ETH zürich

Power Electronic Systems Laboratory

Medium-Frequency Transformers
for Smart Grid Applications: Challenges and Opportunities

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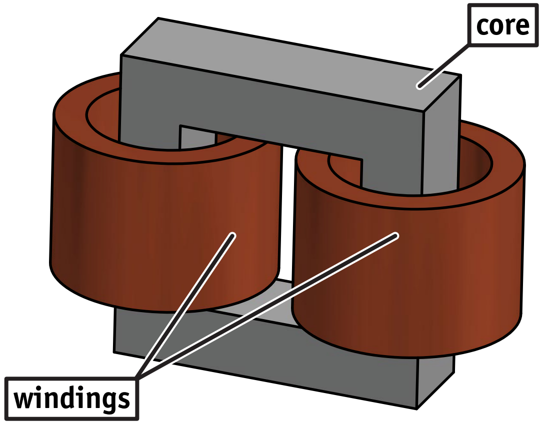
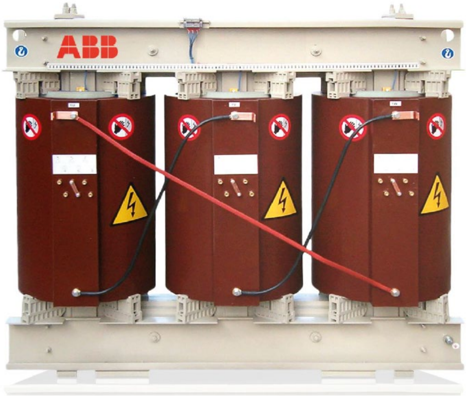
Transformers: Principle

- **Construction**
  - One **magnetic core**
  - Two **windings** (at least)
- **Functionalities**
  - **Voltage conversion**
  - **Galvanic insulation**
- **Usages**
  - **Isolation** (converters, drives, etc.)
  - Interfacing of **different voltages**
- **Key component of power grids**
  - **Efficiency**
  - **Weight / volume**
  - **Functionalities**

▼ Transformer Schematic



▼ Transformer / 1 MVA / 50 Hz



[ABB]

Transformers: Performances

- **Low-Frequency Transformer (LFT)**
- **Advantages**
  - Relatively **inexpensive**
  - Highly **robust / reliable**
  - Highly **efficient** (98.0% to 99.5%)
- **Weaknesses**
  - **Voltage drop** under load
  - **Not directly controllable**
  - **Large volume / heavy**
  - **Fire hazards**
  - **Only AC** (no DC)
- **Compatible with future applications?**

▼ **Welding Transformer**

[africancrisis.org]

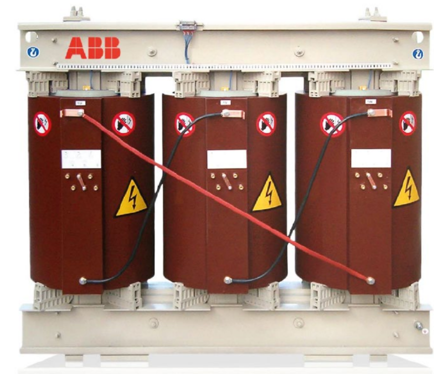
Transformers: Limitations

▼ Transformer / Stanley / 1885

[Edison Tech Center]

130 years

▼ Modern Transformer

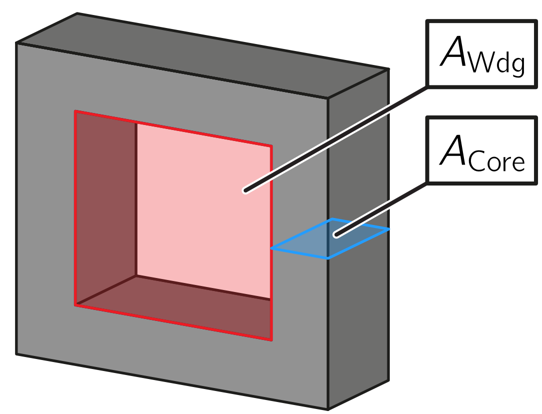


[ABB]

- **Similar geometry and materials**
- **Similar performances**
- **Where are the limitations?**
  - $A_{\mathrm{Wdg}} A_{\mathrm{Core}} = \frac{\sqrt{2}}{\pi} \frac{P}{k_{\mathrm{w}} J_{\mathrm{RMS}} B_{\mathrm{p}} f}$
  - **Physical limitations**

P : Rated Power
k_{w} : Fill factor
J_{RMS} : Current density
B_{p} : Flux density
f : Frequency

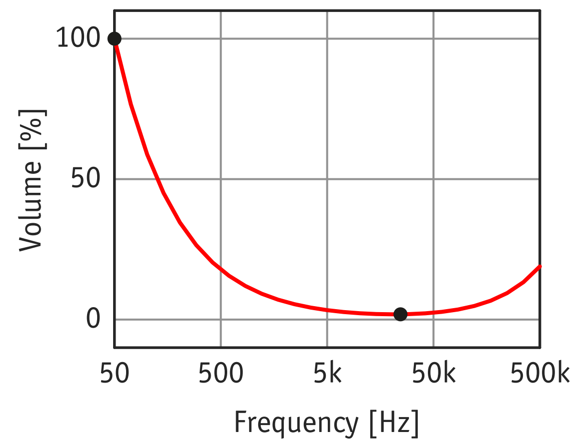
▼ Area Product



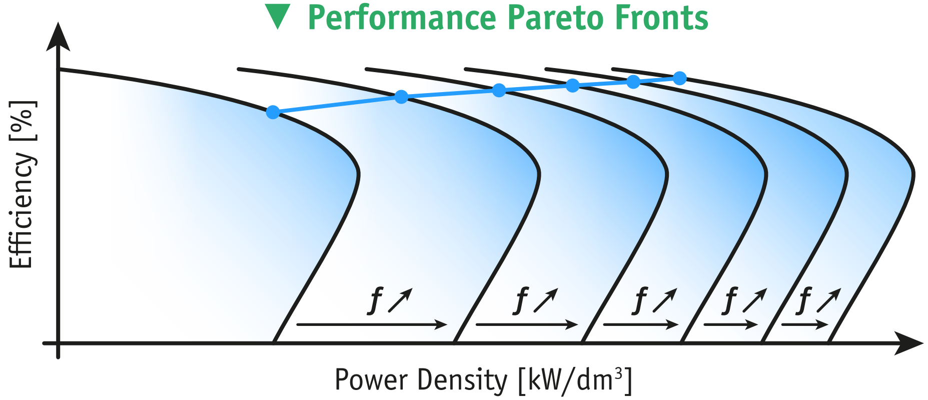
Transformers: Scaling Laws

- **Scaling laws**
  - $A_{\mathrm{Wdg}} A_{\mathrm{Core}} = \frac{\sqrt{2}}{\pi} \frac{P}{k_{\mathrm{w}} J_{\mathrm{RMS}} B_{\mathrm{p}} f}$
  - $V \propto (A_{\mathrm{Wdg}} A_{\mathrm{Core}})^{\frac{3}{4}} \propto \frac{1}{f^{\frac{3}{4}}}$
- **Medium-Frequency Transformer (MFT)**
- **Increased power density**
- **Increased efficiency**

▼ Scaling Laws



▼ Performance Pareto Fronts



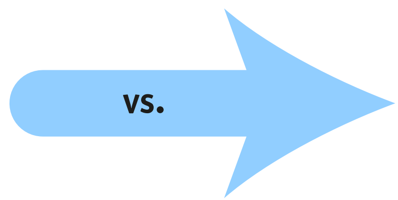
▼ Traction MFT

Transformers: Comparison LFT/MFT

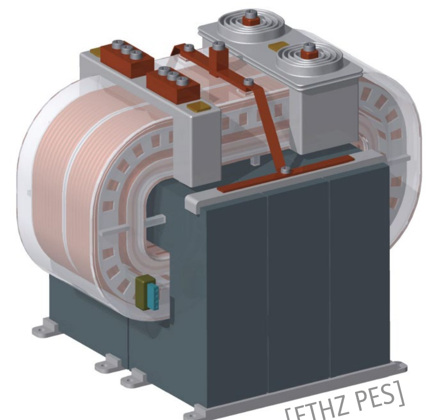
- Single phase **25 kW MV/LV transformer**
- Comparison is **“not fair”** (for both sides)

▼ 60 Hz

[HPS MILLENNIUM]



▼ 50 kHz



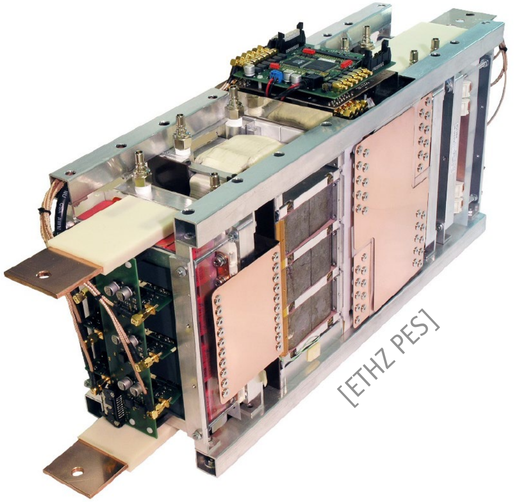
[ETHZ PES]

25 kVA	≈	31 kVA
5 kV / 240 V	≈	4 kV / 400 V
60 Hz	x 800	50 kHz
98.3%	+ 1.2%	99.5%
230 dm^3	÷ 80	2.8 dm^3
160 kg	÷ 30	5.1 kg

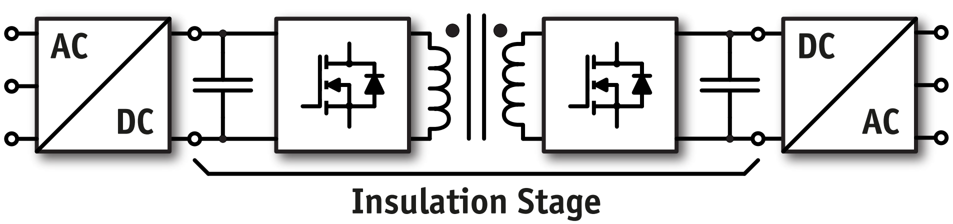
Challenges: #1 Power Electronic

- **No MF grids or loads**
- **AC-DC / DC-DC** converters
- **Advantages**
  - **Voltage / current** control
  - **DC / AC** buses
- **Weaknesses**
  - **Complexity / robustness**
  - **Costs / efficiency**
- **MFT requires converters**

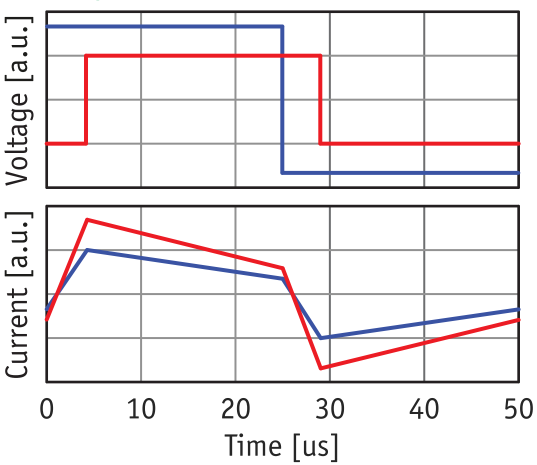
▼ **160 kW / 20 kHz / DC-DC**



▼ **Typical MV/MF Energy Conversion**



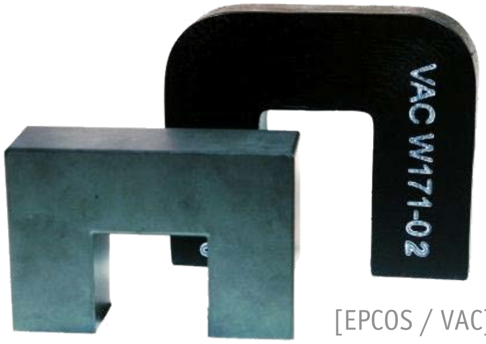
▼ **Typical Transformer Excitation**



Challenges: #2 Core Losses

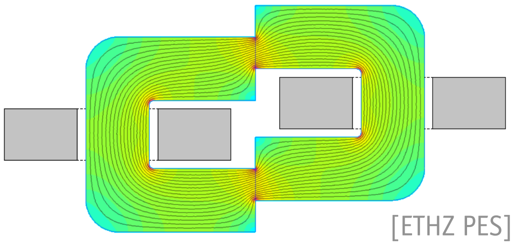
- **Critical at MF**
  - **Hysteresis**
  - **Eddy currents**
  - Non-sinusoidal flux
- **Other materials**
  - Silicon steel [0.1-1 kHz]
  - Nanocrystaline [1-20 kHz]
  - Ferrite [10-300 kHz]
- Lower **saturation flux**
- **Loss computation** is difficult
- **Optimal frequency / flux density**

▼ **Ferrite / Nanocrystaline Cores**



[EPCOS / VAC]

▼ **Non-ideal Flux Distribution**



[ETHZ PES]

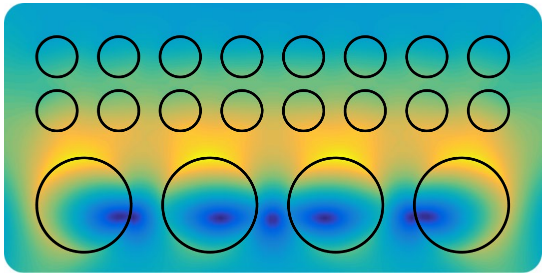
Challenges: #3 Winding Losses

- **Critical at MF**
  - **Skin** effect
  - **Proximity** effect
- **Other configurations**
  - **Foil** conductors
  - **HF litz** wires
- Lower **fill factor**
- **Loss computation** is difficult
- **Optimal frequency / wire**

▼ HF Litz Wire

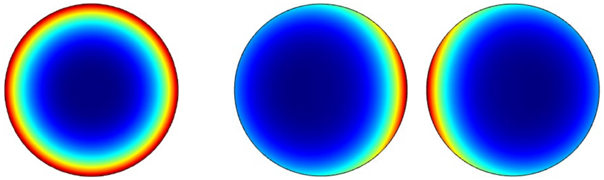
[Pack]

▼ Magnetic Stray Field



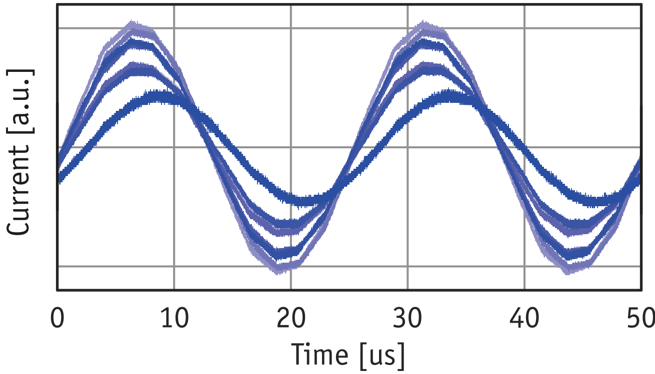
[ETHZ PES]

▼ Skin / Proximity Effects



[ETHZ PES]

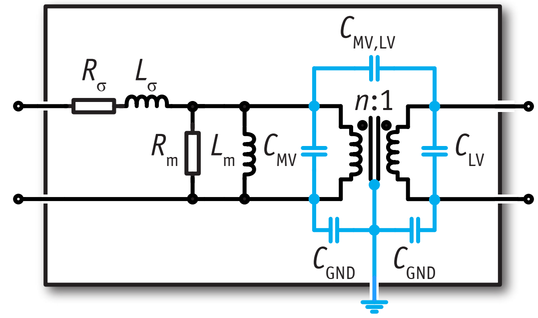
▼ Litz Wire Current Distribution



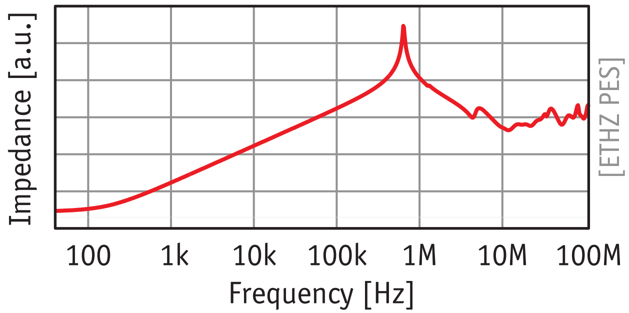
Challenges: #4 Parasitics

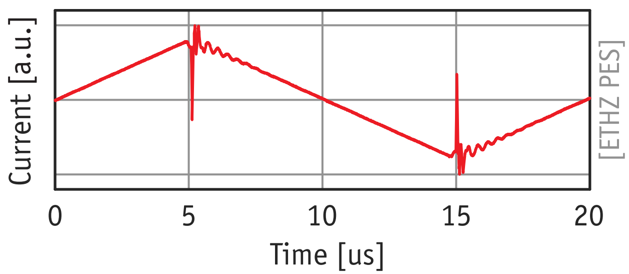
- **Magnetic parasitics**
  - **Leakage** flux
  - **Magnetizing** flux
- **Electric parasitics**
  - Winding **capacitances**
  - Earth **capacitances**
- **Problems**
  - Non-ideal current waveforms
  - **Oscillations**
  - **EMI** problems
- **Parasitics are more important at MF and HF**

▼ Transformer Equivalent Circuit



▼ Resonances

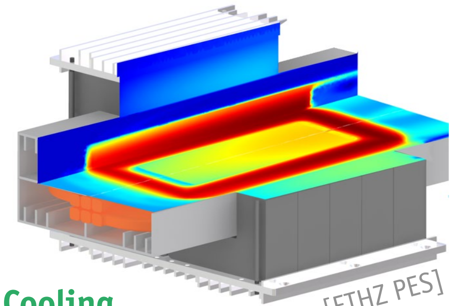




Challenges: #5 Heat Management

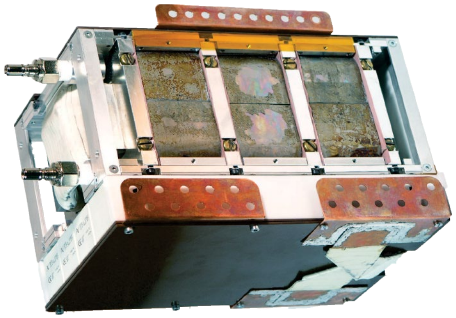
- Increased **loss density**
- Critical for the **cooling**
- **Dry-type**
  - **Convective** cooling
  - **Water** cooling
  - **Phase change** cooling
- **Oil-type**
- Efficient cooling is required

Forced Air Cooling



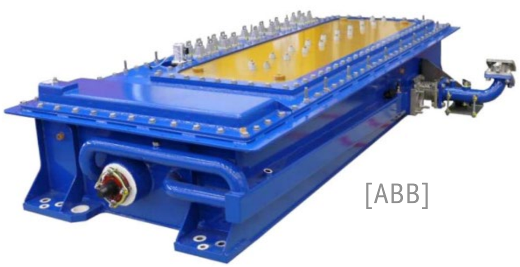
[ETHZ PES]

Water Cooling



[ETHZ PES]

Forced Oil Cooling



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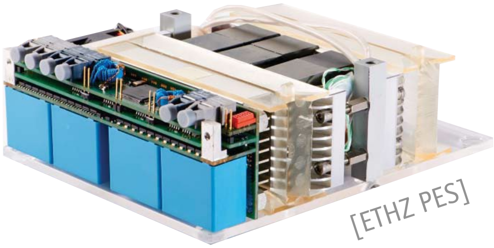
Phase Change Cooling



[ETHZ PES]

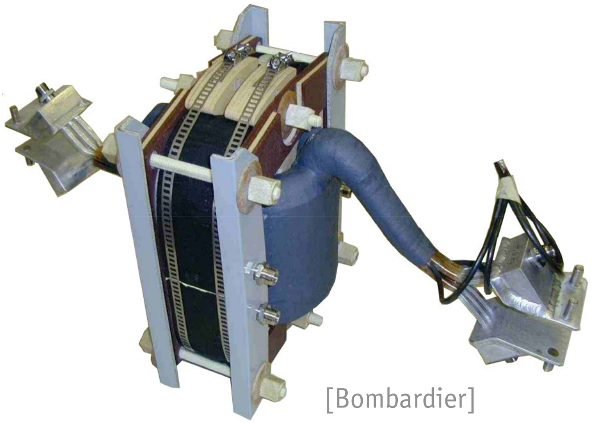
Challenges: #6 Insulation Coordination

- **MV** voltages (1-36 kV)
- **DC / AC / MF** voltages (DC-1 MHz)
- High **switching speeds** (5-80 kV/us)
- **Potential problems**
  - **Dielectric losses**
  - Thermal **breakdown**
  - Partial **discharges**
  - **Space charge** migration
  - Cracks / delamination / voids
- **Insulation type**
  - **Air** insulation
  - **Dry-type** insulation
  - **Oil** insulation
- **Reliability of MFT insulation is unclear**

▼ **Oil Insulation**

[Siemens]

▼ **Dry-type Insulation**

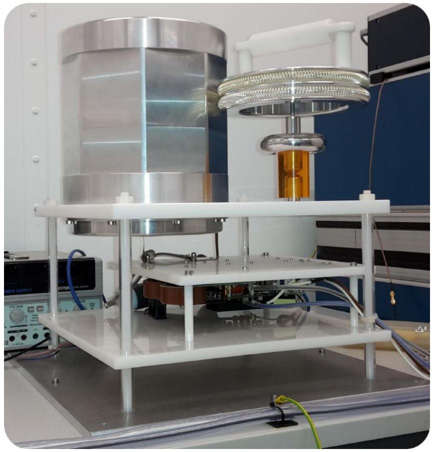


[Bombardier]

SCCER-FURIES: Insulation

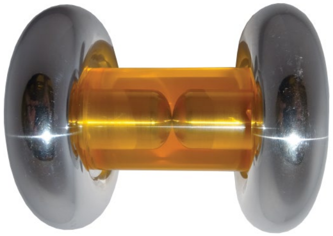
- **Insulation of MFTs**
  - **Material** testing
  - **Insulation** concept
- **MV/MF** insulation **test bench**
  - **30 kV AC or DC**
  - **2.5 kV PWM**
  - **Breakdown** / partial **discharges**
  - Dielectric **spectroscopy**
- **Selection of materials and concepts**

▼ Measurement Setup



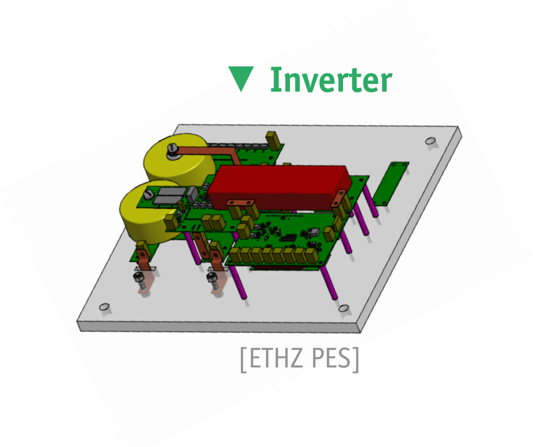
[ETHZ PES/HVL]

▼ Epoxy Specimen



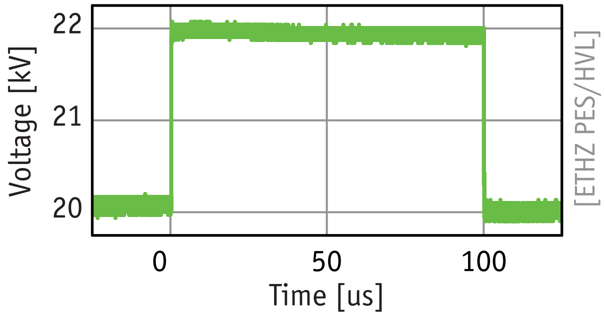
[ETHZ HVL]

▼ Inverter



[ETHZ PES]

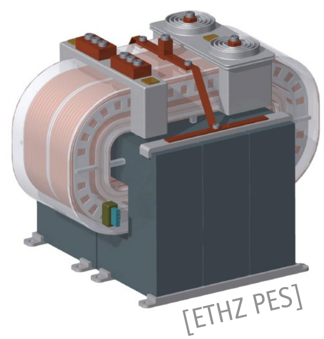
▼ Waveform



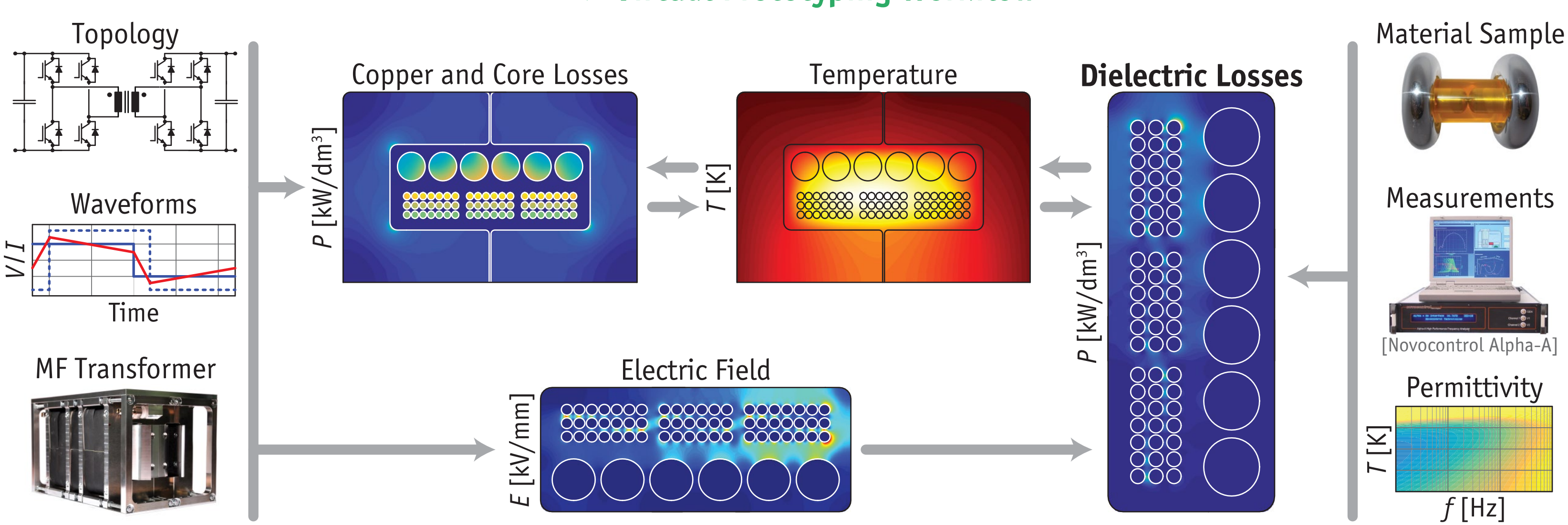
SCCER-FURIES: Transformer

- **Virtual transformer prototyping**
  - Copper / core / cooling losses
  - Temperature
  - **Insulation stress**
- **Design of a 7 kV / 50 kHz / 25 kW transformer**

▼ 25 kW / 50 kHz



▼ Virtual Prototyping Workflow

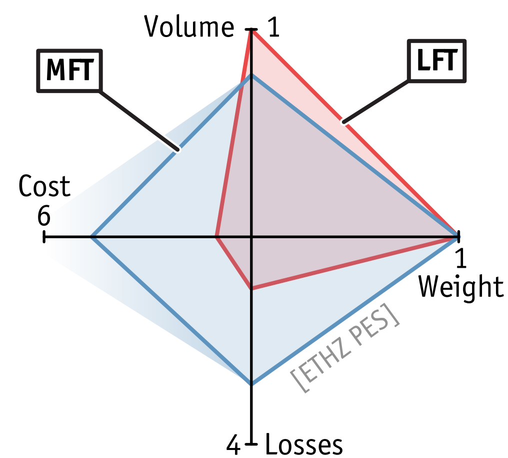


Applications: AC-AC

- **Efficiency** challenge
- **Cost / robustness** challenge
- **Compatibility** with existing devices

- **Alternative solutions**
  - **Tap changers** (already available)
  - **Series regulators** (already available)
  - **Hybrid transformers** (ETHZ HPE)
- MFTs are not replacing low-frequency transformers

▼ LFT / MFT: AC-AC



▼ MV Substation

[Siemens]

▼ Solid-State Transformer

[UNIFLEX]

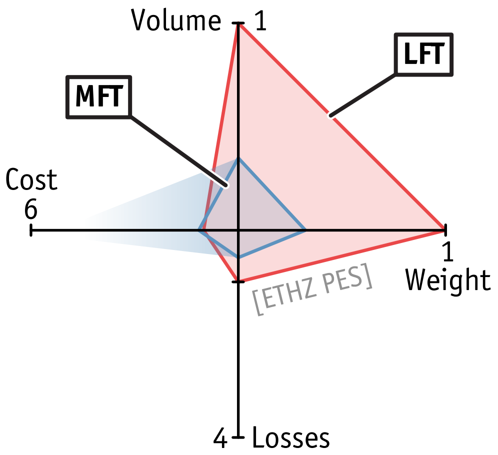
Applications: AC-DC / DC-DC

- **AC-DC**
  - **Efficiency / cost** challenge more balanced
  - **Robustness** challenge
  - **Datacenters**
  - **DC microgrids**

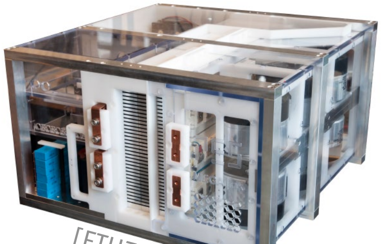
- **DC-DC**
  - **No other option**
  - **DC collecting** grids
  - **DC distribution** grids

- **MFTs are interesting for DC**

▼ **LFT / MFT: AC-DC**

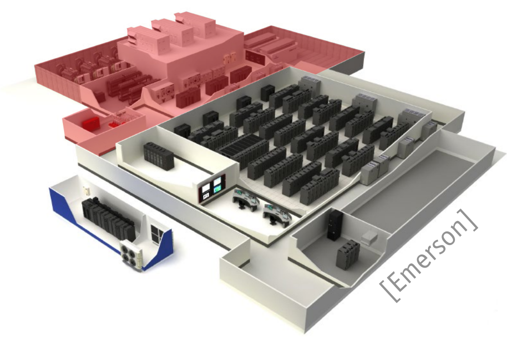


▼ **MV AC-DC Converter**



[ETHZ PES]

▼ **Datacenter**



[Emerson]

▼ **Offshore HVDC**

[ABB]

Applications: Weight / Space Limited

- Electric **mobility**
- Electric **traction**
- MV / DC **naval** applications
- More electric **aircrafts**

- **MFTs offers a competitive advantage**

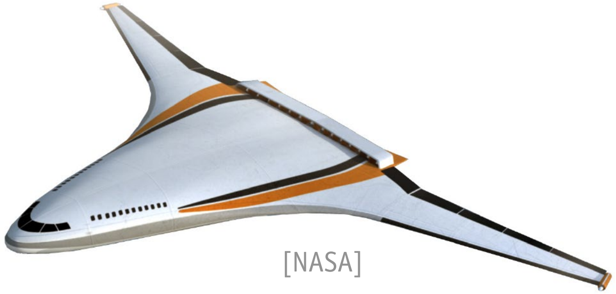
▼ **MFT-based Traction Chain**

[ABB]

▼ **MFT-based Locomotive**

[ABB]

▼ **Future Electric Aircraft**

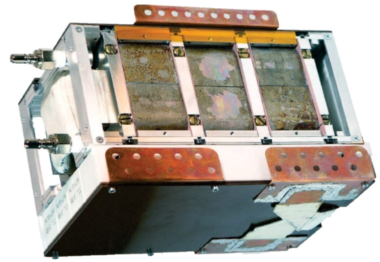


[NASA]

Conclusion

- Medium-frequency transformers
  - Increased **power density**
  - Increased **efficiency**
- **Challenges**
  - Require **power electronic**
  - **Magnetic / electric** design at MF
  - **Insulation / heat management**
- **Applications**
  - **AC-DC / DC-DC**
  - **Weight / space** constrained
- **MFTs are interesting for future grids**
- **MFTs are not replacing LFTs**

▼ 160 kW / 20 kHz

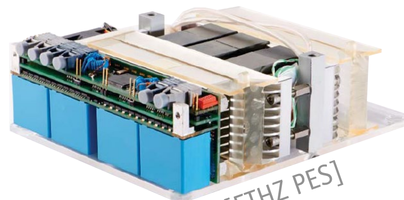


[ETHZ PES]

▼ 450 kW / 8 kHz

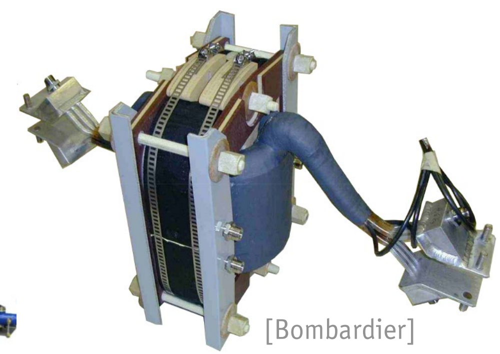
[STS Trafo]

▼ 6.3 kW / 100 kHz



[ETHZ PES]

▼ 350 kW / 8 kHz



[Bombardier]

▼ 150 kW / 1.75 kHz

[ABB]

Thank You! Questions?

Acknowledgement

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Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

References

[1] L. Heinemann, "An Actively Cooled High Power, High Frequency Transformer with High Insulation Capability", APEC, 2002
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[4] C. Zhao et al., "Power Electronic Traction Transformer - Medium Voltage Prototype", IEEE Trans. Ind. Electron., 2014
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