Advanced Magnetics Modelling for Converter Optimisation

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Research Groups at D-ITET

- **D-ITET**
  - Department of Information Technology and Electrical Engineering
  - App. 35 Professors in 4 core research areas

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**Electronics and Photonics**

**Energy**

**Information & Communication**

**Biomedical Engineering & Neuroinformatics**
Professorship in HIGH POWER ELECTRONICS

- Established in August 2010
- High power, medium voltage laboratory
- Personnel:
  - 10-13 Ph.d. students, 1 senior scientist
  - 1 Permanent Lab-Engineer
- Research in close collaboration with industry
- 60-70% external funding
Major Research Topics

- Comprehensive Modelling of Converter Systems
- Multi-Criteria Optimisation
- Efficient Design of Converters
- Identify Technological Barriers
- New Topologies / Modulation
- Advanced Passives
- Control Methods
New High Power Laboratory-Facilities

- 3 reconfigurable Faraday test cells
- 3 reconfigurable fence-test cells
- Max. cell size: 57 m$^2$
- Sources:
  - 0 … 400 V/800 V  250 kVA
  - 0 … 25 kV$_{AC}$  250 kVA
  - 0 … 35 kV$_{DC}$ (Bidirectional)  250 kW
  - 0 … 2 kV$_{DC}$ (Bidirectional)  100 kW/1.2 kA
- > 150 kW water cooling
- > 2 × 30 kW air cooling
- 2 t crane
New High Power Laboratory-Facilities

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- 3 reconfigurable fence-test cells
- Max. cell size: 57 m²
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  - 0 ... 400 V/800 V 250 kVA
  - 0 ... 25 kV\textsubscript{AC} 250 kVA
  - 0 ... 35 kV\textsubscript{DC} 250 kW (Bidirectional)
  - 0 ... 2 kV\textsubscript{DC} 100 kW/1.2 kA (Bidirectional)
- >150 kW water cooling
- >2 × 30 kW air cooling
- 2 t crane
Content

- Converter Optimisation

- Dual Active Bridge
  - Leakage Inductance
  - Thermal Model – Water Cooling
  - Measurement Results

- Resonant Converter
  - Isolation Design
  - Thermal Model – Litz Wire
  - Measurement Results
Magnetic Devices

Modelling for Converter Optimisation
Power Electronic Converter Systems

- Most PE converters utilise some kind of magnetic device
- Most of the magnetic devices are custom design
- Magnetics significantly impact system power density / efficiency

Types of magnetic devices
- Inductor: PFC / Non-isolated DC-DC
- Power transformer: Grid / Isolated DC-DC / Pulse transformer
- (EMI) filter: DM / CM / harmonics
- Current transducer
- ...
Example: Converter for Traction Applications

- "Hybrid" traction vehicle with onboard battery storage
- Replace diesel engine
- Reduction of power pulsation in grid
- Drive without "external supply" (e.g. in shunt yard)
- System power 183 kW
Battery Interface System Topology

- **Modular Dual Active Bridge (DAB)**
  - Input: Battery
    - Parallel connection
  - Output: 2.8 kV DC link
    - Series connection
  - Soft switching
  - Isolation (Required by specification)
  - SiC MOSFETs
  - HF operation

[Diagram of Battery Interface System Topology]
Battery Interface – Degrees of Freedom

Full-bridge
- Switch selection
- Chip area/parallel switches
- Modulation scheme

Transformer
- Core geometry
- Core material
- Winding specs.
- No. of turns ($N_P, N_S$)
- Leakage inductance
- Isolation coordination
- Integrated cooling
- Parasitic elements

Full-bridge
- Switch selection
- Chip area/parallel switches
- Modulation scheme

Switching frequency

Control
Phase shift
Duty cycle

Switching frequency

Control Platform
Multi-Domain Models → Calculation of Performance

- Mapping of design space into system performance space

Performance Space
- Efficiency
- Power Density
- Costs
- Reliability
- etc.

System
- Phase-Shift DC/DC Conv.
- Resonant DC/DC Conv.
- DC Link AC/AC Conv.
- Matrix AC/AC Conv.
- etc.

Components
- Power Semiconductor
- Interconnections
- Inductors, Transf.
- Capacitors
- Control Circuit
- etc.

Materials
- Semiconductor Mat.
- Conductor Mat.
- Magnetic Mat.
- Dielectric Mat.
- etc.

- Evaluation Formulas
- Lifetime Models
- Cost Models
- etc.

- Specifications
- Operation Limits
- Converter Topology
- Modulation Scheme
- Control Concept
- Operating Mode
- Operating Freq.
- etc.

- Doping Profiles
- Geometric Properties
- Winding Arrangements
- Magnetic Core Geometries
- etc.
Multi-Domain Models → Optimisation Procedure

- Models for different domains
- Linkage of models
  - Virtual prototype
    (Automated design)
    (Digital twin)

- Advantages
  - Faster design process
  - Lower costs
  - Lower prototyping effort
  - Error detection w/o hardware
  - Better insight in converter
  - Access to all signals
Technology Benchmarking & "Tradeoff" Analysis

- Projection from (multi-dimensional) design to (multi-dimensional) performance space
- Identification of the potential of technologies
- Analysis of the design tradeoff
- Long term: User-based design ⇒ Automatic design
Example: Design Tradeoff for 48 V Telecom DC Supplies

\[ oc \rho - \eta = w \rho \cdot \frac{P_{out}}{Vol} + w \eta \cdot \frac{P_{out}}{P_{in}} \]

Phase-Shift PWM with LC Output Filter
\[ \approx 2.3 \text{ kW/dm}^3 / \eta \approx 99\% \]

Maximum Efficiency
Maximum Power Density

Series-Parallel Resonant Converter
\[ \approx 10.4 \text{ kW/dm}^3 / \eta \approx 96.2\% \]

Phase-Shift PWM with Current Doubler
\[ \approx 9.0 \text{ kW/dm}^3 / \eta \approx 94.4\% \]
System Evaluation: System Performance Maps

System Model
- Topology / Modulation / Control

Component Models
- Semiconductors / Capacitors / Magnetics / Cooling

Material Data

System Performance Map

\[ z = h_i(v) \]

\[ v = g_i(v) \]

\[ y = f_i(x) \]
Example: System Performance Map for PFC Rectifier

Conventional PFC with Diode Rectifier

Bridgeless PFC

Triangular current mode (TCM) PFC

Prototype of 3.2kW Bridgeless PFC Rectifier
230V_{AC} to 365V_{DC} @ 99.3% / 1.35kW/dm³

J. Biela et al., Pareto Optimal Design and Performance Mapping of Telecom Rectifier Module Concepts, Keynote Paper at the Conversion and Intelligent Motion (PCIM) Conference China, Shanghai, China, June 2010
Multi-Domain Models for Converter Optimisation

- Multi-domain converter model
  - Electrical
  - Magnetic
  - Semiconductor device
  - Thermal
- Material/component data base

![Diagram of Multi-Domain Models for Converter Optimisation](image)
Converter Optimisation – Model of Magnetic Components

- Multi-domain model of magnetics
  - Magnetic field
  - HF / core losses
  - Electric field / Isolation
  - Mechanical vibrations / acoustic noise
- Thermal model
Content

- Converter Optimisation
- Dual Active Bridge
  - Leakage Inductance
  - Thermal Model – Water Cooling
  - Measurement Results
- Resonant Converter
  - Isolation Design
  - Thermal Model – Litz Wire
  - Measurement Results
Dual Active Bridge Converter
– Traction Applications –
System specifications

- Battery voltage range: 518 V..835 V
- Nominal DC link voltage: 2800 V
- Peak regulated voltage: 3000 V
- Unregulated voltage: 4200 V
- System power: 183 kW
  - Peak for 300 s: >234 kW
- Battery current (cont.): 220 A
  - Peak for 300 s: 280 A
- Insulation voltage:
  - Working: 4.2 kV
  - Impulse P-S: 18 kV
- Efficiency: >95%
- Ambient temperature: 75 °C
- Water temperature: 60 °C
- Maximum weight: 25 kg
- Maximum dimensions: 75 cm × 36 cm × 20 cm

Overhead line

AC

DC

2.8 kV

DC

AC

M 3~
Optimisation procedure

- **Pre-selected technologies**
  - **Semiconductors**
    - SiC MOSFETs
    - Water Cooling
  - **Transformer**
    - Foil windings
    - Ferrite core
    - Integrated water cooling

- **Topology: (Modular) Dual Active Bridge (DAB)**
### Transformer insulation design

- **Minimum distance for insulation**
  \[ d_{iso,min} > \frac{V_{iso}}{k_{iso}E_{iso}} \]

  with
  - \( V_{iso} \) Basic insulation voltage requirement
  - \( E_{iso} \) Dielectric strength of the isolation material
  - \( k_{iso} \) Safety factor (here: 0.25)

- **Important design issues**
  - Avoid sharp edges (e.g. foil winding tips)
  - Avoid air voids (e.g. in potting material)
Transformer Leakage Inductance
– Comparison of Models –
Leakage Inductance Calculation Principles

- Assumption
  - Balanced magnetomotive forces
  - 3D $H$-field
- $H$-field
- Leakage inductance

\[ MMF_{pri} = N_1 \cdot I_1 = -N_2 \cdot I_2 = -MMF_{sec} \Rightarrow I_m = 0 \]
\[ I_m = 0 \Rightarrow \text{"Leakage field" distribution} \]

\[ \Rightarrow \text{Energy } W_{mag} \]
\[ W_{mag} = \frac{1}{2} L \sigma I^2 \Rightarrow L \sigma = \frac{2W_{mag}}{I^2} \]
Leakage Inductance Model: 2D + 1D ⇒ 3D

- **Step I:** 2D magnetic field distribution ⇒ Leakage inductance per length: $L'_\sigma$
- **Step II:** Multiplication with length ⇒ $L_\sigma$

**Scope of comparison: Step I**
- Benchmark: $L'_\sigma$ by 2D FEM

2D inside-window geometry:
- Windings → Blocks
- Homogeneous current distribution (DC)

Leakage inductance model
Dowell, Rogowski, Roth, Margueron, MGD

Leakage inductance per unit length $L'_\sigma$

Scaling length:
e.g. Mean length of turns $l_m$

Leakage inductance $L_\sigma = L'_\sigma \cdot l_m$

Step I
2D

Step II
1D

3D

$N_1 \cdot I_1 = -N_2 \cdot I_2$

$2I \cdot 2N - 1I \cdot 1N$
Leakage Inductance per Length Models (2D)

1D: $\vec{H}(x)$

- Single space harmonics (1D Fourier series)
- Kapp/Dowell

2D: $\vec{H}(x,y)$

- Double space harmonics (2D Fourier series)
- Rogowski
- Roth

- PEEC formulae, discrete images
- Margueron

- Conductor: filamentary current, circular field, discrete images

Mean Geometric Distances (MGD)

Leakage inductance per unit length $L_\sigma'$
1D Axial Flux Model by Kapp (1907)

- **Assumptions**
  - 1D leakage field ⇒ $\vec{H} = H_y(x)\vec{e}_y$
  - Windings up to yokes
  - Core material $\mu_{r,\text{core}} \to \infty$
  - Homogeneous current distribution (no eddy currents)

- **$H$-field with Ampere’s law**
  - $H(x) \propto x$ in windings
  - $H(x) = \text{const.}$ between windings
  
  \[ \oint_{\partial A} \vec{H} \cdot d\vec{s} = I \]

- **Magnetic energy** per unit length

- **Leakage inductance** per unit length

\[ L'_{\sigma} = \frac{\mu_0 N^2}{h_w} \left( d + \frac{a_1 + a_2}{3} \right) \frac{1}{h_w} \]

($N$: Number of turns of excited winding)
Dowell’s model (1966)

- **Assumptions**
  - 1D leakage field ⇒ \( \vec{H} = H_y(x) \hat{e}_y \)
  - Windings up to yokes
  - Core material \( \mu_{r, \text{core}} \to \infty \)
  - Eddy currents included (\( I = i \sin(\omega t) \))

- With Ampere’s law and Faraday’s law

\[
\frac{\partial}{\partial S} \vec{H} \cdot d\vec{s} = I \\
\frac{\partial}{\partial S} \vec{E} \cdot d\vec{s} = -\int \frac{d\vec{B}}{dt} \cdot d\vec{A}
\]

⇒ 2nd-order differential equation for \( J_z(x, \omega) \)
⇒ Winding voltage \( V(\omega) \)

- **Leakage inductance** per unit length

\[
L'_{\sigma}(\omega) = \Im \left( \frac{V(\omega)}{\omega} \right)
\]

\[
L'_{\sigma} = \left( \mu_0 N^2 l_m \frac{1}{h_w} \right) \left( d + F_{L1}(\omega) \frac{a_1}{3} + F_{L2}(\omega) \frac{a_2}{3} \right)
\]

\( F_{L,k}(\omega) \) Frequency correction factor for conductor \( k \)

\[
F_{L,k}(m=1) = \frac{3 \Im(M)}{[(v \sqrt{2f})^2]}
\]

\[
\Im(M) = v \frac{\sin(2v) - \sinh(2v)}{\cos(2v) - \cosh(2v)} ; \quad v = \frac{a_k}{\delta} ; \quad \delta = \frac{1}{\sqrt{\pi/\mu_0 \sigma}}
\]

\( f \) Frequency
\( \sigma \) Conductivity
Rogowski’s model (1908)

- Assumptions
  - Windings of equal height
  - Core material $\mu_{r,\text{core}} \to \infty$
  - Homogeneous current distribution

- Windings mirrored across leg-edges (in $x$-direction)

- $J_z(x,y)$ as Fourier series in $x$-direction (Single space harmonics)

- $A_z(x,y)$ with Poisson’s equ.

- Magnetic energy per unit length

- Leakage inductance per unit length

$m$ is the Rogowski factor

$$K = 1 - \frac{1-e^{-kh}}{kh} \left[ \left( 1 - \frac{1}{2} e^{-2kb} (1 - e^{-kh}) \right) \left( 1 + e^{-k(g-b)} \right) - e^{-k(2b+2g+h)} \right]$$

$K$ is the Rogowski factor

$W'_{\text{mag}} = \frac{1}{2} \mu_0 \iint_{\text{window}} H^2 \, dA = \frac{1}{2} \iint_{\text{window}} \vec{A} \cdot \vec{J} \, dA$

$$L'_\sigma = \frac{2W_{\text{mag}}}{I^2} = K \mu_0 N^2 \left( d + \frac{a_1 + a_2}{3} \right) \frac{1}{h_w}$$

Windings with different height

$\rightarrow$ Averaged height $h = \sqrt{h_1 h_2}$

Non-axial field due to gaps $b$ & $g$ is considered
Roth’s model (1928)

- **Assumptions**
  - Core material $\mu_{r,\text{core}} \to \infty$
  - Homogeneous current distribution

- **Mirror conductors** $k$ across window edges

- $J_{z,k}(x, y)$ of conductor $k$ in window as 2D Fourier series
  (Double space harmonics)

- $A_{z,k}(x, y)$ with Poisson’s equation $\Delta A_{z,k}(x, y) = -\mu J_{z,k}(x, y)$

- **Superpose** ($l$ total number of conductors in window)
  - Current distribution $J_z(x, y) = \sum_{k=1}^{l} J_{z,k}(x, y)$
  - Potential $A_z(x, y) = \sum_{k=1}^{l} A_{z,k}(x, y)$

- **Solve analytically**
  (Costly $H$-field calculation avoided)

- **Leakage inductance** per unit length $L'_\sigma = \frac{2W'_{\text{mag}}}{I^2}$

- **2D infinite series** (No closed form)
  - Fast convergence $\propto \frac{1}{n^3}$
Margueron’s model (2007 & 2010)

- **Assumptions**
  - Homogeneous current distribution
  - Discrete amount of images (approximation)
  - Core material with finite permeability $\mu_{r,\text{core}}$

- **Discrete mirroring of conductors** (In figure 1 image layer)

- **Calculate**
  - Potential of each conductor $k \quad A_{z,k}(x,y,w_k,h_k)$

- **Superpose** ($n$ total number of discrete conductors: Original + mirrored ones)
  - Total potential
    \[ A_z(x,y) = \sum_{k=1}^{n} A_{z,k}(x,y) \]

- **Solve**
  - 2007 – Numerical integration with explicit field calculation
  - 2010 – Analytical integration without explicit field calculation
    \[ \Rightarrow \text{Much faster!} \]

- **Leakage inductance** per unit length
  \[ L'_\sigma = \frac{2W_{\text{mag}}}{I^2} \]

- **Closed form solution**
Mean Geometric Distance (MGD) model (1934)

- Introduced by J.C. Maxwell in 1865, applied to transformers by Petrov in 1934

- Assumptions
  - Infinitely thin currents (Winding blocks $\rightarrow$ Winding filaments)
  - Discrete amount of images (approximation)
  - Core material $\mu_{r,\text{core}} \rightarrow \infty$

- Ampere’s law
  - Self inductance per unit length $L'_1$
    $\Rightarrow$ Mean geometric distance of winding to itself
  - Mutual inductance per unit length $M'$
    $\Rightarrow$ Mean geometric distance between two windings

- Leakage inductance per unit length: $L'_\sigma = L'_1 - \frac{N_1}{N_2} M'$

- Closed form solution
Considered Transformers

- Ferrite cores (high $\mu_r$)
- Wide range of geometries
- Calculation performed for core window

- 3 E-Cores
- 3 U-Cores

No.1 (4xUU93/152/30)  No.2 (E80/38/20)  No.3 (E100/60/28)
No.4 (UR72/130/27)  No.5 (UR116/154/38)  No.6 (UR54/74/27)

10 cm
Considered Transformers – Data

- Ferrite cores (high $\mu_r$)
- Wide range of geometries
  ⇒ Calculate $L'_\sigma$ for cross section of each transformer

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>Core</th>
<th>Core specifications</th>
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<tr>
<td>No. 1</td>
<td>20</td>
<td>20</td>
<td>E</td>
<td>4x UU 93/152/30</td>
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<tr>
<td>No. 2</td>
<td>23</td>
<td>26</td>
<td>E</td>
<td>E80/38/20</td>
</tr>
<tr>
<td>No. 3</td>
<td>19</td>
<td>18</td>
<td>E</td>
<td>E100/60/28</td>
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<tr>
<td>No. 4</td>
<td>20</td>
<td>1350</td>
<td>UR</td>
<td>custom, UR 72/130/27</td>
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<tr>
<td>No. 5</td>
<td>10</td>
<td>952</td>
<td>UR</td>
<td>custom, UR 116/154/38</td>
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<tr>
<td>No. 6</td>
<td>32</td>
<td>480</td>
<td>UR</td>
<td>custom, UR 54/74/27</td>
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</tbody>
</table>
Error vs. Calculation Time of Models

**Model**
- Kapp
- Dowell
- Rogowski simple
- Rogowski complete
- Roth
- Margueron 2007
- Margueron 2010
- MGD

**Transformer**
- No.1
- No.2
- No.3
- No.4
- No.5
- No.6

**Graphical Representation**
- **Dowell & Kapp:** Inaccurate (1D-approx.)
- **MGD:** Inaccurate (different winding height and width)
- **Margueron 2007:** Slow (explicit field calculation)

**Legend**
- Different symbols represent different models and transformers.

**Figure Description**
- The graph shows the trade-off between calculation time and error for different models and transformers.
- Models are categorized based on their accuracy and computational effort.
- Key findings include:
  - Kapp and Dowell models are inaccurate due to 1D approximations.
  - Margueron 2007 models are slow due to explicit field calculations.
  - MGD model is inaccurate due to different winding parameters.

**References**
Error vs. Calculation Time of Models (Zoomed)

- **Rogowski**
  - Very fast, moderately accurate
- **Roth**
  - Very accurate, moderately fast
- **Margueron 2010**
  - Moderately fast & accurate / Finite $\mu_r,\text{core}$ considered
- **MGD**
  - Accuracy strongly depends on geometry

![Graph showing error vs. calculation time for different models and transformers]
Scale to 3D leakage inductance

- Leakage inductance per unit length $L'_\sigma$
  - Acquired analytically (e.g. Roth)
  - Verified by 2D FEM
- Next step: 3D Leakage inductance $L_\sigma = L'_\sigma \cdot l_m$

Circular center leg

Rectangular center leg

$\begin{align*}
l_m &= \pi \cdot D_m = \pi \cdot \frac{D_1 + D_2}{2} \\
l_m &= 2(b_m + c_m) = 2 \left( \frac{b_1 + b_2}{2} + \frac{c_1 + c_2}{2} \right)
\end{align*}$
Measurement Results

- Average: $\approx 15\%$ error
- 2 main error sources:
  - Field distribution inside/outside-window different
  - Scaling length: Curvature of field must be considered
- Measured with DPG10 Power Choke Tester DPG10 - 1000B

<table>
<thead>
<tr>
<th>Transformer</th>
<th>$L_\sigma$ (µH)</th>
<th>3D FEM</th>
<th>Roth: $L_\sigma$</th>
<th>Roth: $L'_\sigma$</th>
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</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>26.90*</td>
<td>2.7%</td>
<td>18.9%</td>
<td>-0.01%</td>
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<tr>
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<td>9.4%</td>
<td>-0.01%</td>
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<td>-3.8%</td>
<td>-0.04%</td>
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<td>-0.05%</td>
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<tr>
<td>No. 6</td>
<td>26.60</td>
<td>5.6%</td>
<td>12.3%</td>
<td>-0.01%</td>
</tr>
</tbody>
</table>

*other prototypes: 25.8 µH, 26.5 µH
Field distribution inside/outside-window

- Different cross section geometry
  - Different magnetic field distribution
  - Different $L'_\sigma$
Literature: Leakage inductance

1) **G. Kapp**, *Transformatoren für Wechselstrom und Drehstrom*, Julius Springer Verlag, 3rd edition, 1907


3) **W. Rogowski**, *Ueber das Streufeld und den Streuinduktionskoeffizienten eines Transformators mit Scheibenwicklung und geteilten Endspulen*, Dissertation, Technische Hochschule zu Danzig, 1908


8) **J.C. Maxwell**, *A Treatise On Electricity and Magnetism*, Clarendon Press Series, 1873

**Transformer modelling – Winding Losses**

- **Winding losses**
  - **High frequency effects (Dowell)**
    - Skin effect losses
    - Proximity effect losses
    \[
    P_{\text{Skin}} = F_F(f) R_{DC} I_p^2
    \]
    \[
    P_{\text{Prox}} = G_F(f) \hat{H}_E^2
    \]
    \[
    F_F = \frac{\nu}{4} \frac{\sinh \nu + \sin \nu}{\cosh \nu - \cos \nu} \quad \text{and} \quad G_F = \frac{b \nu}{\sigma h} \frac{\sinh \nu - \sin \nu}{\cosh \nu + \cos \nu}
    \]
    \[
    R_{DC} = \frac{1}{\sigma bh}, \quad \nu = \frac{h}{\delta}, \quad \delta = \frac{1}{\sqrt{\pi \mu_0 \sigma f}}
    \]
  - **Optimum foil thickness**

![Diagram of transformer losses](image)

**Graph**
- Losses [W] vs Diameter [mm]
  - $P_{\text{Total}}$
  - $P_{\text{Skin}}$
  - $P_{\text{Prox}}$

---

Core Loss Calculation with Steinmetz Equation

- Steinmetz Equation
  \[ P = k f^\alpha B^\beta \]

- Parameters \( k, \alpha \) and \( \beta \)
  - Extract from data sheet
  - Valid only in a limited \( B, f \), and Temp.-range

- Only for sinusoidal flux waveforms
- DC bias/offset not considered
Improved Generalised Steinmetz Equation (iGSE)

- Steinmetz Equation: \( P = k f^\alpha B^\beta \)  ➤ Sinusoidal flux waveform
- Core Losses depend on \( \frac{dB}{dt} \)  ➤ General Approach
- Improved Generalised Steinmetz Equation (iGSE)

\[
P_v = \frac{1}{T} \int_0^T k_i \left| \frac{dB}{dt} \right|^{\alpha} (\Delta B)^{\beta - \alpha} \, dt \quad \text{with} \quad k_i = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} \left| \cos \theta \right|^{\alpha 2^\beta - \alpha} d\theta}
\]

- Piecewise linear flux waveforms

\[
P_v = \frac{k_i}{T} \left[ DT \left( \frac{\Delta B}{DT} \right)^\alpha (\Delta B)^{\beta - \alpha} + (1-D)T \left( \frac{\Delta B}{1-D}T \right)^\alpha (\Delta B)^{\beta - \alpha} \right]
\]

- iGSE for sinusoidal waveforms

\[
P_v = \frac{1}{T} \int_0^T k_i \left| \frac{dB}{dt} \right|^{\alpha} (\Delta B)^{\beta - \alpha} \, dt = kf^\alpha \left( \frac{\Delta B}{2} \right)^\beta
\]
Example for flux waveform

\[ B(t) = A[(1 - c) \sin(\omega t) + c \sin(3\omega t)] \]
Core Loss Model – iGSE: Missing Losses

- Improved Generalised Steinmetz Equation (iGSE)

\[ P_v = \frac{1}{T} \int_0^T k_i \left| \frac{d\Delta B}{dt} \right|^\alpha (\Delta B)^{\beta-\alpha} dt \quad \text{with} \quad k_i = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos \theta|^\alpha 2^{\beta-\alpha} d\theta} \]

- Steinmetz parameter valid only in limited range of \( f, B \) and Temperature
- Missing
  - Relaxation losses \( \rightarrow i^2 \text{GSE} \) (improve iGSE)
  - Impact of DC offset in flux \( \rightarrow \text{SGC} \) (Steinmetz Premagnetisation Graph)

\[ P_v = \frac{k_i}{T} \left[ DT \left( \frac{\Delta B}{DT} \right)^\alpha (\Delta B)^{\beta-\alpha} + (1-D)T \left( \frac{\Delta B}{(1-D)T} \right)^\alpha (\Delta B)^{\beta-\alpha} \right] = \ldots \]
Thermal Model – Heat Transfer Mechanisms

- **General thermal resistance**
  \[ R_{th} = \frac{\Delta T}{P} = f(T) \]

- **Conduction**
  - Usually independent of temperature
  - Important: Accurate material data
  - Difficulty: Interface between materials
  \[ R_{th} = \frac{\Delta T}{P} = \frac{1}{A\lambda} \]

- **Convection**
  - Conduction + fluid flow
  - Dependent on temperature
  - Empirical equations available
    (e.g. VDI Heat Atlas)
  \[ R_{th} = \frac{\Delta T}{P} = \frac{1}{\alpha A} \]

- **Radiation**
  - Usually negligible
  - Difficult to model
    (nonlinear / line of sight)
  \[ P = \varepsilon_{eff} A_1 \sigma \left( T_b^4 - T_a^4 \right) \]
Thermal model of transformer

Top cut view

Front cut view

Primary foil winding

Secondary foil winding

Primary windin
Secondary windin
Bobbin
Heat sink
AlN
Ambient (water)

Core

5.5 mm
29 mm +0/-0.2

Core center limb
81 mm

Primary foil winding

Secondary foil winding

Bobbin

29 mm +0/-0.2

E-core

Primary foil winding

Bobbin

29 mm +0/-0.2

4.4 mm
8.8 mm
Thermal Model of Water Cooling I

- Thermal model of water channel
  - Thermal resistance between hot surface and channel wall
    \[ R_{th,r} = \frac{d_{ch}}{w l \lambda_{HS}} \]
  - Thermal resistance from channel wall to cooling fluid
    \[ R_{th,d} = \frac{1}{\alpha l d} \]
  
  with
  \[ \alpha = \frac{N_u \lambda_{\text{fluid}} d}{d} \]
  Heat transfer coefficient
  \[ N_u \]
  Nusselt number
  \[ \lambda_{HS} \& \lambda_{\text{Fluid}} \]
  Thermal conductivity
  \[ d \approx 2 \sqrt{A/\pi} \]
  Channel hydraulic diameter

- Nusselt number is a function of
  - Average ducted fluid velocity \( V \)
  - Duct geometry
  - Fluid Prandtl number \( P_r \)
  - Analytical models for Nusselt number
Thermal Model of Water Cooling II

- **Water flow in structures with multiple parallel channels**
  \[ \Delta p_{tot} = \Delta p_1 = \Delta p_2 = \ldots = \Delta p_i \text{ (pressure loss (Pa))} \]

- **Darcy-Weisbach pressure loss equation**
  \[ \Delta p = \frac{\dot{V}^2}{\left( \sum \sqrt{K_i/f_i} \right)^2} ; \dot{V} = V \cdot A ; K_i = \frac{\pi^2 \cdot d_i^5}{8 \rho l_i} \]

  - \( V \text{ (m/s)} \) Fluid velocity
  - \( \dot{V} \text{ (m}^3/\text{s)} \) Flow rate
  - \( f_i \) Channel friction factor
  - \( K_i \) Constant
  - \( \rho \text{ (kg/m}^3\text{)} \) Fluid density

- **Channel friction factor \( f_i \)**
  - Different formulas for laminar / turbulent flow
  - Function of Reynolds number
  - Turbulent flow ⇒ Include channel roughness
  - **Reynolds number is a function of fluid velocity**
    - Iterative solving necessary
    - \(< 10\) iteration steps sufficient
Thermal Model: 3D-FEM Simulation of Water Flow

- Velocity profile of the cooling structure
- 8 l/min flow rate
- Fluid velocity in transformer channels

<table>
<thead>
<tr>
<th>FEM</th>
<th>Analytical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid velocity</td>
<td>0.115 m/s</td>
</tr>
</tbody>
</table>
Thermal Model: Validation with 3D-FEM Simulation

- **Conditions**
  - Same material parameters
  - Same losses
  - 20 °C water temperature
  - 8 l/min flow rate

<table>
<thead>
<tr>
<th></th>
<th>$T_{C1}$</th>
<th>$T_{C2}$</th>
<th>$T_{C3}$</th>
<th>$T_{AlN}$</th>
<th>$T_{Wp}$</th>
<th>$T_{Pot}$</th>
<th>$T_{Ws}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3D FEM</strong></td>
<td>70 °C</td>
<td>40 °C</td>
<td>29 °C</td>
<td>71 °C</td>
<td>78 °C</td>
<td>77 °C</td>
<td>81 °C</td>
</tr>
<tr>
<td><strong>Analytical</strong></td>
<td>72 °C</td>
<td>42 °C</td>
<td>28 °C</td>
<td>68 °C</td>
<td>83 °C</td>
<td>80 °C</td>
<td>88 °C</td>
</tr>
</tbody>
</table>
Optimisation Results

- Modular Dual Active Bridge (DAB) converter

\[ I_{L} = \frac{N_{1}}{N_{2}} \]

\[ n = \frac{N_{1}}{N_{2}} \]

\[ \sigma \phi = 100 \% \]

\[ V_{C} \]

\[ 200kW \iff \eta = 98.7\% \iff 6^{\frac{kW}{dm^3}} \iff 2.8^{\frac{kW}{kg}} \]

Specifications ①

Electrical model ②

Change control param. ③

Conduction and switching losses ③

Pre-check constraints \( P_{out}, \eta, T_{HS} \)

Transformer optimization loop ⑤

Geometry/winding ⑤

Check constraints \( B_{m}, L_{\sigma}, d_{iso, min} \)

No feasible transformer used control parameters

Core & winding losses

Transformer thermal model

Feasible designs pareto curves ⑥

Optimal design ⑦

Transformers

Specifications

Electrical model

Change control param.

Conduction and switching losses

Pre-check constraints \( P_{out}, \eta, T_{HS} \)

Transformer optimization loop

Geometry/winding

Check constraints \( B_{m}, L_{\sigma}, d_{iso, min} \)

No feasible transformer used control parameters

Core & winding losses

Transformer thermal model

Feasible designs pareto curves

Optimal design

(a) N97 Custom Cores

(b) N97 Standard Cores
Prototype System

- **Single module specifications**
  - Nominal battery side voltage: 700 V
  - Nominal DC link side voltage: 700 V
  - Nominal power: 38.5 kW
  - Max. continuous power: 50 kW
  - Switching frequency: 35 kHz
  - Efficiency: 98.5%
  - Dimensions: 36 cm × 19.5 cm × 11.8 cm
  - Power density: 6 kW/dm³
  - Weight: 18 kg

![Diagram of module components]

- Transformer terminals
- Terminals of power semiconductors
- Power terminals
- Power boards
- Cooling water inlet/outlet
- Auxiliary supply boards
- FPGA control board
- Transformer core
- Cooling structure of the transformer

Dimensions:
- 11.8 cm
- 36 cm
- 19.5 cm
Prototype System

- **Single module specifications**
  - Nominal battery side voltage: 700 V
  - Nominal DC link side voltage: 700 V
  - Nominal power: 38.5 kW
  - Max. continuous power: 50 kW
  - Switching frequency: 35 kHz
  - Efficiency: 98.5 %
  - Dimensions: 36 cm × 19.5 cm × 11.8 cm
  - Power density: 6 kW/dm³
  - Weight: 18 kg
Prototype System - Volume & Loss Breakdown

- **Component volumes**

- **Component losses**
Transformer specifications

- Standard core: EPCOS UU 93/152/30
- Core material: N97
- Primary turns: 20
- Secondary turns: 20
- Foil winding height:
  - Primary: 90 mm
  - Secondary: 80 mm
- Foil thickness: 100 µm
- Leakage distance: 17.5 mm
- Isolation voltage: 4.2 kV
- Maximum frequency: 35 kHz
- Leakage inductance: 26.5 µH
- Losses (worst case):
  - Primary winding: 69 W
  - Secondary winding: 147 W
  - Core: 28 W
- Materials:
  - Winding isolation: BERGQUIST Poly-Pad K10
  - Potting: Copaltec FR22
Eddy Currents in Cooling Structure

- **Aluminium bar**
  - Better thermal behaviour (part of the structure)
  - Thickness not limited
  - Manufacturability: Bar only on one side
    - Influence on H-field
    - Can lead to higher losses in windings

- **Aluminium Nitride bar**
  - Thickness $\geq 1\text{mm}$
  - Larger thickness non-standard $\rightarrow$ higher cost

- **Calculated induced losses (FEM)**

<table>
<thead>
<tr>
<th></th>
<th>Al bar</th>
<th>AlN bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced losses</td>
<td>75 W</td>
<td>36 W</td>
</tr>
</tbody>
</table>

Calculated induced currents in structure with Al bar

$J_{\text{m}} = 4 \times 10^8 \text{Am}^{-2}$

Calculated induced currents in structure with AlN bar

$J_{\text{m}} = 1.3 \times 10^8 \text{Am}^{-2}$
Hydraulic Measurements Results

- Simplified pressure drop relation

\[ \Delta p = \eta \frac{\rho \dot{V}^2}{A_c^2} \sim kV^2 \]

\( \eta \) Coefficient of fluid resistance
\( \rho \) Fluid density
\( \dot{V} \) Flow rate
\( A_c \) Water channel cross section

Characteristic curve for 25°C & 60°C

- measured points 25°C
- interpolated curve 25°C
- measured points 60°C
- interpolated curve 60°C
Dual Active Bridge Thermal Test @ 700 V/60 A

- **Water inlet flow 8 l/min**
- **After 90 min water flow change: 8 l/min ⇒ 15 l/min**
  - Secondary winding temperature (thermocouple)
    - 83°C @ 8 l/min
    - 78°C @ 15 l/min

**Comparison at inlet flow ⇒ 8 l/min**

<table>
<thead>
<tr>
<th></th>
<th>3D FEM</th>
<th>Analytical</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{C1}$</td>
<td>70°C</td>
<td>72°C</td>
<td></td>
</tr>
<tr>
<td>$T_{C2}$</td>
<td>40°C</td>
<td>42°C</td>
<td>63°C</td>
</tr>
<tr>
<td>$T_{C3}$</td>
<td>29°C</td>
<td>28°C</td>
<td>27°C</td>
</tr>
<tr>
<td>$T_{A1N}$</td>
<td>71°C</td>
<td>68°C</td>
<td></td>
</tr>
<tr>
<td>$T_{WP}$</td>
<td>78°C</td>
<td>83°C</td>
<td></td>
</tr>
<tr>
<td>$T_{Pot}$</td>
<td>77°C</td>
<td>80°C</td>
<td></td>
</tr>
<tr>
<td>$T_{Ws}$</td>
<td>81°C</td>
<td>88°C</td>
<td>83°C</td>
</tr>
</tbody>
</table>
Leakage Inductance Measurement Results

- Pulse test @ $V_{DC} = 400$ V
- Current ramps up to 65 A
- Inductance value: $L = \frac{V_{DC}}{di/dt}$

<table>
<thead>
<tr>
<th></th>
<th>Analytical</th>
<th>3D FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage inductance</td>
<td>26.5 µH</td>
<td>26.2 µH</td>
</tr>
</tbody>
</table>

![Graph showing leakage inductance measurement results with current vs. leakage inductance and analytical vs. 3D FEM values.](image-url)
Dielectric Withstand Test

- **Partial discharge measurement**
  - Omicron MPD600 measurement device
  - HV transformer by Agea-Kull AG
  - Voltage between primary & secondary
  - Core/aluminium/primary grounded
  - 50 Hz AC measurement
  - Measurement duration for \( \approx 1 \) h
- **Partial discharge level**: <18 pC
- **DC voltage test**
  - 4.2 kV between primary & secondary
  - Test duration: 2 h

![Diagram of test setup]

- High Voltage Area
- HV transformer
- Test object
- Filter
- GND
- Input
- CPL 542
- Safe Area
- PC
- Fiber optical cables
- Battery
- MPD 600
- MCU 550
Optimisation of Control Parameters – Procedure

- Optimal parameters identified for full operation range
- Optimised converter parameters fixed
- Constraint for phase shift angle

\[-\frac{\pi}{2} < \phi_2 < \frac{\pi}{2}\]

\(|\phi_2| > \frac{\pi}{2} \Rightarrow \text{Reactive energy increases}\)
- Optimal parameters for every operating point
- Constraint for phase shift angle
  \[-\frac{\pi}{2} < \phi_2 < \frac{\pi}{2}\]
  \(|\phi_2| > \frac{\pi}{2} \Rightarrow \text{Reactive energy increases}\)
- 4 (out of 8) optimal modulation schemes result
Optimisation of Control Parameters – Results

- Optimal parameters for every operating point
- Constraint for phase shift angle
  \[-\frac{\pi}{2} < \phi_2 < \frac{\pi}{2}\]
  
  \(|\phi_2| > \frac{\pi}{2} \Rightarrow \text{Reactive energy increases}\)
- 4 (out of 8) modulation schemes are used
- Results are stored in 2D LUT

- General PWM generator
  \(\Rightarrow\) Voltage second balancing

\[
\begin{align*}
\text{ PWM modulator} & \\
\text{clk} & \Rightarrow N_{\text{PWM}} & \text{Time calculations} & \Rightarrow \text{clk} & \delta_p & \phi & \delta_s & \text{reset} \\\n\text{Comparator value calculation for primary side} & \Rightarrow \text{clk} & \text{FSM 12} & S_1 & S_2 & S_3 & S_4 & \text{reset} \\\n\text{Comparator value calculation for secondary side} & \Rightarrow \text{clk} & \text{FSM 34} & \text{reset} & S_5 & S_6 & S_7 & S_8 & \text{reset} \\\n\end{align*}
\]

![Diagram](image)

- Buck operation
- Unity mode
- Boost operation

- Voltage Gain
- Current/Power limit
- Power [kW]
Control of a Single Module
PWM modulator – Simulation Results for Flux Balancing

Without voltage second balancing

With voltage second balancing
DAB Measurement Results for Start-Up

- **Single Active Bridge mode during start-up**
  - DC link is charged ("black-start")
  - DC link side switches are blocked
- **Dual active bridge mode in open loop**
DAB Measurement Results for Closed Loop

- Current control mode
- Voltages controlled by external power supplies
- Full power reversal @ 700 V/60 A
Literature: DAB Converter Design


4) V. V. Kantor, *Methods of calculating leakage inductance of transformer windings*, Elektrotechnika, 2009


9) K. Venkatachalam, Ch. R. Sullivan, T. Abdallah, and H. Tacca, *Accurate prediction of ferrite core loss with non sinusoidal waveforms using only Steinmetz parameters*, in Proc. of IEEE Workshop on Computers in Power Electronics, pp. 36-41, 2002
Solid State Modulators

2.88 MW / 3.5 ms Modulator for European Spallation Source (ESS)
ESS Modulator Specifications

- **LINAC**
  - Ion/metal collision
  - Application

- **Klystron**
  - Modulator
  - \( \approx 50 \) modulators

- **Pulse power**  
  - 2.88 MW

- **Pulse voltage**  
  - 115 kV

- Acceleration of ions
- Neutron beam
- E.g. materials research
  (Soft condensed matter...)

- RF power for SC cavities
- Power for klystron

---

**Electrical Network**

- RF powering cell #1
- Electrical pulsed power
- Klystron modulator (Power Supply)
- Klystron A
- RF power
- SC cavity #A
- Klystron B
- RF power
- SC cavity #B
- RF powering cell #N

---

**Similar to RF powering cell #1**
ESS Modulator – Basic Configuration

- Pulse power: 2.88 MW
- Pulse voltage: 115 kV
- Pulse width: 3.5 ms
- Repetition rate: 14 Hz
- Average power: 141 kW
- Efficiency: ≥ 90%
- Rise/fall time: ≤ 150 µs
- Arc energy: ≤ 10 J

Diagram:
- AC to DC converters
- Parallel connection
- Series connection
- Energy Storage
- 400 V 3-phase 50 Hz
- Rise/fall time ≤ 150 µs
- Arc energy ≤ 10 J
Basic System Configuration

- **Pulse power**: 2.88 MW
- **Pulse voltage**: 115 kV
- **Pulse width**: 3.5 ms
- **Repetition rate**: 14 Hz
- **Average power**: 141 kW
- **Efficiency**: ≥ 90 %
- **Rise/fall time**: ≤ 150 µs

- **High switching frequency**
- **Rel. small transformer**
- **Modules**
  - ▶ 2 parallel
  - ▶ 9 in series

![Diagram of the basic system configuration](image-url)
Modulator System Optimisation

- **Pulse power**: 2.88 MW
- **Efficiency**: ≥ 90%
- **Pulse voltage**: 115 kV
- **Pulse width**: 3.5 ms
- **Repetition rate**: 14 Hz
- **Average power**: 141 kW
- **Rise/fall time**: ≤ 150 µs

---

**Pulse specifications**: \( V_{\text{sec}}, I_{\text{prim}}, N, f, \ldots + T_{\text{max}}, E_{\text{max}}, B_{\text{max}}, \Delta T_{J,\text{max}} \)

**Electrical SPRC Bm model**

**Transformer optimization** (Geometric parameters, # of turns,...)

**Core geometry**

**Winding arrangement**

**Core losses**

**Winding losses**

**Analytical calculation of parasitics** \( L_s, C_s \)

**Analytical maximum electrical field evaluation**

**Thermal model**

**Optimal transformer design**

**Post isolation field conform design check**

**2D FEM evaluation of detailed geometry including all permittivities**

**Obtain most critical oil and creepage paths**

**Calculate safety factor ‘q’**

\( q > 1 \)

**Checked optimal single SPRC Bm design**

**Global specifications fulfilled**

**Yes**

**No**

**Variation of the number of SPRC Bms**

**Optimal design & Optimal number of modules**

---

**High Power Electronic Systems (HPE)**

- **Pulse power**: 2.88 MW
- **Efficiency**: ≥ 90%
- **Pulse voltage**: 115 kV
- **Pulse width**: 3.5 ms
- **Repetition rate**: 14 Hz
- **Average power**: 141 kW
- **Rise/fall time**: ≤ 150 µs
Isolation Design

Based on Critical Field Path

Literature
1. M. Jaritz, S. Blume, and J. Biela, *Design procedure of a 14.4kV, 100kHz transformer with a high isolation voltage (115kV)*, IEEE Transactions on Dielectrics and Electrical Insulation
**Optimisation Procedure: Isolation Design**

- Chose winding/core configuration (Step 0)
- Optimisation procedure for system design
- Subroutine: Transformer optimisation

**Isolation design step 1:**
- E-field calculation with mirroring method
- E-field only for critical points
  → Fast evaluation possible
- Limitation of max. allowed E-field
  → $E_{\text{max}} < 11.5 \text{ kV/m}$

**Isolation design step 2:**
- Detailed isolation check
  → Post optimisation based on critical field path
Winding Configuration (Step 0 – Pre-Optimisation)

- **Secondary winding**: 2 layers
- **5 options for winding arrangement**: a)–e)
  - a) Standard
  - b) Flyback
  - c) s-Winding \( \Delta x > 0 \)
  - d) s-Winding \( \Delta x = 0 \)
  - e) s-Winding + Field control ting

- **Field shape ring**
  - 43% reduction of \( E_{\text{max}} \)
  - Limited increase of HF-losses

\[
E_{\text{max}} \text{ evaluation results}
\]

<table>
<thead>
<tr>
<th>Config.</th>
<th>( \Delta x ) (mm)</th>
<th>( E_{\text{max}} ) (kV/mm)</th>
<th>( W'_{E} ) (mJ/m)</th>
<th>( V_{WS} ) (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>6.1</td>
<td>16.5</td>
<td>435.2</td>
<td>( V_{\text{sec}} )</td>
</tr>
<tr>
<td>(b)</td>
<td>6.1</td>
<td>15.8</td>
<td>433.7</td>
<td>( V_{\text{sec}}/2 )</td>
</tr>
<tr>
<td>(c)</td>
<td>2.1</td>
<td>16</td>
<td>401.3</td>
<td>( 4V_{\text{sec}}/N_i )</td>
</tr>
<tr>
<td>(d)</td>
<td>0</td>
<td>16.1</td>
<td>385.9</td>
<td>( 4V_{\text{sec}}/N_i )</td>
</tr>
<tr>
<td>(e)</td>
<td>0</td>
<td>11.2</td>
<td>461.6</td>
<td>( 4V_{\text{sec}}/N_i )</td>
</tr>
</tbody>
</table>
Winding Configuration – 2 Layer Secondary (Step 0 – Pre-Optimisation)
Transformer Design: $E_{\text{max}}$ Evaluation (Step I)

- Peak E-field calculation by mirroring
- Single permittivity considered $\varepsilon_r = 3.2$
- Performed for selected points

- Field control ring (highest potential)
  \[ E_{\text{max}} < 11.5 \text{ kV/m} \]
- Midel 7131 isolation oil ($\varepsilon_r = 3.2$)

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity</th>
<th>Electrical strength (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>POM [20]</td>
<td>3.5</td>
<td>50</td>
</tr>
<tr>
<td>PC [21]</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>PA2200 [22]</td>
<td>3.8</td>
<td>92</td>
</tr>
<tr>
<td>EPR S1 [23]</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity</th>
<th>Breakdown voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIDE7131 [18]</td>
<td>3.2</td>
<td>75</td>
</tr>
</tbody>
</table>

![Diagram showing field distribution and core with $E_{\text{max}} = 11.24 \text{ kV}$]
Peak E-field calculation (Step I)

- Peak E-field calculation by mirroring
- Core surface $\sigma \to \infty$
- "Homogeneous" permittivity
- Turn $\Rightarrow$ Line charges @ defined potential
  (16 charges @ $d = 0.04r$)
- E-field by superposition
- Only points with high potential evaluated
Limit Curves for Ester and Mineral Oil (Step II – Post-optimisation)

- Scaling of available breakdown data
  - AC, LI, and SI breakdown data (Fitted by Weibull distribution)
  - Pulse shape Scaling of breakdown data (between LI and SI data)
  - Volume effect ($n$-times larger)
    \[ P_n(V) = 1 - \exp \left[ -n \cdot \left( \frac{V}{\alpha} \right)^\beta \right] \]
  - Withstand probability ⇒ "Withstand voltage"

Example based on LI and SI impulse data
Critical field path analysis (Step II – Post-optimisation)

- 2D FEM simulation → $E$-field (in different planes)
- Identify most critical field path
- Inhomogeneous fields are critical
- Calculate $E_m(z) = \frac{1}{z} \int_{x_1}^{z} E(z') dz'$

Example based on LI and SI impulse data
Example: Field Conform Design of Transformer

- **Comparison:** Oil limits ⇔ Critical averaged field $E_m$
- **Averaged field:** $E_m(z) = \frac{1}{z} \int_{x_1}^{x} E(z')dz'$
- **Avoid horizontal voltage stress on insulation surfaces**

<table>
<thead>
<tr>
<th>$E_{krit}$ (kV/mm)</th>
<th>Oil gap z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>30</td>
</tr>
<tr>
<td>12</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

Design curve MIDEL 7131
Transformer Prototype

- **Winding**  \[ N_p = 2 / N_s = 40 \]
- **Litz wire** \( N_p \) 18 x 405 x 0.071
- **Litz wire** \( N_s \) 1125 x 0.071 (in 2 layer)
- **Losses** 97.4 W
- **Volume** 13.2 l
Partial Discharge Measurement of Pulse Transformer I

- Omicron MPD600 PD measurement system
- IEC 60270:2000 ⇒ $Q_{IEC}$
- Pulse transformer tested @ $82 \text{kV}_{\text{RMS}}$ @ 50 Hz
- Long term test (60 min)
Partial Discharge Measurement of Pulse Transformer II

- Omicron MPD600 PD measurement system
- IEC 60270:2000 $\Rightarrow Q_{IEC}$
- Stepwise increase of test voltage by $\approx 9\%$ starting at $82\,kV_{RMS}$ @ 50 Hz
- Short term tests ($\geq 5\,\text{min} @ \text{each voltage}$)
Modulator System Optimisation

- Pulse power: 2.88 MW
- Efficiency: ≥ 90%
- Pulse voltage: 115 kV
- Pulse width: 3.5 ms
- Repetition rate: 14 Hz
- Average power: 141 kW
- Rise/fall time: ≤ 150 µs

---

**Pulse specifications (Vsec, Iprim, N, f, ...) & Constraints (Tmax, Emax, Bmax, ΔTJ, ...)**

**Electrical SPRC Bm model**

**Transformer optimization (Geometric parameters, # of turns, ...)**

**Winding arrangement**

**Core geometry**

**Core losses**

**Winding losses**

**Analytical calculation of parasitics Lσ, Cσ**

**Analytical maximum electrical field evaluation**

**Thermal model**

**T < Tmax**

**E < Emax**

**ΔTJ < ΔTJ(max)**

**Optimal transformer design**

**Optimal # of semiconductors**

**Post isolation field conform design check**

**2D FEM evaluation of detailed geometry including all permittivities**

**Obtain most critical oil and creepage paths**

**Calculate safety factor ‘q’**

**q > 1**

**Yes**

**No**

**Checked optimal single SPRC Bm design**

**Global specifications fulfilled**

**Yes**

**No**

**Variation of the number of SPRC Bms**

---

**High Power Electronic Systems**

---

**ETH Zürich**

---

**High Power Electronic Systems HPE**

---

**90 | 127**
Thermal Model of Magnetic Components

Thermal Model of Winding
- Solid & Litz Wire -

Literature
Heat Flow in Winding

- Tangential heat flow $\dot{Q}_{\text{tan}}$ along wire
- Radial heat flow $\dot{Q}_{\text{rad}}$ from layer to layer
- Thermal resistance based on conduction
- Tangential:
  - Heat conduction through wire
    
    $R_{\text{th,tan}} = \frac{1}{N_{pL}} \sum_{i=1}^{N_{pL}} \frac{l_w \cdot (2i-1)}{\lambda_{Cu} A_{Cu}}$
    
    $= \frac{l_w \cdot N_{pL}}{\lambda_{Cu} A_{Cu}}$

    with
    - $N_{pL}$ Turns per layer
    - $A_{Cu}$ Wire cross sectional area
    - $l_w$ Mean turn length
    - $\lambda_{Cu}$ Thermal conductivity of copper
Electro-Thermal Analogy

- Heat flow modelling by
  - Electrical flow field $\Rightarrow$ Electrical equivalent circuit ("Standard")
  - Electrostatic field
    $\Rightarrow$ Electrical field lines $\Rightarrow$ Heat flux lines

### Electrostatic field

- Charge $Q$
- Capacitance $C$
- Voltage $V$
- Permittivity $\varepsilon$
- Electrical flux density $\varepsilon E$

### Electrical flow field

- Current $I$
- Conductance $G$
- Specific conductivity $\sigma$
- Current density $J$

### Thermal flow field

- Heat transfer rate $\dot{Q}$
- Thermal Conductance $G_{sh}$
- Temp. Difference $\Delta T$
- Thermal conductivity $\lambda$
- Heat flux / Heat flow density $q$

\[
Q = C \cdot V \\
I = G \cdot V \\
\dot{Q} = G_{sh} \cdot \Delta T
\]
Thermal Model for Orthogonal & Orthocyclic Windings

- Orthogonal layers

- Orthocyclic layers
Basic Structure I: Orthogonal Layers

- 2 layers separated by isolation layer $h$ with permittivity $\varepsilon_{\text{Lay}}$
- Wire isolation thickness $\delta$ with permittivity $\varepsilon_{\text{Iso}}$
- Capacitance $C_{\text{orth}}$ for basic cell
  1) Approximation of electrical field lines
  2) Energy $W$ in different sections
  3) Equivalent capacitance $C_{\text{orth}}$
  4) Equivalent thermal resistance $R_{\text{th,rad,orth}}$

\[ E \]

\[ W_{\text{all}} = W_{\text{Lay}} + W_{\text{Iso}} + W_{\text{Air}} \]

\[ C_{\text{orth}} \]

\[ \varepsilon_0 \]

\[ \varepsilon_{\text{Lay}} \]

\[ \varepsilon_{\text{Iso}} \]

\[ R_{\text{th,rad,orth}} = \left[ \frac{2\lambda_{\text{air}}}{\alpha} \left( Y + \frac{\lambda_{\text{air}}}{8\lambda_{\text{iso}}} \left( \frac{2\delta}{r_0} \right) Z \right) \right]^{-1} \]
Basic Structure II: Orthocyclic Layers

- 2\textsuperscript{nd} layer in “gap” of 1\textsuperscript{st} layer ⇒ Orthocyclic structure
- Wire isolation thickness $\delta$ with permittivity $\varepsilon_{\text{Iso}}$
- Capacitance $C_{\text{cyc}}$ for basic cell
  
  1) Electrical field lines
  2) Energy $W$ in different sections
  3) Equivalent capacitance $C_{\text{cyc}}$
  4) Equivalent thermal resistance $R_{\text{th, rad, cyc}}$

\[
W_{\text{all}} = W_{\text{Lay}} + W_{\text{Iso}} + W_{\text{Air}}
\]

\[
R_{\text{th, rad, cyc}} = \left[ \frac{\lambda_{\text{Air}} l_w}{M_{\text{Air}} + M_{\text{Iso}}} \frac{\delta \lambda_{\text{Air}}}{\lambda_{\text{Iso}} r_0^2} \left( r_0 - \frac{\delta}{2} \right) \right]^{-1}
\]
Thermal Resistance of Ideal Winding Configuration

- Ideal winding configuration
  - Only orthogonal or
  - Orthocyclic layers

- Radial and tangential heat flow in parallel

\[ R_{th,Nx} = \left( R_{th,tan} \parallel R_{th,rad} \right) \frac{N_L}{N_{pL}} \]

with

- \( N_L \) Number of layers
- \( N_{pL} \) Number of turns per layer
Thermal Resistance of Typical Real Winding Configuration

- Real winding configuration
  - Only orthogonal and
  - Orthocyclic layers
- Radial and tangential heat flow in parallel

\[ R_{th,Nx} = \left( R_{th,tan} \parallel R_{th,cyc} \right) \frac{N_L - N_{orth}}{N_{pL}} + \left( R_{th,tan} \parallel R_{th,orth} \right) \frac{N_{orth}}{N_{pL}} \]

with
- \( N_L \) Number of layers
- \( N_{orth} \) Number of orthogonal layer
- \( N_{pL} \) Number of turns per layer
Thermal Resistance of Litz Wire

- Basic cell of litz wire (A1) ⇒ Transformed to square litz wire bundle (A2)
  - $N_S$ strands/ $r_{0,L}$ strand radius
  - Side length $\sqrt{N_S} \times 2r_{0,L}$
- Orthocyclic $R_{th,L,cyc}$ between single strands
- Orthogonal $R_{th,L,orth}$ for strands at "boundary"
- Thermal resistance of litz wire basic cell (A1)

\[
R_{th,Litz} = R_{th,L,cyc} \left( \frac{\sqrt{N_S} - 1}{\sqrt{N_S}} \right) + 2 \cdot \frac{1}{2} R_{th,L,orth} \frac{1}{\sqrt{N_S}}
\]
Thermal Resistance of Litz Wire

- Thermal resistance of litz wire basic cell

\[ R_{th,Litz} = R_{th,L,cyc} \left( 1 - \frac{1}{\sqrt{N_S}} \right) + \frac{R_{th,Lorth}}{\sqrt{N_S}} \]

- Thermal resistance of complete litz wire winding

\[ R_{th,Nx} = \left( R_{th,tan||(R_{th,cyc} + R_{th,litz})} \right) \frac{N_L - N_{orth}}{N_{pL}} \]

\[ + \left( R_{th,tan||(R_{th,orth} + R_{th,litz})} \right) \frac{N_{orth}}{N_{pL}} \]
Validation of Thermal Winding Model – Measurement Setup

- Temperature measurement on setups with
  - Solid wire: $D = 3\text{mm}$ in air and epoxy potting
  - Litz wire in air: $1260 \times 0.1\text{mm} / 420 \times 0.071\text{mm}$
- Heat source: Resistor $\Rightarrow$ Known heat flow/losses
- Enforced 1D heat flow
Validation of Thermal Model – Measurement Results

- Temperature measurement on setups with
  - Solid wire: \( D = 3\text{mm} \) in air and epoxy potting
  - Litz wire in air: 1260 x 0.1mm / 420 x 0.071mm
- Thermal resistance depends on mechanical tension on wire

<table>
<thead>
<tr>
<th>Type</th>
<th>Measured ( R_{th,Nxm}[^{\circ}\text{C/W}] )</th>
<th>Calculated ( R_{th,Nx}[^{\circ}\text{C/W}] )</th>
<th>Error (%)</th>
<th>( N_{orth} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Wire</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D = 3\text{mm} )</td>
<td>2.06</td>
<td>1.6343</td>
<td>-20.7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.1124</td>
<td>+2.5</td>
<td>6</td>
</tr>
<tr>
<td>( D = 3\text{mm} ) (Epoxid resin)</td>
<td>0.46</td>
<td>0.3481</td>
<td>-24.8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.53</td>
<td>+15</td>
<td>6</td>
</tr>
<tr>
<td>Litz Wire</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1260 x 0.1mm</td>
<td>2.51</td>
<td>3.8</td>
<td>+51.4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.7 (incl. twist pitch length)</td>
<td>+47.4</td>
<td>1</td>
</tr>
<tr>
<td>420 x 0.071mm</td>
<td>2.10</td>
<td>2.91</td>
<td>+38.6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.88 (incl. twist pitch length)</td>
<td>+37.1</td>
<td>1</td>
</tr>
</tbody>
</table>
Modulator System Optimisation

- **Pulse power**: 2.88 MW
- **Efficiency**: ≥ 90%
- **Pulse voltage**: 115 kV
- **Pulse width**: 3.5 ms
- **Repetition rate**: 14 Hz
- **Average power**: 141 kW
- **Rise/fall time**: ≤ 150 µs

---

**Electrical SPRC Bm model**

- Pulse specifications \( V_{sec}, I_{prim}, P_{sec}, \ldots \) & Constraints \( T_{max}, E_{max}, B_{max}, \Delta T_{J,max} \)

**Transformer optimization (Geometric parameters, # of turns,...)**

**Core geometry**

- Core losses
- Winding arrangement
- Analytical calculation of parasitics \( L_p, C_p \)

**Core losses**

- Analytical maximum electrical field evaluation

**Winding arrangement**

- \( E_{design} \)
- \( \Delta T_J < \Delta T_{J,max} \)

**Thermal model**

- \( T < T_{max} \)
- \( E < E_{max} \)

**Optimal transformer design**

- \( \Delta T_J < \Delta T_{J,max} \)
- \( E < E_{max} \)

**Post isolation field conform design check**

- 2D FEM evaluation of detailed geometry including all permittivities
- Obtain most critical oil and creepage paths
- Calculate safety factor ‘\( q \)’

**Optimal # of semiconductors**

- \( q > 1 \)
- \( \Delta T_J < \Delta T_{J,max} \)

**Optimal design & Optimal number of modules**

- Global specifications fulfilled
- Variation of the number of SPRC Bms
Thermal Model of HF Transformer

- **Test cast:** HF/HV transformer
- **Winding** \( N_p = 2 / N_s = 40 \)
- **Litz wire** \( N_p \) \( 18 \times 405 \times 0.071 \)
- **Litz wire** \( N_s \) \( 1125 \times 0.071 \)
- **Frequency** 105 kHz
### Calculated thermal resistors

#### Heat transfer: Conduction

<table>
<thead>
<tr>
<th></th>
<th>$R$ (K/W)</th>
<th>$\lambda$ (W/Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{cl}$</td>
<td>5.64</td>
<td>$\lambda_{core}$</td>
</tr>
<tr>
<td>$R_{wp}$</td>
<td>1</td>
<td>$\lambda_{iso,liw,2}$, $\lambda_{iso,str}$, $\lambda_{air}$</td>
</tr>
<tr>
<td>$R_{ws}$</td>
<td>1.8</td>
<td>$\lambda_{iso,liw,2}$, $\lambda_{iso,str}$, $\lambda_{air}$</td>
</tr>
<tr>
<td>$R_{bwp}$</td>
<td>2</td>
<td>$\lambda_{bwp}$</td>
</tr>
<tr>
<td>$R_{bws}$</td>
<td>1.18</td>
<td>$\lambda_{bws}$</td>
</tr>
</tbody>
</table>

#### Heat transfer: Convection

<table>
<thead>
<tr>
<th></th>
<th>$R$ (K/W)</th>
<th>$\lambda$ (W/Km)</th>
<th>Equ. for $Nu$ [32]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{htop,c}$</td>
<td>30.26</td>
<td>$\lambda_{air}$  [32]</td>
<td>F2 (7), (8)</td>
</tr>
<tr>
<td>$R_{bot,c}$</td>
<td>39.82</td>
<td></td>
<td>F2 (10)</td>
</tr>
<tr>
<td>$R_{v,c}$</td>
<td>8.77</td>
<td></td>
<td>F2 (1)</td>
</tr>
<tr>
<td>$R_{htop,ws}$</td>
<td>51.48</td>
<td></td>
<td>F2 (7), (8)</td>
</tr>
<tr>
<td>$R_{bot,ws}$</td>
<td>67.74</td>
<td></td>
<td>F2 (10)</td>
</tr>
<tr>
<td>$R_{v,ws}$</td>
<td>26.68</td>
<td></td>
<td>F2 (1)</td>
</tr>
<tr>
<td>$R_{hgap,wp-bws}$</td>
<td>65.22</td>
<td></td>
<td>F3 (4), (5)</td>
</tr>
<tr>
<td>$R_{hgap,ws-bws}$</td>
<td>12.6</td>
<td></td>
<td>F3 (4), (5)</td>
</tr>
<tr>
<td>$R_{vgap,ws-bws}$</td>
<td>29.86</td>
<td></td>
<td>F3 (8)</td>
</tr>
<tr>
<td>$R_{hgap,ci-bwp}$</td>
<td>14.08</td>
<td></td>
<td>F3 (4), (5)</td>
</tr>
<tr>
<td>$R_{vgap,ci-bwp}$</td>
<td>64.92</td>
<td></td>
<td>F3 (8)</td>
</tr>
<tr>
<td>$R_{wp-amb}$</td>
<td>24.3</td>
<td></td>
<td>F4 (7), (8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$R$ (K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{ws-amb}$</td>
<td>13.95</td>
</tr>
<tr>
<td>$R_{c-amb}$</td>
<td>5.81</td>
</tr>
<tr>
<td>$R_{cl-wp}$</td>
<td>13.57</td>
</tr>
<tr>
<td>$R_{wp-ws}$</td>
<td>75.26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$T_{amb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26 °C</td>
</tr>
</tbody>
</table>
Series-Parallel Resonant Converter Module

- **Switching frequency > Resonance frequency**
  - Soft switching for all MOSFETs (ZVS)
  - High efficiency
  - $f$-control for droop compensation
- **Inherent limitation of short circuit current**
- **Switching freq.** 105 kHz
- **Input voltage** 400 V
- **Output voltage** 12.8 kV
- **Output power** pulsed 160 kW
- **Output power** avg. 7.8 kW

![Diagram of Series-Parallel Resonant Converter Module](image-url)
Integration of Resonant Inductance

- **Resonant inductance** \( 5.1 \, \mu H - L_{\sigma,Trafo} = 0.9 \, \mu H \)
  - Fully integrated in the transformers leakage (a)
  - Leakage plus stray cores (b)
  - Leakage plus air coil (c)

- **Comparison**

<table>
<thead>
<tr>
<th></th>
<th>Losses</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-core (a)</td>
<td>82 W</td>
<td>48 l</td>
</tr>
<tr>
<td>E-core (a)</td>
<td>66 W</td>
<td>46 l</td>
</tr>
<tr>
<td>Stray core (b)</td>
<td>362 W</td>
<td>25 l</td>
</tr>
<tr>
<td>Air coil (c)</td>
<td>97 W</td>
<td>12.8 l</td>
</tr>
</tbody>
</table>
ESS Modulator – Series-Parallel Resonant Converter Module

- **H-bridge**
- **Input voltage**
- **Output voltage**
- **Output power** pulsed
- **Switching freq.**
- **Resonant induct.**

\[ L_{\sigma, Trafo} = 0.9 \mu H \]

- 650 V MOSFETs (STY139N65M5)
- 400 V
- 12.8 kV
- 160 kW
- 105 kHz
- 5.1 \mu H

H-bridge: 6 x 650V MOSFETs in parallel

Diodes

\[ L_S, C_S, C_P \]

Resonant induct. 5.1 \mu H

Input voltage

Output voltage
Validation of Thermal Design – HF Transformer I

- **Test Parameters**

<table>
<thead>
<tr>
<th>Electrical Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{prim}}$</td>
<td>152V</td>
</tr>
<tr>
<td>$I_{\text{prim}}$</td>
<td>450A</td>
</tr>
<tr>
<td>$n$</td>
<td>20</td>
</tr>
<tr>
<td>$f$</td>
<td>105.8kHz</td>
</tr>
<tr>
<td>$P_{\text{rr}}$</td>
<td>14Hz</td>
</tr>
<tr>
<td>$T_p$</td>
<td>3.5ms</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High Frequency Losses</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{wp}}$</td>
<td>1.08W</td>
</tr>
<tr>
<td>$P_{\text{ws}}$</td>
<td>0.92W</td>
</tr>
<tr>
<td>$P_{\text{cc}}$</td>
<td>0.34W</td>
</tr>
<tr>
<td>$P_{\text{cr}}$</td>
<td>0.79W</td>
</tr>
</tbody>
</table>

- **Test results (thermal camera)**

<table>
<thead>
<tr>
<th>Measured Temperature</th>
<th>Calculated Temperature</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{1,bf}$</td>
<td>34.18°C</td>
<td>$T_{1,\text{calc}}$</td>
</tr>
<tr>
<td>$T_{2,bf}$</td>
<td>40.52°C</td>
<td>$T_{2,\text{calc}}$</td>
</tr>
<tr>
<td>$T_{3,bf}$</td>
<td>35°C</td>
<td>$T_{3,\text{calc}}$</td>
</tr>
</tbody>
</table>
Test results (thermal camera)

<table>
<thead>
<tr>
<th>Measured Temperature</th>
<th>Calculated Temperature</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{1,bf}$ 34.18°C</td>
<td>$T_{1,calc}$ 34.61°C</td>
<td>1.3%</td>
</tr>
<tr>
<td>$T_{2,bf}$ 40.52°C</td>
<td>$T_{2,calc}$ 42.97°C</td>
<td>6%</td>
</tr>
<tr>
<td>$T_{3,bf}$ 35°C</td>
<td>$T_{3,calc}$ 39.38°C</td>
<td>+12.5%</td>
</tr>
</tbody>
</table>

![Diagram of thermal camera test results](image)
ESS Modulator – Converter with SiC

- **Improved efficiency**
  - 1.2 kV SiC MOSFETs: No balancing / Lower conduction losses
  - 1.7 kV SiC Diode: Lower losses in rectifier
  - $L_s \Rightarrow 2 \times L_s @ \frac{1}{2} I$: 2 $\times$ volume / $\frac{1}{2}$ losses
  - New core material: N97 instead of N87
  - New efficiency: $\approx 94.4\%$ (+1.5% / Old: 92.9%)
ESS Modulator – Built in Cooperation with Ampegon

H-bridge
6 Mosfets in Parallel for each Leg

Air toroid $L_S$

896 NP0 Capacitors $C_S$

Series Parallel Resonant Converter Basic Module (SPRC-BM)

Diodes
624 NP0 Capacitors $C_F$

15kV-100kHz-Transformer (115kV Insulation Design)

Output-Rectifier

DC-link supply

Control unit

Oil tank

Single SPRC BM

Oil tank

Transformers

Rectifiers

Transformer feedthrough
ESS Modulator – Measurement Results

- Full power operation
- Klystron load
- $2 \times 9$ modules
- Ripple within specifications

Rise Time $= 107.8\,\mu s$

Fall Time $= 83.5\,\mu s$
Conclusion

– Wrapping up –
System Optimisation
- Multi-physics model ➔ Best Design
- Power density limit by magnetic devices

Leakage inductance
- $L_\sigma$ – 2 step calculation
- 2D
  - Rogowski: Very fast
  - Roth: Very accurate
- 1D – Mean turn length (needs to be improved)

Isolation design
- Evaluation of E-field by mirroring method
- Critical field path < Limiting curve

Thermal model
- Analogy: Electrostatic field ↔ Thermal flow field
- Winding arrangement
  - Orthogonal
  - Orthocyclic
- Capacitance ➔ Thermal resistance
  - Round wire
  - Litz wire
Back Matter

– Additional Slides –
Dyna-Source
A Flexible, Highly Dynamic, Low Ripple Arbitrary Current Source
Applications & Requirements

Power-HiL Simulations

Switchgear characterization

Requirements
- High Peak Power
- High continuous current
- High Dynamic
- Ultra-low Ripple
- Arbitrary waveform

High power current source

Power Supply for Accelerators

Current waveform

Accelerator
Specifications & Topology

- **System specifications** (20 Stacks)
  - Output voltage: $\pm 10 \text{kV}$
  - Peak current: 30 kA
  - Continuous current: 20 kA
  - Current gradient: $>200 \text{ A} / \mu \text{s}$
  - Current ripple: $<0.1 \%$

- **Single stack prototype**
  - Output voltage: $\pm 10 \text{kV}$
  - Peak current: 1.5 kA
  - Continuous current: 1.0 kA
  - Current gradient: $>10 \text{ A} / \mu \text{s}$
  - Current ripple: $<0.1 \%$

---

**Modular Multilevel Marx Type Converter (M3TC)**

- Output voltage: $-10 \text{kV}..10 \text{kV}$
- SiC MOSFET: 0.55 kV
- IGBT: 1.2 kV, 1.7 kV
- VC: $0..550 \text{V}$
- $V_{\text{out}}$
- $L_{\text{ind}}$
- $R_{\text{ind}}$
- $V_{M3TC}$
- $V_{2,M3TC}$
- $V_{1,M3TC}$
- $V_{\text{cut}}$

**Unidirectional Unipolar 1.2kV (5kW)**

- Grid: 400V
- Single Stack

**6x Interleaved Current Shaping Converter**

- $V_{C} = 0..550 \text{V}$
System Concept – "Voltage Adding"

- **Current shaping converter**
  - 6-phase interleaved buck converter
  - High bandwidth/ Low ripple

- **Step voltage generator**
  - Modular Multilevel Marx-Type Converter (M3TC)
Design Procedure

- **Design challenges**
  - High dynamic & low ripple
  - Wide operation range (0 .. 550 V)
  - Robustness against sudden disturbances (arc)
  - Wide range of loads

- **Design parameters**
  - Number of modules \( n \)
  - Switching frequency \( f_s \)
  - Module inductance \( L_i \)
  - Output Capacitance \( C_{out} \)

---

Starting values:
- Switching frequency: \( f_s \)
- Number of interleaved modules: \( n \)

Iterate module inductance: \( L_i \)

- Steady state models
- Transient models

Calculate maximum module current ripple:

\[
\Delta i_{pp,\text{mod}}(L_i)
\]

Determine:
- Worst case output voltage: \( V_c \)

Calculate maximum converter output ripple:

\[
\Delta i_{pp,\text{cont}}(L_i)
\]

Calculate minimum converter gradient:

\[
di_{\text{cont}}/dt(L_i)
\]

Iterate output capacitance: \( C_{out} \)

- Steady state models
- Transient models

Determine:
- Load ripple frequency \( o_n \)
- Worst case load

Calculate maximum load current ripple:

\[
\Delta i_{pp,\text{load}}(L_i, C_{out}, R_{ss})
\]

Calculate minimum load gradient:

\[
di_{\text{load}}/dt(L_i, C_{out}, R_{damp})
\]

Check the overshoot of \( i_{\text{load}} \)

Store feasible solutions

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![Graph showing output capacitance vs. module inductance](image)

**6 phases - 60 kHz**

- Current ripple 100ppm constraint
- \( L_i,\text{min} \) robustness constraint
- Reduced ripple
- Increased robustness
- Current gradient 10A/μs constraint
- Increased dynamics
- Feasible design space

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**Design challenges**

- High dynamic & low ripple
- Wide operation range (0 .. 550 V)
- Robustness against sudden disturbances (arc)
- Wide range of loads

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**Design parameters**

- Number of modules \( n \)
- Switching frequency \( f_s \)
- Module inductance \( L_i \)
- Output Capacitance \( C_{out} \)
Advanced Control Concept

- Transients: Adaptive hysteresis controller
  - Near-optimal transient response
  - Inherent disturbance rejection

- Steady state: PI controller + Phase shifting
  - Good steady state performance
  - Constant switching frequency
  - Optimal interleaving
Current shaping converter

- **Single module** (buck converter)
  - Output voltage: 0 V – 550 V
  - Peak current: 250 A
  - Continuous current: 165 A
  - Switching frequency: 60 kHz
  - Rated power (cont.): 90 kW
  - Rated power (pulsed): 140 kW
  - Volume: 8.3 L
  - SiC Module (Semikron) SKM350MB120SCH17
  - Water cooled heat sink
  - Potted inductor cores

![Diagram of current shaping converter](image)

- **Hysteretic PI control**
  - Current [A]: -0.1, 0, 0.1, 0.2, 0.3, 0.4, 0.5
  - Time [ms]: 0, 0.1, 0.2, 0.3, 0.4, 0.5
  - 2.6A/μs

![Graph showing current and time](image)
Inductor Thermal Model

- **Analytical thermal model**
  - Only thermal conduction considered
  - Losses Distributed $P_{\text{Core}}$ & $P_{\text{Wdg}}$
  - Potting $\lambda_{\text{Potting}} = 0.6 \text{ W/(m K)}$
  - Heat sink $R_{\text{th,HS}}$ (FEM)
  - Winding $R_{\text{th,w}}$ (Litz wire thermal model)
  - Wdg.-to-core $R_{\text{th,w-p,i}}$ (based on geometry)
  - Aluminum side walls neglected
  - Litz wire 3 x 735 strands - 0.1 mm - 3.7 mm
    2x 100 µm Kapton
Inductor Thermal Model - FEM Validation

- **Analytical thermal model**
  - Only thermal conduction considered
  - Losses Distributed $P_{Core}$ & $P_{Wdg}$
  - Potting $\lambda_{Potting} = 0.6 \text{ W/(m K)}$
  - Heat sink $R_{th,HS}$ (FEM)
  - Winding $R_{th,w}$ (Litz wire thermal model)
  - Wdg.-to-core $R_{th,w-p,c}$ (based on geometry)
  - Aluminum side walls neglected
  - Symmetry assumed

- **FEM Thermal Model**
  - Complete module simulation
  - Detailed geometry
  - Concentrated winding incl. isolation
  - Validation of thermal model
Heat Sink Model

- $R_{th,HS}$ with FEM simulation
  - Single design – no optimisation
  - Fast convergence (<1min.)
  - High accuracy
  - Only aluminium heat sink
- 10 l/min water flow
- Separate $R_{th}$-values for (based on hot spot)
  - Inductor
  - SiC module

\[ \Delta T_{avg} = 26^\circ C \]
\[ \Delta T_{max} = 34^\circ C \]
\[ R_{th,HS} = 26 \text{ K/kW} \]
\[ R_{th,max} = 34 \text{ K/kW} \]
### Optimised Inductor Design & Verification

- **Core material**: SiFe 3% / 0.1mm
- **Winding**: 3 x Litz (0.1mm - 600 strands)
- **Inductance**: 250 µH
- $B_{\text{max}}$ (pulse mode): 1.6 T
- $P_{\text{core}}$ (cont. mode): 350 W
- $P_{\text{w}}$ (cont. mode): 210 W
- $\Delta T_{\text{max}}$ (measured): 68 °C
- Elevated core losses due to high DC bias

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![Diagram showing components of the inductor system]

- **Potted inductor core**
- **SiC MOSFET driver board**
- **Busbar connection to capacitor bank**
- **Isolated drivers**
- **Winding thermocouples**
- **Current measurement board**

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![Graph showing measured and calculated winding temperatures]

**Measured vs. Calculated Winding Temperature [°C]**

- $P_{\text{core}} = 350$ W
- $P_{\text{core}} = 190$ W
- $P_{\text{core}} = 95$ W
- $P_{\text{core}} = 30$ W

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**Core material**: SiFe 3% / 0.1mm

- Litz winding: 3 x Litz (0.1mm - 600 strands)
- Inductance: 250 µH
- $B_{\text{max}}$ (pulse mode): 1.6 T
- $P_{\text{core}}$ (cont. mode): 350 W
- $P_{\text{w}}$ (cont. mode): 210 W
- $\Delta T_{\text{max}}$ (measured): 68 °C
- Elevated core losses due to high DC bias