Power Conversion Solutions for Industry e Transportation

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27 Maggio 2025

Agenda

- INTRODUCTION
- MAGNETICS THEORY
- MATERIALS
- LOSSES IN MAGNETICS DEVICES
- PARASITICS
- SiC AND GaN MAGNETICS DESIGN APPROACH
- CUSTOMIZATIONS: REAL EXAMPLES
- APPLICATIONS

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Introduction

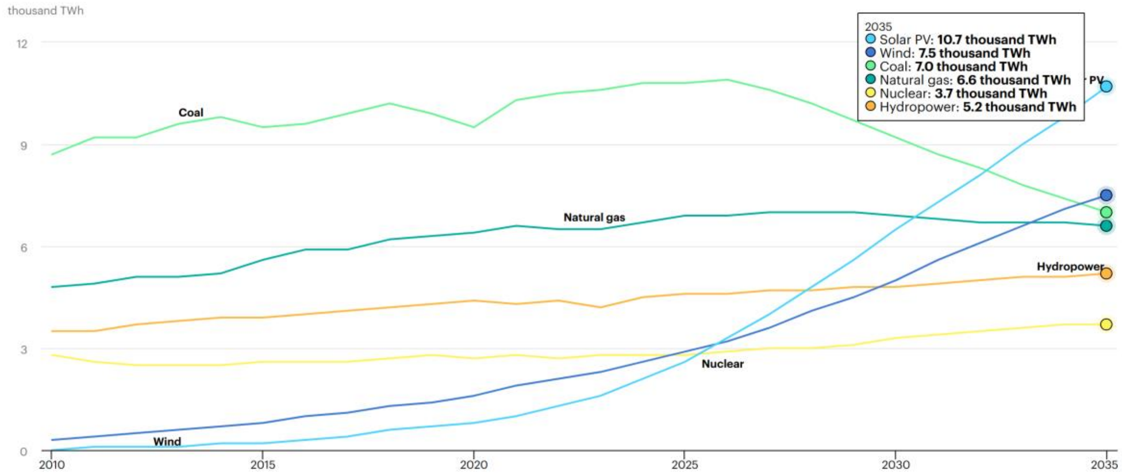
Magnetics components for tomorrow's energy needs

Global Demand is exploding

- Solar PV is set to become the world's largest renewable energy source by 2029 (source)
- 30% of global electricity will come from Solar PV and Wind by 2030 (source)

Electrification is everywhere

- Inverters – Grid-tied, micro, string
- Battery Systems – Energy Storage, backup/UPS, BMS
- EV chargers – AC and DC fast chargers



World Electricity Generation, 2010-2035- World Energy Outlook 2024

Introduction

Key Challenges for Magnetics Today

Performance Killers

Parasitic elements that degrade inductor and transformer performance — harder to ignore at high frequencies

Power Density Bottlenecks

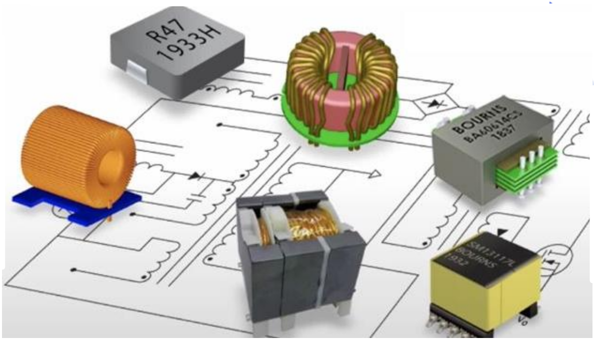
Thermal limits, material constraints, and EMI are capping performance in compact designs

Magnetics Require Mastery

Semiconductors evolve fast but magnetic losses remain stubborn - demanding specialized expertise to keep up

High Frequency, Higher Risk

Higher switching shrinks size, but amplifies core and copper losses — demanding smarter design and material choices



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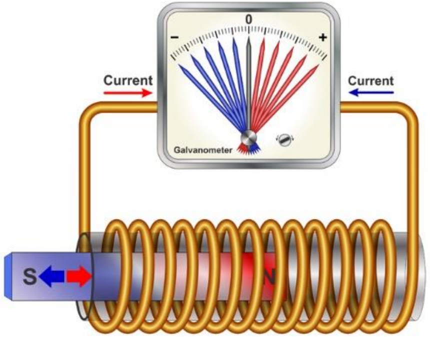
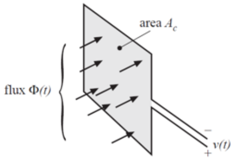


Basic Magnetics Theory

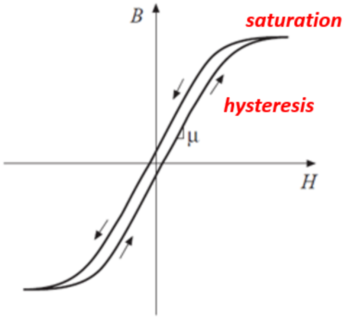
Faraday's Law



$$v(t) = A_c \frac{dB(t)}{dt}$$

H: magnetizing field
B: magnetic flux density

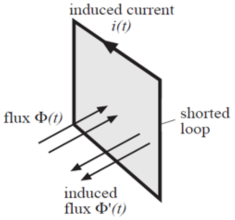
Core material characteristics



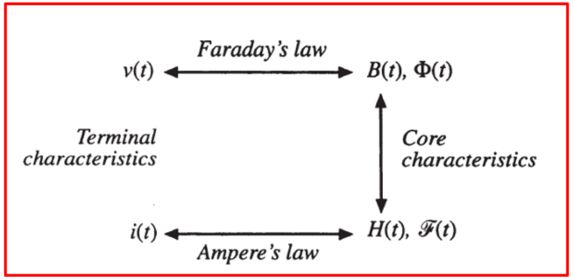
$$B = \mu H$$

$$\mu = \mu_r \mu_0$$

Lenz's Law

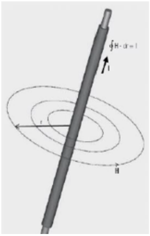


The voltage $v(t)$ induced by the changing flux $\phi(t)$ is of the polarity that tends to drive a current through the loop to counteract the flux change.

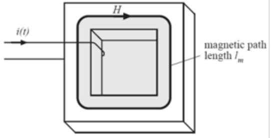


Biot-Savart's Law

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



Ampere's Law

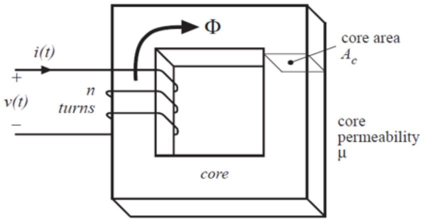


$$\oint_{\text{closed path}} \boldsymbol{H} \cdot \boldsymbol{dl} = \textit{total current passing through interior of path}$$

$$H(t)\, l_m = n\, i(t)$$

Basic Magnetics Theory

A simple inductor



Faraday's law:

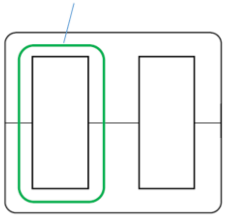
For each turn of wire, we can write

$$v_{turn}(t) = \frac{d\Phi(t)}{dt}$$

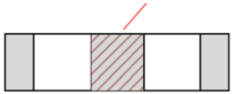
Total winding voltage is

$$v(t) = n\, v_{turn}(t) = n\, \frac{d\Phi(t)}{dt}$$

L_m: magnetic path length



A_C: cross sectional area



Express in terms of the average flux density $B(t) = \Phi(t)/A_c$

$$v(t) = n\, A_c \frac{dB(t)}{dt}$$

From Ampere's law, we have

$$H(t)\, l_m = n\, i(t)$$

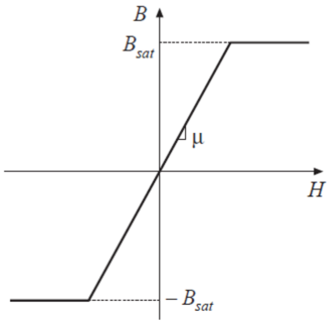
$$v(t) = n\, A_c \frac{dB(t)}{dt} \quad \xrightarrow{B = \mu H} \quad v(t) = \mu n A_c \frac{dH(t)}{dt} \quad \xrightarrow{H(t)\ell_m = ni(t)} \quad v(t) = \frac{\mu n^2 A_c}{\ell_m} \frac{di(t)}{dt}$$

$$v(t) = \frac{\mu n^2 A_c}{\ell_m} \frac{di(t)}{dt}$$

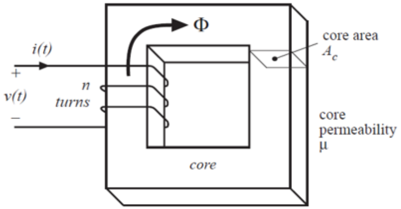
$$\boxed{v(t) = L \frac{di(t)}{dt}} \quad \Rightarrow \quad \boxed{L = \frac{\mu n^2 A_c}{\ell_m}}$$

Saturation

$$B = \begin{cases} B_{sat} & \text{for } H \geq B_{sat}/\mu \\ \mu H & \text{for } |H| < B_{sat}/\mu \\ -B_{sat} & \text{for } H \leq B_{sat}/\mu \end{cases}$$



$$I_{sat} = \frac{B_{sat}\, l_m}{\mu\, n}$$



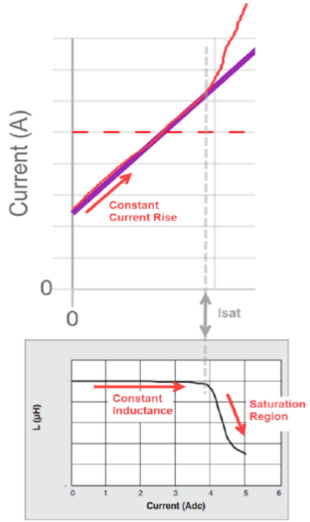
$|I| < I_{sat}$ the device behaves as an inductor

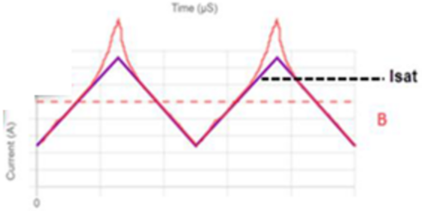
$|I| > I_{sat}$ the flux density *B(t)* = *Bsat* is constant Faraday's law states that the terminal voltage = 0, hence theoretically **the magnetic device behavior approaches a short circuit.**

$$v(t) = nA_c \frac{dB_{sat}}{dt} = 0$$

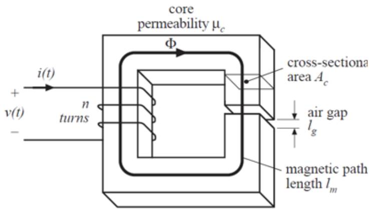
$$v/_L = di/dt$$

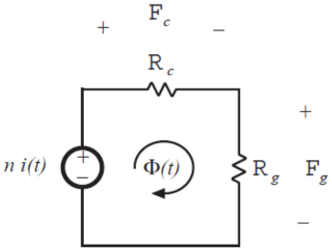
$I > I_{SAT}$
L drop, di/dt increase





Effect of air gap

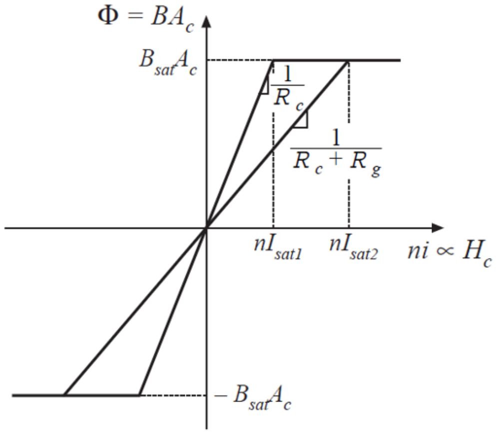




$$L = \frac{\mu n^2 A_c}{\ell_m}$$

L with no Gap

$$L = \frac{n^2}{R_c}$$



$$F_c + F_g = n\,i$$

$$n\,i = \Phi\left(R_c + R_g\right)$$

$$R_c = \frac{l_c}{\mu A_c}$$

$$R_g = \frac{l_g}{\mu_0 A_c}$$

$$n\,i = \Phi\left(R_c + R_g\right)$$

$$I_{sat} = \frac{B_{sat}A_c}{n}\left(R_c + R_g\right)$$

Faraday's law: $v(t) = n\dfrac{d\Phi(t)}{dt}$

Substitute for Φ: $v(t) = \dfrac{n^2}{R_c + R_g}\dfrac{di(t)}{dt}$

Hence inductance is

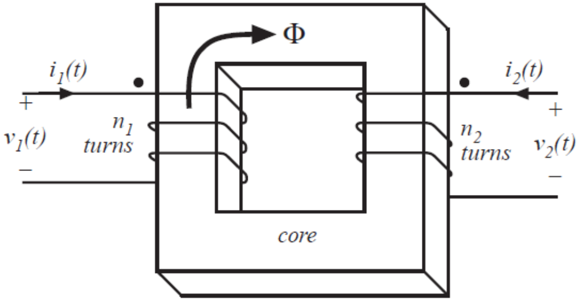
$$L = \frac{n^2}{R_c + R_g}$$

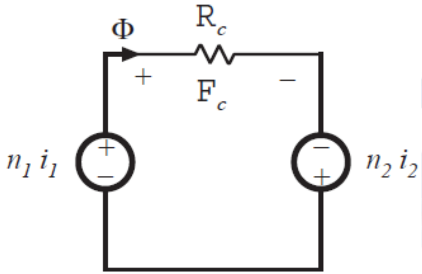
Effect of air gap:

- decrease inductance
- increase saturation current
- inductance is less dependent on core permeability

- Discrete gap(s): ferrites
- Distributed gap: powder cores

Ideal Transformer modelling





$\mu \rightarrow \infty$, $R \rightarrow 0$

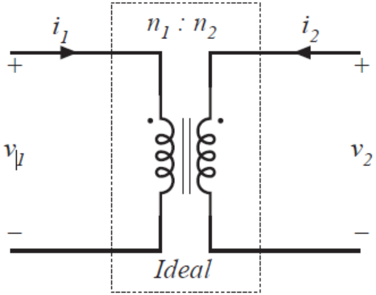
MMF $F_c = \Phi R$ also approaches zero. We then obtain

$$0 = n_1 i_1 + n_2 i_2$$

Also, by Faraday's law,

$$v_1 = n_1 \frac{d\Phi}{dt}$$

$$v_2 = n_2 \frac{d\Phi}{dt}$$



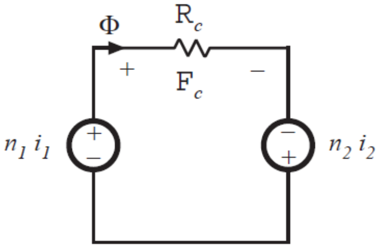
Eliminate Φ :

$$\frac{d\Phi}{dt} = \frac{v_1}{n_1} = \frac{v_2}{n_2}$$

Ideal transformer equations:

$$\boxed{\frac{v_1}{n_1} = \frac{v_2}{n_2}} \quad \text{and} \quad n_1 i_1 + n_2 i_2 = 0$$

Transformer modelling



For nonzero core reluctance, we obtain

$$\Phi\, R = n_1 i_1 + n_2 i_2 \quad \text{with} \quad v_1 = n_1 \frac{d\Phi}{dt}$$

Eliminate Φ:

$$v_1 = \frac{n_1^2}{R} \frac{d}{dt}\left[i_1 + \frac{n_2}{n_1} i_2 \right]$$

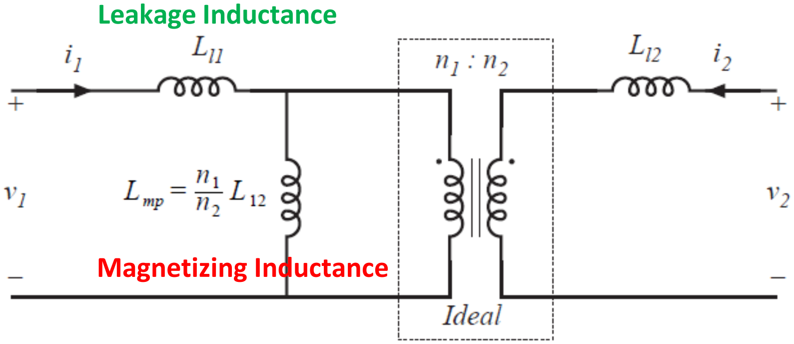
This equation is of the form

$$v_1 = L_{mp} \frac{d\, i_{mp}}{dt}$$

with

$$L_{mp} = \frac{n_1^2}{R}$$

$$i_{mp} = i_1 + \frac{n_2}{n_1} i_2$$



- Models magnetization of core material
- A real, physical inductor, that exhibits saturation and hysteresis
- If the secondary winding is disconnected:

  we are left with the primary winding on the core

  primary winding then behaves as an inductor

  the resulting inductor is the magnetizing inductance, referred to the primary winding
- Magnetizing current causes the ratio of winding currents to differ from the turns ratio

In practice, there is some flux which links one winding but not the other, by "leaking" into the air or by some other mechanism. This flux leads to *leakage inductance,* i.e., additional effective inductances that are in series with the windings.

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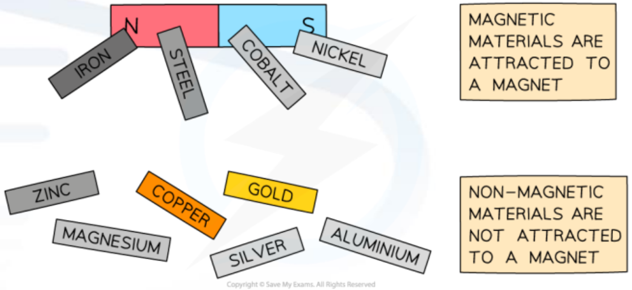
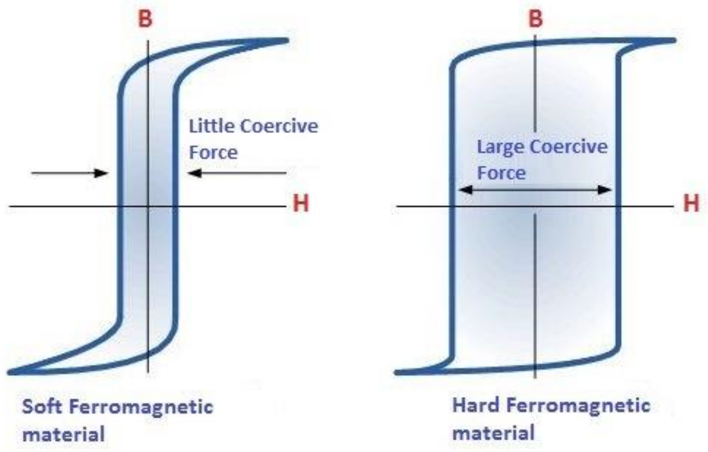


Magnetics Materials



Hysteresis loop for Soft and Hard magnetic material

Soft

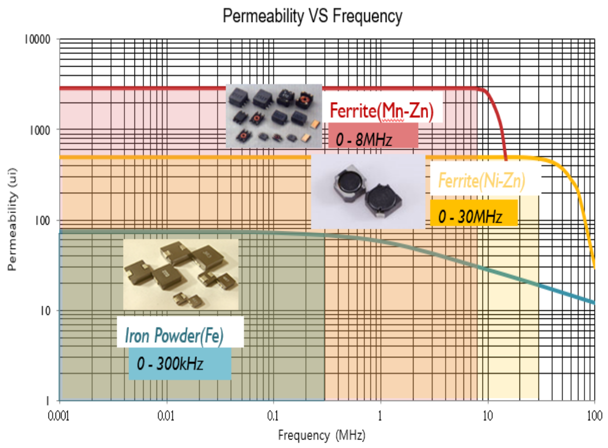
	Material	Permeability	Bsat	Core Loss	Cost
Powder	Ni Fe Mo	14-550	0.7	Lowest	High
	Fe SiB C	60	1.0	Low	Medium
	Ni Fe	14-160	1.5	Moderate	Medium
	Fe Si Al	26-125	1.0	Low	Low
	Fe Si Al Ni	14-125	1.3		Medium
	Fe Si	26-90	1.6	High	Low
	Fe	10-100	1.2	High	Lowest
Lamination or strip	Fe Si	1,500-10,000	2.0	High	Lowest
	Amorphous	10k-100,000	1.5	Low	Medium
	NanoCrystalline	15k-100,000	1.2	Low	High
Ceramic	Ferrite	15-20,000	0.45	Lowest	Lowest

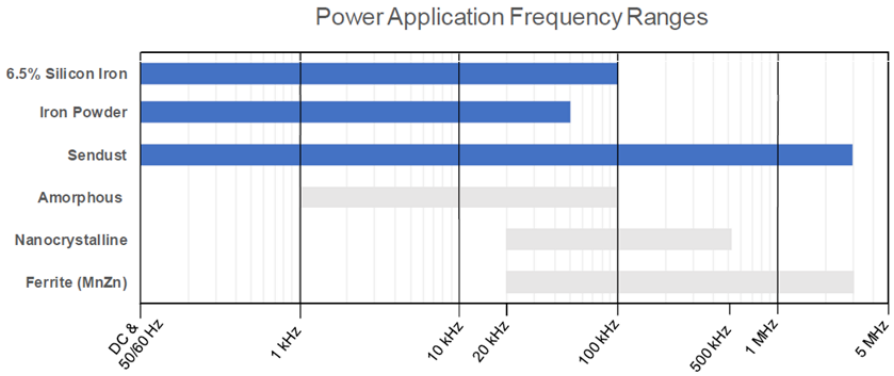
$$\boxed{L = \frac{\mu n^2 A_c}{\ell_m}}$$

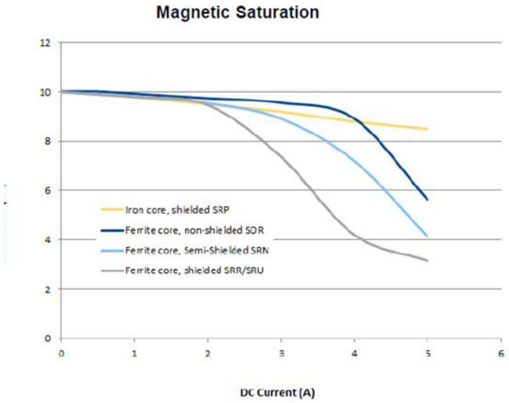
Hard

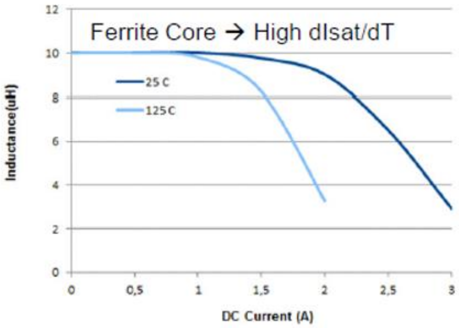
- NdFeB
- AlNiCo
- Cobalt alloys

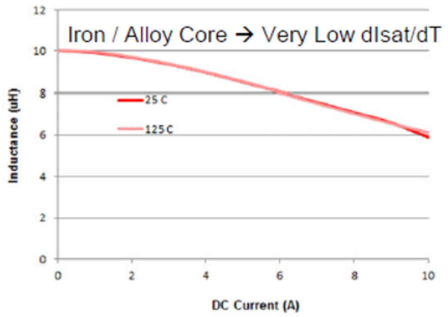
Magnetics Materials

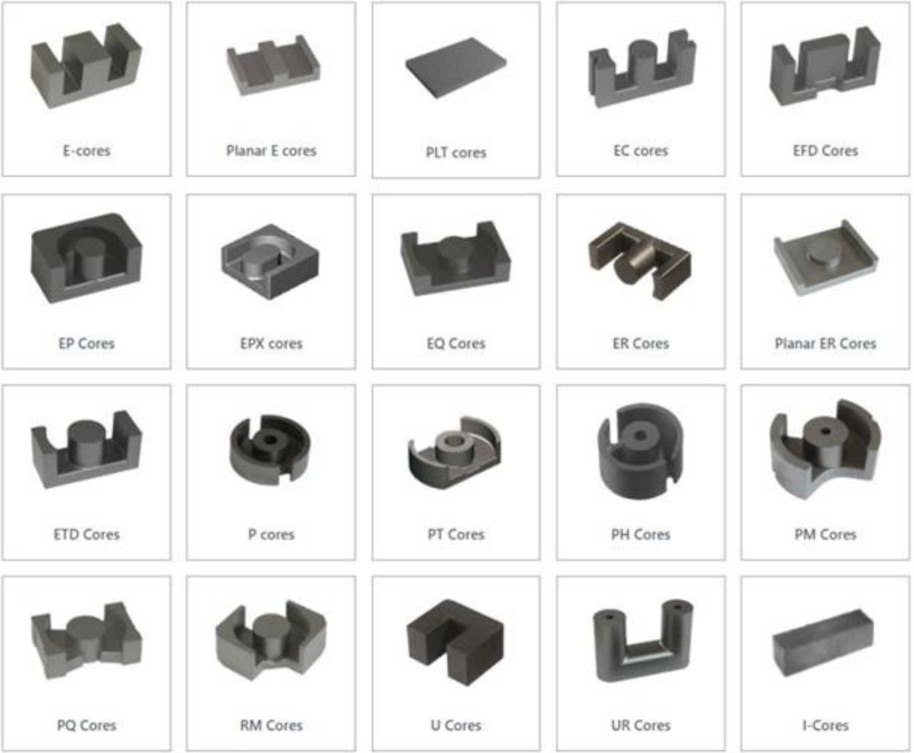










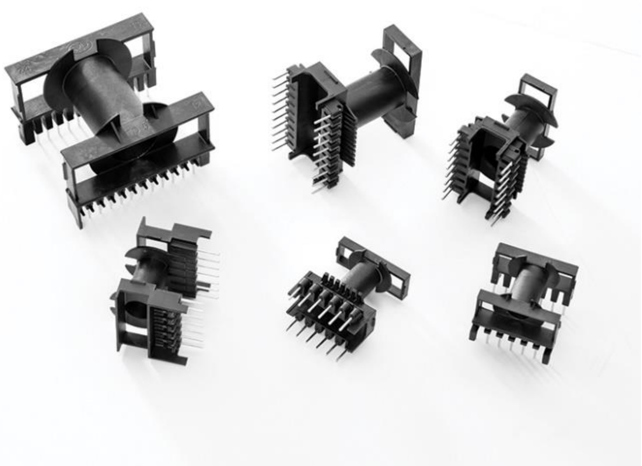

E-cores
Planar E cores
PLT cores
EC cores
EFD Cores
EP Cores
EPX cores
EQ Cores
ER Cores
Planar ER Cores
ETD Cores
P cores
PT Cores
PH Cores
PM Cores
PQ Cores
RM Cores
U Cores
UR Cores
I-Cores

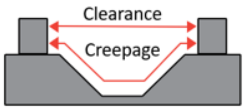
Bobbins

- Size
- Material
- Temperature rating
- UL flammability (e.g. UL94 V1 or V2)
- UL Insulation System

UL1446 rating

- Class A 105°C
- Class B 130°C
- Class F 155°C
- Class H 180°C

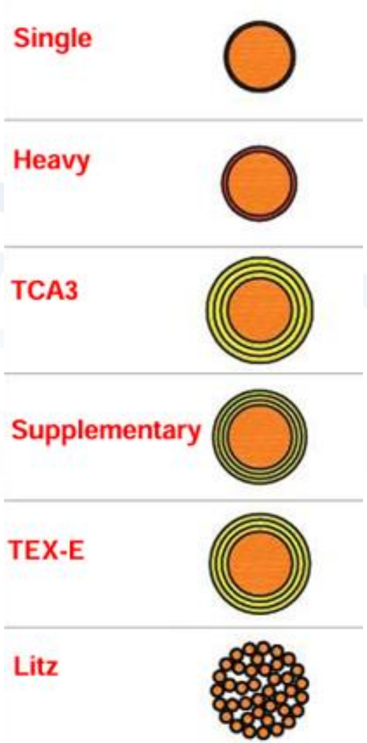


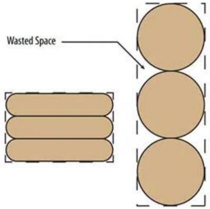


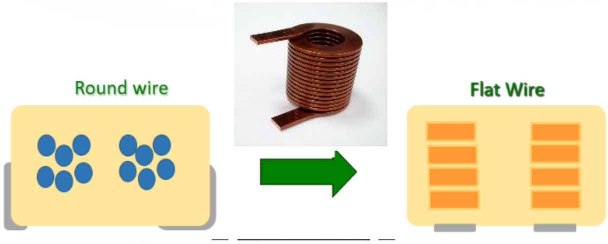
Wires

Chosen wire depends on safety grade and dielectric requirements

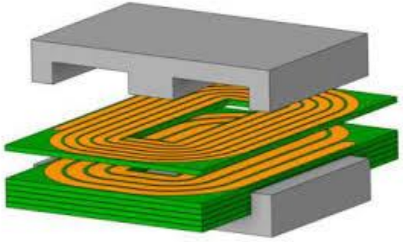
- Single insulation magnet wire
- Heavy insulation magnet wire
- Basic / Supplementary insulation
- Triple Insulated Wire (TCA3 or TEX-E)
- Fully Insulated Wire
- Litz Wire
- Flat Wire

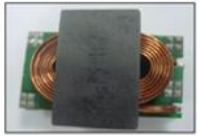






Planar Magnetics





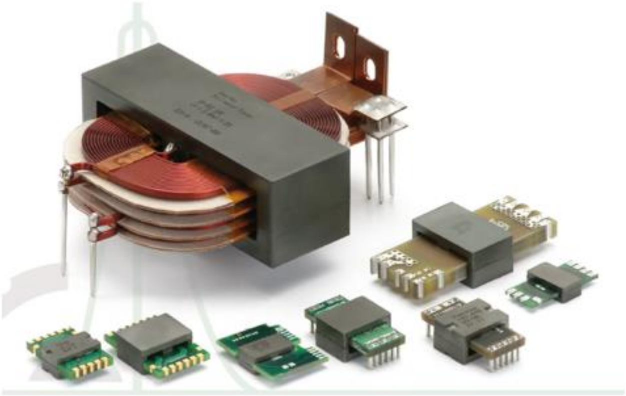
Features:

1. Very low profile;
2. Excellent thermal characteristics;
3. Low leakage inductance;
4. High efficiency;
5. Wide working frequency ;
6. High reliability;
7. Low radiation interference

Typical Application:

1. Communications Base Station
2. Telecom Power
3. Fast Charger
4. Networking Equipment Module Power

Technical standard: IEC,AEC-Q200



Examples

Working Frequency(KHZ)	Input Voltage(V)	Output Voltage(W)	Output Power(W)	Inductance (uH)	Turn Ratio(Turns)	L*W*H (mm)
300	36~57	1.2	100	100+/-15%	Pri-Sec: 16TS:1TS	24*21.2 *12

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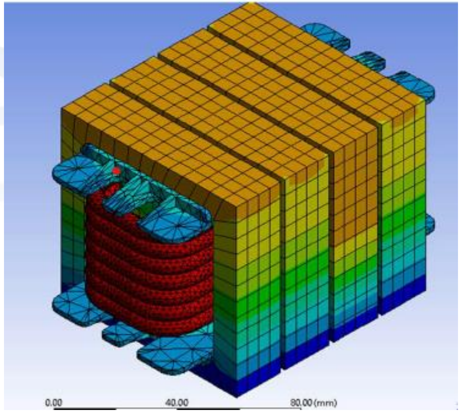
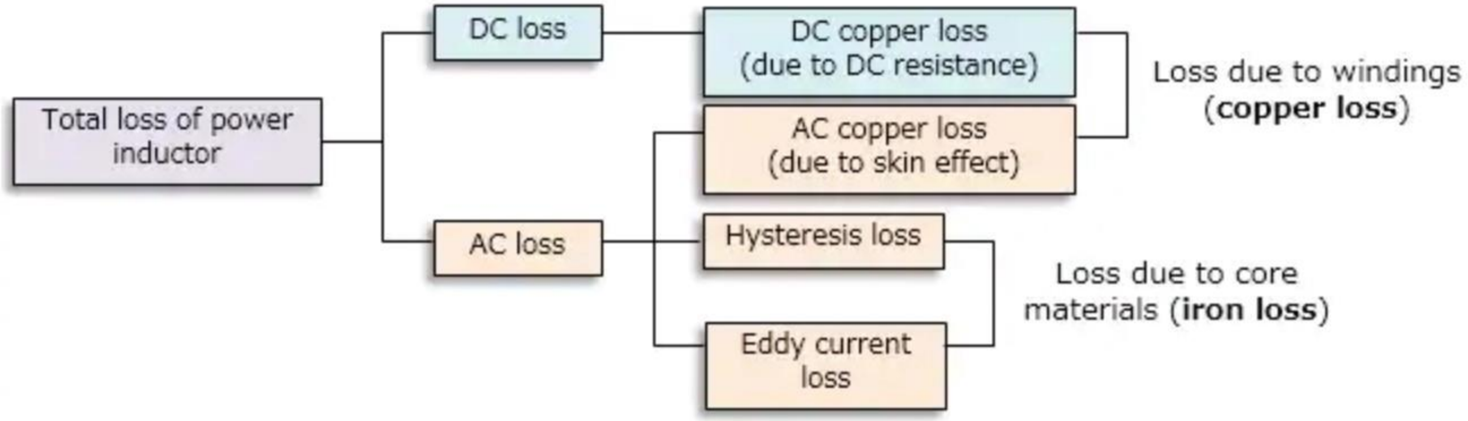


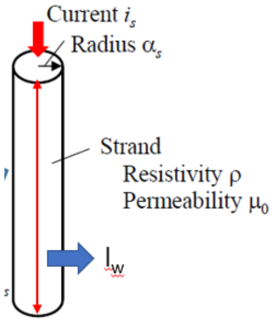
Losses in Magnetics



Source * https://product.tdk.com/en/techlibrary/applicationnote/howto_power-inductors.html

Copper Losses

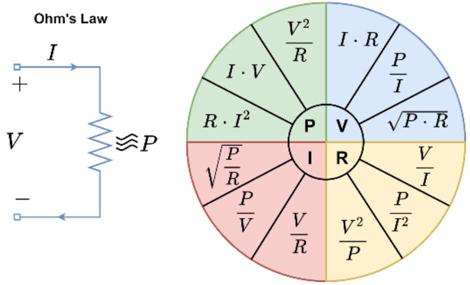
DC losses



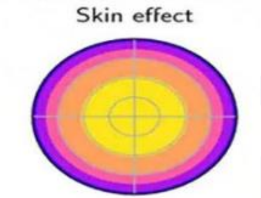
$$R_{dc} = \frac{4\rho_c N l_w}{\pi s d^2}$$

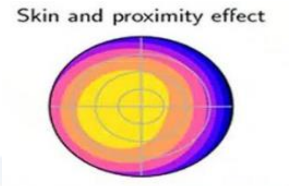
ρ_c = resistivity of annealed copper
N = number of turns
l_w = mean length of one turn [m]
s = number of wire strands
d = wire strand diameter [m]

Ohm's Law Calculator



AC losses



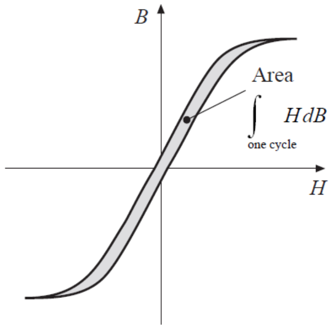


When the alternating current flows through the wire, it tends to concentrate more on the outer surface due to the skin effect. This results in an underutilization of the inner part of the wire that, leads to energy losses.

When multiple windings are near each other, their magnetic fields interact, resulting in energy losses

Litz wire is a type of stranded wire designed to mitigate the skin effect, a phenomenon where alternating current (AC) tends to flow primarily on the surface of a conductor, increasing resistance at higher frequencies. Litz wire achieves this by using many small, insulated wire strands twisted together, allowing the current to distribute more evenly across the cross-section, reducing resistance and losses.

Core losses: Hysteresis losses



$$W = \left(A_c l_m\right) \int_{\text{one cycle}} H\,dB$$

The term *Ac lm* is the volume of the core
The integral is the area of the *B-H* loop.

(energy lost per cycle) = (core volume) (area of *B-H* loop)

$$P_H = \left(f\right)\left(A_c l_m\right) \int_{\text{one cycle}} H\,dB$$

Hysteresis loss is directly proportional to applied frequency

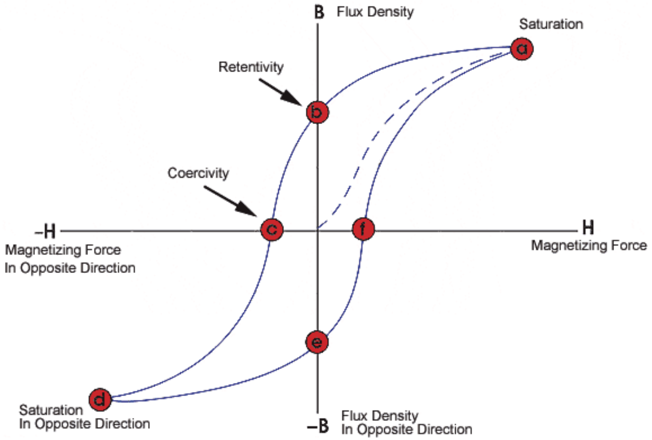
Hysteresis loss varies directly with applied frequency

- Dependence on maximum flux density: how does area of *B-H* loop depend on maximum flux density (and on applied waveforms)?
- Empirical equation (Steinmetz equation):

$$\boxed{P_H = K_H f B_{\max}^{\alpha} (core\ volume)}$$

The parameters K_H and α are determined experimentally.

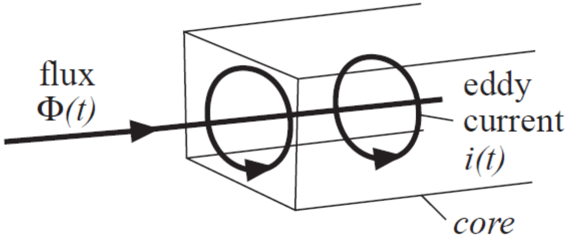
Dependence of P_H on *Bmax* is predicted by the theory of magnetic domains.



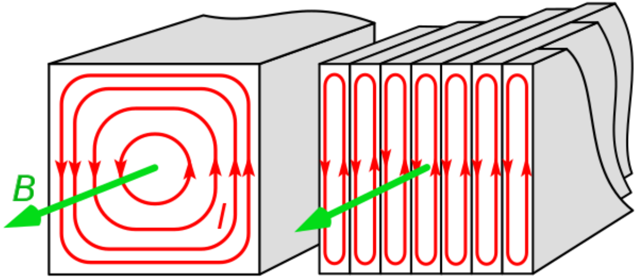
Core losses: Eddy Current Losses

Magnetic core materials are, unfortunately, reasonably good conductors of electric current. Hence, according to Lenz's law, magnetic fields within the core induce currents ("eddy currents") to flow within the core.

The eddy currents flow such that they tend to generate a flux which opposes changes in the core flux ϕ*(t).*
The eddy currents tend to prevent flux from penetrating the core.



Eddy current loss $i^2(t)R$



$$P_e = k_e \frac{(tfB_m)^2}{\rho}$$

P_e: Eddy current loss

t: Iron plate thickness

f: Frequency

B_m: Maximum magnetic flux density

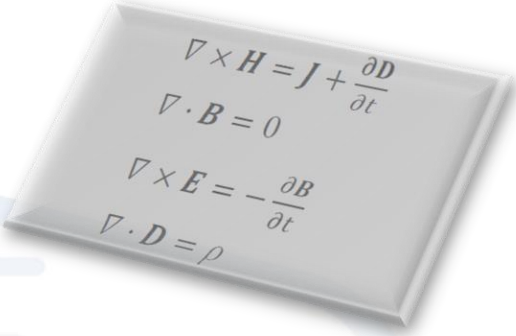
ρ: Resistivity of magnetic substance

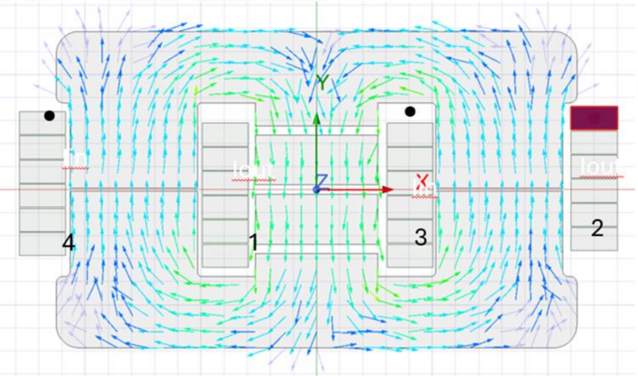
k_e: Constant of proportionality

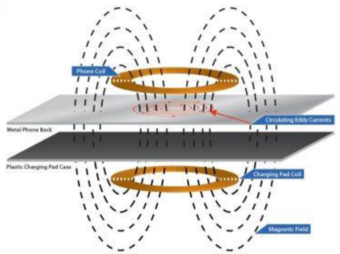
Losses directly proportional to square of frequency

Simulations Tools

- Finite Element Analysis
- Flexible X-Y (2D) or XYZ (3D) Modelling
- Types of Analysis Possible:
  - Static
  - Low Frequency
  - Transient Analysis
- Mechanical Analysis Possible







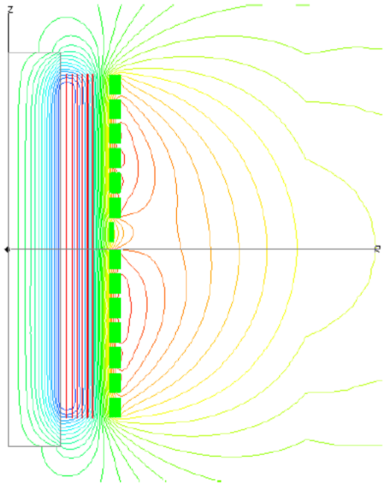
Simulations Tools

Magnetic effects:

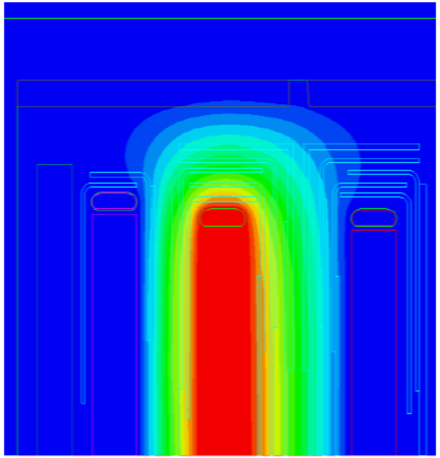
- Nonlinear Materials
- Eddy Currents

Electric Field Effects:

- Varying Dimensions and Shapes
- Varying Dielectric Permittivity



Magnetic flux lines



Voltage Contours

Simulations Tools

Inductor Loss Calculator

Product Type: High Current Shielded
Part Series: SRP1050WA
Part Number: SRP1050WA-100M

Part Number	Size (L x W x H in mm)	Inductance (µH)	DCR @ 25 °C (mΩ)	Current Rating (A)	Saturation Current (A)	Operating Temp Min-Max (°C)
SRP1050WA-100M	11 x 10 x 5.4	10	0.023	9	13	-55 - 165

SRP1050WA-100M
Magnetic Products

- View Product Series
- Get Datasheet
- View Design Files

Input

Buck | Boost

V_{in}		(V)
V_{out}		(V)
I_{out}		(A)
Frequency		(kHz)

Calculate Now | Reset

Output

Duty	0.000	(%)
I_{ripple}	0.000	(A)
P_{core}	0.000	(W)
P_{dc}	0.000	(W)
P_{total}	0.000	(W)

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- PARASITICS
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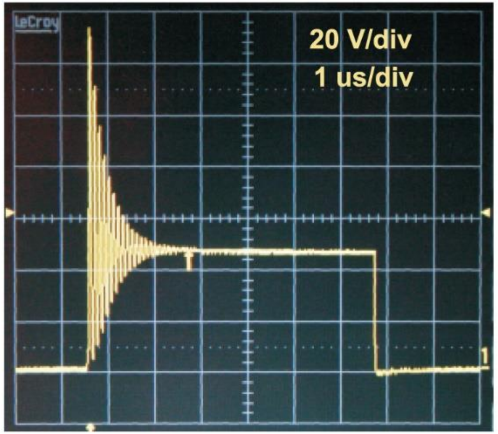
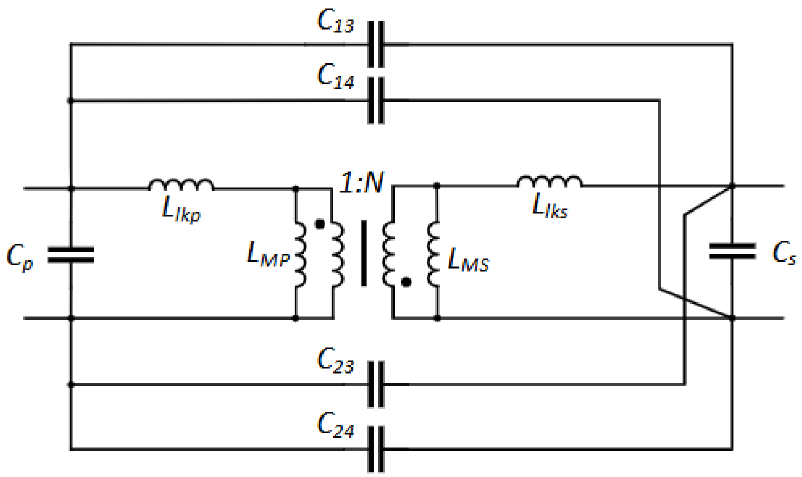
- CUSTOMIZATIONS: REAL EXAMPLES
- APPLICATIONS



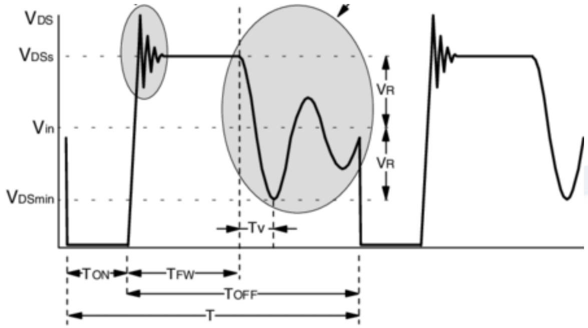
Parasitics



*Flyback Transformer Equivalent Models

- C_P: Primary Capacitance
- C_S: Secondary Capacitance
- C_{13}, C_{14}, C_{23}, C_{24}: Interwinding Capacitance
- $L_{lkp:}$:primary leakage inductance
- $L_{lks:}$:secondary leakage inductance
- $L_{MP:}$:primary magnetizing inductance
- $L_{MS:}$:secondary magnetizing inductance

Mitigating Parasitics



At high frequencies, parasitic capacitances can resonate with the transformer's inductance, leading to voltage and current oscillations.

- **Resonace**
- **Increased Losses:**
- **Voltage Spikes:**
- **Distortion of Waveforms:**

- **Careful Design:**

Proper winding techniques, insulation, and core selection can minimize parasitic capacitance and inductance.

- **Shielding:**

Shielding between windings can reduce coupling capacitance and its impact on the circuit.

- **Proper Grounding:**

Effective grounding can minimize the effects of stray capacitances and currents.

- **Component Selection:**

Choosing components with low parasitic values can help in reducing the overall parasitic effects in the circuit.

- **Optimized PCB Layout:**

In transformer designs, proper PCB layout can help minimize parasitic capacitance and inductance.

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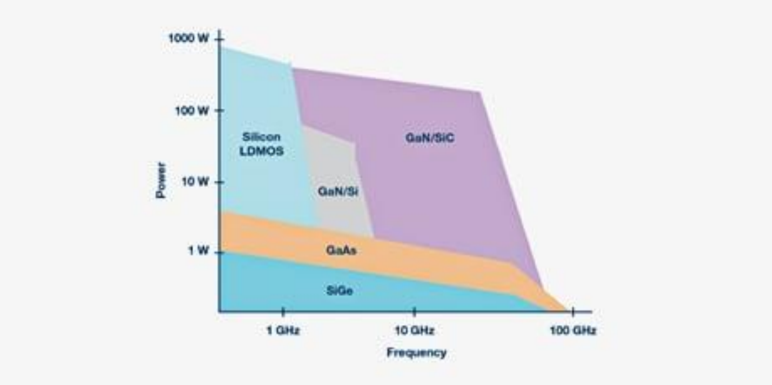


SiC and GaN Magnetics Design Approach

- **SiC operating voltages 650 - 1600 V**
  - Higher efficiency and power density versus Si
  - Faster switching speed versus Si IGBT
    - Si: 5 - 50 kHz
    - SiC: 30 - 300 kHz (Currently 30 - 150 kHz)
- **High temperature range of operation**
    - Greater than ETR –40 to +125 °C

- **GaN operating voltages 650 - 100 V or less**
  - Higher efficiency and power density versus MOSFET
  - Faster switching speed versus MOSFET
    - MOSFET: (80 - 800 kHz)
    - GaN (100 kHz - MHz)
  - Economical pricing compared to SiC

	Si	GaN	4H-SiC
Bandgap (eV)	1.12	3.4	3.26
Electron mobility μ_n ($cm^2/V\,s$)	1400	2000	1000
Breakdown Electric Field E_{br} (MV/cm)	0.3	3.3	2.8
Saturation electron drift velocity V_S (10^6 cm/s)	10	15	22
Thermal conductivity Θ (W/cm K)	1.5	2.53	4.9

End user advantages
- Miniaturization potential
- Safer and more reliable power density

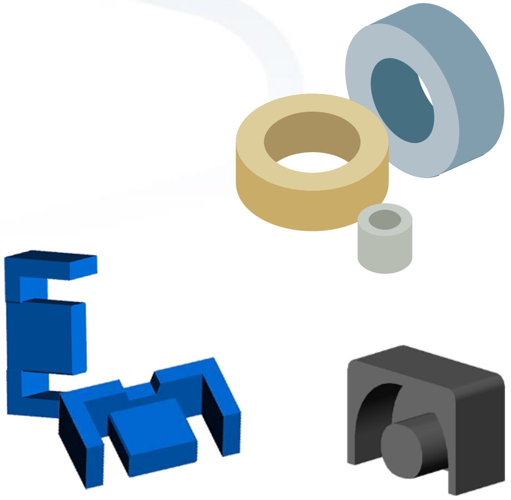
Magnetics component design challenges
- On-state performance at higher voltage
- Higher frequency and temperature operation
- Switching losses
- Safety requirements

Higher Operating Frequency

Core Material Selection

- ***SiC***
  - Operating frequency > ~30 kHz: ferrite (MnZn) versus Fe/Ni powder or amorphous/nanocrystalline

- ***GaN***
  - Operating frequency > ~600 kHz: ferrite (MnZn) or high frequency powder designed for low core loss
  - Limited selection
  - Typically, more expensive



Higher Operating Frequency

Faraday's Law

$$v(t) = A_c \frac{dB(t)}{dt}$$

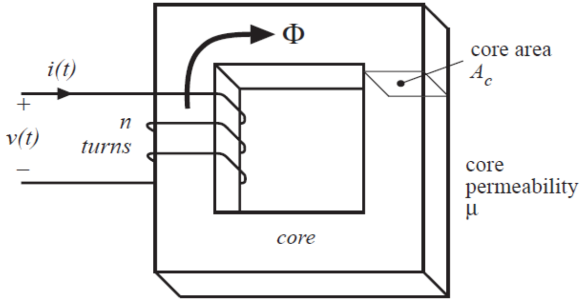
$$B_m = \frac{V \cdot 10^8}{K_f N A_C f}$$

Bm = Operating flux density
V = Voltage
K_f = Scaling factor depending on waveform
N = Turns
A_C = core area

From the equation, <u>ideally</u>, increasing frequency:

- Reducing core area keep the operating flux density about the same
- Fewer wire turns possible, flux density about the same
- Operate at lower flux density

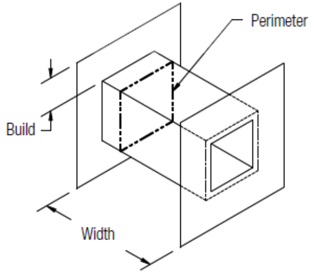
<u>Actually</u>, there are limitations due to core and wires to consider

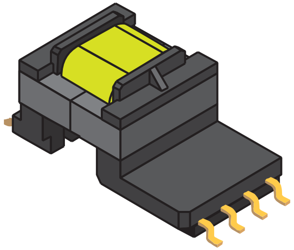


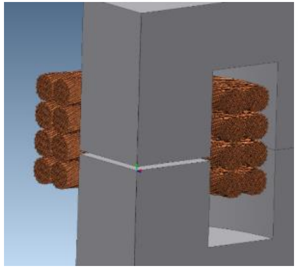
Magnetics Design Limitations for WBG

Calculated core size may be smaller but same power density means same current level

- Copper wire size remains the same
- Wire winding area smaller
- Reduction of wire turns may not be possible
- Coil winding dynamics
  - Winding AC losses
  - Parasitics low
  - Flat wire







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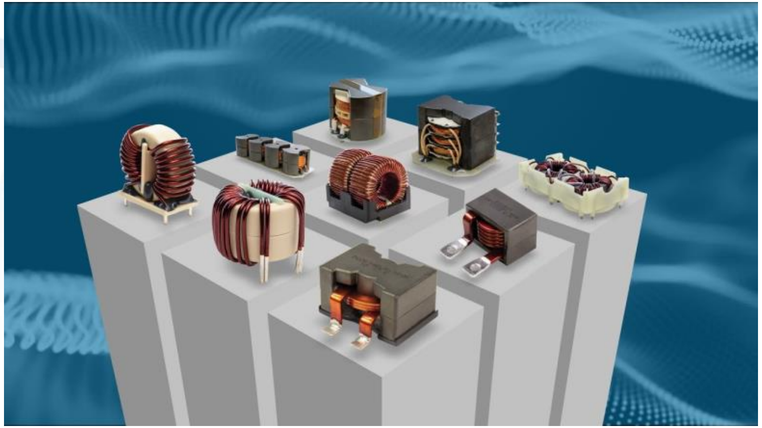
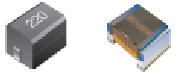


Standard Magnetics

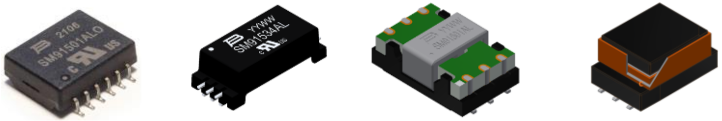
Common Mode Chokes

Chip Inductors

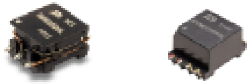
Common Mode Chip Inductors – LAN, CANBus



Wirewound Chip Inductors



BMS Transformers



Push Pull Transformers

Flyback

LAN Transformers

Non-shielded

Semi-shielded

Shielded

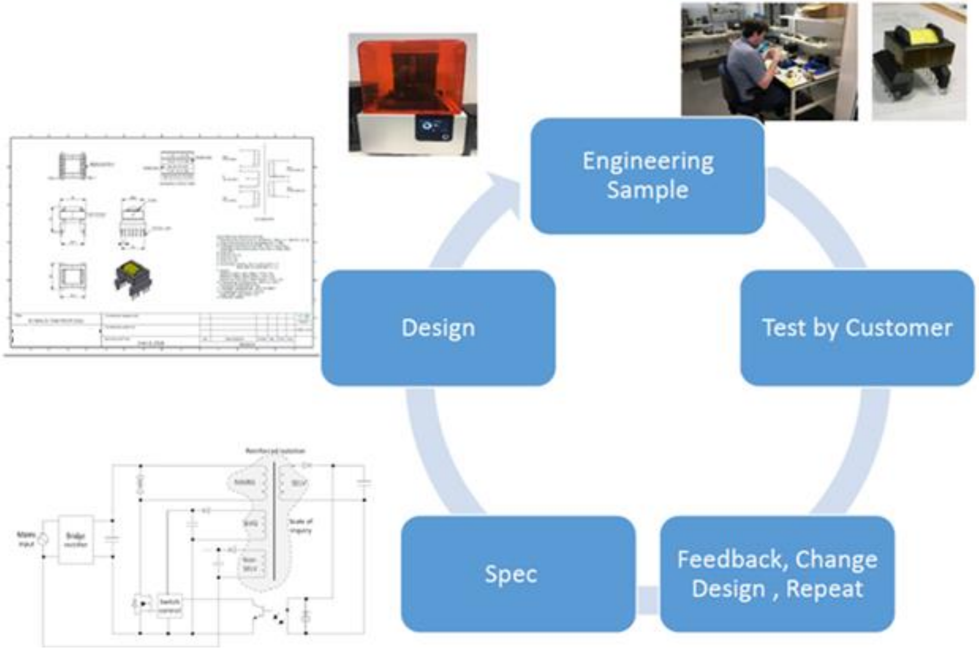
Shielded Molded

High Current

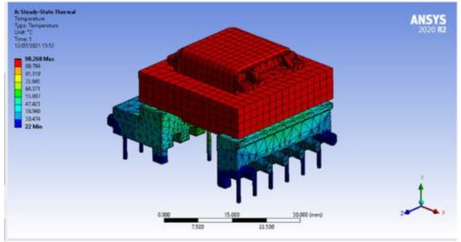
SMD Power Inductors

Custom Magnetics

Custom Magnetics

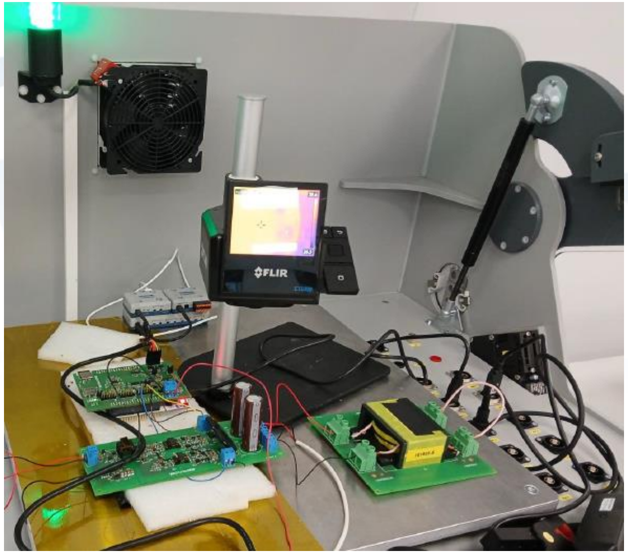


- Magnetic FEA Analysis
- Thermal Analysis
- Mechanical/electrical simulation
- Prototypes / pre-series
- Hi-pot / impulse test




FLIR
130.0°C
115.8°C
81.1°C

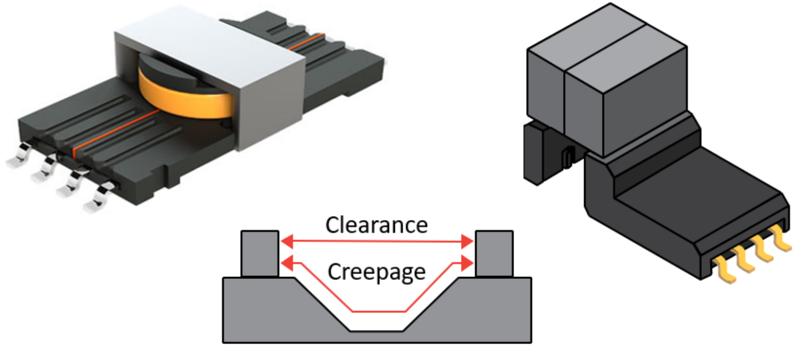

max 80.3°C
81.1
30.0


FLIR

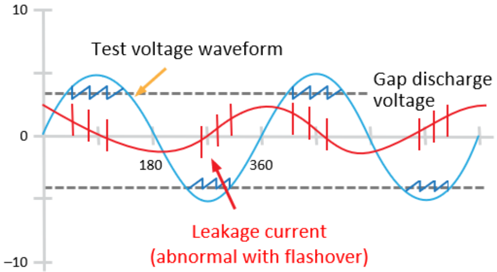
Magnetics Design Limitations

Construction Requirements for Safety Standard Distances, Insulation Level, and Dielectric

- Peak working voltage
- Overvoltage category / Hi-Pot test voltage
- Specific standards to be met
- Level of insulation required (functional, basic, supplementary, reinforced)



Dielectric Test Waveform



Peak Working Voltage

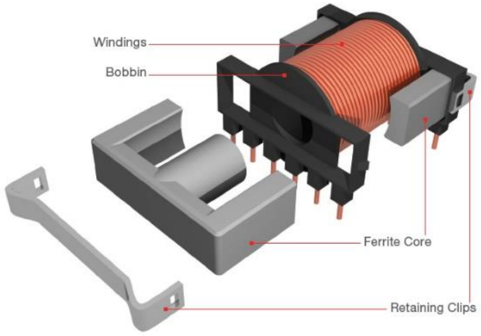
Overvoltage Category

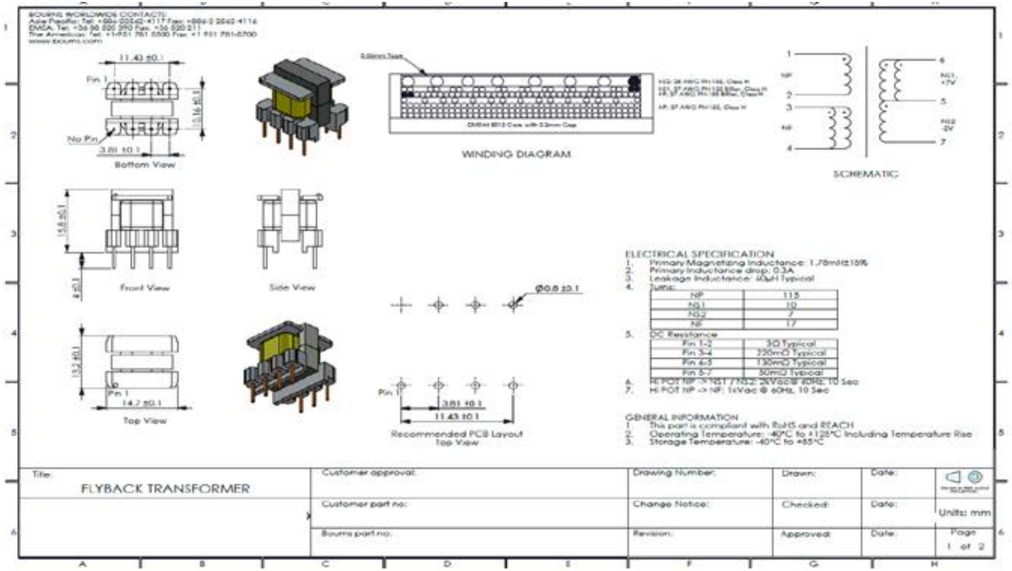
Altitude (Above Sea Level)

Level of Insulation

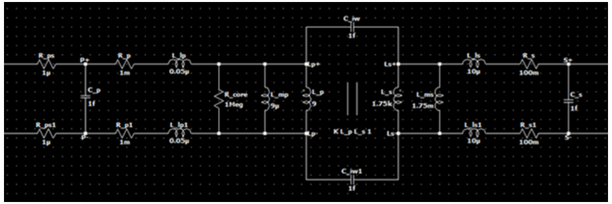
Standards:
IEC 62368
IEC 60664
IEC 61558

Flyback





- **Turns ratio**
- **Inductance**
- **Core Shape EF, EFD, ETD, EER, EI**
- **Core material**
- **Gap length**
- **Bobbin**
- **Insulating Tape**
- **Insulated wire**
- **Varnish**

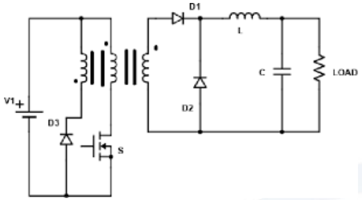


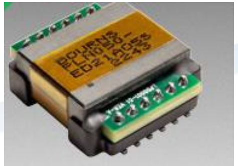
Spice Model: parasitic parameter

- L_P: primary inductance
- L_S: secondary inductance
- L_K: leakage inductance
- C_p: primary capacitance
- C_S: secondary capacitance
- C_I: interwinding capacitance

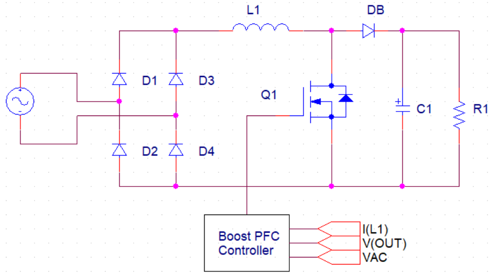
Custom Magnetics

Forward Transfomers

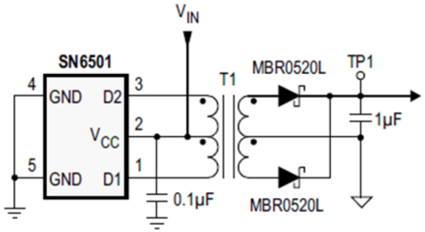


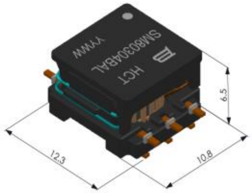


PFC Inductors

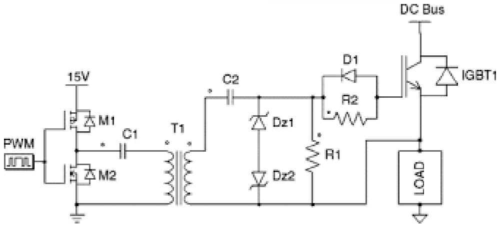


Push-Pull Transfomers





Gate Driver Transfomers



LLC DC/DC Converter

- DC input voltage from PFC (+100Hz AC ripple)
- DC output isolated voltage to HV battery

- H bridge: generates a square pulse waveform

- **Lr: resonant inductor**
- **Cr: resonant capacitor**
- **Lm: magnetizing inductance of the isolation transformer**

- LLC: Square waveform → almost-sinusoidal

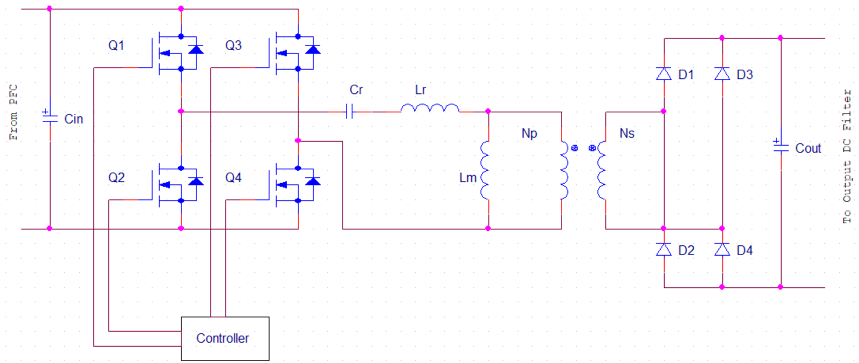
- Isolation transformer:
  - Galvanic isolation input/output
  - Block conductive EMI noise
  - Protect primary from load short circuit

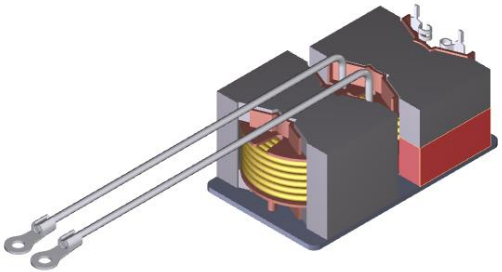
- Ns/Np
  - nominal input and output voltages

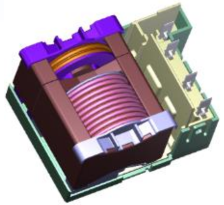
- $f_{SWITCH} < f_{RESONANCE}$ → higher current in the resonant tank, higher conduction losses

- $f_{SWITCH} > f_{RESONANCE}$ → higher switching losses

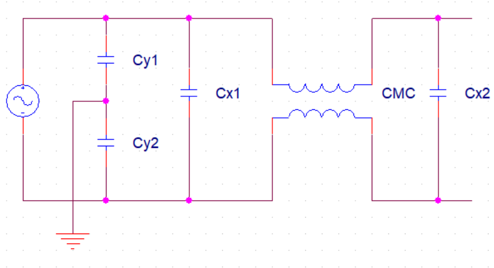
- $f_{SWITCH} = f_{RESONANCE}$ → best working efficiency

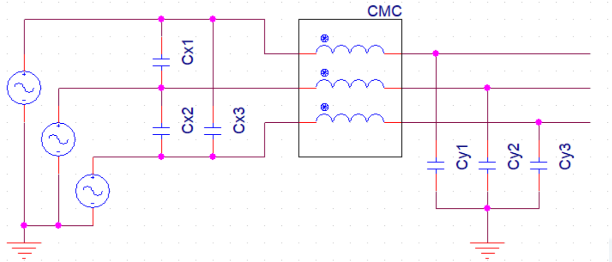


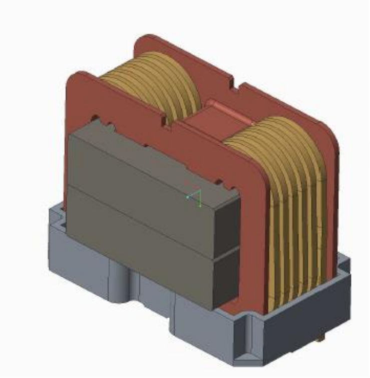


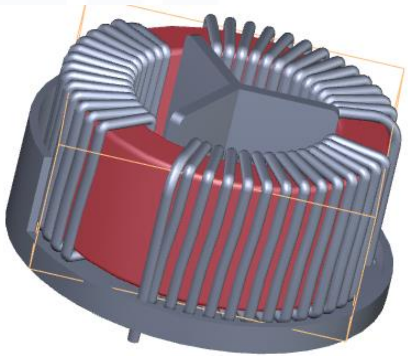


Common Mode Chokes





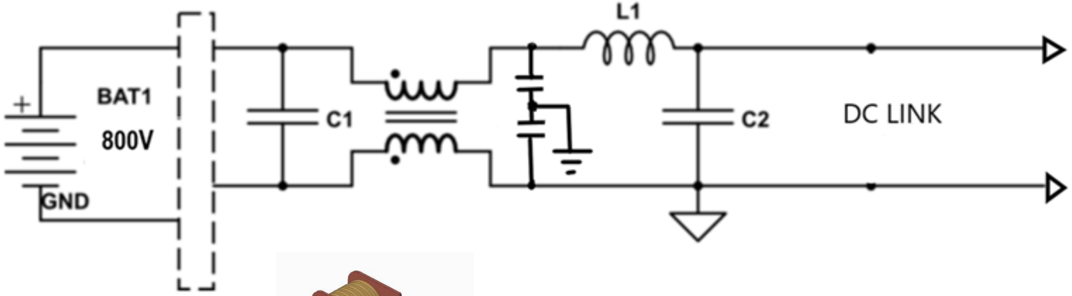


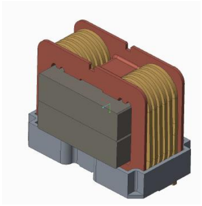


High-voltage CMC and DMC

Applications directly connected to high voltage battery (400Vdc or 800Vdc)

- EV Electronic fans
- EV PTC heaters





CMC

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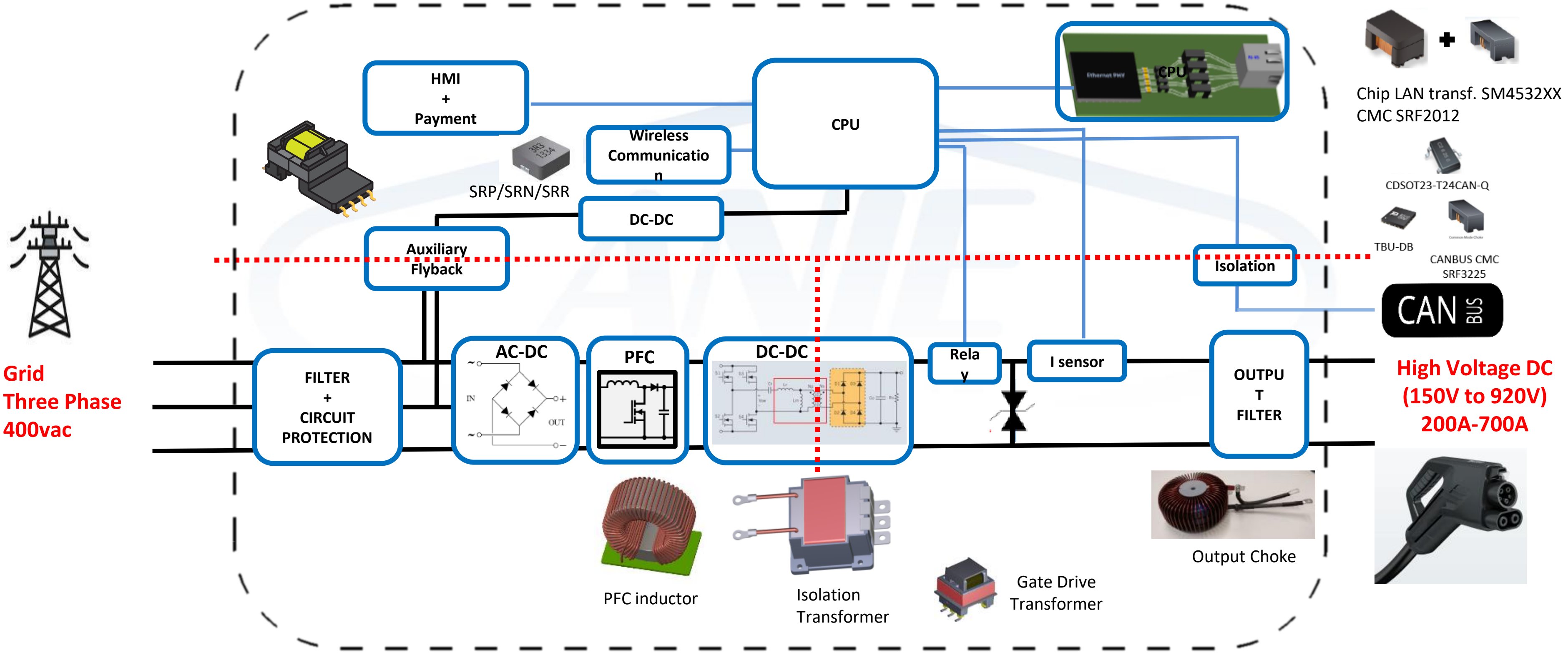
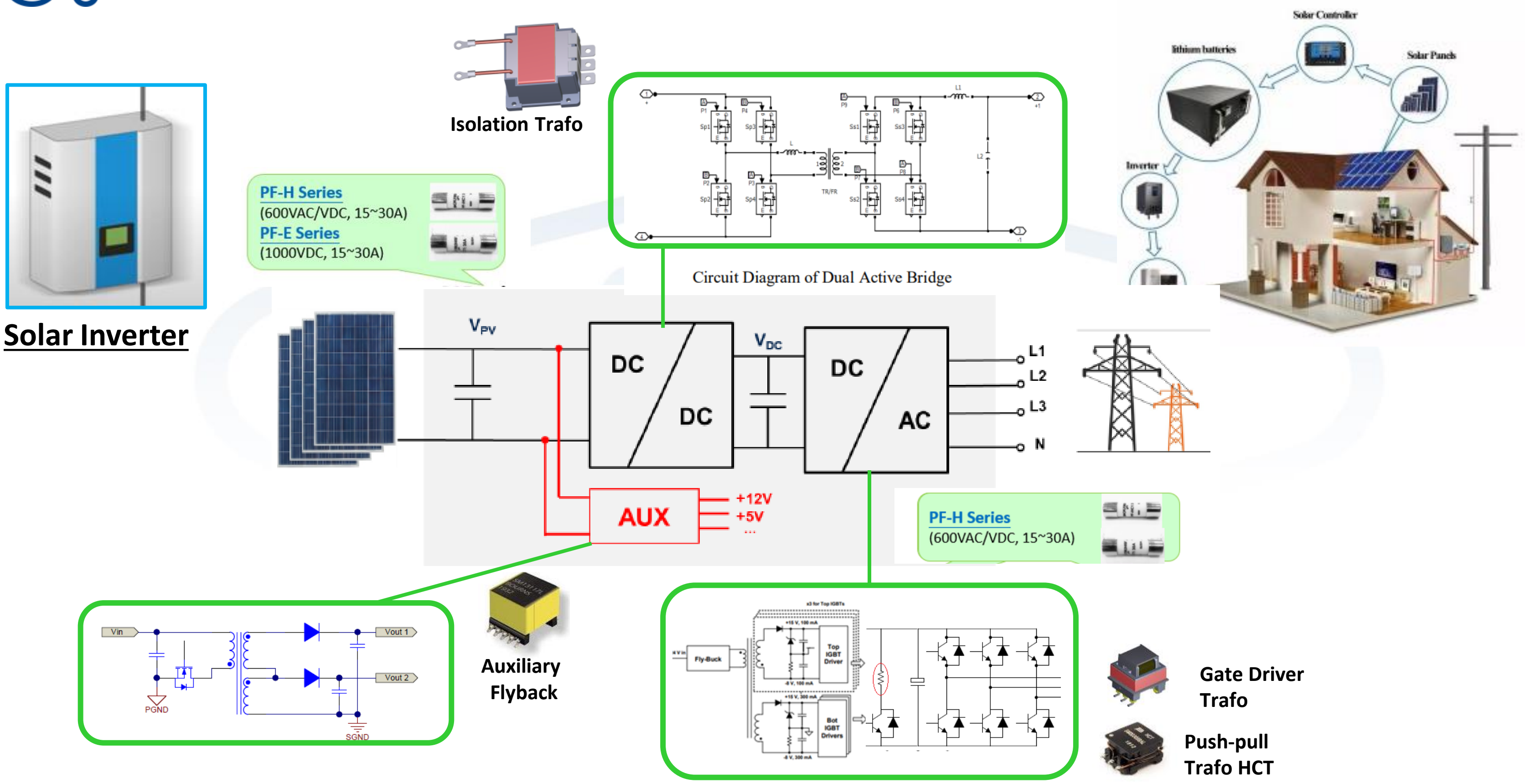
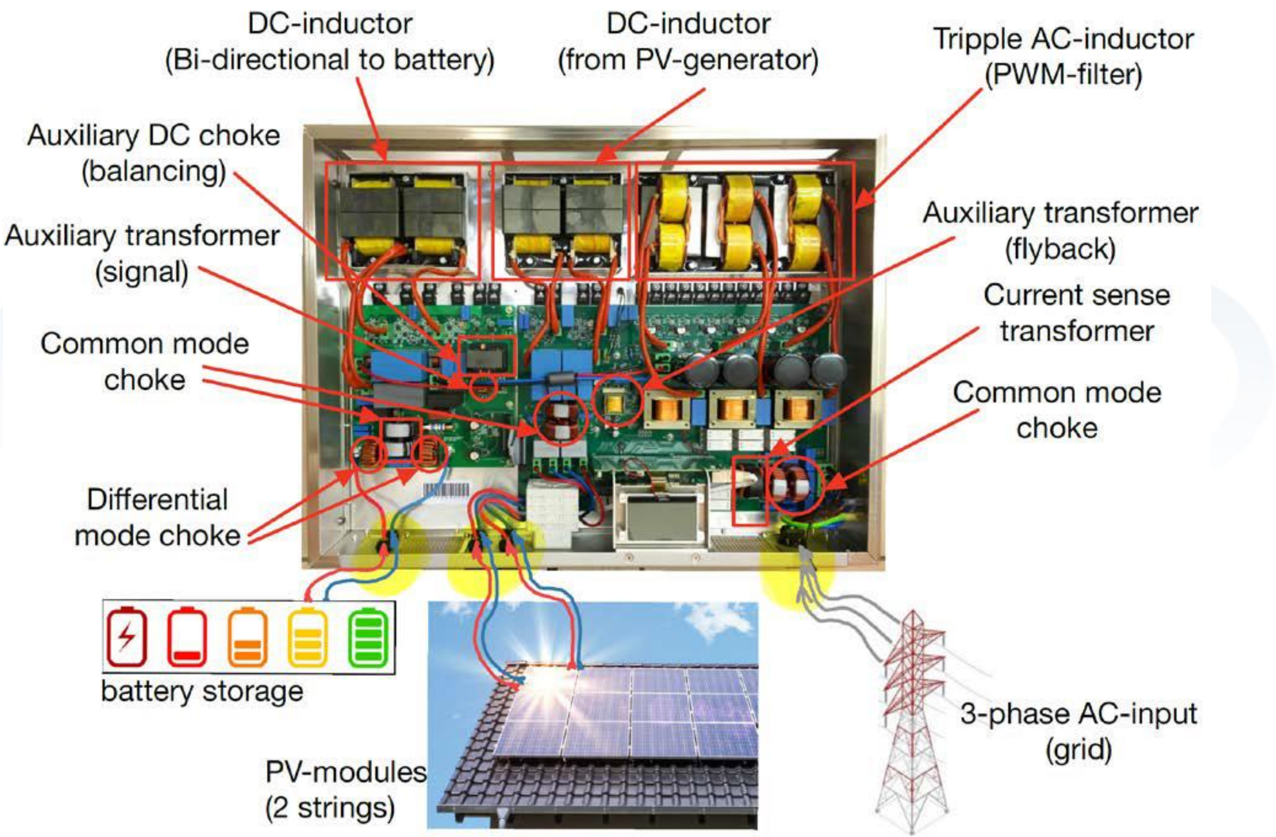
DC Chargers


HMI
+
Payment
CPU
CPU
Chip LAN transf. SM4532XX
CMC SRF2012
Wireless
Communicatio
n
SRP/SRN/SRR
DC-DC
CDSOT23-T24CAN-Q
TBU-DB
CANBUS CMC
SRF3225
Auxiliary
Flyback
Isolation
CAN BUS
Grid
Three Phase
400vac
FILTER
+
CIRCUIT
PROTECTION
AC-DC
PFC
DC-DC
Rela
y
I sensor
OUTPU
T
FILTER
High Voltage DC
(150V to 920V)
200A-700A
PFC inductor
Isolation
Transformer
Gate Drive
Transformer
Output Choke

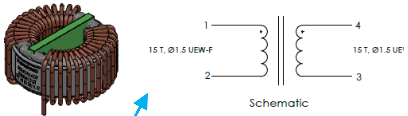
PV Solar Systems

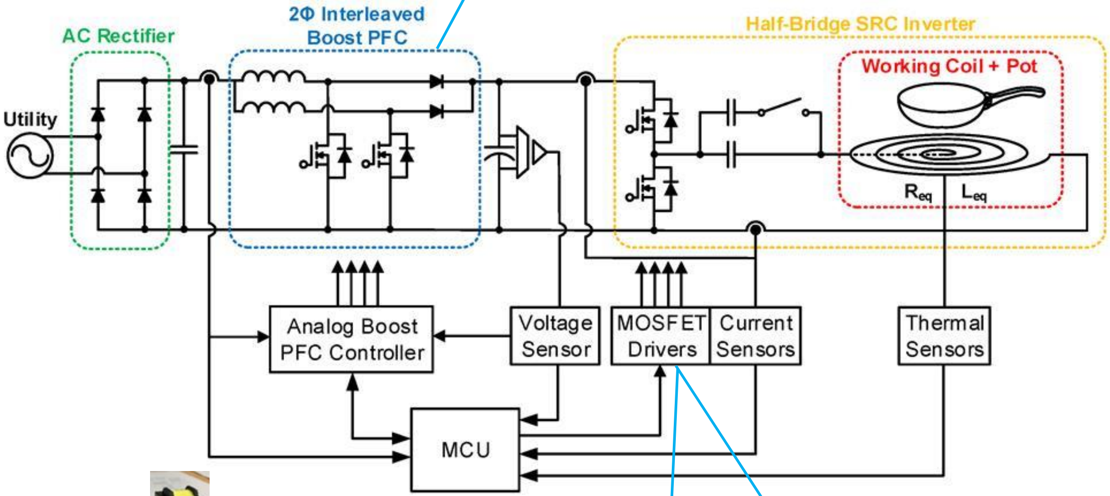


PV Inverter


DC-inductor
(Bi-directional to battery)
DC-inductor
(from PV-generator)
Tripple AC-inductor
(PWM-filter)
Auxiliary DC choke
(balancing)
Auxiliary transformer
(signal)
Common mode
choke
Differential
mode choke
Auxiliary transformer
(flyback)
Current sense
transformer
Common mode
choke
battery storage
PV-modules
(2 strings)
3-phase AC-input
(grid)

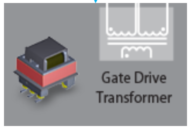
Home Appliances





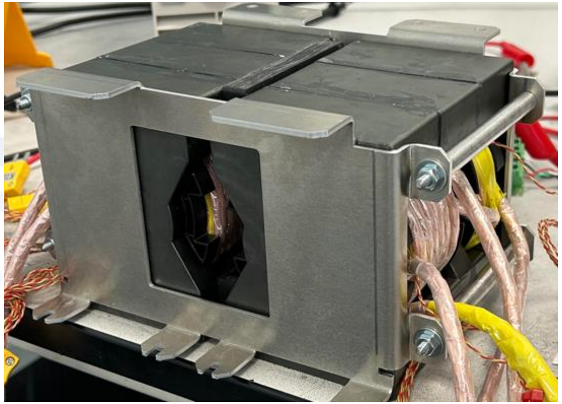
Flyback

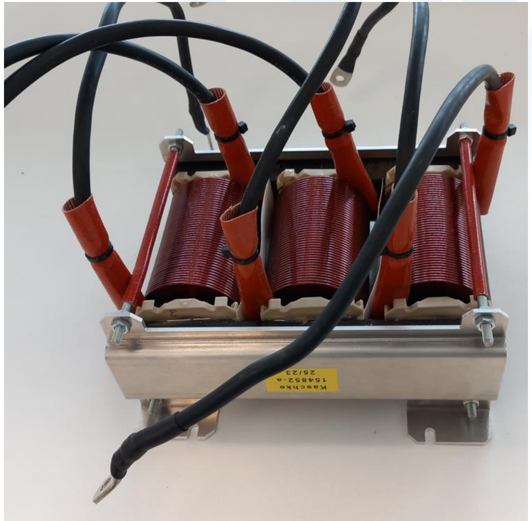
Auxiliary Power Supply

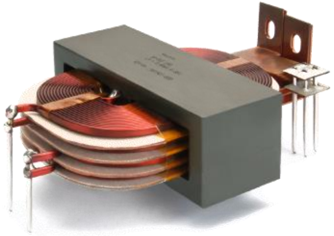


HCT push-pull trafo with SN650x for IGBT gate driver

From Miniaturized to High Power Magnetics







Thanks!