PSMA

Basics of Magnetics for Switching Power Webinar Series

Basics of Power Inductors

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Presenter: George Slama, Wurth Electronics

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Basics of Power Inductors

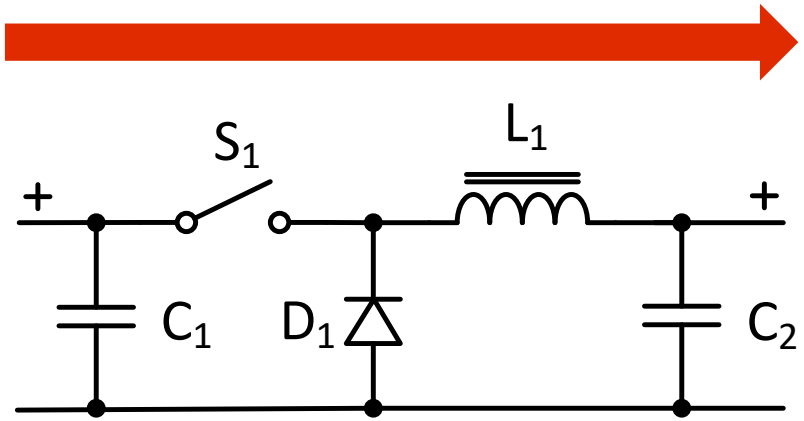
George Slama
Senior Application and Content Engineer
Würth Elektronik

Today’s outline

- What’s so important about inductors?
- The laws that govern magnetics
- Core materials and characteristics
- Energy storage and gaps
- Inductors in converters
- Saturation current
- Rated current
- Frequency
- Temperature
- Coupled inductors
- Flyback ‘transformers’

What’s so important about inductors?

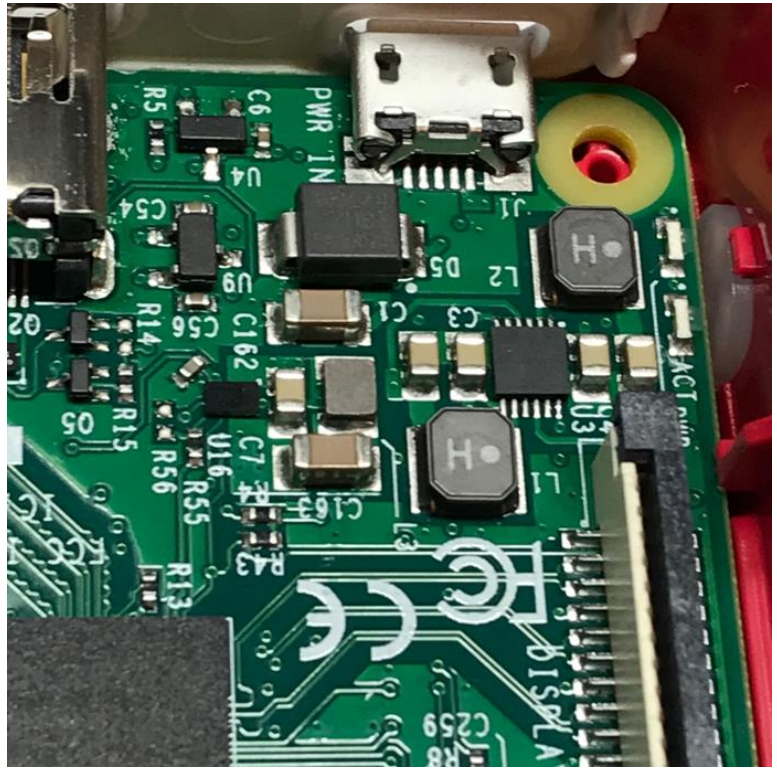
3.7 V



1.0 V

What’s so important about inductors?

- Buck regulators make up the vast majority switch mode power supplies
- Therefore it is important to understand how they work and the impact of their characteristics on the power supply circuit
- Most courses in electrical engineering give little time to magnetic devices
- To be a good power supply designer, you must understand how all the key components work and interact with each other in the power system



Key points about inductors

- Inductors oppose changes in current flow
- Current in an inductor cannot change instantaneously but changes with time however the voltage, including polarity can change instantly
- In switching circuits applying a rectangular wave voltage causes a linearly increasing current ramp called magnetizing current
- Magnetizing currents create magnetic fields
- Magnetic fields store energy
- Inductors are temporary energy storage devices
- Used in low pass filters with capacitors for current and voltage smoothing
- A saturated inductor acts like a piece of wire (dc resistance only)

System of units

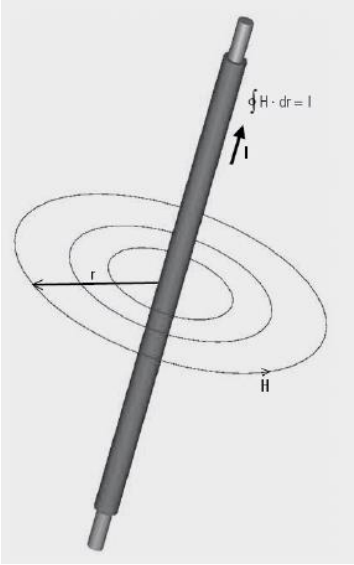
Symbol	Name of Quantity	SI Units	CGS Units	CGS►SI
Φ	Total magnetic flux (V·s)	Weber (Wb)	Maxwell (Mx)	$x10^{-8}$
B	Magnetic flux density (magnetic induction)	Tesla (T) Wb/m^2	Gauss (G)	$x10^{-4}$
F	Magnetomotive Force (MMF) Total Field	A·T	Gilbert (Gb)	x10/4π
H	Magnetic field intensity (strength)	A·T/m	Oersted (Oe)	x79.578
R	Reluctance (F/Φ)	A·T/Wb	Gb/Mx	$x79.578x10^{6}$
L	Inductance	Henry (H)	Henry (H)	=
μ	Permeability (B/H)	$4\pi\cdot10^{-7}$	1	$x1.257x10^{-6}$
W	Energy	Joule (J)	Erg	$x10^{-7}$

The laws

- Biot-Savart law (1820)

  The magnetic field generated by a current varies directly with the current intensity and inversely to the distance from the conductor.

$$H = \frac{I}{2\pi r}$$

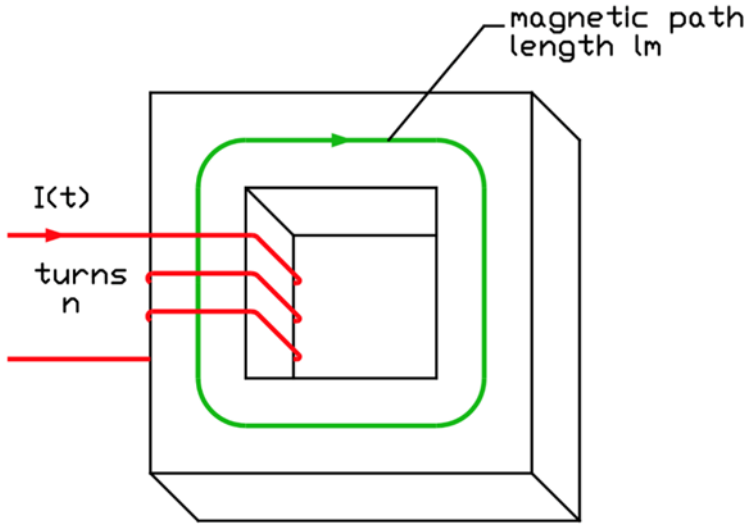


- Ampere's law (1826)

  The net magnetomotive force (MMF) around a closed path is equal to the total current passing through the interior of the path.

$$F = \oint_{closed\ path} H dl = NI$$

$$H = \frac{N \cdot I}{l_e}$$

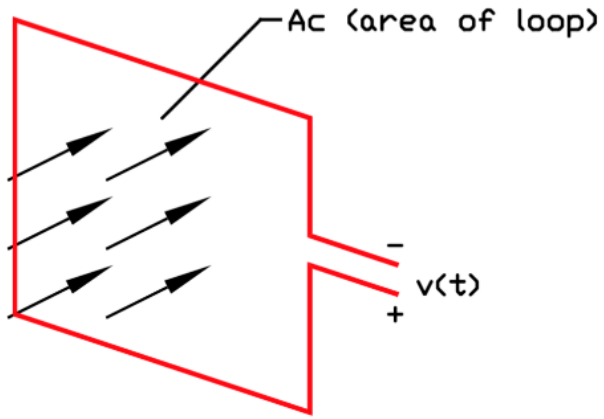


More laws

- Faraday's law (1831)

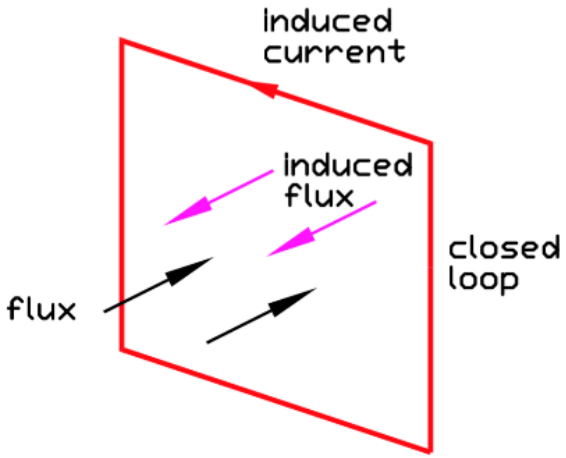
  The magnitude of the induced emf is proportional to the rate of change of the magnetic flux.

$$V(t) = -N\frac{d\Phi}{dt} \qquad B_{max} = \frac{E \cdot dt}{A \cdot N}$$



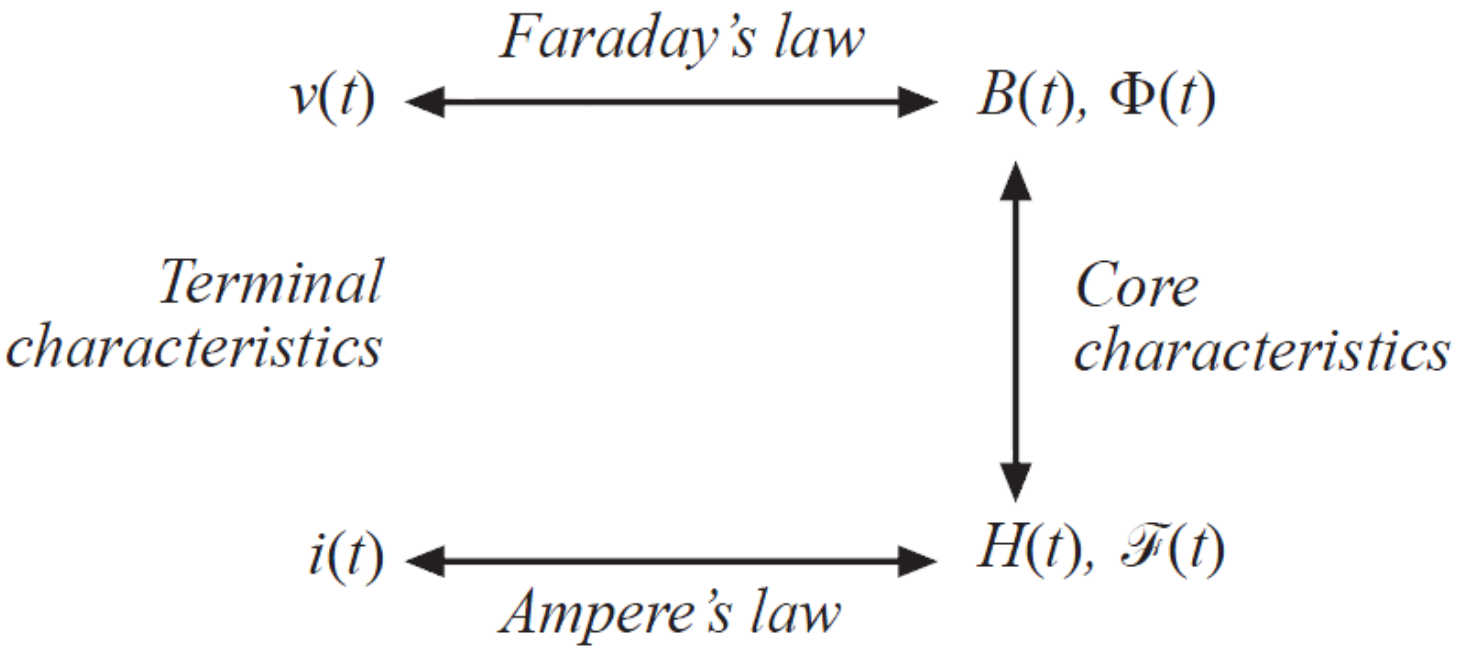
- Lenz's law (1834)

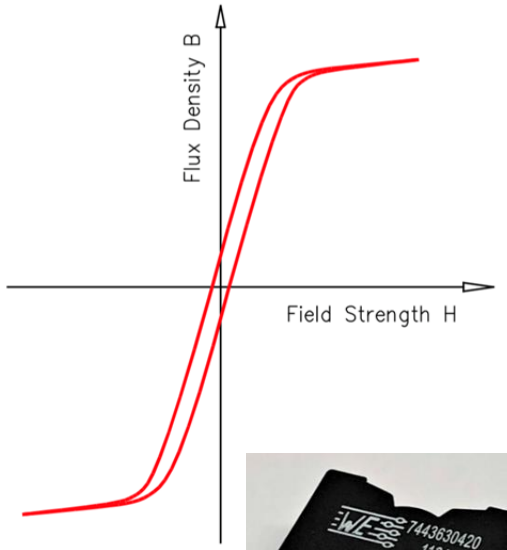
  An induced electric current always flows in such a direction that it opposes the change producing it.



Connect the dots

4.2 µH
30 A



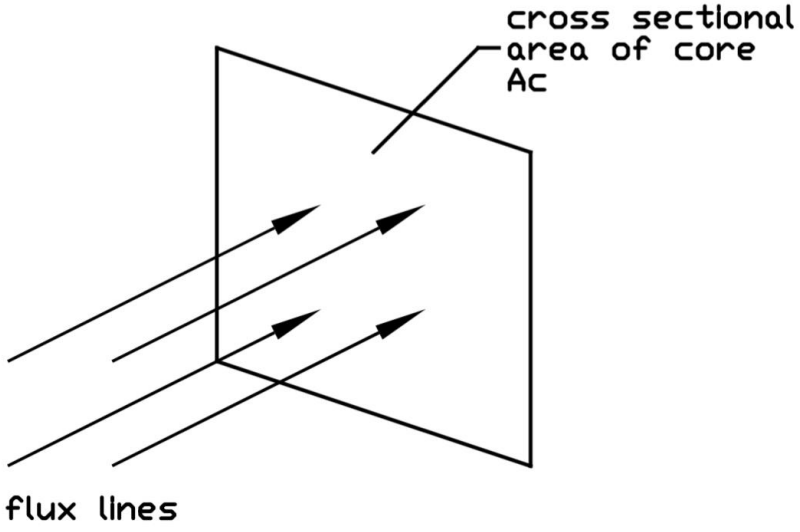


PQ 2014
7 turns

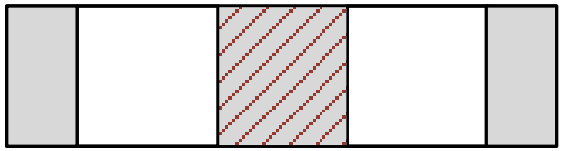
Total flux (Φ), flux density (B)

The total magnetic flux Φ passing through an area A_e is related to the flux density B according to

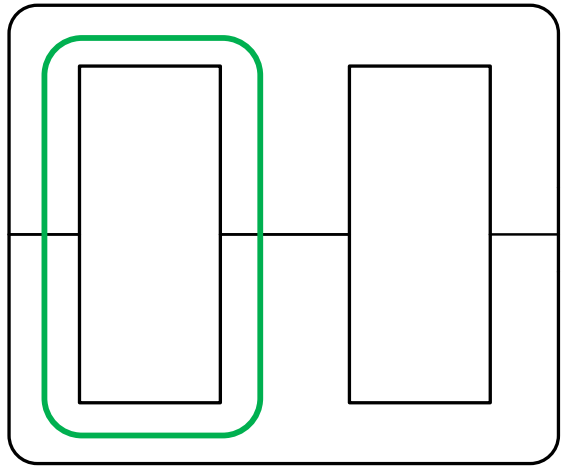
$$\Phi = \int_{surface} B \cdot dA$$



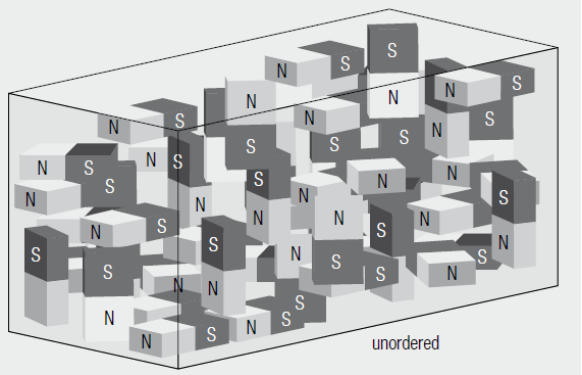
A_e – Cross-sectional Area

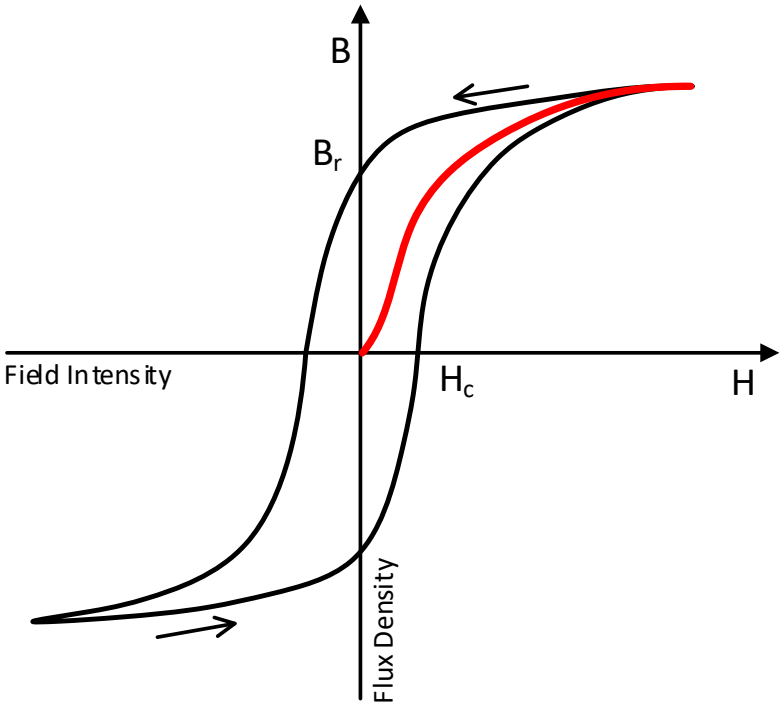


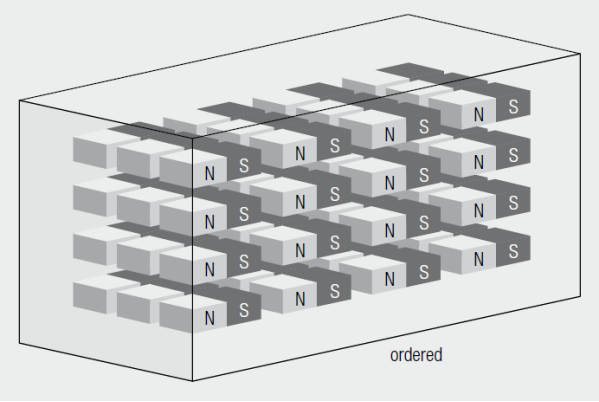
l_e – magnetic path length



Elemental magnetics

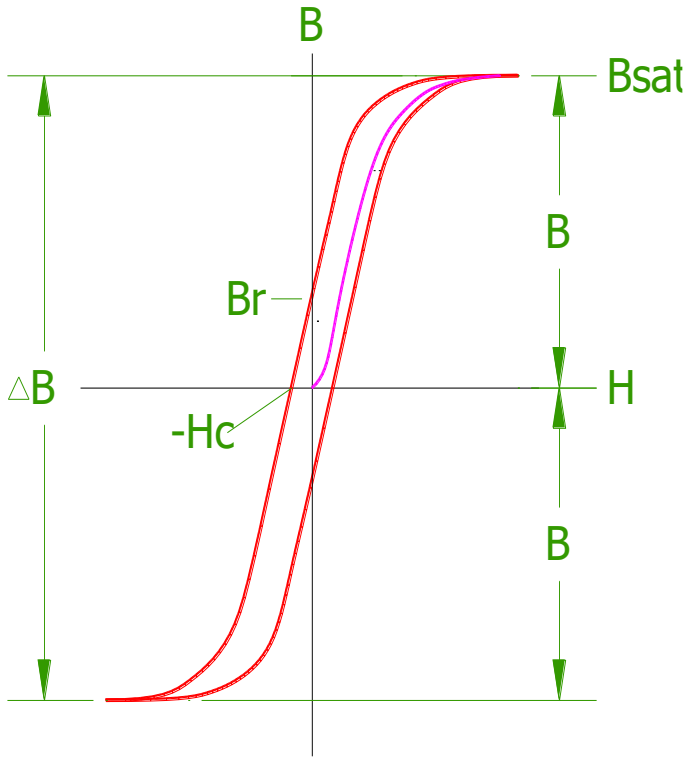


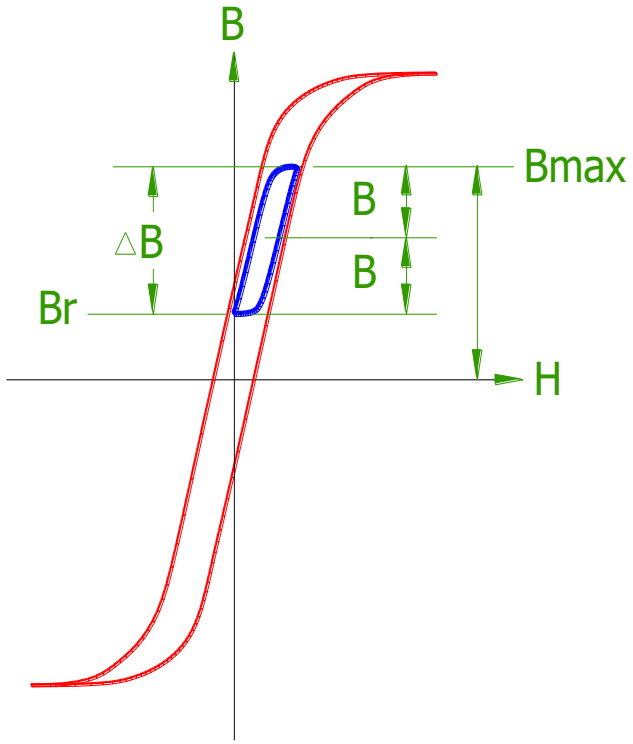




B-H Curve Terms

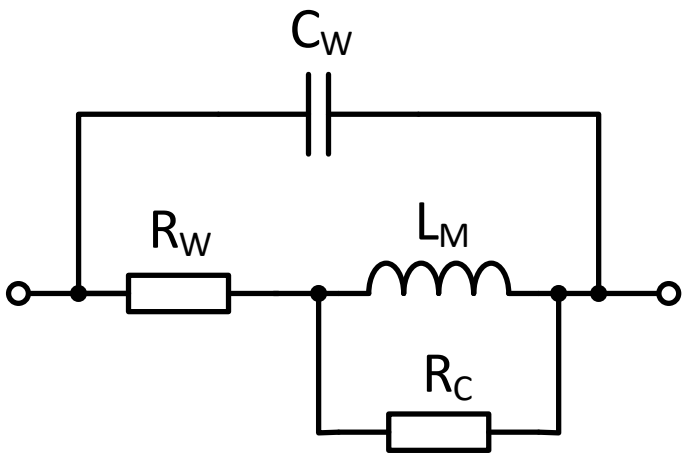
- ΔB = total flux swing (pk to pk)
- B = one half ΔB
- B_{pk} , B_{max} = flux swing from zero
- B_{sat} = flux saturation level
- B_r = remanence - flux at zero H
- H_c = coercivity – field strength at zero B





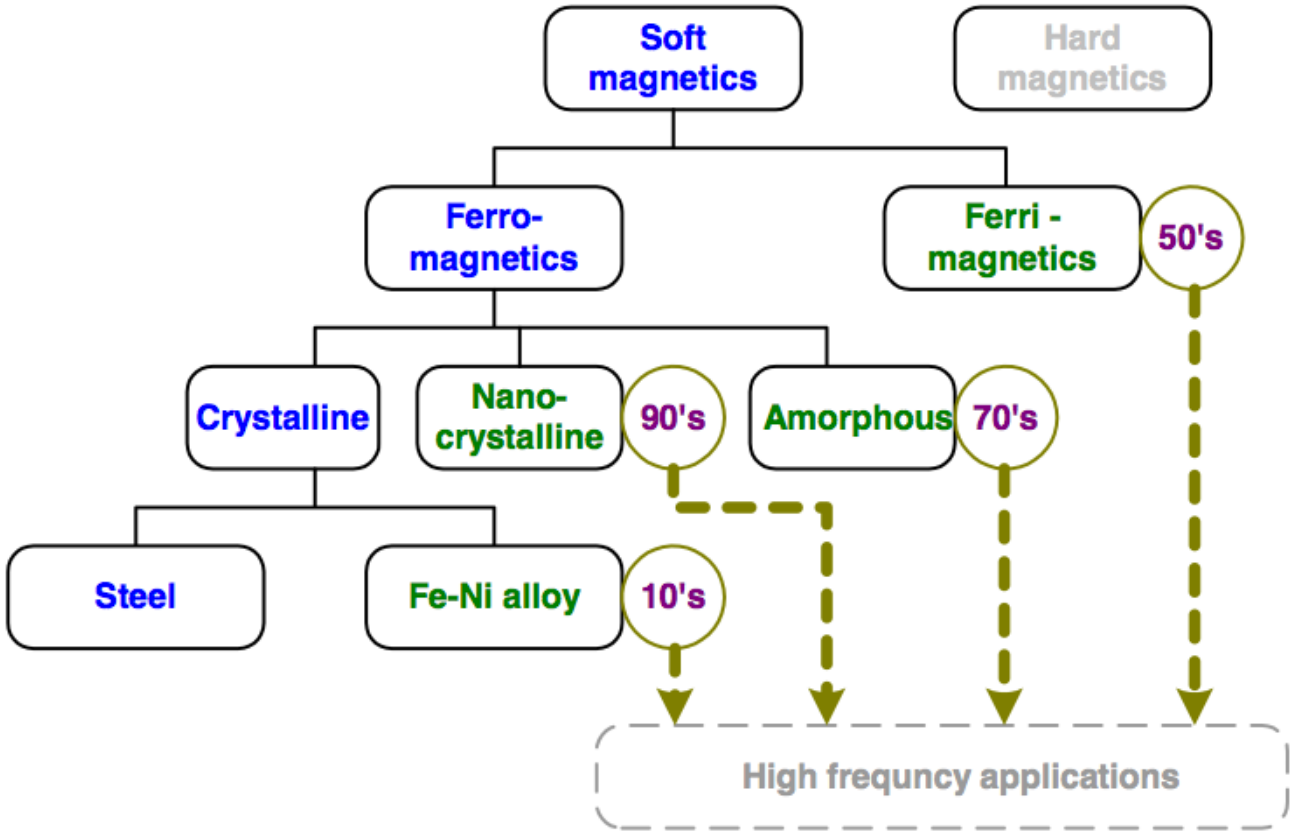
The B-H curve shows flux density as a function of an applied magnetic force.

Inductor equivalent circuit



- R_W – dc winding resistance + ac losses from skin & proximity effects
- C_W – winding self capacitance
- R_C – core losses
- L_M – magnetizing inductance

Overview of core materials

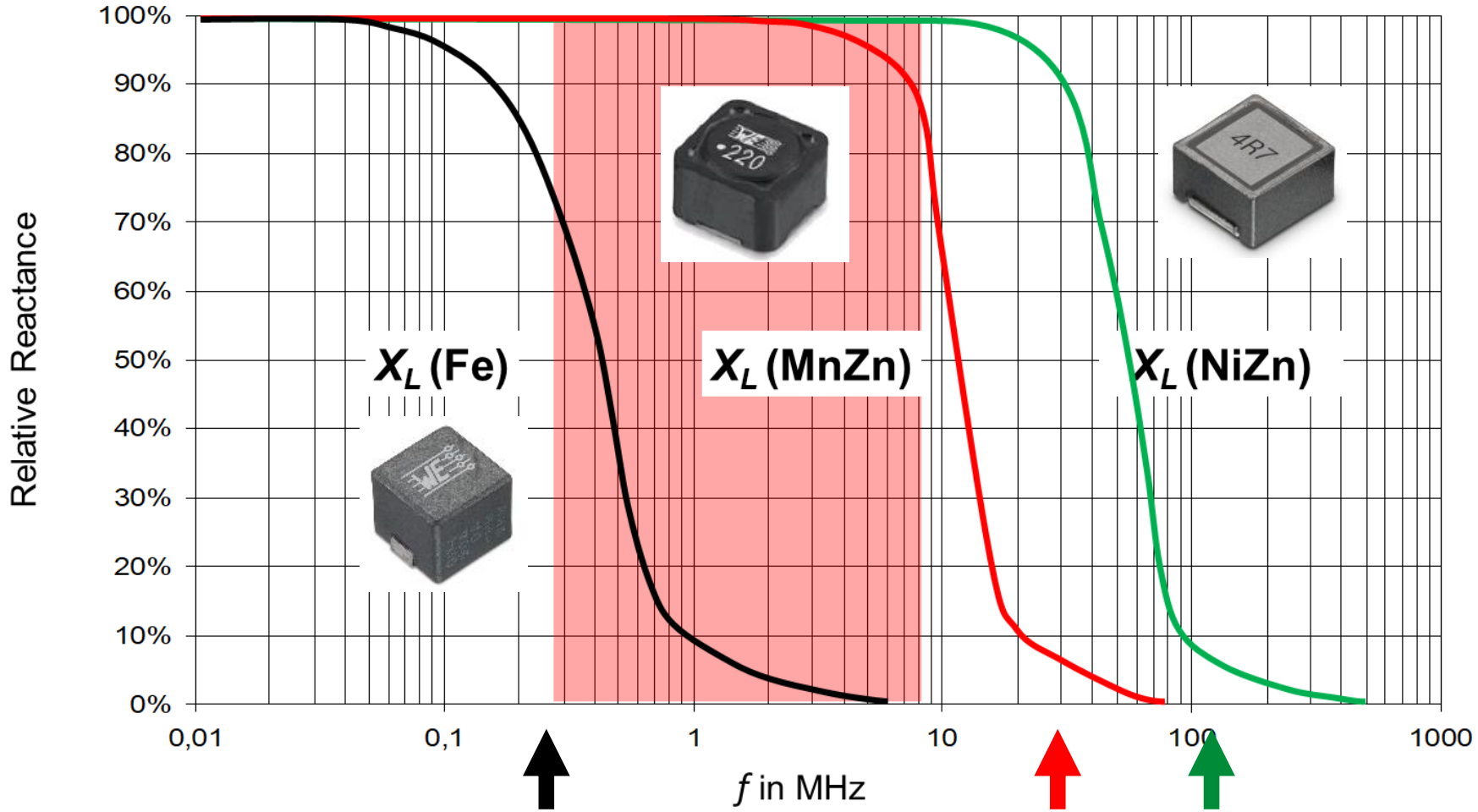


Core materials

Material		Trade names	Permeability	Bsat	Core Loss	DC Bias	Cost
Powder	Ni Fe Mo	MPP	14-550	0.7	Lowest	Good	High
	Fe SiB C	AmoFlux®,	60	1.0	Low	Good	Medium
	Ni Fe	Hi-Flux™, High Flux	14-160	1.5	Moderate	Best	Medium
	Fe Si Al	Kool Mμ®, Sendust	26-125	1.0	Low	Good	Low
	Fe Si Al Ni	Optilloy™	14-125	1.3		Good	Medium
	Fe Si	XFlux®, Fluxsan™, MegaFlux®	26-90	1.6	High	Best	Low
	Fe	Iron	10-100	1.2	High	Poor	Lowest
Lamination or strip	Fe Si	Oriented M-4	1,500-10,000	2.0	High	Best	Lowest
	Amorphous	Metglas 2605	10k-100,000	1.5	Low	Best	Medium
	NanoCrystalline	Viroperm 500F	15k-100,000	1.2	Low	Best	High
Ceramic	Ferrite		15-20,000	0.45	Lowest	Poor	Lowest

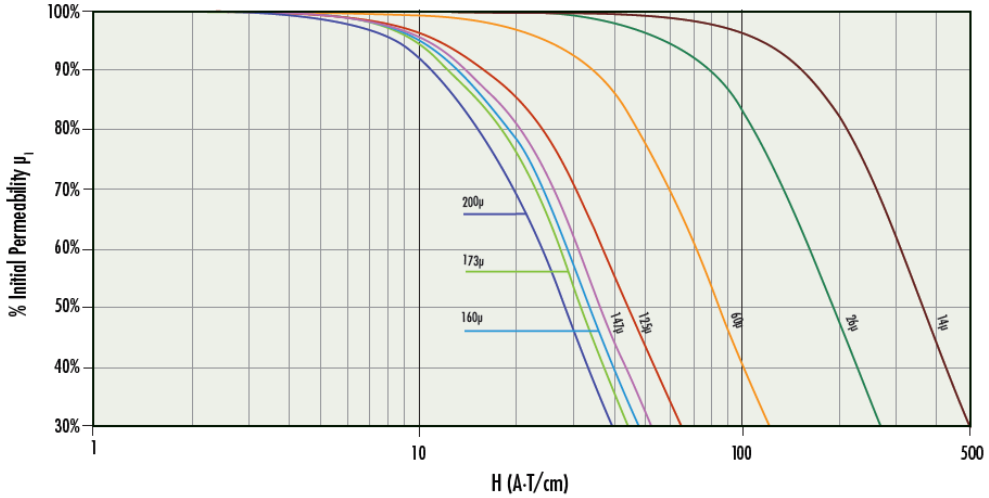
Trademarks owned by their respective companies

Core material selection

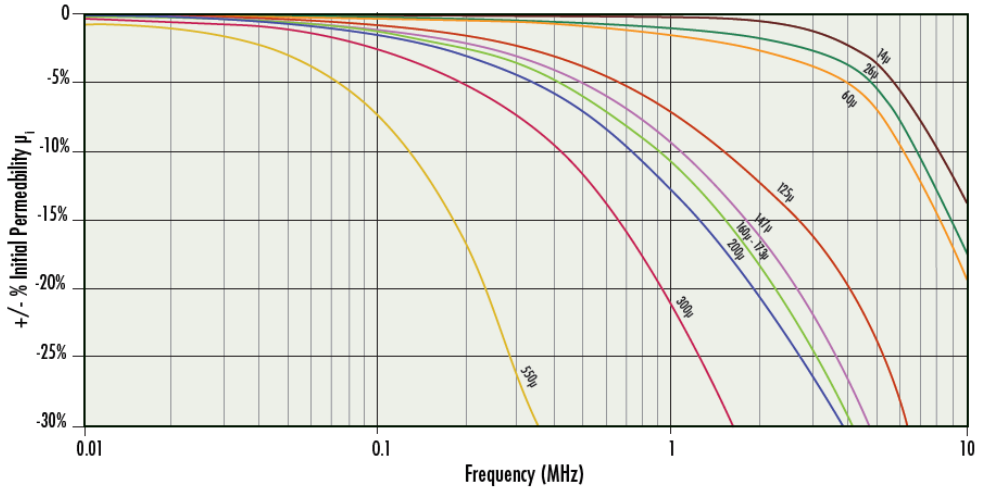


Powder core characteristics

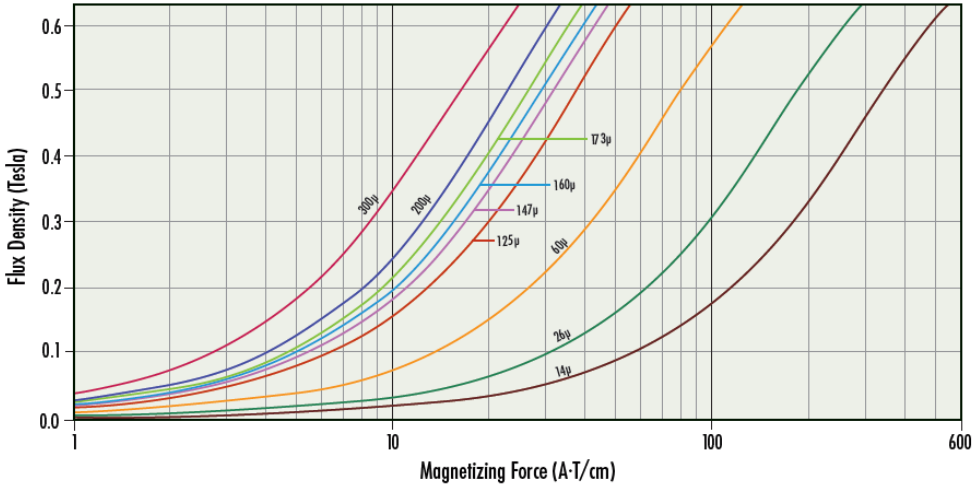
Permeability vs. DC Bias



Permeability vs. Frequency



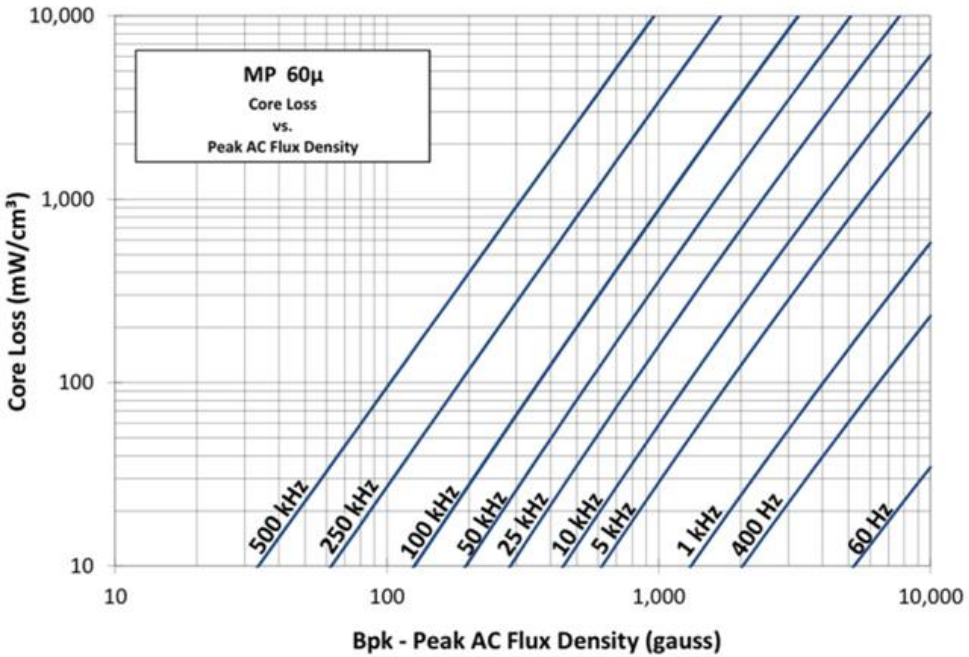
DC Magnetization



Magnetics MPP Cores

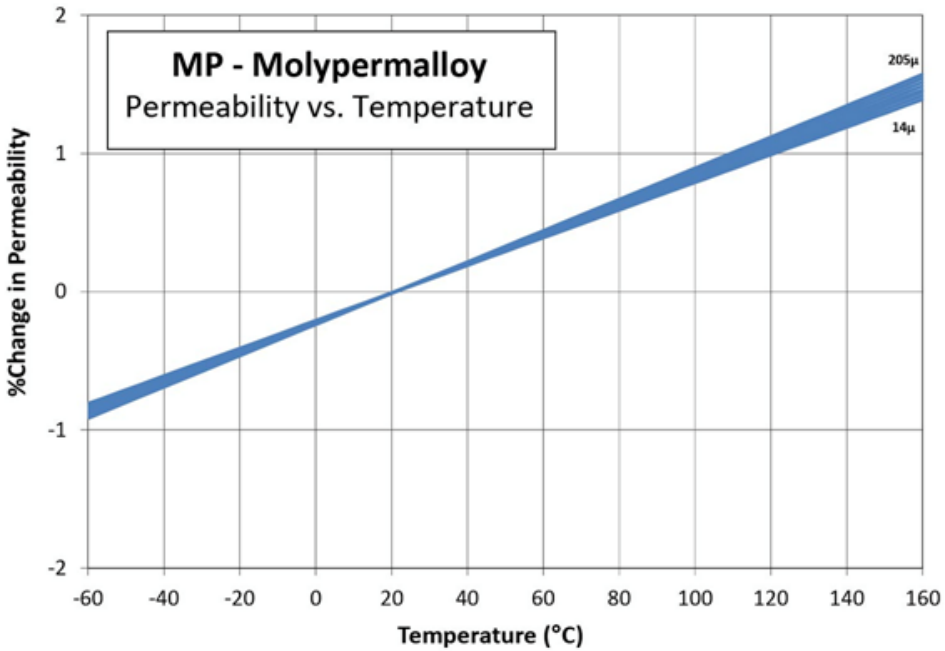
Powder core characteristics

Core Loss Density



(1 Telsa = 10,000 Gauss)

Permeability vs. Temperature

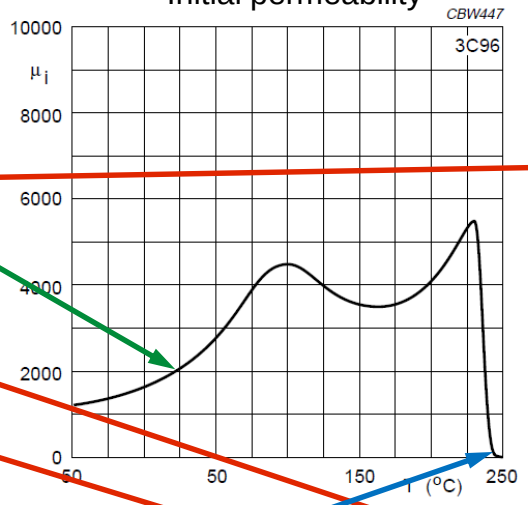


Micrometals-Arnold MPP Cores

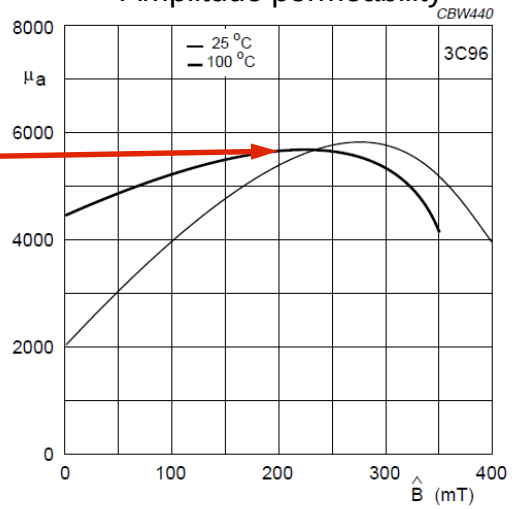
Ferrite core characteristics

	CONDITIONS	VALUE	UNIT
μ_i	25 °C; ≤10 kHz; 0.25 mT	2000 ±20%	
μ_a	100 °C; 25 kHz; 200 mT	≈ 5500	
B	25 °C; 10 kHz; 1200 A/m	≈ 500	mT
	100 °C; 10 kHz; 1200 A/m	≈ 440	
P_V	100 °C; 100 kHz; 100 mT	≈ 40	kW/m³
	100 °C; 100 kHz; 200 mT	≈ 300	
	100 °C; 500 kHz; 50 mT	≈ 250	
ρ	DC; 25 °C	≈ 5	Ωm
T_C		≥ 240	°C
density		≈ 4800	kg/m³

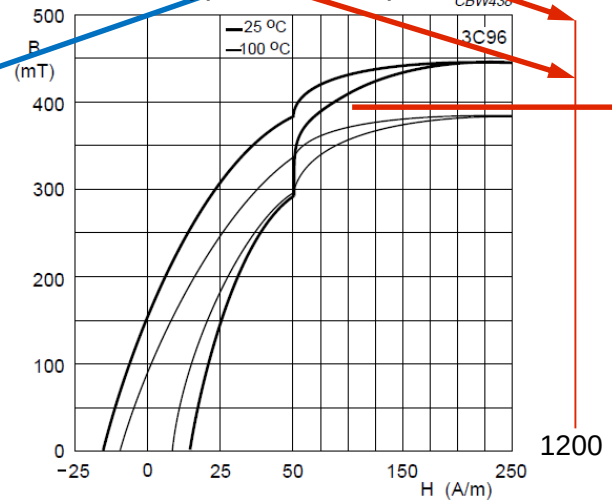
Initial permeability



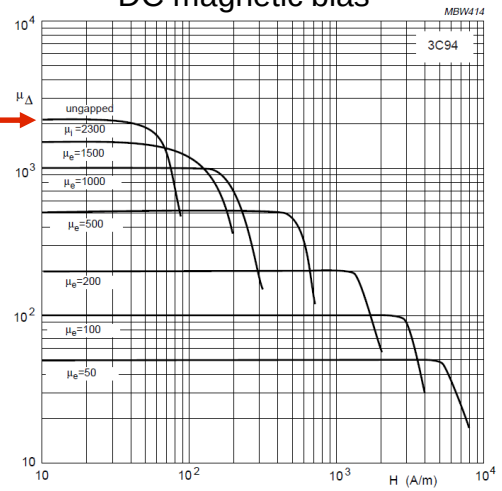
Amplitude permeability



Typical B-H loops



DC magnetic bias



1200

Source: Ferroxcube Data Handbook 2013 – 3C96

Ferrite core characteristics

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μ_i	25 °C; ≤10 kHz; 0.25 mT	2000 ±20%	
μ_a	100 °C; 25 kHz; 200 mT	≈ 5500	
B	25 °C; 10 kHz; 1200 A/m	≈ 500	mT
	100 °C; 10 kHz; 1200 A/m	≈ 440	
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	100 °C; 100 kHz; 200 mT	≈ 300	
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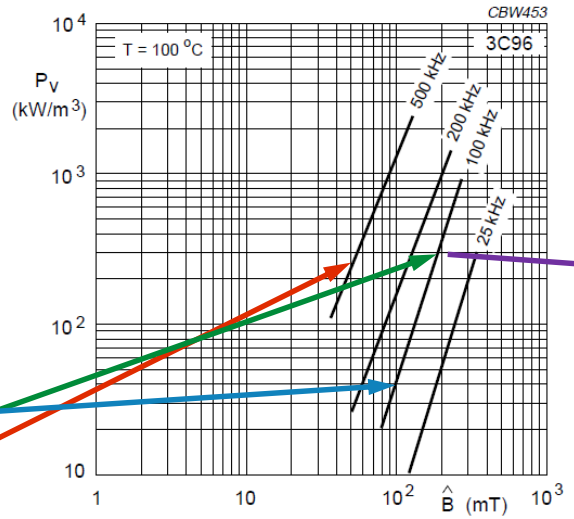
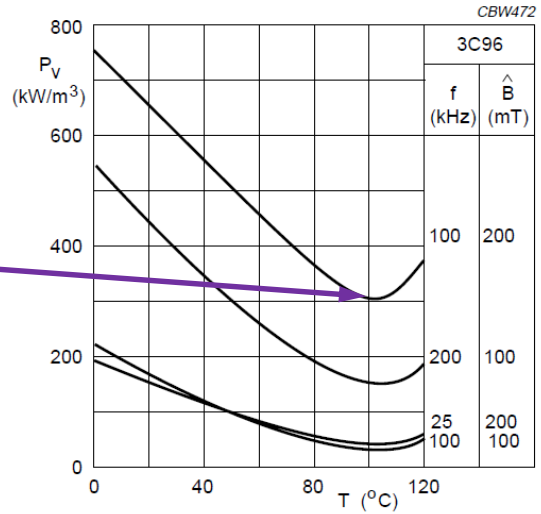
ρ	DC; 25 °C	≈ 5	Ωm
T_C		≥ 240	°C
density		≈ 4800	kg/m³

Source: Ferroxcube Data Handbook 2013 – 3C96

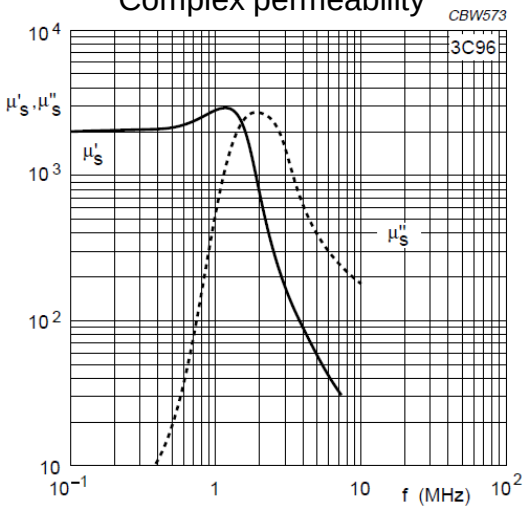
Power Loss vs peak flux



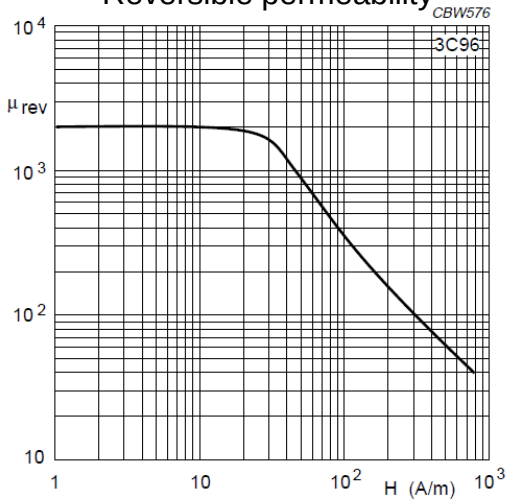
Power Loss Freq-Flux-Temp



Complex permeability



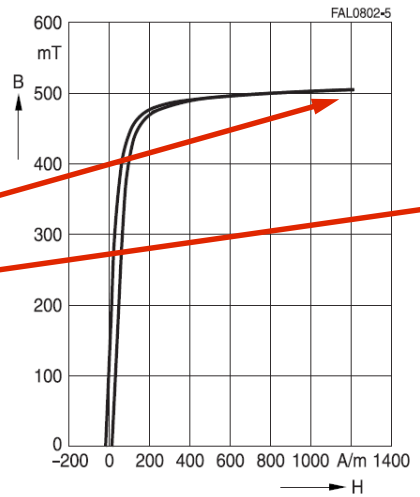
Reversible permeability



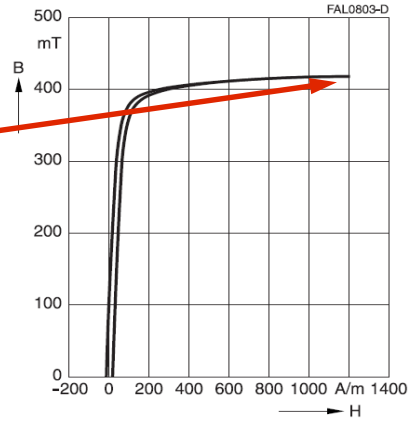
TDK N96

Preferred application			Power transformers
Material			N96
Base material			MnZn
	Symbol	Unit	
Initial permeability (T = 25 °C)	μ_i		2900 ±25%
Flux density (H = 1200 A/m, f = 10 kHz)	B_S (25 °C) B_S (100 °C) B_S (140 °C)	mT mT mT	500 410
Coercive field strength (f = 10 kHz)	H_c (25 °C) H_c (100 °C) H_c (140 °C)	A/m A/m A/m	16 15
Optimum frequency range	f_{min} f_{max}	kHz kHz	25 500
Hysteresis material constant	η_B	10^{-6}/mT	<0.5
Relative loss factor at f_{min} at f_{max}	tan δ/μ_i	10^{-6} 10^{-6}	<2 <20
Curie temperature	T_C	°C	>240
Mean value of α_F at 25 … 55 °C		10^{-6}/K	1
Density (typical values)		kg/m³	4850
Relative core losses (typical values)	P_V		
100 kHz, 200 mT, 25 °C		kW/m³	325
100 kHz, 200 mT, 60 °C		kW/m³	330
100 kHz, 200 mT, 100 °C		kW/m³	390
100 kHz, 200 mT, 140 °C		kW/m³	—
300 kHz, 100 mT, 100 °C		kW/m³	—
Resistivity	ρ	Ωm	10
Core shapes			E, EQ, PQ, ETD

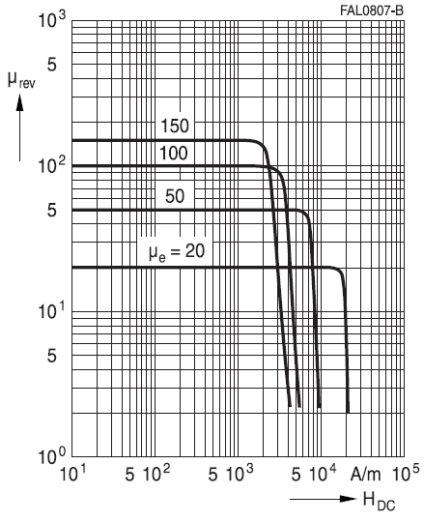
Dynamic magnetization curves
(typical values)
(f = 10 kHz, T = 25 °C)



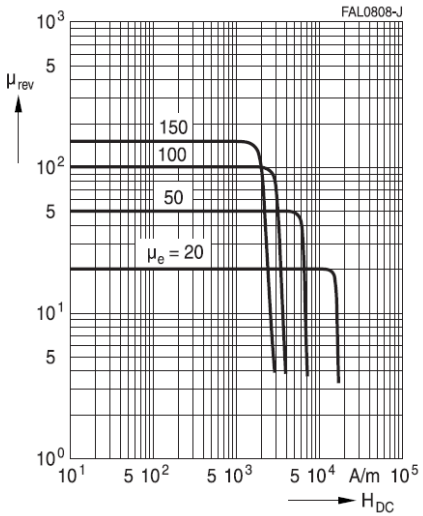
Dynamic magnetization curves
(typical values)
(f = 10 kHz, T = 100 °C)



DC Magnetic bias
measured on EQ30 cores
($\hat{B} \leq 0.25$ mT, f =10 kHz, T = 25 °C)

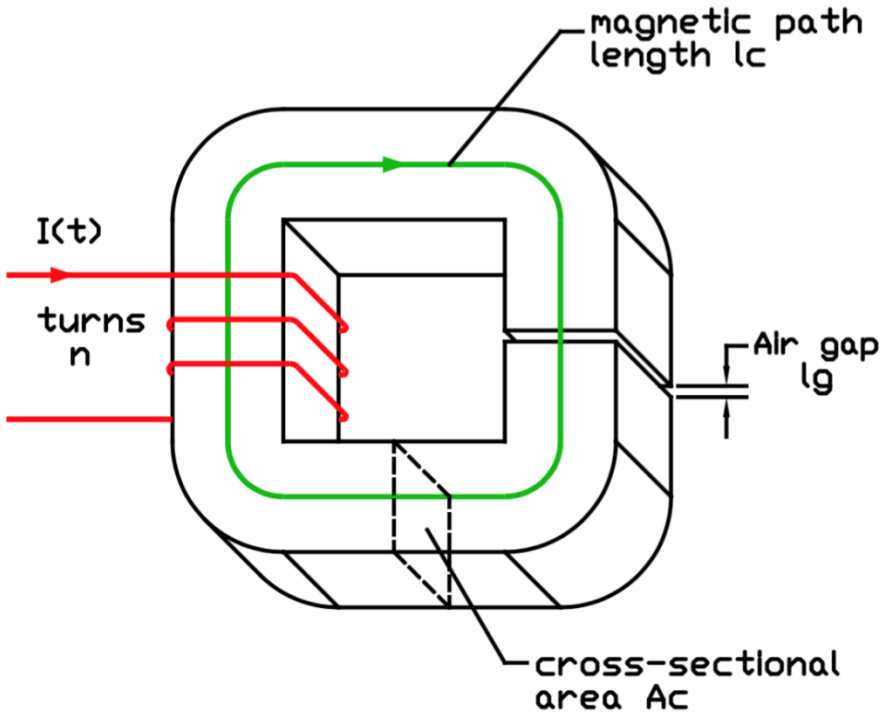


DC Magnetic bias
measured on EQ30 cores
($\hat{B} \leq 0.25$ mT, f =10 kHz, T = 100 °C)



Source: TDK Databook 2017

Where is the energy stored?



- Imagine MMF is like voltage, flux like current and reluctance (1/permeability) like resistance
- Core is low reluctance, gap is high reluctance therefore MMF is greatest across gap

Gaps store energy

$$W = \frac{1}{2}\int HBdv$$

$$W = \frac{1}{2}H_c B_c V_c + \frac{1}{2}H_g B_g V_g$$

$$B = \mu_0 \mu_r H \quad \text{therefore} \quad H = \frac{B}{\mu_0 \mu_r}$$

$$W = \frac{1}{2}\frac{B_c}{\mu_0 \mu_r} B_c l_c A_c + \frac{1}{2}\frac{B_g}{\mu_0} B_g l_g A_c$$

$$W = \frac{1}{2}\frac{B^2 A_c}{\mu_0}\left(\frac{l_c}{\mu_r} + l_g\right)$$

V_c is the volume of the core where

$$V_c = l_c A_c$$

V_g is the volume of the air gap where

$$V_g = l_g A_c$$

Flux is uniform so $B_c = B_g$ neglecting fringing

Also $A_c = A_g$

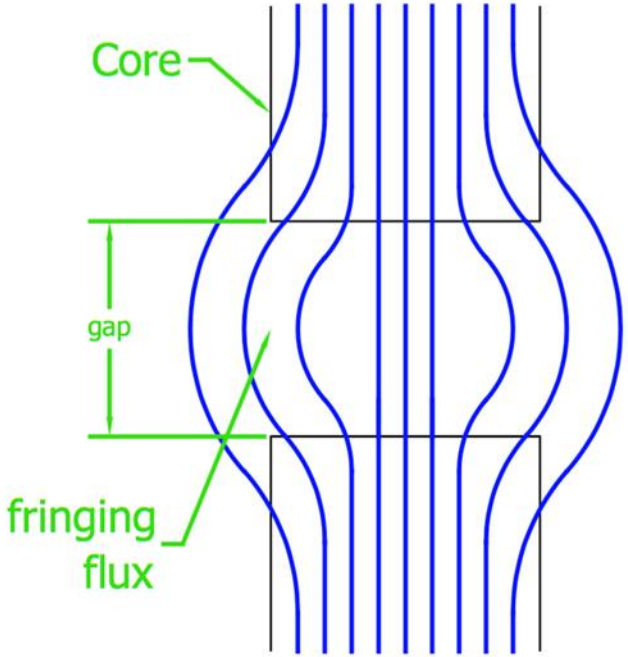
Typically, μ_r in power ferrite is 2300, therefore l_c/μ_r is a very small number compared to l_g

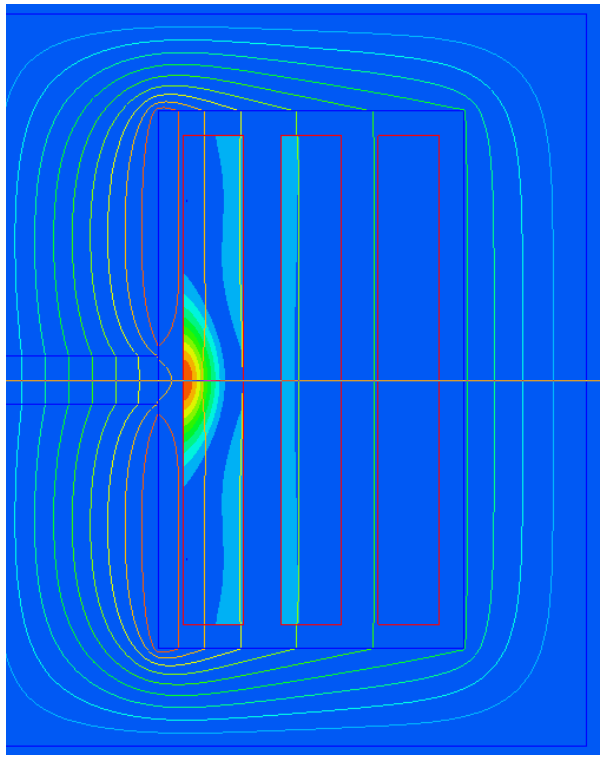
Gaps cause fringing

Fringe factor

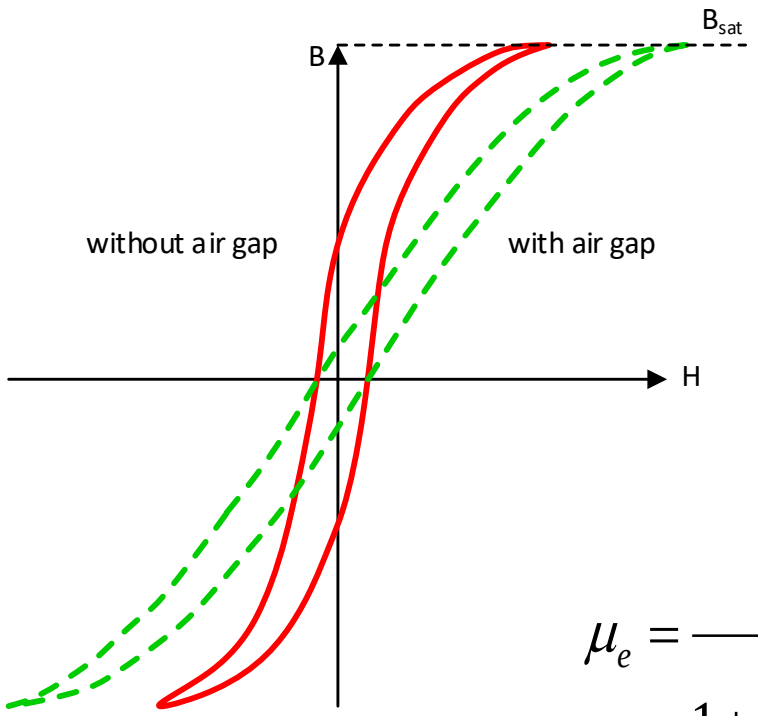
$$F_F = 1 + \frac{l_g}{\sqrt{A_c}} \ln\left(\frac{2l_w}{l_g}\right)$$

F_F = increase in inductance
l_g = gap length
l_w = window length
A_c = core area

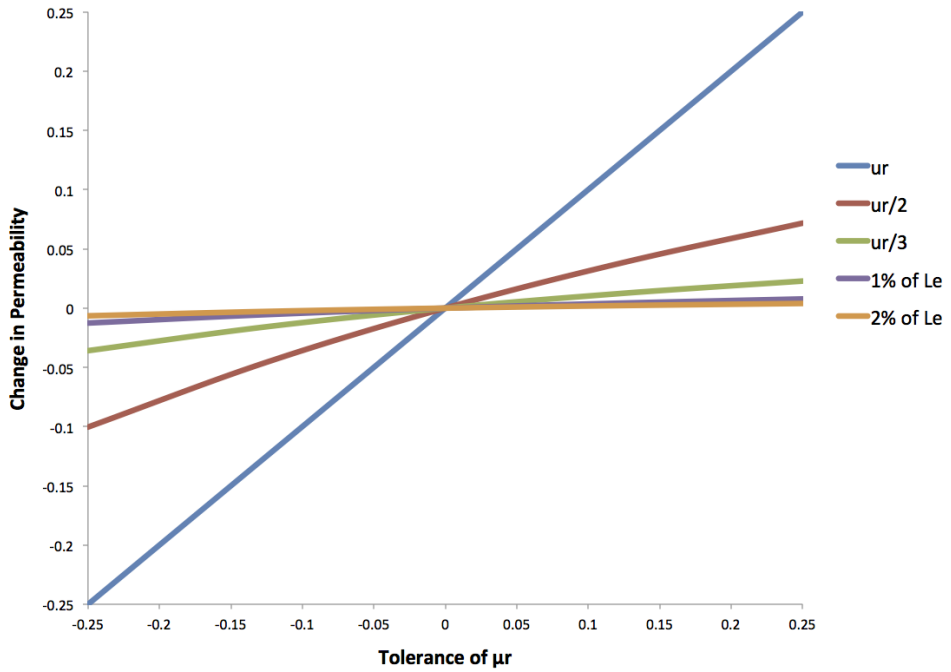




Gaps stabilize permeability

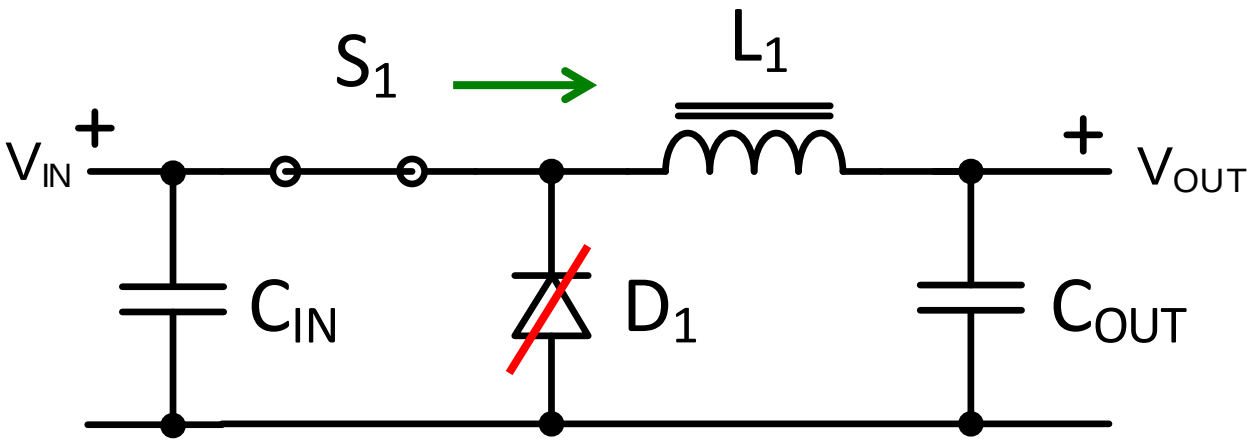


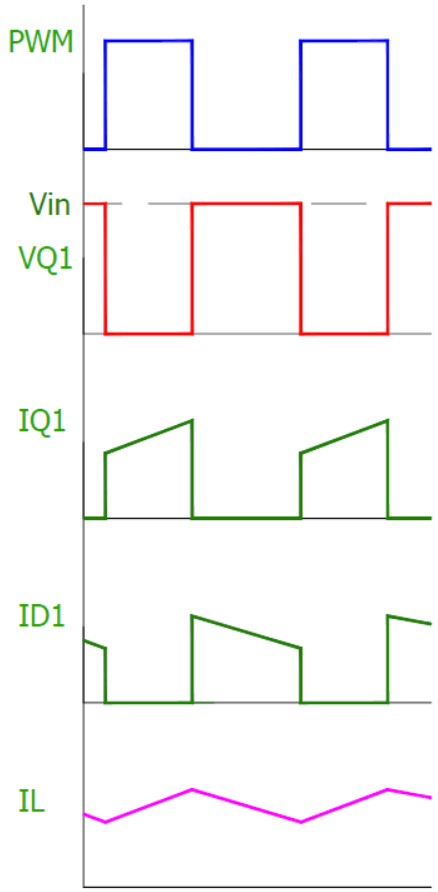
$$\mu_e = \frac{\mu_r}{1 + \mu_r \left(\frac{l_g}{l_e} \right)}$$



μ_e = effective permeability

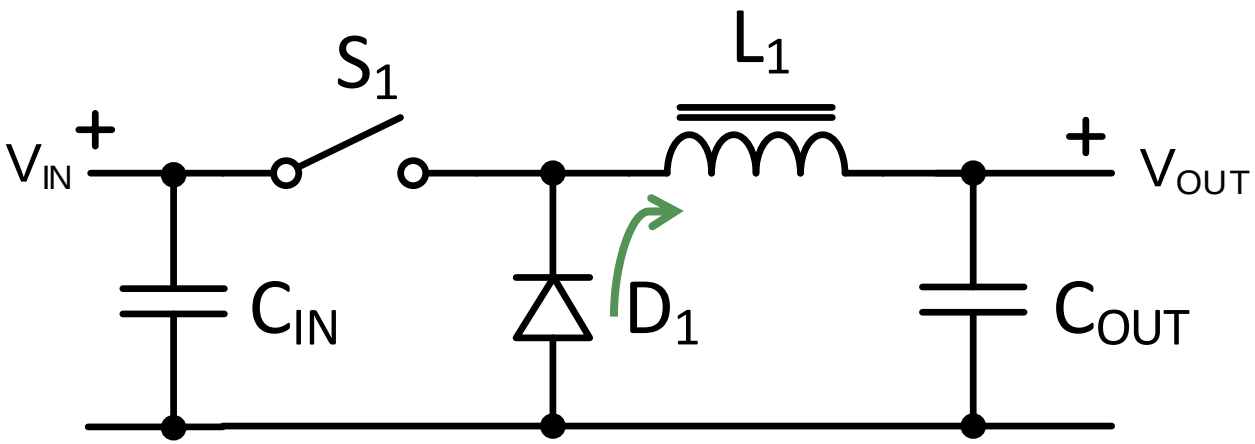
Buck converter

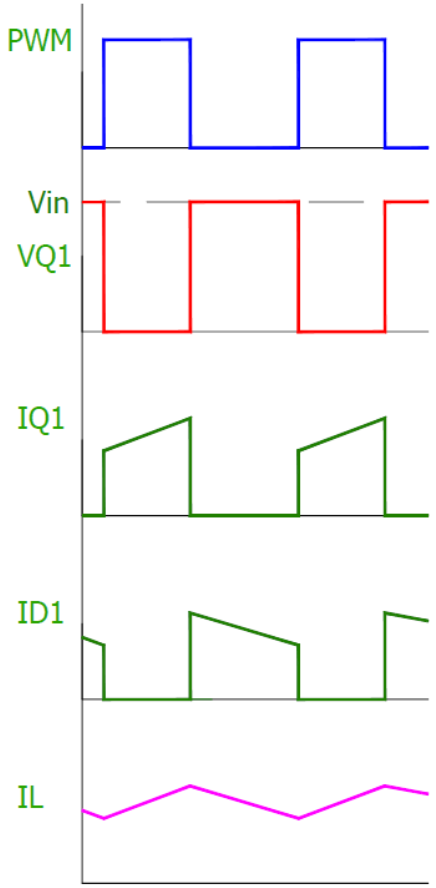




$$\frac{V_{out}}{V_{in}} = \left(\frac{t_{on}}{T}\right) = D$$

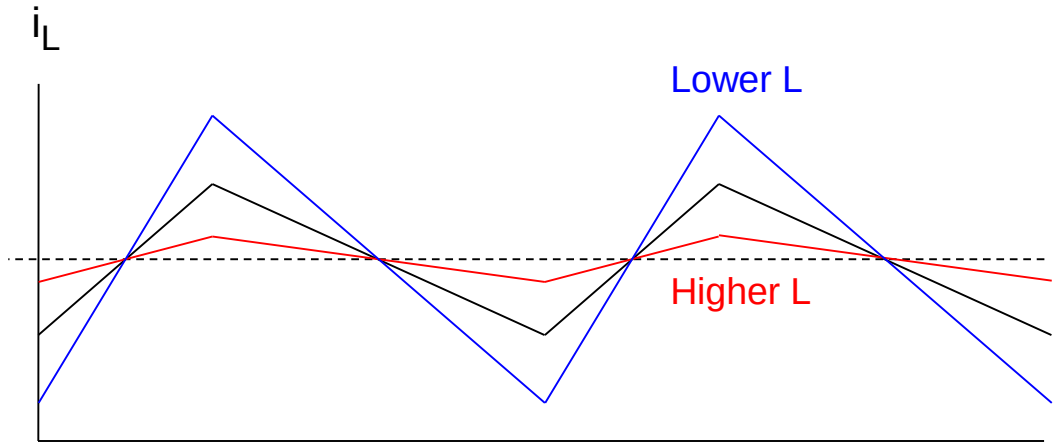
Buck converter





$$\frac{V_{out}}{V_{in}} = \left(\frac{t_{on}}{T}\right) = D$$

Effect of changing inductance value



$$L = \frac{Edt}{di}$$

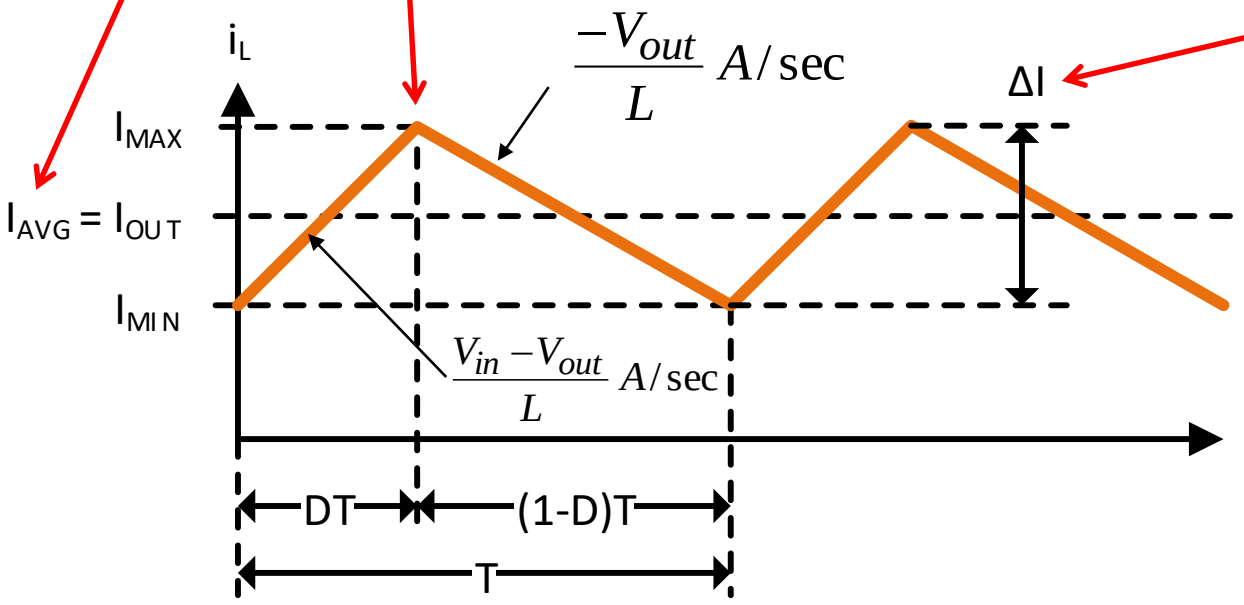
$$di = \frac{Edt}{L}$$

- Effect of raising and lowering L while holding V_{IN}, V_{OUT}, I_{OUT} and *f* constant
- Lowering L increases ΔI, raising L decreases ΔI
- The choice of L is a trade off between the size, the copper losses and the core losses

Important parameters of the inductor

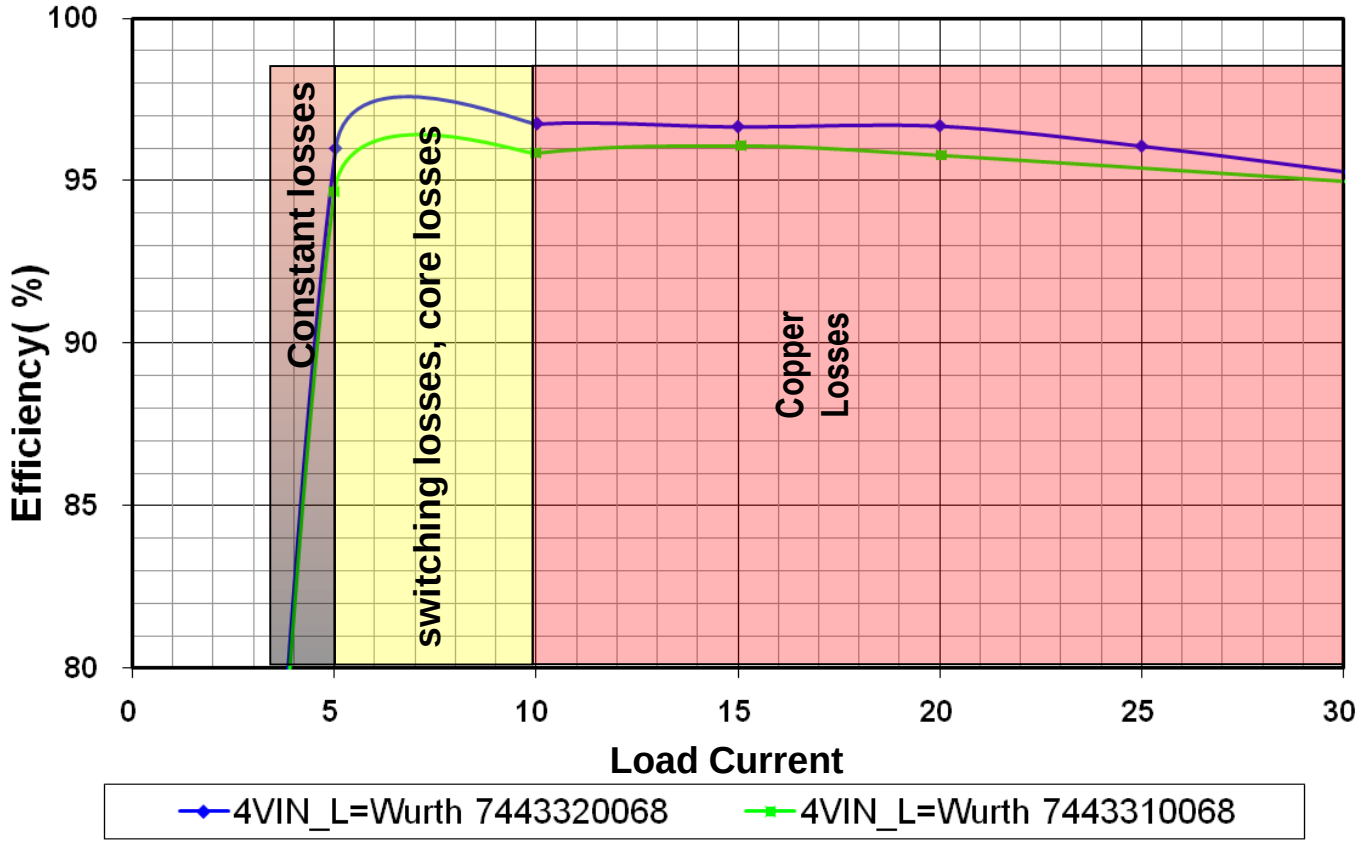
I_{AVG}, I_{OUT}, I_{DC}, I_L ALL ARE THE SAME, they refer to the average inductor current
Is the starting point of inductor current rating selection
Used to estimate DC copper losses

I_{MAX}, I_{PEAK} Determines the size of the inductor through the energy storage required
Used to determine minimum inductor saturation rating



ΔI Peak to peak ripple current
. determined by inductance value
Used to estimate the core losses

Losses - Efficiency

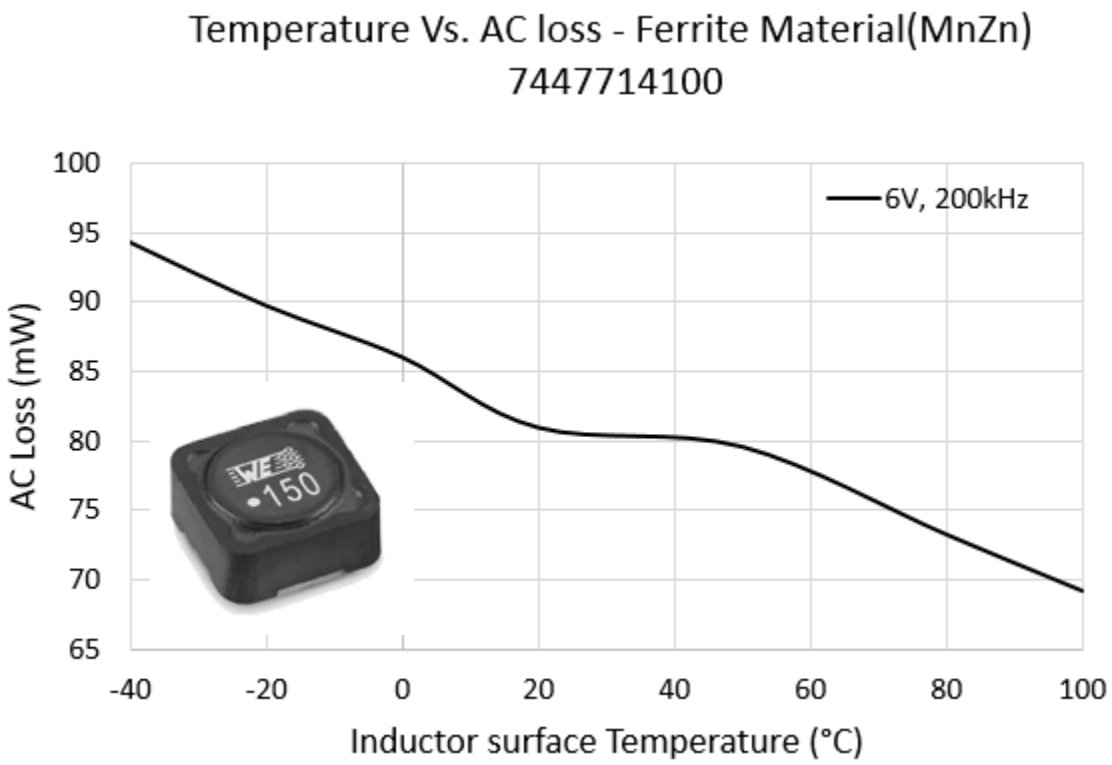


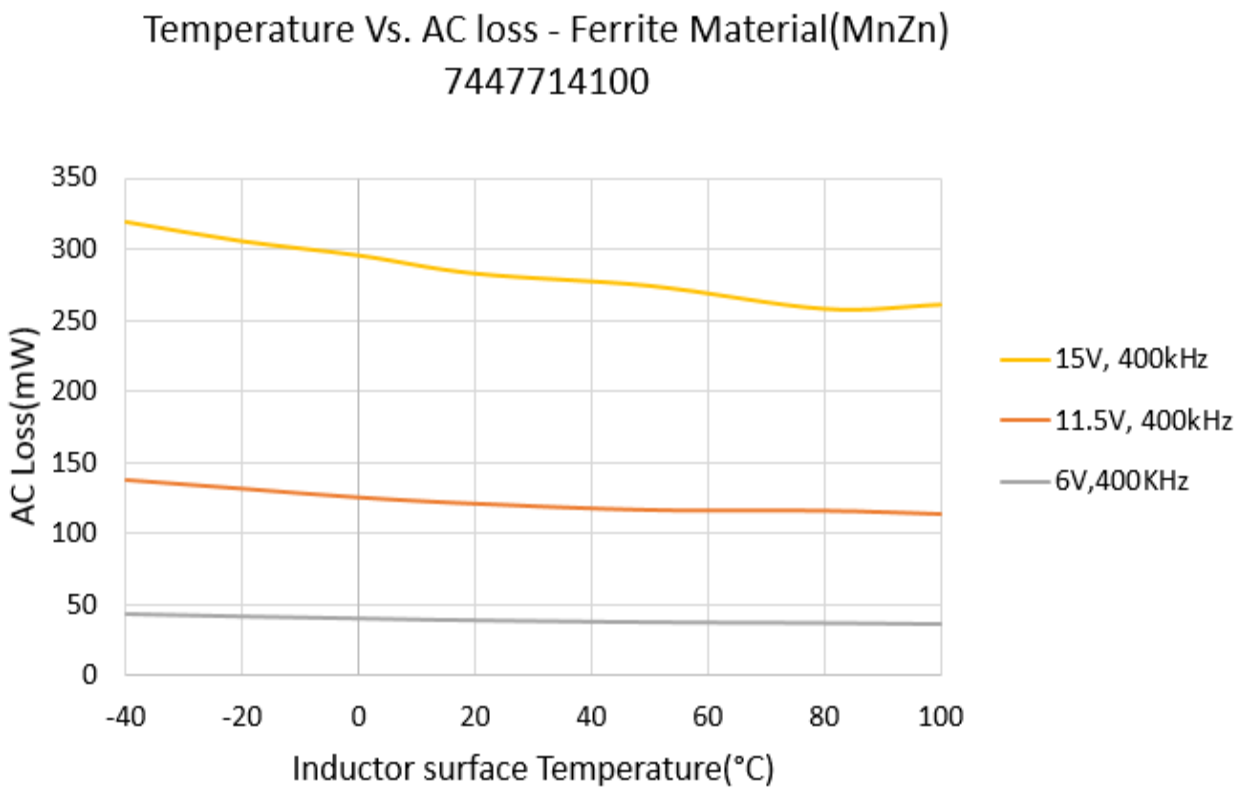
Ferrite

Iron Powder

Iron Powder Ferrite

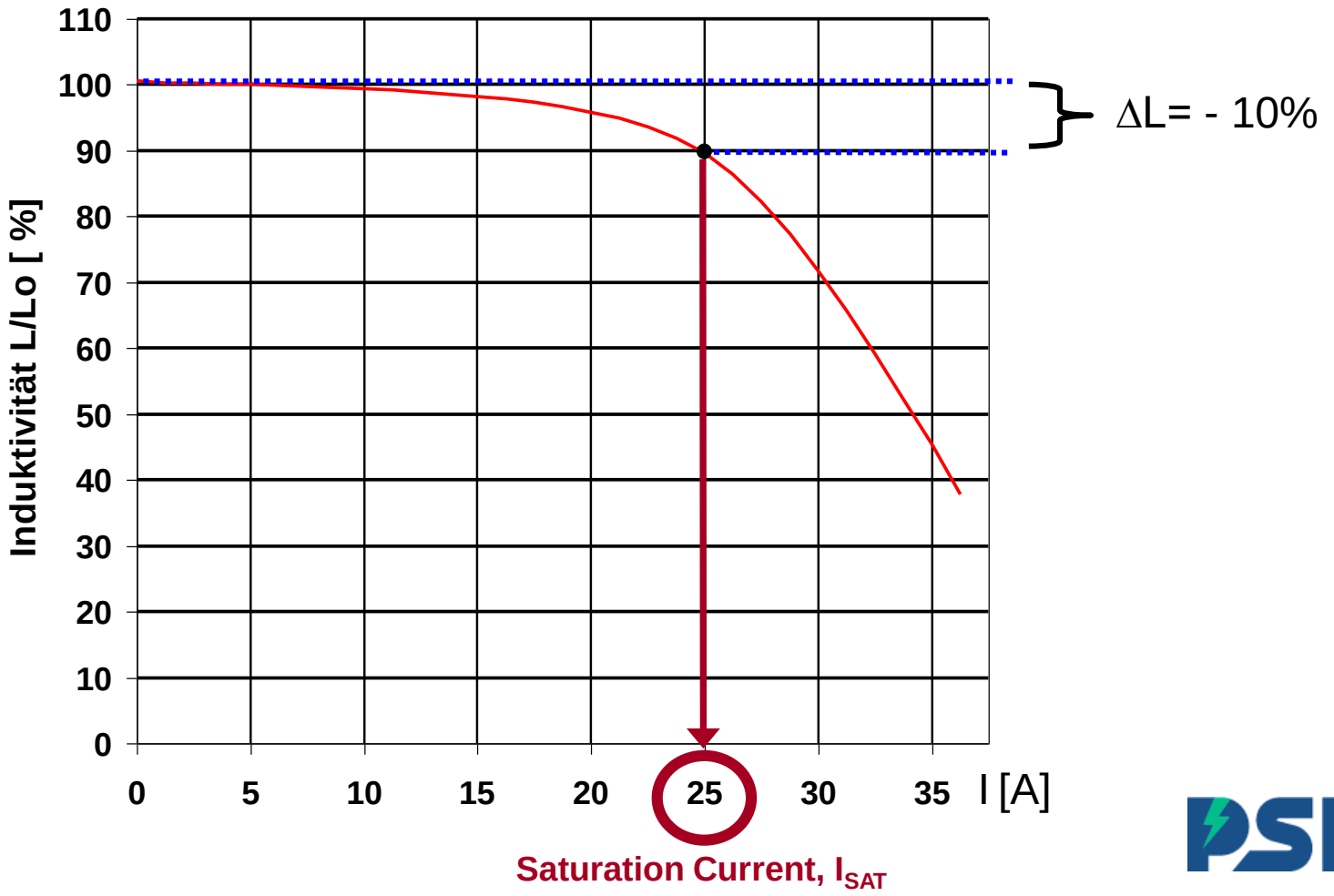
AC Losses


Temperature Vs. AC loss - Ferrite Material(MnZn)
7447714100
6V, 200kHz
AC Loss (mW)
100
95
90
85
80
75
70
65
-40
-20
0
20
40
60
80
100
Inductor surface Temperature (°C)
150

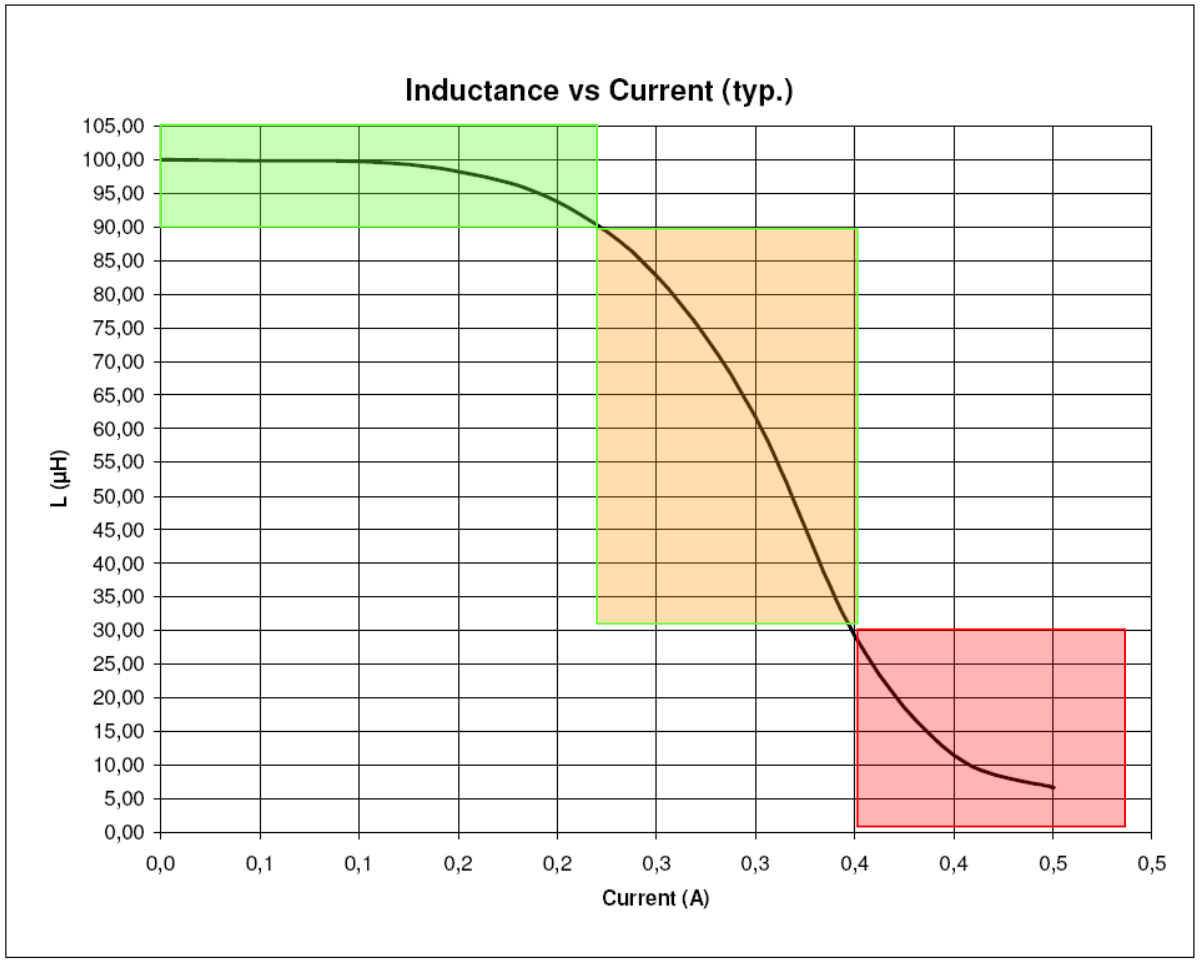

Temperature Vs. AC loss - Ferrite Material(MnZn)
7447714100
AC Loss(mW)
350
300
250
200
150
100
50
0
-40
-20
0
20
40
60
80
100
Inductor surface Temperature(°C)
15V, 400kHz
11.5V, 400kHz
6V,400KHz

Definition of Saturation current

- Its important to realize that every manufacturer uses a different value of percent drop.
- Also different series of inductors may use different percentages – typically 10-30%
- Some definitions will go to 50%



Operation Area



safe operation area

critical operating area

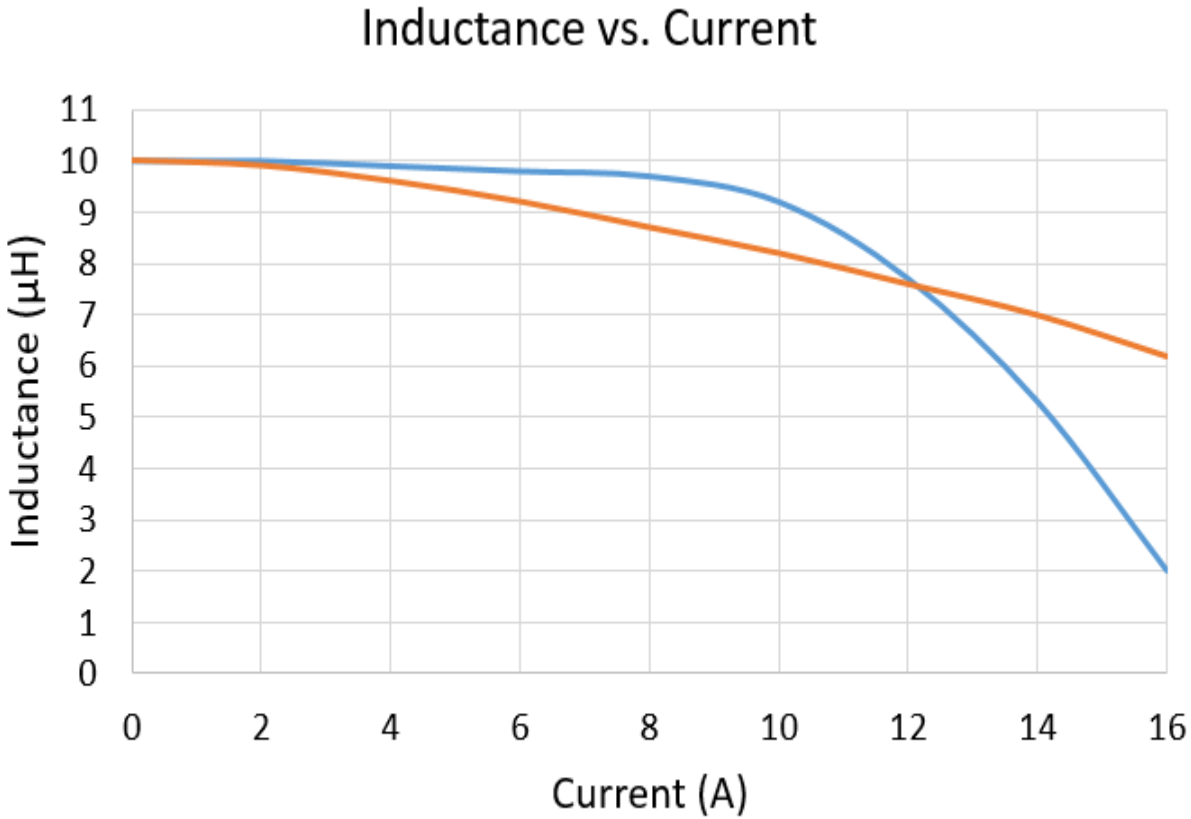
total saturation area

Important when using inductors made out of ferrite

Saturation: Ferrite vs. Iron Powder

WE-PD

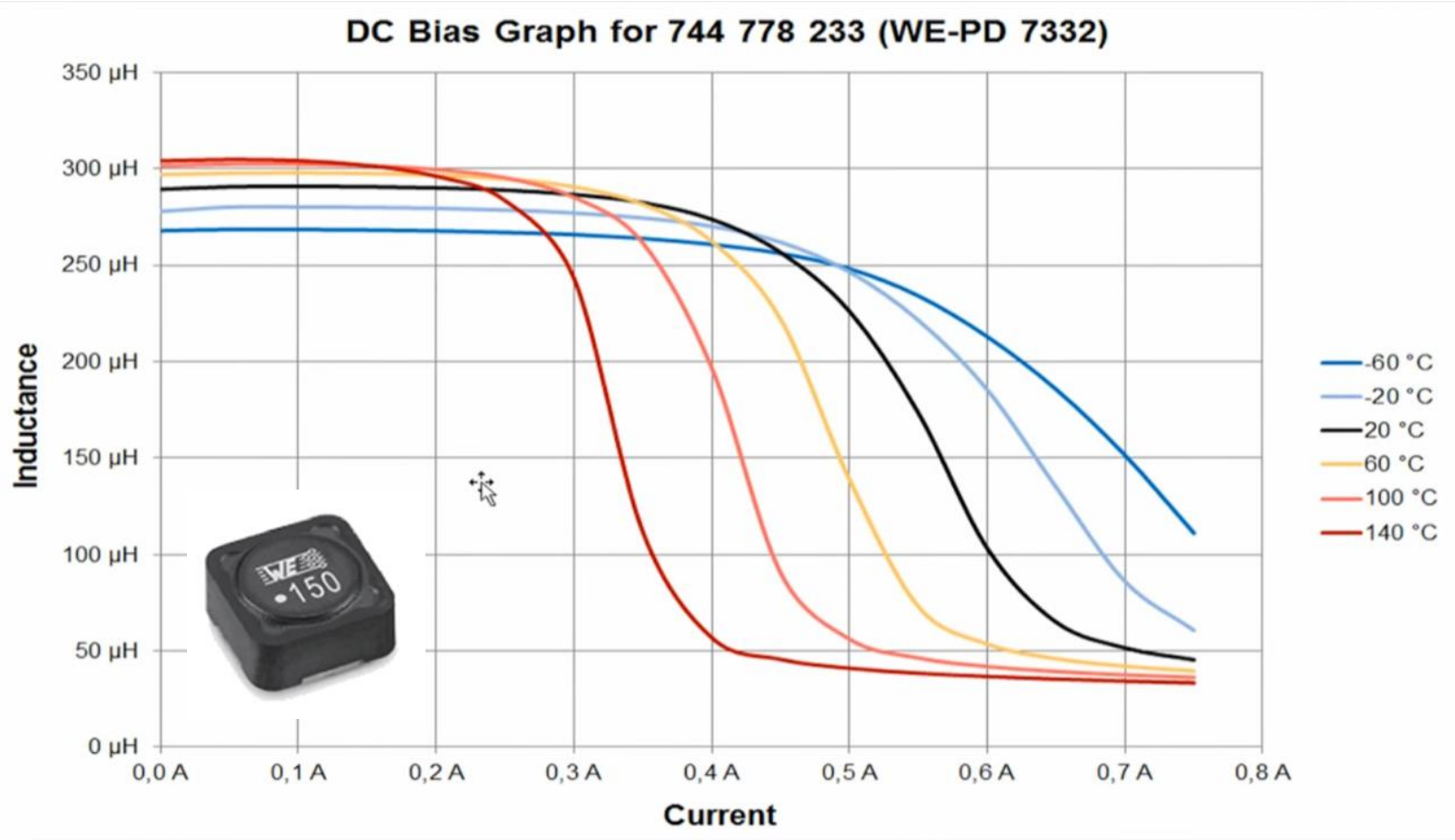
WE-HCI



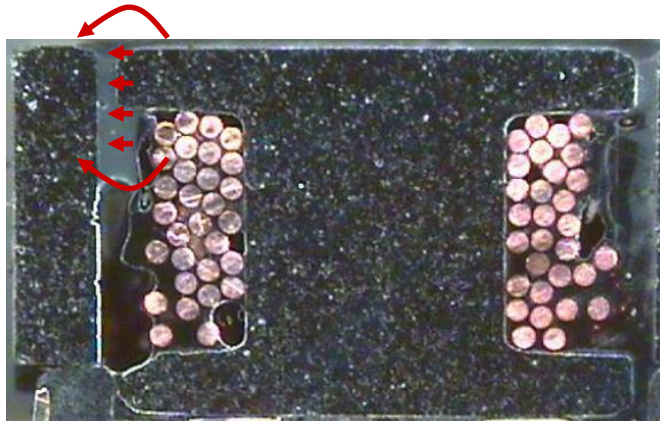
Soft Saturation

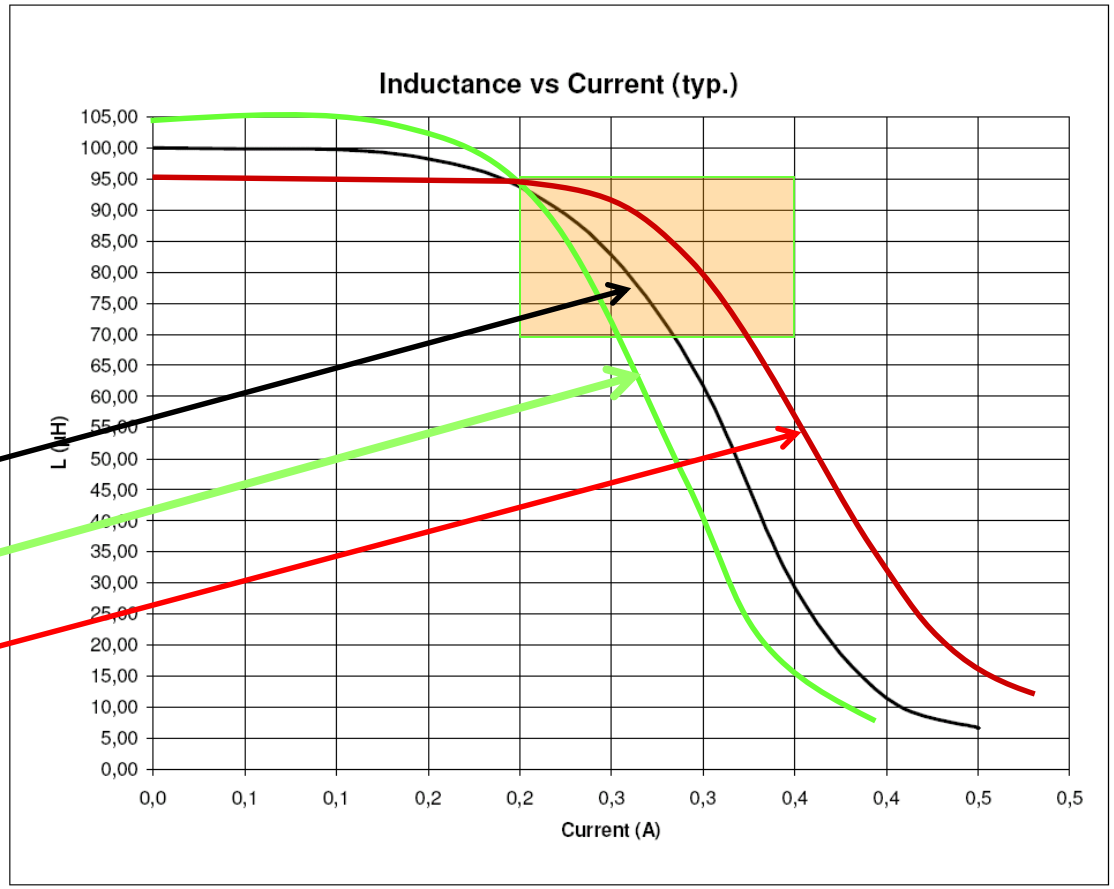
Hard Saturation

B_{sat} vs. temperature



Saturation current – impact of gap





defined air gap

air gap > too small

air gap > too big

Inductor selection

- Desired inductance value – know the minimum or maximum
- Tolerance and under what conditions (i.e. dc bias)
- Rated current to temperature
- Saturation current and applicable tolerance
- Mounting style
- If self shielding is required
- Sharp or soft roll-off
- Frequency of operation

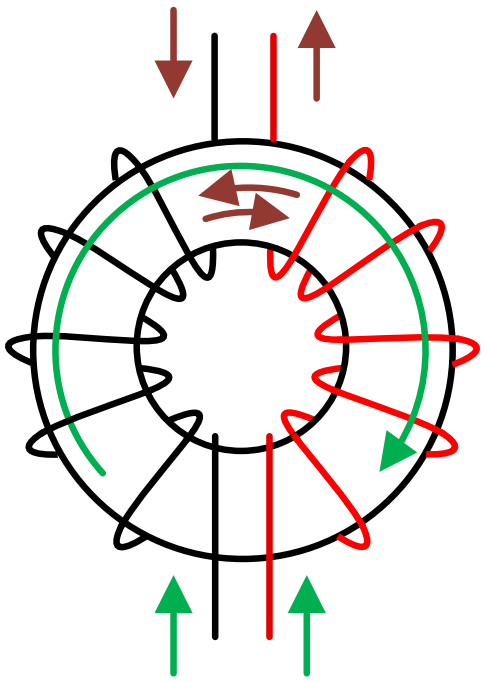
Crossroads

- Inductor:
  - An magnetic device that impedes the change in the flow of electric current by storing and releasing energy from its magnetic field.
- Coupled Inductor:
  - A coupled inductor is an inductor with two or more windings on the same core which takes advantage of magnetic coupling to influence the behavior of each winding on the other.
- Transformer:
  - A magnetic device that transfers energy instantaneously through it magnetic field. Typically changes the voltage of current and can provide galvanic isolation.

Common Mode Inductors

- a.k.a current compensated chokes
- Windings are in the same direction
- Flux from common mode current add in the core
- Flux from differential currents cancel in core
- Allows use of high permeability cores which are sensitive to dc bias
- Reduces number of turns which reduce winding self capacitance which limits high frequency response
- This makes the filter smaller than using two cores
- When fluxes add, inductance increases
- Tight coupling desired

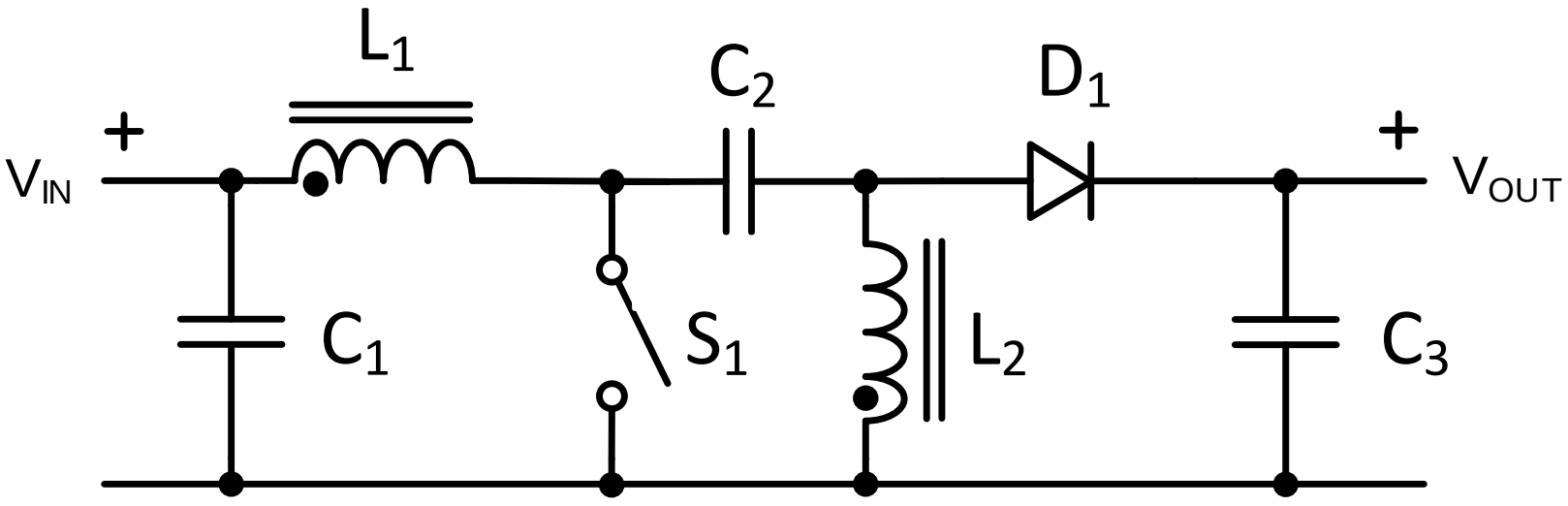
Flux from differential currents cancel



Flux from common currents add

SEPIC

- Non inverting
- Ground referenced
- Low ripple
- Can use individual or coupled inductors

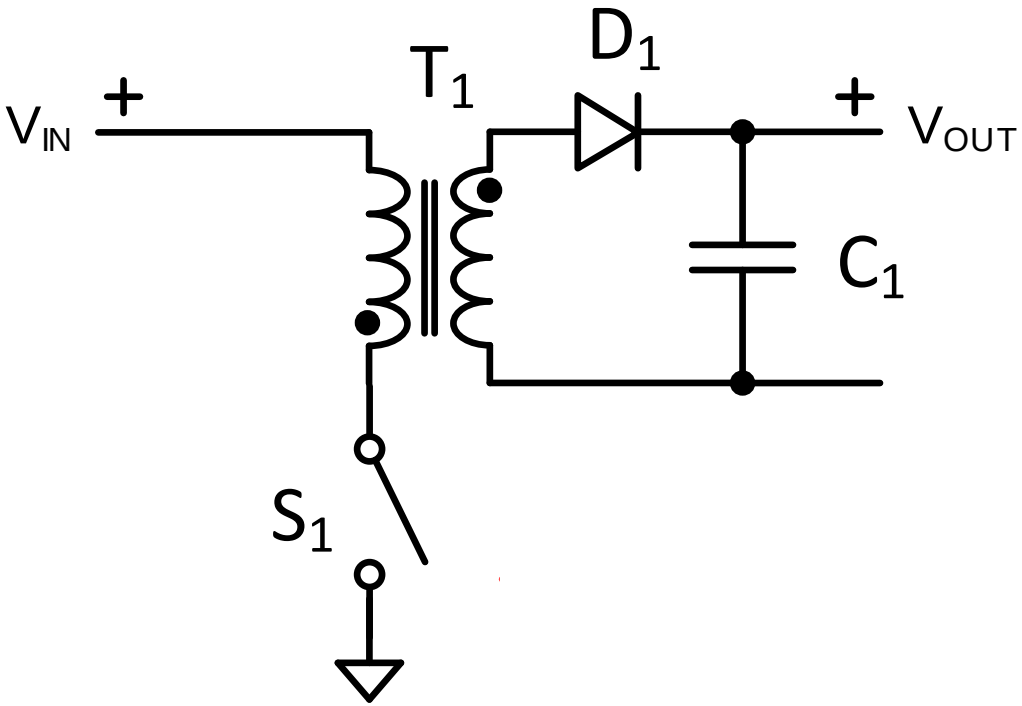


Flyback ‘transformers’

- By definition, as an energy storage device it’s an inductor
- The circuit operates this device as two separate inductors that use the same core to link them together.
- Because they are linked by the mutual flux, the voltages and currents have transformer like property of turns ratio
- Because the input and output use different windings it has the transformer property of galvanic isolation

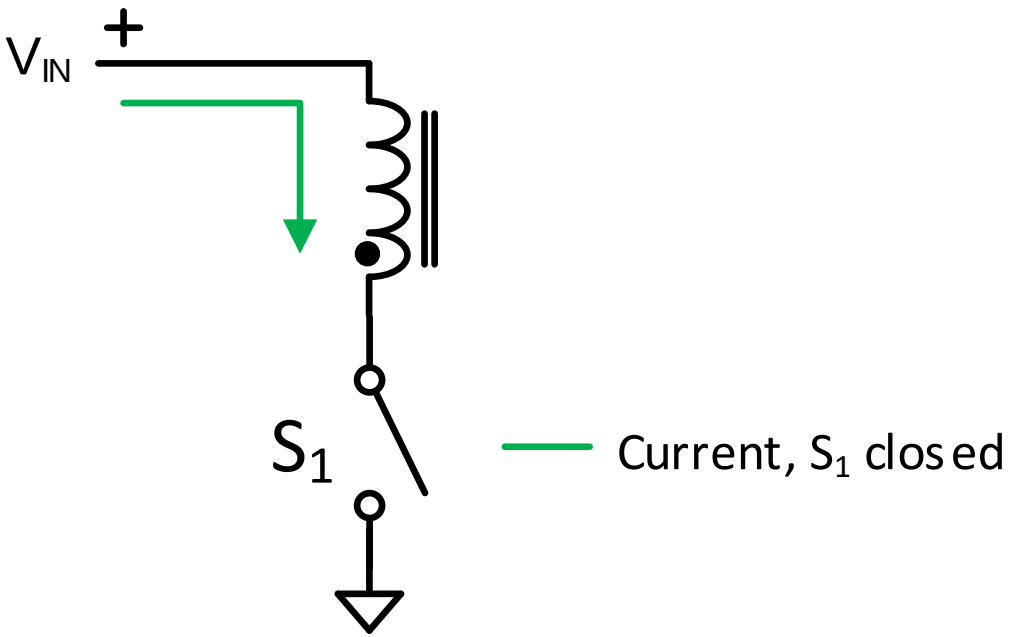
Isolated Flyback

- Transformer-choke
- Transformer isolated version of a buck-boost
- Each circuit period has its own inductor but share the same core
- One coil builds the magnetic field
- The other harvests it
- Voltages exist on both coils giving it transformer like ratios



Isolated Flyback

- Transformer isolated version of a buck-boost
- Both step up and step down
- Multiple outputs
- Optimizes duty cycle for large voltage differences
- Wide input range



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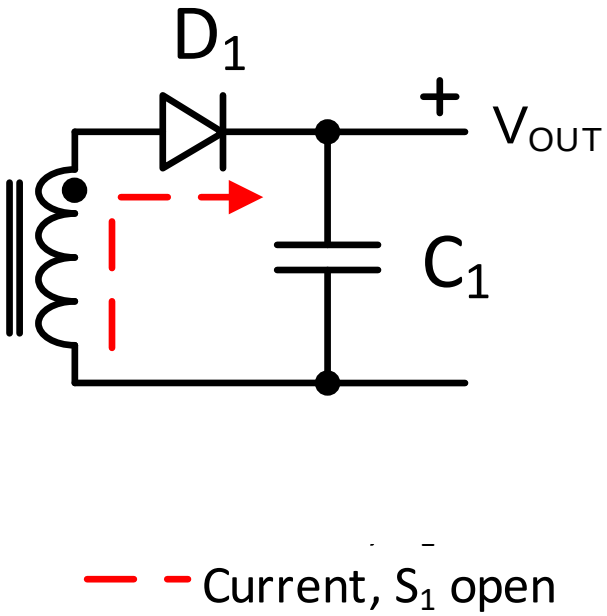
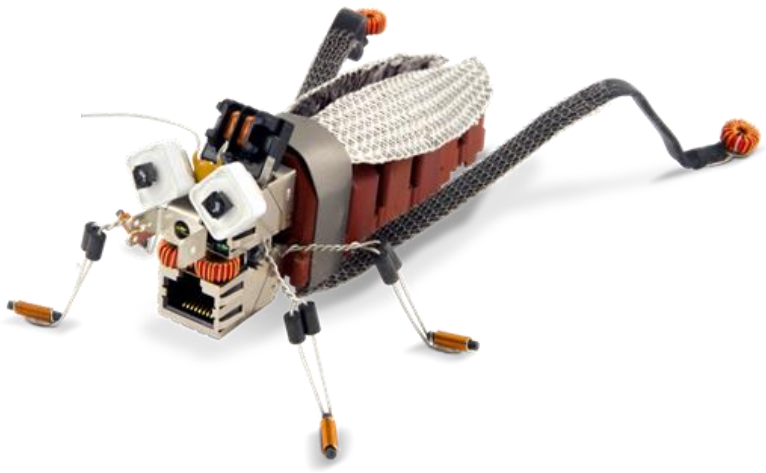


Conclusion

- Inductors play a key role in power electronics as energy storage devices for efficient power transfer
- They must be properly rated to perform under all expected conditions
- There is a wide selection of materials suitable a wide variety of applications
- Many resources are available from the many material suppliers, distributors, IC and magnetics manufacturers who are members of the PSMA



The art of magnetics

Thank you