HIGH-POWER MV MFT DESIGN OPTIMIZATION CHALLENGES

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The workshop is chaired by Prof. Drazen Dujic, EPFL (Switzerland) and Prof. Johann W. Kolar, ETH Zürich (Switzerland)

All presentations and discussions will be in English.
Online since February 2014
Currently: 12 PhD students, 1 Post Doc, 1 Scientist
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

**Components**
- Semiconductor devices
- Magnetics
- Characterization
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: $\approx 10kUSD / MW$
- 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
MEDIUM-HIGH FREQUENCY CONVERSION

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
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
ABB - 1.2 MW 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 [1], [2]
ABB - 1.2 MW 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 [1], [2]

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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
MEDIUM FREQUENCY TRANSFORMERS

What are the design challenges?
WHY MFT?

- 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

\[
AP = \frac{Pt}{KfKuBmJf} = \frac{Power}{size} \quad \text{waveform} \quad \text{insulation} \quad \text{material} \quad \text{cooling} \quad \text{frequency}
\]

- Approximate transformer scaling relation
- Example: frequency impact on the transformer size (Prof. Akagi)
MFT HALL OF FAME - WHICH ONE IS THE BEST MFT?

**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
MATERIALS, TECHNOLOGIES, DESIGN CHOICES

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

What design choices are available?
**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>
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<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 ~ 1.6 T</td>
<td>0.8 \cdot 10^4 ~ 50 \cdot 10^4</td>
<td>2 ~ 20 W/kg</td>
<td>&lt; 5 \cdot 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 · 10^4 ~ 100 · 10^4</td>
<td>&lt; 50 W/kg</td>
<td>3 · 10^4 ~ 5 · 10^5 S/m</td>
</tr>
</tbody>
</table>

Example: Measured B-H curve of VITROPERM 500F
**MAGNETIC MATERIALS - FERRITES**

**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 (-0.4) T 0.1 (-0.3) (10^3) (-0.2) (10^3) (-0.1) (10^3) (-0.0) (10^3)</td>
<td>5 (100) W/kg</td>
<td>&lt; 1 (10^{-5}) S/m</td>
<td></td>
</tr>
</tbody>
</table>

▲ Example: Measured B-H curve of Ferrite N87

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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.it.iwatsu.co.jp/en

▲ EPFL characterisation setup for magnetic materials
WINDINGS

Few options only...
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/cm$^3$</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/cm$^3$</td>
</tr>
<tr>
<td>Melting point</td>
<td>660 °C</td>
</tr>
</tbody>
</table>
INSULATION MATERIALS

What is the working voltage? PD? BIL?
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**

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

- \( V_{BD} \) 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 [4]
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)

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DESIGN CHALLENGES

Using materials and technologies optimally...
MFT DESIGN CHALLENGES

- Skin and proximity effect losses
- Cooling
- Non-sinusoidal excitation
- Insulation
- Accurate electric parameter control

▲ left: Transformer equivalent scheme; middle: typical waveforms for resonant operation; right: MFT heat evacuation issues
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
- $0.1 \text{ [Hz]} \ (\Delta = 0.01)$
- $\Delta$ - the penetration ratio
- $H \text{ [mA/m]}$
- $J \text{ [A/mm}^2\text{]}$
- $H$ and $J$ distribution within the core window area
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Example of the Foil Winding MFT Geometry Cross-Section

- Generic foil winding geometry
- $\Delta$ - the penetration ratio

$H$ [mA/m]

$J$ [A/mm²]

$0.1 \text{ [Hz]}$ ($\Delta = 0.01$)

$100 \text{ [Hz]}$ ($\Delta = 0.3$)

$\Delta$ - H and J distribution within the core window area
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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

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**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](image1)

![Partially utilized core window height](image2)
THERMAL COORDINATION

MFT Losses:
▶ Winding Losses
▶ Core Losses

Heat Transfer Mechanisms:
▶ Conduction

▶ Convection

▶ Radiation

Qualitative Analysis:

Heat transfer

\[ Q_h = h A \Delta T \]

Temperature gradient

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

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

Temperature Distribution Example:
THERMAL COORDINATION (CONT.)

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

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

The diagram illustrates a detailed thermal network with multiple components such as resistances ($R$) and temperatures ($T$), connected in series and parallel configurations. The network is partitioned into different zones, with specific components like convective ($C$) and radiation ($R$) resistances, and core ($C$) and secondary ($S$) elements. The model includes various temperature values and connections that are typical in thermal modeling to understand the heat distribution and transfer within the system.
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

Voltage Distribution

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

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

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

![Transformer equivalent scheme; middle: typical waveforms for resonant operation; right: MFT heat evacuation issues](image)
MFT DESIGN OPTIMIZATION

Maximizing performances over the available design space?
MFT DESIGN OPTIMIZATION

EPFL PhD: Villar [6]
EPFL: 300kW, 2kHz

ETHZ PhD: Ortiz [7]
ETHZ: 166kW, 20kHz

CHALMERS PhD: Bahmani [8]
CHALMERS: 50kW, 5kHz
MFT DESIGN OPTIMIZATION (CONT.)

Focus

- High voltage MFT design - insulation coordination
- Precise parameter control - resonant operation
- High power conversion - thermal design
- Characterization of magnetic materials

Design algorithm

Optimization

Prototype

- \( P = 100 \text{ kW} \)
- \( V_p = V_s = 750 \text{ V} \)
- \( f_{sw} = 10 \text{ kHz} \)
MFT dimension analysis for constant $B_m$ and $J$

<table>
<thead>
<tr>
<th></th>
<th>Formula</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Surface</td>
<td>$S_c = C_1 f^2$</td>
<td>$k^2$</td>
</tr>
<tr>
<td>Volume and Mass</td>
<td>$M = \gamma V = C_2 f^3$</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>$P = UI$</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>$P_{Cu} = F R f^2$</td>
<td>$F(f) k^3$</td>
</tr>
<tr>
<td>Core Losses</td>
<td>$P_{Fe} = K f^a B_m f^b V$</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>$(F(f) + f^a) / (kf)$</td>
</tr>
<tr>
<td>Relative Cost</td>
<td>$\varepsilon = M / P$</td>
<td>$1 / (kf)$</td>
</tr>
</tbody>
</table>

Where: $F(f)$ - skin and proximity effect correction factor
SUMMARY

**Variety of MFT designs**
- Shell Type, Core Type, C-Type
- Copper, Aluminum
- Solid wire, Hollow conductors, Litz wire, Foil
- SiFe, Nannocrystalline, 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 [9]
REFERENCES


ECPE Workshop pdf can be downloaded from:

- https://pel.epfl.ch/publications_talks_en
HIGH-POWER MV MFT DESIGN OPTIMIZATION CHALLENGES

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