TRIAD MAGNETICS

Guide to Inductors

GUIDE TO INDUCTORS

Lodestone, one of the most common iron core oxides, is made of the mineral magnetite. As its name implies, it is naturally magnetic.

Though its magnetic properties were known upon its discovery in antiquity, no major research was done into magnetite until Hans Christian Oersted discovered the relationship between electricity and magnetism in 1820. He posited and proved that a magnetic effect could be created by flowing electricity.

Following Oersted, Joseph Henry and Michael Faraday studied coil circuits, proving that the spark created by circuits during a current interruption was caused by an electromotive force created by the coil itself. Further, they proved that magnetic movement can produce electrical current.

Together, these three men are considered to be the fathers of modern electronics.

Inductance and Related Parameters

Technicians and electrical engineers alike regularly use or encounter inductors in the course of their work. The design and manufacture of such inductors is best left to specialists, but it is important for anyone using them to have a thorough understanding of their basic functional and operational principles.

Inductance

When the electric current flowing through a coil is varied, such as an AC flow, this change creates a similar change in the coil's magnetic field.

The resultant change in magnetic field induces a second current, in opposition to the source current, in the coil. This is known as self-inductance, or inductance, which is defined as the property of an electric circuit that opposes changes to the current that is flowing through it.

More specifically, inductance (represented as L in equations and measurements) is the amount that rate of change in current is multiplied by in order to obtain the induced electromagnetic force (EMF). The equation for this is: $e = -L(di/dt)$.

Here inductance, L, is the constant — it is referred to as the coefficient of self-induction and is measured in henrys (H). It is negative in the equation to indicate that the inductance voltage has opposite polarity from the source voltage. One henry is equivalent to an induced EMF of 1 volt per one ampere-per-second of current change.

The amount of inductance in a coil is determined by the amount of flux linking that coil. The amount of flux itself is determined by the size of the coiled wire, the number of turns in the coil, and the arrangement of those turns. The presence, or absence, of a magnetic material in the core of the coil is also a factor.

Flux

The energy stored in the form of magnetic flux is known as a flux linkage. This energy level is determined by the inductance of the coil and the value of the coil's current, represented by this equation: W = ½LI2. In this way, an inductor can be used to store energy in addition to its primary transfer capabilities.

The flux of a coil (ø) is measured by number of lines or by maxwells (Mx). The number of lines of force per unit area, the flux density (B), is measured in gauss. Flux density is a measure of maxwells per square centimeter and is proportional to magnetizing force (H), depending on the permeability (μ) of the core medium: B = μH.

A coil is not required to have a magnetic material core in order to have inductance. Coils with high frequencies in particular do not require a magnetic core. On the other hand, they are basically essential for a reasonable amount of inductance to exist in medium and low frequency coils.

Permeability

The permeability of a medium is defined as the ratio between lines of force in a medium and the number of lines the same magnetizing force would create in air.

The amount of permeability is further complicated by two factors. The first is hysteresis, or the concept that the permeability of an iron core depends on the core's past usage, or its "history" so to speak. The second is the presence of an incoming DC current flow into the coil.

The presence of DC flow in a coil makes incremental permeability a necessary factor in establishing inductance. Incremental permeability is the permeability of a magnetic material to AC currents that are superimposed on top of a DC current.

Time Constants

It is normal for inductors to have some ohmic losses. These losses, when in series with inductance (L), are represented as a resistance (R). As voltage (V) is applied to an inductor, the current gradually rises to its steady value (V/R), as represented by this equation:

$$Ir = [(V/R)(1 - \varepsilon{-}tR/L)]$$

The time constant, L/R = T, is a measure of the time, in seconds, it takes a given current to reach 63.2% of its ultimate value. An inductor's current decay follows a logarithmic curve provided by a similar equation:

$$Id = [(V/R)(\varepsilon\ {-}t/T\ )]$$

BASICS OF INDUCTORS

Inductors are used to store energy, create impedance, and modulate the flow of current. There are many types of inductors, as well as many core and winding styles, suited to different circuits.

Inductors resist changes in currents through their windings — that is, they try to make any changing current more stable. They limit current increases by converting energy from the increasing current into a magnetic field. As the current decreases, energy that is stored in the magnetic field is converted back into the current; this is then added back into the decreasing current in order to prevent it from dropping as quickly. The current is then changed by the voltage across the inductor. This voltage can oppose the source to convert current into the magnetic field, or the voltage can add to the source to convert magnetic field energy into current.

Inductance is measured in henries. One henry is defined as the inductance that creates one volt across the inductor when the current is changing at a rate of one ampere per second.

Power inductors are typically used to smooth the flow of current. When current is always flowing in one direction (but varies in magnitude), power inductors reduce the value of current peaks by converting the increase in current into magnetic energy, then releasing this energy back into electrical current when the current magnitude is reduced. In this way, they smooth the current by reducing the peak current and increasing the minimum current.

The energy stored in the inductor can be calculated by:

Joules = ½ * Inductance (in henries) * Current squared (in amperes)

This holds true as long as the inductance value remains as expected.

Inductors also create near lossless impedance. This enables them to be used as filters, allowing lower frequencies to see smaller impedances and higher frequencies to see higher impedances.

Core Materials and Shapes

Depending on circuit type and power requirements, there are many choices for core materials and even more options for core shape and size.

Core materials include silicon steel, powdered iron or nickel, other alloys, ferrites, and even air. Each material has its own magnetic properties: how much energy can be stored, how much inductance the core can create, how much energy will be lost (due to hysteresis and eddy current losses), and how stable these factors are with changing temperatures, currents, and frequencies.

Core shapes include stamped laminations, “C” cores (strip-wound rectangular cores), toroids (donut or annulus), and many ferrite shapes: U, E, planar, pot, etc. Depending on the construction of the coil around it, each shape has various benefits and drawbacks.

The proper choice of core material and shape will create an inductor that best meets the needs of the customer: electrical performance, size, shape, cost, etc.

When comparing energy storage to core weight and volume, toroidal cores are a near-perfect core shape; every portion of the core is used to wind upon, and every portion of the core can be covered by the winding.

The magnetic field of a toroidal winding is confined almost completely to the physical space of the winding, which means that the majority of the lines of force are found within the form of the toroidal core.

Flux density of a toroid is essentially uniform throughout the entire electromagnetic path. Permeability, given a particular set of conditions, is effectively constant. Externally originating magnetic fields have little to no effect on toroid-constructed cores.

However, there are disadvantages to toroidal cores — primarily cost. Some of the more effective materials used in toroidal cores are more expensive than standard materials.

Winding is another source of cost increase. Toroidal cores are not adaptable to multiple windings — the process of simultaneously winding more than one coil — thereby increasing production costs. Another restriction is the size of the wire, as winding machines used for toroidal wiring have difficulty handling the finer wires often used.

The windings of a toroid coil can be trimmed at the bridge to achieve very precise, close-tolerance inductance values. Because of their adaptability to shaft mounting, inductors with toroidal cores can also be easily stacked in banks. Shielding between stacked toroidal coils is only required in unique cases.

Toroidal inductors largely feature powdered metal cores. These inductors, known as differential mode inductors, feature greater energy storage properties than inductors with other high-frequency core materials. Additionally, their toroidal construction leads to controlled magnetic fields with minimal stray fields.

Toroidal inductors made with ferrite are known as common mode inductors and function slightly differently than differential mode inductors. Always constructed with two or more separate and identical windings, common mode toroidal inductors filter signals common to both power lines. Differential currents cancel themselves out in toroidal inductors, which leads to very high common mode signal inductance without the need to store the power line frequency energy.

Inductor Applications

The range of applications for inductors is quite varied.

Common mode inductors are often utilized in applications that use higher frequencies, known as switched mode applications. Common mode toroidal inductors are most effective at reducing signals from the switched mode circuitry frequencies as well as their harmonics at even higher frequencies. They remain effective at ranges surpassing 10 MHz and reduce electromagnetic interference from offending frequencies.

When combined with other components, such as resistors, inductors become important aspects of phase-shifting and phase-adjusting devices. They are also commonly used as complex loading devices and transient suppressing chokes for voltage surge protection.

Toroidal inductors' small size and low weight make them ideal for a number of high-performance but space-sensitive applications — in the aerospace industry, for instance. The toroidal core shape maximizes the use of the core and minimizes winding resistance.

Differential mode inductors are intended to smooth the flow of current by storing and releasing that stored energy to smooth out the peaks and valleys of current flow. These inductors can store significant amounts of energy and work from DC through very high frequencies.

Considerations for Inductor Design

Aside from intended end use, there are a number of important factors to take into account when designing or specifying an inductor: core material, wire and winding, and packaging.

Core Material

The selection of a core material is very important, as some materials can store very large energies at DC or low frequencies but have high losses at high frequencies. Core materials that have low losses at high frequencies tend to not be able to store as much energy. The best material selection depends greatly on the circuit requirements.

The many different core materials used in inductors can be generally categorized as solid magnetic metallic, powder and ceramic, and sometimes even air.

Iron cores for inductors are manufactured either from a strip or tape of sheet steel that is wrapped around itself, washer-like preforms that are stacked atop each other, or stamped shapes. Many magnetic metallic alloys are sensitive to pressure (especially nickel alloys), so they must be cushioned and handled gently.

Powder cores are blends of powdered metals that are annealed, pressed, and sintered into their final core shape. Powdered metals commonly used for inductor cores include molybdenum permalloy, a nickel-iron-molybdenum blend, carbonyl iron, and various ferrite blends.

A primary benefit of powdered metal cores — particularly molybdenum permalloy cores — over solid cores is that they contain a uniform distribution of air gaps due to the granular nature of the raw material. This leads to fairly constant permeability and a fairly constant core loss in a wide variety of use scenarios. Powdered ferrite cores can achieve high electrical resistance and low eddy current losses.

Powdered metal can also be altered by adding additional metal powders to the mix in order to achieve special core properties, such as extremely stable temperature characteristics.

Wire and Winding

Above all else, the wire and winding of your inductor is its most important component. When choosing wire for your winding, you must consider wire material, width, coating or insulation material, and winding method.

Round copper wire is by far the most commonly used for inductor winding, though other options include copper or aluminum in sheet, square, or rectangular sizes. Litz wire — a specialty wire made of numerous individual strands twisted or braided together — is also an option.

Wire coating can have a significant impact on the manufacturing and functioning of an inductor. Nyleze is a solderable coating with high-abrasion resistance — which is important during the winding process — that can operate in conditions as hot as 155 degrees Celsius (266 degrees Fahrenheit). Thermaleze is also abrasion resistant and can withstand temperatures up to 200 degrees Celsius (392 degrees Fahrenheit), but it cannot be directly soldered. PTFE-insulated wire (frequently recognized as Teflon-insulated wire) can help an inductor maintain low winding capacitance. These are only a small sampling of available wire coatings. Your specific needs will determine the best option.

For medium- and high-frequency applications, distribution of capacitance throughout the coil must be considered. Therefore, the winding methods that counter it — such as the bank and progressive methods in toroidal windings or single layer in bobbin windings — should be used. Foil windings can have significant capacitance from turn to turn.

Losses within the winding are the result of heat caused by current passing through the winding resistance. At low frequencies, this is generally just $W = I^2 * R$, where the R equals the DC resistance. But at high frequencies, the effective resistance can be tens or hundreds of times greater due to skin effects and proximity effects. The number of winding layers and conductor size are the major factors in how much higher the effective AC resistance is compared to the DC resistance; fewer layers and smaller conductor size reduce the AC resistance at high frequencies. Choosing the correct winding method and conductor(s) is paramount in designing a high-current, high-frequency inductor that operates as intended.

Packaging

An inductor's packaging is not the material in which it is shipped but rather the material in which it is sealed. Packaging can be categorized as open, no packaging, molded, or metal-encased.

Open coils are generally comprised of the winding, core, and plastic-insulated termination leads. Open coils derive most of their protection from their impregnation. They can also be sealed with plastic, but this is for mechanical protection against scraping or breakage as opposed to environmental protection.

For an inductor to be properly environmentally protected, it must be molded in such a way as to be fully encapsulated or hermetically sealed and possibly encased in a metal housing. Molded coils are fully encapsulated in a material such as thermoplastic, various thermoset compounds, or varnish. Metal-encased coils are the most secure and can most easily have electrostatic and magnetic shielding added.

INTRODUCTION TO POWER INDUCTORS

Power inductors are incredibly important magnetic components, found in everything from household appliances to the national power grid — any application that requires control of current.

Generally speaking, power inductors are characterized by three primary characteristics: high level of induction, significant energy storage and sizes larger than other varieties of inductors. (Note: the CMT photo above does not meet this characterization!)

Inductors can be called by different names, especially depending on their application: inductors, reactors or chokes. They all are inductors, but if they are used to provide reactive impedance then they are often referred to as reactors. If they are used to filter out some frequencies then they are often called chokes (as they “choke out” those frequencies).

All inductors store energy. It is this storage of energy that allow an inductor to smooth the current flowing through them, taking a bit of energy from the highest points of current, releasing this energy into the lowest points. This reduces the difference between the peaks and valleys, (otherwise known as "ripple current") and smooths the flow of current in the circuit.

Common applications for power inductors are filter reactors for both input and smoothing rectifier circuits, charging inductors in pulse networks, interference reduction filters for applications such as power lines of mobile equipment, and saturable reactors in certain types of control circuits.

Basics of Power Inductors

Though all of these applications are common for power inductors, by far the single most common power inductor application is as a power supply filter.

Considerations for power supply filters are generally very similar to those of other types of circuits. Considerations for power inductors to be used in power supply filter applications, however, are generally fewer in number and notably more straightforward.

Power supply filters, more commonly known as chokes, have simpler requirements in large part because their intended use limits them to operate at a single frequency — the AC power, or switching, frequency.

Inductors limit the rate of current change through them. In order to maintain current flow through one leg of a rectifier circuit at all times, it is important that the circuit’s choke has a sufficiently high level of inductance. Inductance, measured in Henrys, can be calculated using any number of formulas, depending on the power inductor and how it’s being used. Generally the power inductor’s inductance must be high enough to prevent current from decreasing to zero, at the circuits minimum load.

For power inductors designed for use in power supplies operating at a single DC output current level, inductance is very simple to calculate. In other supply applications, the load current can vary widely, making inductance calculation more difficult — different currents require different inductances. To counter this, power inductors known as swinging chokes can be used.

Swinging chokes — especially common in transmitter power supplies, which have widely varying output currents — have inductance values that decrease as the current running through their coil increases. A 5:1 inductance rating for a current increase of 10:1 is a typical scenario for swinging chokes — 25 Henrys of inductance at 20 milliamperes (mA) of current drops to 5 henrys at 200 mA. Swinging chokes essentially adjust their inductance according to current.

Electrical Characteristics

Power inductors usually have both a direct current in the winding and an AC voltage across the terminals. To estimate inductance in such an inductor, assuming an iron core and superimposed direct current, use the following equation:

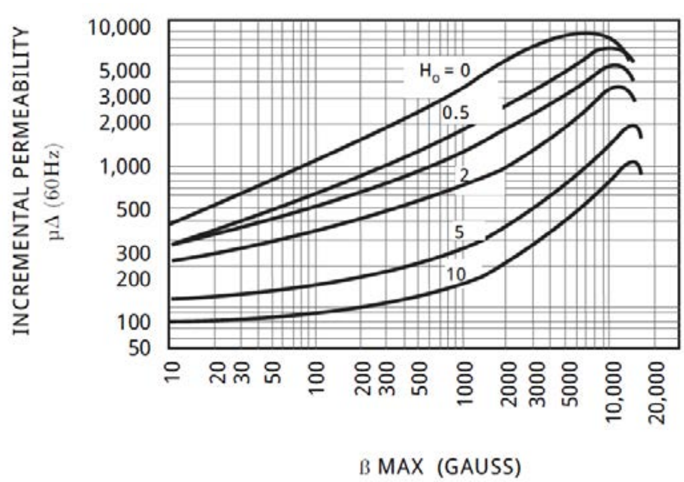
$$L = \frac{3.2\, N^2\, A_c \ \text{X}\ 10^{-8}}{l_g + (l_c /\ \mu\Lambda)}$$

Here, L is the effective inductance (in Henrys), N is the number of turns in the winding, Ac is the net cross-sectional area of the core (in square inches), Ig is the total length of the air gap (in inches), Ic is the mean magnetic path length of the core (in inches), and μΔ is the incremental permeability of the core material.

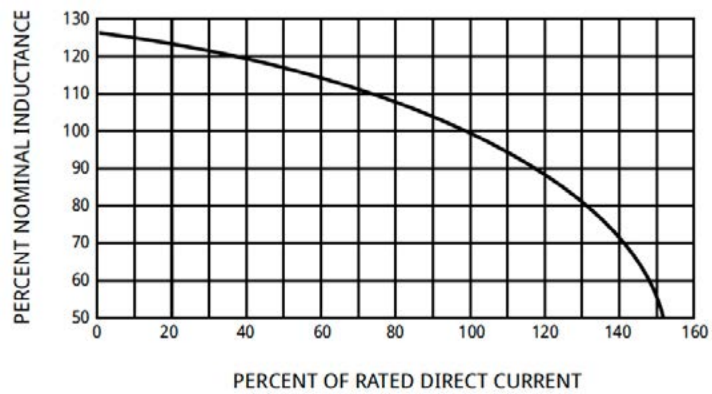
The numerator of this formula is fairly straightforward. The denominator, notably more complex, represents the effective magnetic path length — the total length of the air gap plus the core path length, divided by their respective permeability. A gap's permeability can be regarded as unity, making effective length the same as the length of the gap. The "effective" gap length may be substantially different than the physical gap length due to fringing flux in the gap area, especially as the gap grows large. Fringing flux can increase losses in the core and coil and usually should be minimized as much as possible.

Permeability

Reactors are often designed based in large part on the correct proportioning of the air gap and core path lengths. Incremental permeability, or effective permeability (permeability when an alternating magnetic force is superimposed on a direct magnetic force), is determined by: the characteristics of the material of the core; the DC magnetizing force the core produces; and the amount of AC flux in the core. Permeability data is best obtained direct from a core manufacturer, who should be able to provide charts plotting effective permeability against both DC magnetizing force and AC flux density, such as the one shown here.



In most core materials, as the DC magnetizing force in a core increases the effective permeability decreases; as effective permeability decreases, effective inductance of a choke is decreased. Air gaps in the core along the magnetic path stabilize the permeability of the core, minimizing, to an extent, the effects of DC current in the winding. Effects of DC current in a silicon steel core filter reactor are shown in this chart.



Other types of core materials can have much flatter, or much steeper curves.

Swinging chokes, also called non-linear inductors, are commonly used in applications that use a DC current from a power supply that must vary widely. They are designed explicitly for this reason: a change in DC current has a definite and clear effect on the choke's inductance.

AC and DC Flux

DC flux in a filter reactor is, under common conditions, much greater than AC flux. If AC is between 5 and 10 volts, a fairly standard level, AC flux density will be between 300 and 1000 gauss while DC flux density would be between 12,000 and 14,000 gauss.

If AC flux were increased high enough in a swinging choke, the total flux would match the core material's saturation level — this would result in low inductance, non-linearity, and poor filtering in power supply circuit scenarios. This impact on performance makes proper AC voltage specifications very important.

DC flux does not create any losses within the core; without a changing flux there can be no losses due to eddy currents or core hysteresis. However, the DC current that is creating the DC flux does create losses in the winding.

AC flux does create losses within the core; if the magnitude of the flux or frequency of the AC current is high enough then significant, even extreme losses can occur. The AC current within the windings can create high losses due to proximity effects; these effects can make the AC resistance of the coil appear to be many orders of magnitude higher than the measured DC resistance.

Testing

Chokes intended for use in circuits with very high AC voltages and DC current in the winding should be tested on an inductance bridge. This will help to determine whether a particular choke will function properly in the application. Set the AC voltage to the expected circuit voltage and increase the DC current while observing the inductance: if inductance remains linear until the rated DC current is reached, it will be suitable for use in that particular circuit; if inductance drops off prior to reaching the DC current, indicating core saturation, the choke will not work as expected in the circuit.

To maintain good regulation and low losses in a filter section, DC resistance in the inductor should be kept at the lowest possible value. Winding the inductor with the largest wire size allowed by the number of required turns and available space can help to ensure this. Because of this, required DC resistance is a primary factor in the ultimate size of an inductor — in order to maintain the correct DC resistance, an inductor may need to be increased in size to accommodate a larger winding wire.

Heat and Insulation

Dielectric strength does not directly indicate the maximum continual voltage that can be applied to an inductor, causing misunderstanding about insulation ratings. To ensure normal life expectancy, an inductor’s insulation should be rated for twice or more of the RMS working voltage, plus 1000 volts as a safety factor.

Losses in the core and coil of a power inductor lead to heat. Many power inductors operate at fairly low AC flux levels, meaning core losses are only a small part of total losses. Coil losses, caused by resistance in the winding wire, generate most of the heat. The large wire size used in power inductors to minimize DC resistance is designed to keep coil losses low enough not to cause excessive heating.

Construction

Power inductors can be constructed open style and varnish-impregnated (generally for commercial applications with little or no environmental requirements), or hermetically sealed (designed to withstand extreme temperature and environmental conditions). The basic coil and core construction is similar in all types.

Core Material

Power inductors generally require high induction levels, so materials should be chosen with that factor in mind. High permeability materials, which feature low saturation points, should generally be avoided. Silicon steel, for example, is a steel alloy containing between 3-4% silicon with a high saturation point and moderate permeability — it is widely used as a power inductor core material for low frequency applications. Grain-oriented silicon steel can also help to achieve higher inductance levels, allowing it to be used to reduce the size and weight of a power inductor. Though more expensive than standard laminate cores, these size and weight reductions afforded by using grain-oriented silicon steel cores can help offset those costs.

Core Shape

C cores are another popular construction option. C cores are wrapped with a continuous strip of generally very thin material before being cut into two C-shaped halves. The thin material construction reduces core loses at high frequencies, and the cuts allow for gaps, if desired. Ferrite and powdered cores are available in a variety of shapes; these different shapes, and different core materials, can be used for specific applications to best solve the inductive requirements. These materials are generally much better suited for high frequency circuits.

Insulation

In order to achieve the proper dielectric strength when operating at maximum temperature, a power inductor must be insulated. The insulation material must be able to maintain its properties even after experiencing the physical stresses of winding and the thermal stresses of use. Commercial specifications organize insulation materials by maximum operating temperature. These are commonly grouped as 105˚C, 130˚C, 155˚C, 180˚C, 200˚C, 220˚C, and even higher continuous temperatures.

External Packaging

The type of external packaging the power inductor requires depends largely on the amount of protection the application dictates. Many applications, including commercial and industrial applications, do not require particular protection requirements, allowing for the use of open construction.

Other factors that determine the need for external packaging, as well as what type of packaging would best accommodate the inductor, include available space, heat dissipation requires, and cost. Open construction offers good heat dissipation but little environmental protection. Hermetically sealed inductors — inductors that are sealed in a metal casing that is then filled with an epoxy resin and sealed — are highly protected and typically more aesthetically pleasing, but have worse heat dissipation and higher costs.

Specifying Power Inductors

As a good starting point in specifying a custom power inductor, there are 10 factors to consider. Some of them are determined by the electrical requirements of the specific circuit in which it will be used, while others are determined by the overall anticipated use. The factors are:

1. Application and circuit — Charging inductors require circuit schematics, while filter inductors only need the type of circuit to be specified
2. Inductance and tolerance — Because of design complexity and number of variables, you should allow for 10% tolerance in inductance, as compared to 20% or more in off-the-shelf inductors
3. AC operating voltage and frequency
4. DC current, or range of DC current, required of the coil
5. DC resistance, if required, and tolerance
6. Dielectric strength and/or maximum working voltage
7. Case type
8. Terminals — Options include wire leads, turrets, lugs, etc.
9. Environmental requirements - ambient temperatures, humidity levels, altitude levels, etc.
10. Applicable military, commercial, and industrial specifications

Power Inductors compared with Common Mode Inductors

It is important to understand the difference in application and specification between power inductors and common mode inductors: Common Mode inductors are designed specially to create an inductive impedance to signals that are “common” to the current that supplies power to a circuit and that current’s return path.

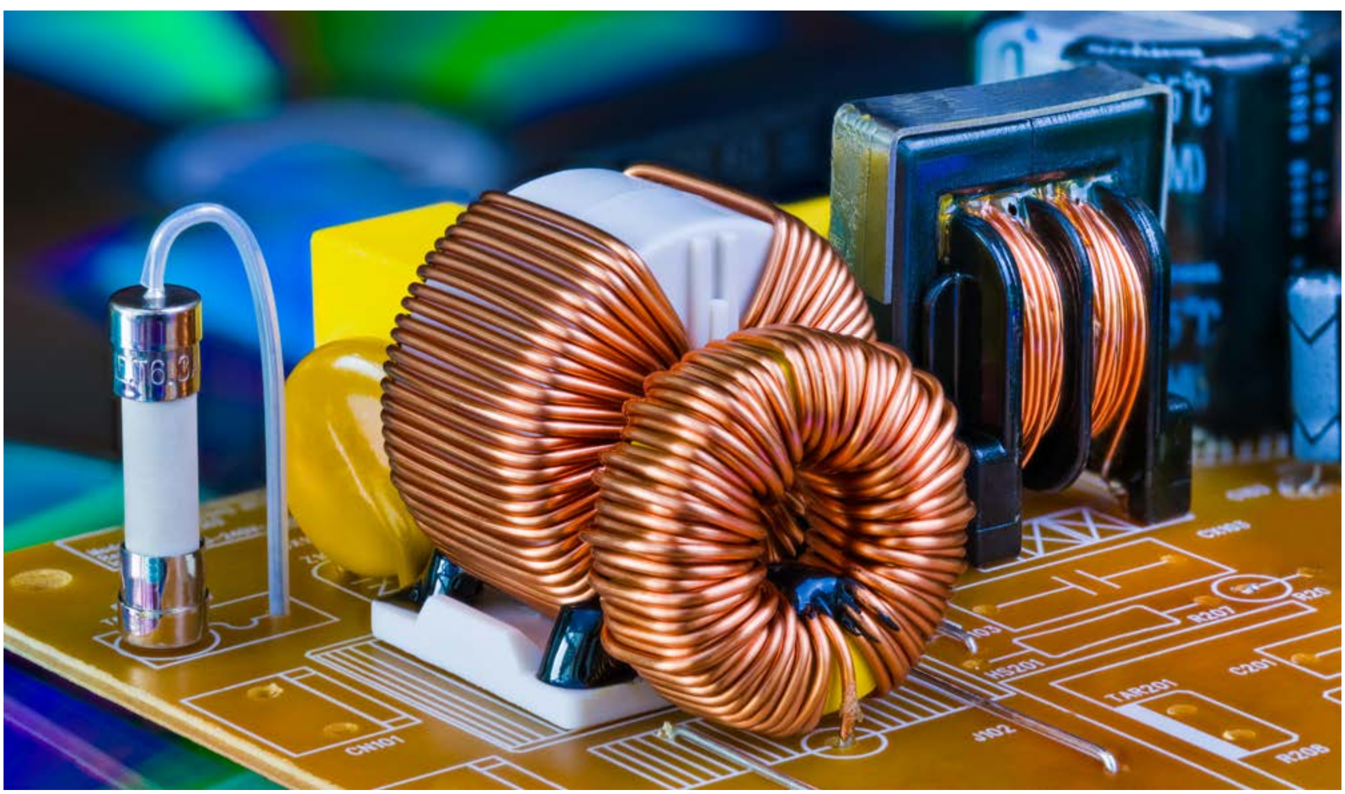
The smallest and most effective method to accomplish this is to design an inductor with two identical windings where the power current flows through one winding on its way to the circuit, and back through the other winding as it returns. No filtering of this "differential" current is required so the windings are phased so these two identical and opposite currents cancel each other. This phasing configuration allows the common mode signals to see a quite significant impedance for such a physically small unit.

Specifications for common mode inductors state the inductance that applies to the common mode signals, and the rated current for the differential power current that may be many amps – it is important to understand that a common mode signal is usually very small, so the actual stored energy within a common mode inductor is very tiny compared to the energy storage that the common mode inductance and the differential mode currents together would imply. The rated inductance and the rated current should NOT be considered together. Common mode inductors should not be used for any other type of filtering without complete understanding of the application.

Power Inductors from Triad Magnetics

As with any magnetic component, power inductors can quickly become a very complex part to specify or design. To determine which options will best suit your needs, you must consider factors such as available space, required mounting, terminations, cost, and environmental concerns such as shielding.

Triad Magnetics is a leading magnetics manufacturer with more than 75 years of experience designing and manufacturing high-quality magnetics components, including inductors. To learn more about inductors or request assistance in specifying one for your next project, visit **TriadMagnetics.com** today.



ABOUT TRIAD MAGNETICS

EXPERIENCE

With more than 500 transformer manufacturers in the world, we realize you have a choice. Why choose Triad Magnetics? Having served the needs of our industry for more than 75 years, we believe our experience makes the difference. If there is one point our experience has taught us, it is that we must remain flexible and adaptable to the changing needs of the market.

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