MEDIUM FREQ. TRANSFORMER DESIGN OPTIMIZATION FOR SOLID STATE TRANSFORMERS

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EPFL — STI — IEL — PEL

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http://pel.epfl.ch
PEL RESEARCH FOCUS

MVDC Technologies and Systems
- System Stability
- Protection Coordination
- Power Electronic Converters

High Power Electronics
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion

Components
- Semiconductor devices
- Magnetics
- Characterization

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INTRODUCTION and MOTIVATION

Why high power medium frequency transformers are important technology?
LINE FREQUENCY TRANSFORMERS

IEC 60076-1 definition - Power Transformer: A static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.

Line Frequency Transformers

- Around for more than 100 of years
- Operated at low (grid) frequencies: 16.7Hz, 25Hz, 50/60Hz
- Standardized shapes and materials
- Cheap: \( \approx 10\text{kUSD} / \text{MW} \)
- Efficient: above 99% for utility applications
- Simple and reliable device

What are the problems?

- Bulky - for certain applications
- Inefficient - for certain applications
- Uncontrollable power flow
- Fixed transformation (power, voltage, current, frequency)

▲ Source: www.abb.com
Switched Mode Power Supply (SMPS) Technologies

- Medium or High frequency conversion is not a new thing!
- Widely deployed in low voltage/power applications
- High efficiency
- Galvanic isolation at high frequency (standardized core sizes and shapes)
- Compact size (e.g. laptop chargers)
- Increased power density
- Cost savings

Could a Solid State Transformer provide that for a High Power Medium Voltage Applications?

▲ SMPS Technologies; Source: www.mouser.ch/new/tdk/epcos-smps/
What is a Solid State Transformers?

- Not a transformer replacement?
- Should not be compared against 50/60 Hz transformer!

What is it?

- A converter
- A converter with galvanic isolation
- Can be designed for DC and AC (1-ph, 3-ph) grid
- Can be used in LV, MV and HV applications
- Can be made for AC-AC, DC-DC, AC-DC, DC-AC conversion
- Has power electronics on each terminal
- Transformer frequency higher than 50/60 Hz

Excellent tutorials are available at: https://www.pes.ee.ethz.ch

▲ Simplified SST concept
APPLICATIONS

Railway
- 1-phase AC grids [1]
- Few voltage levels: 15kV (16.7Hz) or 25kV (50Hz)
- Low frequency (historically): (15kV) 16.7Hz or (25kV) 50Hz
- On-board installations - serious space constraints
- Volume and Weight reduction - system savings
- Reliability - high number of devices?
- Efficiency - easy to beat traction LFT
- Control - similar to existing solutions
- Cost?

Utility
- 3-phase AC grids
- Many voltage levels: 3.3, 4.16, 6, 11, 15, 20kV, ...
- Grid frequency: 50Hz or 60Hz
- Sub-station installations - relatively low space constraints
- Volume and Weight reduction - not that relevant
- Reliability - even more complex due to 3-phases
- Efficiency - hard to beat distribution LFT
- Control - improved compared to existing solutions
- Cost?

▲ ABB’s PETT (Source: www.abb.com)
▲ GE’s SST [2] (Source: www.ge.com)
APPLICATIONS (CONT.)

MVDC Grids
▶ Increased interest into DC grids
▶ Need for high power DC-DC converters
▶ Galvanic isolation seen as necessary
▶ Bidirectional power flow
▶ High efficiency

Marine LVDC / MVDC Distribution
▶ System level benefits
▶ Improved partial load efficiency
▶ No frequency synchronization of generators
▶ Integration of storage technologies
▶ Protection coordination

MVDC grids (Source: www.english.hhi.co.kr)
MVDC marine distribution (Source: www.abb.com)
RAILWAY ON-BOARD ELECTRICAL SYSTEM

Railway on-board transformers:
- Step-down voltage to low levels
- Already optimized for low weight and volume
- Reduced efficiency as a price to pay
- Form factor depends on the mounting method
- Predominantly oil cooled / insulated
- Air cooled / solid insulation available as well

Few things to consider:
- 50Hz transformer is already fairly small
- 16.7Hz transformer is relatively bulky and inefficient
- Single galvanic isolation - insulation coordination
- Often, new train design defines the available space
- Design customization is common
- Power levels are modest and below 15MW
- Different from the utility transformers

▲ Various realization of traction transformers, Source: www.abb.com
RAILWAY SST

What traction SST offers in perspective:
- Improved efficiency (specially for 15kV, 16.7Hz systems)
- Weight reduction - less raw materials
- Volume reduction - questionable due to insulation coordination
- Control features

Why is traction SST not out yet?
- Conservative traction market
- Lack of business case
- Reliability concerns
- Very hard to compete in 25kV, 50Hz grids
- Not a major performance increase
- Increased cost compared to state-of-the-art solutions

Prototypes
- ALSTOM
- ABB
- BOMBARDIER
- ...

▲ On-board traction system evolution with SST [1]
ABB - 1.2MW PETT

Characteristics
- 1-Phase MVAC to MVDC
- Power: 1.2MVA
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1500V
- 9 cascaded stages \((n + 1)\)
- input-series output-parallel
- double stage conversion

99 Semiconductor Devices
- HV PEBB: 9 x (6 x 6.5kV IGBT)
- LV PEBB: 9 x (2 x 3.3kV IGBT)
- Bypass: 9 x (2 x 6.5kV IGBT)
- Decoupling: 9 x (1 x 3.3kV Diode)

9 MFTs
- Power: 150kW
- Frequency: 1.75kHz
- Core: Nanocrystalline
- Winding: Litz
- Insulation / Cooling: oil

\[\text{ABB PETT scheme [3], [4]}\]
ABB - 1.2MW PETT DESIGN

Retrofitted to shunting locomotive
- Replaced LFT + SCR rectifier
- Propulsion motor - 450kW
- 12 months of field service
- No power electronic failures
- Efficiency around 96%
- Weight: ≈ 4.5 t

Technologies
- Standard 3.3kV and 6.5kV IGBTs
- De-ionized water cooling
- Oil cooling/insulation for MFTs
- n + 1 redundancy
- IGBTs used for bypass switch

Displayed at:
- Swiss Museum of Transport
- https://www.verkehrshaus.ch

▲ ABB PETT prototype [3], [4]
UTILITY SST

Quite different from railways

- 50 / 60 Hz grids
- Higher powers: MW, GW
- Much higher voltage: MV, HV
- High efficiency needed (> 99 %)
- High reliability needed
- High availability needed
- Weight may not be important
- Volume may not be important

Challenges

- Business case
- Cost
- Efficiency
- Reliability
- Availability

Design of a converter is the least problem!

▲ Possible future grid connections (www/english.hhi.co.kr)
### SST Pros
- Flexible grid interface
- AC-DC, AC-AC, DC-DC, DC-AC
- Galvanic isolation
- Advanced control features

### SST Cons
- Compromised efficiency
- Increased complexity
- Higher cost
- Reliability
- Scalability

### SST Future Research
- System level optimization
- Efficiency improvements
- Insulation coordination
- Protection
- MFT design optimization
- ...

#### ABB PETT scheme: Not that simple...
MEDIUM FREQUENCY TRANSFORMERS

What are the design challenges?
MOTIVATION

- **Lower Volume** – easier system integration
- **Lower Weight** – especially important for onboard traction applications
- **Less Material** – lower investment cost, lower environmental footprint
- **Improved Efficiency** – application specific case
- **Modularity** – fractional power processing

\[
A_p = \frac{P_t}{K_fK_uB_mJ_f}
\]

- Approximate transformer scaling relation
- Example: frequency impact on the transformer size (Prof. Akagi)

Three-phase 200-V, 5-kVA, 50-Hz Transformer

Single-phase, 250-V, 5-kVA, 20-kHz Transformer
WHICH ONE IS THE BEST MFT?

ABB: 350kW, 10kHz
IKERLAN: 400kW, 600Hz
STS: 450kW, 8kHz
IKERLAN: 400kW, 6kHz

ABB: 3x150kW, 1.8kHz
FAU-EN: 450kW, 5.6kHz
CHALMERS: 50kW, 5kHz
EPFL: 300kW, 2kHz

BOMBARDIER: 350kW, 8kHz
ETHZ: 166kW, 20kHz
ETHZ: 166kW, 20kHz
ACME: ???kW, ???kHz

ALSTOM: 1500kW, 5kHz
KTH: 170kW, 4kHz
ETHZ: 166kW, 20kHz
EPFL: 100kW, 10kHz
## DESIGN CONSTRAINTS

### Electrical [1]
- Inductance
- $B < B_{sat}$
- Turns ratio
- Duty cycle
- Frequency
- $DCR < DCR_{max}$
- $J < J_{max}$
- Leakage inductance
- Self capacitance
- Self resonance
- Skin and Proximity effects
- EMI, EMC
- Shielding
- Efficiency
- Safety
- Isolation

### Mechanical
- $A_{wdg} > A_{wdg-min}$
- Size (L, W, H)
- Volume
- Surface area
- Weight
- Safety
- Creepage distances
- Clearance distances
- Insulation class
- Materials
- Safety
- Environmental

### Thermal
- $T < T_{max}$
- $P_{wdq} < P_{wdq-max}$
- $P_{core} < P_{core-max}$
- Environmental

---

[1] Source: George Slama, Würth Elektronik, APEC2019 Educational Seminar
SKIN AND PROXIMITY EFFECT

Effects

- Non-uniform current density
- Under-utilization of the conductor material
- Localized H-field distortion within the conductor volume
- Impact on conduction losses
- Impact on leakage inductance

Example of the Foil Winding MFT Geometry Cross-Section

- Generic foil winding geometry
- $\Delta$ - the penetration ratio
- $J$ (A/mm$^2$)
- $H$ (mA/m)
- $0.1$ [Hz] ($\Delta = 0.01$)

$\Delta$ - the penetration ratio

H and J distribution within the core window area
**SKIN AND PROXIMITY EFFECT**

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**Example of the Foil Winding MFT Geometry Cross-Section**

▲ Generic foil winding geometry

▲ H and J distribution within the core window area

*Δ - the penetration ratio

0.1 [Hz] (Δ = 0.01)
100 [Hz] (Δ = 0.3)
SKIN AND PROXIMITY EFFECT

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▶ Non-uniform current density
▶ Under-utilization of the conductor material
▶ Localized H-field distortion within the conductor volume
▶ Impact on conduction losses
▶ Impact on leakage inductance

Example of the Foil Winding MFT Geometry Cross-Section

▲ Generic foil winding geometry

▲ H and J distribution within the core window area

<table>
<thead>
<tr>
<th>Δ - the penetration ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 [Hz] (Δ = 0.01)</td>
</tr>
<tr>
<td>100 [Hz] (Δ = 0.3)</td>
</tr>
<tr>
<td>1000 [Hz] (Δ = 1)</td>
</tr>
</tbody>
</table>
SKIN AND PROXIMITY EFFECT

**Effects**

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\[ \begin{align*}
0.1 \text{ [Hz]} & \quad (\Delta = 0.01) \\
100 \text{ [Hz]} & \quad (\Delta = 0.3) \\
1000 \text{ [Hz]} & \quad (\Delta = 1) \\
5000 \text{ [Hz]} & \quad (\Delta = 2.15)
\end{align*} \]

- \( \Delta \) - the penetration ratio

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▲ H and J distribution within the core window area
SKIN AND PROXIMITY EFFECT

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Example of the Foil Winding MFT Geometry Cross-Section

- Generic foil winding geometry
- $H$ and $J$ distribution within the core window area

$\Delta$ - the penetration ratio

- $0.1 \ [Hz] \ (\Delta = 0.01)$
- $100 \ [Hz] \ (\Delta = 0.3)$
- $1000 \ [Hz] \ (\Delta = 1)$
- $5000 \ [Hz] \ (\Delta = 2.15)$
- $10000 \ [Hz] \ (\Delta = 3)$
SKIN AND PROXIMITY EFFECT

Effects

- Non-uniform current density
- Under-utilization of the conductor material
- Localized H-field distortion within the conductor volume
- Impact on conduction losses
- Impact on leakage inductance

Example of the Foil Winding MFT Geometry Cross-Section

- Generic foil winding geometry
- H and J distribution within the core window area
**EDGE EFFECT**

**MFT with fully filled core window height**
- Only $H_y$ component exists
- $H$ field is tangential to the foil surface

**MFT with 80% filled core window height**
- Both $H_x$ and $H_y$ components exist
- $H$ field is not tangential to the foil surface

▲ Fully utilized core window height

▲ Partially utilized core window height
MFT Losses:
- Winding Losses
- Core Losses

Heat Transfer Mechanisms:
- Conduction

- Convection

- Radiation

Heat transfer
\[ Q_h = hA\Delta T \]

Temperature gradient
\[ \Delta T = \frac{Q_h}{hA} \]

Size decrease \((A \downarrow)\) implies \(\Delta T \uparrow\)

Temperature Distribution Example:
**Core Materials:**
- Thermal conductivity varies from 4Wm/K (ferrites) to 8.35Wm/K (Nanocrystalline)
- Isotropic thermal conductivity (e.g. ferrites)
- Anisotropic thermal conductivity (laminated cores e.g. Nanocrystalline)

**Windings:**
- Copper and Aluminum conductors combined with insulation
- Low $R_{th}$ along the conductor path due low $R_{th}$ of Cu and Al
- High $R_{th}$ in radial direction due to layers of insulation with high $R_{th}$

**Winding insulation and cooling:**
- Much higher insulation level requirement than within the winding insulation
- Good insulators have very low thermal conductivity (solid or fluid)
- Fluid based insulation provides much better cooling due to convection

▲ Ferrite core - Isotropic
▲ Metglas core - Anisotropic
▲ Cross section of a round wire winding [5]
▲ MFT cross section area
**NONSINUSOIDAL VAVEFORMS**

**DAB Converter:**
- $V_{1,2}$ square
- $I$ non-sinusoidal

**Series Resonant Converter:**
- $V_{1,2}$ square
- $I$ sinusoidal

**Core Losses:**
- Data-sheet data is for sinusoidal excitation
- Derived Steinmetz coefficients describe sinusoidal excitation losses
- Core is excited with square pulses
- Losses are effected
- Generalization of Steinmetz model

**Winding Losses:**
- Current waveform impacts the winding losses
- Copper is a linear material
- Losses can be evaluated in harmonic basis
- Current harmonic content must be evaluated
- Total losses are the sum of the individual harmonic losses

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INSULATION COORDINATION

MFT Geometry Crosssection:

HF Winding Model:

MFT Electric Parameters:
- Parasitic capacitance cannot be neglected for HF
- Capacitances exist between turns, windings and core
- For pulse excitation voltage distribution is nonlinear
- Higher voltage gradient at the winding input than expected
- Damped oscillatory transient due to turn inductance
- Higher max voltage than expected during transient
- Need for overall insulation reinforcement
- Turn to turn insulation must especially be increased

\[
V(x) = V \frac{\sinh(\alpha x)}{\sinh(\alpha h)} \quad \alpha = \sqrt{\frac{c}{k}}
\]
ACCURATE MFT ELECTRIC PARAMETER CONTROL

DAB Converter:

- Leakage Inductance
- Controllability of the power flow
- Higher than $L_{\sigma,\text{min}}$:
  \[ L_{\sigma,\text{min}} = \frac{V_{DC1}V_{DC2}\varphi_{\text{min}}(\pi - \varphi_{\text{min}})}{2P_{out}\pi^2 f_s n} \]
- Magnetizing Inductance is normally high

Series Resonant Converter:

- Leakage inductance is part of resonant circuit
- Must match the reference:
  \[ L_{\sigma,\text{ref}} = \frac{1}{\omega_0^2 C_r} \]
- Magnetizing inductance is normally high
- Reduced in case of LLC
- Limits the magnetization current to the reference $I_{m,\text{ref}}$
- Limits the switch-off current and losses
  \[ L_m = \frac{nV_{DC2}}{4f_s I_{m,\text{ref}}} \]
- $I_{m,\text{ref}}$ has to be sufficiently high to maintain ZVS

▶ $V_{1,2}$ square
▶ $I$ non-sinusoidal

▶ $V_{1,2}$ square
▶ $I$ sinusoidal
MFT CHALLENGES - SUMMARY

- **Skin and proximity effect losses**: impact on efficiency and heating
- **Cooling**: increase of power density → decrease in size → less cooling surface → higher $R_{th}$ → higher temperature gradients
- **Non-sinusoidal excitation**: impact on core and winding losses and insulation
- **Insulation**: coordination and testing taking into account high $\frac{dv}{dt}$ characteristic for power electronic converters
- **Accurate electric parameter control**: especially in case of resonant converter applications

▲ left: Transformer equivalent scheme; middle: typical waveforms for resonant operation; right: MFT heat evacuation issues
MATERIALS

What design choices are available?
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
**Ferromagnetic - Silicon Steel**

- Iron based alloy of Silicon provided as isolated laminations
- Mostly used for line frequency transformers

**Advantages**

- Wide initial permeability range
- High saturation flux density
- High Curie-temperature
- Relatively low cost
- Mechanically robust
- Various core shapes available (easy to form)

**Disadvantages**

- High hysteresis loss (irreversible magnetisation)
- High eddy current loss (high electric conductivity)
- Acoustic noise (magnetostriction)

<table>
<thead>
<tr>
<th>Saturation B</th>
<th>Init. permeability</th>
<th>Core loss (10 kHz, 0.5T)</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 ~ 2.2 T</td>
<td>0.6 ~ 100 · 10³</td>
<td>50 ~ 250 W/kg</td>
<td>2 · 10⁻⁷ ~ 5 · 10⁻⁷ S/m</td>
</tr>
</tbody>
</table>

Example: Measured B-H curve of M330-35 laminate
MAGNETIC MATERIALS - AMORPHOUS ALLOY

Ferromagnetic - Amorphous Alloy

- Iron based alloy of Silicon as thin tape without crystal structure
- For both line frequency and switching frequency applications

Advantages

- High saturation flux density
- Low hysteresis loss
- Low eddy current loss (low electric conductivity)
- High Curie-temperature
- Mechanically robust

Disadvantages

- Relatively narrow initial permeability range
- Very high acoustic noise (magnetostriction)
- Limited core shapes available (difficult to form)
- Relatively expensive

<table>
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<tr>
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<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 ~ 1.6 T</td>
<td>0.8 · 10^4 ~ 50 · 10^4</td>
<td>2 ~ 20 W/kg</td>
<td>&lt; 5 · 10^5 S/m</td>
</tr>
</tbody>
</table>

Example: Measured B-H curve of Metglas 2605SA
Ferromagnetic - Nanocrystalline Alloy

- Iron based alloy of silicon as thin tape with minor portion of crystal structure
- For both line frequency and switching frequency applications

Advantages

- Relatively narrow initial permeability range
- High saturation flux density
- Low hysteresis loss
- High Curie-temperature
- Low acoustic noise

Disadvantages

- Eddy current loss (compensated thanks to the thin tape)
- Mechanically fragile
- Limited core shapes available (difficult to form)
- Relatively expensive

<table>
<thead>
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<th>Init. permeability</th>
<th>Core loss (10kHz, 0.5T)</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ~ 1.2 T</td>
<td>$0.5 \cdot 10^4 \sim 100 \cdot 10^6$</td>
<td>&lt; 50 W/kg</td>
<td>$3 \cdot 10^4 \sim 5 \cdot 10^6$ S/m</td>
</tr>
</tbody>
</table>

Example: Measured B-H curve of VITROPERM 500F
Ferrimagnetic - Ferrites
- Ceramic material made from powder of different oxides and carbons
- For both line frequency and switching frequency applications

Advantages
- Relatively narrow initial permeability range
- Low hysteresis loss
- Very low eddy current loss
- Low acoustic noise
- Relatively low cost
- Various core shapes available

Disadvantages
- Low saturation flux density
- Narrow range of initial permeability
- Magnetic properties deteriorate with temperature increase
- Mechanically fragile

<table>
<thead>
<tr>
<th>Saturation B</th>
<th>Init. permeability</th>
<th>Core loss (10kHz, 0.5T)</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 ~ 0.5 T</td>
<td>$0.1 \cdot 10^{3}$ ~ $20 \cdot 10^{3}$</td>
<td>5 ~ 100 W/kg</td>
<td>$&lt; 1 \cdot 10^{-3}$ S/m</td>
</tr>
</tbody>
</table>

Example: Measured B-H curve of Ferrite N87
Material characterisation

- Data sheet are often not sufficient
- Power electronics = non-sinusoidal waveforms

Calorimetric approach

- Core sample placed in thermally isolated chamber
- Measure temperature difference between the inlet- and outlet coolant
- Time consuming and difficult to exclude winding loss

Electrical approach

- Two windings installed on the sample core
- RF Power amplifier provides sinusoidal on the primary winding
- Primary winding current sensing using shunt resistor, to obtain H
- Secondary winding voltage sensing using resistor divider, integrated to get B
- Control unit for reference signal generation and data acquisition

▲ Commercial B-H Analyser; Source: www.iti.iwatsu.co.jp/en

▲ EPFL characterisation setup for magnetic materials
WINDING MATERIALS

Copper winding
- Flat wire - low frequency, easy to use
- Litz wire - high frequency, limited bending
- Foil - provide flat windings
- Hollow tubes - provide cooling efficiency
- Better conductor
- More expensive
- Better mechanical properties

Copper Parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity</td>
<td>$58.5 \cdot 10^6$ S/m</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>$1.7 \cdot 10^{-8}$ Ωm</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>401 W/mK</td>
</tr>
<tr>
<td>TEC (from 0° to 100° C)</td>
<td>$17 \cdot 10^{-6}$ K⁻¹</td>
</tr>
<tr>
<td>Density</td>
<td>8.9 g/cm³</td>
</tr>
<tr>
<td>Melting point</td>
<td>1083 °C</td>
</tr>
</tbody>
</table>

Aluminium winding
- Flat wire
- Foil - skin effect differences compared to Copper
- Hollow tubes
- Difficult to interface with copper
- Offer some weight savings
- Cheaper
- Somewhat difficult mechanical manipulations

Aluminum Parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity</td>
<td>$36.9 \cdot 10^6$ S/m</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>$2.7 \cdot 10^{-8}$ Ωm</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>237 W/mK</td>
</tr>
<tr>
<td>TEC (from 0° to 100° C)</td>
<td>$23.5 \cdot 10^{-6}$ K⁻¹</td>
</tr>
<tr>
<td>Density</td>
<td>2.7 g/cm³</td>
</tr>
<tr>
<td>Melting point</td>
<td>660 °C</td>
</tr>
</tbody>
</table>
Multiple influencing factors

- Operating voltage levels
- Over-voltage category
- Environment - IP class
- Temperature
- Moisture
- Cooling implications
- Ageing (self-healing?)
- Manufacturing complexity
- Partial Discharge
- BIL
- Cost

Dielectric properties

- Breakdown voltage (dielectric strength)
- Permittivity
- Conductivity
- Loss angle
- ...

<table>
<thead>
<tr>
<th>Dielectric material</th>
<th>Dielectric strength (kV/mm)</th>
<th>Dielectric constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Oil</td>
<td>5 - 20</td>
<td>2 - 5</td>
</tr>
<tr>
<td>Mica tape</td>
<td>60 - 230</td>
<td>5 - 9</td>
</tr>
<tr>
<td>NOMEX 410</td>
<td>18 - 27</td>
<td>1.6 - 3.7</td>
</tr>
<tr>
<td>PTFE</td>
<td>60 - 170</td>
<td>2.1</td>
</tr>
<tr>
<td>Mylar</td>
<td>80 - 600</td>
<td>3.1</td>
</tr>
<tr>
<td>Paper</td>
<td>16</td>
<td>3.85</td>
</tr>
<tr>
<td>PE</td>
<td>35 - 50</td>
<td>2.3</td>
</tr>
<tr>
<td>XLPE</td>
<td>35 - 50</td>
<td>2.3</td>
</tr>
<tr>
<td>KAPTON</td>
<td>118 - 236</td>
<td>3.9</td>
</tr>
</tbody>
</table>

▲ Variety of choices available...
**INSULATING MATERIALS - AIR**

**Air**
- Generally good electric insulator
- Available
- Add no mass to design
- Free
- Provides cooling
- Not sufficient alone
- Additional insulation (e.g. turn-to-turn)
- Generally, not the smallest design
- Dielectric strength variation - **Pachen Law**

\[
V_{BD} = \frac{Bpd}{\ln(Ad) - \ln\left(\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right)}
\]

- \(V_{BD}\) breakdown voltage in volts
- \(p\) - pressure in pascals
- \(d\) - gap distance in meters
- \(\gamma_{se}\) - secondary electron emission coef.
- \(A, B\) - parameters experimentally determined

\[\text{Paschen curve for air}\]
INSULATING MATERIALS - OIL

Oil
- In use for a very long time
- Excellent insulating properties
- Good thermal conductivity
- High voltage transformers
- Insulate and cool at the same time
- Natural or forced convection
- Self-healing (PD)
- Environmental concerns

Challenges
- Not a power electronics technology
- Integration issues
- Thermal expansion
- Forced convection - need for pump
- Flammability (mineral oils)
- Adds weight to the design
- Oil degradation

▲ left: Distribution oil transformer; right: New traction oil transformer; www.abb.com

▲ Oil insulated HFT PD testing [6]
INSULATING MATERIALS - SOLIDS

Solid Insulation
- Dry Type designs
- Vacuum-Pressure Impregnation (VPI)
- Vacuum-immersion (resin-encapsulated)
- Vacuum-fill (solid-cast)
- Variety of resin mixtures available
- Need for specialized equipment

Challenges
- Direct impact on thermal design
- Adds weight to the design
- Ageing uncertainty
- Mixed frequency stress
- Partial Discharge
- Mechanical strength - cracks
- CTI - Creepage distances

▲ left: www.sts-trafo.com; right: www.siemens.com
▲ Resin-Encapsulated transformer winding (www.schneider-electric.com)
▲ Solid-Cast transformer winding (www.schneider-electric.com)
SUMMARY - TECHNOLOGIES AND MATERIALS

ABB: 350kW, 10kHz
IKERLAN: 400kW, 6kHz
KTH: 170kW, 4kHz
ETHZ: 166kW, 5kHz
ETHZ: 166kW, 20kHz
EPFL: 100kW, 10kHz
ACME: ???kW, ???kHz
FAU-EN: 450kW, 5.6kHz
CHALMERS: 50kW, 5kHz
EPFL: 300kW, 2kHz
STS: 450kW, 8kHz
IKERLAN: 400kW, 600Hz
ABB: 3x150kW, 1.8kHz
BOMBARDIER: 350kW, 8kHz
ALSTOM: 1500kW, 5kHz
KTH: 170kW, 4kHz
ETHZ: 166kW, 20kHz
MFT MODELING

The underlying analytical descriptions?
MODELING: RELEVANT EFFECTS

- Core Losses
- Winding Losses
- Leakage Inductance
- Magnetizing Inductance
- Thermal Model
Different core loss models:
- Based on characterization of magnetic hysteresis \([7, 8, 9]\)
- Based on loss separation \([10]\)
- Time domain core loss model \([11]\)
- Based on Steinmetz Equation (MSE \([12]\), IGSE \([13]\), iIGSE \([14]\))

Original Steinmetz Equation:
\[
P_c = K f^a B_m^\beta
\]

Improved Generalized Steinmetz Equation (IGSE):
\[
P_c = \frac{1}{T} \int_0^T k_i \left| \frac{dB(t)}{dt} \right|^\alpha (\Delta B)^{\beta-\alpha} dt
\]
\[
k_i = \frac{K}{(2\pi)^{a-1} \int_0^{2\pi} |\cos(\theta)|^a 2^{\beta-a} d\theta}
\]

Characteristic Waveform:
\[
\begin{align*}
\frac{d(B(t))}{dt} &= \begin{cases} 
0 & \text{for} \ (1 - D)T \\
\frac{2\Delta B}{DT} & \text{for} \ DT
\end{cases}
\end{align*}
\]

Application of IGSE on the Characteristic Waveform:
\[
P_s = 2^{\alpha+\beta} k_i f^a B_m^\beta D^{1-a}
\]
\[
k_i = \frac{K}{2^{\beta-1} \pi^{a-1} \left(0.2761 + \frac{1.7061}{a+1.354}\right)}
\]
### Foil Winding Electromagnetic Field Analysis:

- Dowell foil winding loss model [15]
- Porosity factor validity analysis [16], [17]
- Round wire winding loss model [18]
-...

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

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

\[ a = \frac{1 + j}{\delta}; \quad \delta = \sqrt{\frac{\rho}{\pi \mu_f}}; \]

\[ P_o = \frac{1}{\sigma} \int JJ^* dV; \quad P_o = I^2 \frac{L_w}{\delta \sigma h_w} m \left[ \zeta_1 + \frac{2}{3}(m^2 - 1)\zeta_2 \right]; \]

\[ \zeta_1 = \frac{\sinh(2\Delta) + \sin(2\Delta)}{\cosh(2\Delta) - \cos(2\Delta)}; \quad \zeta_2 = \frac{\sinh(\Delta) - \sin(\Delta)}{\cosh(\Delta) + \cos(\Delta)}; \quad \Delta = \frac{d_{eq}}{\delta}; \]

### Winding Equivalence:

\[ d_{eq} = d_1 \sqrt{\frac{\pi}{4}}; \quad d_i = \frac{d_w - N_{sh} d_{eq}}{N_{sh} - 1}; \quad m = N_{sh}; \]

\[ N_{sh} = \sqrt{\frac{N_s}{K_w}}; \quad N_{sv} = \sqrt{K_w N_s}; \]

\[ K_w = \frac{h_w}{d_w}; \quad \Delta' = \sqrt{\eta \Delta}; \quad \eta = d_{eq} \frac{N_{sv}}{H_w}; \]
MODELING: F-DEPENDENT LEAKAGE INDUCTANCE

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

\[
L_{\sigma} = N_1^2 \mu_0 \frac{I_w}{H_w} \left[ \frac{d_{w1eq}m_{w1}}{3} F_{w1} + \frac{d_{w2eq}m_{w2}}{3} F_{w2} \right]
\]

Frequency dependent portion due to the magnetic energy within the copper volume of the windings

\[
+ \left( \frac{d_d}{d_{w1i}} (m_{w1} - 1)(2m_{w1} - 1) \right)
\]

Portion due to magnetic energy within the inter-winding dielectric volume

\[
+ \left( \frac{d_{w2i}^2 (m_{w2} - 1)(2m_{w2} - 1)}{6m_{w2}} \right)
\]

Portion due to magnetic energy within the inter-layer dielectric of the primary winding

\[
+ \left( \frac{d_{w2i} (m_{w2} - 1)(2m_{w2} - 1)}{6m_{w2}} \right)
\]

Portion due to magnetic energy within the inter-layer dielectric of the secondary winding

where:

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

\[
\varphi_1 = \frac{\sinh(2\Delta) - \sin(2\Delta)}{\cosh(2\Delta) - \cos(2\Delta)}; \quad \varphi_2 = \frac{\sinh(\Delta) - \sin(\Delta)}{\cosh(\Delta) - \cos(\Delta)};
\]

\[
\Delta' = \sqrt{\eta \Delta}; \quad \eta = \frac{d_{eq} N_{sv}}{H_w}; \quad m = N_{sh}; \quad d_i = \frac{d_w - N_{sh} d_{eq}}{N_{sh} - 1};
\]
Influence of Winding Geometry on Leakage Inductance:

Hybrid Leakage Inductance Model [19]:

- Rogowski correction factor:
  \[ h_{eq} = \frac{h_w}{K_R} \]
  \[ K_R = 1 - \frac{1 - e^{-nh_w/(d_{w1}+d_d+d_{w2})}}{\pi h_w/(d_{w1} + d_d + d_{w2})} \]

- Correction of Dowell's model \((H_w \rightarrow h_{eq})\):
  \[
  L_\sigma = N_1^2 \mu_0 \frac{l_w}{H_w} \left[ \frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2} + d_d \right. \\
  + \frac{m_{w1}-1}{6 m_{w1}} + \left. d_{w1i} \frac{(m_{w1}-1)(2m_{w1}-1)}{6 m_{w1}} + d_{w2i} \frac{(m_{w2}-1)(2m_{w2}-1)}{6 m_{w2}} \right] \\
  \Delta' = \sqrt{\eta \Delta}; \quad \eta = d_{eq} \frac{N_{sv}}{H_w};
  \]
MODELING: LEAKAGE INDUCTANCE (HYBRID MODEL)

Influence of Winding Geometry on Leakage inductance:

Hybrid Leakage Inductance Model [19]:

- 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 (\(H_w \to h_{eq}\)):
  \[
  L_\sigma = N_1^2 \mu_0 \frac{l_w}{h_{eq}} \left[ \frac{d_{w1}m_{w1}}{3} F_{w1} + \frac{d_{w2}m_{w2}}{3} F_{w2} + d_d \right. \\
  \left. + d_{w1i} \frac{(m_{w1} - 1)(2m_{w1} - 1)}{6m_{w1}} + d_{w2i} \frac{(m_{w2} - 1)(2m_{w2} - 1)}{6m_{w2}} \right] \\
  \Delta' = \sqrt{\eta \Delta}; \quad \eta = d_{eq} \frac{N_{sv}}{h_{eq}};
  \]
MODELING: MAGNETIZING INDUCTANCE

Magnetic Circuit with an Air-Gap:

Magnetizing Inductance Calculation:

\[ L_m = \frac{\mu_0 N^2 A_c}{I_m \mu_r + d} \]

Air-Gap Calculation:

\[ d = \mu_0 N^2 A_c - \frac{I_m \mu_r}{L_m} \]

Fringing Effect:

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

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June 12, 2019
Conduction  
\[ Q_h = kA \frac{\Delta T}{L} \]

Top: \[ h = \frac{k(0.65 + 0.36R_{\Delta L}^{1/6})^2}{L} \quad L = \text{Area} / \text{Perimeter} \]

Convection over Hot-Plate  
\[ Q_h = hA(T_s - T_{\infty}) \]

Side: \[ h = \frac{k}{L} \left( 0.825 + \frac{0.387R_{\Delta L}^{1/6}}{1+(0.492/Pr)^{9/16}} \right)^2 \quad L = \text{Height} \]

Bottom: \[ h = \frac{k0.27R_{\Delta L}^{1/4}}{L} \quad L = \text{Area} / \text{Perimeter} \]

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: \( R_{\Delta L} \) - Rayleigh number, \( Pr \) - Prandtl number, \( \varepsilon \) - Emissivity, \( \sigma \) - Stefan–Boltzmann constant [20], [21], [22]
**MODELING: THERMAL MODEL**

**Modes Of Heat Transfer:**
- Conduction
- Convection
- Radiation

**Partitioning Into Zones:**
- Zone 1: Top Yoke
- Zone 2: Outer Limb
- Zone 3: Bottom Yoke
- Zone 4: Center Limb
- Zone 5: Top Cooler
- Zone 6: Bottom Cooler

**Detailed Thermal Network Model [23]:**

```
Rcc,v1  Ta1  Pcv1

Rcc,h1  Rcc,h2
Rcc,v2
Rcc,h3  Rcc,h4
Rcc,v3
Rcc,v4

Rca,cv1  Rca,r1
Rcc,sl,out
Rca,cv2  Rca,r2
Rcc,sy,b

Rw 1c,cd  Rw 1c,r
Rw 1a,cv  Ta2
Rw 2c,cd  Rw 2c,r
Pw 1
Rw 1w 2,cd  Rw 1w 2,r
Rw 1,cd2  Rw 1a,cv1
Rw 2,cd1  Rw 2a,cv1

Rcc,sl,in1
Rcc,sl,out1
Tc1  Tc2  Tc3  Tc4  Tc5  Tc6  Tc7  Tc8
Tw 1,hs  Tw 2,hs  Tw 1,sc  Tw 2,sc
Tw 2,sw 1  Tw 2,sw 2
Tc2,s,in  Tc2,s,out
1  2  3  4  5  6  7  8  9  10
```

**Planes of Symmetry:**

**IEEE PELS Webinar**

June 12, 2019
**MODELING: THERMAL MODEL**

**Modes Of Heat Transfer:**
- Conduction
- Convection
- Radiation

**Planes of Symmetry:**

**Partitioning Into Zones:**

**Detailed Thermal Network Model [23]:**

![Detailed Thermal Network Model](image-url)
MODELING: THERMAL MODEL

Modes Of Heat Transfer:
- Conduction
- Convection
- Radiation

Planes of Symmetry:

Partitioning Into Zones:

Detailed Thermal Network Model [23]:

IEEE PELS Webinar
June 12, 2019
Power Electronics Laboratory | 49 of 72
MODELING: THERMAL MODEL

Modes Of Heat Transfer:
- Conduction
- Convection
- Radiation

Partitioning Into Zones:
- Zone1: Top Yoke
- Zone2: Outer Limb
- Zone3: Bottom Yoke
- Zone4: Center Limb
- Zone5: Bottom Cooler
- Zone6: (W1)
- Zone7: (W2)
- Zone8: Top Cooler
- Zone9: (W3)

Detailed Thermal Network Model [23]:

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June 12, 2019
Power Electronics Laboratory | 49 of 72
Implementation of Thermal Network Model:

- Admittance Matrix:
  \[ Q_{(n)} = Y_{th(n \times n)} \Delta T_{(n)} \]

- Rearranging the nodes:
  \[
  \begin{bmatrix}
  Q_{(m)}
  \end{bmatrix}
  =
  \begin{bmatrix}
  Y_{thAA(m \times m)} & Y_{thAB(m \times p)} \\
  Y_{thBA(p \times m)} & Y_{thBB(p \times p)}
  \end{bmatrix}
  \begin{bmatrix}
  \Delta T_{A(m)} \\
  \Delta T_{B(p)}
  \end{bmatrix}
  \]

- Kron reduction:
  \[
  \Delta T_{A(m)} = \left( Y_{thAA(m \times m)} - Y_{thAB(m \times p)} Y_{thBB(p \times p)}^{-1} Y_{thBA(p \times m)} \right)^{-1} Q_{A(m)}
  \]
  \[
  \Delta T_{A(m)} = Y_{Kron(m \times m)}^{-1} Q_{A(m)}
  \]

- Kron matrix:
  \[
  Y_{Kron(m \times m)} = Y_{thAA(m \times m)} - Y_{thAB(m \times p)} Y_{thBB(p \times p)}^{-1} Y_{thBA(p \times m)}
  \]

Analytical Model Results for the optimal MFT prototype:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_1 [^\circ C])</td>
<td>(T_2 [^\circ C])</td>
<td>(T_3 [^\circ C])</td>
<td>(T_4 [^\circ C])</td>
<td>(T_5 [^\circ C])</td>
</tr>
<tr>
<td>51.3</td>
<td>59.9</td>
<td>58.4</td>
<td>73.75</td>
<td>124.6</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Hot-spot nodes</th>
<th>$T_1 [^\circ C]$</th>
<th>$T_2 [^\circ C]$</th>
<th>$T_3 [^\circ C]$</th>
<th>$T_4 [^\circ C]$</th>
<th>$T_6 [^\circ C]$</th>
<th>$T_9 [^\circ C]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM 2D detail 1</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>70</td>
<td>120</td>
<td>106</td>
</tr>
<tr>
<td>FEM 2D detail 2</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>76</td>
<td>127</td>
<td>125</td>
</tr>
<tr>
<td>FEM 3D full</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>75</td>
<td>122</td>
<td>113</td>
</tr>
<tr>
<td>Analytical</td>
<td>51.3</td>
<td>59.9</td>
<td>58.4</td>
<td>73.75</td>
<td>124.6</td>
<td>116.3</td>
</tr>
</tbody>
</table>

2D symmetry detail 1:

2D symmetry detail 2:

Full 3D model:
MFT DESIGN OPTIMIZATION

Brute force academic example? You may do it differently!
### 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
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:

  \[
  \begin{align*}
  P_n & = 100kW \\
  f_{sw} & = 10kHz \\
  V_1 & = 750V \\
  V_2 & = 750V \\
  L_{\sigma,1,2} & = 3.27\mu H \\
  L_m & = 1.8mH
  \end{align*}
  \]
Algorithm Specifications:

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- **Electrical Specifications:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_n$</td>
<td>100 kW</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>10 kHz</td>
</tr>
<tr>
<td>$V_1$</td>
<td>750 V</td>
</tr>
<tr>
<td>$V_2$</td>
<td>750 V</td>
</tr>
<tr>
<td>$L_{\sigma,1,2}$</td>
<td>3.27 μH</td>
</tr>
<tr>
<td>$L_m$</td>
<td>1.8 mH</td>
</tr>
</tbody>
</table>

▲ 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:
  
  \[
  \begin{align*}
  P_n &= 100kW \\
  V_1 &= 750V \\
  V_2 &= 750V \\
  L_{\sigma1,2} &= 3.27\mu H \\
  f_{SW} &= 10kHz \\
  L_m &= 1.8mH
  \end{align*}
  \]
**Algorithm Specifications:**

- **Used Software Platform:**
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- **Used Hardware Platform:**
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- **Performance Measure:**
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- **Electrical Specifications:**
  - \( P_n = 100kW \)  \( f_{sw} = 10kHz \)
  - \( V_1 = 750V \)  \( V_2 = 750V \)
  - \( L_{\sigma,1,2} = 3.27\mu H \)  \( L_m = 1.8mH \)
**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:**

<table>
<thead>
<tr>
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<th>Value</th>
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<tr>
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<tr>
<td>$f_{sw}$</td>
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</tr>
<tr>
<td>$L_{\sigma 1,2}$</td>
<td>3.27$\mu$H</td>
</tr>
<tr>
<td>$L_m$</td>
<td>1.8mH</td>
</tr>
</tbody>
</table>

$\Delta$ MFT design optimization algorithm
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:**

<table>
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<tr>
<td>$P_n$</td>
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</tr>
<tr>
<td>$L_m$</td>
<td>1.8mH</td>
</tr>
</tbody>
</table>

$\Delta$ MFT design optimization algorithm
**DESIGN OPTIMIZATION: RESULTS**

**Applied Filters:**

<table>
<thead>
<tr>
<th>$T_{W_{max}}$ [$^\circ$C]</th>
<th>$T_{C_{max}}$ [$^\circ$C]</th>
<th>$V_{max}$ [$l$]</th>
<th>$M_{max}$ [kg]</th>
<th>$\eta_{min}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>100</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

**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:**

<table>
<thead>
<tr>
<th>$T_{W_{\text{max}}} ,[^\circ \text{C}]$</th>
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100kW, 10kHz MFT PROTOTYPE
Assembly, testing and design tool verification!
MFT PROTOTYPE: DESIGN ASSEMBLY

Optimal MFT Design 3D-CAD  
Coil-Formers 3D-CAD  
Coil-Formers 3D-Print  
Primary Winding  
Secondary Winding  
Core Assembly  
MFT Assembly 1  
MFT Assembly 2  
Litz-Wire Termination  
MFT Prototype
CONVERTER READY MFT

MFT Prototype

Prototype Specifications:

- **Core:**
  - 12 stacks of 4 x SiFERRITE U-Cores (UU9316 - CF139)

- **Windings:**
  - 8-Turns
  - Square Litz Wire (8.7x8.7mm, 1400 strands, AWG 32, 43.69mm²)

- **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:**

<table>
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<th>Parameter</th>
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<tr>
<td>$P_n$</td>
<td>100kW</td>
</tr>
<tr>
<td>$f_{SW}$</td>
<td>10kHz</td>
</tr>
<tr>
<td>$V_1$</td>
<td>750V</td>
</tr>
<tr>
<td>$V_2$</td>
<td>750V</td>
</tr>
<tr>
<td>$L_{a1,2}$</td>
<td>4.2µH</td>
</tr>
<tr>
<td>$L_m$</td>
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$\Delta$ 100kW, 10kHz MFT including resonant capacitors
MEASUREMENTS: ELECTRIC PARAMETERS

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:

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
- 10\(\text{pC}\) - between primary and secondary winding at 4\(kV\)

**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 $I_{DC}$

**Measurement Results:**

![Graphs showing waveforms and measurements](image-url)

**Test Setup:**
- B2B MFT test setup

- Experimental results: left: MFT primary waveforms; right: MFT secondary waveforms
MEASUREMENTS: THERMAL RUN

Measurement Setup:

Thermal Run:

- **No-Load Operation:**
  - Voltage $U_{12}$ vs. time $t$
  - Current $I_1$ vs. time $t$

- **Full-Load Operation:**
  - Voltage $U_{12}$ vs. time $t$
  - Current $I_1$ vs. time $t$

Thermal Profile:

- **Cooler Central Point Temperature [°C]**
  - Top Cooler Surface
  - Between Top Cooler and Core
  - Between Bottom Cooler and Core

- **Core Outer Limb Hot-Spot Temperature [°C]**
  - Left Limb
  - Right Limb

- **Secondary Winding Hot-Spot Temperature [°C]**
  - Measurement Point 1
  - Measurement Point 2

- ** Thermal heat run results**
CONCLUSION

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

Components & Materials

Algorithm

Design Selection

Prototype

Testing

3D-Design

Components & Materials

ELECTRICAL INPUTS

DIELECTRIC DISTANCES

OPTIMISATION VAR RANGES

PREPARE DATA

CORE MATERIALS DATA

CORE DIMENSIONS DATA

WIRE DATA

DATA BASE

INPUTS

DIRECT USER INPUTS

Winding Losses Calculation

Magnetic Energy Calculation

Core Losses Calculation

Mass and Volume Calculation

Hot-Spot Temperature Calculation

OPTIMISATION ENGINE

SAVE DESIGN

Calculate $d_{\text{w}}$ to match $L_{\text{Ä},\text{ref}}$

Calculate $l_{\text{g}}$ to match $L_{\text{m},\text{ref}}$

Datasheet values

$\text{AWG}, K_w, F_{\text{wg}}$

$\text{diw} \geq d_{\text{w}}^1, w^2$

$\text{lg} \geq 0$

$\text{TC,hs} \leq \text{TC,hs max}$

$\text{TW,hs} \leq \text{TW,hs max}$

$\text{Un}, \text{In}, f, D, L_{\text{Ä},\text{ref}}, L_{\text{m},\text{ref}}$

$\text{dw}^1_{c}, \text{dw}^2_{c}, \text{dw}^1_{\text{w}^2}$

$B_{\text{sat}}, K, \cdot, \cdot, \cdot, \mu_r, F_{\text{cg}}$

$N_1, J, \text{AWG}, K_w, K_C, K_m$
CONCLUSION

- Complex and challenging design optimization
- Large number of available materials
- Customized designs prevail
- Research opportunities...
Drazen Dujic is an Assistant Professor and Head of the Power Electronics Laboratory at EPFL. He received the Dipl.Ing. and MSc degrees from the University of Novi Sad, Novi Sad, Serbia in 2002 and 2005, respectively, and the PhD degree from Liverpool John Moores University, Liverpool, UK in 2008. From 2003 to 2006, he was a Research Assistant with the Faculty of Technical Sciences at University of Novi Sad. From 2006 to 2009, he was a Research Associate with Liverpool John Moores University. After that he moved to industry and joined ABB Switzerland Ltd, where from 2009 to 2013, he was Scientist and then Principal Scientist with ABB Corporate Research Center in Baden-Dättwil, and from 2013 to 2014 he was R&D Platform Manager with ABB Medium Voltage Drives in Turgi. He is with EPFL since 2014.

His research interests include the areas of design and control of advanced high power electronic systems and high-performance drives, predominantly for the medium voltage applications related to electrical energy generation, conversion and storage. He has authored or co-authored more than 100 scientific publications and has filed twelve patents.

In 2018 he received EPE Outstanding Service Award from European Power Electronics and Drives Association (EPE) and 2014 The Isao Takahashi Power Electronics Award for Outstanding Achievement in Power Electronics. He is Senior Member of IEEE, EPE Member, and serves as Associate Editor for IEEE Transactions on Power Electronics, IEEE Transactions on Industrial Electronics and IET Electric Power Applications.

Marko Mogorovic received the Dipl.Ing. degree from the University of Belgrade, Belgrade, Serbia, in 2013 and MSc degree from the École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland, in 2015. Currently, he is about to obtain the Ph.D. degree at Power Electronics Laboratory at EPFL, Lausanne, Switzerland. His current research focus is on the design optimization of the high power medium frequency transformers for medium voltage applications and emerging solid state transformers.

He is an IEEE Student Member.

Material presented in the webinar has been developed during his PhD research project.
REFERENCES


Tutorial pdf can be downloaded from:

- https://pel.epfl.ch/publications_talks_en
MEDIUM FREQ. TRANSFORMER DESIGN OPTIMIZATION FOR SOLID STATE TRANSFORMERS

Prof. Drazen Dujic
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