Superconducting Transformers
Prof. Dr.-Ing. Mathias Noe, Karlsruhe Institute of Technology
Institute for Technical Physics
EASITrain Summer School, September 3rd-7th 2018, Vienna
Motivation of Superconducting Transformers

- Motivation
- Different Types
- A few Basics
- State-of-the-Art
- Applications
- Summary
Motivation of Superconducting Transformers

Manufacturing and transport

- Compact and lightweight (~50 % Reduction)
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Environment and Marketing
- Energy savings (~50 % Reduction)
- Ressource savings
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- Inflammable (no oil)
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Operation
- Low short-circuit impedance
  - Higher stability
  - Less voltage drops
  - Less reactive power
- Active current limitation
  - Protection of devices
  - Reduction of investment
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Operation
- Low short-circuit impedance
  - Higher stability
  - Less voltage drops
  - Less reactive power
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  - Protection of devices
  - Reduction of investment

Enables a new class of transformers
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Different Types of Superconducting Transformers

**Warm Iron Core**
- Cryostat
- LN$_2$
- Iron Core

- Low Cooling Power
- Iron at Room Temperature
- Expensive Cryostat
- 3 Cryostats needed

**Cold Iron Core**
- Cryostat
- LN$_2$
- Iron Core

- Simple Cryostat
- Simple Cooling interface
- High Cooling Power (Iron core loss at low temp.)

**Conduction Cooled**
- Cryostat
- LN$_2$
- Iron Core

- Simple Cryostat
- Iron at Room Temperature
- Long recooling after quench
- Temperature difference
- Not suitable for high voltage
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Transformer Flux Linkage

Stray flux  Stray flux

Main flux

$\Phi_H \over 2$

$\Phi_H$

$H_\sigma$

$I_{os}$  $I_{us}$

M. Noe, EASITrain Summer School 2018, Vienna, Superconducting Transformers
Transformer Inductances

Main Inductance

\[ L_H = \mu_0 \cdot \mu_r \cdot w_{os}^2 \cdot \frac{A_{Fe,eff}}{\ell_{Fe}} \]

Stray Inductance

\[ L_\sigma = \frac{2\pi \cdot \mu_0 \cdot w_{os}^2}{h_w} \left( \frac{r_{us} \cdot b_{us}}{3} + r_{Spalt} \cdot a_w + \frac{r_{os} \cdot b_{os}}{3} \right) \]

\[ r_{os} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} + a_w + \frac{b_{os}}{2}, \quad r_{us} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} \quad \text{und} \quad r_{Spalt} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} + a_w \]
Electrical Circuit

\( f_H \): main flux
\( f_o \): stray flux

\( R_1 \): resistance primary winding
\( L_{1\sigma} \): Stray inductance primary winding
\( R_2 \): resistance secondary winding
\( L_{2\sigma} \): Stray inductance secondary winding
\( L_h \): main inductance
\( R_{FE} \): iron core loss

What is different between normal and superconducting transformers?
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# History of LTS Transformers

<table>
<thead>
<tr>
<th>Year</th>
<th>Organization</th>
<th>Country</th>
<th>Power in kVA</th>
<th>Data</th>
<th>Voltage per winding</th>
<th>Super-cond.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>GEC-Alstom</td>
<td>F</td>
<td>80</td>
<td>660V/1040V 124A/77A</td>
<td>2.14 V</td>
<td>NbTi</td>
</tr>
<tr>
<td>1988</td>
<td>Kyushu University</td>
<td>J</td>
<td>72</td>
<td>1057V/218V 68A/332A</td>
<td>-</td>
<td>NbTi</td>
</tr>
<tr>
<td>1991</td>
<td>Toshiba</td>
<td>J</td>
<td>30</td>
<td>100V/100V 300A/300A</td>
<td>-</td>
<td>NbTi</td>
</tr>
<tr>
<td>1991</td>
<td>Ktio</td>
<td>J</td>
<td>100</td>
<td>6600V/210V 15A/476A</td>
<td>4.57 V</td>
<td>Cu/NbTi</td>
</tr>
<tr>
<td>1992</td>
<td>Kyushu University</td>
<td>J</td>
<td>1000</td>
<td>3300V/220V 303A/4545A</td>
<td>10 V</td>
<td>NbTi</td>
</tr>
<tr>
<td>1993</td>
<td>ABB</td>
<td>CH</td>
<td>330</td>
<td>6000V/400V 56A/830A</td>
<td>7.9 V</td>
<td>NbTi</td>
</tr>
<tr>
<td>1995</td>
<td>Osaka University</td>
<td>J</td>
<td>40</td>
<td>460V/150V 50A/200A</td>
<td>0.45 V</td>
<td>NbTi</td>
</tr>
</tbody>
</table>

Source: Technik und Einsatz von HTSL Leistungstransformatoren, Diss. E. Sissimatos 2005
630 kVA Transformer (ABB)

Worldwide first field test of a superconducting transformer

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>630 kVA</td>
</tr>
<tr>
<td>Voltage</td>
<td>18 720 / 420 V</td>
</tr>
<tr>
<td>Group</td>
<td>Dyn11</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Short circuit impedance</td>
<td>4.6%</td>
</tr>
<tr>
<td>Current</td>
<td>11.2 / 866</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Cooling</td>
<td>LN$_2$ bei 77 K V</td>
</tr>
<tr>
<td>Losses at I$_r$</td>
<td>337 W @ 77 K</td>
</tr>
</tbody>
</table>

Quelle: H. Zueger et al, Cryogenics 1998 Volume 38, Number 11
1 MVA Transformers – 1996 - (Kyushu)

- Rated power: 1 MVA
- Rated Voltage: 22/6,9 kV
- Frequency: 60 Hz
- Short-circuit voltage: $u_k = 5\%$
- Cooling: subcooled LN$_2$ at 64 K
- Volume: 1,5 m x 1,2 m x 2,7 m (l x w x h)
- Weight: 5100 kg
- Bi-2223 Superconductor
- Losses: 160 W bei 65 K
- Successful Field Test

1 MVA Mobile Transformer - 2001 (Siemens)

- Rated Power: 1 MVA
- Rated Voltage: 25/1,4 kV
- Frequency: 50 Hz
- SC impedance: $u_k = 25\%$
- Cooling LN$_2$ at 67 K
- Volume: 0,88 m x 0,406 m x 1,08 m (l x w x h)
- Weight active part: 1010 kg
- Weight LN$_2$ Tank: 272 kg
- Length Bi-2223 tapes: 6,8 km
- Losses: 1960 W bei 67 K
- Efficiency: $\eta = 97,75\%$
- Efficiency of normal train transformers: $\eta = 92 - 95\%$
1 MVA Mobile Transformer – 2001 (Siemens)

Innovative conductor: transposed Roebel bar
- Bi-2223 tapes
  (3.65 x 0.258 mm²)
- 13 strand cable
- No cabling I_c degradation

Losses
- Iron Core: 700 W
- Stray field (Iron): 280 W
- Winding and current leads: 780 W
- Thermal losses: 200 W

Total loss: 1960 W @ 67 K
Total loss: 23 kW @ RT

Efficiency supercond.: 97.75%
Efficiency normal: 92-95 %

Transformer installed in frame
1 MVA Mobile Transformer - 2001 (Siemens)

HTS-Train transformer left
Normal train transformer right

HTS-Transformer in test field
## Major HTS Transformers Projects

<table>
<thead>
<tr>
<th>Country</th>
<th>Inst.</th>
<th>Application</th>
<th>Data</th>
<th>Phase</th>
<th>Year</th>
<th>HTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switzerland</td>
<td>ABB</td>
<td>Distribution</td>
<td>630 kVA, 18.42 kV/420V</td>
<td>3 Dyn11</td>
<td>1996</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Japan</td>
<td>Fuji Electric</td>
<td>Demonstrator</td>
<td>500 kVA, 6.6 kV/3.3 kV</td>
<td>1</td>
<td>1998</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Germany</td>
<td>Siemens</td>
<td>Demonstrator</td>
<td>100 kVA, 5.5 kV/1.1 kV</td>
<td>1</td>
<td>1999</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>USA</td>
<td>Waukesha</td>
<td>Demonstrator</td>
<td>1 MVA, 13.8 kV/6.9 kV</td>
<td>1</td>
<td>-</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>USA</td>
<td>Waukesha</td>
<td>Demonstrator</td>
<td>5 MVA, 24.9 kV/4.2 kV</td>
<td>3 Dy</td>
<td>-</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Japan</td>
<td>Fuji Electric</td>
<td>Demonstrator</td>
<td>1 MVA, 22 kV/6.9 kV</td>
<td>1</td>
<td>2001</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Germany</td>
<td>Siemens</td>
<td>Railway</td>
<td>1 MVA, 25 kV/1.4 kV</td>
<td>1</td>
<td>2001</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>EU</td>
<td>CNRS</td>
<td>Demonstrator</td>
<td>41 kVA, 2050 V/410 V</td>
<td>1</td>
<td>2003</td>
<td>P-YBCO/S-Bi 2223</td>
</tr>
<tr>
<td>Korea</td>
<td>U Seoul</td>
<td>Demonstrator</td>
<td>1 MVA, 22.9 kV/6.6 kV</td>
<td>1</td>
<td>2004</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Japan</td>
<td>Fuji Electric</td>
<td>Railway</td>
<td>4 MVA, 25 kV/1.2 kV</td>
<td>1</td>
<td>2004</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Japan</td>
<td>Kyushu Uni.</td>
<td>Demonstrator</td>
<td>2 MVA, 66 kV/6.9 kV</td>
<td>1</td>
<td>2004</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>China</td>
<td>IEE CAS</td>
<td>Demonstrator</td>
<td>630 kVA, 10.5 kV/400 V</td>
<td>3</td>
<td>2005</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Japan</td>
<td>U Nagoya</td>
<td>Demonstrator</td>
<td>2 MVA, 22 kV/6.6 kV</td>
<td>1</td>
<td>2009</td>
<td>P-Bi 2223/S-YBCO</td>
</tr>
<tr>
<td>Japan</td>
<td>Kyushu Uni.</td>
<td>Demonstrator</td>
<td>400 kVA, 6.9 kV/2.3 kV</td>
<td>1</td>
<td>2010</td>
<td>YBCO</td>
</tr>
<tr>
<td>Germany</td>
<td>KIT</td>
<td>Demonstrator</td>
<td>60 kVA, 1 kV/600 V</td>
<td>1</td>
<td>2010</td>
<td>P-Cu/S-YBCO</td>
</tr>
<tr>
<td>USA</td>
<td>Waukesha</td>
<td>Prototype</td>
<td>28 MVA, 69 kV</td>
<td>3</td>
<td>Not completed</td>
<td>YBCO</td>
</tr>
<tr>
<td>Australia</td>
<td>Callaghan Innovation</td>
<td>Demonstrator</td>
<td>1 MVA, 11 kV/415 V</td>
<td>3 Dy</td>
<td>2013</td>
<td>YBCO</td>
</tr>
<tr>
<td>China</td>
<td>IEE CAS</td>
<td>Demonstrator</td>
<td>1.25 MVA, 10.5 kV/400 V</td>
<td>3 Yyn0</td>
<td>2014</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Germany</td>
<td>KIT/ABB</td>
<td>Demonstrator</td>
<td>577 kVA, 20 kV/1 kV</td>
<td>1</td>
<td>2015</td>
<td>P-Cu/S-YBCO</td>
</tr>
</tbody>
</table>
Objective: Develop and field test a 1 MVA HTS transformer using YBCOa

Project Partners: Gallaghan Innovation, Wilson Transformers, General Cable ...

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Voltage</td>
<td>11,000 V</td>
</tr>
<tr>
<td>Secondary Voltage</td>
<td>415 V</td>
</tr>
<tr>
<td>Maximum Op. Temp.</td>
<td>70 K, liquid nitrogen cooling</td>
</tr>
<tr>
<td>Target Rating</td>
<td>1 MVA</td>
</tr>
<tr>
<td>Primary Connection</td>
<td>Delta</td>
</tr>
<tr>
<td>Secondary Connection</td>
<td>Wye</td>
</tr>
<tr>
<td>LV Winding</td>
<td>20 turns 15/5 Roebel cable per phase (20 turn single layer solenoid winding)</td>
</tr>
<tr>
<td>LV Rated current</td>
<td>1390 A rms</td>
</tr>
<tr>
<td>HV Winding</td>
<td>918 turns of 4 mm YBCO wire per phase (24 double pancakes of 38.25 turns each)</td>
</tr>
<tr>
<td>HV Rated current</td>
<td>30 A rms</td>
</tr>
</tbody>
</table>

First HTS Roebel wire in field test

Source: Gallaghan Innovation
**Current Limiting Transformer - 2013**

**Objective:** Develop and field test a 1 MVA HTS transformer using YBCOa

**Project Partners:** IRL, Wilson Transformers, General Cable ...

**HV Winding**
- 4 mm wide YBCO
- $I/I_c \sim 25\%$
- Polyimide wrap insulation
- 24 double pancakes

**LV Winding**
- YBCO Roebel Cable
- $L = 20 \text{ m}$
- 15 strands
- 5 mm width
- $I_c \sim 1400 \text{ A} @ 77 \text{ K}$, sf

**Objective:** Develop and field test a 1 MVA HTS transformer using YBCOa

<table>
<thead>
<tr>
<th>Source</th>
<th>Heat load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat</td>
<td>113 W</td>
</tr>
<tr>
<td>Electrical bushing</td>
<td>343 W</td>
</tr>
<tr>
<td>AC loss in LV</td>
<td>390 W</td>
</tr>
<tr>
<td>AC loss in HV</td>
<td>90 W</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>936 W</strong></td>
</tr>
</tbody>
</table>

Efficiency at 100% load: ~ 97%
Efficiency at 50% load: 98.5%

Current standard
Efficiency at 50%: 99.27%

Manufacturing and Test of a 1MVA-Class Superconducting Fault Current Limiting Transformer

02.06.2017, Karlsruhe

Sebastian Hellmann (KIT) / Markus Abplanalp (ABB)
Main transformer parameters:

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>$P_{\text{nom}}$</td>
<td>577.4</td>
<td>kVA</td>
</tr>
<tr>
<td>Primary winding (normal-conducting winding)</td>
<td>$U_{\text{prim}}$</td>
<td>20</td>
<td>kV</td>
</tr>
<tr>
<td></td>
<td>$I_{\text{prim}}$</td>
<td>28.9</td>
<td>A</td>
</tr>
<tr>
<td>Secondary winding (superconducting winding)</td>
<td>$U_{\text{sec}}$</td>
<td>1</td>
<td>kV</td>
</tr>
<tr>
<td></td>
<td>$I_{\text{sec}}$</td>
<td>577.4</td>
<td>A</td>
</tr>
<tr>
<td>Fault duration</td>
<td>$t_{\text{fault}}$</td>
<td>60</td>
<td>ms</td>
</tr>
<tr>
<td>Current limitation 1st HW</td>
<td>$I_{\text{LIM, 1HW}}$</td>
<td>13.55</td>
<td>kA</td>
</tr>
<tr>
<td>Limitation 1st HW in resp. to pros. current</td>
<td>$LIM_{1\text{HW}}$</td>
<td>71.4</td>
<td>%</td>
</tr>
<tr>
<td>Current limitation 6th HW</td>
<td>$I_{\text{LIM, 6HW}}$</td>
<td>6.5</td>
<td>kA</td>
</tr>
<tr>
<td>Limitation 6th HW in resp. to pros. current</td>
<td>$LIM_{6\text{HW}}$</td>
<td>35.7</td>
<td>%</td>
</tr>
</tbody>
</table>
Transformer Design Fix

The design of the transformer is focusing on technology demonstration and includes practical compromises such as:

- Non-optimal cryogenic design
- Relatively short current leads
- Non-sealed cryogenic environment
- No automatic LN$_2$ level control
Transformer Design Fix
Measurements – Current limitation

Prospective current and limited current (simulated and measured) with 25.3 mΩ short-circuit:
Thank you for your Attention

Sebastian Hellmann / KIT / sebastian.hellmann@kit.edu

Sebastian Hellmann – Manufacturing and Test of a 1MVA-Class Superconducting Fault Current Limiting Transformer
One slide about economics of transformers

Cost range of conventional transformers
1 MVA ~ 30,000 US$
50 MVA ~ 730,000 US$

<table>
<thead>
<tr>
<th>Voltage Rating (Primary-Secondary)</th>
<th>Capability MVA Rating</th>
<th>Approximate Price ($)</th>
<th>Approximate Weight &amp; Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Transformer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>230–115kV</td>
<td>300</td>
<td>$2,000,000</td>
<td>170 tons (340,000 lb) 21ft W–27ft L–25ft H</td>
</tr>
<tr>
<td>345–138kV</td>
<td>500</td>
<td>$4,000,000</td>
<td>335 tons (670,000 lb) 45ft W–25ft L–30ft H</td>
</tr>
<tr>
<td>765–138kV</td>
<td>750</td>
<td>$7,500,000</td>
<td>410 tons (820,000 lb) 56ft W–40ft L–45ft H</td>
</tr>
<tr>
<td>Single Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>765–345kV</td>
<td>500</td>
<td>$4,500,000</td>
<td>235 tons (470,000 lb) 40ft W–30ft L–40ft H</td>
</tr>
<tr>
<td>Generator Step-Up Transformer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>115–13.8kV</td>
<td>75</td>
<td>$1,000,000</td>
<td>110 tons (220,000 lb) 16ft W–25ft L–20ft H</td>
</tr>
<tr>
<td>345–13.8kV</td>
<td>300</td>
<td>$2,500,000</td>
<td>185 tons (370,000 lb) 21ft W–40ft L–27ft H</td>
</tr>
<tr>
<td>Single Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>345–22kV</td>
<td>300</td>
<td>$3,000,000</td>
<td>225 tons (450,000 lb) 35ft W–20ft L–30ft H</td>
</tr>
<tr>
<td>765–26kV</td>
<td>500</td>
<td>$5,000,000</td>
<td>325 tons (650,000 lb) 33ft W–25ft L–40ft H</td>
</tr>
</tbody>
</table>

Assumption:
300 m HTS per MVA and phase
30 €/m HTS wire, 4 mm wide
30 k€ for a km
10 MVA → 9 km, 4 mm wide
270 k€ for HTS wire
100 MVA → 90 km, 4 mm wide
2.7 Mio.€ for HTS wire

Motivation of Superconducting Transformers

- Motivation
- Different Types
- A few Basics
- State-of-the-Art
- Applications
- Summary
Application of Transformers?

Many potential applications but which one is attractive enough?
Motivation of Superconducting Transformers

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Status of Superconducting Transformers

- Successful technology development in recent years mainly with YBCO wires
- Successful demonstrator development with a rating up to 4 MVA and medium voltages
- Only a few grid tests have been taken place
- Time seems ready for more 3-phase medium voltage demonstrators and prototypes for long-term field tests
A final remark

Superconducting transformers are attractive but do not solve all transformer challenges!

400 tons
6 Mio US$