications. These components have high variation in performance and can be utilized for both RF and low power conversion applications. In RF applications, these types lend higher current ratings and inductance values as opposed to thin and thick film inductors. However, the tradeoffs are higher tolerance values and low Qs. In terms of power conversion, the multilayer is used for miniaturized devices.



Molded

A molded inductor is a coil pressed and wholly encapsulated by different types of iron powder mixes. As opposed to traditional wire wound inductors, the molded inductor's magnetic powder material is pressed into a mold around a wire coil. Traditional wire wound inductors are processed by wire being wrapped around a solidified magnetic core and finished with either no shielding, resin shielding or shielding sleeves. Molded inductors, by nature of the process, are inherently better in efficiency, shielding and power density compared to all other inductors. The key contributing factor is complete encapsulation and utilization of powder materials to fill in air gaps around the wire coils. Additionally, most molded powders are metal alloy mixes as opposed to ferrite. This allows for much softer inductor saturation. The result of the encapsulation and material selection is superior current capacity and efficiency.

Thin Film

Thin-film inductors are manufactured using photolithography similar to the silicon fabrication process. The result is highly precise inductors with low tolerance and high SRF. This is the preferred inductor for RF circuitry such as oscillation circuits, antenna impedance matching and high frequency filtering. The most popular applications for this inductor type are wireless LAN, Bluetooth, GPS and GSM.

Unshielded Wire Wound

Unshielded wire wound inductors consist of a copper wire wrapped around an SMD magnetic core. These types have no added shielding properties and are an affordable option for general power conversion applications. These parts do not benefit from shielding or increased inductance from added magnetic material around the wire. For this reason, the performance is lower than other shielded wire wound inductors and do not have compact size advantages. These types of inductors benefit in cost competitive applications that have loose dimensional and performance requirements.

Shielded Wire Wound

Shielded wire wound inductors can come in several different forms of SMD inductors. The best description for this type is the utilization of a magnetic sleeve to cover the wire wound wrapped magnetic core. This sleeve limits the radiation of magnetic fields resulting from induced current. As the industry trends to higher current requiring loads, shielding is essential to meet FCC and other national emission standards. This is also important for reducing EMI and limiting the effect of power electronics on nearby sensitive circuitry. The shielded sleeve increases the performance of the inductor in ways other than shielding. Having additional magnetic material around the wire results in higher current density and higher inductance per turn of wire. This allows reduction of wire material per inductance, decreasing the DCR and increasing the current handling. This type of inductor delivers high-performance product at a slightly higher cost due to the added magnetic material.

Resin Shielded Wire Wound

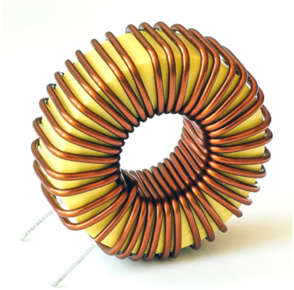
The resin shielded inductor is classified as a partially shielded SMD inductor. The wire wound wrapped magnetic core is coated with magnetic liquid and hardened by a special baking process. This type of inductor is between the shielded and unshielded wire wound inductors in terms of current handling, DCR, and shielding performance. Resin shielded wire wound inductors are also cost competitive when compared with shielded and unshielded wire wound inductors. This type is a good choice for designs with high budget restraints that require compact power conversion.

Drum Core

The drum core inductor is a wire wound through-hole component with visual characteristics of a traditional drum. These inductors can come unshielded, shielded or in heat shrink tubing. The drum core is designed for high inductance filtering or power conversion at frequencies below 100KHz. These types are generally larger and taller than SMD products due to the number of turns needed to achieve high inductance values. The leads of the inductor reduce the risk of vibrations or handling from demounting the product, which can happen in high inductance SMD product. This product will be found closer to the power line side of electronics.

Toroidal

Toroidal inductors utilize toroid-shaped magnetic cores with copper windings. Although it is wire wound, it is not categorized as such due to its distinguishable shape. This inductor is often referred to as shielded because the shape of the core results in minimized magnetic leakage like that of a shielded wire wound inductor. These through-hole components are utilized for high inductance applications at low frequencies such as switching regulators, refrigerators and medical devices. There are inherent difficulties in production of this product, and the impact results in cost disadvantages. Drum core inductors are often used as a substitute when applicable.



Materials

The materials used in inductor construction have a massive impact on the performance and cost of the component. Non-magnetic materials, such as air, alumina and ceramic, are generally used in high frequency applications and are generally less expensive than magnetic materials. Magnetic materials, such as powdered iron, carbonyl powder, metal alloys/composites and ferrites, allow for higher inductance values per turn of wire. Each of the various magnetic material types offers some benefit or trade-off in terms of electrical performance/efficiency and material cost. The electrical requirements of an application can lend insight into the most appropriate material type, so knowing each material type's advantages and disadvantages is crucial when selecting the optimal inductor.

Non-Magnetic

Non-magnetic inductors are those which utilize materials that do not maintain magnetism or magnetic properties. Inductors built from these types of materials do not benefit from enhanced inductance per turn. However, they avoid saturation, core losses and other dynamic effects of magnetic materials. Due to the absence of magnetic cores, these materials create low inductance devices used for high frequency applications. Non-magnetic materials tend to have high Q, high SRF and good stability at inductances less than 100nH. The following types of non-magnetic materials are used in Abracon's current inductor offering.

1. **Air**
Air cores are coils of wire with minimal additional material. Material can be added for ease of assembly or to add structural support to the coil. The nature of the coil is thick wire with spaced out windings creating low DCR and low capacitance parasitics. This results in a high Q product for RF applications requiring high current.

2. **Alumina**
Al_2O_3 is the chemical formula for alumina which is also known as aluminum oxide. This material is used to create thin film, RF wire wound, and multilayer inductors. The result is highly precise devices with respect to inductance tolerance, Q and SRF.

3. **Ceramic**
The term "ceramic" is often used to describe non-magnetic materials in the inductor industry. Without understanding the context, the word "ceramic" is often misinterpreted because ferrites are considered ceramic, and ferrites are highly magnetic. The term ceramic often refers to silicon dioxide (SiO_2) cores

or alumina, (Al_2O_3) cores that have non-magnetic characteristics.

Magnetic/Ferromagnetic

Magnetic/ferro magnetic materials maintain magnetization without applied currents due to the alignment of microscopic atomic structures. The most common materials are alloy mixes consisting of iron, nickel and cobalt. These material types lend to higher inductance capabilities per turn of wire for inductors. This allows for inductor miniaturization, reduced heat losses and increased current capability. These benefits come at the cost of introducing new magnetic loss mechanics and operational limits.

1. **Powder Iron**
   Mixed powdered iron cores are low-cost, high-power alternatives to ferrite types. Besides cost, the benefits are increased efficiencies and high magnetic flux densities for smaller package sizes. The powders are often pressed into a core for wire winding or pressed into a mold with an internal coil. Multilayer inductor technology also utilizes powder irons for enhanced performance. These mixes allow for frequencies up to 10MHz. Powder iron mixes can consist of several different compound types at different sizes of grain, porosity and coatings. In the manufacturing process, this affords a high degree of customization for performance and construction that would otherwise seem impractical for solid materials.

   1. **Carbonyl Powder**
      Carbonyl powders are high purity iron powders with little integrated carbon. Comparative to other powder mixes, carbonyl powders are primarily utilized for higher saturation capabilities. Utilization of this material yields the highest stability and precise inductance values.

   2. **Metal Alloy/Composite**
      Being intentionally vague for IP reasons, manufacturers refer to some powder mixes as metal alloys or metal composites. These can be any combination of iron, nickel, silicon, chromium, aluminum, magnesium, etc. Depending on the targeted application, these products can result in better core losses, permeabilities and/or aesthetic appearances.

2. **Ferrites**
   Ferrites are magnetic materials based on iron oxide. They are often categorized as soft, semi-hard, or hard ferrites, depending on the material’s coercivity. Inductors or filters often use soft magnetization ferrites. Soft ferrites consist of other elements like manganese (Mn), nickel (Ni), or zinc (Zn), depending on the required permeabilities and frequency ranges. Generally, MnZn ferrites/combinations are used for lower frequencies between 200KHz-5MHz, and NiZn ferrites/combinations are used for 1MHz-70MHz. Ferrites have higher resistance than iron powders, resulting in minimalized eddy current losses in the core. The tradeoff is ferrite materials have much lower saturation levels and flux densities. This results in larger product with lower current ratings.

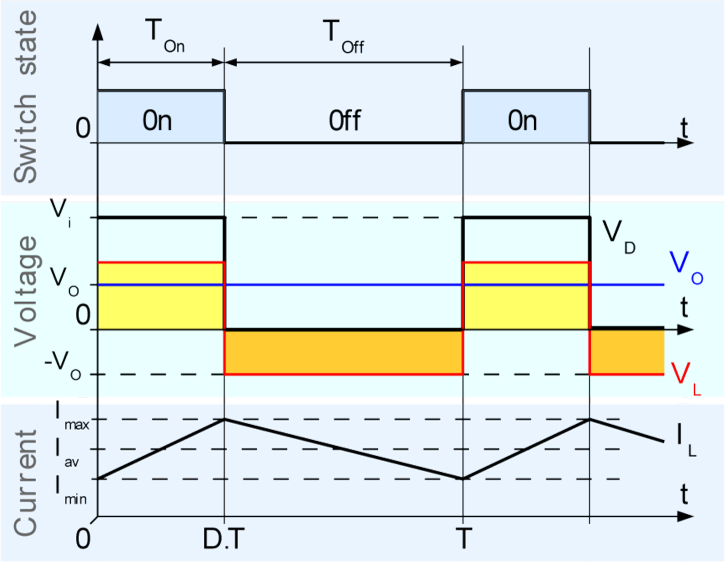
Inductor Applications

Inductors have a wide variety of application uses due to their function of storing and providing energy. Outlined below are the most common applications for inductors. For power conversion applications, inductors can be used to perform buck or boost conversions to regulate supply power to a device.

Inductors are also excellent components for choking, blocking and/or filtering high frequency noise in electrical circuits by utilizing an inductor's impedance to block current changes. Additional applications include LC tank circuits, where an inductor is paired with a capacitor to store energy, and impedance matching, where the inductor impedance matches the source impedance to allow for maximum power transfer.

Power Conversion

There is a high variety of power requirements for electrical and electrical mechanical systems. Inductors, transistors and diodes are utilized to help supply appropriate power levels to peripheral devices and circuits. Inductors aid power regulation by storing and supplying power to a device. The selection of the inductor can impact the efficiency, current output and ripple. The two main power conversions are DC-DC buck and DC-DC boost converters.



[5]

DC-DC Buck Converter

The buck converter is a switching topology that produces and regulates a lower output voltage than the input voltage.

DC-DC Boost Converter

The boost converter is a switching topology that produces and regulates a higher output voltage than the input voltage.

Choking, blocking, attenuating or filtering/smoothing high frequency noise in electrical circuits

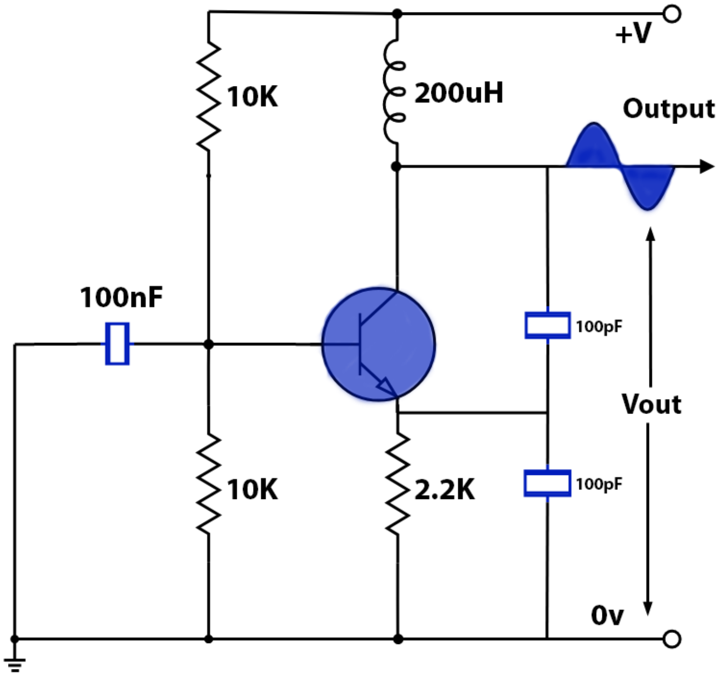
An inductor's impedance can be utilized to block changes in current, exhibiting characteristics of a low pass filter. This behavior is often referred to as choking, attenuating, filtering, smoothing or blocking. Utilizing this feature allows designers to eliminate undesirable signals or noise caused by power supply transients and/or other types of electromagnetic interference (EMI) stemming from PCB trace design or from other electronic devices.

The importance of filtering goes beyond signal integrity. Organizations such as the FCC, IEC, ISO and EN require emissions to be within regulation. Devices sold in the U.S. featuring wireless capabilities and/or power supply designs must meet FCC regulations.

The effectiveness of a choke depends on the core and wire material used. Designers generally look at the Q of an inductor for its filtering capabilities over specified frequencies. Since the Q is unitless and is a ratio between reactance and resistance, high Q indicates an inductor's passive region, whereas low Q indicates the lossy/filtering region. Inductors tend to have a bell-shaped Q curve dependent upon the inductance, whereas ferrite beads have lower Qs for attenuation over a broader range of frequencies.

LC Tank Circuits

High Q inductors are also utilized in oscillation circuits used for radio/microwave transceivers or digital circuitry clocking. When an inductor is paired with a capacitor, the two components' energy storage capabilities create a push-pull dynamic. The capacitor dissipates energy into the inductor for some period, and then the inductor dissipates the energy back into the capacitor for an equivalent period. The frequency of the signal created can be calculated as f=1/(2πsqrt(LC)).



Impedance Matching

Impedance matching typically involves matching the impedance of a power source to the impedance of an electrical load. Maximum power is transferred from the source to the load when the impedance of the load is matched to the impedance of the source, thereby improving the efficiency of the circuit. If the load is capacitive compared to the source, then an inductor can be used to counter the capacitance of the load and can thus match the source impedance.

Author Information:
Power & Energy Engineering Team
Abracon, LLC

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