DESIGN OPTIMIZATION OF MFT FOR HIGH-POWER MV APPLICATIONS

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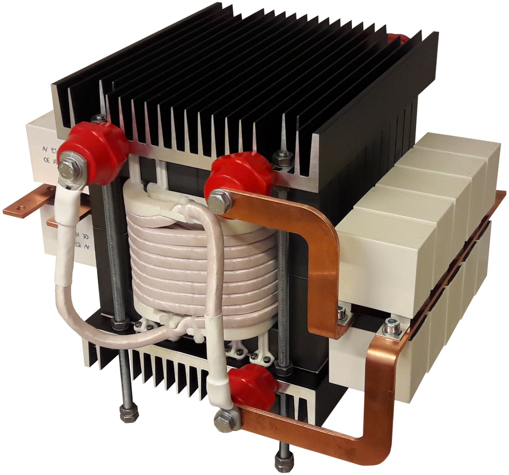
MODELING: RELEVANT EFFECTS

- Modeling
- Design Optimization
- Experimental Verification



MFT MODELING

The underlying analytical descriptions

Different core loss models:

- Based on characterization of magnetic hysteresis [1], [2], [3]
- Based on loss separation [4]
- Time domain core loss model [5]
- Based on Steinmetz Equation (MSE [6], IGSE [7], iIGSE [8])

Original Steinmetz Equation:

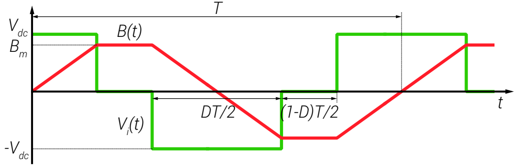
$$P_c = K f^{\alpha} B_m^{\beta}$$

Improved Generalized Steinmetz Equation (IGSE):

$$P_c = \frac{1}{T}\int_0^T k_i \left|\frac{dB(t)}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha} dt$$

$$k_i = \frac{K}{(2\pi)^{\alpha-1}\int_0^{2\pi} |cos(\theta)|^{\alpha} 2^{\beta-\alpha} d\theta}$$

Characteristic Waveform:



$$\left|\frac{dB(t)}{dt}\right| = \begin{cases} 0 & \text{for } (1-D)T \\ \frac{2\Delta B}{DT} & \text{for } DT \end{cases}$$

Application of IGSE on the Characteristic Waveform:

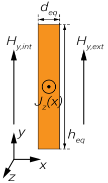
$$P_s = 2^{\alpha+\beta} k_i f^{\alpha} B_m^{\beta} D^{1-\alpha}$$

$$k_i = \frac{K}{2^{\beta-1}\pi^{\alpha-1}\left(0.2761 + \frac{1.7061}{\alpha+1.354}\right)}$$

Foil Winding Electromagnetic Field Analysis:

- Dowell foil winding loss model [9]
- Porosity factor validity analysis [10], [11]
- Round wire winding loss model [12]
- ...

Foil Winding Electromagnetic Field Analysis:



$$H_y = H_{ext}\frac{sinh(ax)}{sinh(ad_{eq})} - H_{int}\frac{sinh(a(x-d_{eq}))}{sinh(ad_{eq})}$$

$$J_z = aH_{ext}\frac{cosh(ax)}{sinh(ad_{eq})} - aH_{int}\frac{cosh(a(x-d_{eq}))}{sinh(ad_{eq})}$$

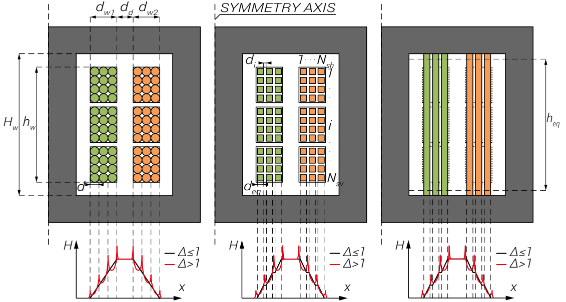
$$a = \frac{1+j}{\delta}; \qquad \delta = \sqrt{\frac{\rho}{\pi\mu f}};$$

Foil Winding Loss Calculation:

$$P_\sigma = \frac{1}{\sigma}\int JJ^* dv; \qquad P_\sigma = I^2\frac{L_W}{\delta\sigma h_W}m\left[\varsigma_1 + \frac{2}{3}(m^2-1)\varsigma_2\right];$$

$$\varsigma_1 = \frac{sinh(2\Delta)+sin(2\Delta)}{cosh(2\Delta)-cos(2\Delta)}; \qquad \varsigma_2 = \frac{sinh(\Delta)-sin(\Delta)}{cosh(\Delta)+cos(\Delta)}; \qquad \Delta = \frac{d_{eq}}{\delta};$$

Winding Equivalence:



$$d_{eq} = d\sqrt{\frac{\pi}{4}}; \qquad d_i = \frac{d_W - N_{sh}d_{eq}}{N_{sh}-1}; \qquad m = N_{sh};$$

$$N_{sh} = \sqrt{\frac{N_S}{K_W}}; \qquad N_{sv} = \sqrt{K_W N_S};$$

$$K_W = \frac{h_W}{d_W}$$

$$\Delta' = \sqrt{\eta}\Delta; \qquad \eta = d_{eq}\frac{N_{SV}}{H_W};$$

MODELING: F-DEPENDENT LEAKAGE INDUCTANCE

Application of Dowell's Model on the Equivalent Foil Winding:

$$L_\sigma = N_1^2 \mu_0 \frac{l_w}{H_w}\Bigg[\underbrace{\frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2}}_{\text{Frequency dependent portion due to the magnetic energy within the copper volume of the windings}}$$

$$+ \underbrace{d_d}_{\text{Portion due to magnetic energy within the inter-winding dielectric volume}}$$

$$+ \underbrace{d_{w1i}\frac{(m_{w1}-1)(2m_{w1}-1)}{6m_{w1}}}_{\text{Portion due to magnetic energy within the inter-layer dielectric of the primary winding}}$$

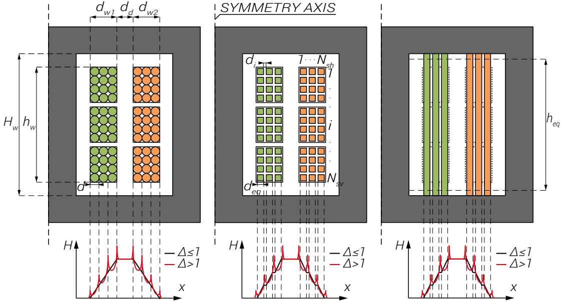
$$+ \underbrace{d_{w2i}\frac{(m_{w2}-1)(2m_{w2}-1)}{6m_{w2}}}_{\text{Portion due to magnetic energy within the inter-layer dielectric of the secondary winding}}\Bigg]$$

where:

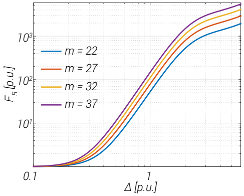
$$F_w = \frac{1}{2m^2\Delta}\left[(4m^2-1)\varphi_1 - 2(m^2-1)\varphi_2\right]$$

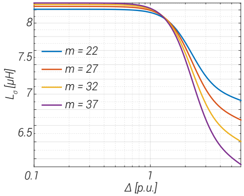
$$\varphi_1 = \frac{sinh(2\Delta) - sin(2\Delta)}{cosh(2\Delta) - cos(2\Delta)}; \qquad \varphi_2 = \frac{sinh(\Delta) - sin(\Delta)}{cosh(\Delta) - cos(\Delta)};$$

Winding Equivalence:



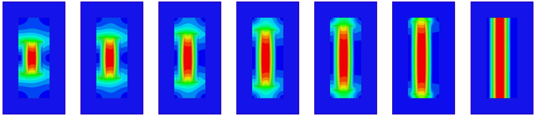
$$\Delta' = \sqrt{\eta}\Delta; \qquad \eta = d_{eq}\frac{N_{sv}}{H_w}; \qquad m = N_{sh}; \qquad d_i = \frac{d_w - N_{sh} d_{eq}}{N_{sh} - 1};$$

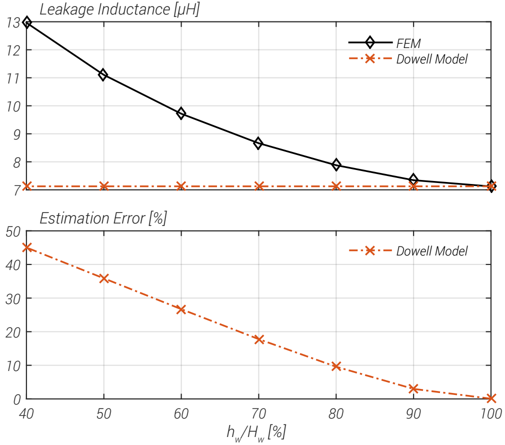




MODELING: LEAKAGE INDUCTANCE (HYBRID MODEL)

Influence of Winding Geometry on Leakage inductance:





Hybrid Leakage Inductance Model [13]:

- Rogowski correction factor:

$$h_{eq} = \frac{h_w}{K_R}$$

$$K_R = 1 - \frac{1 - e^{-\pi h_w/(d_{w1}+d_d+d_{w2})}}{\pi h_w/(d_{w1}+d_d+d_{w2})}$$

- Correction of Dowell's model ($H_w \rightarrow h_{eq}$):

$$L_\sigma = N_1^2 \mu_0 \frac{l_w}{H_w} \left[\frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2} + d_d + d_{w1i} \frac{(m_{w1}-1)(2m_{w1}-1)}{6m_{w1}} + d_{w2i} \frac{(m_{w2}-1)(2m_{w2}-1)}{6m_{w2}} \right]$$

$$\Delta' = \sqrt{\eta}\Delta; \qquad \eta = d_{eq}\frac{N_{sv}}{H_w};$$

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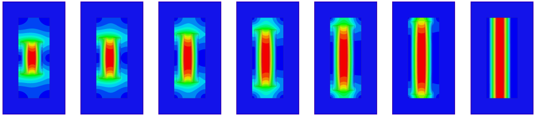

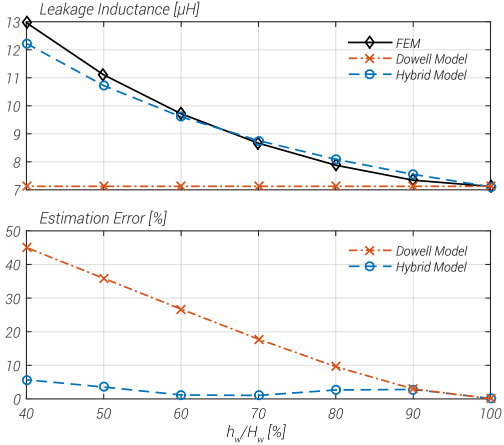

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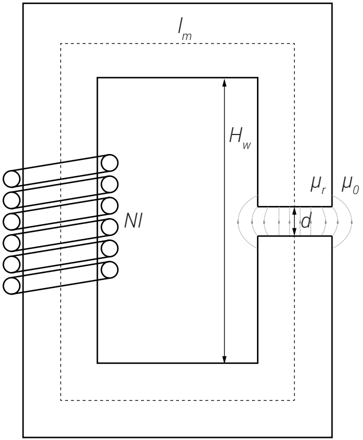
$$\Delta' = \sqrt{\eta}\Delta; \qquad \eta = d_{eq} \frac{N_{sv}}{h_{eq}};$$

Magnetic Circuit with an Air-Gap:



Magnetizing Inductance Calculation:

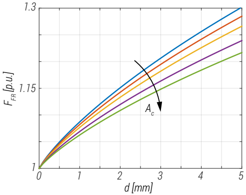
$$L_m = \frac{\mu_0 N^2 A_c}{\frac{l_m}{\mu_r} + d}$$

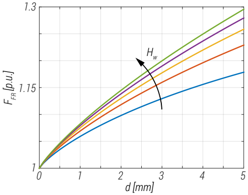
Air-Gap Calculation:

$$d = \mu_0 \frac{N^2 A_c}{L_m} - \frac{l_m}{\mu_r}$$

Fringing Effect:

$$L_m' = L_m F_{FR}; \qquad F_{FR} = 1 + \frac{d}{\sqrt{A_c}} ln\left(\frac{2H_w}{d}\right);$$



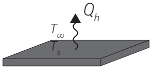


MODELING: HEAT-TRANSFER MECHANISMS

Conduction $Q_h = kA\frac{\Delta T}{L}$

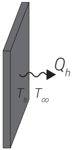
Convection over Hot-Plate $Q_h = hA(T_s - T_\infty)$

Top:



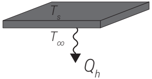
$$h = \frac{k(0.65+0.36R_{a_L}^{1/6})^2}{L} \qquad L = \frac{\text{Area}}{\text{Perimeter}}$$

Side:



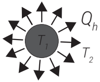
$$h = \frac{k}{L}\left(0.825 + \frac{0.387R_{a_L}^{1/6}}{\left(1+(0.492/P_r)^{9/16}\right)^{8/27}}\right)^2 \qquad L = \text{Height}$$

Bottom:



$$h = \frac{k0.27R_{a_L}^{1/4}}{L} \qquad L = \frac{\text{Area}}{\text{Perimeter}}$$

Radiation $Q_h = hA(T_1 - T_2)$



$$h = \varepsilon\sigma\frac{(T_1+273.15)^4-(T_2+273.15)^4}{(T_1-T_2)}$$

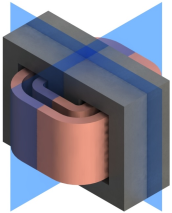
where: R_{a_L} - Rayleigh number, P_r - Prandtl number, ε - Emissivity, σ - Stefan–Boltzmann constant [14], [15], [16]

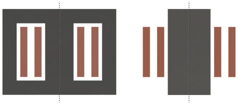
MODELING: THERMAL MODEL

Modes Of Heat Transfer:

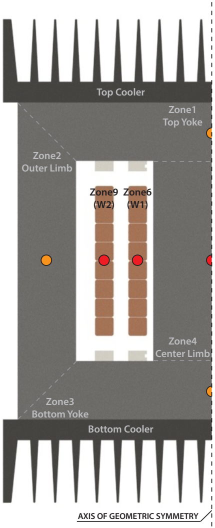
- Conduction
- Convection
- Radiation

Planes of Symmetry:

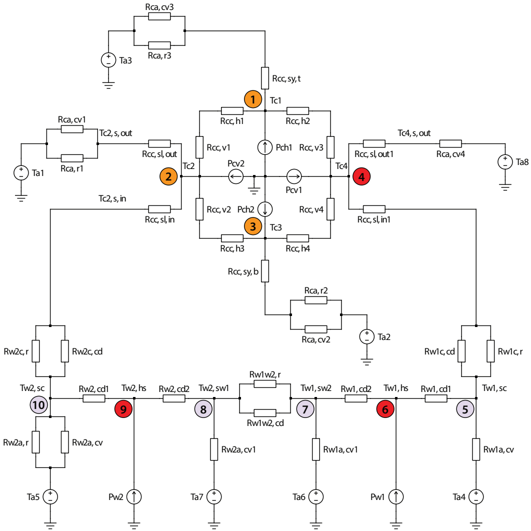




Partitioning Into Zones:



Detailed Thermal Network Model:



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- Conduction
- Convection
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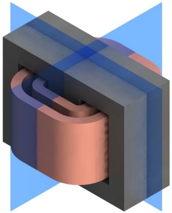

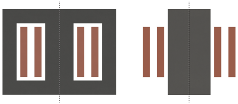

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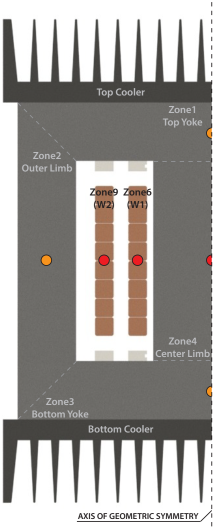

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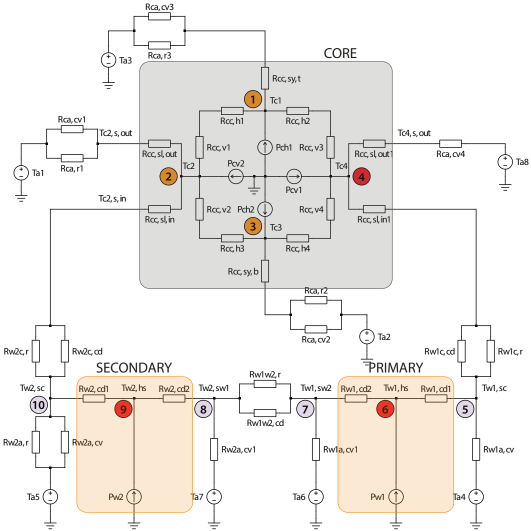

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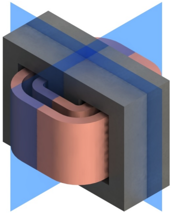

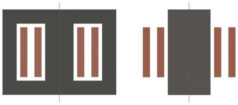

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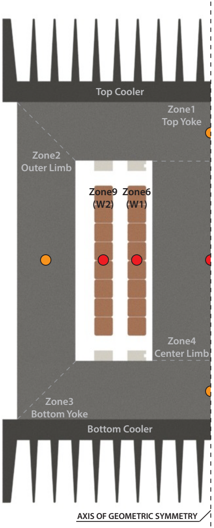

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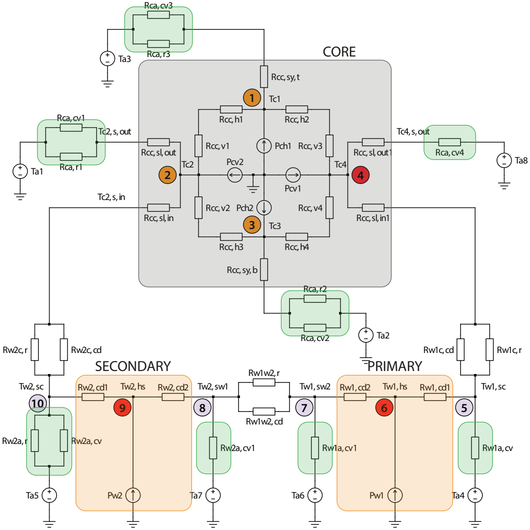

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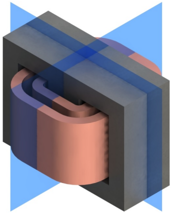

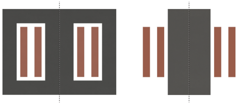

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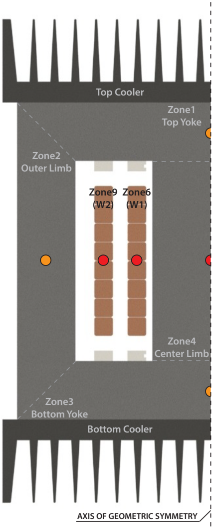

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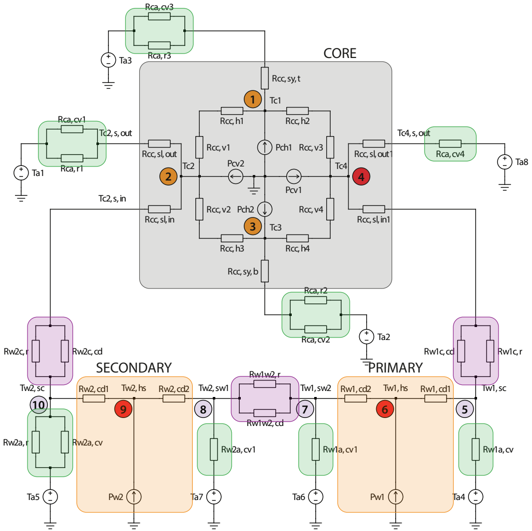


Implementation of Thermal Network Model:

- Admittance Matrix:

$$Q_{(n)} = Y_{th_{(n \times n)}} \Delta T_{(n)}$$

- Rearranging the nodes:

$$\begin{bmatrix} Q_{A_{(m)}} \\ 0_{(p)} \end{bmatrix} = \begin{bmatrix} Y_{thAA_{(m \times m)}} & Y_{thAB_{(m \times p)}} \\ Y_{thBA_{(p \times m)}} & Y_{thBB_{(p \times p)}} \end{bmatrix} \begin{bmatrix} \Delta T_{A_{(m)}} \\ \Delta T_{B_{(p)}} \end{bmatrix}$$

- Kron reduction:

$$\Delta T_{A_{(m)}} = \left(Y_{thAA_{(m \times m)}} - Y_{thAB_{(m \times p)}} Y^{-1}_{thBB_{(p \times p)}} Y_{thBA_{(p \times m)}} \right)^{-1} Q_{A_{(m)}}$$

$$\Delta T_{A_{(m)}} = Y^{-1}_{Kron_{(m \times m)}} Q_{A_{(m)}}$$

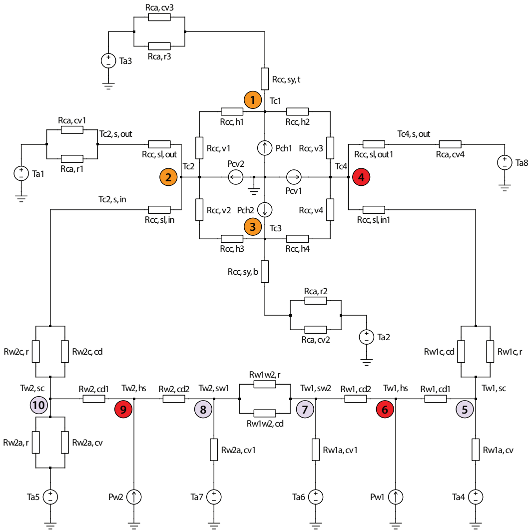
- Kron matrix:

$$Y_{Kron_{(m \times m)}} = Y_{thAA_{(m \times m)}} - Y_{thAB_{(m \times p)}} Y^{-1}_{thBB_{(p \times p)}} Y_{thBA_{(p \times m)}}$$

Analytical Model Results for the optimal MFT prototype:

T_1 $[^oC]$	T_2 $[^oC]$	T_3 $[^oC]$	T_4 $[^oC]$	T_6 $[^oC]$	T_9 $[^oC]$
51.3	59.9	58.4	73.75	124.6	116.3

Detailed Thermal Network Model [17]:



MODELING: THERMAL FEM ANALYSIS

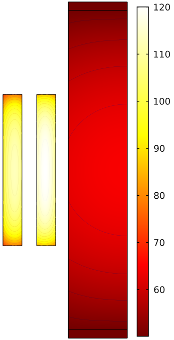
Results:

- Different cooling conditions inside and outside of core window
- High thermal conduction equalizes the temp along the conductors
- Full 3D model estimations correlate well with analytical ones

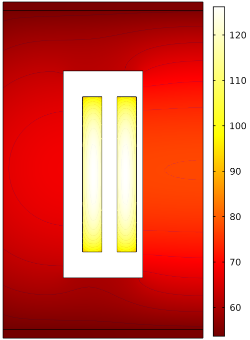
Hot-Spot Temperature Estimation Comparison:

Hot-spot nodes	T_1 [^oC]	T_2 [^oC]	T_3 [^oC]	T_4 [^oC]	T_6 [^oC]	T_9 [^oC]
FEM 2D detail 1	/	/	/	70	120	106
FEM 2D detail 2	/	/	/	76	127	125
FEM 3D full	/	/	/	75	122	113
Analytical	51.3	59.9	58.4	73.75	124.6	116.3

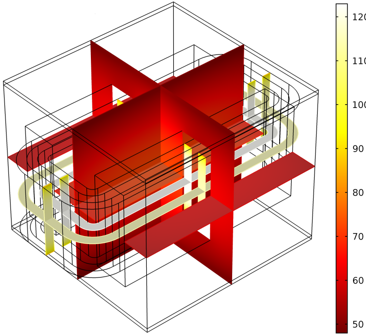
2D symmetry detail 1:



2D symmetry detail 2:



Full 3D model:



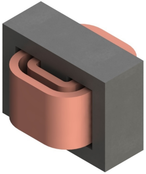
MFT DESIGN OPTIMIZATION

Brute force academic example

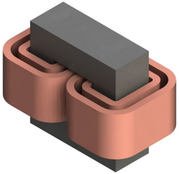
TECHNOLOGIES AND MATERIALS

Construction Choices:

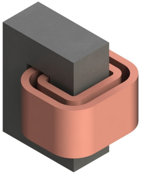
- MFT Types



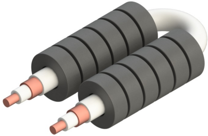
Shell Type



Core Type



C-Type

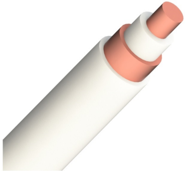


Coaxial Type

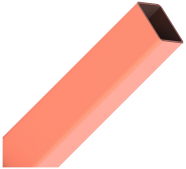
- Winding Types

Litz Wire

Foil



Coaxial

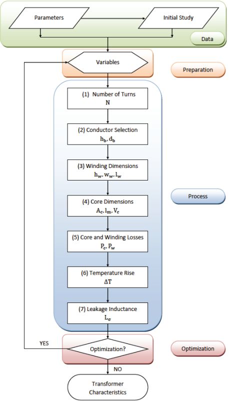


Hollow

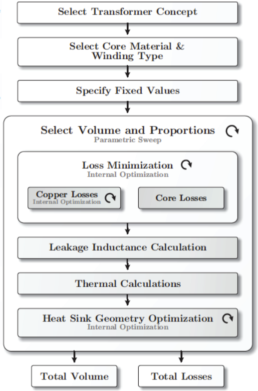
Materials:

- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - **Ferrites**
- Windings
  - **Copper**
  - Aluminum
- Insulation
  - **Air**
  - Solid
  - Oil
- Cooling
  - **Air natural**/forced
  - Oil natural/forced
  - Water

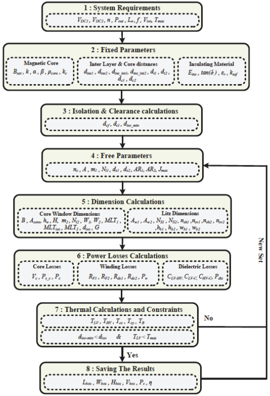
MFT DESIGN OPTIMIZATION



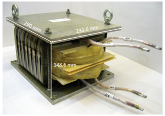
EPFL PhD: Villar [18]



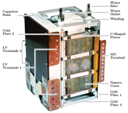
ETHZ PhD: Ortiz [19]



CHALMERS PhD: Bahmani [20]



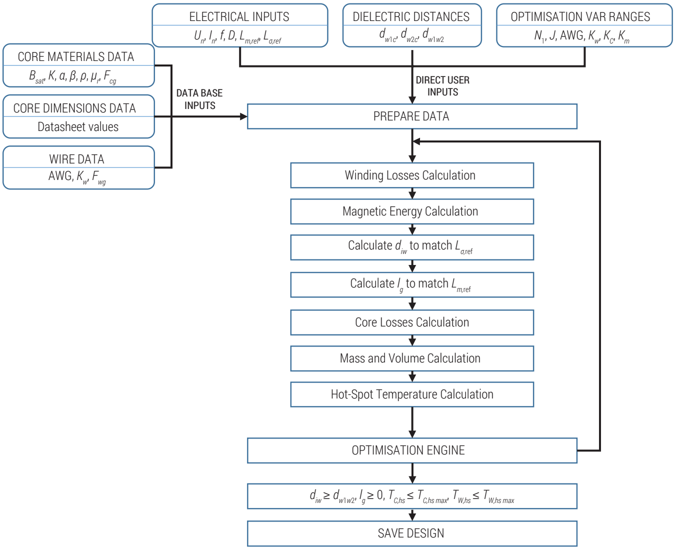
EPFL: 300kW, 2kHz



ETHZ: 166kW, 20kHz

CHALMERS: 50kW, 5kHz

DESIGN OPTIMIZATION: ALGORITHM



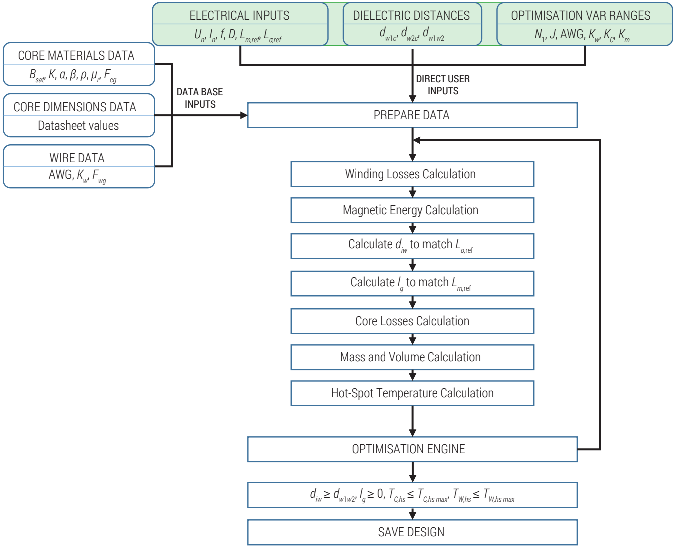
▲ MFT design optimization algorithm

Algorithm Specifications:

- Used Software Platform:
  - MathWorks MATLAB
- Used Hardware Platform:
  - Laptop PC (i7-2.1GHz, 8GB RAM)
- Performance Measure:
  - 59000 designs are generated in less than 190 seconds
- Electrical Specifications:

P_n	$100kW$	f_{sw}	$10kHz$
V_1	$750V$	V_2	$750V$
$L_{\sigma1,2}$	$3.27\mu H$	L_m	$1.8mH$

DESIGN OPTIMIZATION: ALGORITHM



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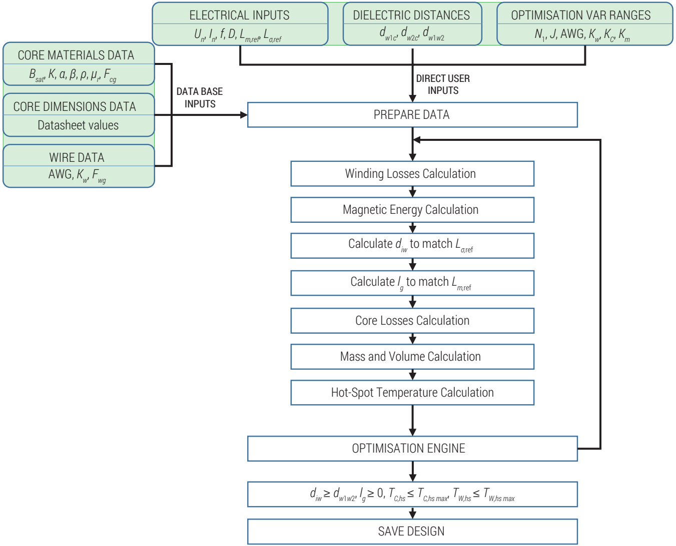

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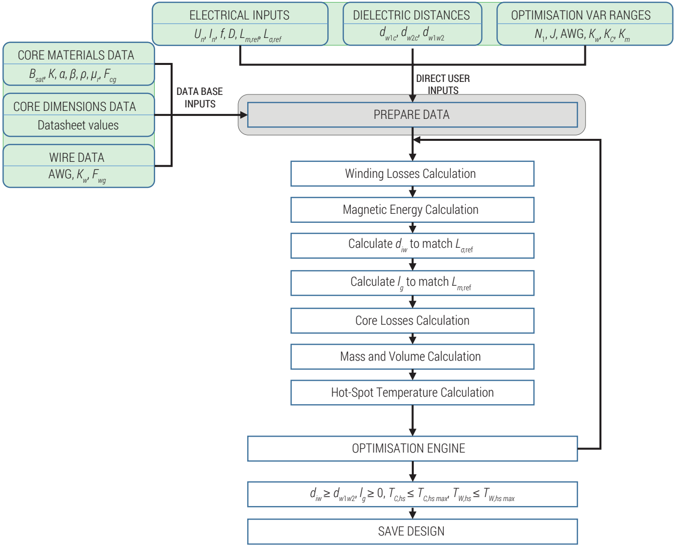
DESIGN OPTIMIZATION: ALGORITHM



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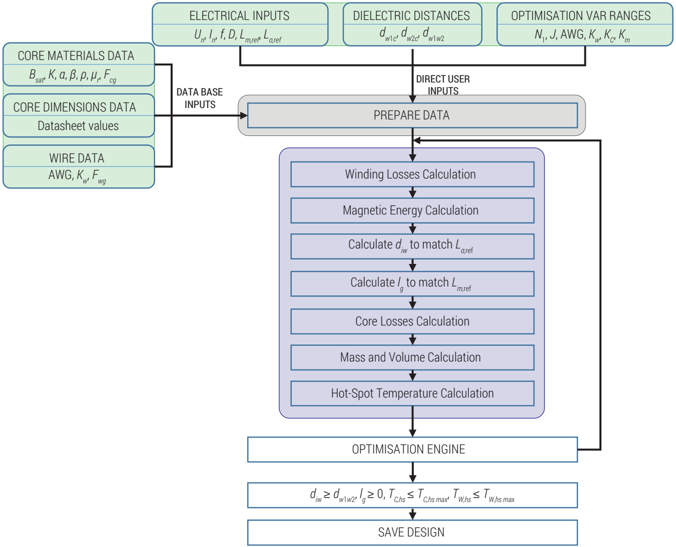

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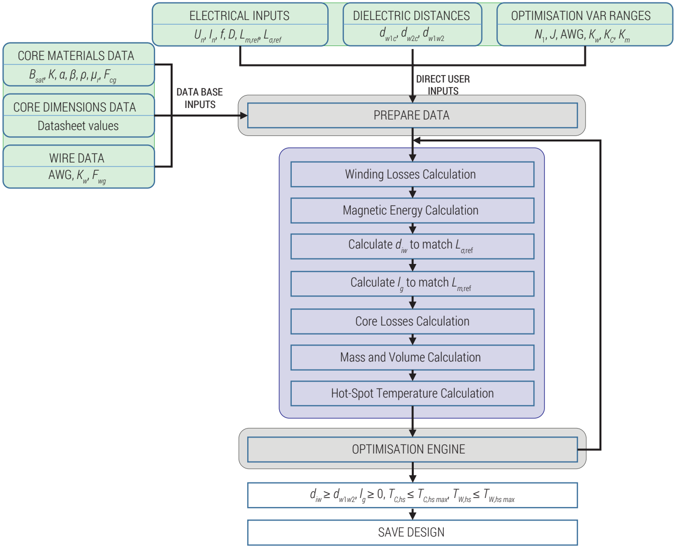
DESIGN OPTIMIZATION: ALGORITHM



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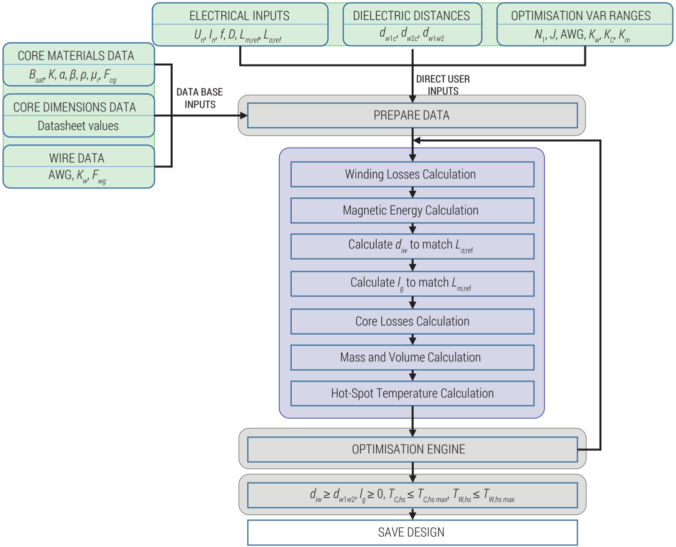
DESIGN OPTIMIZATION: ALGORITHM



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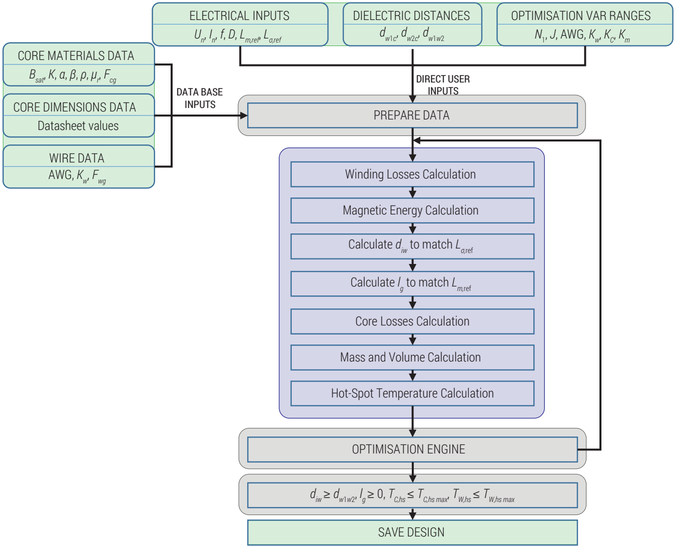
DESIGN OPTIMIZATION: ALGORITHM



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$L_{σ1,2}$	$3.27μH$	L_m	$1.8mH$

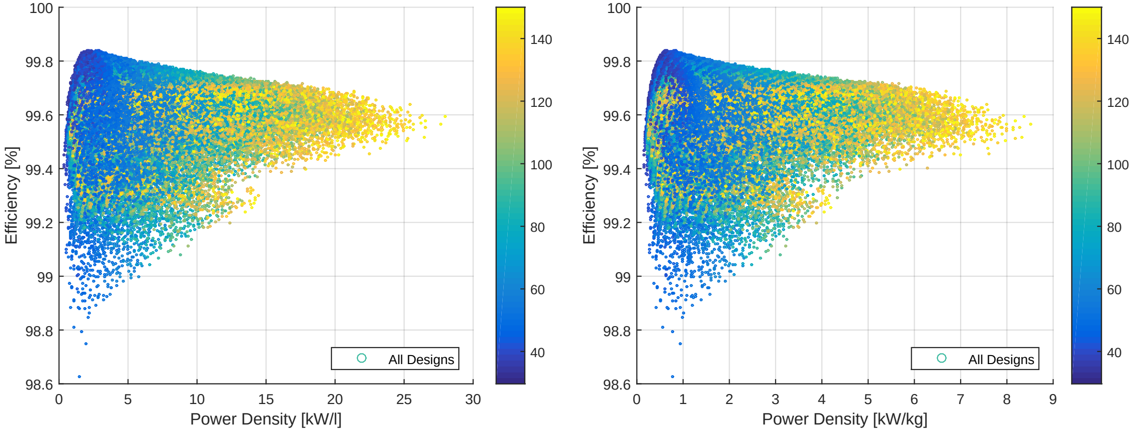
DESIGN OPTIMIZATION: RESULTS

Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
150	100	/	/	/

Number of Designs:

- More than 1.8 Million



▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

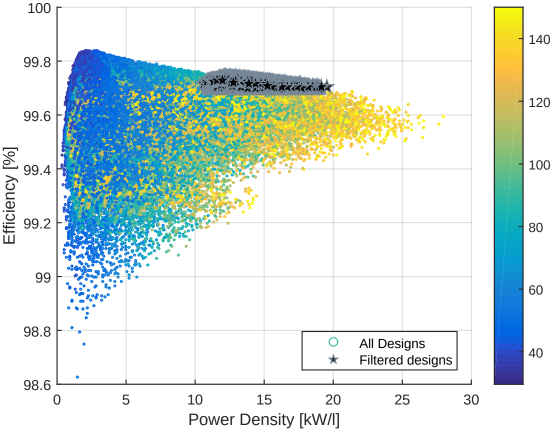
DESIGN OPTIMIZATION: RESULTS

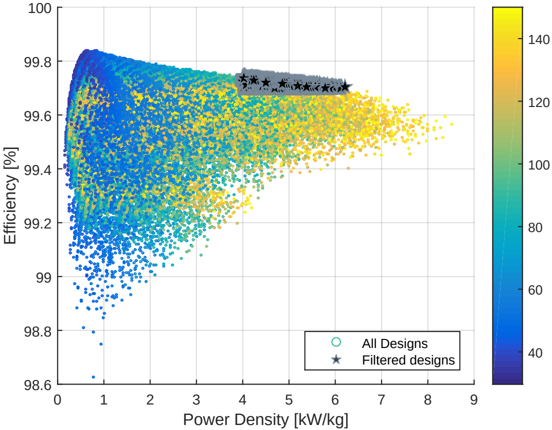
Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
150	100	12	25	99.7

Number of Designs:

- More than 1.8 Million





▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

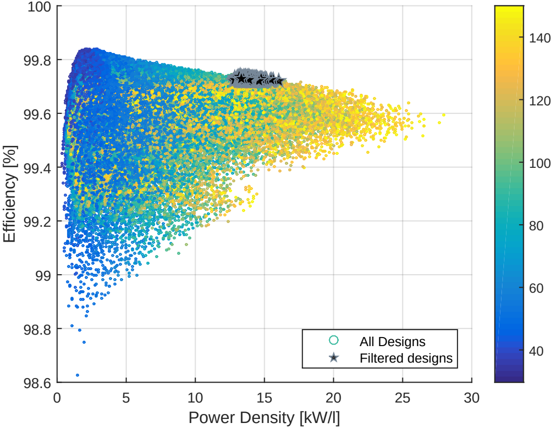
DESIGN OPTIMIZATION: RESULTS

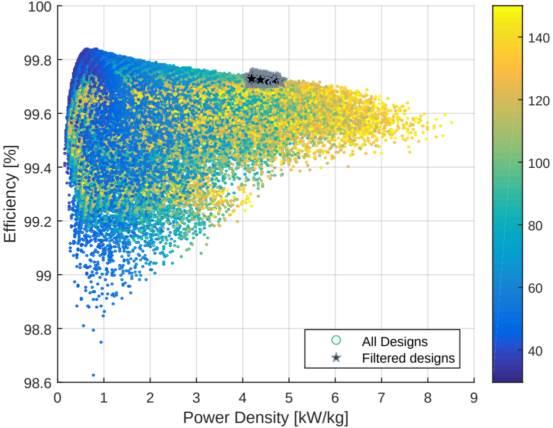
Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
130	80	9	24	99.72

Number of Designs:

- More than 1.8 Million





▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

DESIGN OPTIMIZATION: RESULTS

Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
130	80	9	24	99.72

Number of Designs:

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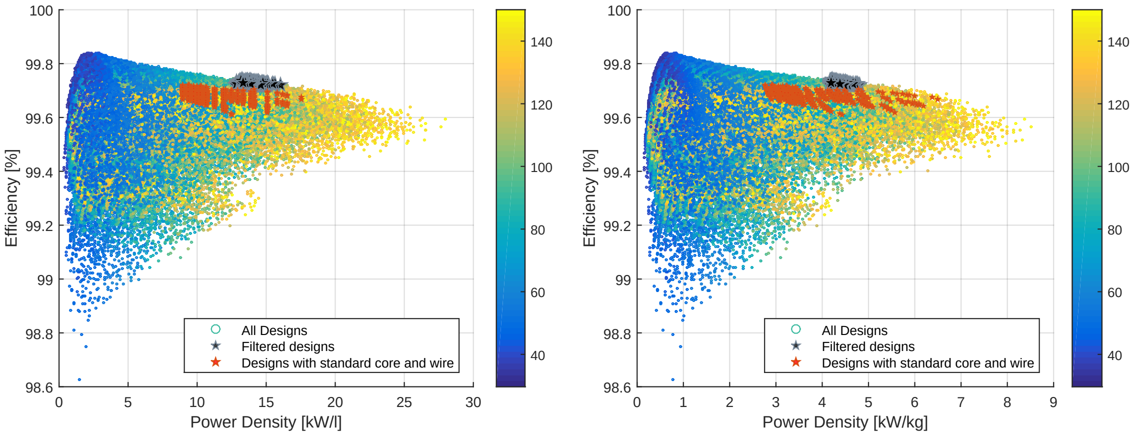


▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

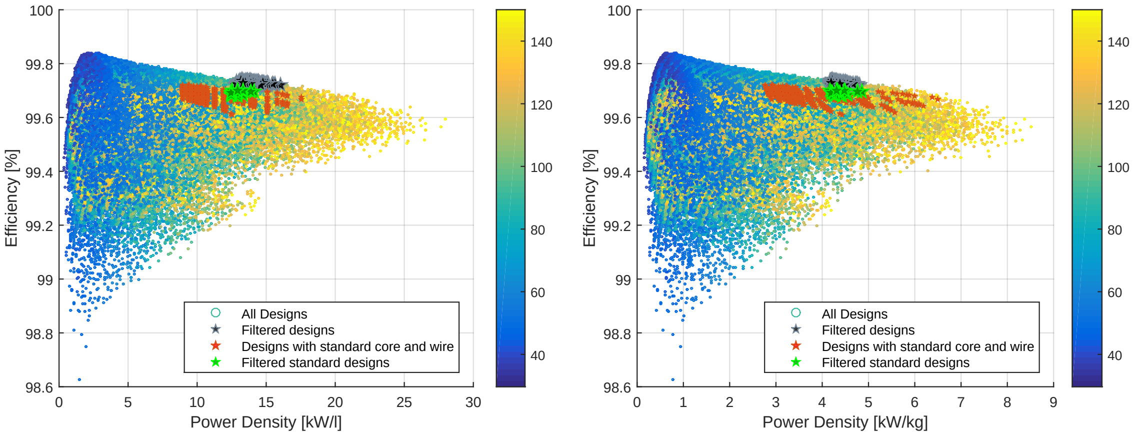
DESIGN OPTIMIZATION: RESULTS

Applied Filters:

T_{Wmax} [^oC]	T_{Cmax} [^oC]	V_{max} [l]	M_{max} [kg]	η_{min} [%]
135	80	10	24	99.6

Number of Designs:

- More than 1.8 Million



▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

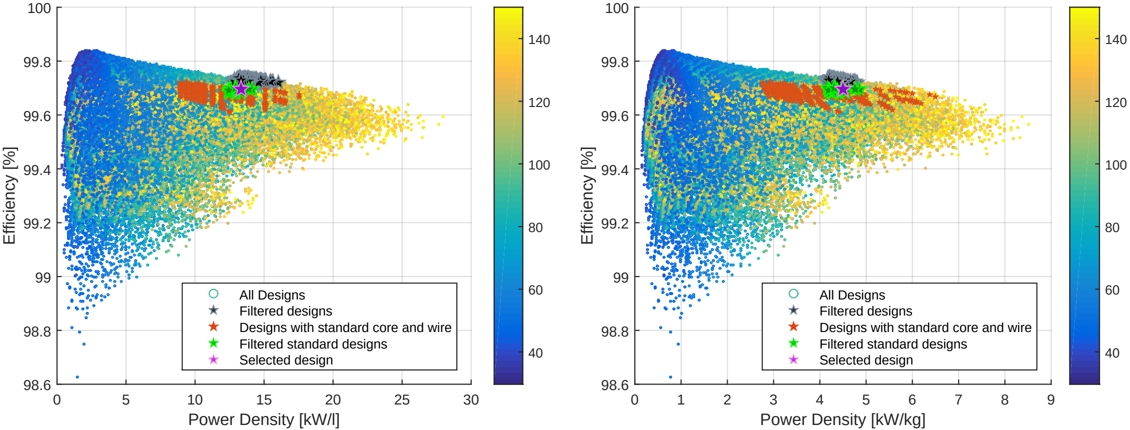
DESIGN OPTIMIZATION: RESULTS

Applied Filters:

T_{Wmax} $[^{o}C]$	T_{Cmax} $[^{o}C]$	V_{max} $[l]$	M_{max} $[kg]$	η_{min} $[\%]$
135	80	10	24	99.6

Number of Designs:

- More than 1.8 Million

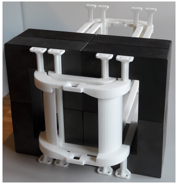


▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

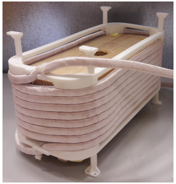
PROTOTYPE: OPTIMAL MFT DESIGN ASSEMBLY

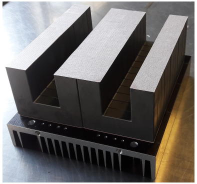

Optimal MFT Design 3D-CAD

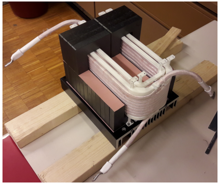

Coil-Formers 3D-CAD

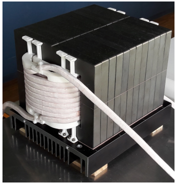

Coil-Formers 3D-Print


Primary Winding


Secondary Winding


Core Assembly


MFT Assembly1

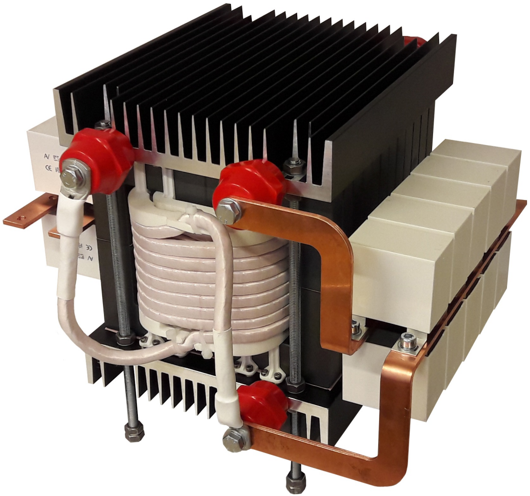

MFT Assembly2


Litz-Wire Termination


MFT Prototype

PROTOTYPE: FINAL ASSEMBLY

MFT Prototype



▲ 100kW, 10kHz MFT including resonant capacitors

Prototype Specifications:

- Core:
  - 12 stacks of 4 x SiFERRITE U-Cores (UU9316 - CF139)
- Windings:
  - 8-Turns
  - Square Litz Wire (8.7x8.7*mm*, 1400 strands, AWG 32, 43.69mm^2)
- Coil-Formers:
  - Additive manufacturing process (3-D printing)
  - High strength thermally resistant plastic (PA2200)
- Resonant Capacitor Banks:
  - (7x5μF + 1x2.5μF) AC film capacitors in parallel
  - Custom designed copper bus-bars
- Electrical Ratings:

P_n	$100kW$	V_1	$750V$	$L_{\sigma 1,2}$	$4.2\mu H$
f_{sw}	$10kHz$	V_2	$750V$	L_m	$750\mu H$

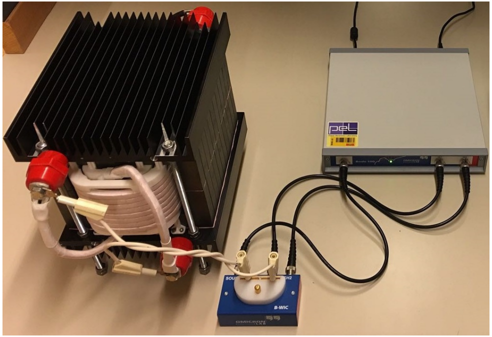
EXPERIMENTAL VERIFICATION

Full power rated B2B resonant test setup

Measurement of Electric Parameters:

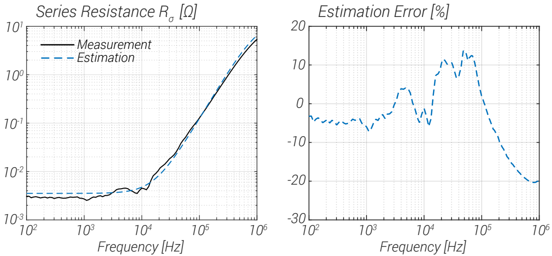
- Network Analyzer Bode100
- Impedance Measurement
- Results at 10kHz: $L_\sigma = 8.4\mu H$, $L_m = 750\mu H$, $R_\sigma = 0.2\mu\Omega$

LV Measurement Setup:

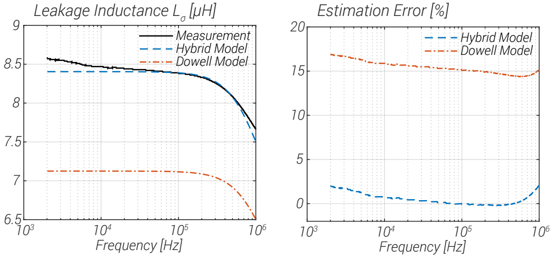


▲ Electrical measurements using Bode100

Series Resistance Measurement:



Leakage Inductance Measurement:

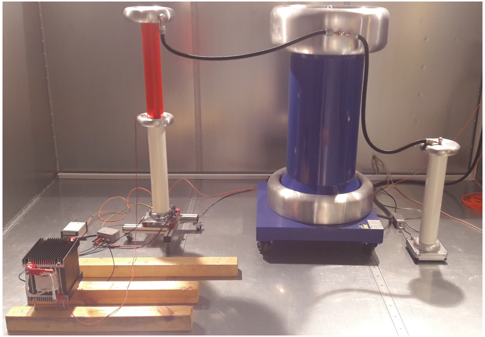


MEASUREMENTS: DIELECTRIC PARAMETERS

Dielectric Withstand Test:

- Partial Discharge measurement between all conductive parts
- High Voltage 50Hz source within a Faraday cage
- 10pC - between primary and secondary winding at 4kV

HV Measurement Setup:

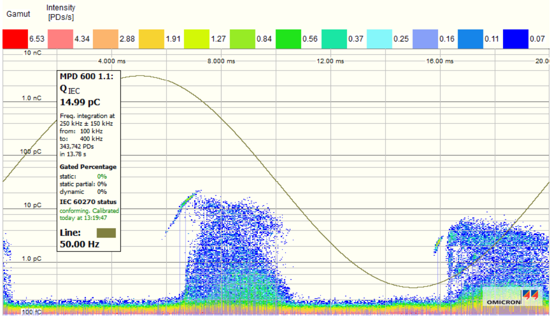


▲ MFT during AC test

PD Test Settings:

- Front of the voltage profile: $V = 6kV$
- Flat back of the voltage profile: $V = 4kV$
- Peak PD at periods where $|dV/dt|$ increases after the V peak
- PD is influenced by combination of V and $|dV/dt|$

Measured PD at flat back $V = 4kV$:

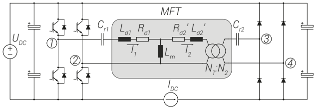


▲ MPD600 obtained measurement results

MEASUREMENTS: LOAD TEST

Test Setup Topology:

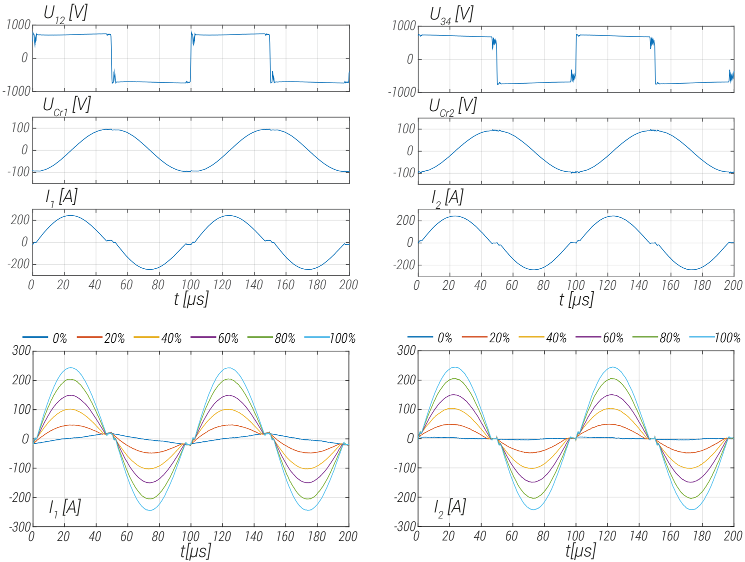
- B2B Resonant Converter
- Input voltage maintained by U_{DC}
- Power circulation via I_{DC}



Test Setup:

▲ B2B MFT test setup

Measurement Results:



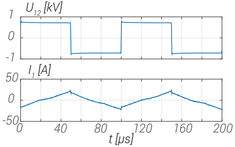
▲ Experimental results: left: MFT primary waveforms; right: MFT secondary waveforms

MEASUREMENTS: THERMAL RUN

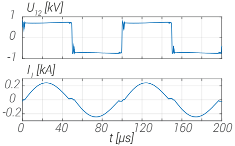
Measurement Setup:

Thermal Run:

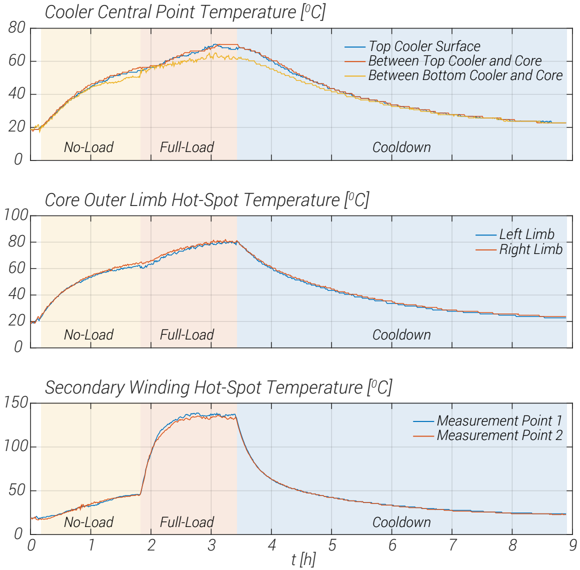
- No-Load Operation:



- Full-Load Operation:



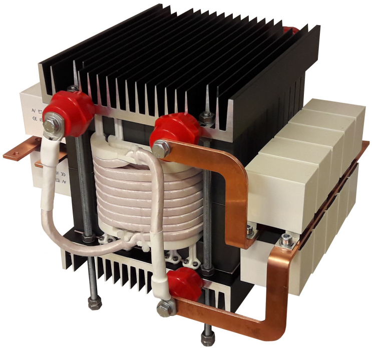
Thermal Profile:

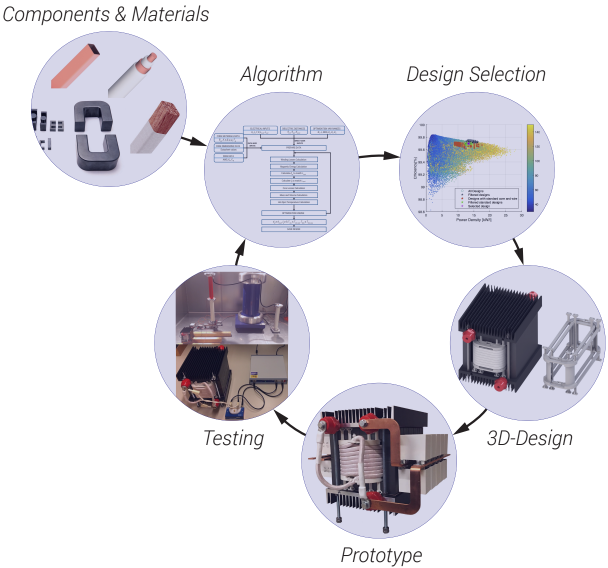


▲ Thermal heat run results

CONCLUSION

- Complex and challenging design optimization
- Large number of available materials
- Customized designs prevail
- Research opportunities...





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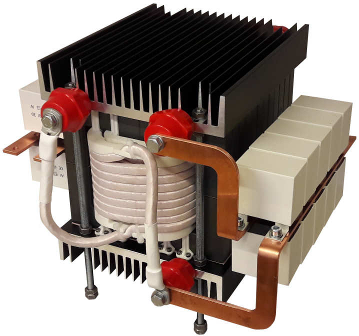

Given:

ECCE 2017
IEEE ENERGY CONVERSION CONGRESS & EXPO
Cincinnati OHIO October 1–5

Upcoming:

pcim
EUROPE

ICPE 2019
ECCE Asia

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Q AND A

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DESIGN OPTIMIZATION OF MFT FOR HIGH-POWER MV APPLICATIONS

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