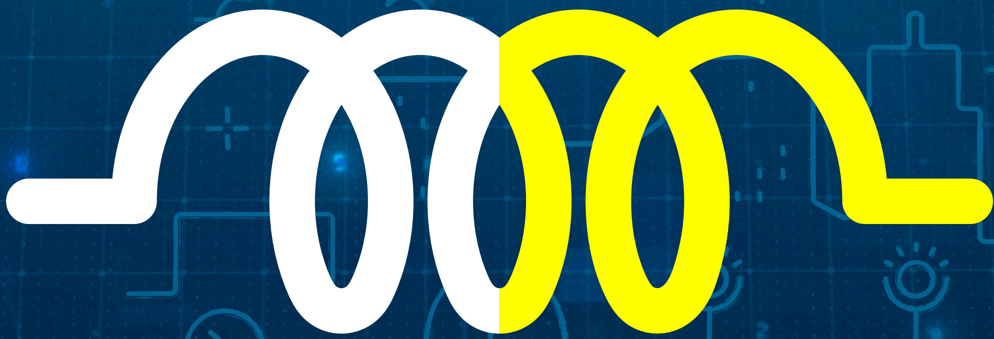
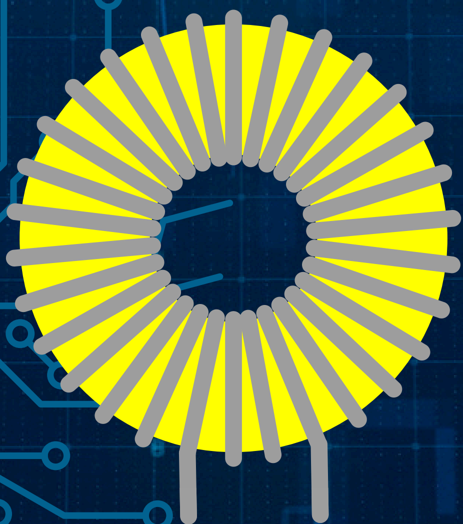
INDUCTOR





By Bargunan Ponnusamy

INDUCTOR FUNDAMENTALS

INDUCTOR

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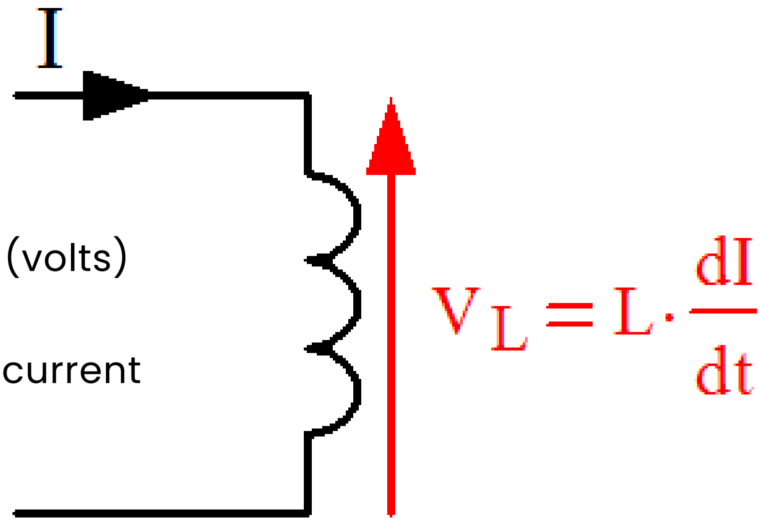
INDUCTOR FUNDAMENTALS

Basic Physical Principles

An inductor is a passive electronic component that stores energy in a magnetic field when electric current flows through it. The fundamental property of an inductor is its ability to resist changes in current. This resistance to current change is quantified as inductance, measured in henries (H).

The basic relationship is defined by Faraday's Law & Lenz's law:

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



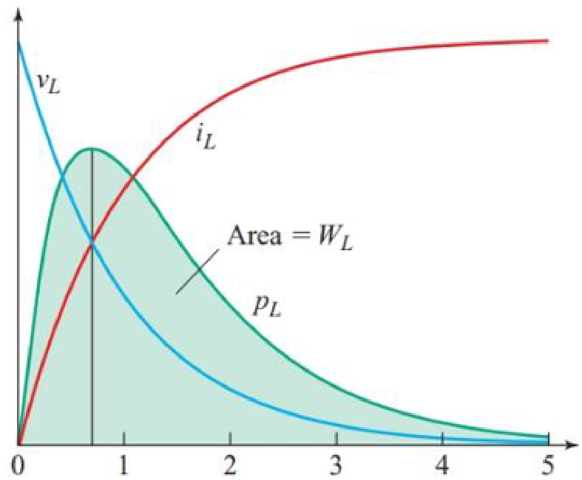
Where:
V = voltage across the inductor (volts)
L = inductance (henries)
dI/dt = rate of change of current (amperes per second)

Magnetic Field and Energy Storage

When current flows through an inductor, it creates a magnetic field around the conductor. This stored energy property is what makes inductors essential in filtering, energy transfer, and power conversion applications.

The energy stored in this magnetic field is:

$$E = \frac{1}{2} L I^2$$



Where:
E = energy (joules)
L = inductance (henries)
I = current (amperes)

INDUCTOR FUNDAMENTALS

Self-Inductance

Self-inductance is the property of a single inductor (coil) where a changing current in the coil induces a voltage (electromotive force, EMF) in the same coil.

Formula:

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

Where:

- V = Induced voltage (Volts)
- L= Inductance (Henries)
- (dI/dt) = Rate of current change (Amps per second)

Example:

- Inductors in power supplies: When current changes rapidly, the inductor opposes the change by inducing a voltage in itself.
- Flyback in MOSFETs: When switching off, the inductor's self-induced voltage causes voltage spikes.

Mutual Inductance

Mutual inductance occurs when two or more coils are magnetically coupled, and a changing current in one coil induces a voltage in another nearby coil.

Formula:

$$V_{induced} = M \times \frac{dI}{dt}$$

Where:

- M = Mutual inductance (Henries)
- (dI/dt) = Rate of current change in the first coil

Example:

- Transformers: Primary coil's changing current induces voltage in the secondary coil.
- Wireless power transfer: Coils in chargers induce voltage in receiver coils via magnetic coupling.

**Transformers will be discussed in a different Guide*

TIME CONSTANT OF AN INDUCTOR

The time constant (τ) of an RL circuit defines how quickly the current rises or falls in the circuit when power is applied or removed.

$$T = \frac{L}{R}$$

Where:

- T = Time constant in seconds (s)
- L = Inductance in Henrys (H)
- R = Total series resistance in Ohms (Ω)

Key Behavior:

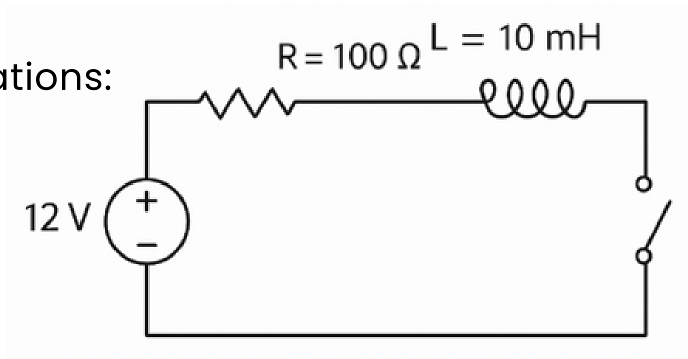
- In one time constant (τ), the current changes by about 63.2% of its final value.
- In five time constants (5τ), the current is considered to have fully stabilized (~99.3% of its final value).

Ex1: Relay Coil Activation

Problem:

A relay coil has the following specifications:

- Inductance L=10 mH
- Coil resistance R=100 Ω
- Applied voltage V=12 V



Calculation:

$$T = \frac{L}{R} = \frac{10\times10^{-3}}{100} = 0.0001s = 100\mu s$$

Interpretation:

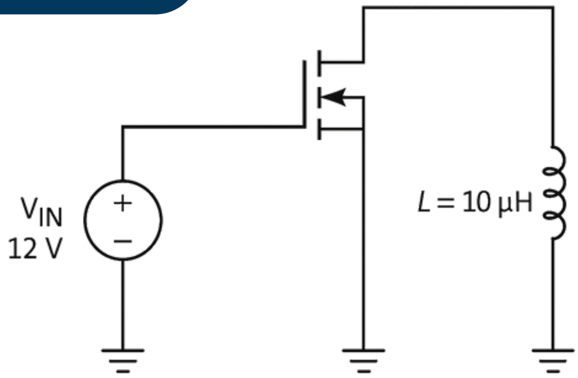
- In 100 μs, the coil current will reach about 63.2% of its maximum value.
- The relay will typically activate within 3 to 5 time constants (300 – 500 μs).

TIME CONSTANT OF AN INDUCTOR

Ex2: Buck Converter Inductor Charging

A buck converter uses an inductor with:

- Inductance L=22 μH
- Series resistance R=0.05 Ω



Calculation:

$$T = \frac{L}{R} = \frac{22\times10^{-6}}{0.05} = 0.00044s = 440\mu s$$

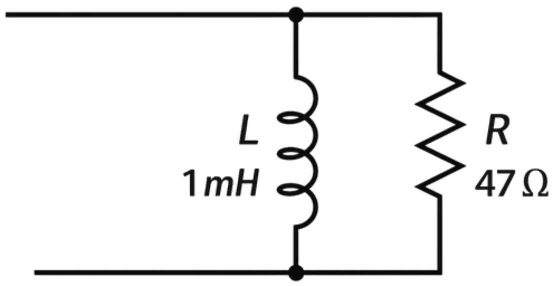
Interpretation:

- In 440 μs, the current will reach about 63.2% of its target (steady-state) current during the ON phase.
- The time constant directly affects ripple current and switching behavior in power supplies.

Ex3: 4: Snubber Circuit Decay

Snubber circuit across a relay uses:

- Inductor L=1 mH
- Resistance R=47 ΩR



Calculation:

$$T = \frac{L}{R} = \frac{1\times10^{-3}}{47} \approx 21.3\mu s$$

Interpretation:

- In 440 μs, the current will reach about 63.2% of its target (steady-state) current during the ON phase.
- The time constant directly affects ripple current and switching behavior in power supplies.

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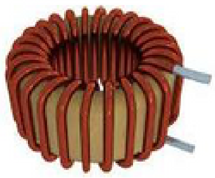
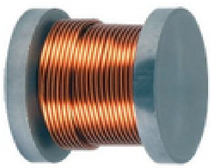
INDUCTOR TYPES

Core Types

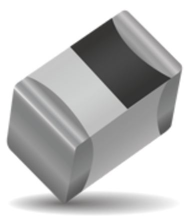
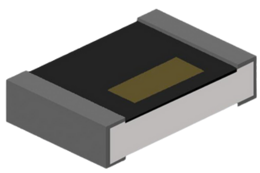
Core Type	Permeability	Density	Core Loss	EMI	Typical Applications
Air	Low	None	Minimal	Low	RF circuits, high-frequency applications
Powder	Medium	Medium	Medium	Low	Power supplies, lower frequency filtering
Ferrite	High	Medium-High	Low to Medium	Medium	General purpose, switching power supplies
Ceramic	Low	None	Very Low	Low	High-frequency applications, RF

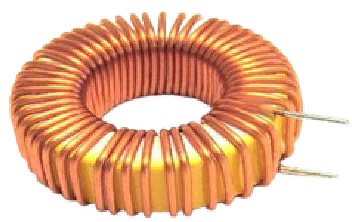





Construction Type

Inductors are built in various ways to balance performance, size, and cost. The following are common construction methods with their benefits and trade-offs.

Type	Structure	Pros	Cons	Typical Use Cases
Wirewound	Wound wire/core	High Q, handles high current	Large size, costly	Power circuits, RF applications
Multilayer	Printed layers	Small size, high-frequency	Low Q factor	RF circuits, filters
Thin-film	Deposited film	Precise, excellent for RF	Low current capability	Precision RF circuits
SMD	Flat package	Compact, auto-assembly	Lower power capacity	PCB applications, mass production
Axial/Radial	Leaded	Easy for prototyping	Bulky	Thru-hole assembly, prototypes
Toroidal	Ring core	Low EMI emissions	Difficult to wind	Power circuits, EMI suppression



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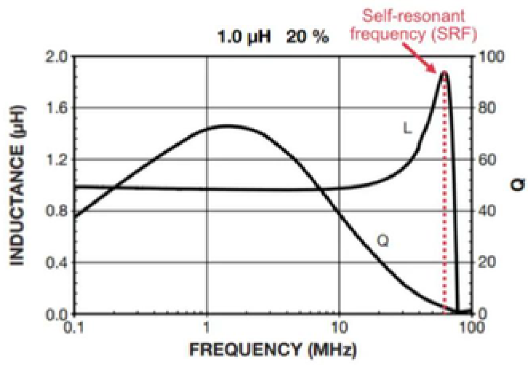
KEY PARAMETERS

Primary Electrical Parameters

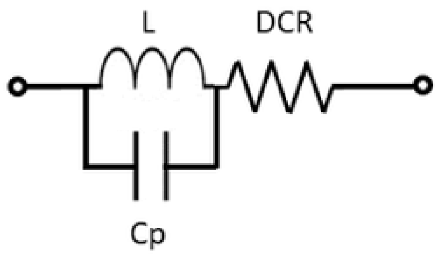
Inductance Value (L)

- Inductor's ability to store energy.
- Units: Henry [H]
- Typical Tolerance: ±5%, ±10%, or ±20%



Self-Resonant Frequency (SRF)

- Frequency {Where Cp resonates}
- Above SRF - Inductor behaves capacitively
- Affected By: Winding / Core / Dimensions



DC Resistance (DCR)

- Resistance of the conductor material at DC
- Determines conduction losses (I^2R)
- Typically specified at 25°C

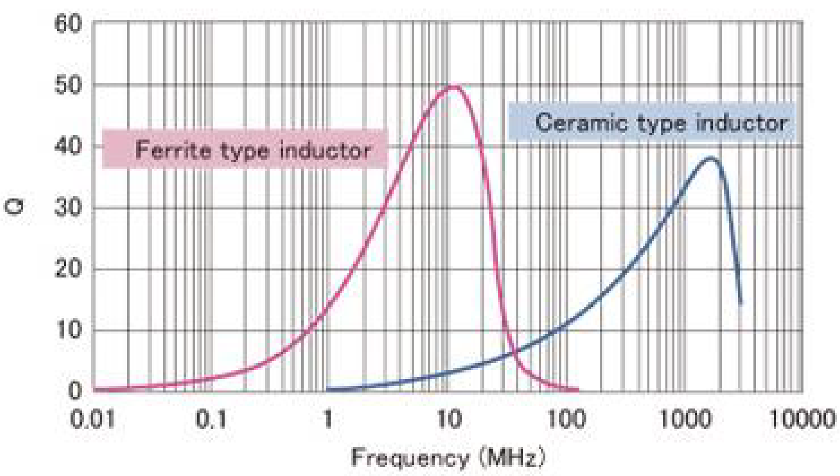
Quality Factor

Higher Q means lower losses and narrower bandwidth

$$Q = \omega L / R$$

Where:

- $\omega = 2\pi f$ (angular frequency)
- L = inductance
- R = effective resistance at frequency f



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KEY PARAMETERS

Mechanical and Environmental Parameters

Physical Dimensions

- Size (length, width, height)
- Weight
- Mounting requirements
- Terminal type and spacing

Environmental Ratings

- Operating Temperature Range: Typically -40°C to +85°C or +125°C
- Storage Temperature Range: Often wider than operating range
- Humidity Resistance: Sealed vs. open construction
- Shock and Vibration Rating: Important for automotive and industrial applications
- IP Rating: For harsh environment applications

Advanced Specifications

Temperature Dependence

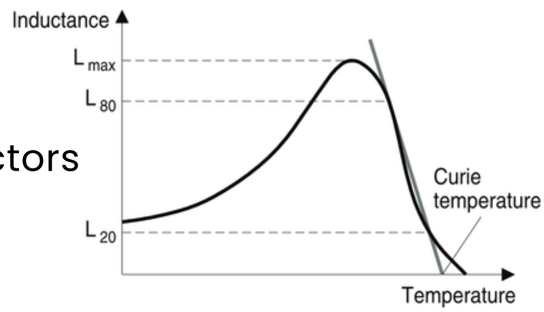
- Temperature Coefficient of Inductance (TCL): Change in inductance per degree C
- Temperature Rise: Self-heating at rated current
- Curie Temperature: Magnetic core becomes paramagnetic

Frequency Characteristics

- Impedance vs. Frequency Graph: Shows behavior across frequency range
- Inductance vs. Frequency: Typically decreases at higher frequencies
- AC Resistance (RAC): Effective resistance at specific frequencies

Magnetic Shielding

- Shielded vs. Unshielded: EMI Impact
- Coupling Coefficient: For coupled inductors
- Magnetic Field Strength: By distance



BEHAVIOR IN DIFFERENT FREQUENCIES

Frequency Range	Inductor Behavior	Key Consideration
DC (0 Hz)	Acts like a short circuit	Passes steady current
Low Frequency	Low impedance, increasing with f	Useful for filtering
High Frequency	High impedance, may block signals	Effective for EMI suppression
Near SRF	Resonates, impedance drops	Potential signal integrity issue
Above SRF	Behaves like a capacitor	Parasitic effects dominate

Impedance of an Inductor

$$\boxed{Z_L = j\omega L = j2\pi f L}$$

Where:

- ZL = Inductive reactance (Ohms)
- f = Frequency (Hz)
- j = Imaginary unit

At higher frequencies, the inductor's opposition to current increases significantly.

DC (0 Hz) Behavior

At DC, an inductor behaves like a short circuit because:

- The inductor resists changes in current but does not resist steady current.
- The inductive reactance (XLX_LXL) is zero at DC:

$$\boxed{Z_L = 2\pi f L = 0\Omega} \quad \text{(when f=0)}$$

Real-World Implication:

- After the transient phase, a DC current will flow freely through an inductor.
- Example: In a power supply, the inductor will pass steady-state current with minimal voltage drop.

BEHAVIOR IN DIFFERENT FREQUENCIES

Low-Frequency Behavior

At low frequencies (tens of Hz to a few kHz):

- The inductor presents low but increasing impedance.
- The voltage across the inductor starts to rise with increasing frequency.

$$\boxed{Z_L = 2\pi f L}$$

Real-World Implication:

- In low-frequency AC circuits, inductors can be used to block or filter out higher-frequency signals.
- In power line filters (50/60 Hz), inductors offer some opposition to current changes but allow reasonable conduction.

High-Frequency Behavior

At high frequencies (kHz to MHz and above):

- The inductor's reactance increases significantly.
- The inductor behaves like an open circuit to high-frequency signals.

$$\boxed{Z_L = 2\pi f L} \quad \text{(large value)}$$

Key Effects:

- Inductors can block or attenuate high-frequency signals effectively.
- Parasitic capacitance and self-resonance start to dominate beyond a certain frequency.

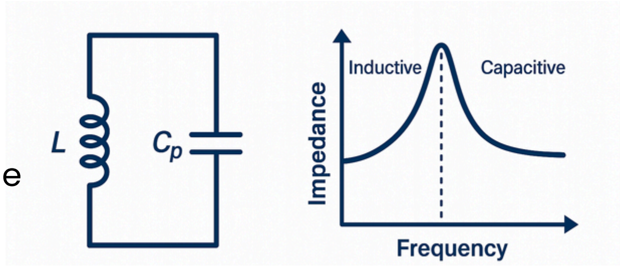
BEHAVIOR IN DIFFERENT FREQUENCIES

Self-Resonant Frequency (SRF)

Every real-world inductor has some parasitic capacitance. At a specific frequency, the inductor's reactance and its parasitic capacitance cancel each other, forming the self-resonant frequency (SRF).

$$f_{SRF} = \frac{1}{2\pi\sqrt{LC_p}}$$

Where:
L = Inductance
Cp = Parasitic capacitance



Behavior at SRF:

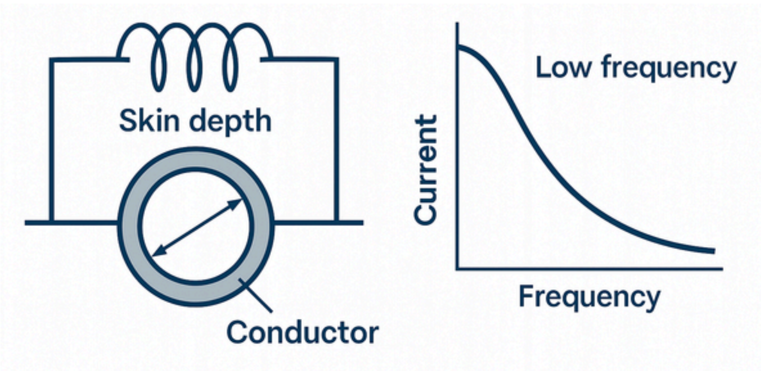
- **Below SRF:** The inductor is inductive (normal behavior).
- **At SRF:** The inductor's impedance is minimal (resonance point).
- **Above SRF:** The inductor starts behaving like a capacitor.

Skin Effect at High Frequencies

At high frequencies, the current tends to flow near the surface of the conductor (skin effect), effectively increasing the resistance and power loss of the inductor.

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}}$$

Where:
- δ = Skin depth
- ρ = Resistivity of the conductor
- μ = Magnetic permeability
- ω = Angular frequency



Result:

- Higher AC resistance compared to DC resistance.
- Increased power dissipation.

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BEHAVIOR IN DIFFERENT FREQUENCIES

Low Frequency Behavior (DC to 100kHz)

Core Materials for Low Frequency:

Material	Advantages	Disadvantages	Best Applications
Silicon Steel	High saturation, Low cost	High losses above 10 kHz	Line frequency, High power
MPP (Molypermalloy)	Excellent DC bias, Low loss	Higher cost	High current DC filters
Sendust	Good saturation, Moderate cost	Higher loss than MPP	General purpose power
High Flux	Very high saturation	Moderate loss	High current inductors

Design Considerations:

- Core losses generally less significant
- DC resistance dominates losses
- Low Skin effect below 50kHz
- Larger wire gauge practical
- Thermal management focused on I^2R losses

Medium Frequency Behavior (100kHz to 1MHz)

Core Materials for Medium Frequency:

Material	Advantages	Disadvantages	Best Applications
MnZn Ferrite	Low loss, High permeability	Lower saturation	Most switching power supplies
Iron Powder	Good DC bias, Cost-effective	Higher core loss	Buck converters, Output filters
Kool Mμ	Better than iron powder, Lower loss	Higher cost than powder	Higher frequency DC-DC converters

Design Considerations:

- Balance between copper and core losses
- Skin effect becomes significant (wire selection critical)
- Parasitic capacitance effects emerge
- EMI considerations become important
- Thermal management must address both copper and core losses

BEHAVIOR IN DIFFERENT FREQUENCIES

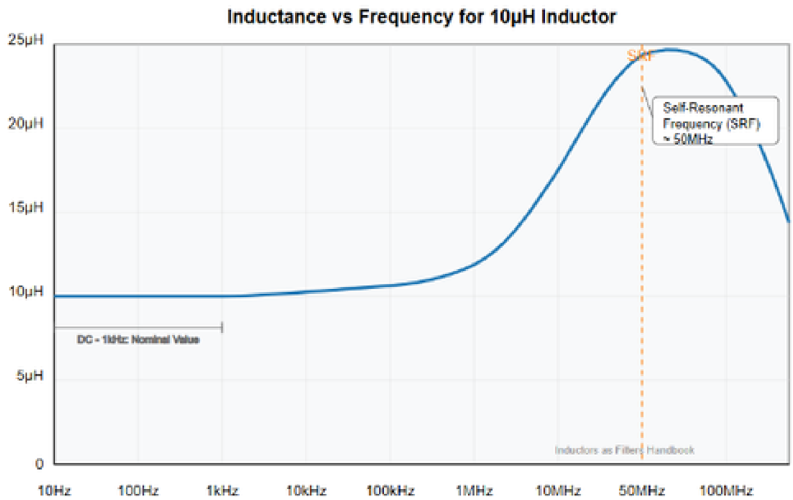
High Frequency Behavior (1MHz to 100MHz)

Core Materials for High Frequency:

Material	Advantages	Disadvantages	Best Applications
NiZn Ferrite	Low loss at high frequency	Lower permeability	RF applications, EMI filters
Air Core	No core losses, No saturation	Very low inductance density	RF circuits, VHF applications
Micrometals	Good Q, Temperature stable	Limited shapes	RF power, Resonant circuits

Design Considerations:

- Parasitic capacitance becomes dominant concern
- Skin and proximity effects dominate copper losses
- Litz wire is often necessary
- Self-resonant frequency critical
- Layout parasitic may exceed component values



Very High Frequency Behavior (>100MHz)

Core Materials for Medium Frequency:

- Air core spiral inductors
- Printed circuit inductors
- MEMS-based inductors
- Film inductors
- Integrated circuit inductors

Design Considerations:

- Q factor typically lower
- Distributed parameters dominate
- Parasitic coupling to nearby components
- Modeling requires electromagnetic simulation
- Self-resonance often limits usable range

INDUCTOR SELECTION

Application Requirements Analysis

Requirement	Description	Typical Consideration
Inductance Value	Required inductance for circuit function	Based on operating frequency and circuit design equations
Current Rating	Maximum current inductor must handle	Consider both average and peak currents
Size Constraints	Maximum physical dimensions allowed	PCB space allocation, height restrictions
Frequency Range	Operating frequency of the circuit	Affects core material selection and construction
Temp. Range	Operating environment	Impacts material selection and derating
EMI Requirements	Electromagnetic interference concerns	May require shielded vs unshielded designs

Current Rating Selection

- Saturation Current > Maximum DC current + ½ ripple current
- RMS Current Rating > RMS current in application
- Peak Current Rating > Maximum transient current expected

Frequency Considerations

- Operating frequency should be at least 5-10× lower than SRF
- Core material should be optimized for operating frequency range

Physical and Environmental Factors

Footprint and Mounting

- Surface mount vs. through-hole requirements
- Height restrictions (z-height)
- Thermal management spacing needs

Environmental Stress Factors

- High ambient temperature (typically derate current by 1-2% per °C above 85°C)
- Humidity (sealed vs. open construction)
- Vibration environment (mechanical resonance concerns)

INDUCTORS IN DC-DC

Role of Inductors in DC-DC Converters

Inductors serve three critical functions in DC-DC converters:

- **Energy Storage:** Temporarily store energy during switching cycles
- **Current Smoothing:** Filter switching pulses to provide continuous output current
- **Voltage Transformation:** Enable step-up or step-down voltage conversion

Energy storage capability is what enables efficient power transfer between input and output:

- The energy storage capability of inductors is what allows efficient power transfer between input and output.
- The stored energy is given by the formula:

$$W = \frac{1}{2}LI^2$$

where:

W = energy stored (in joules)
L = inductance (in henries)
I = current (in amperes)

INDUCTORS IN DC-DC

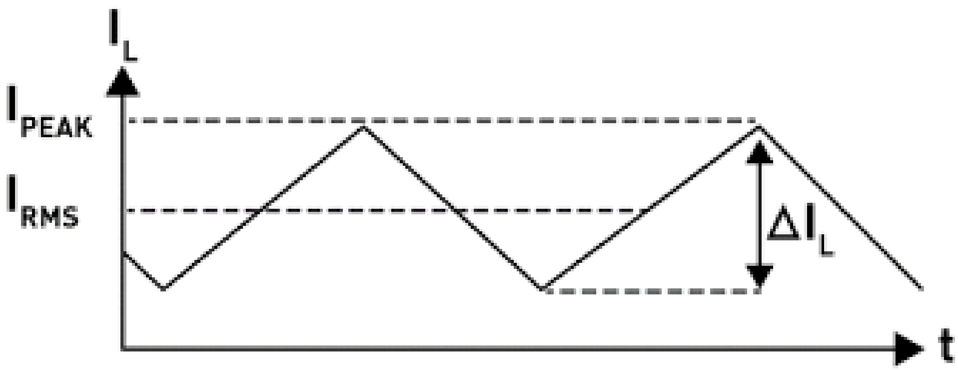
Current Ripple Calculation

Ripple current in Buck converter:

$$\Delta IL = (V_{in} - V_{out})\left(\frac{DutyCycle}{(f \times L)}\right)$$

Ripple current in Boost converter:

$$\Delta IL = V_{in}\left(\frac{DutyCycle}{(f \times L)}\right)$$



Impacts of Current Ripple

Impact Area	High Ripple	Low Ripple
Output Voltage Ripple	Higher	Lower
Inductor Size	Smaller	Larger
Core Losses	Higher	Lower
Transition between CCM/DCM	More likely at light loads	Stays in CCM to lower power
EMI Generation	Higher	Lower
Transient Response	Typically, faster	Typically, slower

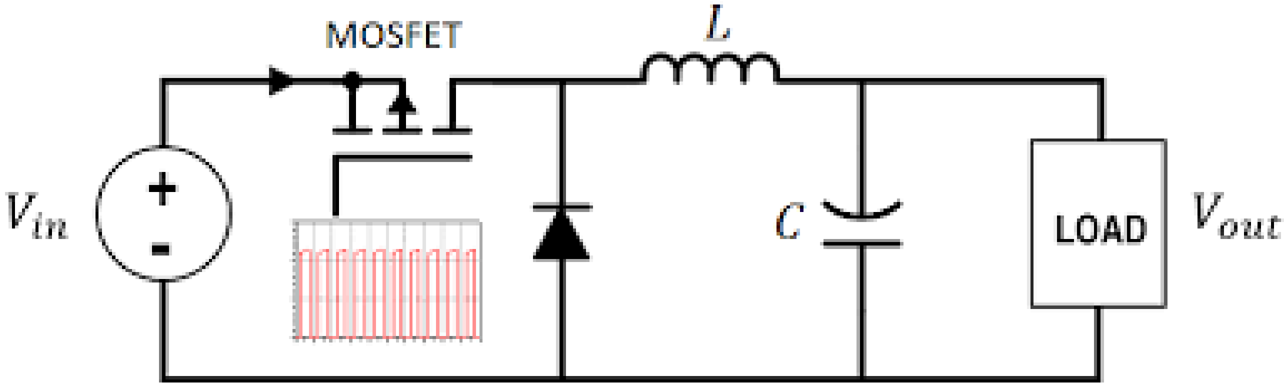
Impacts of Current Ripple

- General purpose: 20-40% of average current
- Low noise applications: <10% of average current
- Size-constrained applications: May accept 40-60%

Buck Converter (Step-Down)

Operation Principle:

- Switch is ON: Inductor charges from input voltage
- Switch is OFF: Inductor discharges to output



Inductor Behavior:

$$\boxed{V_{out} = DutyCycle \times V_{in}}$$

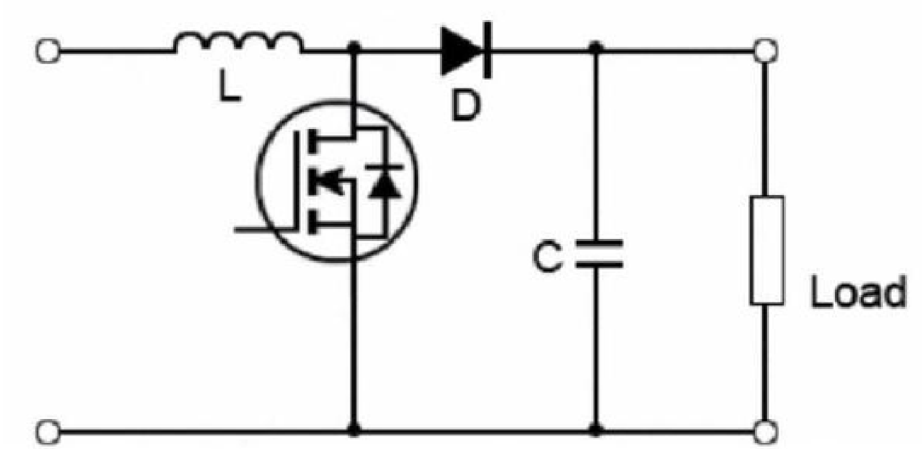
$$\boxed{L = \left(V_{in} - V_{out}\right)\left(\frac{DutyCycle}{(f \times L)}\right)}$$

- Current ramps up during ON time
- And down during OFF time

Boost Converter (Step-Up)

Operation Principle:

- Switch is ON: Inductor charges from input voltage
- Switch is OFF: Inductor voltage adds to input voltage producing higher output



Inductor Behavior:

$$\boxed{V_{out} = \frac{V_{in}}{(1 - DutyCycle)}}$$

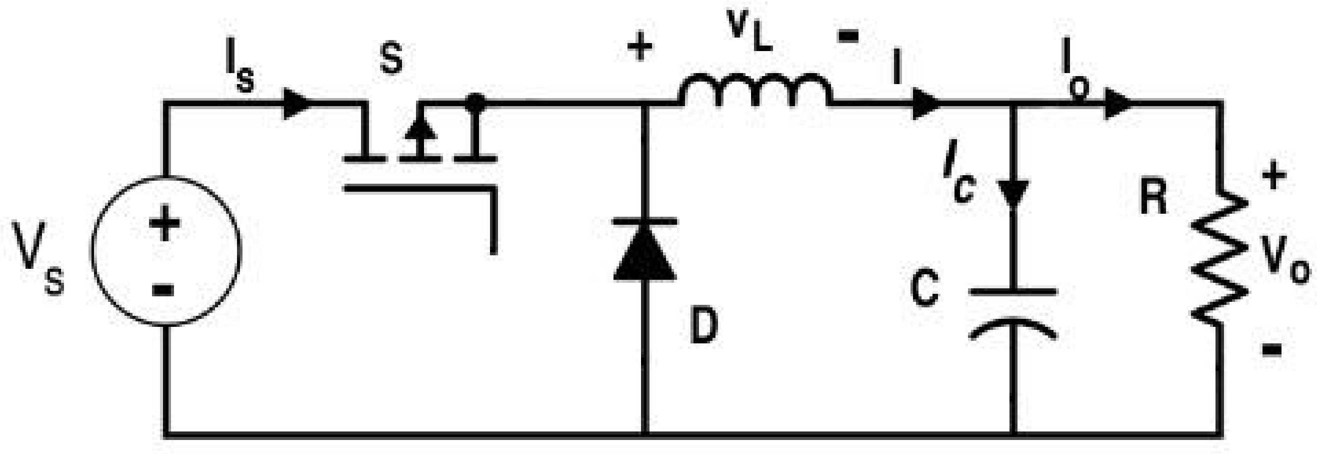
$$\boxed{L = DutyCycle \times \frac{V_{in}}{(f \times \Delta IL)}}$$

- Current ramps up during ON time
- And down during OFF time(to output)

Buck-Boost Converter

Operation Principle:

- Combined buck and boost operation
- Can produce output voltage higher or lower than input



Inductor Behavior:

$$V_{out} = -\, DutyCycle \times \frac{V_{in}}{(1-D)}$$

$$L = DutyCycle \times \frac{V_{in}}{(f \times \Delta IL)}$$

- Acts Like Boost but inverted output.

Conduction Modes

Continuous Conduction Mode (CCM)

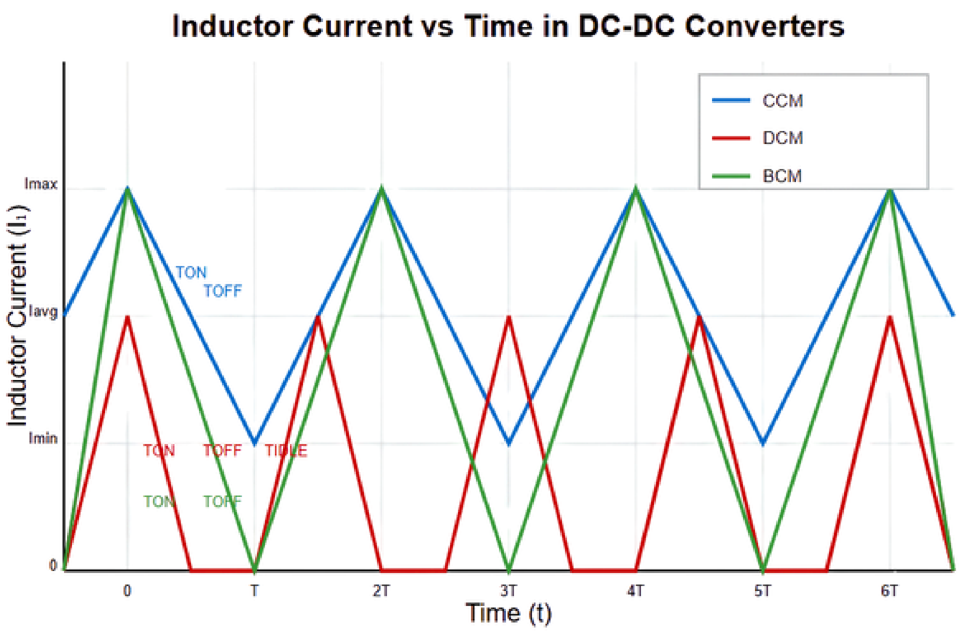
- Inductor current never falls to zero
- More efficient at higher loads
- Lower peak currents for same power delivery
- Requires Larger Inductance
- Smaller ripple on Voltage and Current

Discontinuous Conduction Mode (DCM)

- Inductor current falls to zero during part of switching cycle
- Typically occurs at light loads
- Higher peak currents
- Often simpler control implementation
- Allows use of smaller inductor and simpler control
- More EMI and noise due to abrupt transitions
- Poorer efficiency at high loads

Boundary Conduction Mode (BCM)

- Inductor current just reaches zero at end of switching cycle
- Also called Critical Conduction Mode
- Enables Zero Current Switching (ZCS)
- Tradeoff between CCM and DCM



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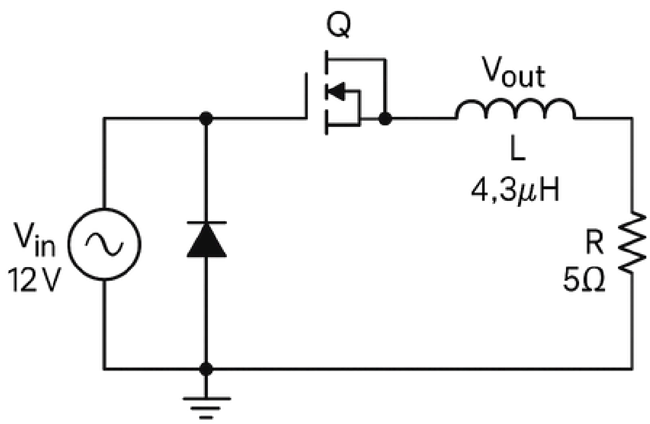
DESIGN EXAMPLE – INDUCTOR SELECTION

Inductor Selection – Buck Converter

Select the proper Inductor for the following Buck:

Parameter	Value	Units
Input Voltage	12	V
Output Voltage	33	V
Output Current	5	A
Switching Frequency	500	kHz
Ripple Current	30%	%
Ambient	85	°C



Calculate inductance:

$$\Delta IL = \left(V_{in} - V_{out}\right)\left(\frac{DutyCycle}{(f \times L)}\right) = (12 - 3.3)\left(\frac{0.275}{500kHz - 1.5A}\right) = 4.0\mu H$$

Calculate peak current:

$$I_{peak} = I_{out} + \frac{\Delta IL}{2} = 5A + \frac{1.5A}{2} = 5.75A$$

Core selection criteria:

$$I_{sat} > 1.3(spare) \times I_{peak} \Rightarrow 1.3 \times 5.75 = 7.5A$$

Core size determination:

$$W = \frac{1}{2}L \times \left(I_{peak}\right)^2 \Rightarrow \frac{1}{2}4\mu H \times (5.75)^2 = 66\mu J$$

DESIGN EXAMPLE – INDUCTOR SELECTION

Material:

AL value: $\frac{75\eta H}{turn^2}\sqrt{\left(\frac{L}{AL}\right)} \Rightarrow \sqrt{\left(\frac{4000\eta H}{75\eta H}\right)} = 7.3\ turns \Rightarrow 8\ turns$

Wire selection: AWG 18 (for current density ~400A/cm²)

Powder Core Selected: $T50-52B$ (Toroidal 0.5inch with Iron Powder)

Verification

DCR Calculation: $8\ turns \times 5.21m\Omega/cm \times\sim 4cm = 167m\Omega$

Power Loss $I^2R = (5A)^2 \times 0.167\Omega = 4.2W$

Temperature rise: 4.2W × 15°C/W = 63°C ($needs\ heat\ sinking$)

Performance Analysis:

Core loss at 500kHz: ~1.2W

Total losses: 5.4W

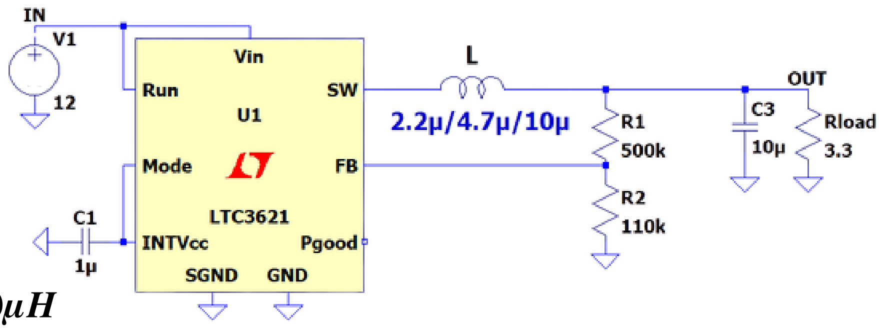
Efficiency impact: 3.2% loss at full load

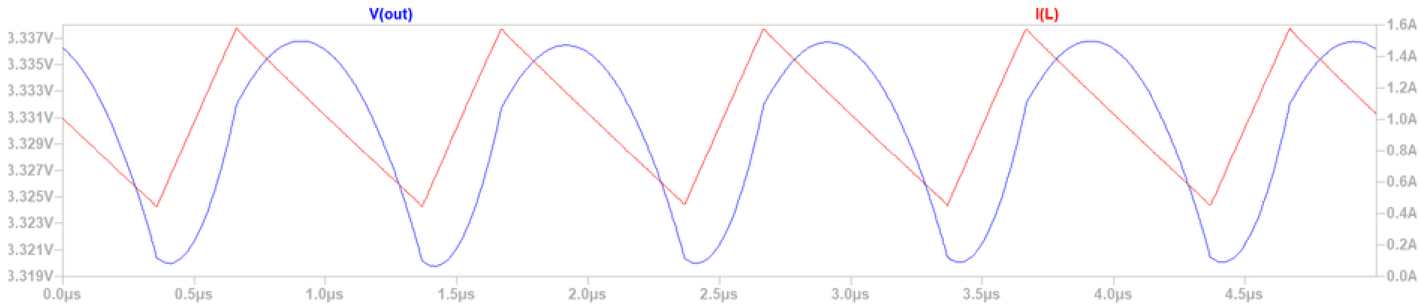
Alternative: MPP core would reduce losses by ~30%

LTSPICE SIMULATION

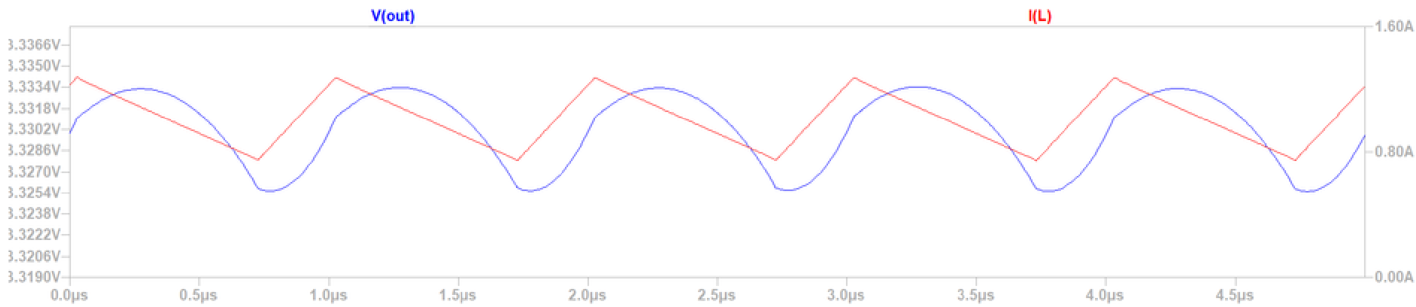
Inductor Effect on Buck Converter

- Buck Converter (LTC3621):
- Input: 12V
- Output: 3.3V
- Current: 1A
- Load: 3.3Ω
- Inductor (L): $2.2\mu H / 4.7\mu H / 10\mu H$

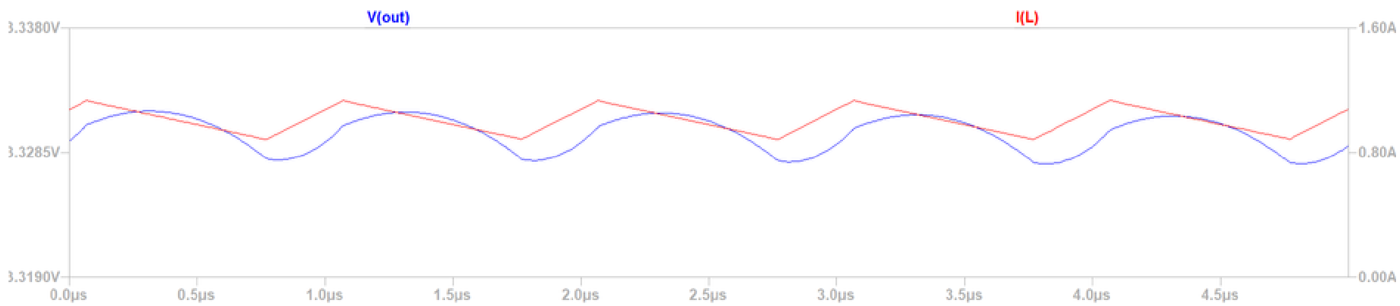




$L = 2.2\mu H$ | $\Delta IL = 1.1A$ | $\Delta Vout = 17mV$



$L = 4.7\mu H$ | $\Delta IL = 0.75A$ | $\Delta Vout = 8mV$



$L = 10\mu H$ | $\Delta IL = 0.25A$ | $\Delta Vout = 4mV$

- Bargunan Ponnusamy