Inductors

Purpose of this content

- This series of content is aimed at supporting engineers to gain a solid foundational knowledge on electrical and electronic components.
- Every Electrical and electronics product development starts with components. The components can be
  - **Passives :** Resistors, Inductors, Capacitors
  - **Semiconductor Discrete devices :** Various types of Diodes, Transistors, FET/MOSFETs, IGBT, Thyristors etc.,
  - **Semiconductor ICs (Actives) :** Analog, Power management, Interface ICs, MCUs, MPU, FPGAs, Sensors etc.,
- So, the first step is to get a deep knowledge on components.
  - Kowing various components available, their specifications and characteristics.
- Next step is designing circuits using components.
  - For creating and simulating the behavior of your circuits before you go for the final board design, there are few free and many paid software tools available. Getting familiar with these tools is essential optimize the development time.
  - https://www.analog.com/en/resources/design-tools-and-calculators/ltspice-simulator.html
  - https://www.ti.com/tool/PSPICE-FOR-TI

Audiences for this content

To whom this content can be useful?

- Undergraduate Engineering students from E&E, ECE, Instrumentation, Mechatronics, Computer Science or students
- Postgraduate engineering students who wants to focus on electrical, electronics products design.
- Students who are in Arts college / Diploma studying electrical, electronics subjects
- Professionals who are starting their career in embedded electronics, hardware design and system design.

Details on content creator & Request to the learner

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Because when different users visits the weblink, that will give us an idea on the number of users consuming this content and that may encourage us to continue spend time to create more such useful content and maintain this website.

Note: This content uses references to some of the great materials out there on the internet from several component manufacturers and other websites etc., We humbly recognize and thank all of those efforts which brings clarity to engineers and help making the product development great.

In case if you are an owner of such content and for some reasons you do not want the references to be a part of these slides, please feel free to write an e-mail to us to remove those references: e-mail: seekerssignpost@gmail.com

Please send us your comments, feedback, content requirement.

Why is it essential to learn in depth about Inductors?

Inductors are fundamental components in electrical and electronic systems, critical for understanding and designing circuits.

- **Energy Storage and Transfer:** Inductors store energy in a magnetic field, enabling functions like filtering, oscillation, and power conversion in circuits (e.g., transformers, DC-DC converters).
- **Circuit Behavior:** Inductors influence how circuits respond to changes in current, impacting transient responses and frequency-dependent behavior in applications like signal processing and RF systems.
- **Power Electronics:** In switching regulators and inverters, inductors smooth current and improve efficiency, critical for modern power supplies in devices like laptops and EVs.
- **Electromagnetic Compatibility:** Understanding inductors helps engineers mitigate electromagnetic interference (EMI), ensuring devices meet regulatory standards.
- **Circuit Design and Analysis:** Mastery of inductors enables engineers to analyze and design complex circuits, including those with resonance, impedance matching, or energy storage requirements.

Content List

- Inductance, stored energy, counter emf
- Series, parallel connection
- Inductors, categorization
- Waveform in RL circuits
- Equivalent circuit
- Specifications
- Decoupling circuits
- LC resonance and damping
- Ferrite Beads, DC Bias considerations
- Common mode choke and filter
- Twisted pair wire
- Differential filter

Simple formulas to start with

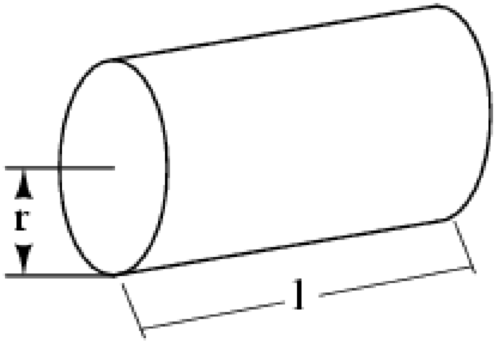
Formula Description	Resistor	Inductor	Capacitor
Defining Equation	$R = \frac{V}{I}$ (Ohm's Law)	$L = \frac{V}{\frac{di}{dt}}$	$C = \frac{Q}{V}$
Physical Property Formula	$R = \rho \frac{l}{A}$	$L = \frac{\mu N^2 A}{l}$ (solenoid)	$C = \epsilon \frac{A}{d}$
Series Connection	$R_{total} = R_1 + R_2 + R_3 + \ldots$	$L_{total} = L_1 + L_2 + L_3 + \ldots$	$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots$
Parallel Connection	$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$	$\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots$	$C_{total} = C_1 + C_2 + C_3 + \ldots$
Energy Stored	Not typically stored (dissipated as heat)	$E = \frac{1}{2} L I^2$	$E = \frac{1}{2} C V^2$
AC Reactance	None (constant resistance)	$X_L = 2\pi f L$	$X_C = \frac{1}{2\pi f C}$
Power Dissipation (DC)	$P = I^2 R$ or $P = \frac{V^2}{R}$	None (no power dissipation in ideal case)	None (no power dissipation in ideal case)
Time Constant	Involved in RC and RL circuits	$\tau = \frac{L}{R}$ (in RL circuit)	$\tau = RC$ (in RC circuit)

- "ρ = resistivity, μ = permeability, ϵ = permittivity"
- Units: Time constant (τ) is in seconds (s), with R in Ohms (Ω), C in Farads (F), and L in Henries (H).
- Time Constant For Capacitor: τ=RC is the time constant in an RC circuit, representing the time it takes for the capacitor to charge to ~63% of its final voltage (or discharge to ~37%).
- For Inductor: τ=L/R is the time constant in an RL circuit, indicating the time for the current to reach ~63% of its final value (or decay to ~37%).

Self Inductance of a Coil

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

$$\mu = \mu_r \mu_0$$



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 = 1.26×10^{-6} T-m/At permeability of free space

A = Area of coil in square meters = πr^2

l = Average length of coil in meters

Core Material	Notation	Permeability
Iron	μ_r FE$_{BASED}$	50 to 150
Nickel-zinc	μ_r NiZn	40 to 1,500
Manganese-zinc	μ_r MnZn	300 to 20,000

A coil of wire where air acts as the core, has the least inductance. Magnetic materials have higher μ_r and hence offer higher inductance for same number of turns.

Faraday’s Law for Inductors

Core Concept

- **Faraday’s Law of Induction**:

$$V = -\frac{d\Phi_B}{dt}$$

Voltage (V) induced in a coil is proportional to the rate of change of magnetic flux (Φ_B).

Application to Inductors

- **Inductor Voltage**:

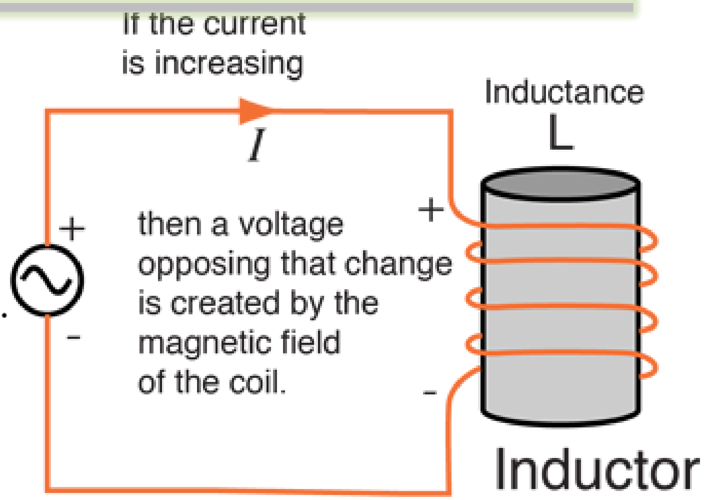
$$V_L = -L\frac{di}{dt}$$

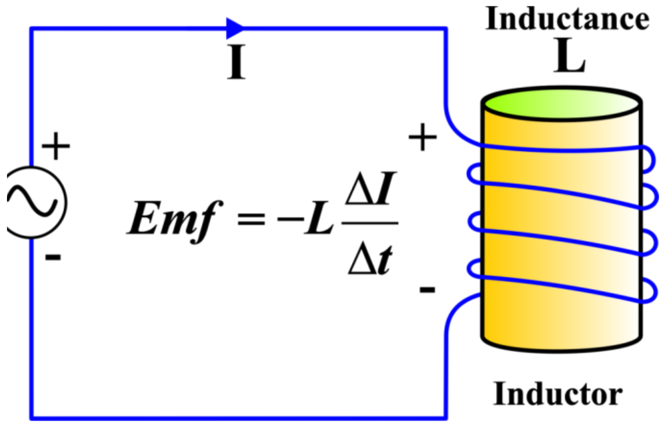
Where:

  - V_L = voltage across the inductor (V)
  - L = inductance (H)
  - $\frac{di}{dt}$ = rate of change of current (A/s)

Key Points

- **Energy Storage**: Inductors store energy in a magnetic field when current changes.
- **Opposition to Change**: Inductors resist sudden current variations (basis of $\tau = \frac{L}{R}$).
- **Discovered**: Michael Faraday, 1831 – foundational to inductor behavior in circuits.



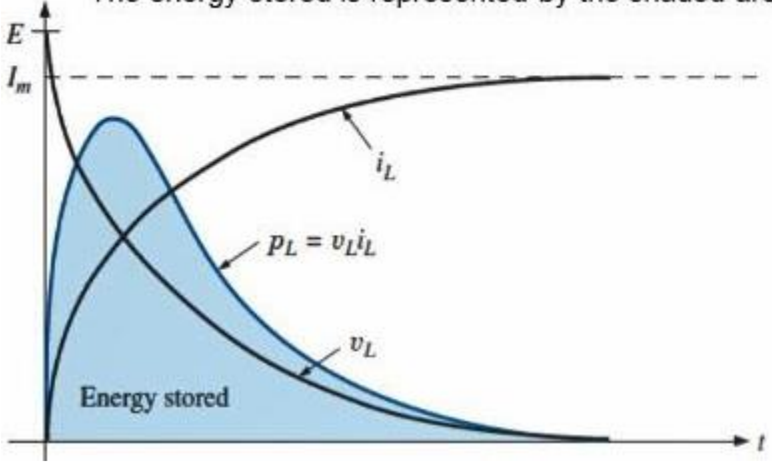


Stored energy, Counter emf

Inductor stores the energy in the electric field.

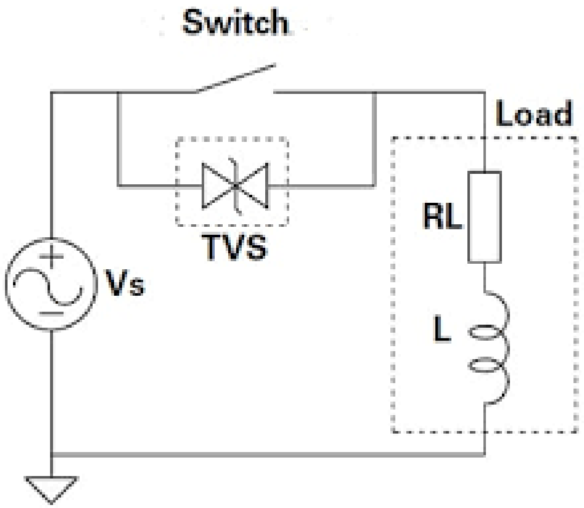
$$W_{stored} = \frac{1}{2} L I_m^2 \qquad \text{(joules, J)}$$

The energy stored is represented by the shaded area under the power curve.



When the current through inductor is interrupted using a relay, the Inductor cannot allow the current to become zero immediately.

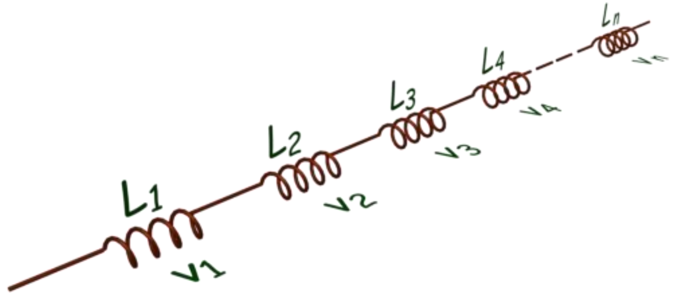
Hence it generates a high voltage counter-emf in order to let the current continue which causes ionization of air between the relay contacts and causes current to continue flow. As the counter emf decays, after a time delay (L/R time constant), the current stops / arc extinguishes.



Series and parallel connection of L

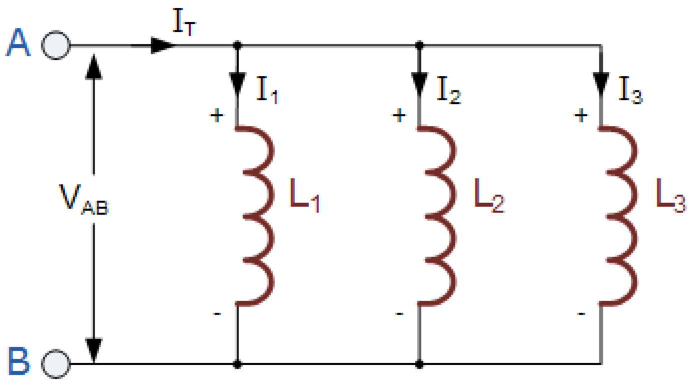
- The equivalent inductance of series connected inductors is the sum of the individual inductances:

$$L_{eq} = L_1 + L_2 + L_3 \ldots\ldots + L_n$$



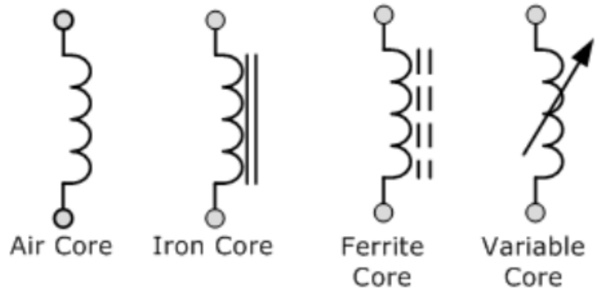
- The equivalent inductance of parallel connected inductors is the reciprocal of the sum of the reciprocals of the individual inductors:

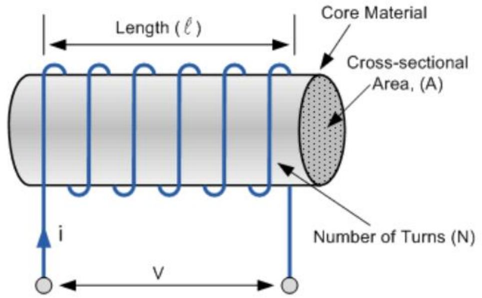
$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \frac{1}{L_n}$$



Inductors

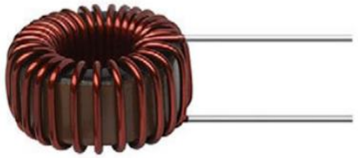
- Inductors are essential passive components in electronics, widely used in filters, transformers, and energy storage applications.
- What's unique about Inductors unlike resistors, it doesn't dissipate energy as heat to control current, rather it is an "Energy storage Element".





Shielded and Unshielded Inductors

Shielded Inductors



A toroidal configuration keeps most of the magnetic flux inside the core

Unshielded Inductors

Fig. 3 - Examples of unshielded power inductors

Unshielded power inductors have an open magnetic circuit where the magnetic flux induced in the core by the current in the winding exits the core and extends through the air to the other side of the core where it completes the flux path. A solenoid inductor is an unshielded inductor.

A shielded inductor is designed so that the magnetic flux never leaves the core, preventing flux from interfering with sensitive components that may be nearby. An example of a shielded inductor is a toroid.

Courtesy: https://www.vishay.com/docs/34450/powind101.pdf

Choice of Shielded Vs Unshielded Inductors

When to Choose Unshielded Inductors:

Low-frequency applications: When EMI is not a critical concern.

Cost-sensitive applications: If cost is a primary consideration as they are cheaper

Applications where size is not a constraint: As they are small it is easierto integrate into larger designs.

When to Choose Shielded Inductors:

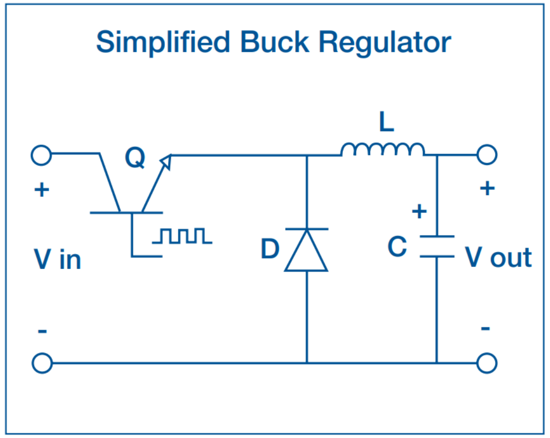
High-frequency applications: Shielding is crucial in high-frequency applications to prevent interference.

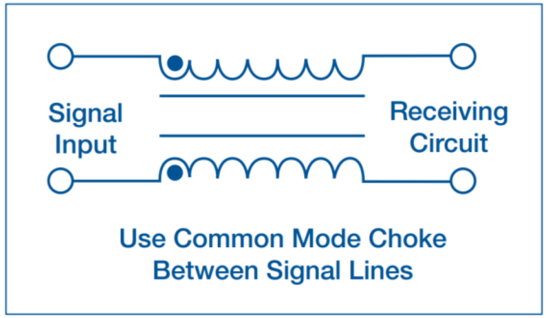
EMI-sensitive environments: When electromagnetic compatibility is a critical requirement.

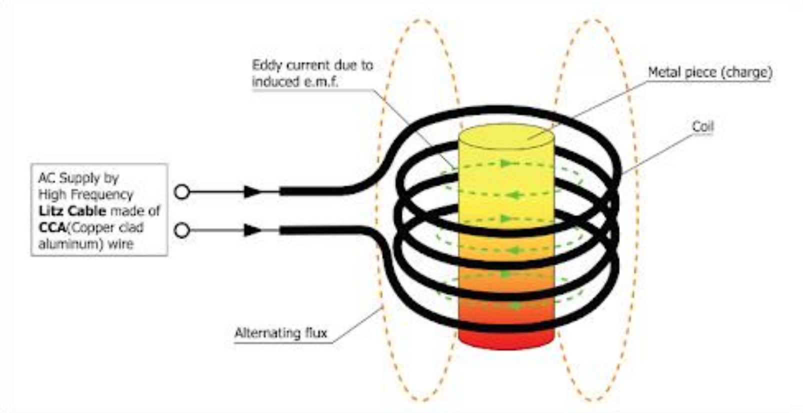
Regulatory compliance: If the application needs to meet specific EMI regulations.

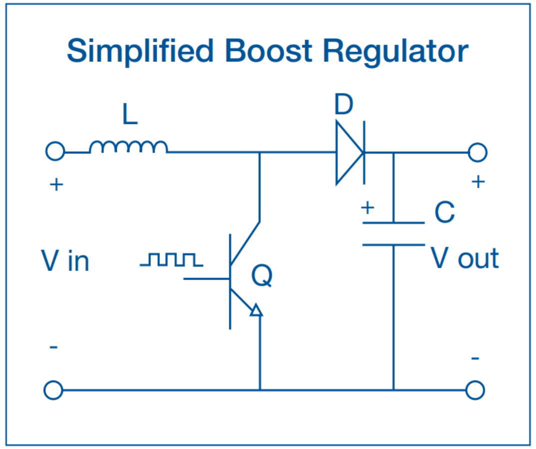
Courtesy: https://www.vishay.com/docs/34450/powind101.pdf

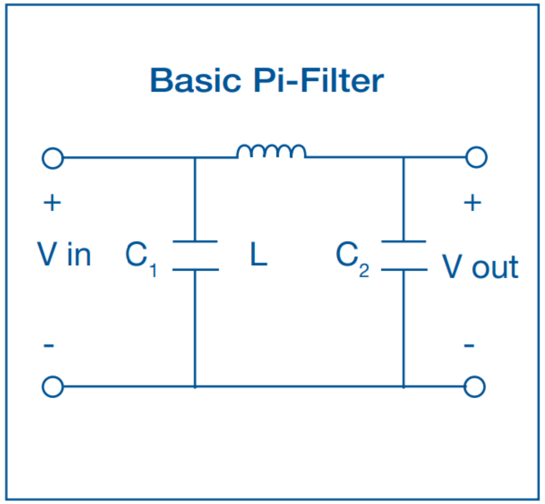
Applications for Inductors

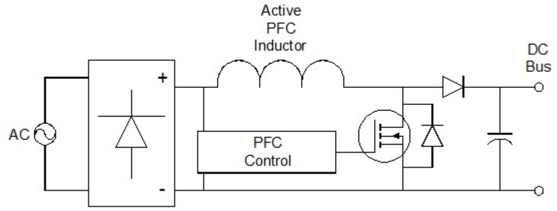










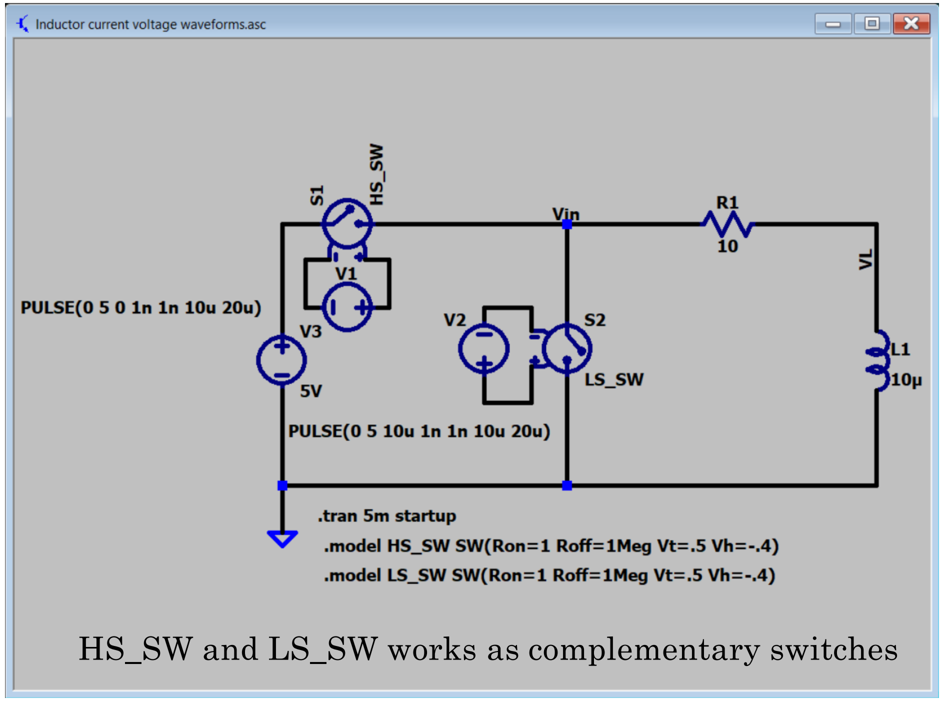


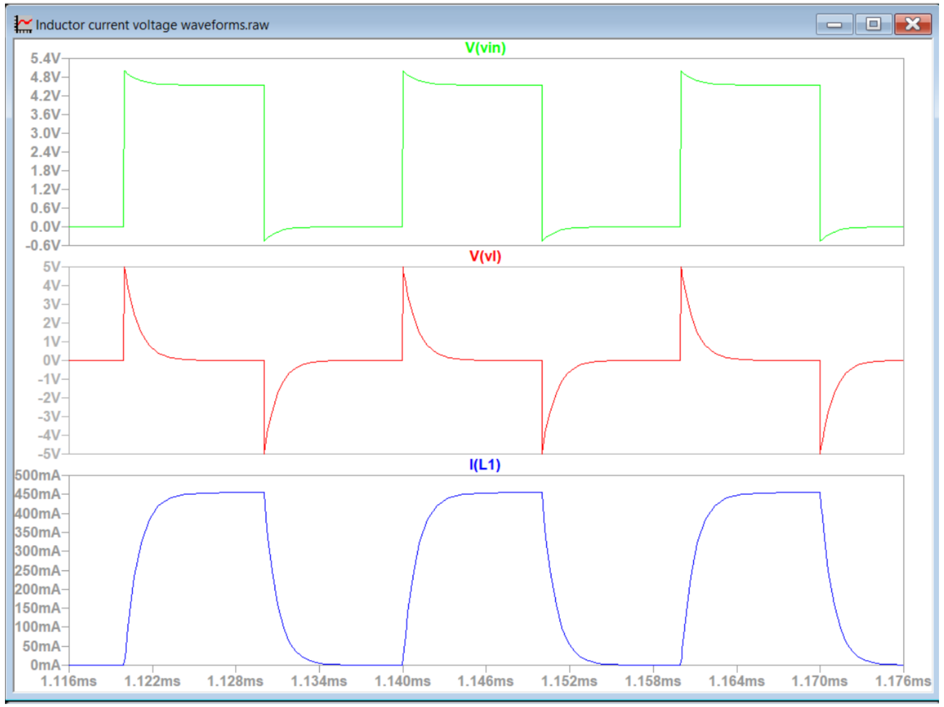
As a filtering element in DC-DC Converters

For mitigating EMI in Power converters

Courtesy: https://www.vishay.com/docs/34450/powind101.pdf

Behavior of an inductor (in switched circuits)



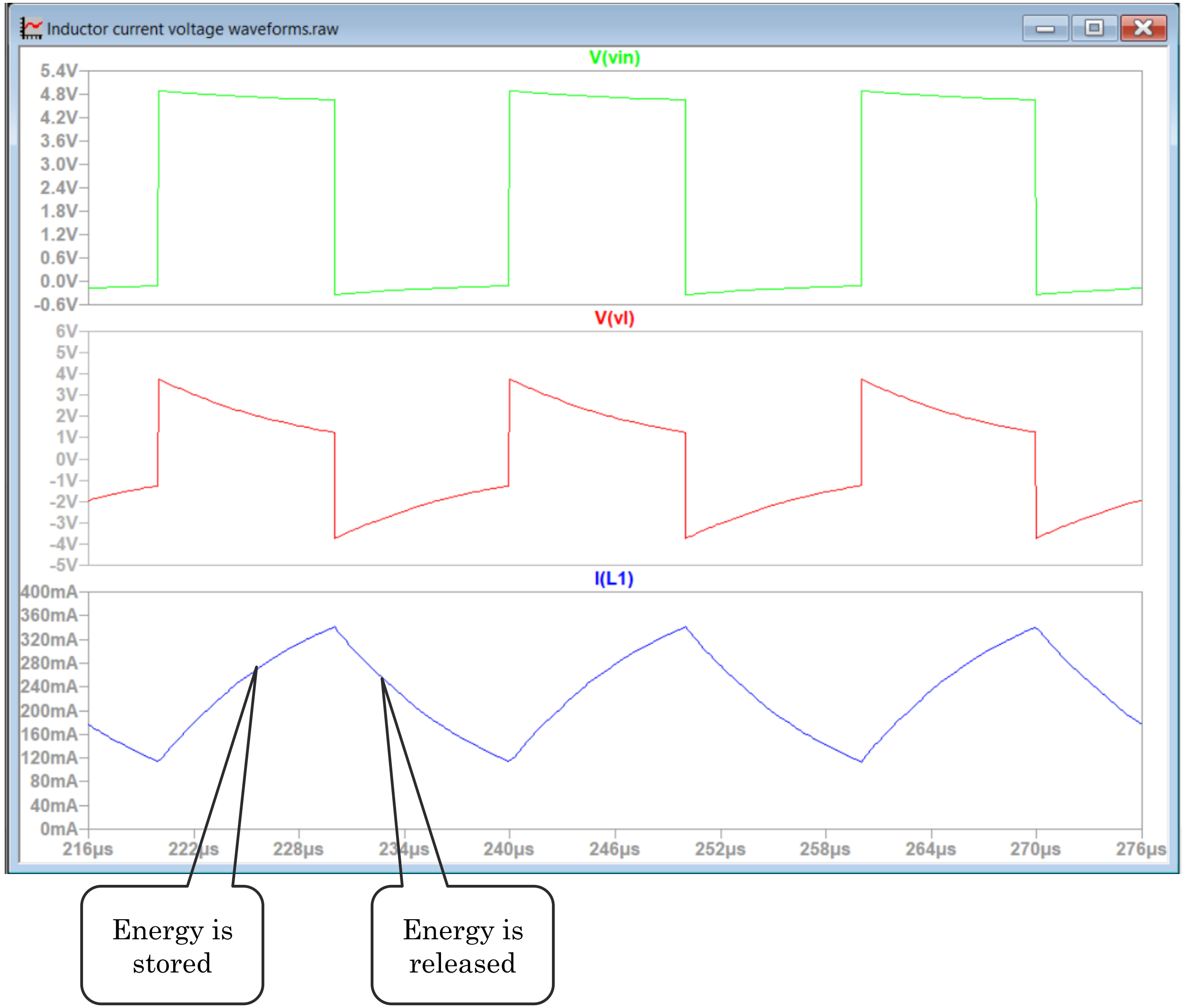


Inductor resists any sudden change in current through it by the generation of counter emf.

When the current tries to rise fast, the counter emf polarity opposes it, thus restricting the rise. When current tries to become zero fast, the counter emf changes direction to let the current continue by releasing the stored energy in it’s magnetic field.

For DC, it acts like a short circuit.

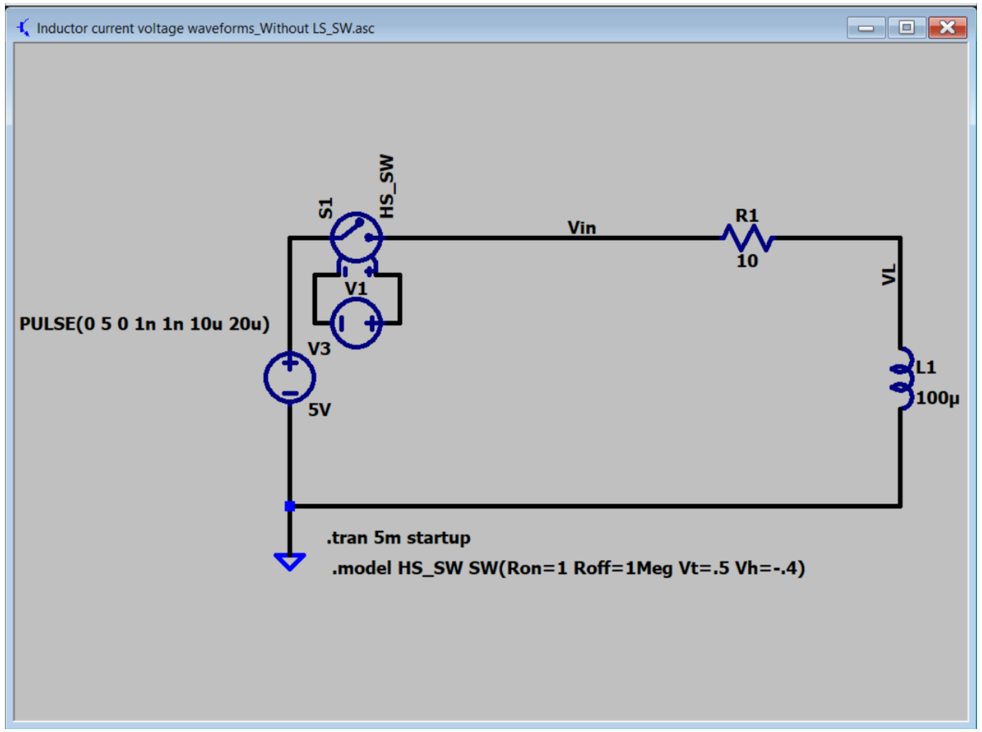
Higher value of L in the RL series circuit

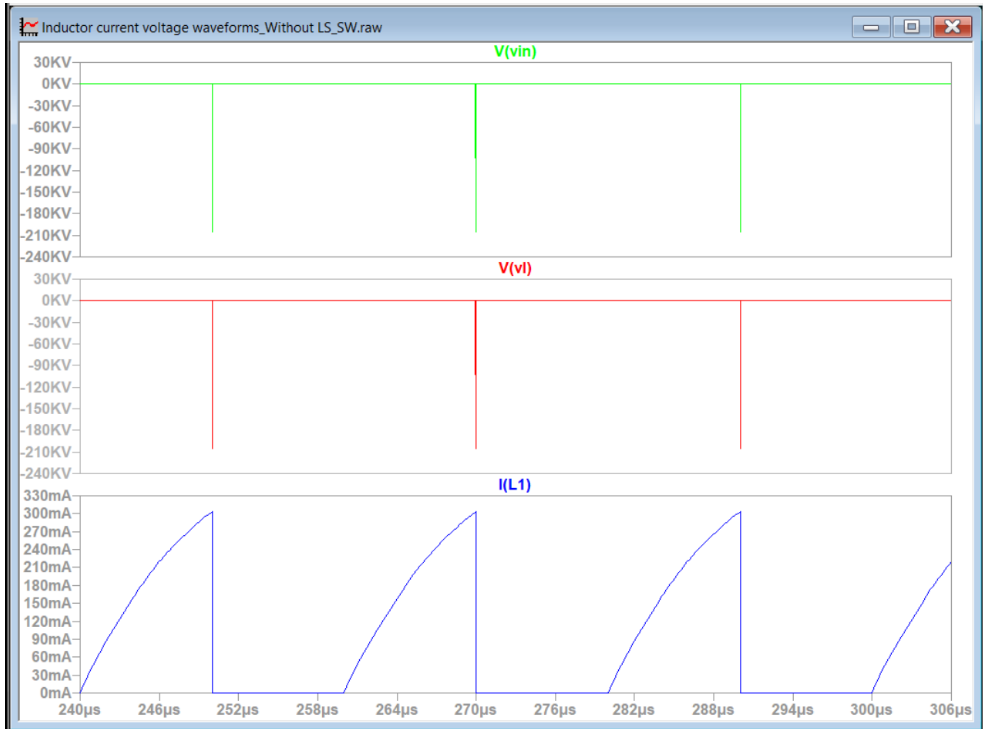


When inductor value is increased from 10uH to 100uH, the RL time constant increases and hence the inductor current waveform doesn't become zero in between the cycles.

(Increasing the switching frequency to 10x has the same effect)

What if the low side switch is removed?

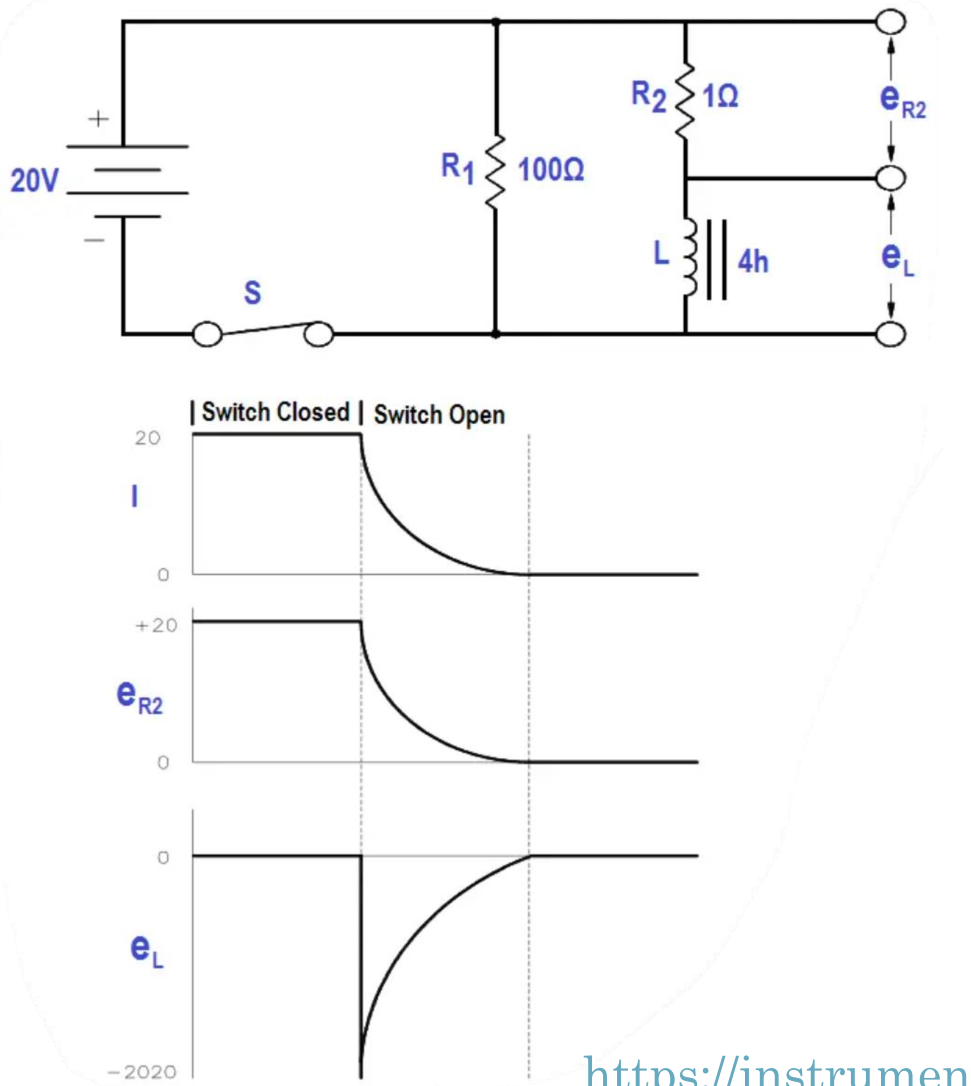




When the high side switch is closed the current rises (as per RL time constant) and then when the switch opened, as inductor cannot let the current become zero immediately, it creates a huge counter emf (100's to 1000's of volts).

Assuming the high side switch is a mechanical switch, the counter emf will increase to a level where it can ionize the airgap and let the current continue to flow in the form of an electric arc, until the stored energy in the magnetic field dissipates.

How much is the counter emf magnitude?



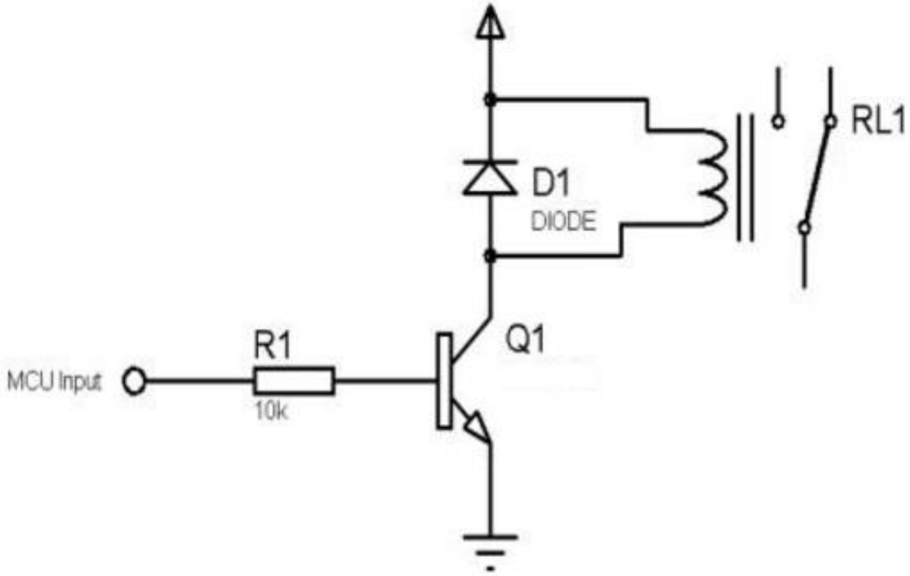
When the switch is in closed position, a current of 20 v/1Ω = 20 amps flows through the inductor. *(In DC circuits, Inductor offers reactance only when the current is trying to rise or fall. Once the current settles, the inductor acts as a short)*

When we open the switch, as there is no source voltage connected now, if there was only R2, current would have become zero. However, as there is "L", it will try resist the change in current, meaning it will try to maintain the 20A. So, in order to do that, the self-induced voltage in the inductor must be enough to push 20 amps through the 101Ω of resistance. The CEMF =R*I = (R2+R1)* I = 101*20 = **2020 volts.**

With the switch open, the circuit looks like a series RL circuit without a battery. The CEMF induced falls off, as does the current, with a time constant of T_L = L/(R1+R2)=4H/101 Ω = **0.039 sec**.

https://instrumentationtools.com/inductive-time-constant/

Relay coil application example



The relay coil can be a considered as an inductor (~500uH).

When the transistor is turned ON, there will be a current through relay coil (depends on winding resistance value)

When the transistor is switched off, without the counter emf circulating diode, the counter emf generated by the coil gets added to the supply voltage and appears at the collector of transistor. The high magnitude of counter emf, may violate the Vcc max of the transistor and causes failure.

The Diode D1 allows the counter emf to circulate through it and the stored energy in the coil gets dissipated in the coil resistance and diode's forward resistance, protecting the transistor.

DC switching of Inductive load

Fig. 2 Reverse voltage waveform when there is no diode

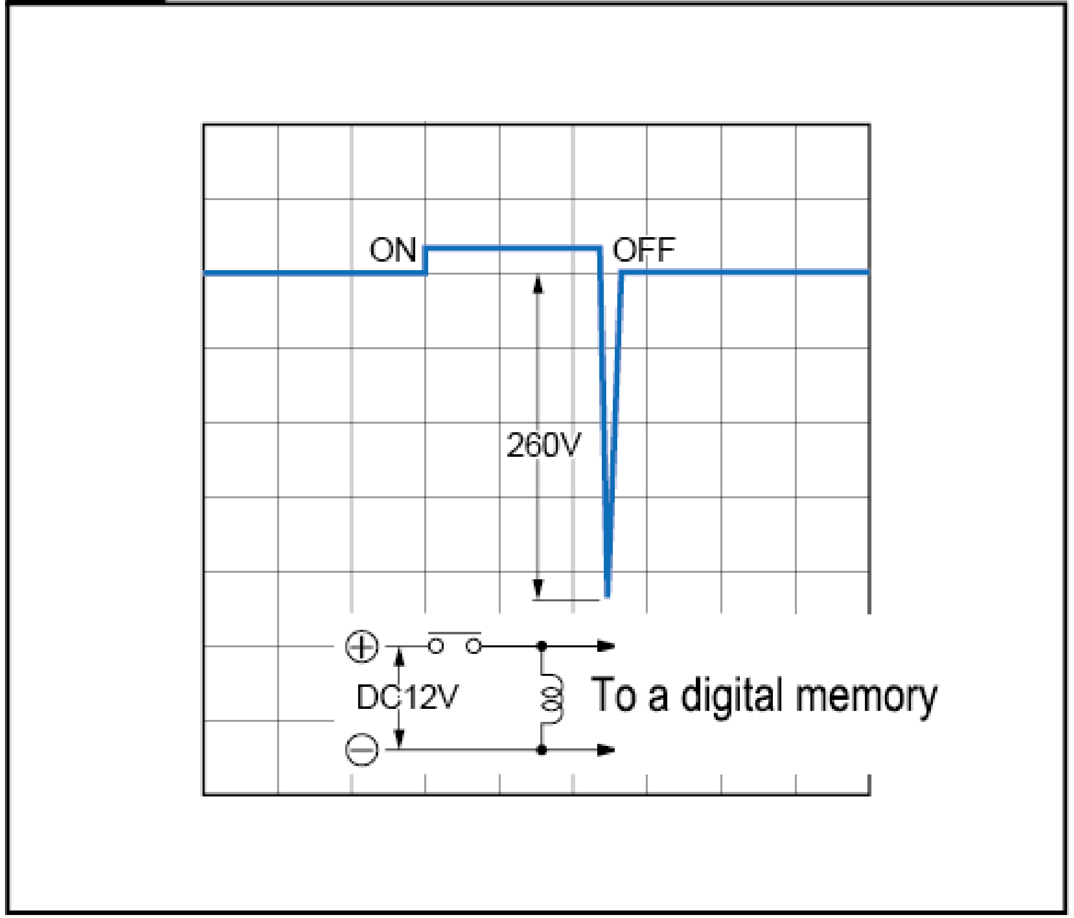


Fig. 1 Protective circuit for a DC inductive load

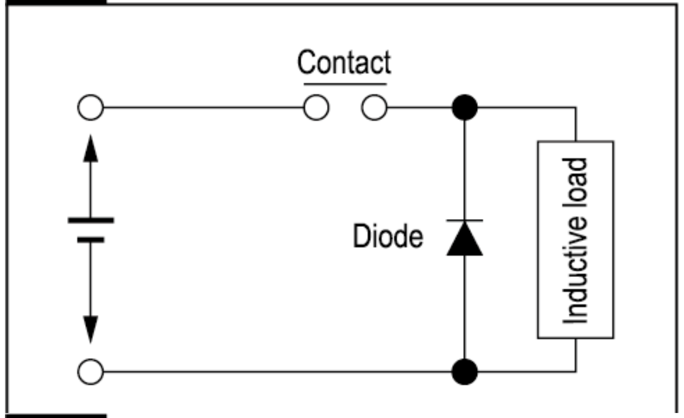
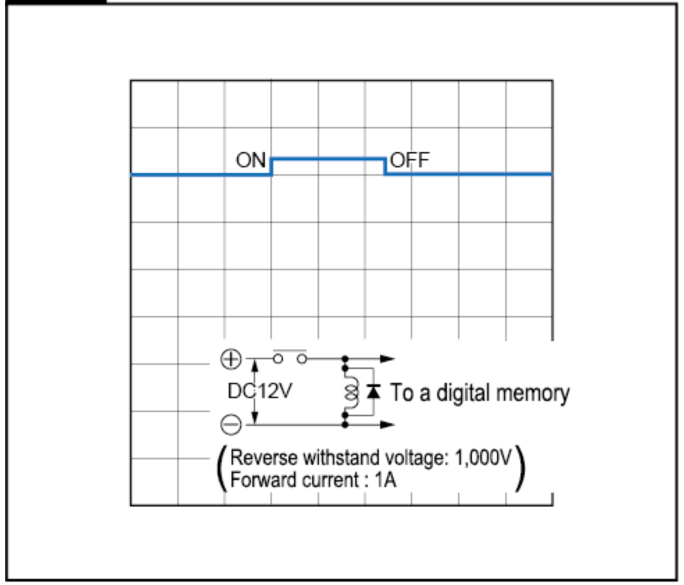


Fig. 3 Reverse voltage waveform in the case when there is a diode



Courtesy: https://ac-blog.panasonic.com/relay/protecting-a-relay-coil-from-a-surge

AC switching

Fig. 4 Protective circuit for an AC inductive load

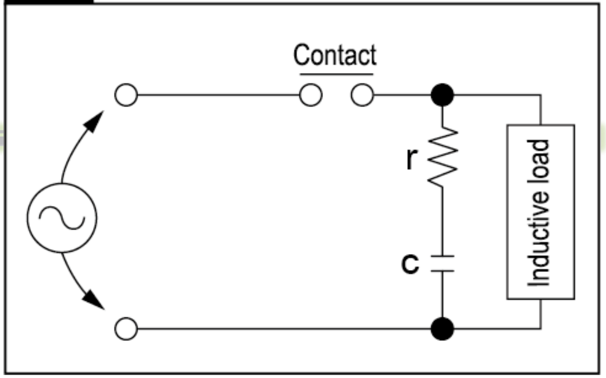


Fig. 5 Reverse voltage waveform in the case when there is a CR protective circuit

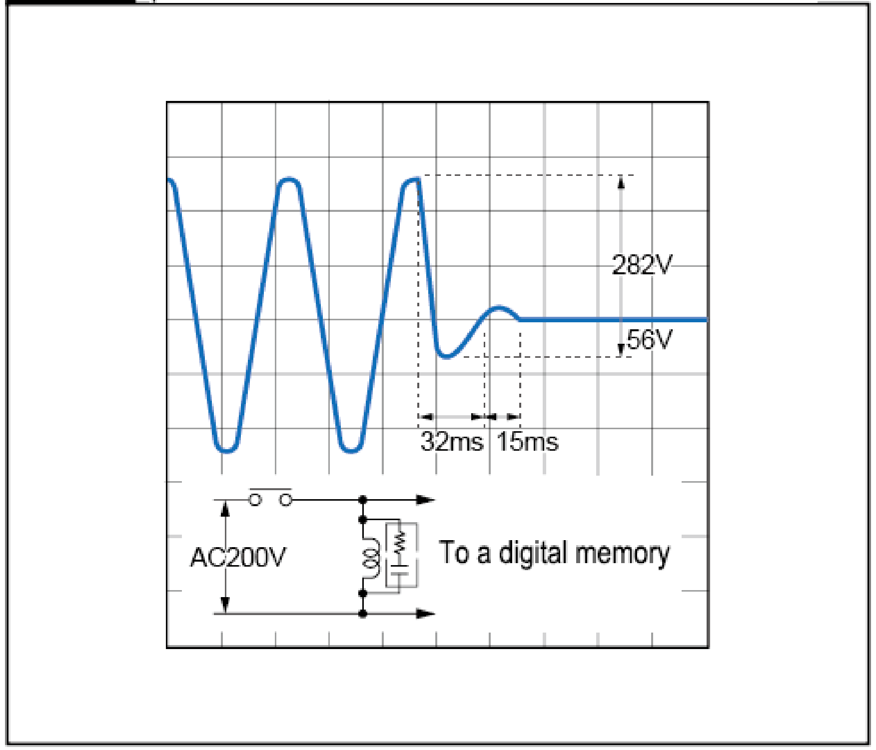
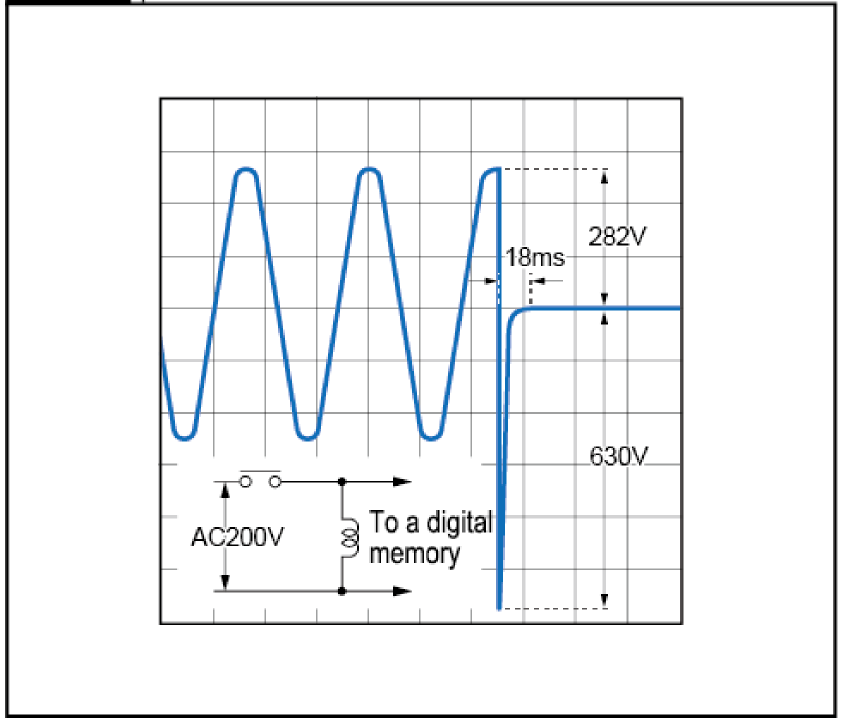
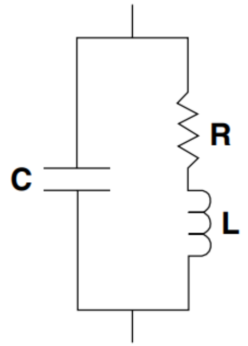


Fig. 6 Reverse voltage waveform in the case when there is no CR protective circuit



Courtesy: https://ac-blog.panasonic.com/relay/protecting-a-relay-coil-from-a-surge

Equivalent circuit of an Inductor



- When many turns of wire are placed close together in a coil, there is an inter winding capacitance (CW)
- CW has significant impact at high frequencies.
- The small inherent wire resistance is called the dc resistance or the winding resistance (RW)
- It is usually ignored in low current circuits. But in case of high current circuits, I2R losses becomes a significant contributor of the losses and hence the temperature rise in Inductors.

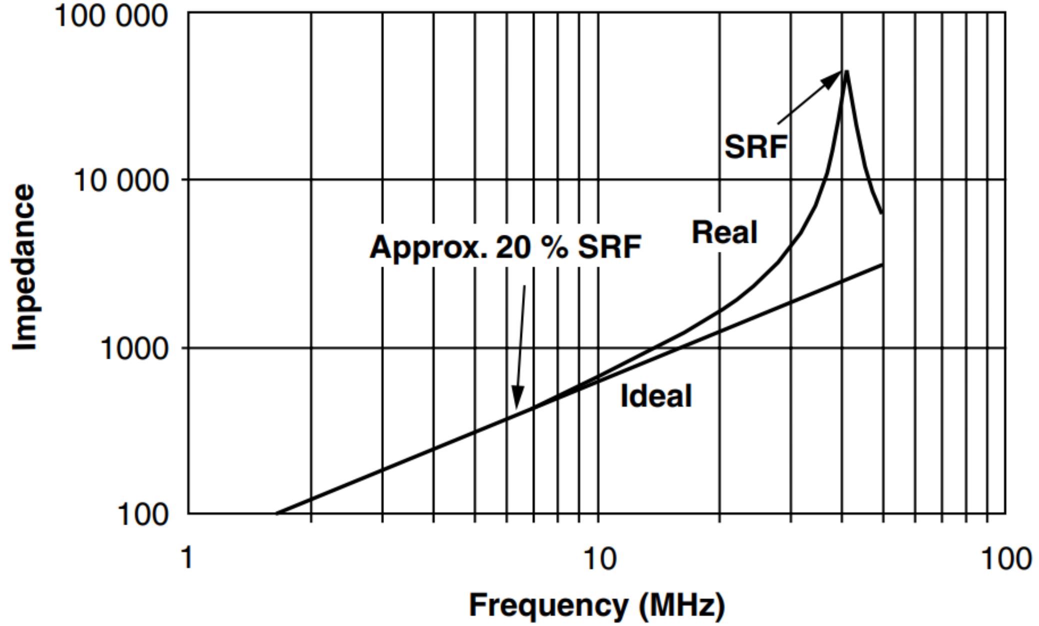


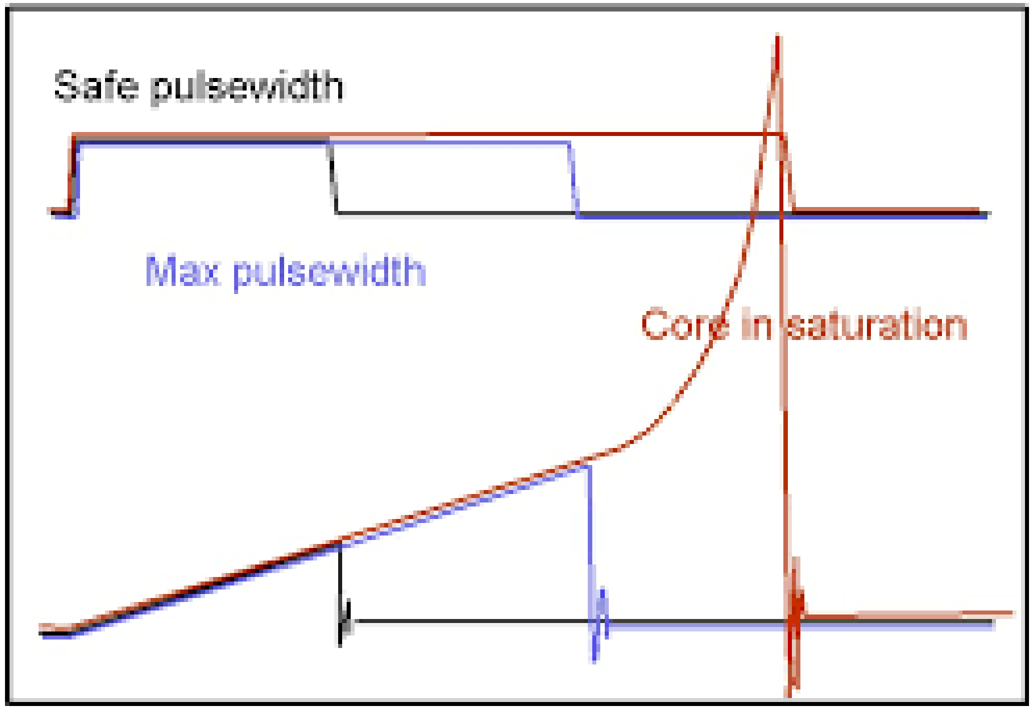
Figure 2. Impedance/Frequency Curves of Real and Ideal 10 μH Inductor

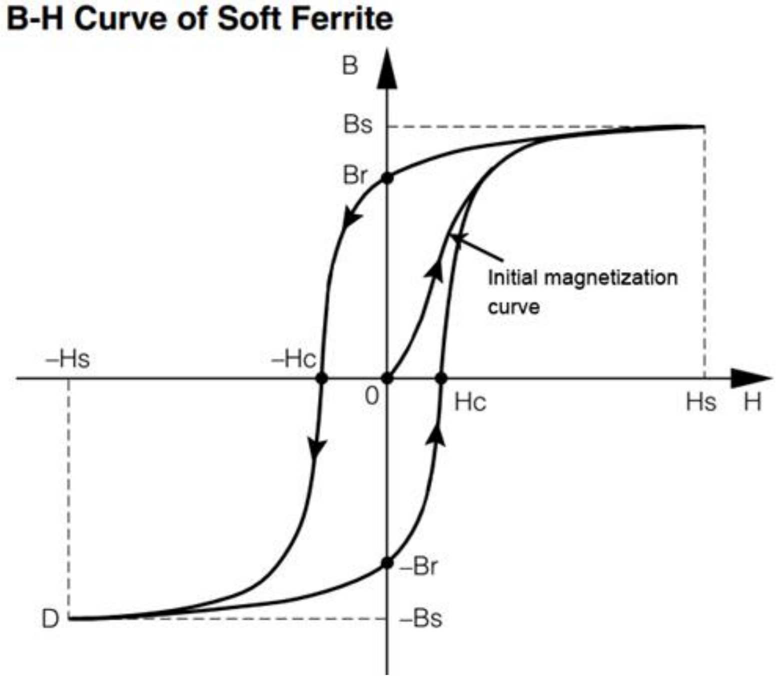
https://www.vishay.com/docs/34098/engnote.pdf

Specifications of an Inductor

- Inductance (L)
  - Measured in Henries (H).
  - Determines energy storage.
- Current Rating (I)
  - Maximum continuous current (A) before overheating.
  - Performance Rated Current (IRP), may also be included on the datasheet. (increasing the PCB area and thickness increases heat dissipation, leading to higher rated current values)
- Saturation Current (I_sat)
  - Current (A) at which the core saturates.
  - Beyond this, inductance drops significantly.
  - Common specified inductance drop percentages include 10 % and 20 %. It is useful to use the 10 % inductance drop value for ferrite cores and 20 % for powdered iron cores in energy storage applications.
- DC Resistance (DCR)
  - Resistance of the coil wire (Ω).
  - Affects power loss ($P = I^2 * DCR$).
- Quality Factor (Q)
  - Ratio of reactance to resistance ($Q = XL / R$).
  - Higher Q = better efficiency in AC circuits.
- Self-Resonant Frequency (SRF)
  - Frequency (Hz) of resonance with parasitic capacitance.
  - Limits high-frequency performance.
- Core Material
  - Air, iron, ferrite, etc.
  - Impacts inductance, saturation, and frequency response.

Saturation current - 1





- Saturation current of an Inductor means, the current at which the core material (iron or ferrite) can no longer linearly increase the amount of magnetic flux with an incremental increase in current as, This is because, the core for it's given size, can store only a given amount of magnetic flux density. (Note: One can increase the saturation current level in a wound-core-inductor by adjusting the air ap in the core)
- Saturation current doesn't apply to air cored inductors.

Saturation current - 2

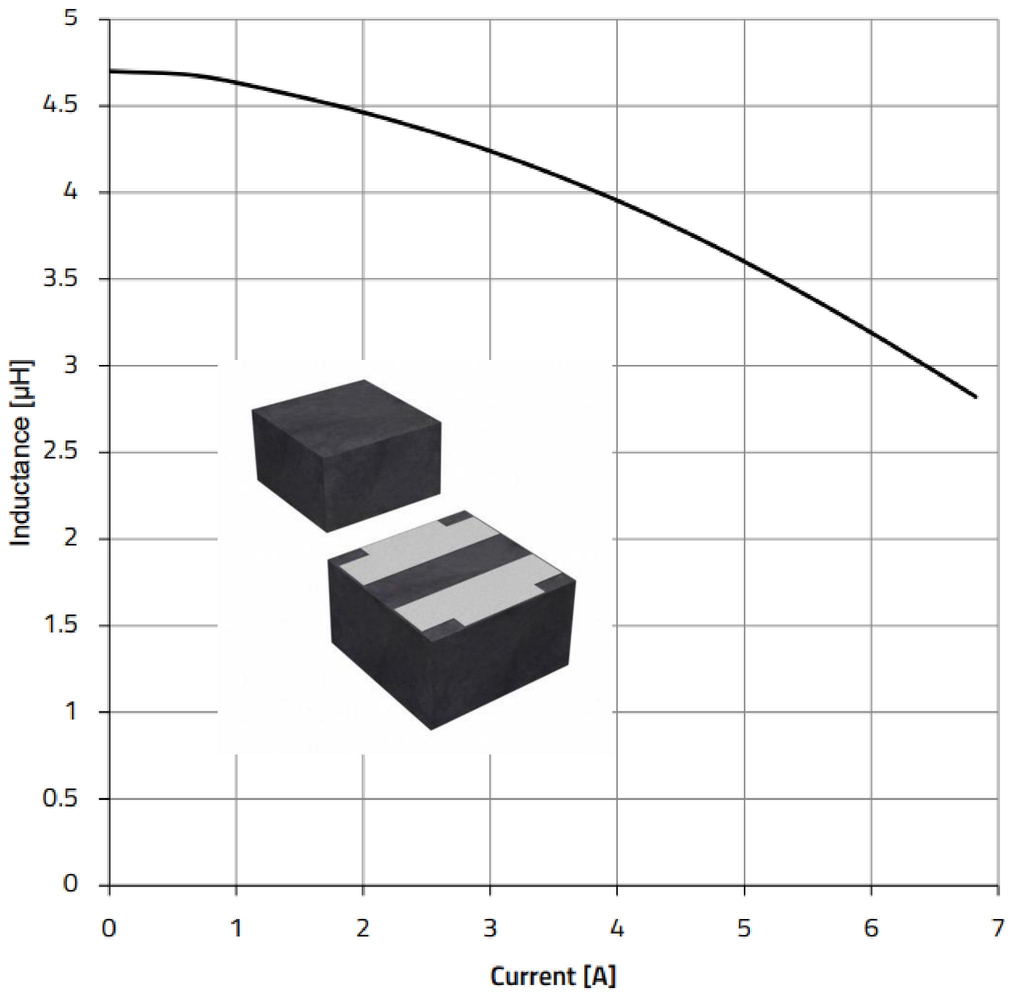
What It Is: $Isat$ is the DC current at which the inductance falls by a specified percentage (typically 10%, 20%, or 30%) from its nominal value due to core saturation.

Why It Matters: As current increases, the core's magnetic flux density (B) approaches its saturation limit ($Bsat$), reducing permeability (μ) and inductance ($L \propto \mu$). This affects circuit performance (e.g., increased ripple in DC-DC converter).

Molded Inductors : In this type of inductors, copper windings are encapsulated in a molded core of iron powder or composite alloy, forming a monolithic, shielded component. These core materials have distributed air gaps (microscopic gaps in the powder matrix), increasing saturation tolerance. Hence, they exhibit soft saturation, meaning inductance drops gradually, allowing operation near or slightly above $Isat$ without failure.

•**Inductors Wound on Core**: **Structure**: Wire wound around a discrete magnetic core (e.g., toroidal, E-core, or drum core), often with a deliberate air gap to control saturation. Wound-core inductors' saturation depends on core type and gap; ferrite cores saturate more sharply unless gapped.

Current characteristics of molded Inductors



Current Vs Inductance Characteristics:

What Happens?

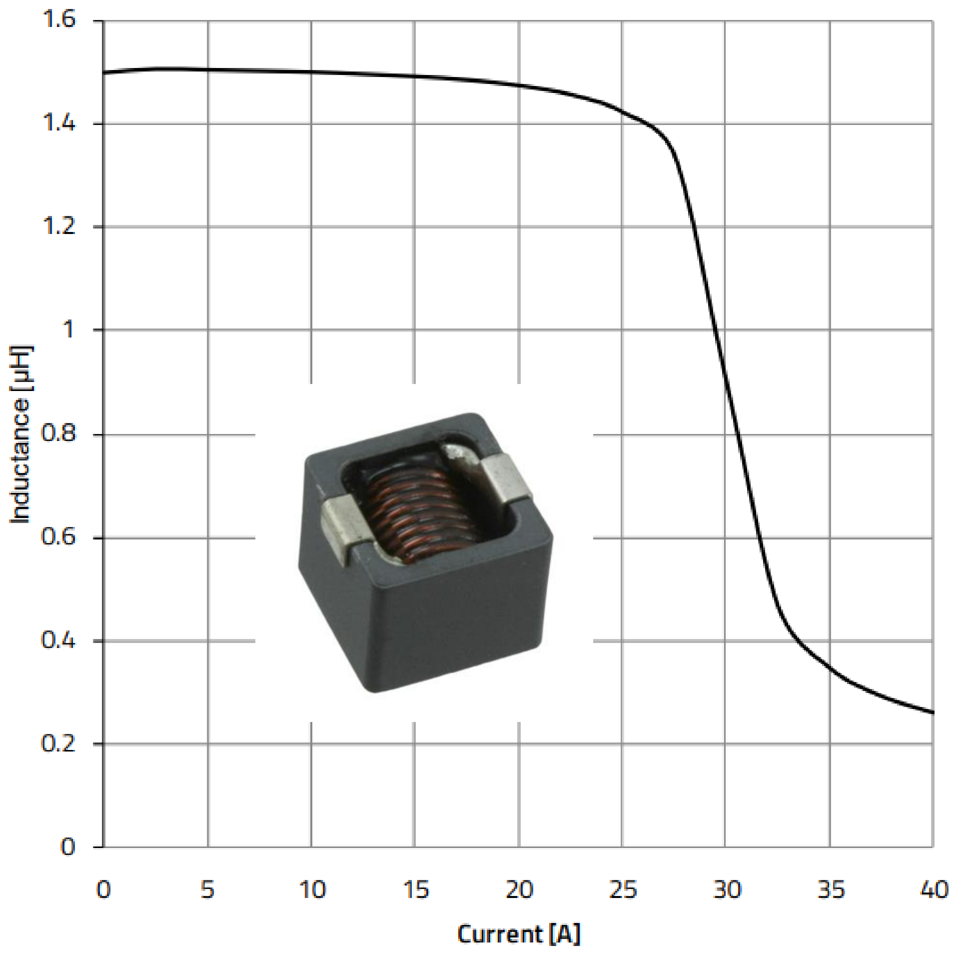
- Inductance (L) stable at low currents.
- Drops gradually as current approaches saturation ($Isat$).

Why?

- Core saturation reduces permeability ($L \propto \mu$).
- Soft saturation happens in moulded inductors: Gradual drop.

https://www.we-online.com/en/components/products/datasheet/74438356047.pdf

Current characteristics of wound-core-Inductors



Current Vs Inductance Characteristics:

- What Happens?
- Inductance (L) stable across the rated current. Drops rapidly as current exceeds saturation ($Isat$).

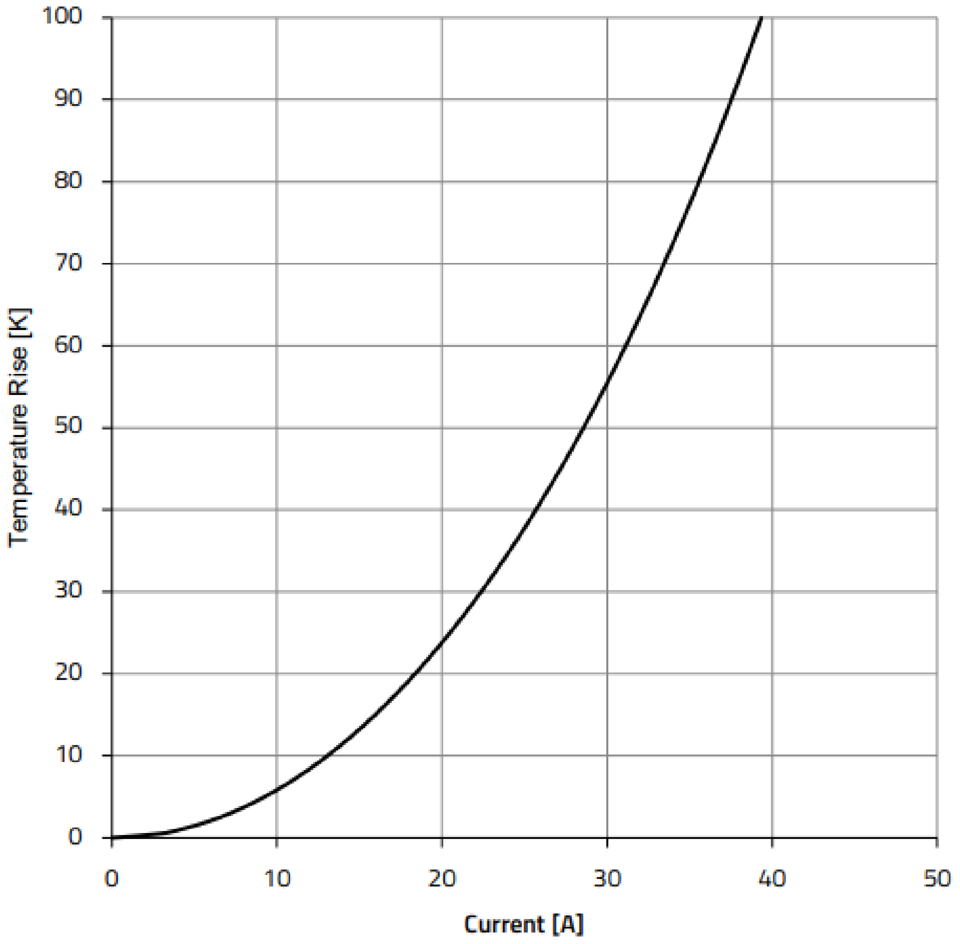
Why?

Core saturation reduces permeability ($L \propto \mu$).

Hard saturation happens causing steep drop of inductance. Hence, needs a careful design to ensure the circuit conditions never cause the inductor to operate beyond saturation current.

https://www.we-online.com/en/components/products/datasheet/7443320150.pdf

Temperature rise in Inductors



Winding / Copper Loses:

Inductors have DC resistance (DCR) which can be few milli ohms to ohms. This winding resistance causes an I^2R losses in an inductor.

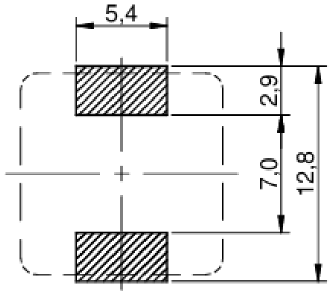
AC Resistance: At high frequencies, the skin effect (current concentrating near the conductor's surface) and proximity effect (current crowding due to nearby conductors) increase effective resistance, amplifying losses for AC ripple currents ($P_{AC}=I^2_{AC,rms}\cdot R_{AC}$).

Core Losses: Hysteresis and eddy current losses heat the core, especially at high frequencies or currents.

https://www.we-online.com/en/components/products/datasheet/7443320150.pdf

Sample specification sheet of an Inductor

Recommended Land Pattern: [mm]



no vias and sensitive traces underneath the component

Schematic:

Electrical Properties:

Properties		Test conditions	Value	Unit	Tol.
Inductance	L	100 kHz/ 250 mV	1	µH	±20%
Rated Current	$I_{R,40K}$	ΔT = 40 K	14	A	max.
Performance Rated Current [1]	$I_{RP,40K}$	ΔT = 40 K	20	A	max.
Saturation Current @ 10%	$I_{SAT,\ 10\%}$	|ΔL/L| < 10 %	15.6	A	typ.
Saturation Current @ 30%	$I_{SAT,30\%}$	|ΔL/L| < 30 %	20	A	typ.
DC Resistance	R_{DC}	@ 20 °C	3	mΩ	typ.
DC Resistance	R_{DC}	@ 20 °C	5	mΩ	max.
Self Resonant Frequency	f_{res}		88	MHz	typ.
Operating Voltage	V		120	V	max.

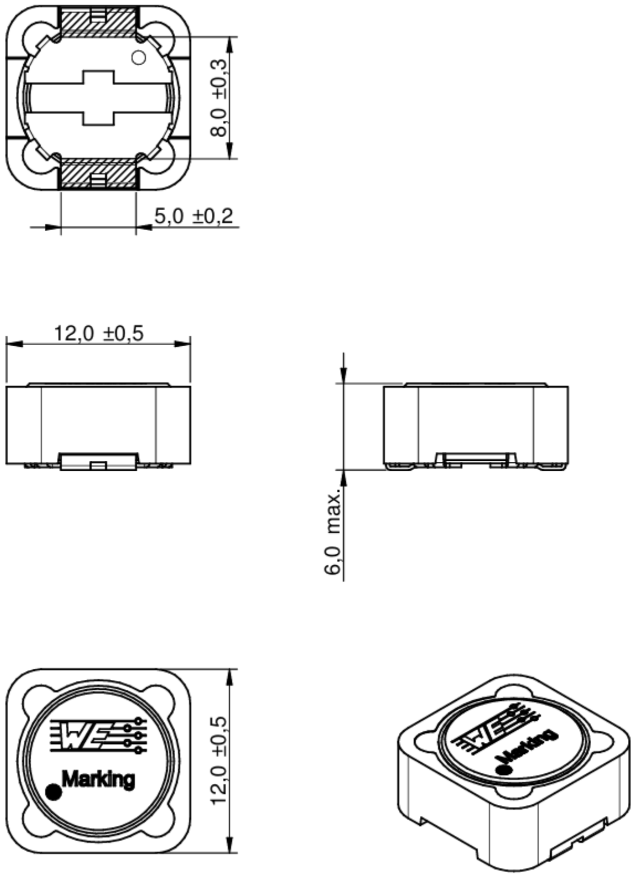
[1] refer to IEC 62024-2-2020

Certification:

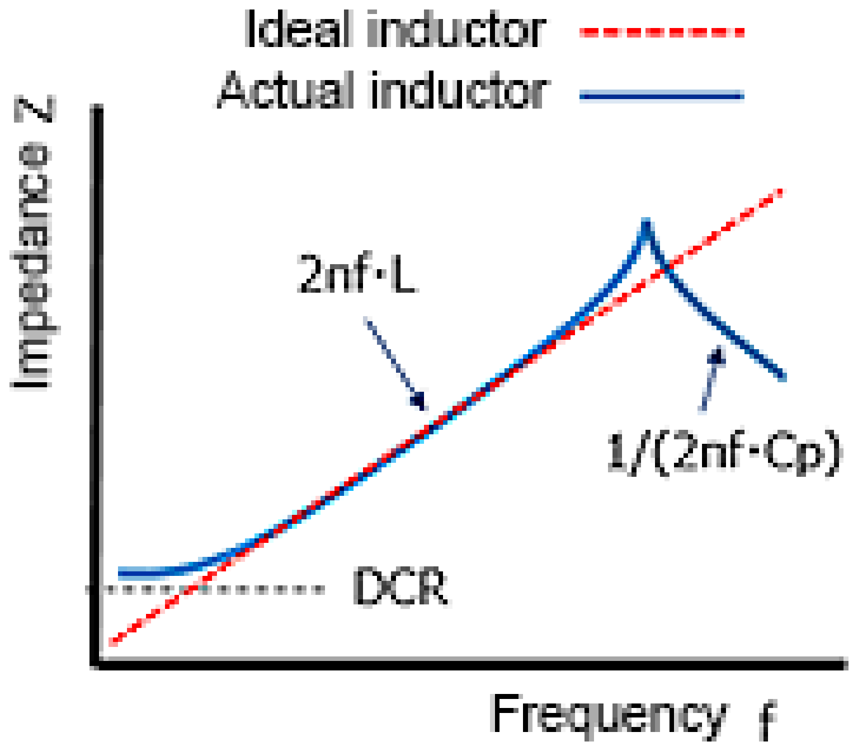
RoHS Approval	Compliant [2011/65/EU&2015/863]
REACh Approval	Conform or declared [(EC)1907/2006]
Halogen Free	Conform [JEDEC JS709B]
Component Qualification	AEC-Q200 Grade 1

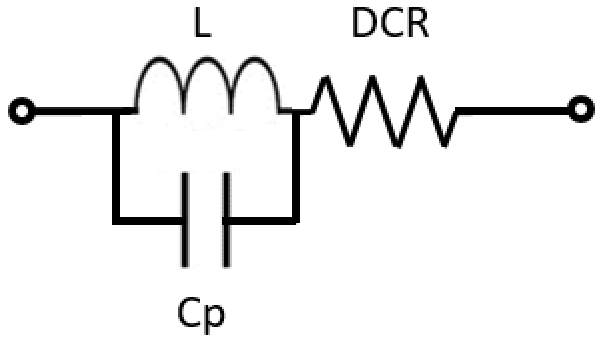
General Information:

Ambient Temperature (referring to I_R)	-40 up to +85 °C
Operating Temperature	-40 up to +125 °C
Storage Conditions (in original packaging)	< 40 °C ; < 75 % RH
Moisture Sensitivity Level (MSL)	1
Test conditions of Electrical Properties: +20 °C, 33 % RH if not specified differently	
Test conditions of Performance Rated Current: refer to IEC 62024-2-2020, Class C (PCB Copper Width: 40 mm; PCB Copper Thickness: 105 µm)	



Equivalent circuit of Inductors





Resistance due to DCR of the winding.

Capacitance due to interturn capacitances of the winding.

Inductive reactance $X_L = 2\pi f L$

https://www.we-online.com/en/components/products/datasheet/7443320150.pdf

Characteristics data for Inductor

WÜRTH ELEKTRONIK REDEXPERT Power Inductors Menu

100 / 2962 items

Order Code	Series	Size	Spec	Type	L_0	$R_{DC,typ}$	I_R	I_{sat}	f_{res}	V_{op}	L	W	H_{Max}	T_{op}	Shielded	AEC-Q	Automotive	Material	Assembli...
74436413300	WE-HCF	2815		Single	33.0 µH	1.33 mΩ	44.0 A	6.00 A	6.29 MHz	80.0 V	27.7 mm	19.1 mm	15.4 mm	125 °C	Shielded	1	×	MnZn	SMT
7443640330	WE-HCF	2818		Single	3.30 µH	2.40 mΩ	35.0 A	100 A	31.3 MHz	80.0 V	28.0 mm	28.5 mm	18.5 mm	125 °C	Shielded	1	×	MnZn	SMT
7443640470	WE-HCF	2818		Single	4.70 µH	2.40 mΩ	35.0 A	78.0 A	20.0 MHz	80.0 V	28.0 mm	28.5 mm	18.5 mm	125 °C	Shielded	1	×	MnZn	SMT
7443640680	WE-HCF	2818		Single	6.80 µH	2.40 mΩ	35.0 A	55.0 A	17.0 MHz	80.0 V	28.0 mm	28.5 mm	18.5 mm	125 °C	Shielded	1	×	MnZn	SMT
7443641000	WE-HCF	2818		Single	10.0 µH	2.40 mΩ	35.0 A	37.0 A	13.0 MHz	80.0 V	28.0 mm	28.5 mm	18.5 mm	125 °C	Shielded	1	×	MnZn	SMT
7443641500	WE-HCF	2818		Single	15.0 µH	2.40 mΩ	35.0 A	26.0 A	11.0 MHz	80.0 V	28.0 mm	28.5 mm	18.5 mm	125 °C	Shielded	1	×	MnZn	SMT
7443642200	WE-HCF	2818		Single	22.0 µH	2.40 mΩ	35.0 A	18.0 A	9.00 MHz	80.0 V	28.0 mm	28.5 mm	18.5 mm	125 °C	Shielded	1	×	MnZn	SMT
7443643300	WE-HCF	2818		Single	33.0 µH	2.40 mΩ	35.0 A	11.5 A	7.00 MHz	80.0 V	28.0 mm	28.5 mm	18.5 mm	125 °C	Shielded	1	×	MnZn	SMT

Buck Converter

Boost Converter

SEPIC

Losses

Rated Current Calculator

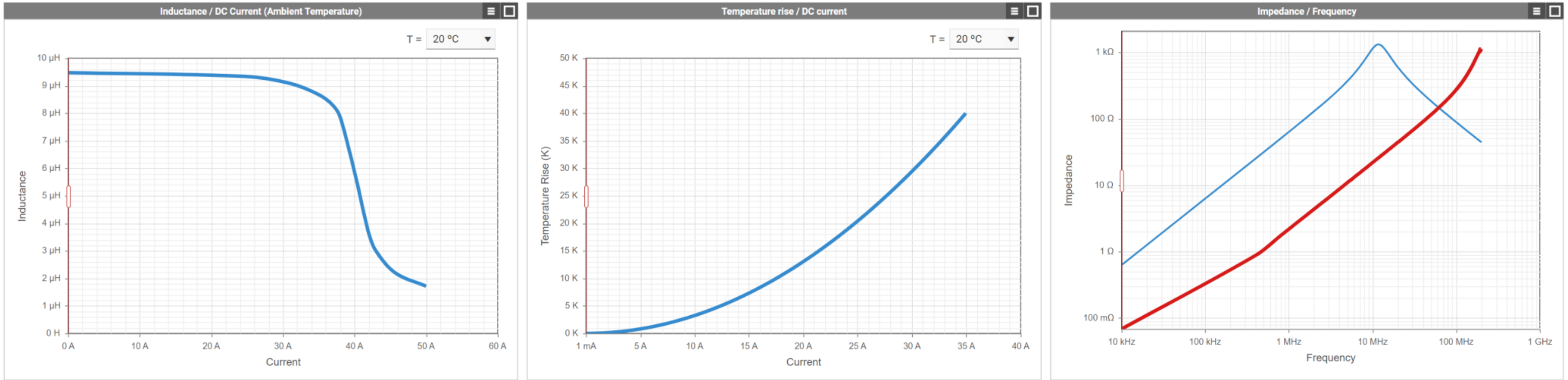
7443641000
WE-HCF · 2818
10.0 µH · 2.40 mΩ

Click and type or drop an Order Code here

ADD

MORE

Show Panel: L vs. I(T) Z vs. F



https://redexpert.we-online.com/we-redexpert/en/#/redexpert-embedded

https://ds.murata.co.jp/simsurfing/powerinductor.html?lcid=en-us&md5=bf1001f9f734fc483fa2ebd5a6ee0562

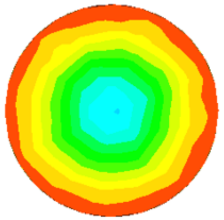
Losses in an Inductor

- **Copper Loss :** The power lost due to the DC resistance of the winding. The power loss is equal to the square of the current multiplied by the resistance of the wire (I^2R).
- **Core Losses :** Core losses are 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. These losses vary considerably from one magnetic material to another. The total core losses are made up of three main components:
  - hysteresis,
  - eddy current and
  - residual losses.
- **Eddy Current Losses :** Eddy current losses are present in both the magnetic core and winding of an inductor.
- As for the core losses, alternating magnetic flux lines will result in eddy currents if the magnetic core material has electrical conductivity. Losses result from this phenomenon since the eddy currents flow in a plane that is perpendicular to the magnetic flux lines
- Eddy currents in the winding (or conductor) contribute to two main types of losses:
  - Losses due to proximity effects
  - Skin effect.

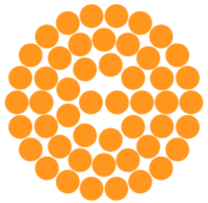
Skin Effect and Litz wire

- **Skin Effect:** The magnetic field associated with the current in the conductor causes eddy currents 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. This phenomenon causes the resistance of the conductor to increase.

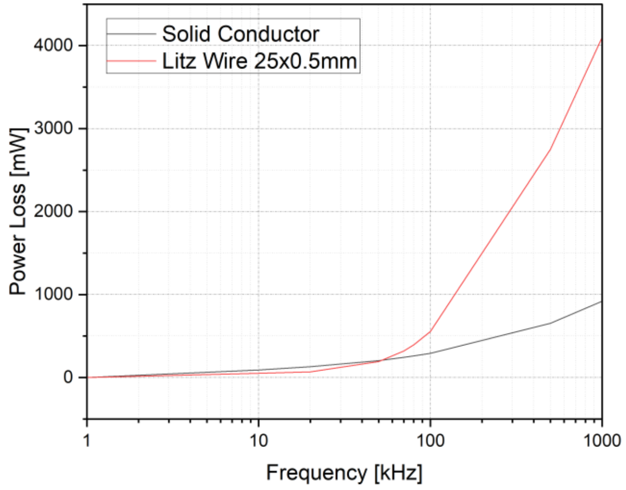
DC current



High frequency current – Skin effect



- **Litz Wire:** To avoid the increase in resistance due to skin effect, Liz wire consists of several 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. Hence a Litz conductor has lower AC losses than comparable solid-wire conductors, which becomes important as the operating frequency increases.



https://www.emworks.com/application/optimize-litz-wire-design-for-minimal-losses-in-high-frequency-applications

Q factor of an Inductor

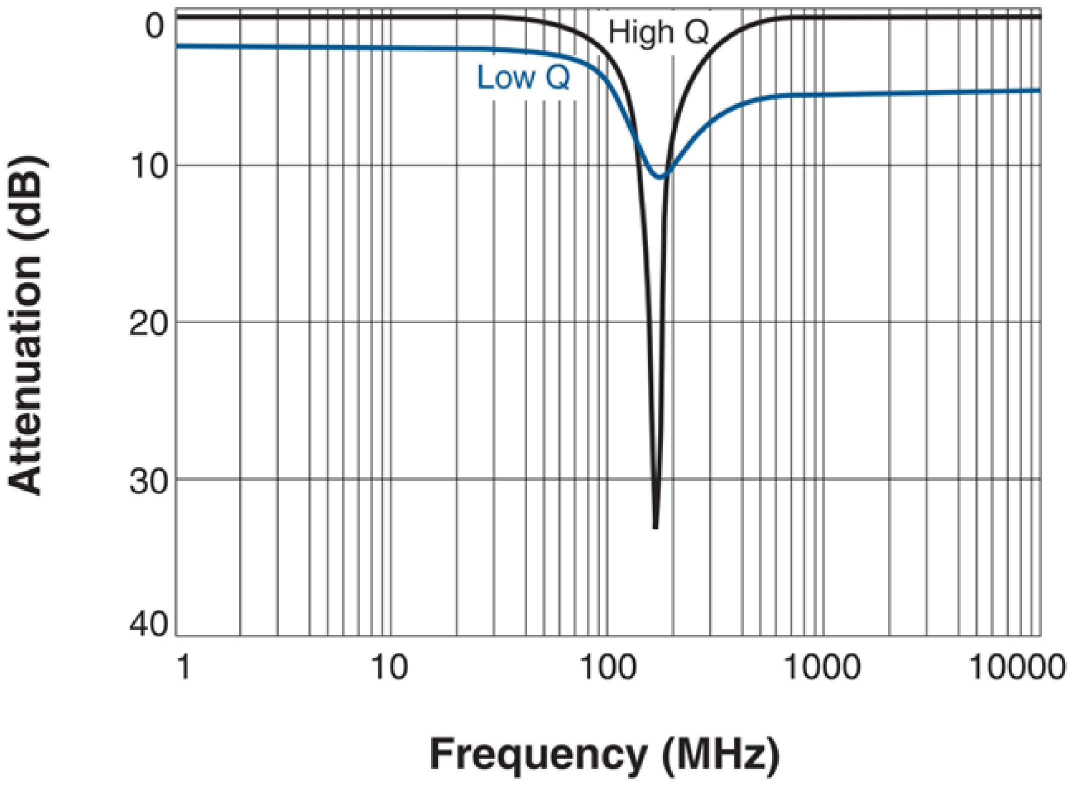


Figure 2. High Q Gives Narrow Bandwidth and Low Insertion Loss

- The Q-factor (Q) of an inductor is defined as the ratio of the inductor's inductive reactance (X) to its internal resistance (R) at a given frequency.
- Formula: Q = X/R
- Significance:
- A higher Q-factor indicates lower energy losses and better suitability for use as a high-frequency inductor.
- A low Q-factor means higher energy losses and the inductor is less suitable for high-frequency applications.

Operating voltage of molded Inductor

- Molded inductors are power inductors where the magnetic core material (typically iron powder or composite alloy) is molded directly around the copper windings, forming a compact, shielded component.

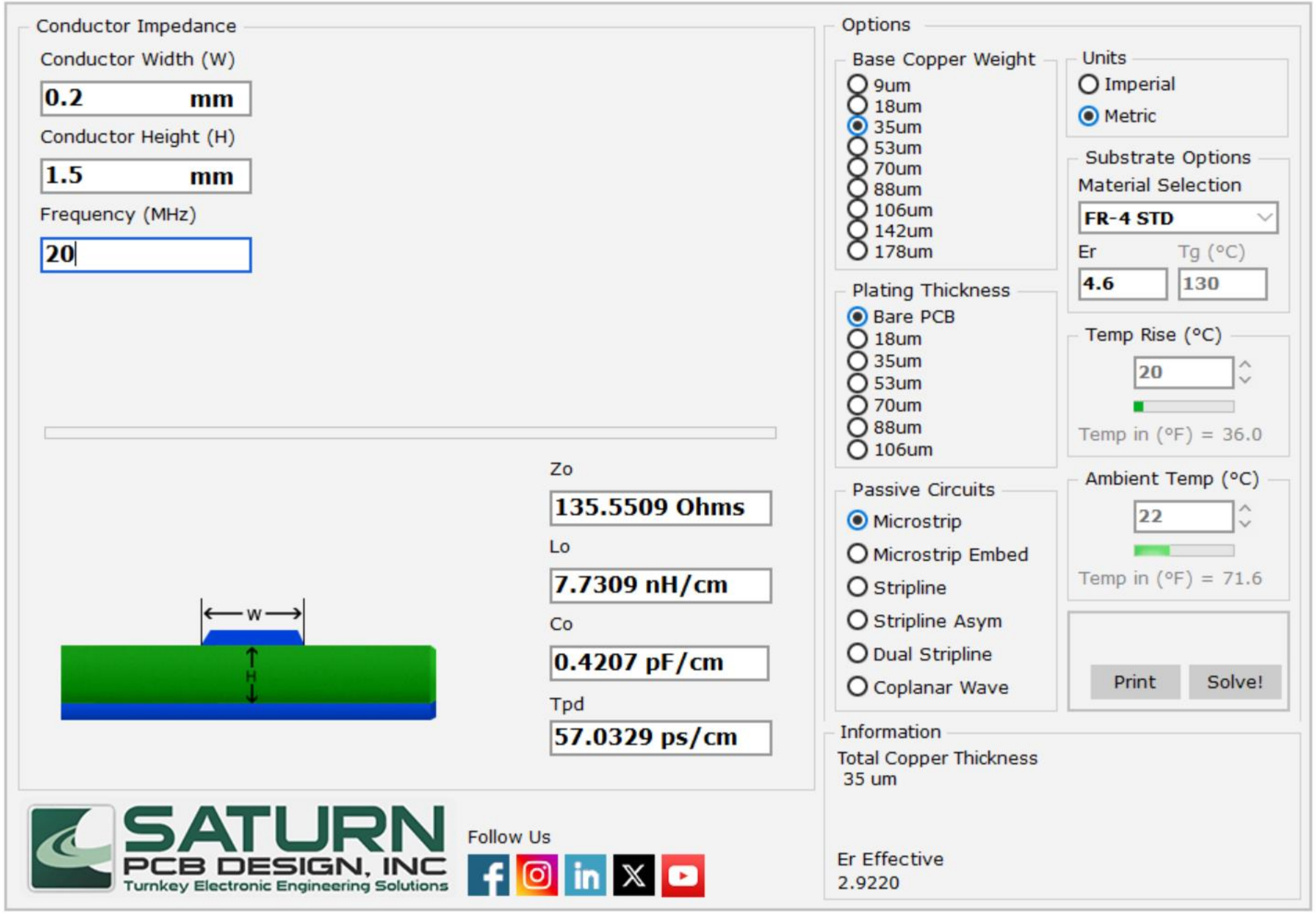
- They are widely used in DC-DC converters, power supplies, and mixed-signal circuits due to their compact size, high current handling, and magnetic shielding,

- The operating voltage (or working voltage) of a molded inductor is the maximum continuous voltage that can be applied across its terminals without causing Insulation breakdown, Performance degradation (e.g., inductance drop, increased losses) and Reduced reliability or shortened lifespan.

- Most off-the-shelf molded inductors are rated between **60–80 V**, with high-voltage variants (e.g., Coilcraft's "V" series) reaching **120 V**. Some specialized parts go higher (e.g., Würth Elektronik's WE-MAPI series, up to 120–150 V, 400V for specific models)

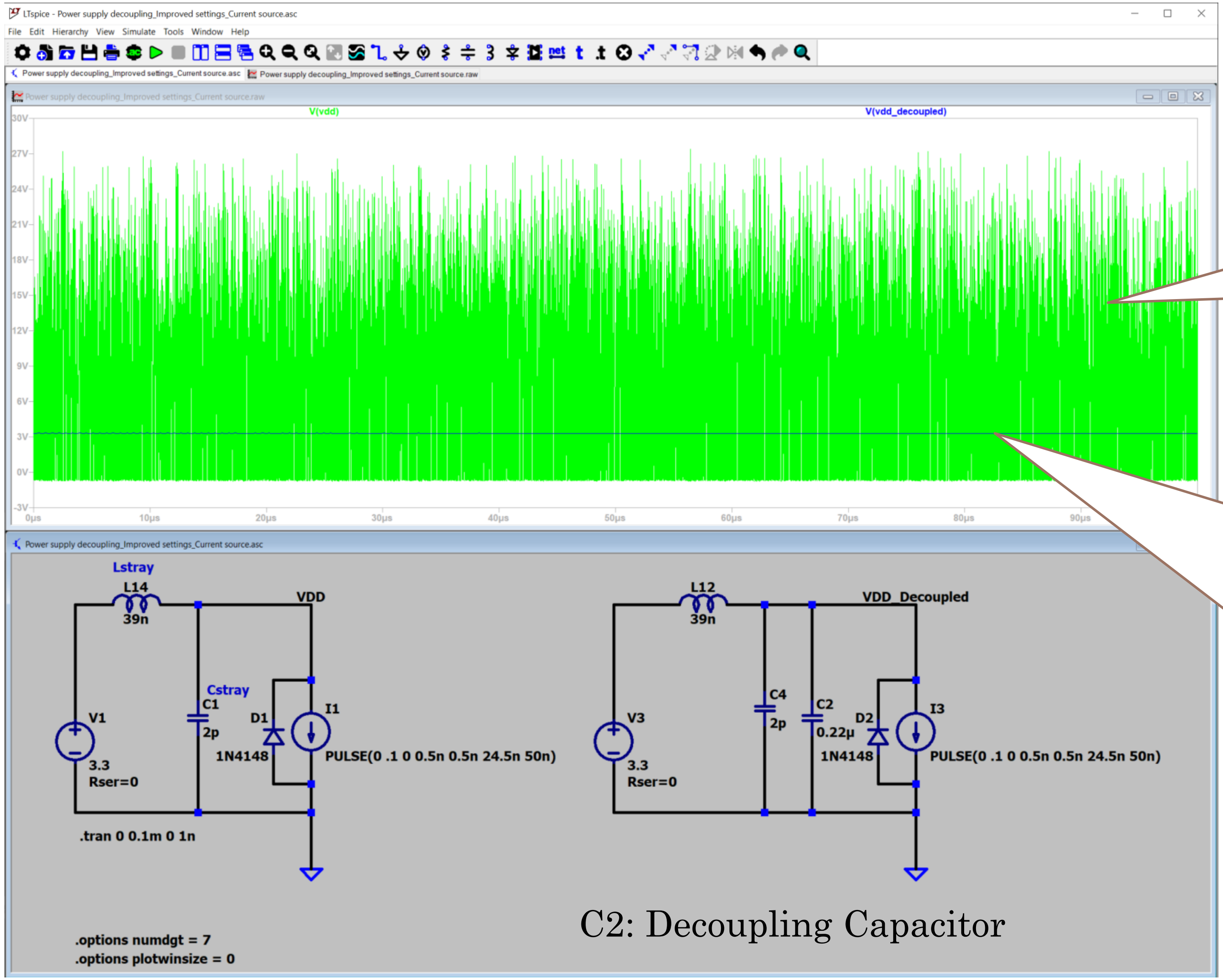
Note: Do check the max operating voltage of the inductor before using to ensure it matches your voltage requirements

Inductance of a PCB trace



- All PCB traces have a certain Inductance and capacitance based on its dimensions.
- For example, in a PCB of thickness 1.5mm, a trace of width of 0.2mm has about 7.7nH per cm of length.
- If the power supply trace of an MCU operating at 20MHz clock, is about 5cm in length with 0.2mm thick trace, then the trace impedance will be around 4.8 Ohms and a 100mA current will cause 480mV drop in the power supply trace.

Decoupling V_{DD} : Voltage Waveforms

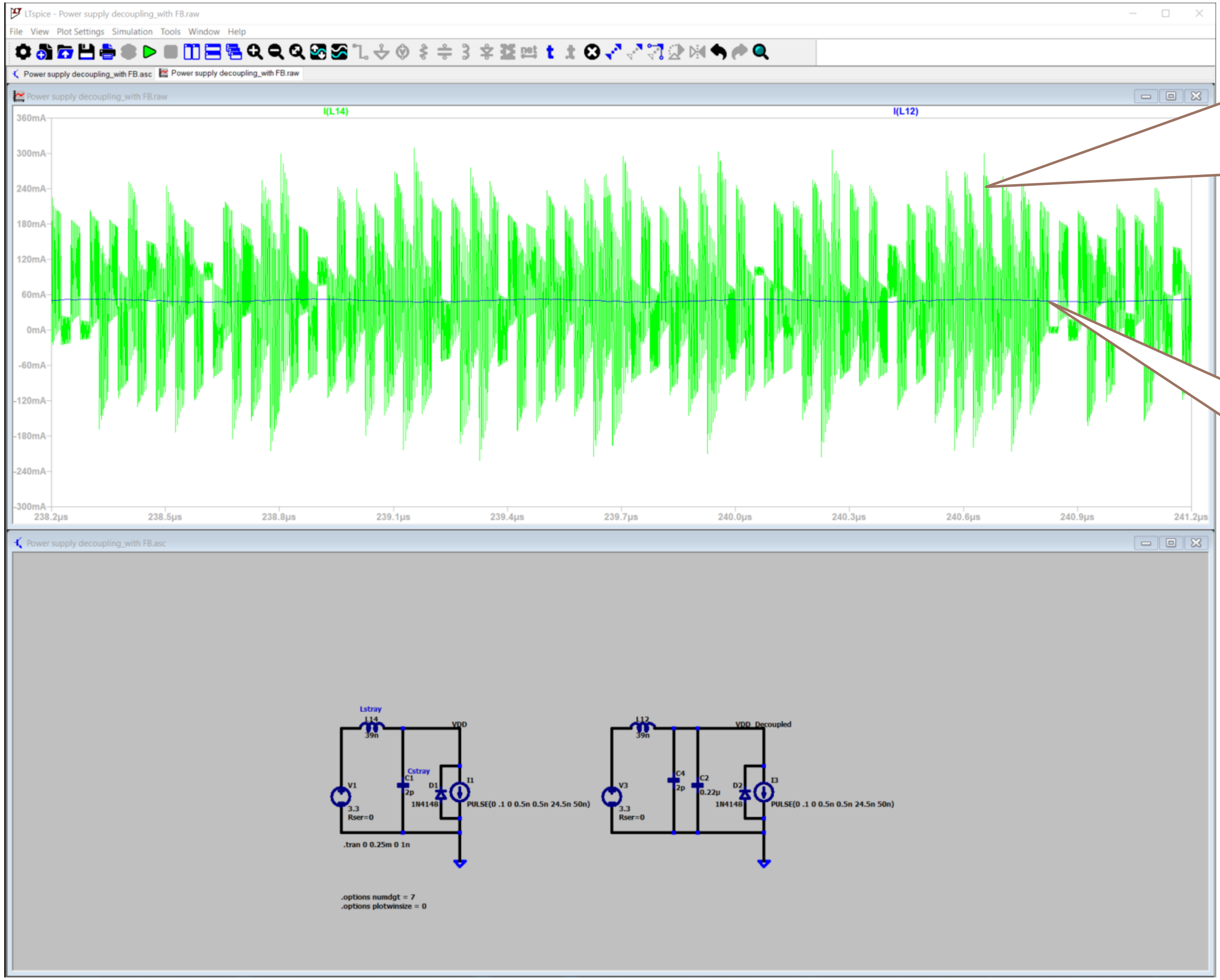


C2: Decoupling Capacitor

Green Trace: V_{DD} is highly noisy due to the counter emf (L*di/dt) generated by the trace inductance

Blue Trace: Addition of a 0.22uF cap close to the V_{DD} pin eliminates this noise, as the capacitor is able to supply the instantaneous current during switching transients, locally. Thus, decoupling the IC from the effects of trace inductance

Decoupling V_{DD} : Current Waveforms



Green Trace: Current in the supply trace without the decoupling capacitor (This will cause high radiated emission of noise through the long trace length.

Blue Trace: Addition of a 0.22uF cap close to the V_{DD} pin eliminates the current noise on the supply trace. Significantly reducing the current noise and thereby the radiated emission.

Decoupling V_{DD} : Trace length, Via

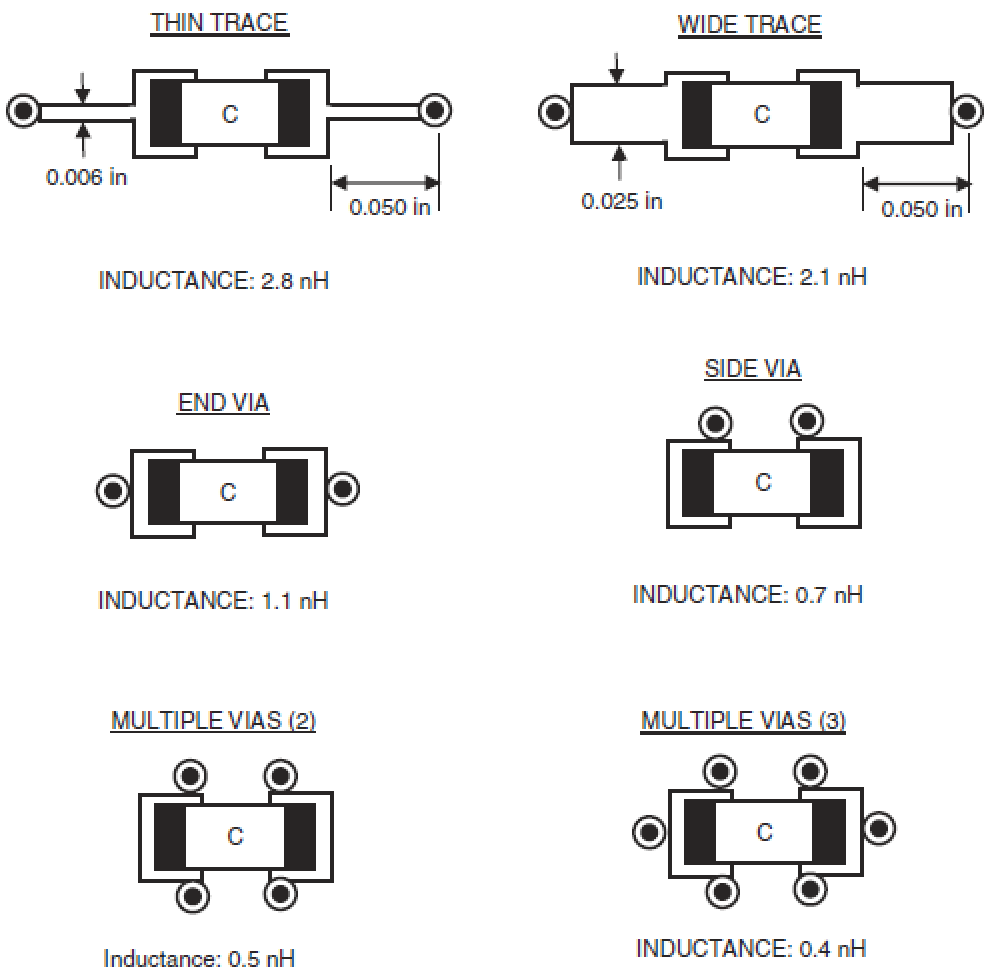
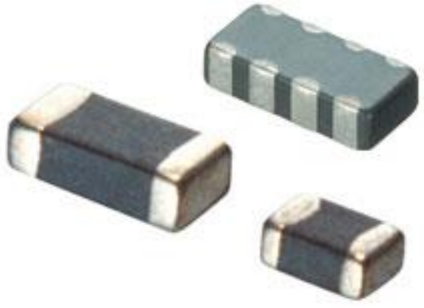


FIGURE 11-25. Inductance of various 0805 SMT decoupling capacitor mounting configurations.

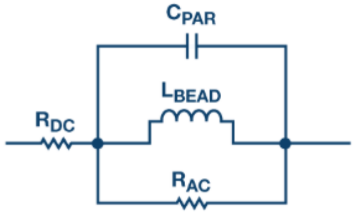
- There are very strict rules on the placement on decoupling capacitor.
- Rule #1: The decoupling capacitor must be placed right on the Vdd and Vss line of the IC supply to be decoupled. Ideally the connecting trace length should be less than 1 mm.
- Rule #2: Ideally, the decoupling capacitor and the IC should be on the same layer. If not, the connecting Vias will add stray inductance and hence placement of Vias and number of vias will be critical.

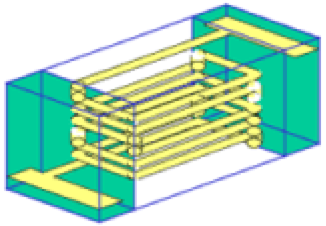
Chip Ferrite Beads

In case of Chip ferrite beads Coil patterns are formed between the layers of the sheets of raw ferrite, and by a process of integration and firing, a 3-dimensional coil structure is produced.



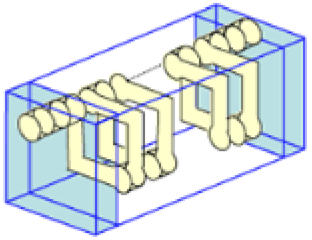
While Inductors are primarily used for energy storage and filtering, ferrite beads are designed to suppress high-frequency noise and electromagnetic interference.



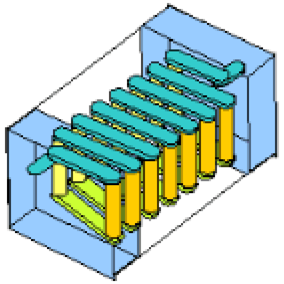


Basic BLM structure

Ferrite beads are designed to act as high-frequency resistors, effectively filtering out high-frequency noise and EMI. They dissipate high-frequency energy as heat.

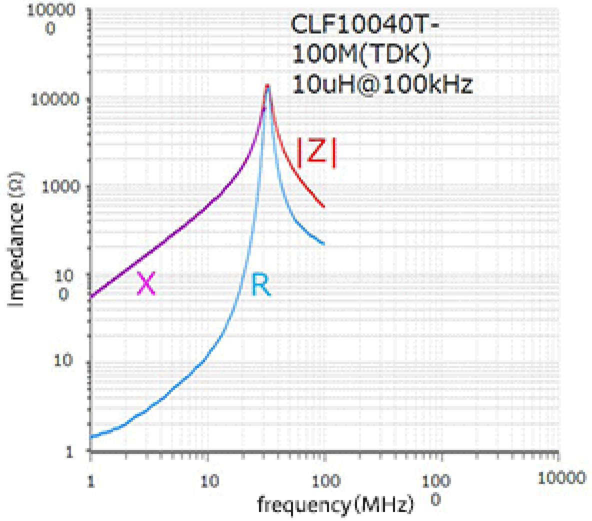


Structure of a BLM-H type with improved high-frequency characteristics (Horizontally wound, horizontally layered structure)



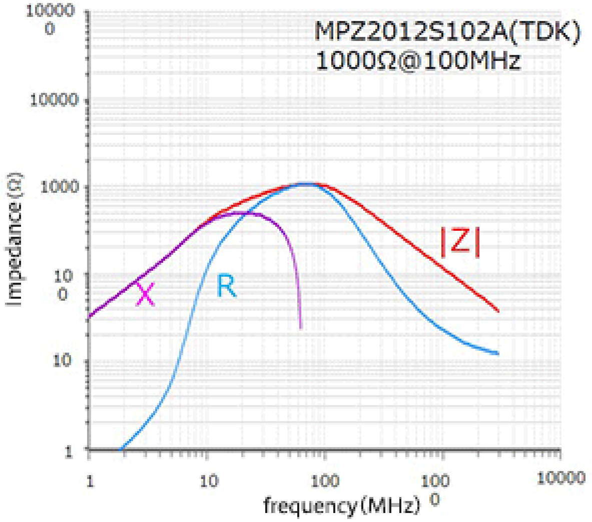
Structure of the BLM-E type (Horizontally wound, vertically layered structure with many via- holes)

Inductors Vs Ferrite Beads



Inductor Impedance

- Low R component (loss).
- High Q.



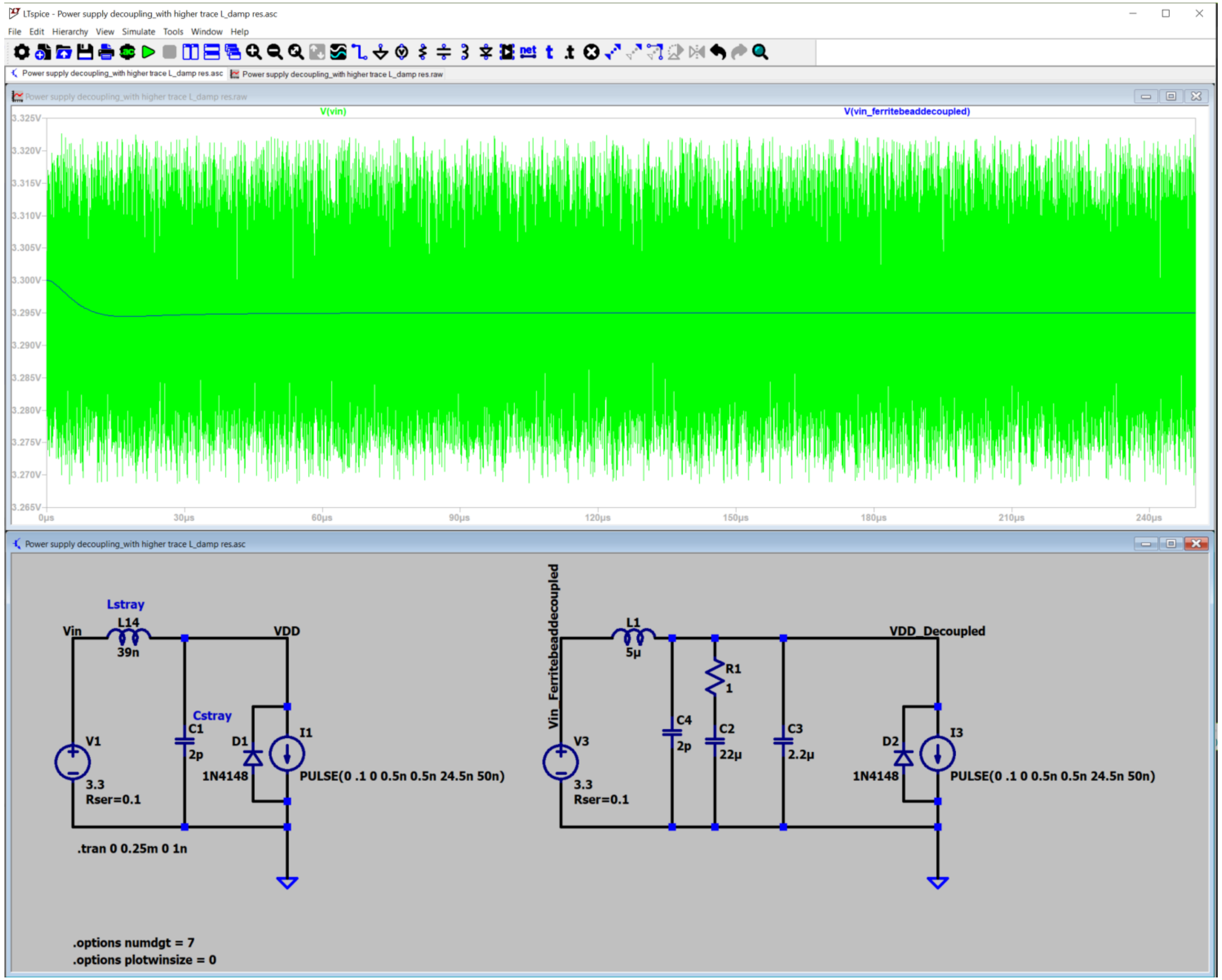
Ferrite Bead Impedance

- High R component (loss).
- Low Q.

- Notice the R, |Z| components of an Inductor and Ferrite Bead. We can notice that the Q factor of ferrite bead is very low, that means, it can be used for frequencies over wide range and is also lossy.
- A ferrite bead is essentially a specialized inductor optimized for high-frequency loss (resistive impedance) rather than energy storage. Its inductance (e.g., 0.3–5 μH) contributes to filtering, but its resistive behavior at high frequencies dissipates noise as heat, unlike a pure inductor.

- Why Capacitor Alone Isn’t Enough?
- A decoupling capacitor is great for local noise filtering at Vdd_digital but doesn’t prevent noise from traveling back to Vsupply. At high frequencies (>50 MHz), the capacitor’s ESL (e.g., 0.7 nH) makes it inductive, reducing its effectiveness.The ferrite bead’s high impedance blocks this noise, complementing the capacitor.

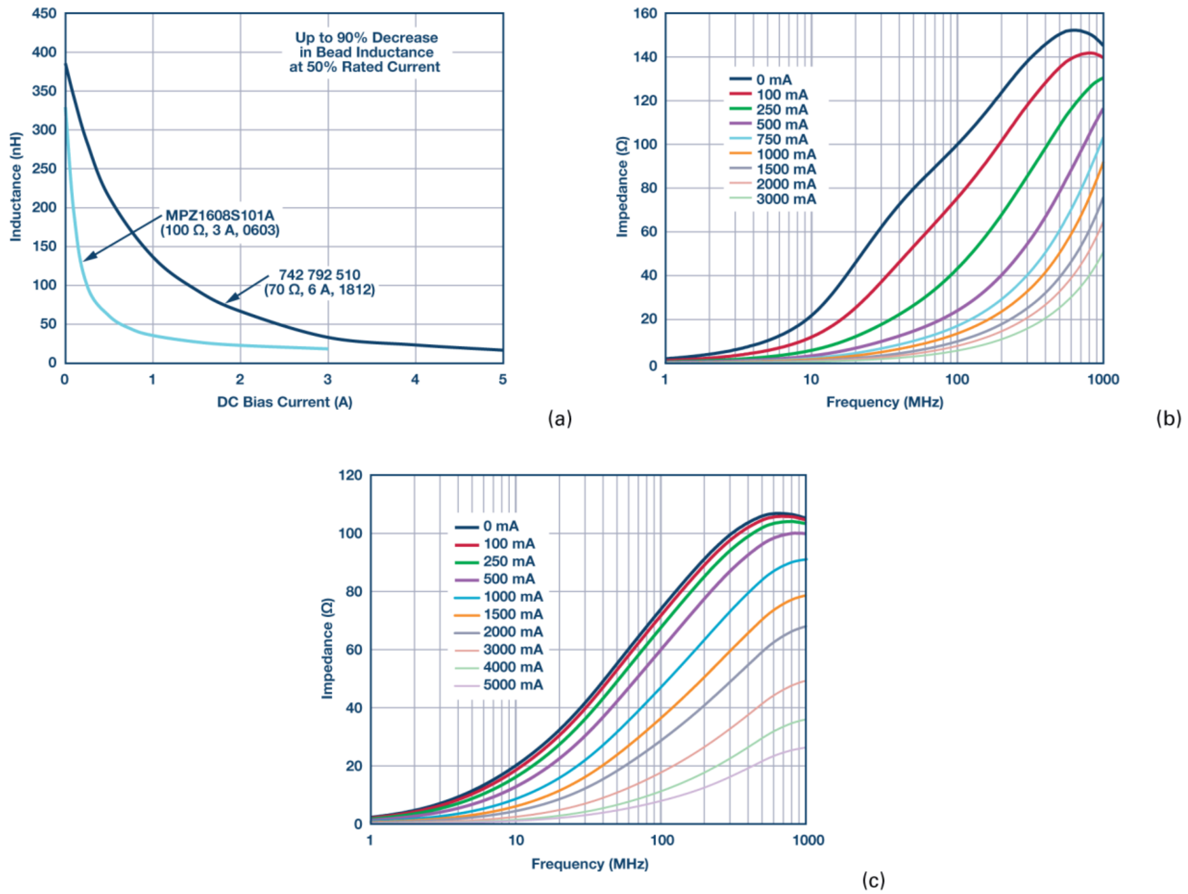
Ferrite bead for isolating Analog, Digital supplies



- Often many embedded circuits need both an analog rail and digital rail. But the power supply available may be a common one.
- When a common power supply is used to power both digital and analog, in order to keep the analog rail noise free, the digital rail uses an inductor of 1~5uH or a ferrite bead just in front of the decoupling capacitor which helps in further isolating the digital noise from polluting the input rail.
- Green waveform shows the noise at power supply (Vin) without a high value inductor or ferrite bead for decoupling. Blue waveform shows Vin after adding an Inductor or Ferrite bead.

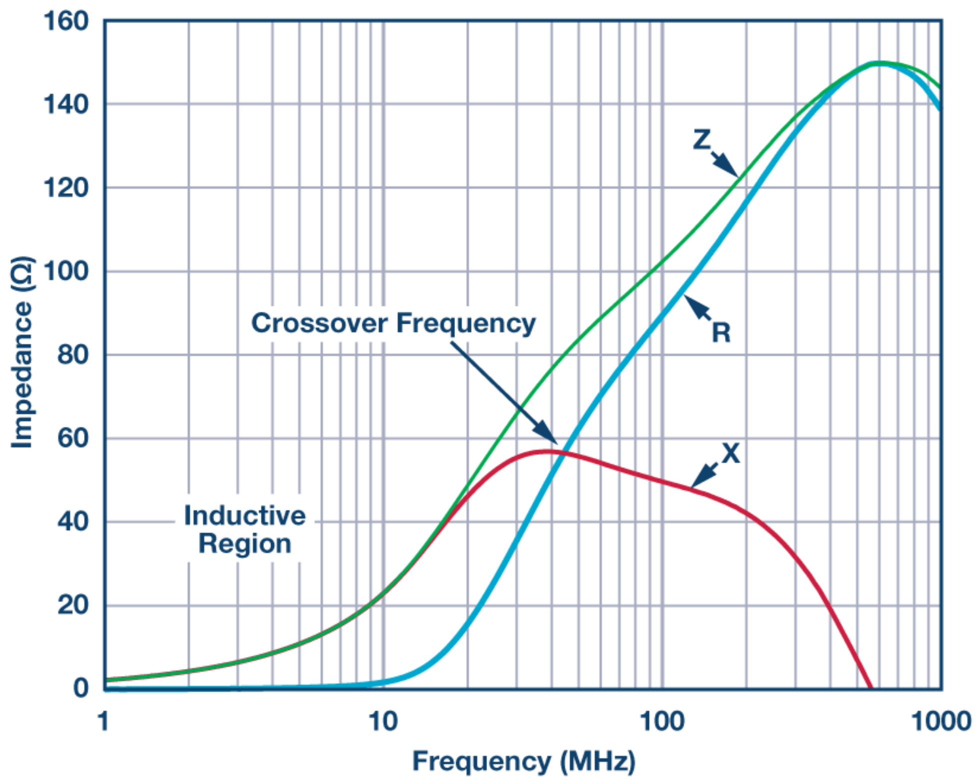
DC Bias considerations for Ferrite

- When using ferrite beads for power supply filtering, the load current going through the ferrite bead is never zero. Like in Inductors, as the dc bias current increases, the core material begins to saturate, which significantly reduces the inductance of the ferrite bead.
- The degree of inductance saturation differs depending on the material used for the core of the component. Figure 3a shows the typical dc bias dependency of the inductance for two ferrite beads. With 50% of the rated currents, the inductance decreases by up to 90%.

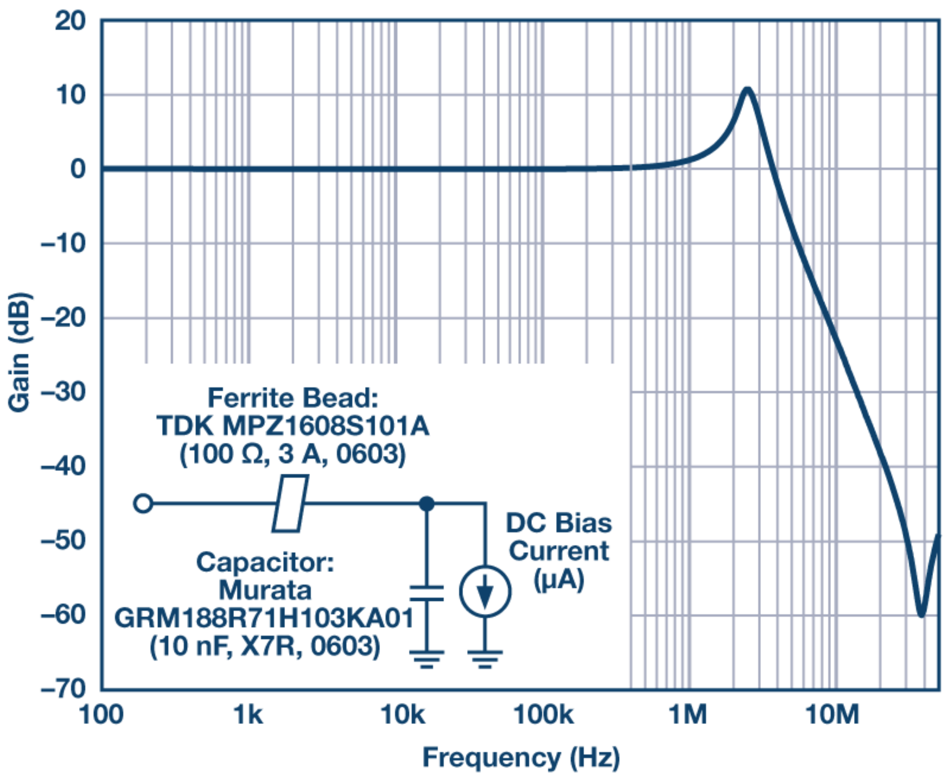


https://www.analog.com/en/analog-dialogue/articles/ferrite-beads-demystified.html

LC Resonance due to Ferrite and capacitor



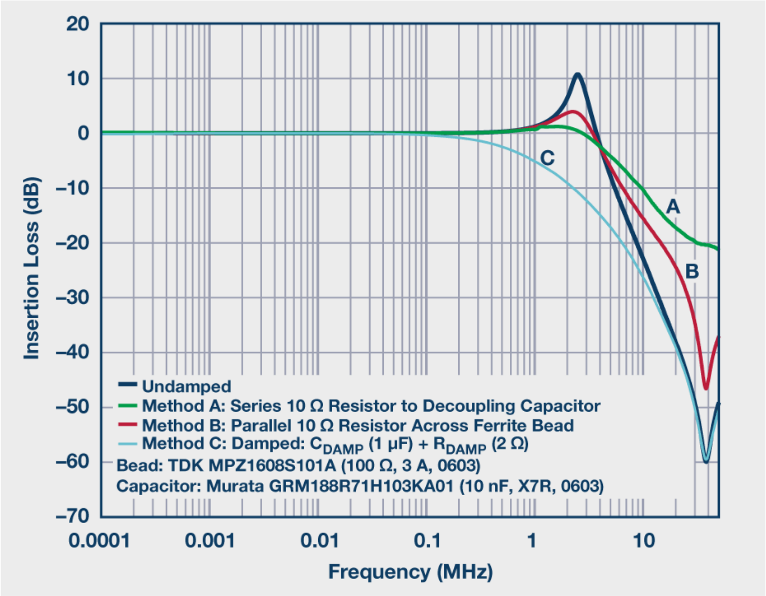
(a)

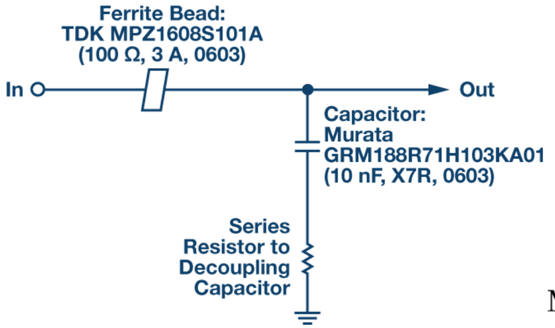


(b)

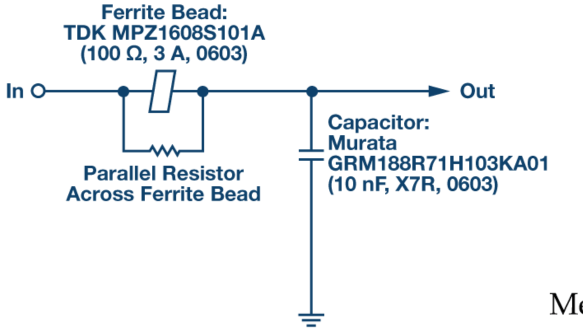
- Resonance peaking is possible when implementing a ferrite bead together with a decoupling capacitor. This commonly overlooked effect can be detrimental because it may amplify ripple and noise in a given system instead of attenuating it. Ferrite's "L" and decoupling capacitor "C" together tends to oscillate as LC resonant circuit.

Damping LC Resonance

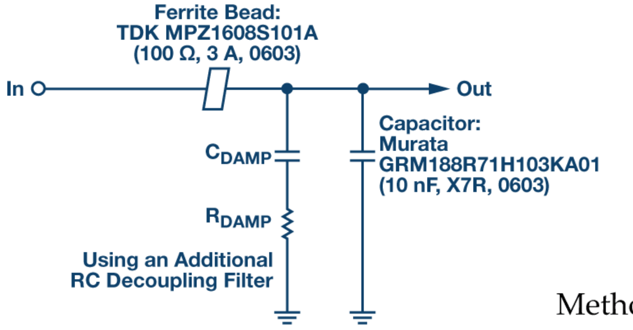




Method A



Method B



Method C

The damping ratio (zeta, ζ) is a dimensionless parameter that describes the damping characteristics of a circuit.

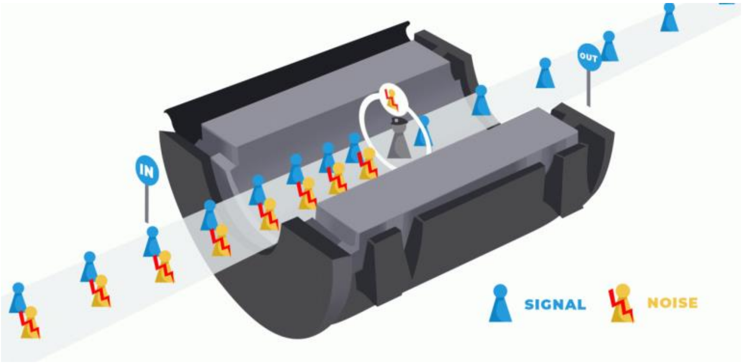
$\zeta = (R / 2) * \mathrm{sqrt}(C/L)$.

Underdamped ($\zeta < 1$): Oscillations decay before settling.

Critically Damped ($\zeta = 1$): Fastest return to equilibrium without oscillation.

Overdamped ($\zeta > 1$): Slowest return to equilibrium without oscillation

Other applications of Ferrite beads

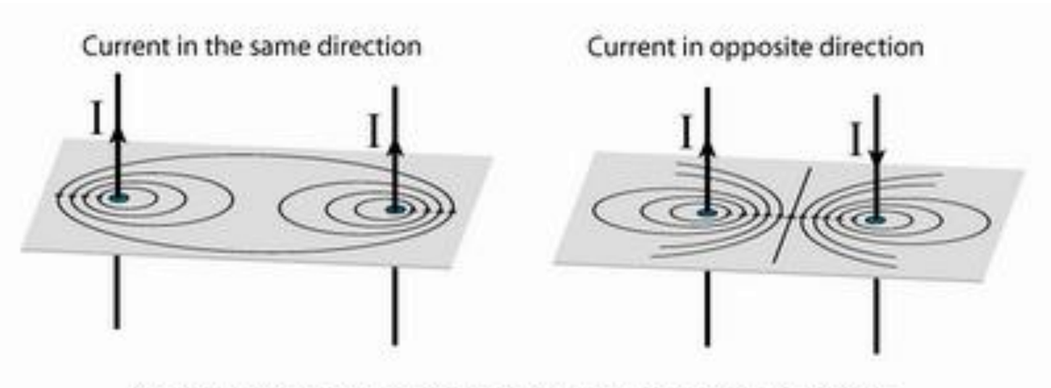


When long communication wires radiate (unwanted radiation is called as noise), a quick fix is to use a Ferrite bead close to the connector or the source

https://resources.altium.com/p/how-do-ferrite-beads-work-and-how-do-you-choose-right-one

Common mode choke

- A common mode choke is an electrical filter that blocks high frequency noise common to two or more data or power lines while allowing the desired DC or low-frequency signal to pass.
- Common mode (CM) noise current is typically radiated from sources such as unwanted radio signals, unshielded electronics, inverters and motors. Left unfiltered, this noise presents interference problems in electronics and electrical circuits.



Catapult field produced by 2 straight curretn carrying conductors

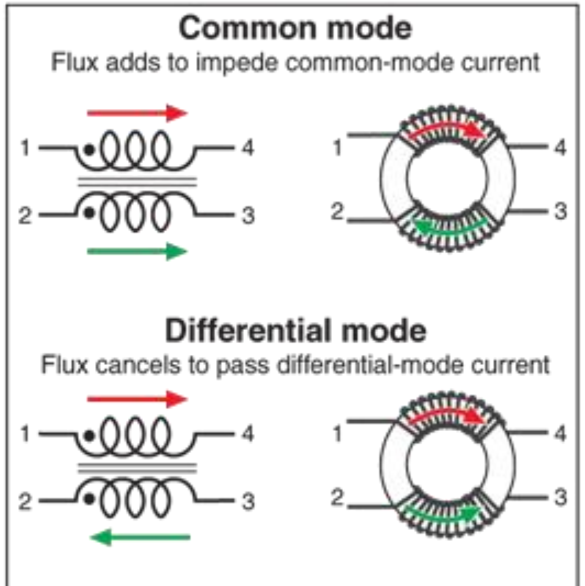
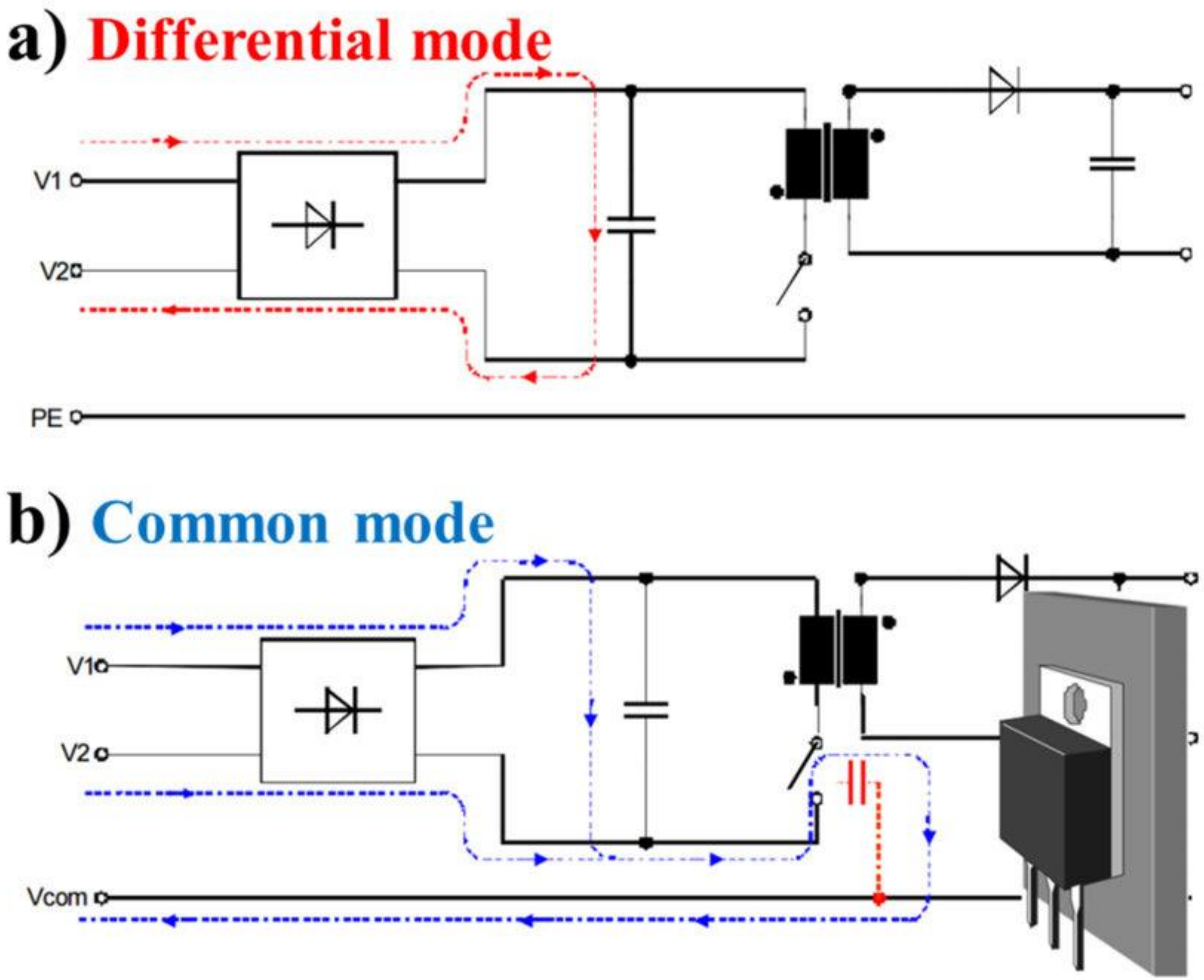


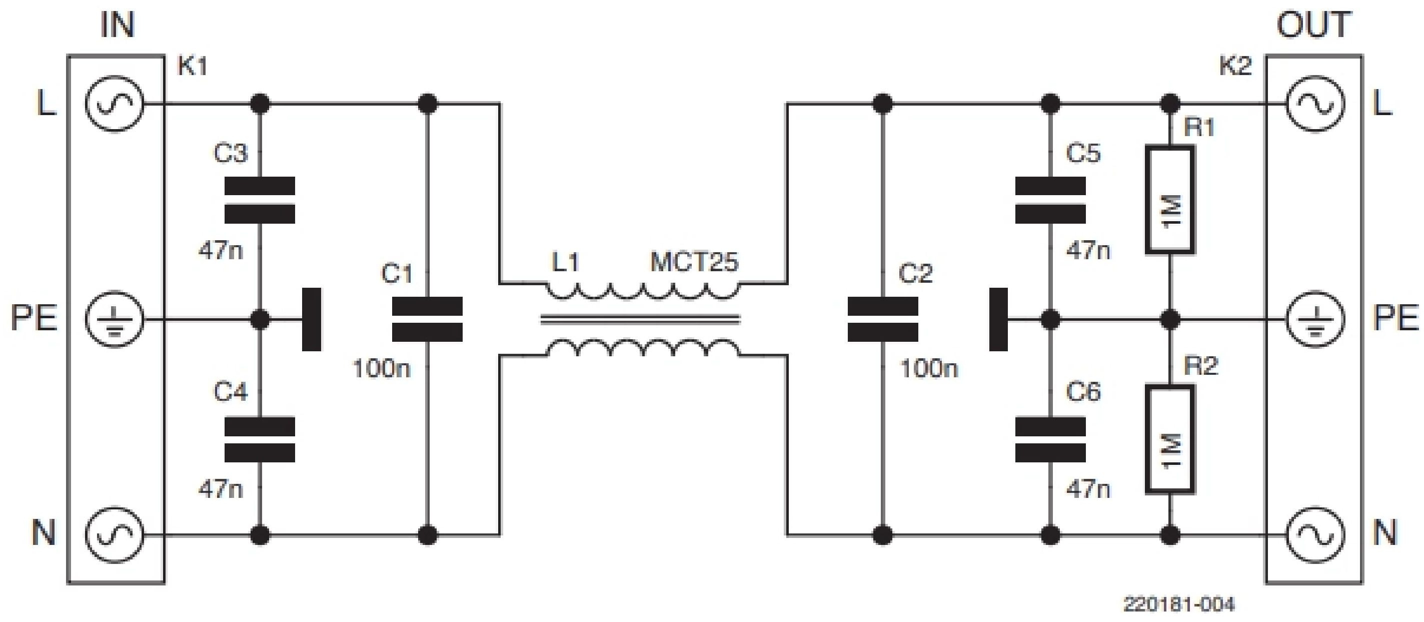
Figure 1. Magnetic flux paths

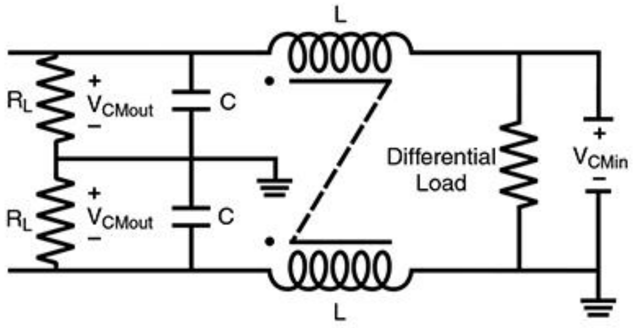
Common mode currents in SMPS



- Common mode currents travel through chassis of equipment or earth or output wires which causes the switching noise currents to radiate energy all around causing disturbance to nearby equipments.
- EMC standards necessitates measurement of common mode current and sets a max threshold to comply with.
- Hence the product design needs to have necessary measures to eliminate or minimize the common mode currents.

Eliminating common mode noise





$$\frac{V_{CMout}(s)}{V_{CMin}(s)} = \frac{1}{1+\frac{L}{R_L}s+LCs^2}$$

$$= \frac{1}{1-LC\omega^2+j\omega\left(\frac{L}{R_L}\right)}$$

$$= \frac{1}{1+j2\zeta\frac{\omega}{\omega_n}-\left(\frac{\omega}{\omega_n}\right)^2}$$

$\omega \equiv$ radian frequency

$R_L \equiv$ the noise load resistance

$$\omega_n \equiv \frac{1}{\sqrt{LC}}$$

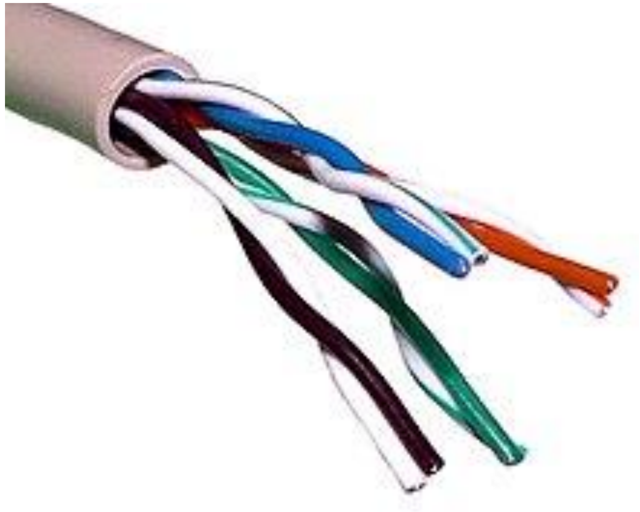
$$\zeta \equiv \frac{L}{2R_L\sqrt{LC}}$$

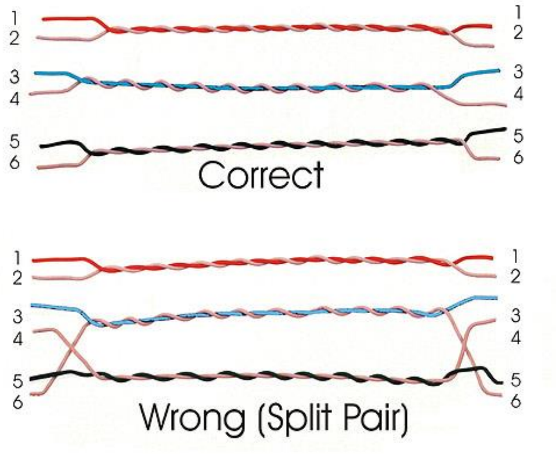
common mode filters serve as transmission lines for differential mode signals, and as inductors for common mode noise.

The impedance of the filters serving as inductors for common mode noise is called common mode impedance.

https://www.coilcraft.com/getmedia/9c231e30-04a2-4463-b679-c38b99b2669e/doc191_CMFiltDesign.pdf

Use of twisted wire pair





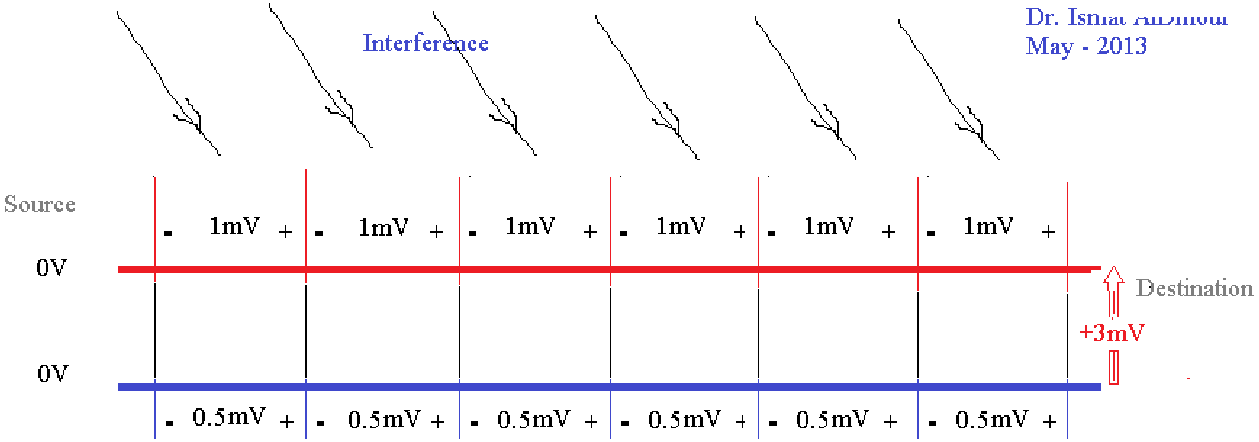


Figure 1: Parallel Pair, the interference causes higher pickup-voltages in red (closer) than blue wire.

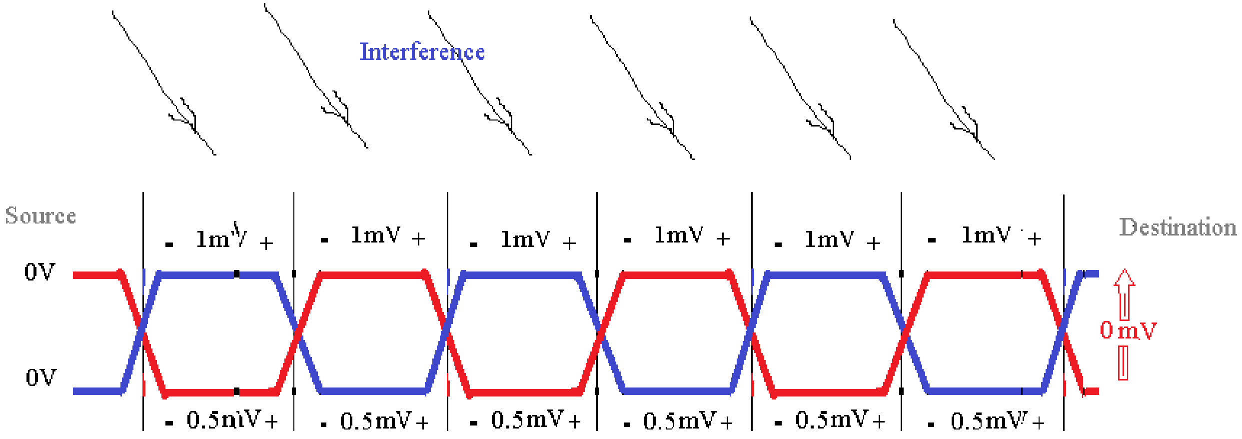
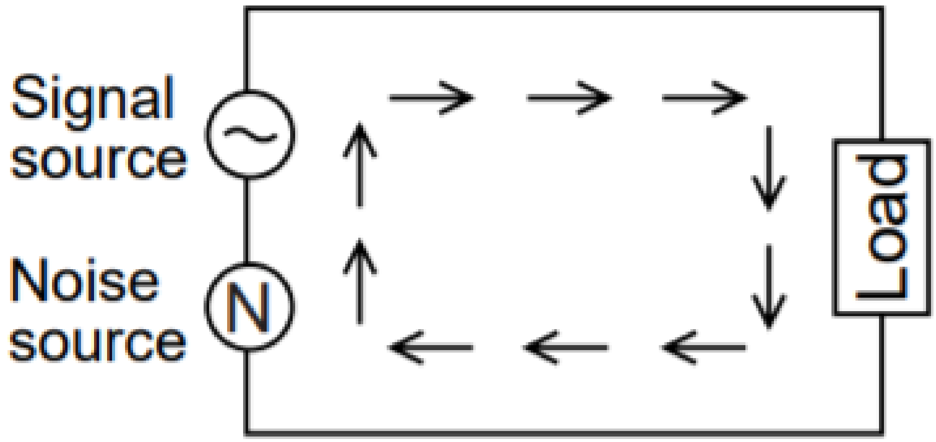


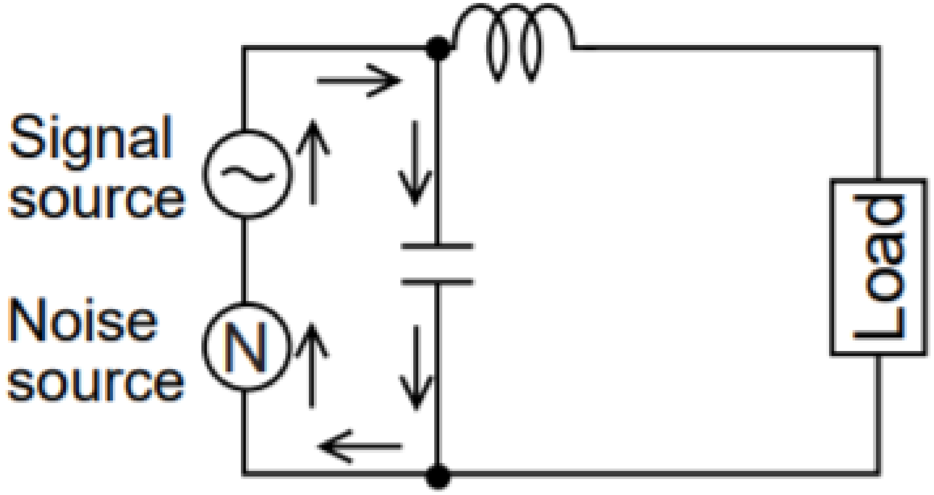
Figure 2: Twisted Pair, the interference alternatively produces high and low pickup-voltages in both wires.

Differential mode filter

- Differential mode noise

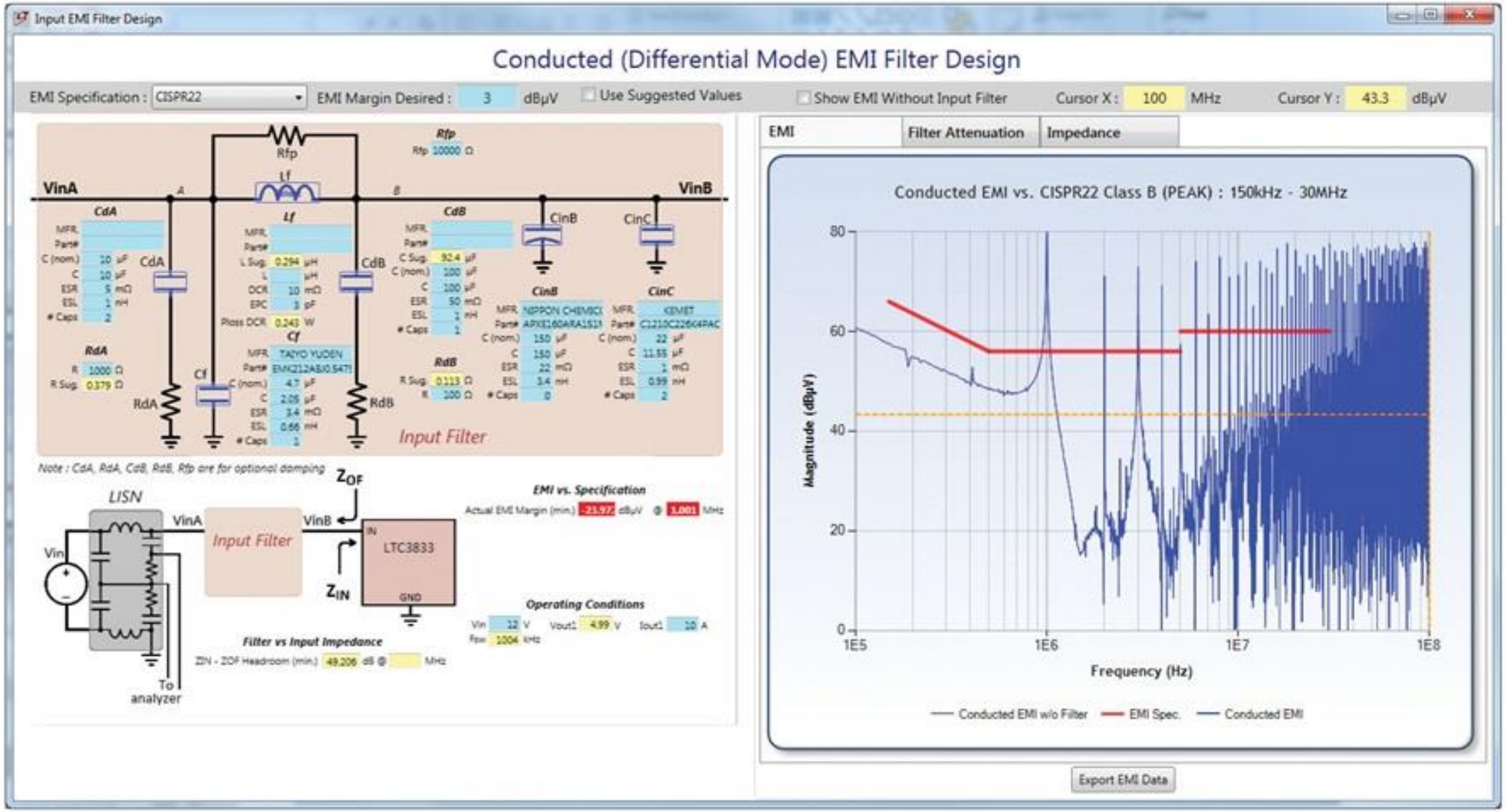


- Suppression method of differential mode noise



https://www.analog.com/media/en/analog-dialogue/volume-54/number-2/speed-up-the-design-of-emi-filters-for-switch-mode-power-supplies.pdf

Differential mode filter design tools



https://www.analog.com/en/lp/ltpowercad.html

https://webench.ti.com/power-designer/switching-regulator/customize/17

AEC-Q200 Qualification for Passives

- What it is : AEC-Q200 is a stress test qualification that ensures passive electronic components meet the requirements for automotive applications. It's governed by the Automotive Electronics Council (AEC).
- What it does : AEC-Q200 establishes standards for pressure resistance, temperature, and safety for passive components. It also specifies the test type, parameters, and quantity for each component.
- What it means : A component is considered "AEC-Q200 qualified" if it passes the stress tests in the AEC-Q200 standard. This certification is considered the industry standard for stress resistance.
- Benefits : AEC-Q200 certification simplifies the process for engineers by removing the need to determine component specifications.

http://www.aecouncil.com/Documents/AEC_Q200_Rev_E_Base_Document.pdf

AEC-Q200 Temperature Grades

Grade	Temperature Range	Types of Components	Typical Applications
0	-50°C to +150°C	Flat chip ceramic resistors, X8R ceramic capacitors	All automotive
1	40°C to +125°C	Capacitor networks, resistors, inductors, transformers, thermistors, resonators, crystals and varistors, all other ceramic and tantalum capacitors	Most underhood
2	-40°C to +105°C	Aluminum electrolytic capacitors	Passenger compartment hot spots
3	-40°C to +85°C	Film capacitors, ferrites, R/R-C networks and trimmer capacitors	Most passenger compartment
4	0°C to +70°C		Non-automotive

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