HIGH POWER MFT DESIGN OPTIMIZATION

Drazen Dujic & Marko Mogorovic
École Polytechnique Fédérale de Lausanne
Power Electronics Laboratory
Switzerland
INSTRUCTORS

**Drazen Dujic**

Experience:

- 2014 – today École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- 2013 – 2014 ABB Medium Voltage Drives, Turgi, Switzerland
- 2009 – 2013 ABB Corporate Research, Baden-Dättwil, Switzerland
- 2006 – 2009 Liverpool John Moores University, Liverpool, United Kingdom
- 2003 – 2006 University of Novi Sad, Novi Sad, Serbia

Education:

- 2008 PhD, Liverpool John Moores University, Liverpool, United Kingdom
- 2005 M.Sc., University of Novi Sad, Novi Sad, Serbia
- 2002 Dipl. Ing., University of Novi Sad, Novi Sad, Serbia

**Marko Mogorovic**

Education:

- Pending PhD, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- 2015 M.Sc., École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- 2013 Dipl. Ing., University of Belgrade, Belgrade, Serbia
- Online since February 2014
- http://pel.epfl.ch
RESEARCH FOCUS

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

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

Characterization
- Semiconductor devices
- Magnetic components
- Systems

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Before the Coffee Break

1) Introduction and Motivation
   ▶ Solid State Transformers
   ▶ Railway and Utility SST
   ▶ Medium Frequency Conversion

2) Medium Frequency Transformers
   ▶ Scaling laws
   ▶ Requirements
   ▶ Challenges

3) MFT Design Examples
   ▶ Railway related designs
   ▶ Utility related designs
   ▶ Other state-of-the-art designs

After the Coffee Break

4) Materials
   ▶ Magnetic materials
   ▶ Winding materials
   ▶ Dielectric materials

5) MFT Modeling
   ▶ Core
   ▶ Winding
   ▶ Thermal

6) MFT Design Optimization
   ▶ Optimization based algorithms
   ▶ Brute force parametric optimization
   ▶ Design examples
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: ≈ 10kUSD / 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
RAILWAY SST

What traction SST offers in perspective:

- Improved efficiency (specially for 16.7Hz systems)
- Weight reduction - less raw materials
- Volume reduction - questionable due to insulation coordination
- Control features

Why traction SST is not out yet?

- Conservative traction market
- Lack of business case
- Reliability concerns
- Very hard to compete in 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]
ALSTOM - 1.5MW E-TRANSFORMER

Ratings
- Power: 1.5MW
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1650 V
- Weight: 3.1 t (vs 6.8 t 16.7Hz LFT)
- Volume: 3.22 m³
- Efficiency: 94%
- Cost: 50% increase

Topology
- 4Q AC-DC + resonant DC-DC
- 8 cascaded stages on primary

Semiconductor Devices
- HV side: 6.5kV IGBTs (48x)
- LV side: 3.3kV IGBTs

MFT
- Power: 1.5MW
- Frequency: 5kHz
- Core: Ferrite
- Insulation / Cooling: Oil

▲ ALSTOM reported Traction SST [3], [4]
ABB - 1.2MW POWER ELECTRONIC TRACTION TRANSFORMER - PETT_

**Ratings**
- Power: 1.2MW
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1800 V
- Efficiency: 95% (peak)

**Topology**
- 4Q AC-AC + AC-DC
- 16 cascaded stages

**Semiconductor Devices**
- HV side: 3.3kV IGBTs
- LV side: 3.3kV IGBTs

**MFT**
- Power: 75kW per MFT
- Frequency: 400Hz
- Core: SiFe
- Insulation / Cooling: oil

▲ ABB reported PETT [5]
ABB - 1.2MW PETT

Characteristics

- 1-Phase MVAC to MVDC
- Power: 1.2MVA
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1500 V
- 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

▲ ABB PETT scheme [6], [7]
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
- IGBT used for bypass switch

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

▲ ABB PETT prototype [6], [7]
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)
UTILITY SST PROJECTS

**UNIFLEX-PM**
- www.eee.nott.ac.uk/uniflex/index.html
- Academic initiative
- Multiport AC-AC-AC
- Power control
- Voltage control
- Reduced scale prototypes

**FREEDM**
- www.freedm.ncsu.edu
- Academic initiative
- Gen-1 SST: Si-based (6.5kV, 3kHz)
- Gen-2 SST: SiC-based (15kV, 10kHz)
- Gen-3 SST: SiC-based (15kV, 40kHz)
- Reduced scale prototypes

**HEART**
- www.heart.tf.uni-kiel.de/en/home
- Academic initiative
- AC grids
- Energy routing
- Control features
- Reduced scale prototypes

▲ UNIFLEX-PM prototype  ▲ FREEDM SSTs [8]  ▲ HEART project
SUMMARY - SOLID STATE TRANSFORMER

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

\[
A_P = \frac{P_t}{K_f K_u B_m J_f}
\]

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

### MFT Dimension Analysis for Constant $B_m$ and $J$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
<th>Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Surface</td>
<td>$S_c = C_1 I^2$</td>
<td>$k^2$</td>
</tr>
<tr>
<td>Volume and Mass</td>
<td>$M = \gamma V = C_2 I^3$</td>
<td>$k^3$</td>
</tr>
<tr>
<td>Current</td>
<td>$I = J S_{Cu}$</td>
<td>$k^2$</td>
</tr>
<tr>
<td>Induced Voltage</td>
<td>$U = C_3 f B_m S_{Fe}$</td>
<td>$f k^2$</td>
</tr>
<tr>
<td>Apparent Power</td>
<td>$P = U I$</td>
<td>$f k^4$</td>
</tr>
<tr>
<td>DC Resistance</td>
<td>$R = N p l / S_{Cu}$</td>
<td>$1 / k$</td>
</tr>
<tr>
<td>Copper Losses</td>
<td>$P_{Cu} = F R I^2$</td>
<td>$F(f) k^3$</td>
</tr>
<tr>
<td>Core Losses</td>
<td>$P_{Fe} = K f^a B_m^b V$</td>
<td>$f^a k^3$</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>$\Delta \theta = (P_{Cu} + P_{Fe}) / (\alpha S_c)$</td>
<td>$k (F(f) + f^a)$</td>
</tr>
<tr>
<td>Relative Losses</td>
<td>$P_r = (P_{Cu} + P_{Fe}) / P$</td>
<td>$(F(f) + f^a) / (k f)$</td>
</tr>
<tr>
<td>Relative Cost</td>
<td>$\epsilon = M / P$</td>
<td>$1 / (k f)$</td>
</tr>
</tbody>
</table>

Where: $F(f)$ - skin and proximity effect correction factor
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
SKIN AND PROXIMITY EFFECT

Effects

- Non-uniform current density
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Example of the Foil Winding MFT Geometry Cross-Section

▲ Generic foil winding geometry

*Δ - the penetration ratio

H and J distribution within the core window area

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

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Example of the Foil Winding MFT Geometry Cross-Section

- Generic foil winding geometry

\[ \Delta - \text{the penetration ratio} \]

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Penetration Ratio [(\Delta)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>100</td>
<td>0.3</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>5000</td>
<td>2.15</td>
</tr>
</tbody>
</table>

\[ H \text{ [mA/m]} \]

\[ J \text{ [A/mm}^2\text{]} \]
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

\[ \Delta - \text{the penetration ratio} \]

\[ \begin{align*}
0.1 \text{ [Hz]} \ (\Delta = 0.01) \\
100 \text{ [Hz]} \ (\Delta = 0.3) \\
1000 \text{ [Hz]} \ (\Delta = 1) \\
5000 \text{ [Hz]} \ (\Delta = 2.15) \\
10000 \text{ [Hz]} \ (\Delta = 3)
\end{align*} \]
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
THERMAL COORDINATION

MFT Losses:
- Winding Losses
- Core Losses

Heat Transfer Mechanisms:
- Conduction
- Convection
- Radiation

Qualitative Analysis:
- Heat transfer
  \[ Q_h = hA\Delta T \]
- Temperature gradient
  \[ \Delta T = \frac{Q_h}{hA} \]
- Size decrease (A ↘) implies ΔT ↗

Temperature Distribution Example:
Core Materials:

- Thermal conductivity varies from 4 Wm/K (ferrites) to 8.35 Wm/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.
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
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

\[ V(x) = V \frac{\sinh(\alpha x)}{\sinh(\alpha h)} \]

\[ \alpha = \sqrt{\frac{c}{k}} \]
ACCURATE MFT ELECTRIC PARAMETER CONTROL

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

**Series Resonant Converter:**
- Leakage inductance is part of resonant circuit
- Must match the reference:
  \[
  L_{\sigma,\text{ref}} = \frac{1}{\omega_0^2C_r}
  \]
- 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
  \[
  L_m = \frac{nV_{DC2}}{4f_{s,l/m,\text{ref}}}
  \]
- $I_{m,\text{ref}}$ has to be sufficiently high to maintain ZVS

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MFT CHALLENGES - SUMMARY

- **Skin and proximity effect losses**: impact on efficiency and heating
- **Cooling**: increase of power density $\Rightarrow$ decrease in size $\Rightarrow$ less cooling surface $\Rightarrow$ higher $R_{th}$ $\Rightarrow$ 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
MFT Clinics
Optimize at will!
TECHNOLOGIES, MATERIALS, DESIGNS

Construction Choices:
- MFT Types
  - Shell Type
  - Core Type
  - C-Type
  - Coaxial Type
- Winding Types
  - Litz Wire
  - Foil
  - Coaxial
  - Hollow

Materials:
- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - Ferrites
- Windings
  - Copper
  - Aluminum
- Insulation
  - Air
  - Solid
  - Oil
- Cooling
  - Air natural/forced
  - Oil natural/forced
  - Water
MFT HALL OF FAME

ABB: 350kW, 10kHz
ABB: 3x150kW, 1.8kHz
BOMBARDIER: 350kW, 8kHz
ALSTOM: 1500kW, 5kHz
IKERLAN: 400kW, 5kHz

IKERLAN: 400kW, 1kHz
FAU-EN: 450kW, 5.6kHz
CHALMERS: 50kW, 5kHz
ETHZ: 166kW, 20kHz
EPFL: 300kW, 2kHz

STS: 450kW, 8kHz
KTH: 170kW, 4kHz
ETHZ: 166kW, 20kHz
EPFL: 100kW, 10kHz
ACME: ???kW, ???kHz
### Construction
- Shell Type
- Coaxial winding

### Electrical Ratings
- Power: 350kW
- Frequency: 10kHz
- Input Voltage: ±3000V
- Output Voltage: ±3000V

### Core Material
- VAC Vitroperm 500F
- U cores

### Windings
- Coaxial (Al inside, Cu outside)

### Cooling
- Winding - De-ionized water
- Core - Air

### Insulation
- Solid

- 350kW MFT by ABB [10]

### MFT dimensions
- Volume: ≈ 37 l
- V-Density: ≈ 9.5 kW/l
- Weight: < 50 kg
- W-Density: ≈ 7 kW/kg

### Insulation Tests
- PD: 38kV, 50Hz, 1 min
- BIL: 95 kV (peak), 10 shots

- Multilevel line side converter by ABB (2002)
ALSTOM MFT - 2003

**Construction**
- Single core with multiple windings

**Electrical Ratings**
- Power: 1.5MW
- Frequency: 5kHz
- Input Voltage: ±1800V
- Output Voltage: ±1650V

**Core Material**
- Ferrite
- Size and shape unclear

**Windings**
- Litz wire

**Cooling**
- Oil (MIDEL)
- Common with power electronics

**Insulation**
- Oil (MIDEL)
- Immersed

---

**MFT dimensions**
- Volume: 0.72 m³ (2.0 x 0.73 x 0.49) m
- V-Density: 2.1 kW/l
- Weight: < 1 t (estimation)
- W-Density: < 1.5 kW / kg (estimation)

**e-Transformer dimensions**
- (2.1 x 2.62 x 0.58) m
- Volume: 3.22 m³
- Weight: 3.1 t (50% less)
**Construction**
- C-type

**Electrical Ratings**
- Power: 75kW (x16)
- Frequency: 400Hz
- Input Voltage: ±1800V
- Output Voltage: ±1800V

**Core Material**
- SiFe
- Custom made sheets

**Windings**
- Bar wire

**Cooling**
- Oil
- Common with power electronics

**Insulation**
- Oil
- Immersed

▲ Enclosure with 16 MFTs by ABB

**MFT dimensions**
- Volume: not reported
- V-Density: ? kW/l
- Weight: not reported
- W-Density: ? kW/kg

**PETT dimensions**
- Volume: 20% less
- Weight: 50% less
- Efficiency: 3% increase

▲ PETT by ABB [5]
BOMBARDIER MFT - 2007

Construction
- Core Type
- Hollow conductors

Electrical Ratings
- Power: 350kW (500kW peak)
- Frequency: 8kHz
- Input Voltage: ±1000V
- Output Voltage: ±1000V

Core Material
- Nanocrystalline
- U cores

Windings
- Hollow tubes

Cooling
- Winding - De-ionized water
- Core - Water cooled heatsink

Insulation
- Solid

350kW MFT by Bombardier [11]

MFT dimensions
- Volume: not reported
- V-Density: ? kW/l
- Weight: 18 kg
- Density: ≈ 7 kW/kg

Insulation Tests
- PD: 33kV, 50Hz
- BIL: 100 kV (1.2/50)

Medium frequency topology by Bombardier
ABB MFT - 2011

**Construction**
- C-core
- Assembly with 3 MFTs

**Electrical Ratings**
- Power: 150kW
- Frequency: 1.75kHz
- Input Voltage: ±1800V
- Output Voltage: ±750V

**Core Material**
- Nanocrystalline
- C-cut cores

**Windings**
- Bar wire

**Cooling**
- Oil

**Insulation**
- Oil
- Immersed

▲ 3 x 150kW MFT by ABB

**MFT dimensions**
- Volume: ≈ 80 l
- V-Density: ≈ 2.4 kW/l
- Weight: ≈ 170 kg
- W-Density: ≈ 1.1 kW/kg

**PETT dimensions**
- Weight: 4.5 t

▲ PETT tank with magnetics by ABB [6], [7]
UEN MFT - 2011

Construction
- Core Type

Electrical Ratings
- Power: 450kW
- Frequency: 5.6kHz
- Input Voltage: ±3600V
- Output Voltage: ±3600V

Core Material
- Nanocrystalline VITROPERM 500F
- U cores

Windings
- Aluminum
- Hollow profiles

Cooling
- Winding - de-ionized water
- Core - Oil

Insulation
- Oil - Immersed (primary to secondary)
- NOMEX - between turns

MFT dimensions
- Volume: not reported
- V-Density: ? kW/l
- Weight: 24 - 38.2 kg
- W-Density: ≈ 18.8 - 11.8 kW/kg

Insulation Tests
- Designed for 25kV railway lines
- PD, BIL: not reported
Construction
- Shell Type
- for the use with HC-DCM-SRC

Electrical Ratings
- Power: 166kW
- Frequency: 20kHz
- Input Voltage: ±1000V
- Output Voltage: ±400V

Core Material
- Nanocrystalline Vitroperm 500F
- C-cores

Windings
- Square Litz Wire

Cooling
- Water-cooled heat sinks

Insulation
- Solid
- Mica tape

MFT dimensions
- Volume: ≈ 5 l
- V-Density: ≈ 32.7 kW/l
- Weight: ≈ 10 kg
- W-Density: ≈ 16.6 kW/kg

Insulation Tests
- No details provided
Construction
- Shell Type
- for the use with TCM-DAB

Electrical Ratings
- Power: 166kW
- Frequency: 20kHz
- Input Voltage: ±750V
- Output Voltage: ±750V

Core Material
- Ferrite N87
- U-cores U96/76/30

Windings
- Square Litz Wire

Cooling
- Winding - Forced air
- Core - Heatsinks (Forced air)

Insulation
- PTFE (teflon)

MFT dimensions
- Volume: ≈ 20 l
- V-Density: ≈ 8.21 kW/l
- Weight: not reported
- W-Density: not reported

Insulation Tests
- No details provided

166kW MFT by ETH [15]
**Construction**
- Core Type

**Electrical Ratings**
- Power: 450kW
- Frequency: 8kHz
- Input Voltage: ±1800V
- Output Voltage: ±1800V

**Core Material**
- Nanocrystalline
- C cores

**Windings**
- Square Litz Wire

**Cooling**
- Winding - Oil
- Core - Air cooled

**Insulation**
- Solid combined with Oil
- Core in the air

**MFT dimensions**
- Volume: ? l
- V-Density: ≈ ? kW/l
- Weight: 50 kg
- W-Density: ≈ 9 kW/kg

**Insulation Tests**
- PD: 37kV, 50Hz (PD < 5pC)
- BIL: not specified

---

**Railway**

**MF Transformer for Traction**

- MF transformer directly linked to catenary (15 kV @ 16 2/3 Hz, 25 kV @ 50 Hz)
- Cascadable – e.g. 9 x 450 kW = 4 MW
- High Voltage P.D. stable insulation system up to 37 kVrms (P.D. < 5 pC)
- Switching frequency: 8 kHz
- Power: 450 kW / 600 kVA (single transformer)
- Weight: 50 kg
- Efficiency: 99.7 %

**Applications**
- Distributed traction power supply possible
- Reducing system weight by 40 %
- Long life time due to P.D. free solid-fluid insulation system
- Low noise
- Environmental insulation and cooling system of transformer

**Your benefits**
- Distributed traction power supply possible
- Reducing system weight by 40 %
- Long life time due to P.D. free solid-fluid insulation system
- Low noise
- Environmental insulation and cooling system of transformer

---

www.sts-trafo.de
Construction
- Core Type

Electrical Ratings
- Power: 240kW
- Frequency: 10kHz
- Input Voltage: ±600V
- Output Voltage: ±900V

Core Material
- Nanocrystalline
- U cores (custom)

Windings
- Litz Wire (4 parallel)

Cooling
- Winding - Air
- Core - Air

Insulation
- Solid - Cast Resin
- Air

MFT dimensions
- Volume: ≈ 67.7 l
- V-Density: ≈ 3.6 kW/l
- Weight: ≈ 42 kg
- W-Density: ≈ 5.7 kW/kg

Insulation Tests
- PD: 53kV, 50Hz
- BIL: 150kV
Construction
- Core Type

Electrical Ratings
- Power: 100kW
- Frequency: 15kHz - 22kHz
- Input Voltage: ±540V
- Output Voltage: ±540V x 24

Core Material
- Nanocrystalline
- U cores

Windings
- Litz Wire

Cooling
- Winding/Core - Oil Immersed
- MFT assembly - Air

Insulation
- Oil (Ester)

MFT dimensions
- Volume: ≈ 91 l (61 l without heatsink)
- V-Density: ≈ 1.1 kW/l
- Weight: ≈ 90 kg
- W-Density: ≈ 1.1 kW/kg

Insulation Tests
- PD: 30kV, 50Hz
- BIL: not reported
Construction

- Core Type

Electrical Ratings

- Power: 100kW
- Frequency: 10kHz
- Input Voltage: ±750V
- Output Voltage: ±750V

Core Material

- SiFerrite (UU9316 - CF139)
- U cores

Windings

- Square Litz Wire

Cooling

- Winding - Air
- Core - Air cooled heatsink

Insulation

- Air

100kW MFT by EPFL [20], [21]

MFT dimensions

- Volume: ≈ 12.2 l
- V-Density: ≈ 8.2 kW/l
- Weight: ≈ 28 kg
- W-Density: ≈ 3.6 kW/kg

Insulation Tests

- PD: 6kV, 50Hz
- BIL: not performed

MFT by EPFL
SUMMARY - MFT DESIGNS

Variety of MFT designs
- Shell Type, Core Type, C-Type
- Copper, Aluminum
- Solid wire, Hollow conductors, Litz wire, Foil
- SiFe, Nannocristalline, Amorphous, Ferrite

Integration with Power Electronics
- Insulation coordination
- Cooling
- Electrical parameters
- Choice of core materials
- Form factor constraints
- Optimization at the system level

Custom designs prevail
There is no best design...

Limited commercial options. Example: STS ⇒

▲ Another overview of MFTs reported in literature [22]
MATERIALS

What design choices are available?
TECHNOLOGIES AND MATERIALS

Construction Choices:

- MFT Types
  - Shell Type
  - Core Type
  - C-Type
  - Coaxial Type

- Winding Types
  - Litz Wire
  - Foil
  - Coaxial
  - Hollow

Materials:

- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - Ferrites

- Windings
  - Copper
  - Aluminum

- Insulation
  - Air
  - Solid
  - Oil

- Cooling
  - Air natural/forced
  - Oil natural/forced
  - Water
MAGNETIC MATERIALS - SILICON STEEL

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 \cdot 10^3</td>
<td>50 ~ 250 W/kg</td>
<td>2 \cdot 10^7 ~ 5 \cdot 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>
<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>0.5 ~ 1.6 T</td>
<td>0.8 · 10⁴ ~ 50 · 10⁴</td>
<td>2 ~ 20 W/kg</td>
<td>&lt; 5 · 10⁻⁶ 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>
<tr>
<th>Saturation B</th>
<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>$0.5 \cdot 10^4 \sim 100 \cdot 10^4$</td>
<td>$&lt; 50 \text{ W/kg}$</td>
<td>$3 \cdot 10^4 \sim 5 \cdot 10^5 \text{ S/m}$</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 10^5 ~ 20 \cdot 10^3</td>
<td>5 ~ 100 W/kg</td>
<td>&lt; 1 \cdot 10^{-5} 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

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

Copper Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity</td>
<td>58.5 \times 10^6 S/m</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>1.7 \times 10^{-8} \Omega m</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>401 W/mK</td>
</tr>
<tr>
<td>TEC (from 0\degree C to 100\degree 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 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity</td>
<td>36.9 \times 10^6 S/m</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>2.7 \times 10^{-8} \Omega m</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>237 W/mK</td>
</tr>
<tr>
<td>TEC (from 0\degree C to 100\degree 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>
**INSULATING MATERIALS**

**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

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

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

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 pumo
- 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 [23]
**INSULATING MATERIALS - SOLID**

**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)
ABB: 350kW, 10kHz

IKERLAN: 400kW, 1kHz

STS: 450kW, 8kHz

IKERLAN: 400kW, 5kHz

ABB: 3x150kW, 1.8kHz

FAU-EN: 450kW, 5.6kHz

KTH: 170kW, 4kHz

ACME: ???kW, ???kHz

BOMBARDIER: 350kW, 8kHz

CHALMERS: 50kW, 5kHz

ETHZ: 166kW, 20kHz

ALSTOM: 1500kW, 5kHz

ETHZ: 166kW, 20kHz

EPFL: 300kW, 2kHz

EPFL: 100kW, 10kHz

?
MFT MODELING
The underlying analytical descriptions?
MODELING: RELEVANT EFFECTS

- Core Losses
- Winding Losses
- Leakage Inductance
- Magnetizing Inductance
- Thermal Model
**MODELING: CORE LOSSES**

**Different core loss models:**
- Based on characterization of magnetic hysteresis [24], [25], [26]
- Based on loss separation [27]
- Time domain core loss model [28]
- Based on Steinmetz Equation (MSE [29], IGSE [30], iIGSE [31])

**Original Steinmetz Equation:**

\[ P_c = K f^\alpha B_m^\beta \]

**Improved Generalized Steinmetz Equation (IGSE):**

\[ P_c = \frac{1}{T} \int_0^T k_i \left| \frac{dB(t)}{dt} \right|^{1-a} (\Delta B)^{\beta-a} \, dt \]

\[ k_i = \frac{K}{(2\pi)^{a-1} \int_0^{2\pi} |\cos(\theta)|^{a-2} \beta^{\beta-a} \, d\theta} \]

**Characteristic Waveform:**

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

**Application of IGSE on the Characteristic Waveform:**

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

\[ k_i = \frac{K}{2^{\beta-1} \pi^{a-1} \left(0.2761 + \frac{1.7061}{a+1.354}\right)} \]
**MODELING: WINDING LOSSES**

**Foil Winding Electromagnetic Field Analysis:**
- Dowell foil winding loss model [32]
- Porosity factor validity analysis [33], [34]
- Round wire winding loss model [35]
- ...

**Foil Winding Electromagnetic Field Analysis:**
\[
H_y = H_{ext} \frac{\sinh(ax)}{\sinh(ad_{eq})} - H_{int} \frac{\sinh(a(x - d_{eq}))}{\sinh(ad_{eq})}
\]
\[
J_z = aH_{ext} \frac{\cosh(ax)}{\sinh(ad_{eq})} - aH_{int} \frac{\cosh(a(x - d_{eq}))}{\sinh(ad_{eq})}
\]
\[
a = \frac{1 + j}{\delta}; \quad \delta = \sqrt{\frac{\rho}{\pi \mu f}};
\]

**Foil Winding Loss Calculation:**
\[
P_\sigma = \frac{1}{\sigma} \int JJ^* dV; \quad P_\sigma = \frac{L_w L_w}{\delta h_w} m \left[ \zeta_1 + \frac{2}{3} (m^2 - 1) \zeta_2 \right];
\]
\[
\zeta_1 = \frac{\sinh(2\Delta) + \sin(2\Delta)}{\cosh(2\Delta) - \cos(2\Delta)}; \quad \zeta_2 = \frac{\sinh(\Delta) - \sin(\Delta)}{\cosh(\Delta) + \cos(\Delta)}; \quad \Delta = \frac{d_{eq}}{\delta};
\]

**Winding Equivalence:**
\[
d_{eq} = d_i \sqrt{\frac{\pi}{4}}; \quad d_i = \frac{d_w - N_{sh} d_{eq}}{N_{sh} - 1}; \quad m = N_{sh};
\]
\[
N_{sh} = \sqrt{\frac{N_s}{K_w}}; \quad N_{sv} = \sqrt{K_w N_s};
\]
\[
K_w = \frac{h_w}{d_w}; \quad \Delta' = \sqrt{\eta} \Delta; \quad \eta = \frac{d_{eq} N_{sv}}{H_w};
\]

---

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October 18, 2017

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MODELING: F-DEPENDENT LEAKAGE INDUCTANCE

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

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

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

\[ + \frac{d_d}{\omega} \]

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

\[ + d_{w1i} \frac{(m_{w1} - 1)(2m_{w1} - 1)}{6m_{w1}} \]

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

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

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

where:

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

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

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

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

Hybrid Leakage Inductance Model [36]:

- Rogowski correction factor:
  \[ h_{eq} = \frac{h_w}{K_R} \]

  \[ K_R = 1 - \frac{1 - e^{-\pi h_w/(d_{w1} + d + d_{w2})}}{\pi h_w/(d_{w1} + d + d_{w2})} \]

- Correction of Dowell’s model (\(H_w \rightarrow h_{eq}\)):
  \[ L_\sigma = N_1^2 \mu_0 \frac{l_w}{H_w} \left[ \frac{d_{w1eq}m_{w1}}{3} F_{w1} + \frac{d_{w2eq}m_{w2}}{3} F_{w2} + d_d + d_{w1i} \frac{(m_{w1} - 1)(2m_{w1} - 1)}{6m_{w1}} + d_{w2i} \frac{(m_{w2} - 1)(2m_{w2} - 1)}{6m_{w2}} \right] \]

  \[ \Delta' = \sqrt{\eta \Delta}; \quad \eta = d_{eq} \frac{N_{sv}}{H_w}; \]
MODELING: LEAKAGE INDUCTANCE (HYBRID MODEL)

Influence of Winding Geometry on Leakage inductance:

![Image showing leakage inductance models for different winding geometries](image)

Hybrid Leakage Inductance Model:

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

  \[ \Delta' = \sqrt{\eta \Delta}; \quad \eta = d_{eq} \frac{N_{sv}}{h_{eq}}; \]
Magnetic Circuit with an Air-Gap:

Magnetizing Inductance Calculation:

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

Air-Gap Calculation:

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

Fringing Effect:

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

![Graphs showing the relationship between Fringing Factor (F_{FR}) and Air-Gap (d) for different values of H_w.](Image)

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Conduction

\[ Q_h = kA \frac{\Delta T}{L} \]

Top:

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

Side:

\[ h = \frac{k0.27R_{al}^{1/4}}{L} \quad L = \text{Height} \]

Bottom:

\[ h = \frac{0.825 + \frac{0.387R_{al}^{1/6}}{\left(1 + (0.492/Pr)^{9/16}\right)^{8/27}}}{L} \]

Convection over Hot-Plate

\[ Q_h = hA(T_s - T_\infty) \]

Radiation

\[ Q_h = hA(T_1 - T_2) \]

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

where: \( R_{al} \) - Rayleigh number, \( Pr \) - Prandtl number, \( \varepsilon \) - Emissivity, \( \sigma \) - Stefan–Boltzmann constant [37, [38], [39]
MODELING: THERMAL MODEL

Modes Of Heat Transfer:

- Conduction
- Convection
- Radiation

Partitioning Into Zones:

- Top Cooler
- Zone 1 (Top Yoke)
- Zone 2 (Outer Limb)
- Zone 3 (Bottom Yoke)
- Zone 4 (Center Limb)
- Bottom Cooler
- Axis of Geometric Symmetry

Detailed Thermal Network Model:

Diagram showing thermal network model with various components and connections.
MODELING: THERMAL MODEL

Modes Of Heat Transfer:

▶ Conduction
▶ Convection
▶ Radiation

Partitioning Into Zones:

Planes of Symmetry:

Detailed Thermal Network Model:
MODELING: THERMAL MODEL

Modes Of Heat Transfer:
- Conduction
- Convection
- Radiation

Planes of Symmetry:

Partitioning Into Zones:

Detailed Thermal Network Model:
MODELING: THERMAL MODEL

Modes Of Heat Transfer:

▶ Conduction
▶ Convection
▶ Radiation

Partitioning Into Zones:

Planes of Symmetry:

Detailed Thermal Network Model:
Implementation of Thermal Network Model:

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

- Rearranging the nodes:
  \[
  \begin{bmatrix}
  Q_{A(m)} \\
  0_{(p)}
  \end{bmatrix} = \begin{bmatrix}
  Y_{thAA(m \times m)} & Y_{thAB(m \times p)} \\
  Y_{thBA(p \times m)} & Y_{thBB(p \times p)}
  \end{bmatrix} \begin{bmatrix}
  \Delta T_{A(m)} \\
  \Delta T_{B(p)}
  \end{bmatrix}
  \]

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

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

Analytical Model Results for the optimal MFT prototype:

<table>
<thead>
<tr>
<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>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>
MODELING: THERMAL FEM ANALYSIS

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

<table>
<thead>
<tr>
<th>Hot-spot nodes</th>
<th>$T_1 \degree C$</th>
<th>$T_2 \degree C$</th>
<th>$T_3 \degree C$</th>
<th>$T_4 \degree C$</th>
<th>$T_6 \degree C$</th>
<th>$T_9 \degree C$</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?
TECHNOLOGIES AND MATERIALS

Construction Choices:

▶ MFT Types

- Shell Type
- Core Type
- C-Type
- Coaxial Type

▶ Winding Types

- Litz Wire
- Foil
- Coaxial
- Hollow

Materials:

▶ Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - Ferrites

▶ Windings
  - Copper
  - Aluminum

▶ Insulation
  - Air
  - Solid
  - Oil

▶ Cooling
  - Air natural/forced
  - Oil natural/forced
  - Water
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:**

  \[
  \begin{align*}
  P_n &\quad 100kW \\
  f_{sw} &\quad 10kHz \\
  V_1 &\quad 750V \\
  V_2 &\quad 750V \\
  L_{\sigma1,2} &\quad 3.27\mu H \\
  L_m &\quad 1.8mH
  \end{align*}
  \]
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<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>
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<td>3.27 $\mu$H</td>
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    L_m &\quad 1.8mH \\
    f_{sw} &\quad 10kHz
  \end{align*}
  \]
DESIGN OPTIMIZATION: ALGORITHM

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  \begin{align*}
  P_n & = 100kW \\
  V_1 & = 750V \\
  V_2 & = 750V \\
  L_{\sigma 1,2} & = 3.27\mu H \\
  L_m & = 1.8mH \\
  f_{sw} & = 10kHz
  \end{align*}
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</table>

**MFT design optimization algorithm**
## DESIGN OPTIMIZATION: RESULTS

### Applied Filters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{W_{\text{max}}}$</td>
<td>°C</td>
<td>150</td>
</tr>
<tr>
<td>$T_{C_{\text{max}}}$</td>
<td>°C</td>
<td>100</td>
</tr>
<tr>
<td>$V_{\text{max}}$</td>
<td>l</td>
<td>/</td>
</tr>
<tr>
<td>$M_{\text{max}}$</td>
<td>kg</td>
<td>/</td>
</tr>
<tr>
<td>$\eta_{\text{min}}$</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>$T_{W\text{max}}$ [$^\circ$C]</th>
<th>$T_{C\text{max}}$ [$^\circ$C]</th>
<th>$V_{\text{max}}$ [l]</th>
<th>$M_{\text{max}}$ [kg]</th>
<th>$\eta_{\text{min}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>100</td>
<td>12</td>
<td>25</td>
<td>99.7</td>
</tr>
</tbody>
</table>

Number of Designs:

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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>130</td>
<td>80</td>
<td>9</td>
<td>24</td>
<td>99.72</td>
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Number of Designs:
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▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature
**DESIGN OPTIMIZATION: RESULTS**

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</tr>
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<tbody>
<tr>
<td>135</td>
<td>80</td>
<td>10</td>
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</tbody>
</table>

Number of Designs:

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Number of Designs:
- More than 1.8 Million

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

Optimal MFT Design 3D-CAD
Coil-Formers 3D-CAD
Coil-Formers 3D-Print
Primary Winding
Secondary Winding

Core Assembly
MFT Assembly1
MFT Assembly2
Litz-Wire Termination
MFT Prototype
**Prototype 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>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<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>$L_{\sigma 1,2}$</td>
<td>4.2μH</td>
</tr>
<tr>
<td>$L_m$</td>
<td>750μH</td>
</tr>
</tbody>
</table>

- 100kW, 10kHz MFT including resonant capacitors

Ee 2017, Novi Sad, Serbia

October 18, 2017
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:

Electrical measurements using Bode100

Series Resistance Measurement:

Leakage Inductance Measurement:
MEASUREMENTS: DIELECTRIC PARAMETERS

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

HV Measurement Setup:
- ▲ MFT during AC test

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

Measured PD at flat back \( V = 4kV \):
- ▲ MPD600 obtained measurement results
Test Setup Topology:
- B2B Resonant Converter
- Input voltage maintained by $U_{DC}$
- Power circulation via $I_{DC}$

Measurement Results:

- $U_{12}$ [V]
- $U_{Cr1}$ [V]
- $I_1$ [A]
- $U_{34}$ [V]
- $U_{Cr2}$ [V]
- $I_2$ [A]

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October 18, 2017

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

Measurement Setup:

Thermal Run:

► No-Load Operation:

► Full-Load Operation:

Thermal Profile:

Cooler Central Point Temperature [°C]

Core Outer Limb Hot-Spot Temperature [°C]

Secondary Winding Hot-Spot Temperature [°C]

▲ Thermal heat run results

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CONCLUSION

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

Components & Materials

Algorithm

Design Selection

Prototype

3D-Design

Testing

Ee 2017, Novi Sad, Serbia

October 18, 2017
CONCLUSION

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

**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 90 scientific publications and has filed eleven patents.

In 2014, he received The Isao Takahashi Power Electronics Award for Outstanding Achievement in Power Electronics, presented at International Power Electronics Conference, IPEC-Hiroshima 2014, Japan. 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 pursuing 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 and EPE Student Member.
ACKNOWLEDGEMENT

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REFERENCES


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Q AND A

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