Frenetic

Practical LLC Transformer Design Methodology

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Agenda

- LLC Basics
- State of the art design methodologies
- Practical design methodology
- Design case

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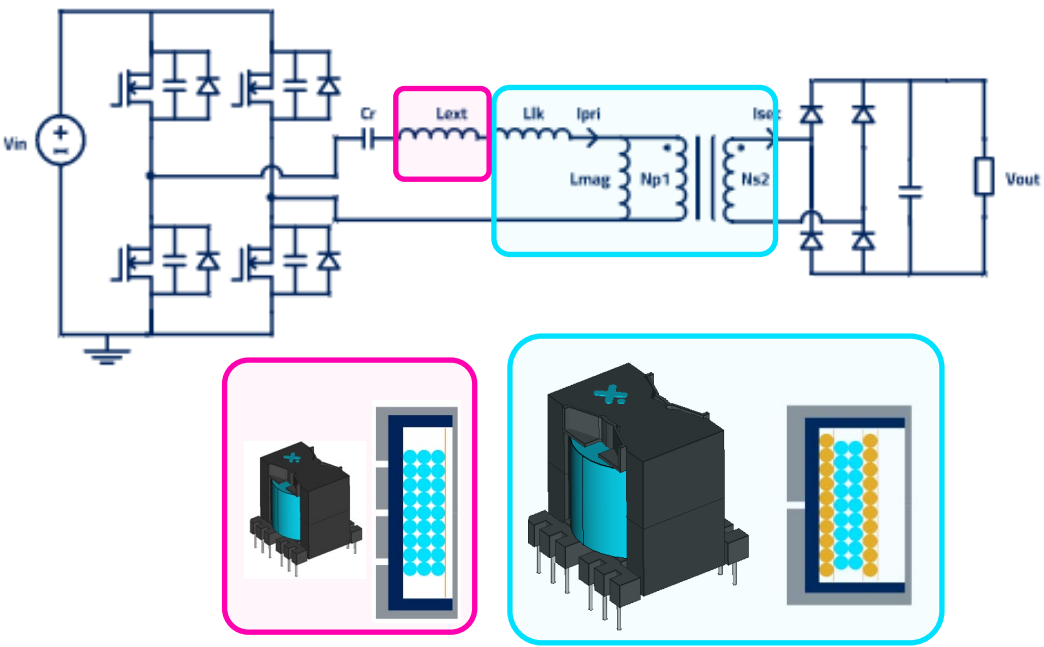
LLC Basics



- Voltage regulation by frequency change
- High efficiency at resonance frequency
- ZVS of primary switches
- ZCS at turnoff of diode bridge
- High power density could be achieved integrated the resonant inductance in the transformer

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State of the art design methodologies

Many different design methodologies have been proposed in the literature. The ones listed below are the root of most of them

Area product

$$A_p = \frac{P}{B_{ac} f J K_f K_u}$$

Rth

$$R_{th} = \frac{\Delta T_{trafo}}{P_{trafo}}$$

Kg Method

$$K_g \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_a}$$

Gapped Transformer

$$A_p = \left[\frac{\sqrt{k_u (1+\gamma)} L_m I_{Lm_{peak}} I_{rms}}{B_{max} K_t k_{up} \sqrt{\Delta T}} \right]^{8/7}$$

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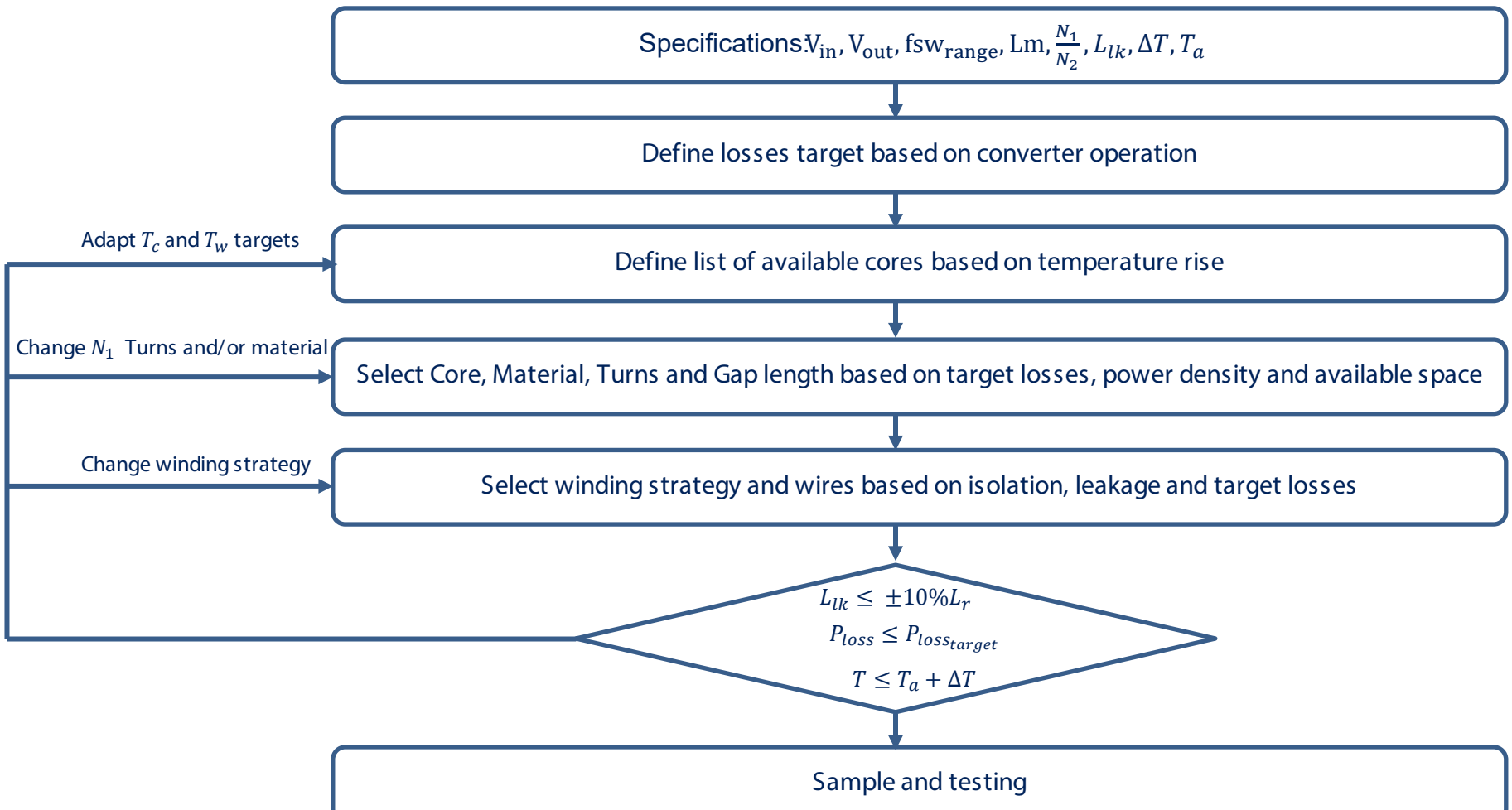
Practical LLC transformer design methodology



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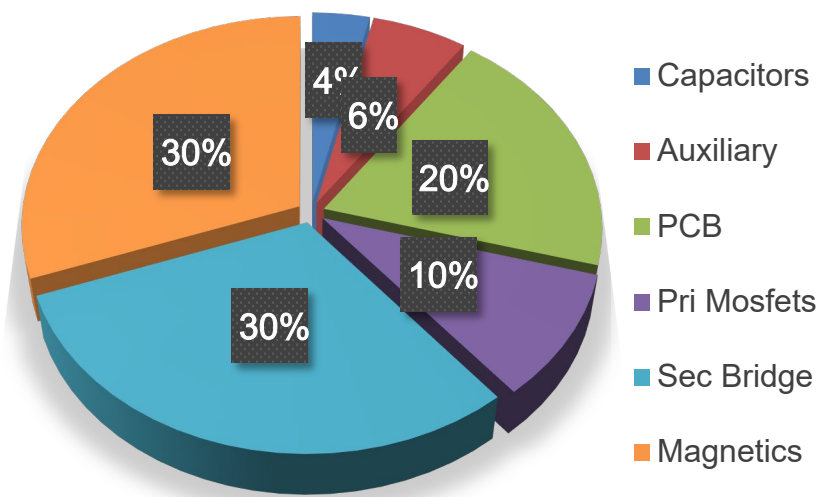
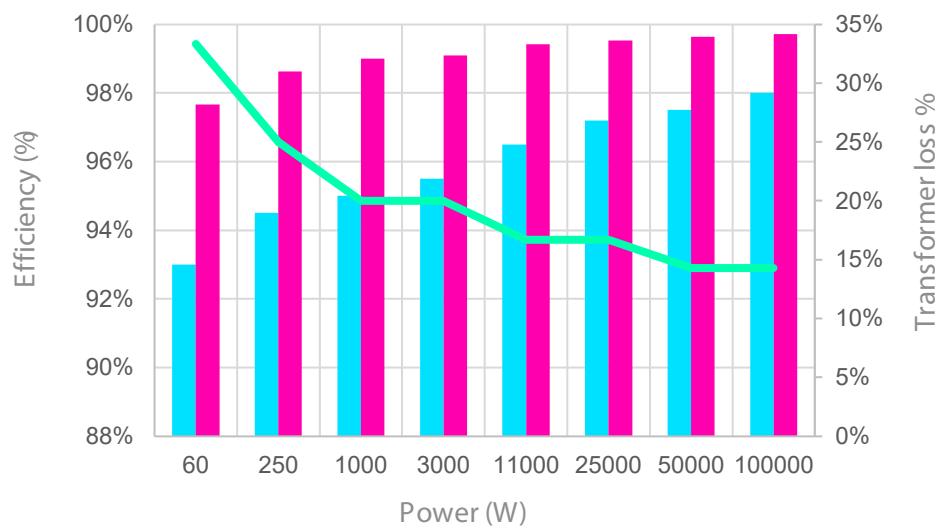
Converter Losses Budget

Basedon the input-output voltagesand power and converter target efficiencythe target lossesshould be defined

3kW LLCLossesDistribution



The larger the power the lower the contribution of the transformer to the total power losses



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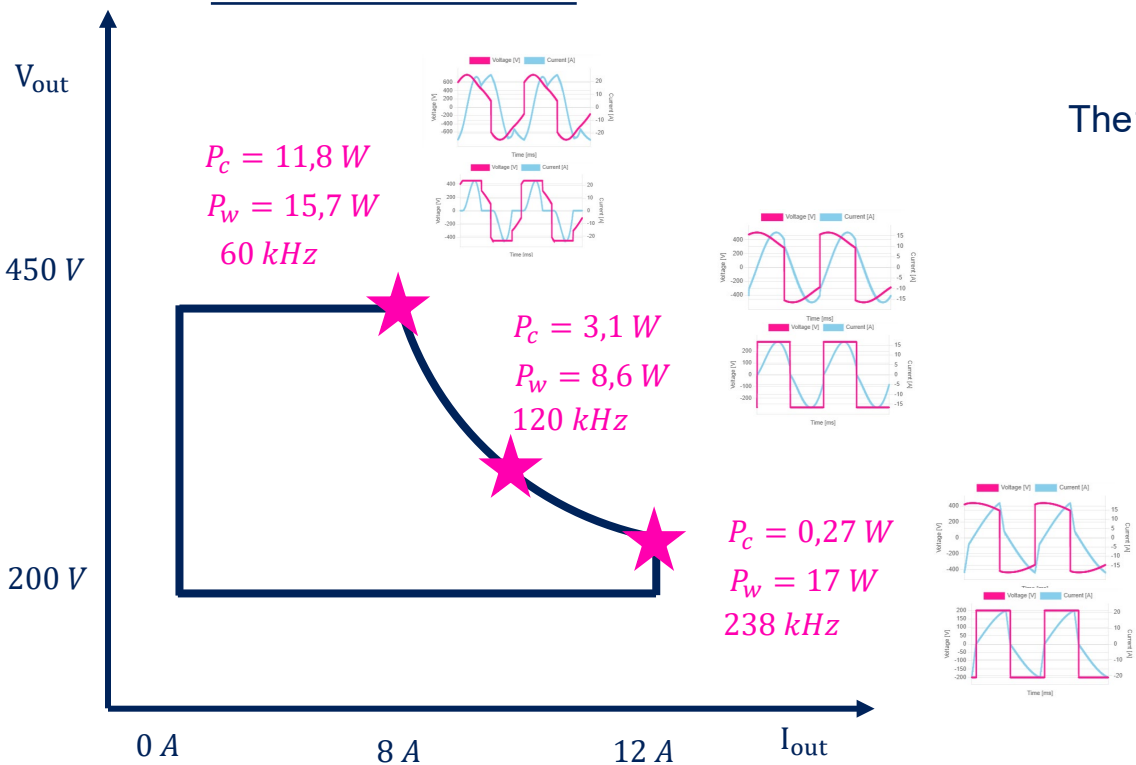
Transformer Losses Target

The target loss should not only consider the converter efficiency but also the frequency range

3 kW LLC Power Profile



The tighter the frequency range the closer to 50% Pc/Pw balance

$$\uparrow\uparrow \frac{f_{sw}}{f_r} \Rightarrow \frac{P_c}{P_c + P_w} \neq 0{,}5$$

Example:

$$\frac{f_{sw}}{f_r} = [0{,}54 \ -1{,}09 - \ 2{,}16] \qquad \frac{P_c}{P_c + P_w} = [0{,}42 \ -0{,}26 - 0{,}02]$$

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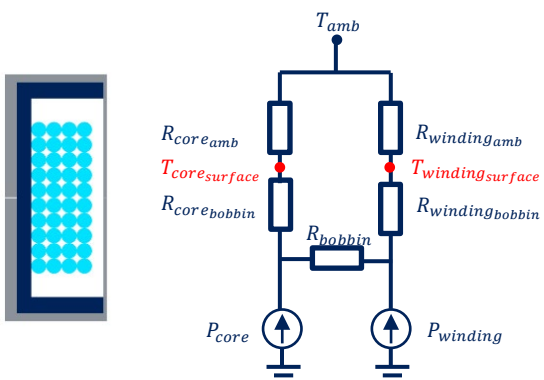
Core list and temperature rise

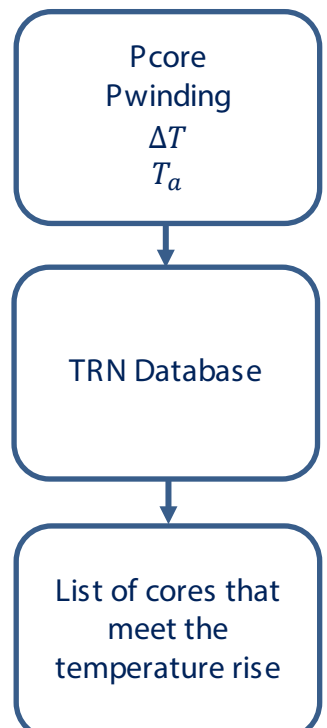
An equivalent thermal resistor network can be developed for each core shape. With the target core and winding losses the core and winding temperature can be predicted reducing thus the wide range of cores to those meeting the ΔT requirement

Simplified Thermal resistor network (TRN)



1. A generic winding can be predefined by fixing a number of turns, a winding utilization factor and a wire diameter

2. The source of the core and winding losses can be assumed to be inner layer and in the core center leg



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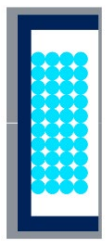
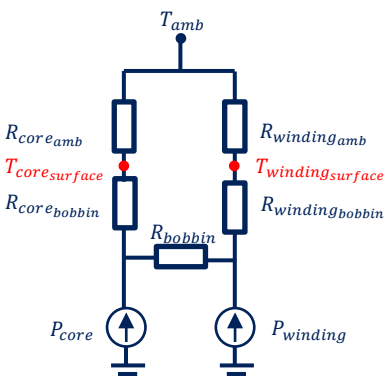
TRN Concept Example

1 – PQ40 Simplified TRN Derivation

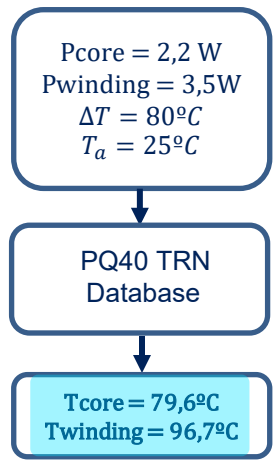


- 70%coil filling factor
- 4 Layers
- 40 Turns
- ODwire = 1,95 mm
- Pcore= 3W
- Pwinding= 2,5W



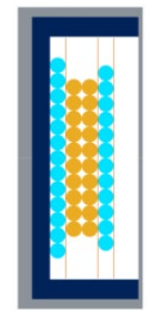
$T_{amb} = 25\ ^{o}\ C$
$R_{core_{amb}} = 20{,}3\ \Omega$
$R_{core_{Cleg}} = 18{,}1\ \Omega$
$R_{core_{bobbin}} = 5{,}79\ \Omega$
$R_{winding_{amb}} = 25{,}5\ \Omega$
$R_{winding_{bobbin}} = 1{,}91\ \Omega$
$P_{core} = 3W$
$P_{winding} = 2{,}5\ W$

2 – New design PQ40 Evaluation



Accurate estimation with simplified TRN

3 – Complete design comparison

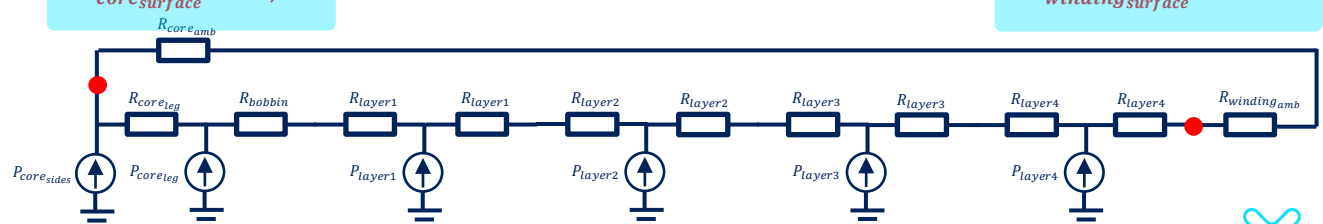


- 25 Turns Primary
- 5 Turns Secondary
- OD wire = 1,6 mm
- Pcore = 2,2W
- Ppri_winding = 1,63W
- Psec_winding = 2,03W

Complete TRN of the transformer

$T_{core_{surface}} = 80{,}6^{o}C$

$T_{winding_{surface}} = 103^{o}C$



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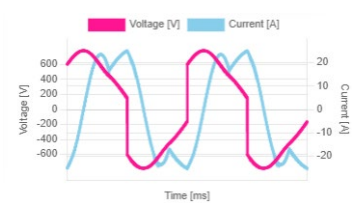
Core List Optimization

- The minimun number of turns can be calculated using IGSE to meet the core los target
- The minimun gap can then be set with the inductance requirement and the core reluctance model
- As a list of cores complying with $\Delta T, P_{core}, L_{mag}$ is obtained

List of cores meeting ΔT
Pcore
Lmag
Lleak Integrated or Not
Size restrictions
Operating Condition

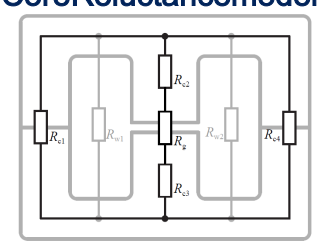


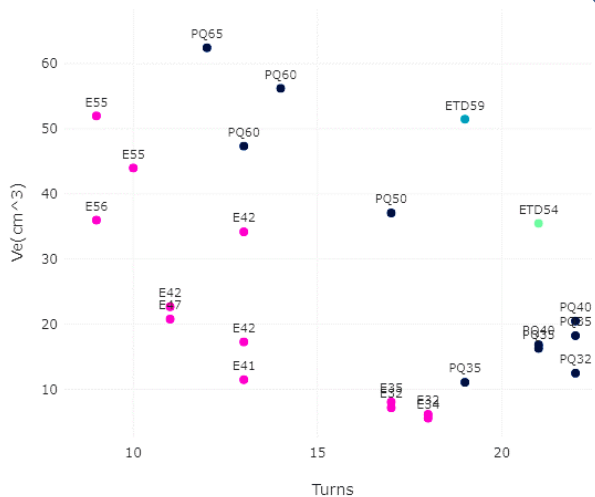
Core material

IGSE

$$P_{core} = f_{sw} * \int_0^T \left(\frac{dB}{dt}\right)^{\alpha} * \Delta B^{\beta-\alpha} * K_i$$

CoreReluctancemodel





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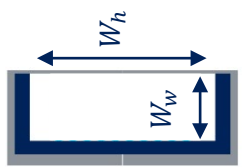
Core Selection

Given the isolation requirements, leakage strategy and RMS currents the conduction area required can be calculated and the smallest core in the list can be choosen

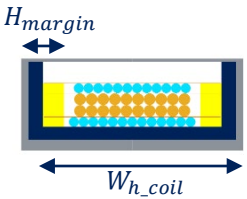
1. Define the available window area of the core according to the isolation and leakage strategies



$$W_a = W_h \cdot W_w$$

- Margin Tape

$$W_h = W_{h_coil} - 2 \cdot H_{margin}$$

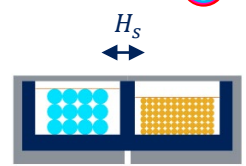


- Triple-Insulated-Wire

$$OD_{wire} = OD_{nom} + 2 \cdot Insulation_{thickness}$$

- Split bobbin for high leakage

$$W_h = W_{h_coil} - H_s$$



2. Define required conduction area based on the current density desired and fixing the inital litz wire strand diameter

$$A_{WNx} = \frac{I_{Nx}}{J_{Nx}} \qquad OD_{nomNx} = \frac{\sqrt{od_{strandNx}} \cdot N_{strandNx}}{Porosity_{factor}}$$

$$N_{strandNx} = \frac{A_{wNx}}{\frac{\pi}{4} od_{strandNx}^2} \qquad A_C = \sum_{x=1}^{n} N_x \cdot OD_{nomNx}^2$$

3. Select the smallest core meeting where the wire fits

$$A_c < W_a$$

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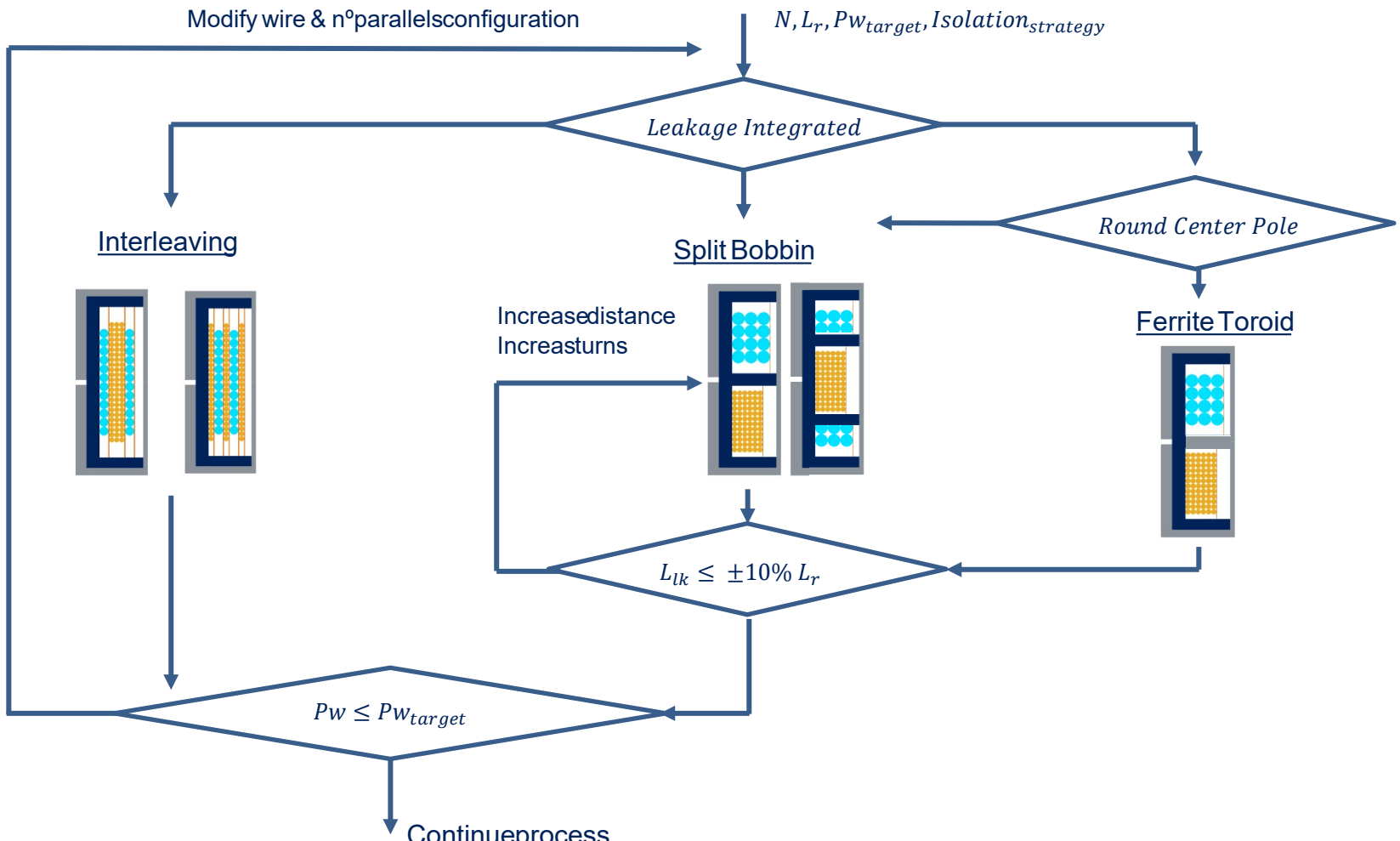
Winding Optimization



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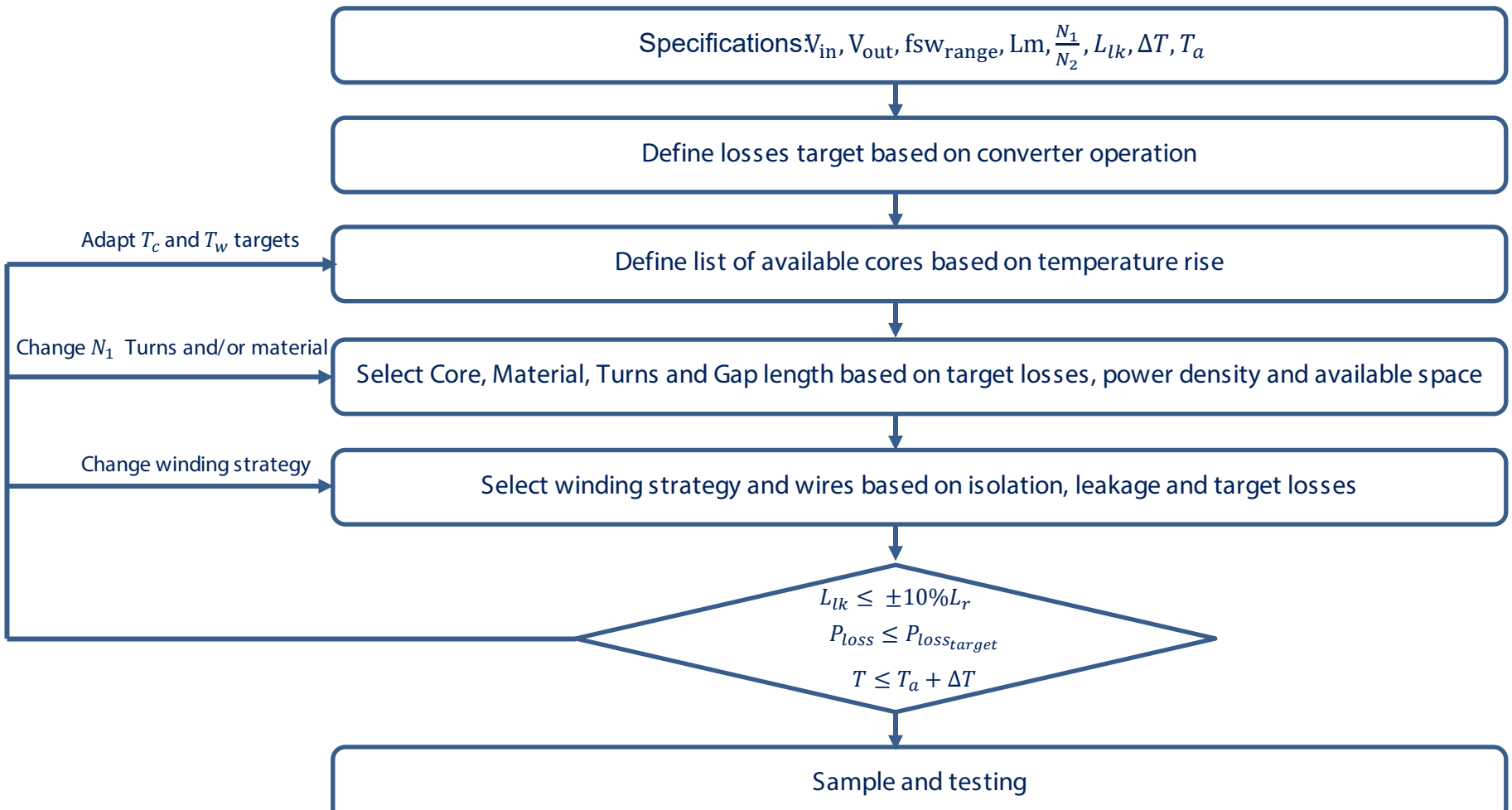
Practical LLC transformer design methodology



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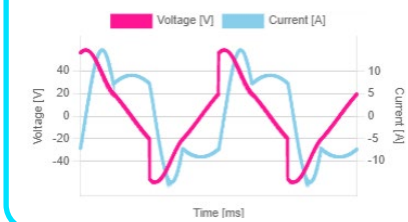
Design Example- Specs

Converter SPECIFICATIONS	
Parameter	**Value**
Input Voltage	18V-33V-36V
Output Voltage	400V
Power	150 W– 250 W– 250 W
Efficiency	96%- 97,1%- 97,4%
L_{mag} / L_{ser}	12,2 µH / 2,2 µH
Fsw_range	50 – 96 – 117 kHz
Resonant Frequency	110 kHz
Dimensions	42 x 42 x 30 mm
T_a / ΔT	25 °C / 80 °C
Cooling	Pure Convection
Leakage	Integrated
Efficiency	94,5%- 96%- 96%
Isolation Requirements	Reinforced OVCII PD2

18Vin-400Vout – 150W – 50kHz



Vrms (V) =	33,3
Irms (A) =	9,47
Vpk (V) =	58,6
Ipk (A) =	14,76

Primary

Vrms (V) =	287,8
Irms (A) =	0,61
Vpk (V) =	400
Ipk (A) =	1,26

Secondary

33Vin-400Vout – 250W – 96kHz

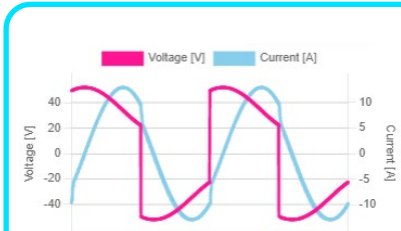
Vrms (V) =	40,6
Irms (A) =	9,55
Vpk (V) =	53,5
Ipk (A) =	13,83

Primary

Vrms (V) =	387,4
Irms (A) =	0,73
Vpk (V) =	400
Ipk (A) =	1,08

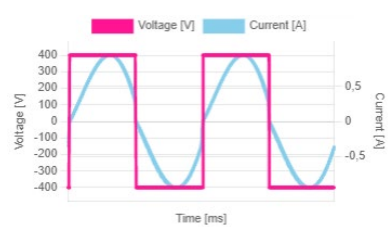
Secondary

36Vin-400Vout – 250W – 117kHz



Vrms (V) =	43,4
Irms (A) =	9,27
Vpk (V) =	52,2
Ipk (A) =	12,94

Primary



Vrms (V) =	400
Irms (A) =	0,68
Vpk (V) =	400
Ipk (A) =	0,94

Secondary

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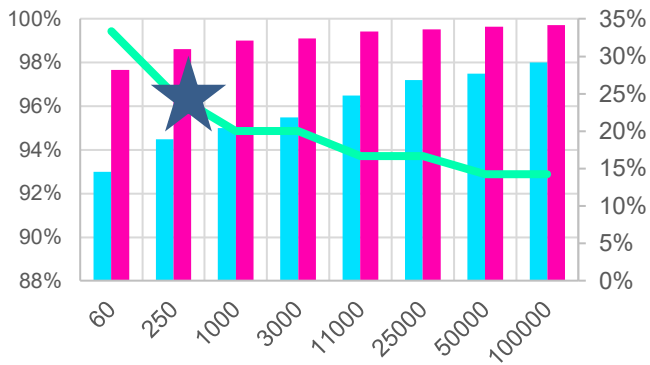
Design Example– Loss Target &ΔT

1 – Target Loss Definition



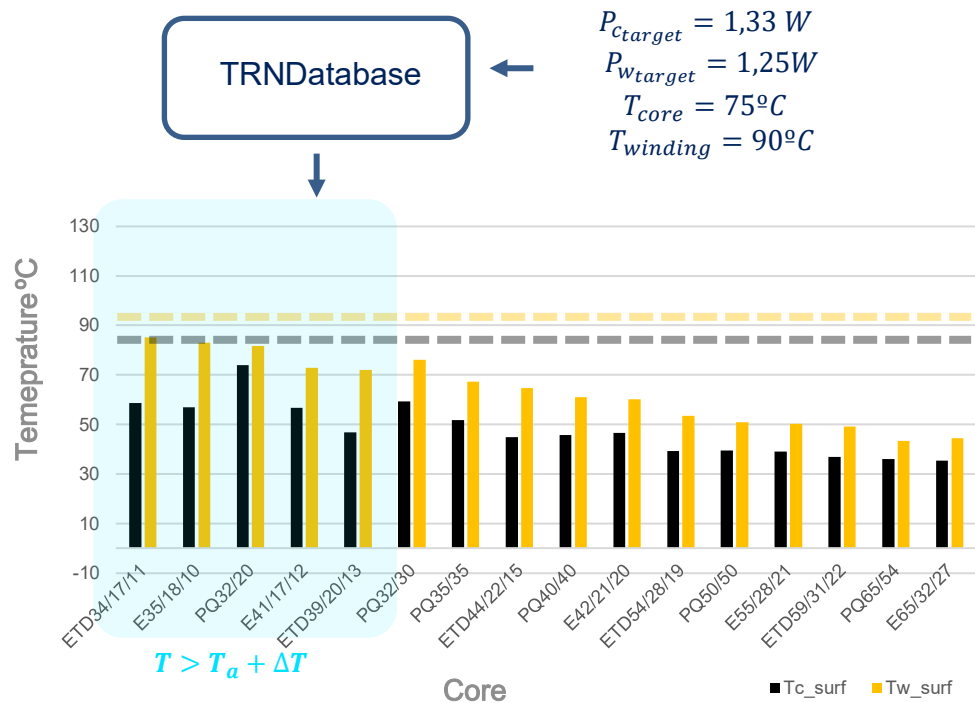
$$Tr_{loss_{target}} = 0{,}25 * (1 - 0{,}96) * 250W = 2{,}5\ W\ @33Vin\&36\text{Vin}$$

$$\frac{P_c}{P_c + P_w}\% = 0{,}5 \rightarrow P_{c_{target}} = 1{,}25W \quad P_{w_{target}} = 1{,}25W\ @33Vin\&36Vin$$

$$Tr_{loss_{target@18Vin}} = 0{,}25 * (1 - 0{,}945) * 150W = 2{,}06\ W$$

$$\frac{P_c}{P_c + P_w}\% = 0{,}65 \rightarrow P_{cu_{target}} = 1{,}33W \quad P_{w_{target}} = 0{,}72W\ @33Vin$$

2 – Trise calculation



**** PQ, ETD, E only shown in this example for simplicity purposes, more cores could be included in the list*

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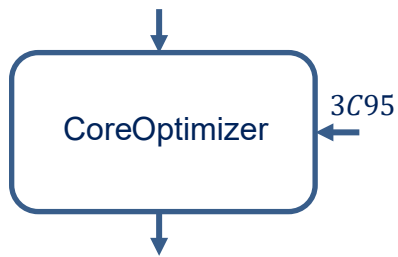
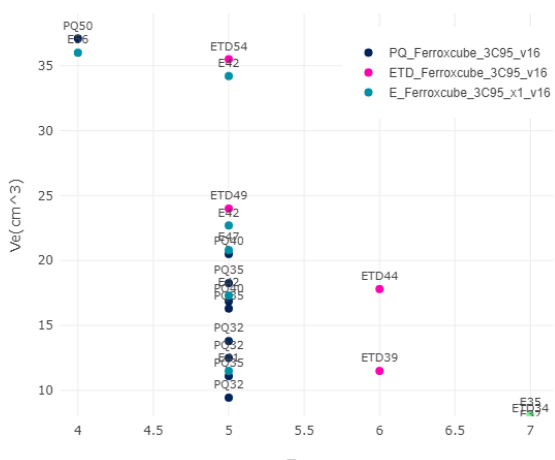
Design Example– Core ListOptimization

3 – Coreturns and gap

$P_{c_{target}} = 1{,}33\ W \quad L_{leak} \rightarrow Integrated$

$L_{mag} = 12{,}2\ uH \quad PQ, ETD, E\ Families$





4 – Window fitting

$J = 6\ A/mm^2$

$Irms_{pri} = 9{,}55A$

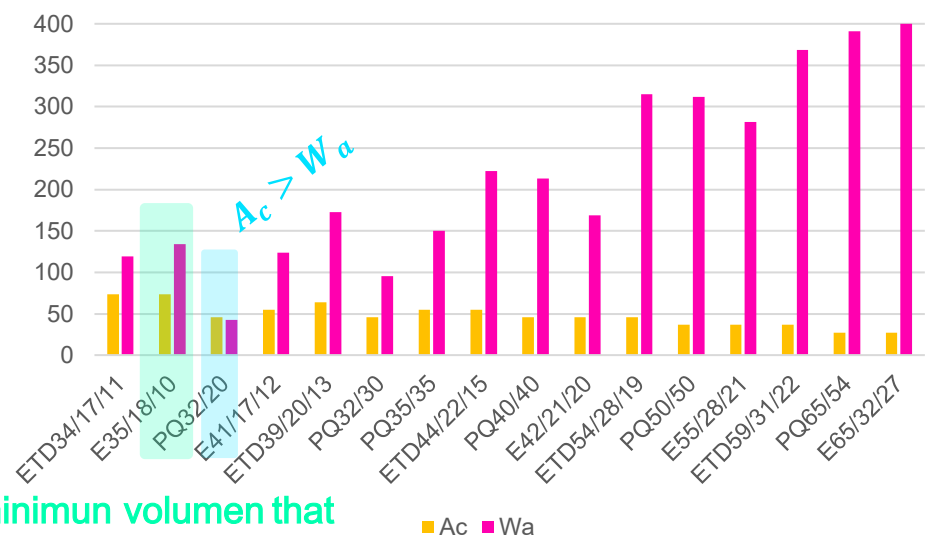
$Irms_{sec} = 0{,}73\ A$

$OD_{nom} = 0{,}07\ mm$

$Split\ bobbin = 1\ mm$

$OD_{pri} = 2{,}19\ mm$

$OD_{sec} = 0{,}6\ mm$



Corewith minimun volumen that satisfies all the requirements

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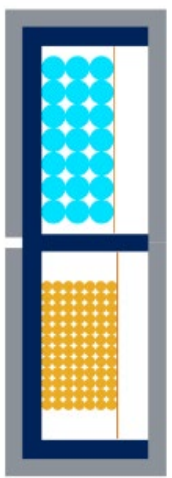
Design Example – Winding Optimization

E35/18/10 - 3C95

Primary – 7 x 3 xLitz 160x0,07

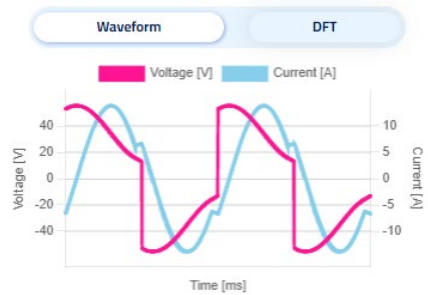
Secondary – 84 x 1 xLitz 30x0,07

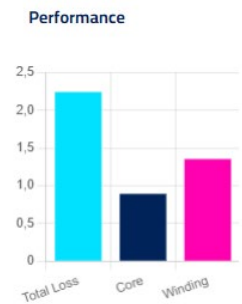


Lmag = 12,3 uH

Lleak = 2,17 uH

33 Vin



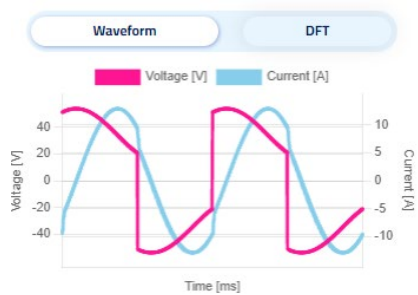


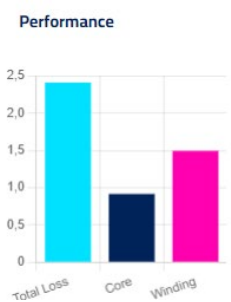
Simulation Results

BpkT (mT)=	133.541
Core Losses (W)=	0.892
Winding Losses (W)=	1.352
Total Losses (W)=	2.24
Max Temp (°C)=	68
Core Surface Temp (°C)=	59
Winding Surface Temp (°C)=	66
Central Leg Surface Temp (°C)=	68

$< 2,5W$

36 Vin



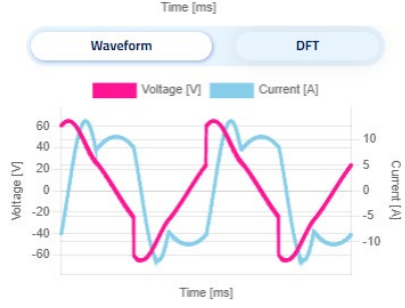


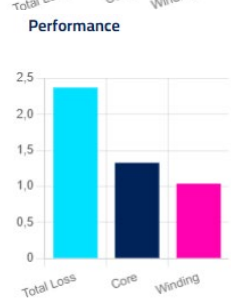
Simulation Results

BpkT (mT)=	124.293
Core Losses (W)=	0.916
Winding Losses (W)=	1.494
Total Losses (W)=	2.41
Max Temp (°C)=	69
Core Surface Temp (°C)=	60
Winding Surface Temp (°C)=	67
Central Leg Surface Temp (°C)=	69

$< 2,5W$

18 Vin





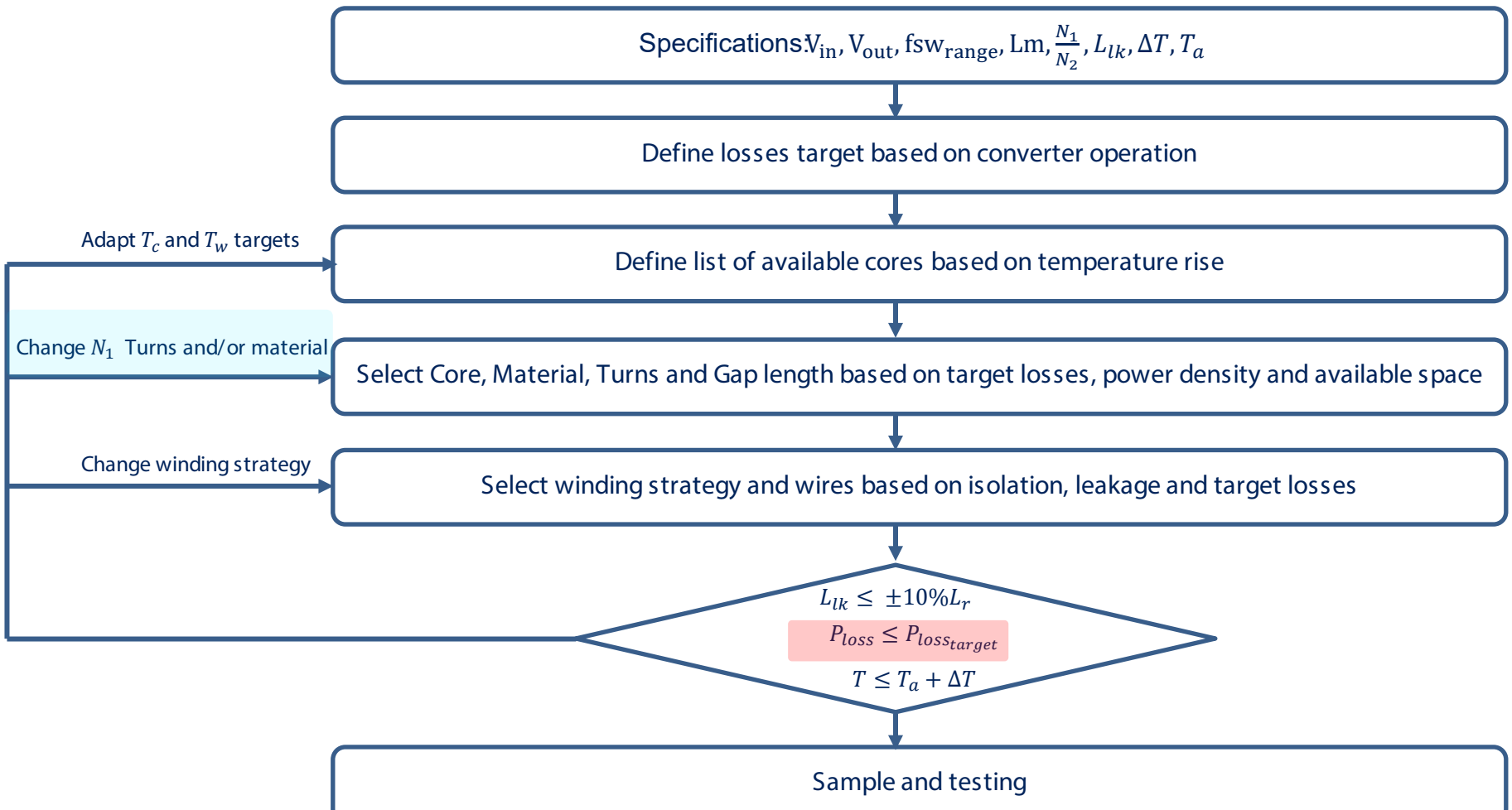
Simulation Results

BpkT (mT)=	208.501
Core Losses (W)=	1.327
Winding Losses (W)=	1.038
Total Losses (W)=	2.37
Max Temp (°C)=	72
Core Surface Temp (°C)=	66
Winding Surface Temp (°C)=	67
Central Leg Surface Temp (°C)=	72

$> 2W$

F

Practical design methodology



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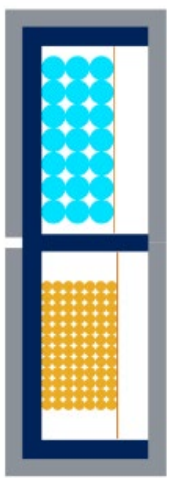
Design Example– SecondIteration

E35/18/10 -3C98

Primary– 7 x 3 xLitz 160x0,07

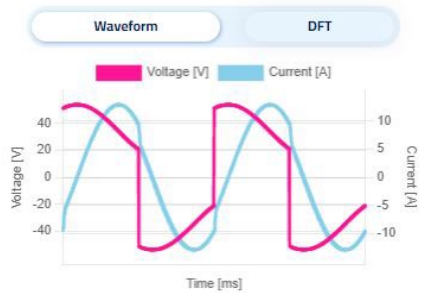
Secondary– 84 x 1 xLitz 30x0,07

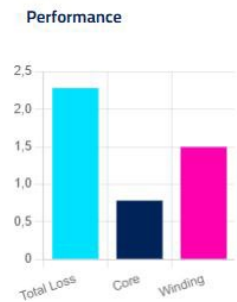


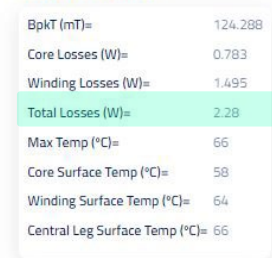
Lmag = 12,3 uH

Lleak = 2,17 uH

33 Vin

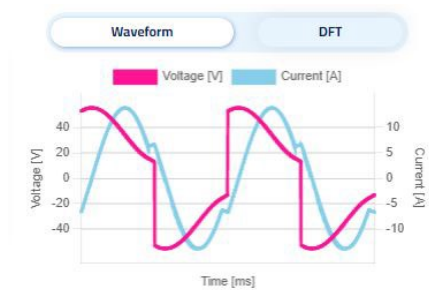


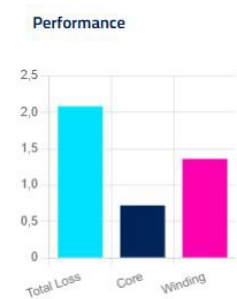


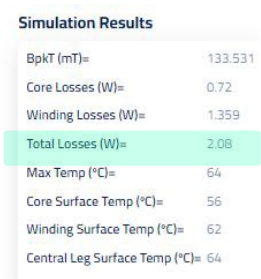


$< 2,5W$

36 Vin

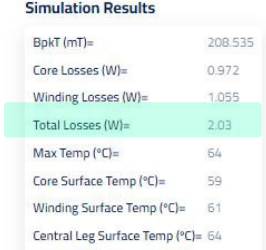






$< 2,5W$

18 Vin



$< 2,06\ W$

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