Superconducting Transformers
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Institute for Technical Physics
EUCAS Short Course Power Applications, September 17th 2017., Geneva
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)

30 MVA Transformers

Trailer failure left something really big in Kendall County road
By Zeke MacCormack  Updated 9:44 pm, Monday, August 25, 2014

©Waukesha

conventionel

superconducting
Motivation of Superconducting Transformers

Manufacturing and transport
- Compact and lightweight (~50 % Reduction)

Environment and Marketing
- Energy savings (~50 % Reduction)
- Ressource savings

Conventional 400 MVA Transformer
Motivation of Superconducting Transformers

Manufacturing and transport
- Compact and lightweight (~50 % Reduction)

Environment and Marketing
- Energy savings (~50 % Reduction)
- Ressource savings
- Inflammable (no oil)
Motivation of Superconducting Transformers

Manufacturing and transport
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- Ressource savings
- Inflammable (no oil)

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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- Low short-circuit impedance
  - Higher stability
  - Less voltage drops
  - Less reactive power
- Active current limitation
  - Protection of devices
  - Reduction of investment

![Diagram](Image)

Enables a new class of transformers
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Different Types of Superconducting Transformers

Warm Iron Core
- LN2
- Cryostat
- LN2
- Iron Core

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

Cold Iron Core
- LN2
- Cryostat
- LN2
- Iron Core

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

Conduction Cooled
- Coldhead
- Vacuum

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

Main flux

\[ \Phi_H \]

Stray flux

\[ \Phi_H \]

Stray flux

\[ H_0 \]

\[ I_{os} \]

\[ I_{us} \]
Transformer Inductances

Main Inductance

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

Stray Inductance

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

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

- $\varphi_H$: main flux
- $\varphi_\sigma$: 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>LN₂ 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 \( \times \) 0,406 m \( \times \) 1,08 m (l \( \times \) w \( \times \) 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>
</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>
</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>
</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>
</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>
</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>
</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>
</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>
</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>
</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>
</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>
</tr>
<tr>
<td>Japan</td>
<td>Kuyshu Uni.</td>
<td>Demonstrator</td>
<td>2 MVA, 66 kV/6.9 kV</td>
<td>1</td>
<td>2004</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>
</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>
</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>
</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>
</tr>
<tr>
<td>USA</td>
<td>Waukesha</td>
<td>Prototype</td>
<td>28 MVA, 69 kV</td>
<td>3</td>
<td>Not completed</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>
</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>
</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>
</tr>
</tbody>
</table>

**HTS**
- Bi 2223
- P-YBCO/S-Bi 2223
- P-Bi 2223/S-YBCO
- YBCO
- P-Cu/S-YBCO
**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>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**
**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
- $L = 20$ m
- 15 strands
- 5 mm width
- $I_c \sim 1400\ A @ 77\ K, \ sf$

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%

Source: Gallaghan Innovation

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

02.06.2017, Karlsruhe

Sebastian Hellmann (KIT) / Markus Abplanalp (ABB)
Introduction – 60kVA Transformer

KIT developed a 60 kVA laboratory demonstrator facilitating a superconducting secondary winding to limit fault currents.
Introduction – 60kVA Transformer

superconducting secondary winding
laminated iron core
normal-conducting primary winding

Main transformer parameters

- Power: 60 kVA
- Ratio: 100 / 60 (turns)
- Voltage: 1 kV / 600 V
- Currents: 60 A / 100 A
- \( j_{\text{prim}} \): 5 A / mm²
- \( j_{\text{sec}} \): 83.3 A / mm²
- \( u_k \): 1.58%
Recovery-under-Load (RuL) measurement for $I_{\text{rec}} = I_{\text{nom}} = 100$ A

$t_{\text{lim}} = 60$ ms

$t_{\text{rec}} \approx 2.3$ s
### 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 prosp. 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 prosp. 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 LN₂ level control
Transformer Design Fix
Measurements – Current limitation

Prospective current and limited current (simulated and measured) with 25.3 mΩ short-circuit:
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><strong>Transmission Transformer</strong></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><strong>Generator Step-Up Transformer</strong></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–20ft 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) 36ft 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

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Application of Transformers?

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

You are lucky and you can choose any application for a superconducting transformer. With which application would you start?

A. Auxiliary transformer
B. Generator transformer
C. Network transformer
D. Distribution transformer
E. Substation transformer
F. Mobile transformer
G. Any other transformer
H. I have no idea

<table>
<thead>
<tr>
<th>Application</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary transformer</td>
<td>30%</td>
</tr>
<tr>
<td>Generator transformer</td>
<td>22%</td>
</tr>
<tr>
<td>Network transformer</td>
<td>17%</td>
</tr>
<tr>
<td>Distribution transformer</td>
<td>9%</td>
</tr>
<tr>
<td>Substation transformer</td>
<td>4%</td>
</tr>
<tr>
<td>Mobile transformer</td>
<td>4%</td>
</tr>
<tr>
<td>Any other transformer</td>
<td>9%</td>
</tr>
<tr>
<td>I have no idea</td>
<td>0%</td>
</tr>
</tbody>
</table>
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- Applications
- Summary
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!