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Superconducting Transformers

Mathias Noe, Institute of Technical Physics, Karlsruhe Institute of Technology, Germany

ESAS Summer School on High Temperature Superconductor Technology for Sustainable Energy and Transport Systems , June 8th-14th 2016, Bologna

Institute for Technical Physics

Outline Superconducting Transformers

- Transformer History
- Basic Transformer Design
- Motivation of Superconducting Transformers
- Basics of Superconducting Transformers
  - Types
  - Electrical Circuit
  - Losses and Loss Evaluation
- State-of-the-Art

Transformer History

- 1831 Michael Faraday – Ellectromagnetic Induction
- 1884 Károly Zipernowsky, Miksa Dén, Ottó Titusz Bláthy – Einankerumformer

Source: Die ersten Transformatoren (Déri-Bláthy-Zipernowsky, Budapest, 1885.) Schloss Széchenyi in Nagycenk

Transformer History

- 1885 William Stanley

Stanley designed and produced transformers with iron plate and iron tape cores.

Primary Voltage 500 V

Power 150 „sixteen candle-power lamps“

The „Stanley Transformer“ was produced for several years by Westinghouse

Copyright: Edison Tech Center

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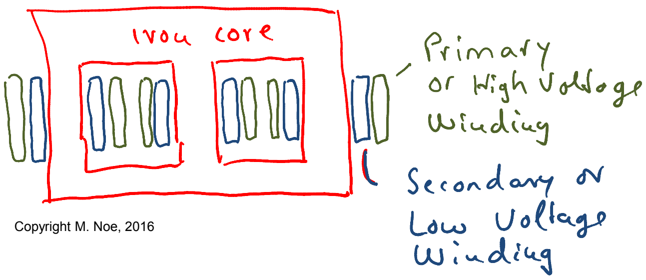
Transformer History

- 1831 Michael Faraday – Electromagnetic Induction
- 1884 Károly Zipernowsky, Miksa Dén, Ottó Titusz Bláthy – Einankerumformer
- 1885 William Stanley – Further development
- 1888 Gisbert Kapp – Major work on theory of transformers
- 1891 Michael von Dolivo-Dobrowolski – three leg design



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- since 1965 epoxy resin transformers

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Maxwell's Equation

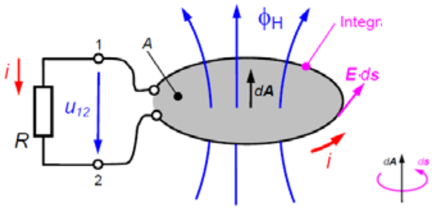
3rd Maxwell Equation – Faraday's Law

$$\oint_C E \cdot ds = -\frac{d}{dt}\int_A B \cdot dA$$

E : Electric Field
B : Magnetic Induction
A : Surface (constant with time)
ds : Length element
dA : Surface element

$$u_{12}(t) = \oint_C E(t)\cdot ds = \int_A \mathrm{rot}[E(t)]\cdot dA = \int_A -\frac{\partial B(t)}{\partial t}\cdot dA = -\frac{d}{dt}\int_A B(t)\cdot dA = -\frac{d}{dt}\phi_H(t)$$

$$u_{12}(t) = -w\cdot\frac{d\phi_H(t)}{dt} = i(t)\cdot R$$



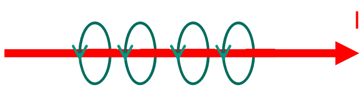
Maxwell's Equation

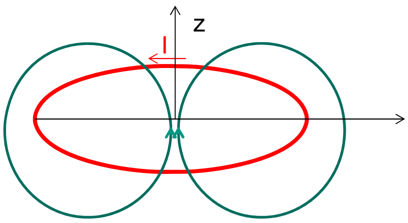
4th Maxwell Equation – Ampere's Law

$$\oint_C H(t)\cdot ds = \int_{A_W} \left(J(t)+\frac{dD(t)}{dt}\right)\cdot dA$$

H : Magnetic Field
J : Current Density
D : Dielectric Displacement
ds : Length element
dA : Surface element

Very often J⊥dA and H||ds and D/dt=0





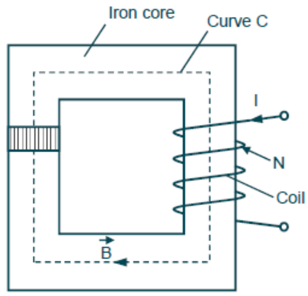
Currents generate magnetic field

$$B\cdot 2\cdot\pi\cdot r = \mu_0\cdot I$$

Vacuum permeability

$$B_{z,0} = \frac{\mu_0\cdot I}{2\cdot R}$$

Magnetic Field in an Iron Core



I current

N number of turns

C induction line

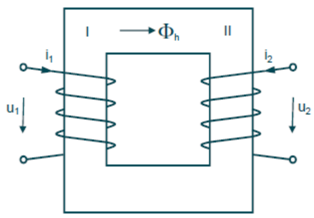
A cross section of iron core

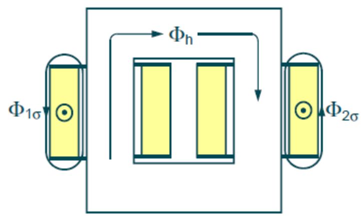
$$\oint_C \vec{H}\, \vec{ds} = N\, I$$

Magnetic field strength:

$$H_{Fe} = \frac{B_{Fe}}{\mu_{Fe}}$$

Single PhaseTransformer



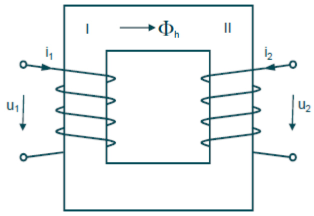


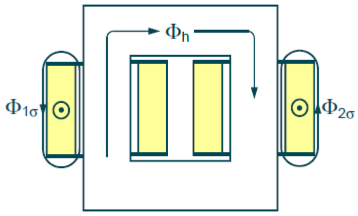
Main flux: $\theta_h = B_{Fe}\, A$

Main inductance: $\theta_h = (i_1\, i_2)\, L_h$

Stray inductance: $\theta_{1\sigma} = i_1 L_{1\sigma}$ $\theta_{2\sigma} = i_2 L_{2\sigma}$

Single PhaseTransformer





Transmission ratio: $$\ddot{u} = \frac{N_1}{N_2}$$

Voltage equations:

$$u_1 = R_1\, i_1 + L_1 \frac{di_1}{dt} + M_{12}\ddot{u}\, \frac{d(\frac{i_2}{\ddot{u}})}{dt}$$ $$L_1 = L_\sigma + L_h$$

$$u_2 = R_2\, i_2 + L_2 \frac{di_2}{dt} + M_{21} \frac{d(i_1)}{dt}$$ $$L_1 = L_\sigma + L_h$$

Single PhaseTransformer

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$$u_2 = R_2\, i_2 + L_2 \frac{di_2}{dt} + M_{21} \frac{d(i_1)}{dt}$$ $$L_1 = L_\sigma + L_h$$

Voltage equations with “transposed” variables:

$$u_1 = R_1 \cdot i_1 + L_1 \cdot \frac{di_1}{dt} + M' \cdot \frac{di_2'}{dt} = R_1 \cdot i_1 + L_1 \cdot \frac{di_1}{dt} + L_h \cdot \frac{di_2'}{dt}$$

$$u_2' = R_2' \cdot i_2' + L_2' \cdot \frac{di_2'}{dt} + M' \cdot \frac{di_1}{dt} = R_2' \cdot i_2' + L_2' \cdot \frac{di_2'}{dt} + L_h \cdot \frac{di_1}{dt}$$

Because of $L_{1/2} = L_{1\sigma/2\sigma} + L_h$ and $L_{2h}' = M' = L_h$ follows:

$$u_1 = R_1 \cdot i_1 + L_{1\sigma} \cdot \frac{di_1}{dt} + L_h \cdot \frac{d(i_1 + i_2')}{dt}$$

$$u_2' = R_2' \cdot i_2' + L_{2\sigma}' \cdot \frac{di_2'}{dt} + L_h \cdot \frac{d(i_1 + i_2')}{dt}$$

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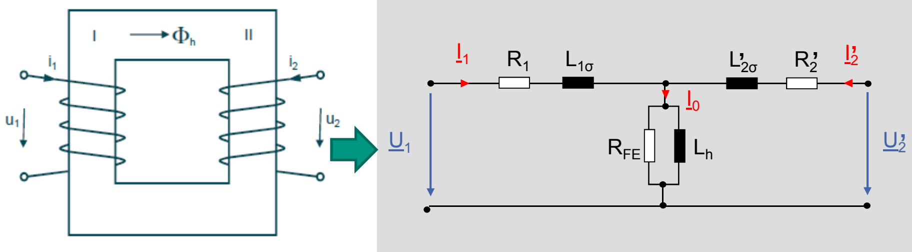
Single Transformer Electrical Circuit



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

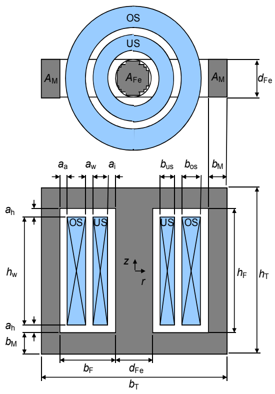
R_{FE}: iron core loss

Transformer Inductances

Main Inductance

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

Stray Inductance



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

$$r_{os} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} + a_w + \frac{b_{os}}{2},\ r_{us} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} \text{ und } r_{Spalt} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} + a_w$$

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    - o Losses and Loss Evaluation
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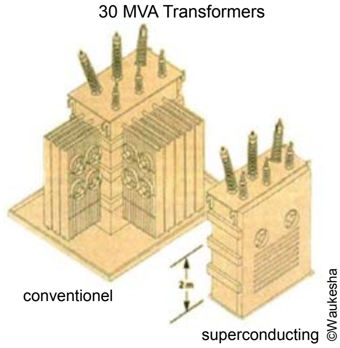
Motivation of Superconducting Transformers

Manufacturing and transport

- Compact and lightweight (~50 % Reduction)



Motivation of Superconducting Transformers

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

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

Conventionel 400 MVA Transformer

©ABB

Motivation of Superconducting Transformers

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- Inflammable (no oil)

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Operation
- Low short-circuit impedance
  - Higher stability
  - Less voltage drops
  - Less reactive power

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Manufacturing and transport
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- Ressource savings
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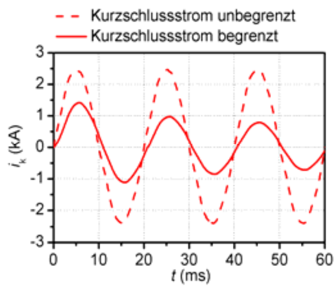
Operation
- Low short-circuit impedance
  - Higher stability
  - Less voltage drops
  - Less reactive power
- Active current limitation
  - Protection of devices
  - Reduction of investment



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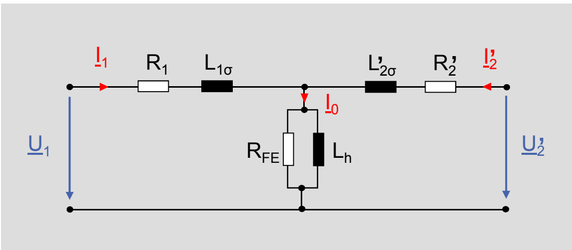
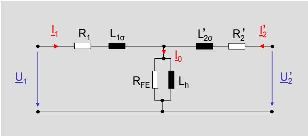
Electrical Circuit



What is different between normal and superconducting transformers ?

Some basic equations



$$S = \frac{U_1 I_1 + U_2 I_2}{2}$$

$$U_1 = \frac{n_1 \omega}{\sqrt{2}} B_{Fe} A_{Fe}$$

$$S = \frac{\omega B_{Fe} A_{Fe}}{\sqrt{2}} \left(\frac{n_1 I_1 + n_2 I_2}{2} \right)$$

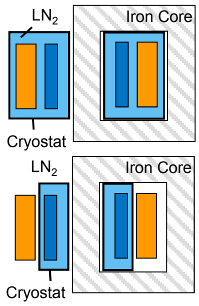
$$n_1 I_1 = n_1 j_1 A_1$$

$$n_2 I_2 = n_2 j_2 A_2$$

$$j_1 = j_2 = j$$

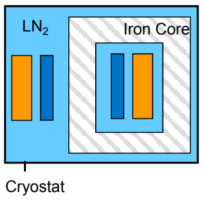
Different Types of Superconducting Transformers

Warm Iron Core



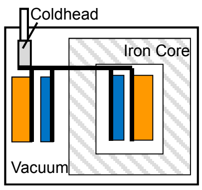
☺ Low Cooling Power
☺ Iron at Room Temperature
☹ Expensive Cryostat
☹ 3 Cryostats needed

Cold Iron Core



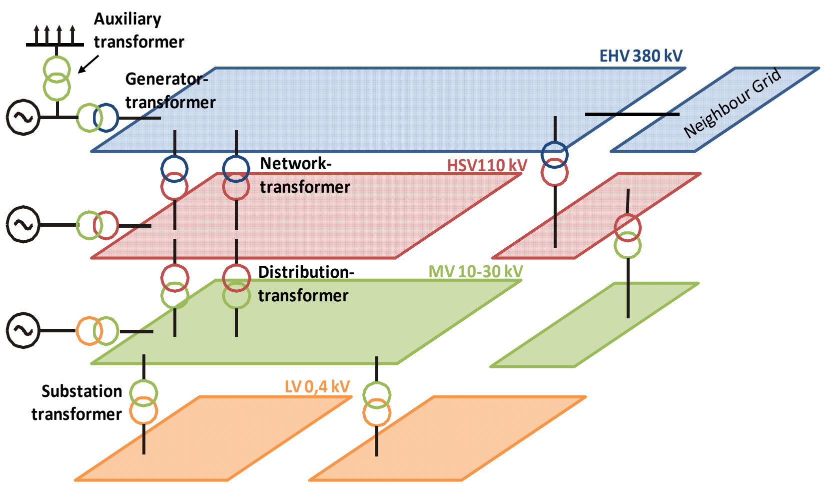
☺ Simple Cryostat
☺ Simple Cooling inerface
☹ High Cooling Power
(Iron core loss at low temp.)

Conduction Cooled



☺ Simple Cryostat
☺ Iron at Room Temperature
☹ Long recooling after quench
☹ Temperature difference
☹ Not suitable for high voltage

Application of Transformers?



Losses in Superconducting Transformers

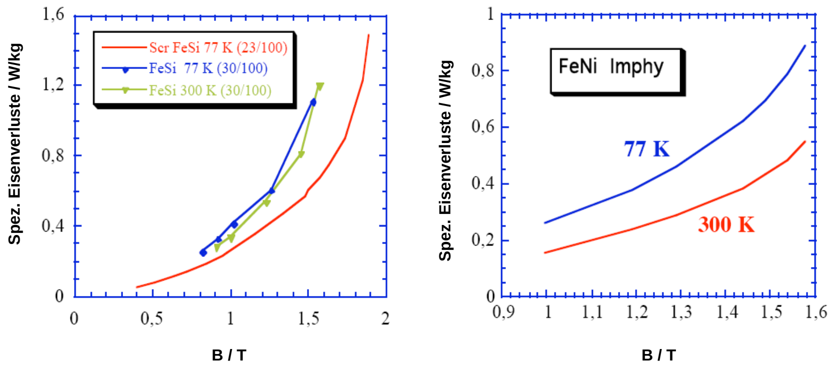
Short-circuit losses

- P_{AC} AC Loss of Superconductor (current dependant)
- P_{CL} Current lead loss (partly current dependant)
- P_{add} Additional loss (current dependant)

No-load operation

- } P_{FE} Iron core loss (eddy currents) (voltage dependant)
- Iron core loss (Hysteresis loss) (voltage dependant)
- P_{Di} Dielectric loss (voltage dependant)
- P_{Th} Thermal loss (not voltage dependant)

Iron Core Losses in Superconducting Transformers



Losses in Superconducting Transformers
Example: Network Transformer

	normal	Superconduct.
S_N [MVA]	31,5	
U_{pN} / U_{sN} [kV]	110 / 20 in YNd5-Schaltung	
I_{pN} / I_{sN} [A]	165 / 909	
u_k [%]	12,1	7
Current density [A/mm^2]	-	54
Total weight [kg]	-	12840

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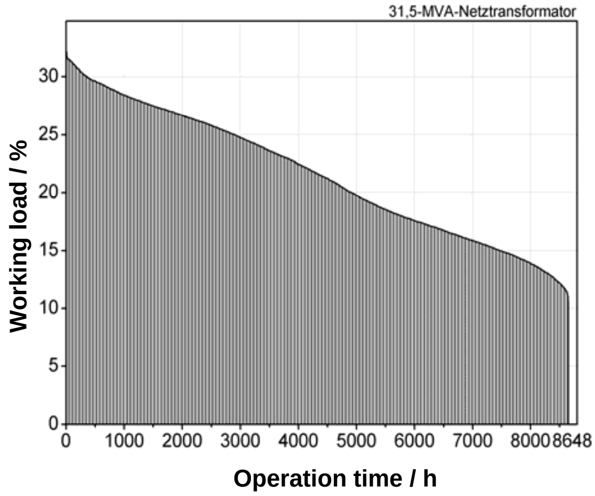
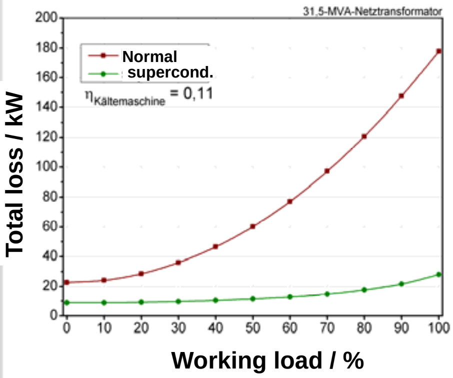
Losses in Superconducting Transformers
Example: Network Transformer

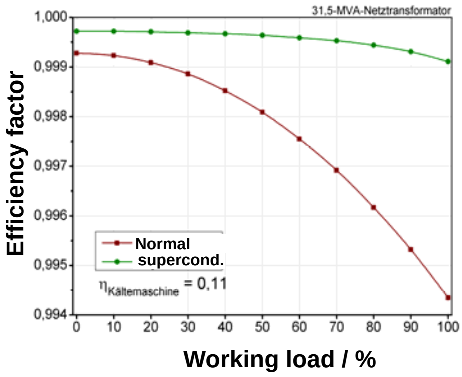


Losses in Superconducting Transformers
Example: Network Transformer

Total Loss



Efficiency Factor



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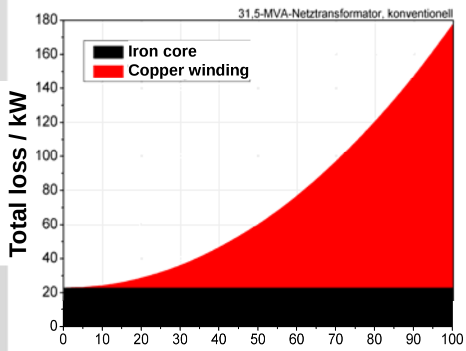
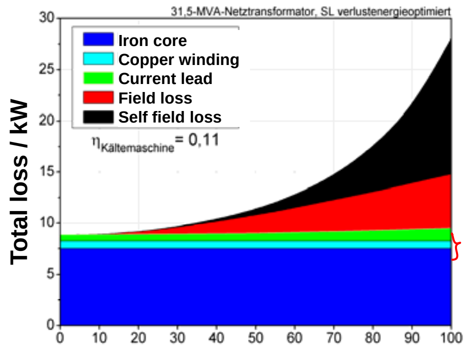
Losses in Superconducting Transformers
Example: Network Transformer

Normal Transformer

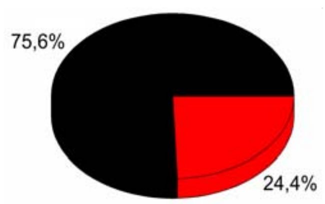


Superconducting Transformer



Losses in Superconducting Transformers
Example: Network Transformer

Normal Transformer

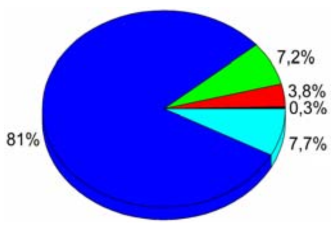


Loss energy per year

$W_{V,ges,konv} = 259,4$ MWh

$\eta_{ges,konv} = 99,56\%$

Superconducting Transformer



Loss energy per year

$W_{V,ges,sl} = 80,2$ MWh

$\eta_{ges,sl} = 99,86\%$

- Iron core
- Copper winding

- Current lead
- Iron core
- Copper winding
- Field loss
- Self field loss

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History of LTS Transformers

Year	Organization	Country	Power in kVA	Data	Voltage per winding	Super-cond.
1985	GEC-Alstom	F	80	660V/1040V 124A/77A	2,14 V	NbTi
1988	Kyushu University	J	72	1057V/218V 68A/332A	-	NbTi
1991	Toshiba	J	30	100V/100V 300A/300A	-	NbTi
1991	Ktio	J	100	6600V/210V 15A/476A	4,57 V	Cu/NbTi
1992	Kyushu University	J	1000	3300V/220V 303A/4545A	10 V	NbTi
1993	ABB	CH	330	6000V/400V 56A/830A	7,9 V	NbTi
1995	Osaka University	J	40	460V/150V 50A/200A	0,45 V	NbTi

Source: Technik und Einsatz von HTSL Leistungstransformatoren, Diss. E. Sissimatos 2005

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Major HTS Transformers Projects

Country	Inst.	Application	Data	Phase	Year	HTS
Switzerland	ABB	Distribution	630 kVA, 18,42 kV/420V	3 Dyn11	1996	Bi 2223
Japan	Fuji Electric	Demonstrator	500 kVA, 6,6 kV/3,3 kV	1	1998	Bi 2223
Germany	Siemens	Demonstrator	100 kVA, 5,5 kV/1,1 kV	1	1999	Bi 2223
USA	Waukesha	Demonstrator	1 MVA, 13,8 kV/6,9 kV	1	-	Bi 2223
USA	Waukesha	Demonstrator	5 MVA, 24,9 kV/4,2 kV	3 Dy	-	Bi 2223
Japan	Fuji Electric	Demonstrator	1 MVA, 22 kV/6,9 kV	1	2001	Bi 2223
Germany	Siemens	Railway	1 MVA, 25 kV/1,4 kV	1	2001	Bi 2223
EU	CNRS	Demonstrator	41 kVA, 2050 V/410 V	1	2003	P-YBCO/S-Bi 2223
Korea	U Seoul	Demonstrator	1 MVA, 22,9 kV/6,6 kV	1	2004	Bi 2223
Japan	Fuji Electric	Railway	4 MVA, 25 kV/1.2 kV	1	2004	Bi 2223
Japan	Kuyshu Uni.	Demonstrator	2 MVA, 66 kV/6.9 kV	1	2004	Bi 2223
China	IEE CAS	Demonstrator	630 kVA, 10.5 kV/400 V	3	2005	Bi 2223
Japan	U Nagoya	Demonstrator	2 MVA, 22 kV/6,6 kV	1	2009	P-Bi 2223/S-YBCO
Japan	Kyushu Uni	Demonstrator	400 kVA, 6.9 kV/2.3 kV	1	2010	YBCO
Germany	KIT	Demonstrator	60 kVA, 1 kV/600 V	1	2010	P-Cu/S-YBCO
USA	Waukesha	Prototype	28 MVA, 69 kV	3	Not completed	YBCO
Australia	Callaghan Innovation	Demonstrator	1 MVA, 11 kV/415 V	3 Dy	2013	YBCO
China	IEE CAS	Demonstrator	1.25 MVA, 10.5 kV/400 V	3 Yyn0	2014	Bi 2223
Germany	KIT/ABB	Demonstrator	577 kVA, 20 kV/1 kV	1	2015	P-Cu/S-YBCO

630 kVA Transformers – 1996 (ABB)

Worldwide first field test

Power	630 kVA
Voltages	18 720 / 420 V
Group	Dyn11
Frequency	50 Hz
SC impedance	4,6%
Currents	11,2 / 866
Superconductor	Bi 2223
Cooling	LN_2 bei 77 K V
Loss at I_r	337 W @ 77 K

Source: H. Zueger et al, Cryogenics 1998 Volume 38, Number 11

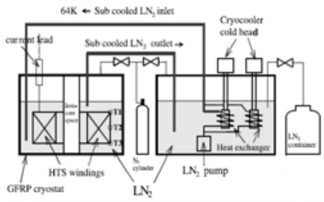
100 MVA – 220/20 kV Transformer

	Normal (%)	HTS (%)	Savings (%)
Weight	100	46	53
Total loss	100	31	69
Investment	100	100	0
TCO [1)]	100	78	22

[1)] Investment and loss for 20 years

1 MVA Transformers – 1996 - (Kyushu)

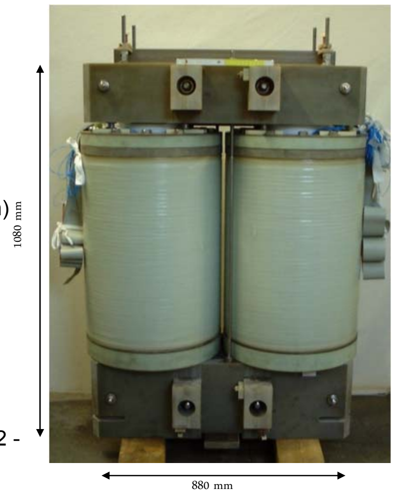
- Rated power: 1 MVA
- Rated Voltage: 22/6,9 kV
- Frequency: 60 Hz
- Short-circuit voltage: $u_k = 5$ %
- Cooling: subcooled LN_2 at 64 K
- Volume: 1,5 m x 1,2 m x 2,7 m (l x w x h)
- Weight: 5100 kg
- Bi-2223 Superconductor
- Losses: 160 W bei 65 K
- Successful Field Test



Source: Kimura et al Physica C 372-376, 2002-S. 1694-1697

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 %



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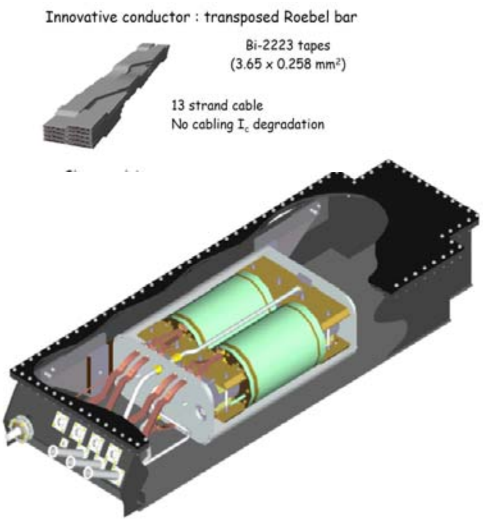
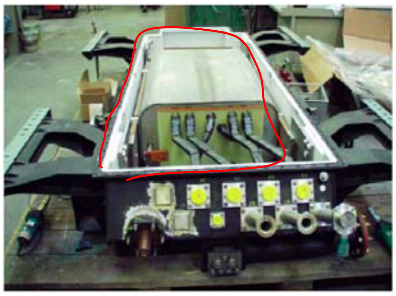


Losses	
Iron Core	700 W
Stray field (Iron)	280 W
Winding and current leads	780 W
Thermal losses	200 W
Total loss	1960 W @ 67 K
Total loss	23 kW @ RT
Efficiency supercond.	97,75%
Efficiency normal	92-95 %



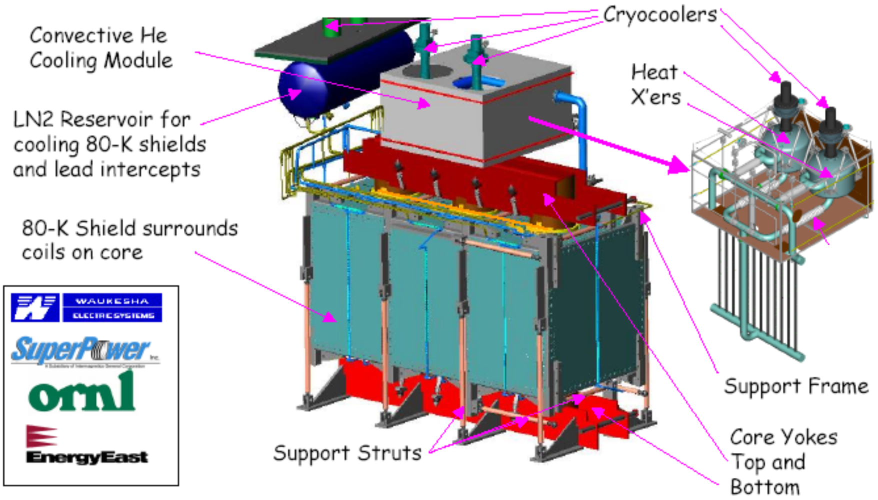
Transformer installed in frame

1 MVA Mobile Transformer - 2001 (Siemens)

HTS-Train transformer left
Normal train transformer right

HTS-Transformer in test field

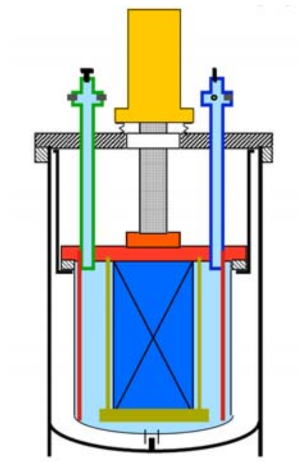
10 MVA Transformer (Waukesha)



10 MVA Transformer (Waukesha)

- Rated power: 5/10 MVA
- Rated Voltage: 24,9 / 4,2 kV
- Rated Current: 67 / 694 A
- Frequency: 60 Hz
- Group: Δ/Y
- Temp. 30-50 K, He-Cooling
- Superconductor Bi 2223

45 kVA Transformer (EU Project Ready)



- Primary Bi 2223
- Secondary YBCO coated conductor
- Conduction cooled
- Temperature 40-80 K

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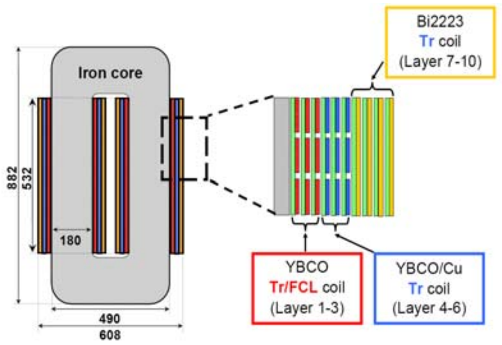
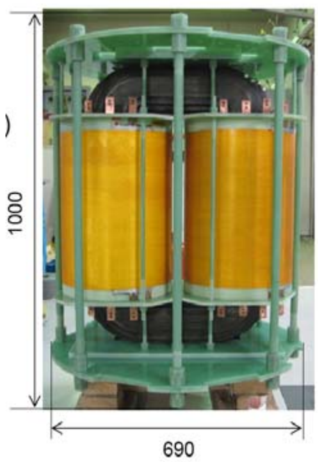
Current Limiting Transformer – 2009 (U Nagoya)

Test of 2 MVA Demonstrator in 2009



60Hz
2MVA
22kV / 6.6kV
52.5A / 175A
YBCO
Bi2223



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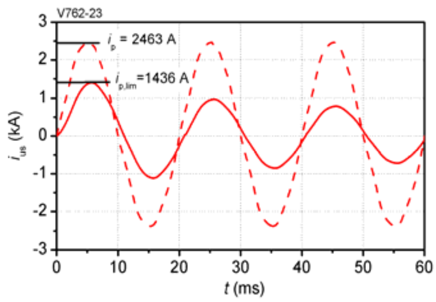
Current Limiting Transformer - 2010 (KIT)

60 kVA Demonstrator with recooling under nominal load

Current Limiting Transformer - 2010 (KIT)

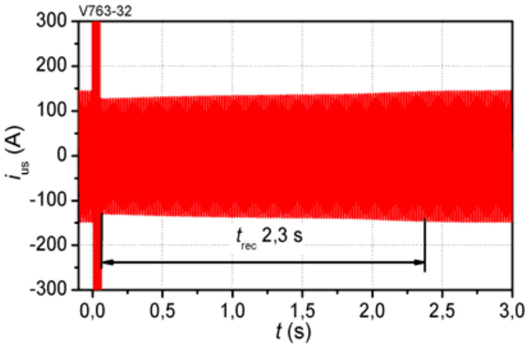
60 kVA Demonstrator with recooling under nominal load



- Prospective current i_p = 2463 A (17 x nominal current)
- Limited current $i_{p,lim}$ = 1436 A (10 x nominal current)
  ➔ Reduction of prospective current down to 58 %
- Maximum HTS temperature after 60 ms short-circuit duration T_{max} = 186 K

Current Limiting Transformer - 2010 (KIT)

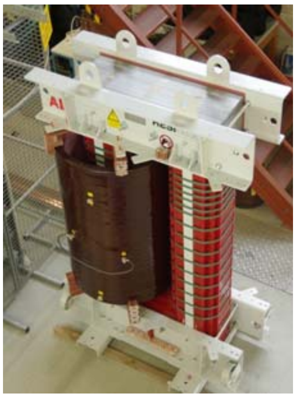
60 kVA Demonstrator with recooling under nominal load

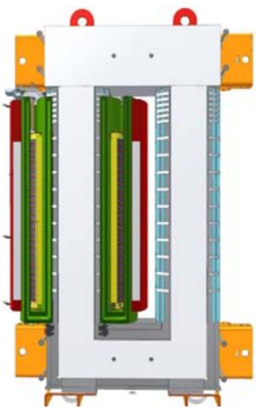


- Maximum HTS temperature after 60 ms short-circuit duration T_{max} = 186 K
- Recooling time at nominal load t_{rec}(102 A) = 2,30 s

Current Limiting Transformer - KIT/ABB

Objective: Further develop technology of superconducting transformers





Power: 577 kVA (1phase)
Voltage: 20 kV/1 kV
u_k: less than 3%
Warm iron core
LN_2 boiling

Status June 2016: All components delivered, assembly nearly finished, tests start very soon

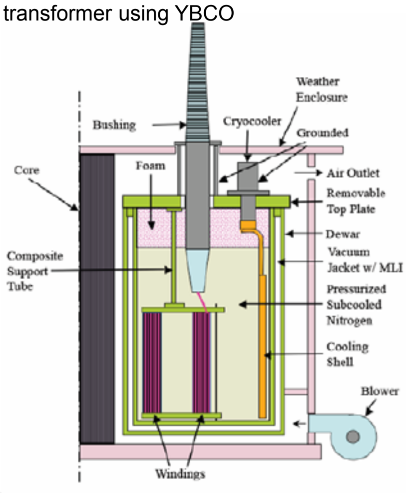
Current Limiting Transformer - 2015 (Waukesha)

28 MVA, 70 kV Prototype

Project Partners: SuperPower, Waukesha, SCE, ORNL, U Houston

Objective: Develop and field test a 28 MVA HTS transformer using YBCO

Parameter	Value
Primary voltage	70.5 kV
Secondary voltage	12.47 kV
Operating Temperature	~ 70 K, press. LN_2 (1.1-3 bar)
Target Rating	28 MVA
Primary Connection	Delta
Secondary connection	Wye
YBCO tape length	~ 12 km of 12 mm wide tape
HV rated current	230 A
LV rated current	1296 A



Source: F. Roy, "The 28-MVA FCL Smart Grid Demo Transformer and Modeling Concerns about its Operation under Fault Conditions," 2nd International Workshop on Modeling HTS, April 11-13, 2011, Cambridge, United Kingdom.

Current Limiting Transformer - 2015 (Kyushu)

Project Partners: Kyushu Electric Power, Kyushu University

Objective: Develop 20 MVA transformer using YBCO

Data of 400 kVA demonstrator tested in 2010

Parameter	Value
Primary Voltage	6.9 KV
Secondary Voltage	2.3 kV
Op. Temp.	LN_2 at -207° C
Target Rating	400 kVA
LV Rated Current	174 A
HV Rated Current	58 A

Source: Superconductivity WEB21, Winter 2011, January 17 2011

D=565 mm
H=810 mm

D=738 mm
H=2300 mm

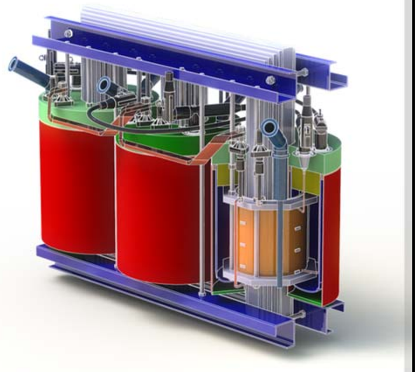
Karlsruher Institut für Technologie

Current Limiting Transformer - 2015 (IRL et. al.)

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

Project Partners: IRL, Wilson Transformers, General Cable …

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



Source: IRL

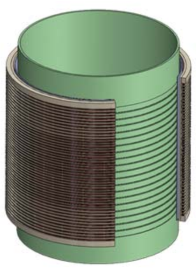
First HTS Roebel wire in field test

Current Limiting Transformer - 2015 (IRL et. al.)

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

Project Partners: IRL, Wilson Transformers, General Cable …

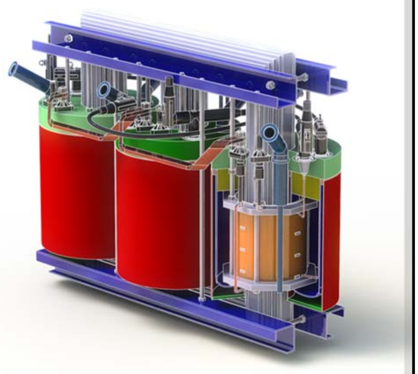
HV Winding



4 mm wide YBCO
I/I_c ~ 25%
Polyimide wrap insulation
24 double pancakes

LV Winding

YBCO Roebel Cable
L = 20 m
15 strands
5 mm width
I_c ~ 1400 A @ 77 K, sf



Source: IRL

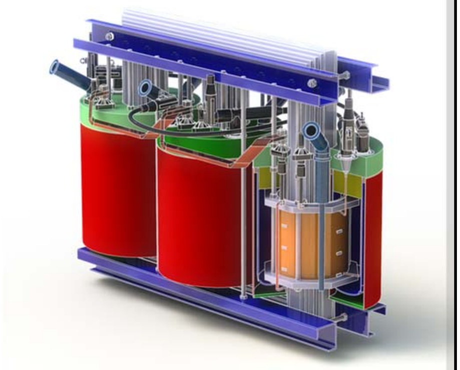
Current Limiting Transformer - 2013

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

Source	Heat load
Cryostat	113 W
Electrical bushing	343 W
AC loss in LV	390 W
AC loss in HV	90 W
Total	**936 W**

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

Current standard
Efficiency at 50% 99.27%



Source: Gallaghan Innovation

More information: Neil D. Glasson, Mike P. Staines, Zhenan Jiang, and Nathan S. Allpress, "Verification Testing for a 1 MVA 3-Phase Demonstration Transformer Using 2G-HTS Roebel Cable", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

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

Future HTS Transformer Applications?

Future R&D

- Reduce AC loss < 0,5 W/kA m
- Reduce wire cost < 10 €/kA m
- Long length wires and tapes > km
- Lower cooling cost < 25 € / W

Literature

Bernd Seeber, Handbook of Applied Superconductivity, Vol. 1 und 2, IOP 1998

Peter J Lee, Engineering Superconductivity, Wiley Interscience 2001