IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Plenary presentation PT-1 given at ACASC/Asian-ICMC/CSSJ Joint Conference, 6-9 January 2020, Okinawa, Japan.

KIT
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Joint Conference
10th ACASC
2nd Asian-ICMC
CSSJ

High-Temperature Superconducting Power Applications to meet major Challenges in Energy Systems

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

January 7th, 2020, Okinawa, Japan

KIT- ENERGY CENTRE

Acknowledgement

- I gratefully acknowledge the support of
  - my co-directors Tabea Arndt and Bernhard Holzapfel
  - my co-workers at the Institute of Technical Physics
  - our project partners from industry, research and academia
  - and all of you that contributed to the successful development of high-temperature superconducting power applications.

Motivation

„Machines are heavier than air and can never fly“
Lord Kelvin, 1895

„I believe, there is a world market of maybe 5 computers.“
Thomas J. Watson, IBM, 1943

„The wall will exist in 50 years and in 100 years.“
Erich Honecker, Staatsratsvorsitzender German Democratic Republic, 1989

„The internet is no mass media“
Matthias Horx, Researcher on trends and future, 2001

„The music download model has failed“
Steve Jobs, Apple, 2003

„Superconducting power applications are too expensive and no solution“
Transmisson and distribution system operator, 2019

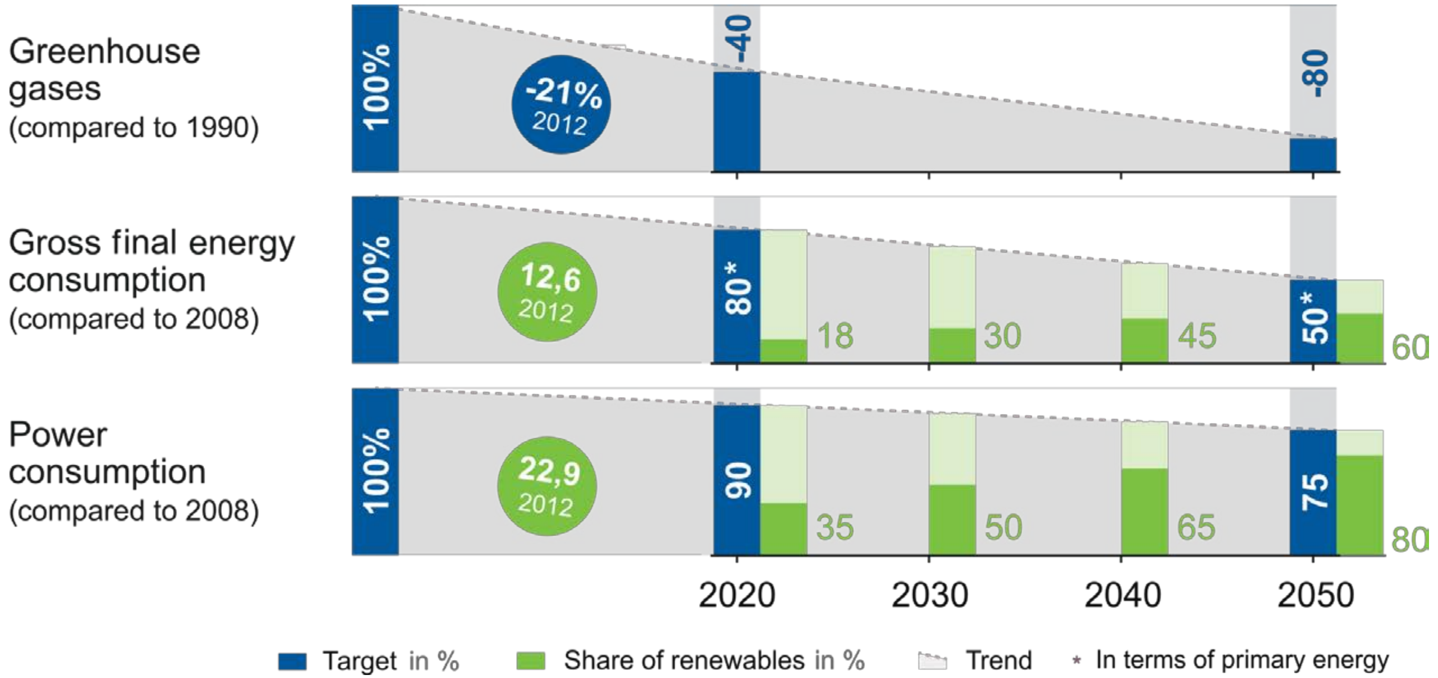
Table of Content

- Major Challenges in Power Systems
- Power Applications
  - Cables
  - Fault Current Limiters
  - Rotating Machines
  - Transformers
  - SMES

  } Benefits
  Development of the State-of-the-Art
  How this meets Power Challenges
- Summary

Major Challenges in Power Systems

- Objectives of the energy transition in Germany



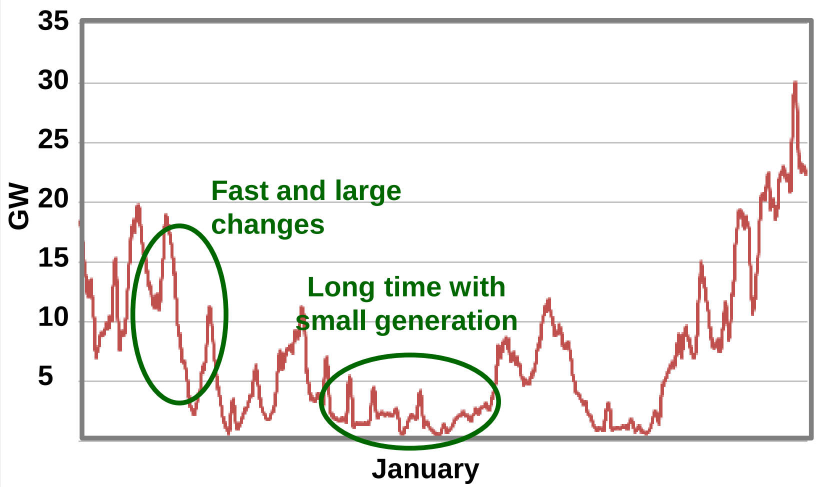
… plus 2022 phase out nuclear and 2038 phase out coal in Germany

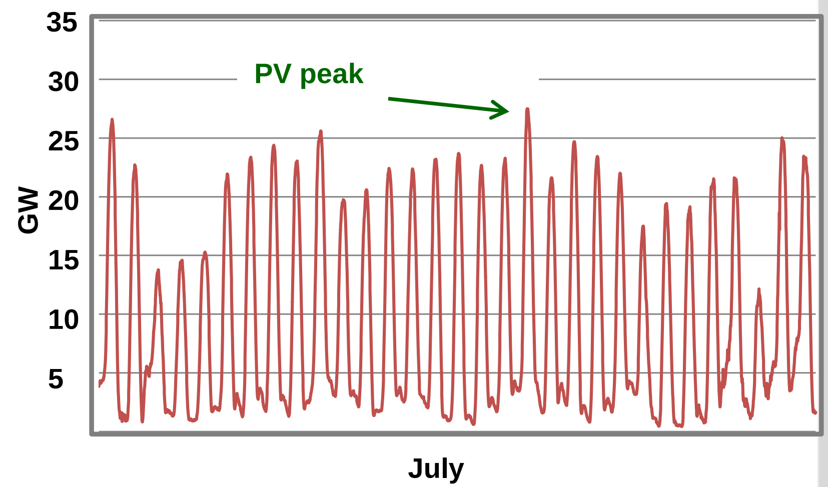
Major Challenges in Power Systems

- **Ensure stable, reliable and economic operation by e.g. balancing fluctuating generation and volatile consumption.**

Typical generation profile of photovoltaic and wind energy in Germany

Data transmission system operators (data 2013)





Major Challenges in Power Systems

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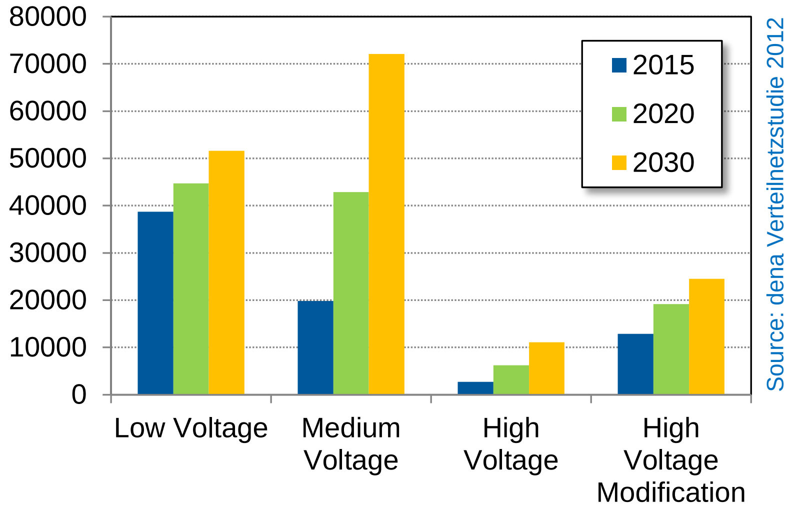
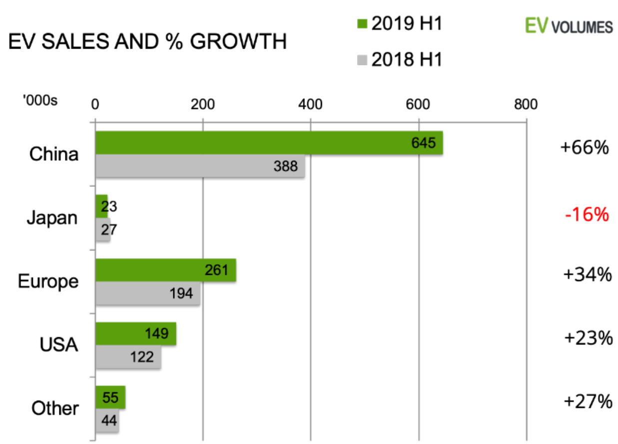
- Ensure stable, reliable and economic operation by e.g. balancing fluctuating generation and volatile consumption.
- **Extension of energy infrastructure to better integrate storage and renewables.**

Network extension in Germany



Major Challenges in Power Systems

- Ensure stable, reliable and economic operation by e.g. balancing fluctuating generation and volatile consumption.
- Extension of energy infrastructure to better integrate storage and renewables.
- **Development of acceptable energy and resource efficient technology solutions and processes to reduce CO_2 emissions.**



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  Benefits

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Benefits of HTS AC Cables

User

- Higher transmission capacity at lower voltage
  - Avoid high voltage equipment in urban areas
- Higher transmission capacity at lower diameter
  - Flexible laying, less underground work
- Three phases in one cable up to high capacities
  - Less right of way, fast cable laying, less underground work

Environment

- Electromagnetic compatible
- Potential of lower losses
- No ground heating

Operation

- Low impedance
- Operation at natural load

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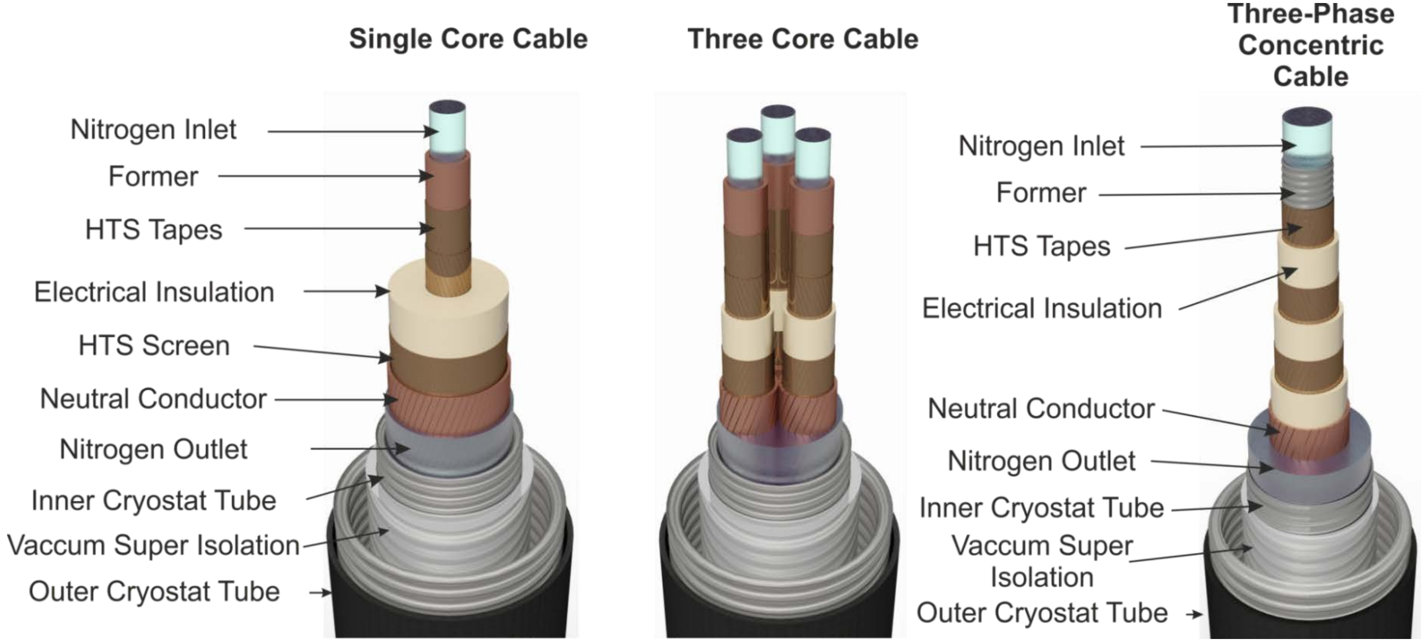
Cable Types – Cold Dielectric



	Three single phases	Three phase in one cryostat	Three phase concentric
Voltage level	High voltage > 110 kV	30-110 kV	10-50 kV
Amount of superconductor	higher	higher	smaller
Cryostat loss	higher	smaller	smaller

State-of-the-Art

- Technology Readiness Level (EU H2020)

9 Actual system proven in operational environment

8 System complete and qualified

7 System prototype demonstration in operational environment

6 Technology demonstrated in relevant environment

5 Technology validated in relevant environment

4 Technology validated in lab

3 Experimental proof of concept

2 Technology concept formulated

1 Basic principles observed

High TRL (7–9)
Med. TRL (4–6)
Low TRL (1–3)

HTS AC MV Cables – State-of-the-Art

2000 – First HTS cable in public grid operation by Southwire

- Three separate phases
- Voltage 12.5 kV
- Current 1250 A
- Length 30 m
- HTS BSCCO
- Total loss 1490 W @ 77 K, 600 A
- 230 W per terminal
- 1 W/m/Phase Cryostat
- 0.2 W/m/Phase @ 600 A

Experimental proof of concept

Stovall et.al. IEEE TASC Vol. 11, No.1, March 2001

9 8 7 6 5 4 3 2 1

2000 2005 2010 2015 2020 2025

HTS AC MV Cables – State-of-the-Art

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2006 – First three phase concentric design in long term (~ 1 year) field test by Ultera (Southwire, nkt cables)

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Three phase co-axial design

Voltage 13.2 kV

Current 3000 A

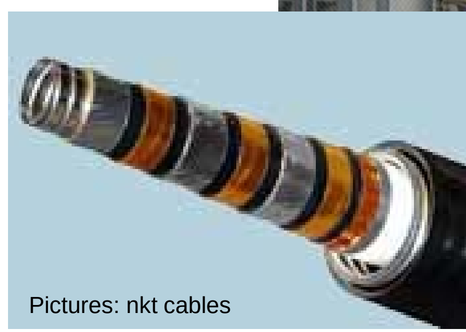
Length 200 m

HTS BSCCO

Ic > 7000 A at 78.5 K

2 W/m Cryostat

Demko et.al. IEEE TASC doi 10.1109/TASC.2007.897842



Pictures: nkt cables

Technology validated in relevant environment

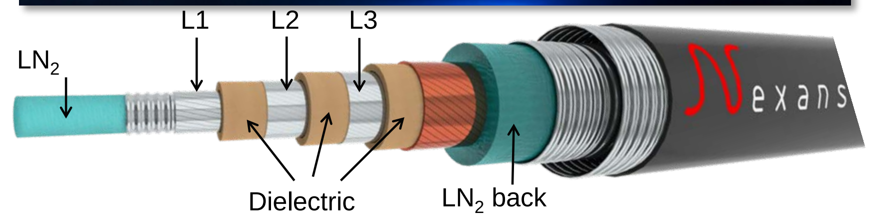
2000 2005 2010 2015 2020 2025

HTS AC MV Cables – State-of-the-Art

2014 – First long term (> 5 years) and continous operation in the grid of Essen by Nexans and Westnetz

- Three phase co-axial design
- Voltage 10 kV
- Power 40 MVA
- Length 1000 m
- HTS BSCCO
- Loss 1.8 kW at 68 K, $I < 0.5\ I_n$

AMPACITY
Smart grids for the city



Stemmle et. al. IEEE PES T&D Conference and Exposition, 14-17 April 2014, Chicago, IL, USU
DOI: 10.1109/TDC.2014.6863566

Technology demonstrated in relevant environment

9 8 7 6 5 4 3 2 1

2000 2005 2010 2015 2020 2025

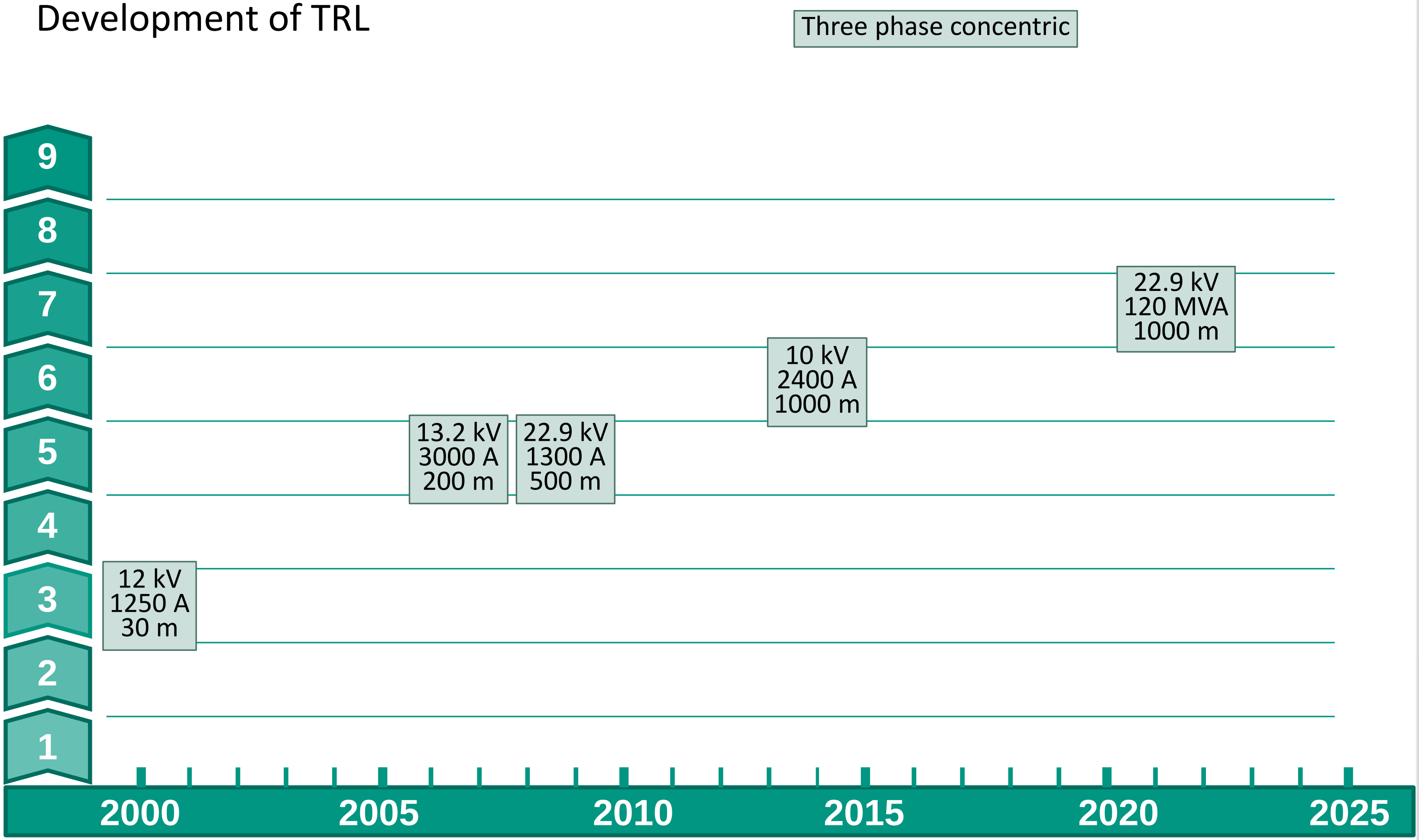
Superconducting AC Cables
State-of-the-Art

Manufacturer	Place ,Country, Year	Data	HTS
SECRI	Shanghai, China, 2021	35 kV, 2.2 kA, 1200 m	YBCO
Nexans	Chicago, US, 2020	12 kV, 200 m	YBCO
LS Cable	Singal, Korea, 2019	22.9 kV, 50 MVA, 1000 m	YBCO
LS Cable	Jeju, Korea, 2016	154 kV, 600 MVA, 1000 m	YBCO
Nexans	Essen, Deutschland, 2014	10 kV, 2.4 kA, 1000 m	BSCCO
Sumitomo	Yokohama, Japan, 2013	66 kV, 1.8 kA, 240 m	BSCCO
LS Cable	Icheon, Korea, 2011	22.9 kV, 3.0 kA, 100 m	BSCCO
LS Cable	Icheon, Korea, 2009	22.9 kV, 1.3 kA, 500 m	BSCCO
Nexans	Long Island, US, 2008	138 kV, 2.4 kA, 600 m	BSCCO/YBCO
LS Cable	Gochang, Korea, 2007	22.9 kV, 1.26 kA, 100 m	BSCCO
Sumitomo	Albany, US, 2006	34.5 kV, 800 A, 350 m	BSCCO
Ultera	Columbus, US, 2006	13.2 kV, 3 kA, 200 m	BSCCO
Sumitomo	Gochang, Korea, 2006	22.9 kV, 1.25 kA, 100 m	BSCCO
Furukawa	Yokosuka, Japan, 2004	77 kV, 1 kA, 500 m	BSCCO

More than 10 years of operational experience and no HTS degradation reported.

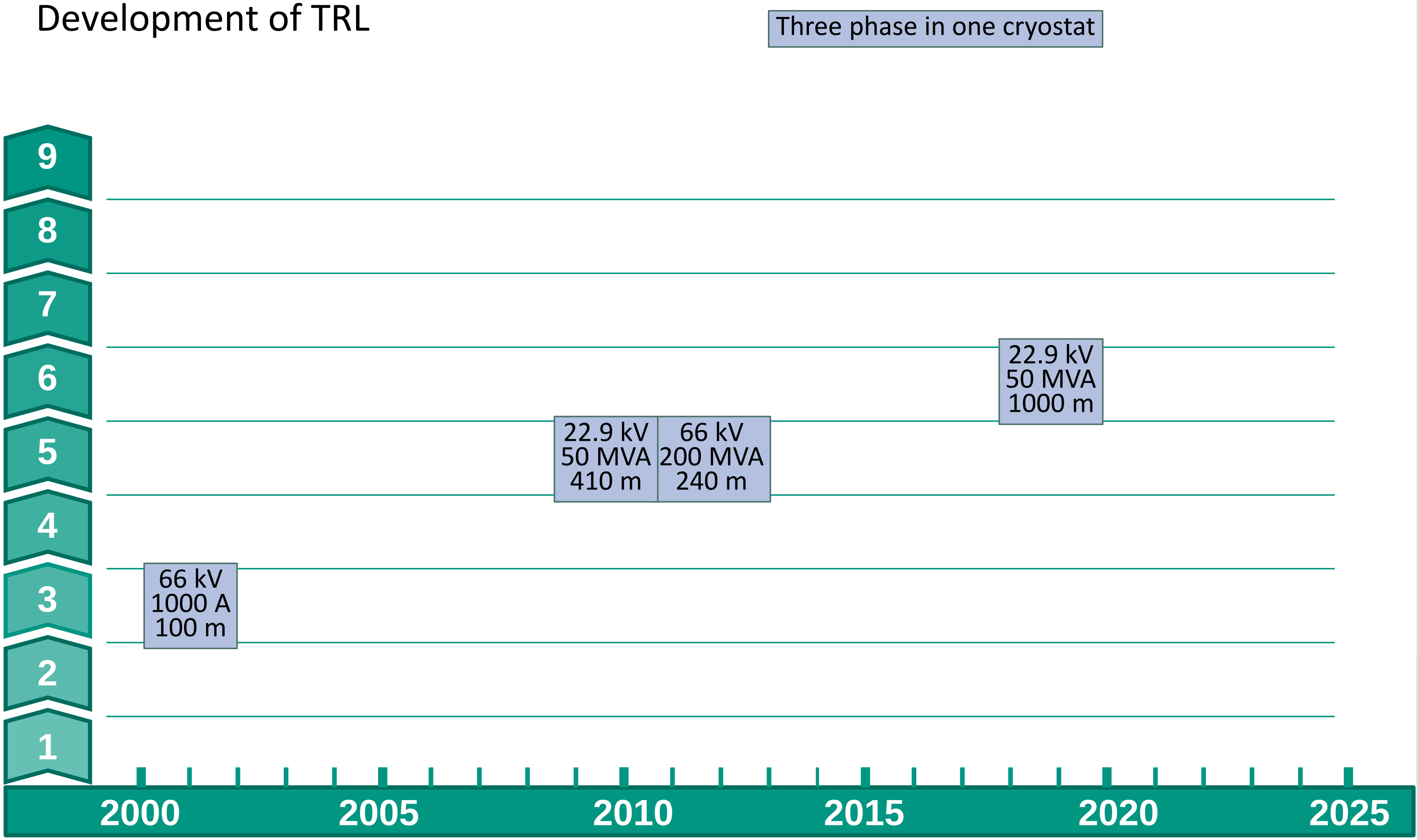
HTS AC MV Cables – State-of-the-Art

Development of TRL



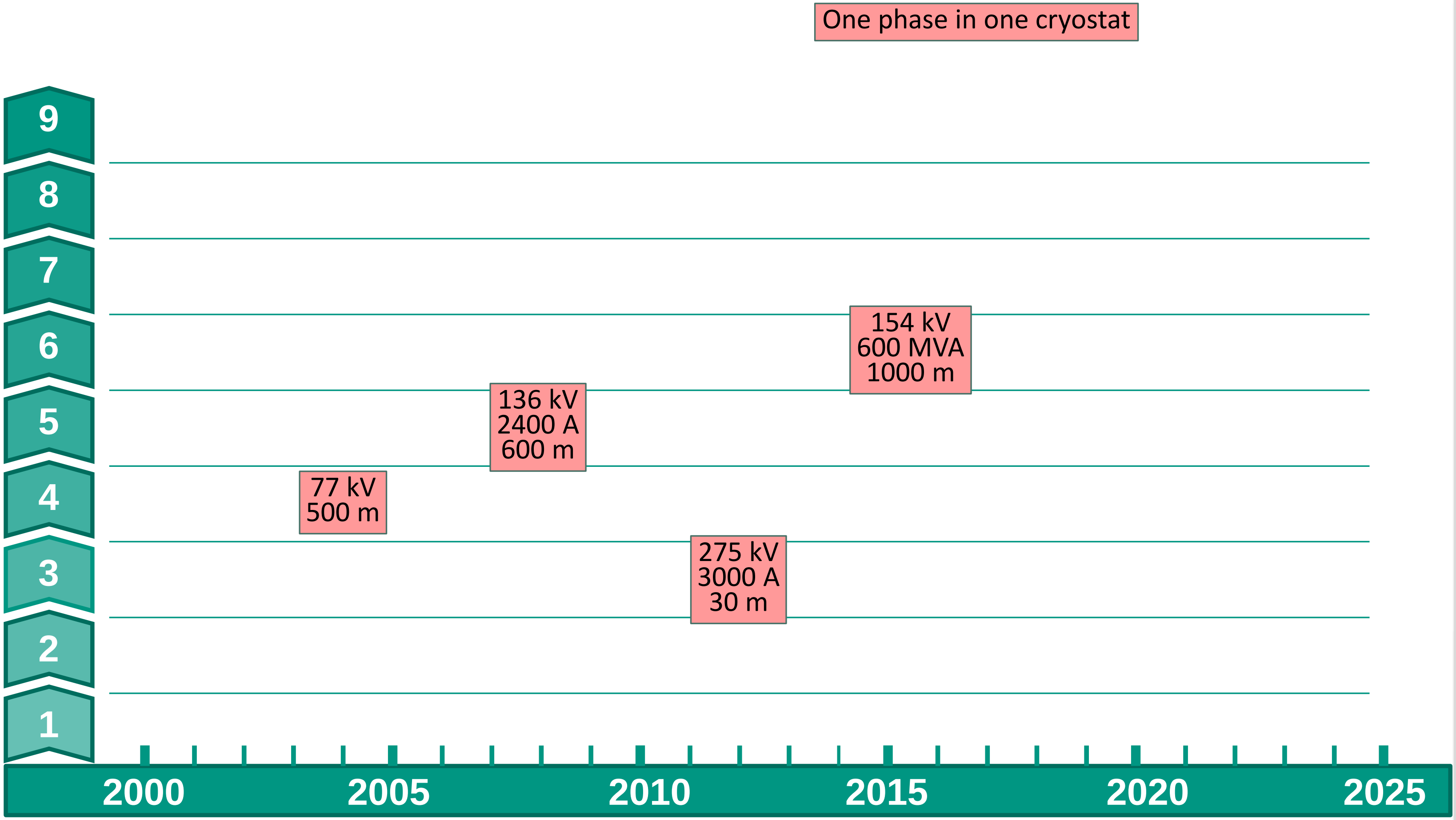
HTS AC MV Cables – State-of-the-Art

Development of TRL



HTS AC HV Cables – State-of-the-Art

Development of TRL



How HTS Cables meet Power System Challenges

- Integration of renewables and EV needs new technologies and transmission and distribution lines.
  - Many new transmission lines need to be built with a large fraction of cables instead of overhead transmission lines.
  - The distribution grid needs a considerable extension.
- A higher acceptance of compact high power lines and a faster approval procedure is achieved.
  - More compact cable ways for very high voltage cables.
  - Use of retrofit ducts in cities avoids new cable ducts.
- Lower losses and consequently CO_2 savings are achieved.
- Environmentally friendly.

1) Ensure stable, reliable and **economic** operation by e.g. balancing fluctuating generation and volatile consumption.
2) Extension of energy infrastructure to better integrate storage and renewables.
3) Development of acceptable energy and resource efficient technology solutions and processes to reduce CO_2 emissions.

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  - Cables
  - **Fault Current Limiters**
  - Rotating Machines
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Benefits

Development of the State-of-the-Art

How this meets Power Challenges

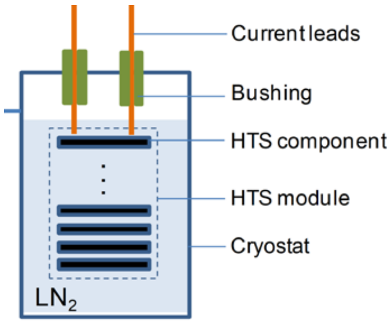
Benefits of Fault Current Limiters

Economic Benefits

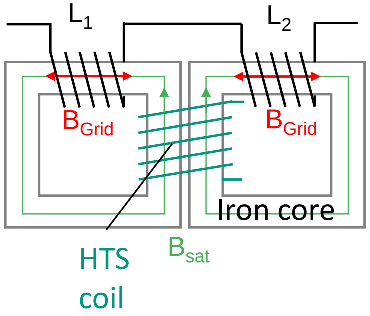
- Delay improvement of components and upgrade power systems
  - e.g. connect new generation and do not increase short-circuit currents
  - e.g. couple busbars to increase renewable generation and keep voltage bandwiths
- Lower dimensioning of components, substations and power systems
  - e.g. FCL in power system auxiliary
- Avoid purchase of power system equipment
  - e.g. avoid redundant feeders by coupling power systems
- Increase availibility and reliability
  - e.g. by coupling power systems
- Reduce losses and CO_2 emissions
  - e.g. equal load distribution with parallel transformers

Different Types of Fault Current Limiters

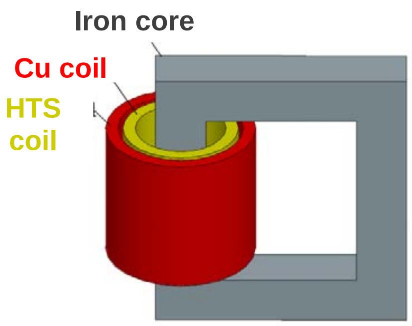
Resistive type



DC biased iron core



Shielded core type



plus many others

Diode bridge

Flux lock type

…

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Fault Current Limiters – State-of-the-Art

2004 – First resistive type SCFCL in grid operation at RWE

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Voltage 10 kV

Current 600 A

Limited Current 8.75 kA

Fault duration 60 ms

BSCCO bulk

Bock et. al. IEEE TASC, Vol. 15, Nr. 2, p 1955-1960, 2005

Technology validated in relevant environment

2000 2005 2010 2015 2020 2025

Fault Current Limiters – State-of-the-Art

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2014 – Resistive type SCFCL in long term grid operation at Westnetz in Essen

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- Voltage 10 kV
- Power 40 MVA
- Limited Current 13 kA
- Fault duration 100 ms
- YBCO tapes

Stemmle et. al, IEEE PES T&D Conference and Exposition, 14-17 April 2014, Chicago, IL, USA, DOI: 10.1109/TDC.2014.6863566

System prototype demonstration in operational environment

2000 2005 2010 2015 2020 2025

Fault Current Limiters – State-of-the-Art

2019 – First 220 kV resistive type SCFCL in grid operation in Russia

- Voltage 220 kV
- Current 1200 A
- Limited Current 7 kA
- Fault duration ?? ms
- 25.2 km, 12mm wide YBCO

Picture and information Superox

Technology demonstrated in relevant environment

9 8 7 **6** 5 4 3 2 1

2000 2005 2010 2015 2020 2025

Superconducting Fault Current Limiters
State-of-the-Art of field tests of resistive Type SFCL

Lead Company	Country	Year	Data	Superconductor
ACCEL/NexansSC	Germany	2004	12 kV, 600 A	Bi 2212 bulk
Toshiba	Japan	2008	6.6 kV, 72 A	YBCO tape
Nexans SC	Germany	2009	12 kV, 100 A	Bi 2212 bulk
Nexans SC	Germany	2009	12 kV, 800 A	Bi 2212 bulk
ERSE	Italy	2011	9 kV, 250 A	Bi 2223 tape
ERSE	Italy	2012	9 kV, 1 kA	YBCO tape
KEPRI	Korea	2011	22.9 kV, 3 kA	YBCO tape
Nexans SC	Germany	2011	12 kV, 800 A	YBCO tape
AMSC / Siemens	USA / Germany	2012	115 kV, 1.2 kA	YBCO tape
Nexans SC	Germany	2013	10 kV, 2.4 kA	YBCO tape
Nexans SC	UK	2015	12 kV, 1.6 kA	YBCO tape
Siemens	Germany	2016	12 kV, 815 A	YBCO tape
Superox	Russia	2019	220 kV, 1.2 kA	YBCO tape
LS Industrial Systems	Korea	2020	25.8 kV, 2 kA	YBCO tape
China Southern Pow. Gr.	China	2023	160 kV, 2 kA	YBCO tape

Table not complete

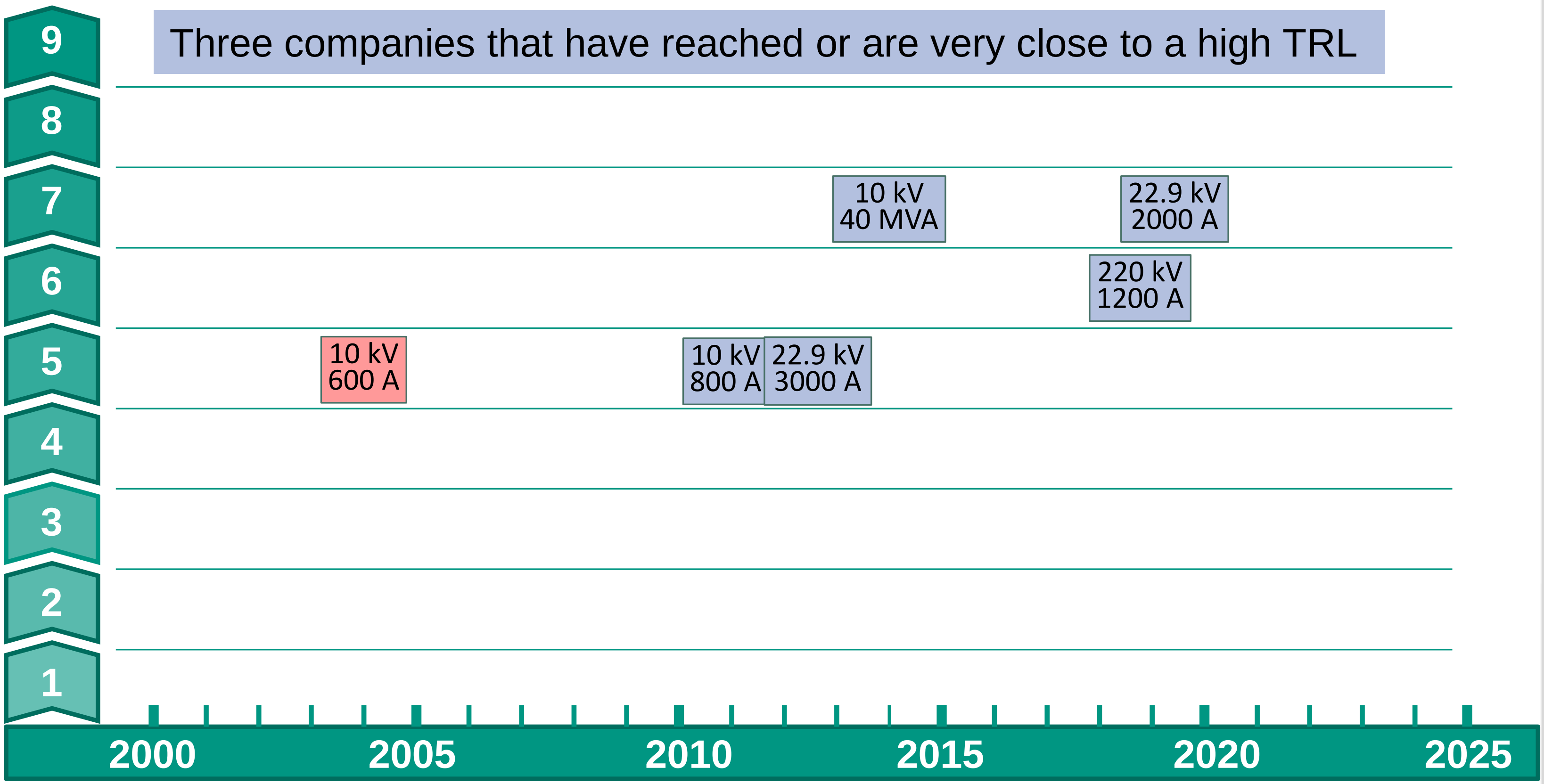
More than 10 successful field tests and a few companies offering commercial systems

HTS Fault Current Limiter – State-of-the-Art

Development of TRL of resistive type SFCLs

BSCCO bulk

YBCO tapes



How SCFCL meet Power System Challenges

- Enable integration of additional generation without increase of short-circuit currents.
- Enable meshing of grids without increase of short-circuit currents
  - Increased security of supply
  - Lower losses
  - Higher power quality
- Enable instantaneous reduction of increasing fault current levels in densely populated areas with automatic recovery (no conventional counterpart so far)

1) Ensure stable, reliable and economic operation by e.g. balancing fluctuating generation and volatile consumption.
2) Extension of energy infrastructure to better integrate storage and renewables.
3) Development of acceptable energy and resource efficient technology solutions and processes to reduce CO_2 emissions.

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Superconducting Rotating Machines

- Promising Applications

Power generators

Picture: Siemens

Ship propulsion

K Umemoto et.al, doi:10.1088/1742-6596/234/3/032060

Hydro generators

Picture Courtesy of Converteam

Wind generators

Picture: Ecoswing EU

Electric aircraft

Picture: Oswald

Others

Picture: Oswald

Benefits of Superconducting Rotating Machines

Example of a Synchronous Machine with Superconducting Rotor

- Smaller volume and weight
  - Half the weight and volume
  - Two times higher power density
- Less resources
  - Higher efficiency
  - Less material
- Improved operation parameters
  - Lower voltage drop (xd~ 0.2-0.3 p.u.)
  - Higher stability
  - Higher torque and dynamics
  - Higher ratio of breakdown torque to nominal torque
  - More reactive power

Enables new drive and generator systems

Rotating Machines – State-of-the-Art

2004 – First superconducting rotating machine in field operation – Synchronous Condenser from AMSC

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Power 8 MVAR

Voltage 13.8 kV

BSCCO tape

..“two production units rated at 12 MVAR, 13.8 kV are on order for delivery to TVA by December 2006 and March 2007”

Source: KALSI S et al., IEEE Trans. on Applied Superconductivity 17, No. 2, 1591-4 (2007).

Technology demonstrated in relevant environment

2000 2005 2010 2015 2020 2025

Rotating Machines – State-of-the-Art

2008 – Largest superconducting rotating machine with a power of 36.5 MW for ship propulsion by AMSC

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- Power 36.5 MW
- Speed 120 U/min
- Voltage 6 kV
- Current 1270 A
- Polepairs 8
- Weight 75 to
- Efficiency > 97 %
- BSCCO

Gamble et.al, IEEE TASC, Vol. 21, Nr. 3, June 2011

Technology validated in lab

2000 2005 2010 2015 2020 2025

Rotating Machines – State-of-the-Art

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2018 – First Multi-Megawatt superconducting wind generator power generation by Ecoswing EU project

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- Power 3.6 MW
- Voltage 690 V
- Torque 2.46 kNm
- Speed 14 rpm
- Cryogenfree cooling at 30 K
- YBCO tapes

Anne Bergen et al 2019 Supercond. Sci. Technol. 32 125006

Technology demonstrated in relevant environment

2000 2005 2010 2015 2020 2025

Superconducting Rotating Machines
State-of-the-Art for ratings larger than 1 MVA

Application	Company	Country	Year	Power	RPM	HTS
Demonstrator	AMSC	US	2003	5 MW	230	BSCCO
Synchron. condenser	**AMSC**	**US**	**2004**	**8 MVAR**		**BSCCO**
Power generator	**Siemens**	**Germany**	**2006**	**4 MVA**	**3600**	**BSCCO**
Ship propulsion	Siemens	Germany	2007	4 MVA	120	BSCCO
Motor	Doosan	Korea	2007	1 MVA	3600	BSCCO
Ship propulsion	Kawasaki	Japan	2009	1 MVA	190	BSCCO
Ship propulsion	AMSC	US	2010	36.5 MVA	120	BSCCO
Hydro generator	GE/Convert.	US/UK		1.7 MW	214	BSCCO
Ship propulsion	Kawasaki	Japan	2016	3 MW	116	BSCCO
Wind generator	**Envision**	**EU H2020**	**2018**	**3.6 MW**	**15**	**YBCO**

In bold field test

Table not complete

So far not many field tests took place.

How Rotating Machines meet Power System Challenges

- Increase energy and resource efficiency (typically more than 50% of our electricity is either produced or used by electric rotating machines).
  - Less volume. less material
  - Higher efficiency
- Enable considerable reduction of CO_2 emissions in electric aircraft and ship propulsion.

1) Ensure stable, reliable and economic operation by e.g. balancing fluctuating generation and volatile consumption.
2) Extension of energy infrastructure to better integrate storage and renewables.
3) Development of acceptable energy and resource efficient technology solutions and processes to reduce CO_2 emissions.

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(Power Applications:)

Benefits

Development of the State-of-the-Art

How this meets Power Challenges

Benefits of Superconducting Transformers

Manufacturing and transport

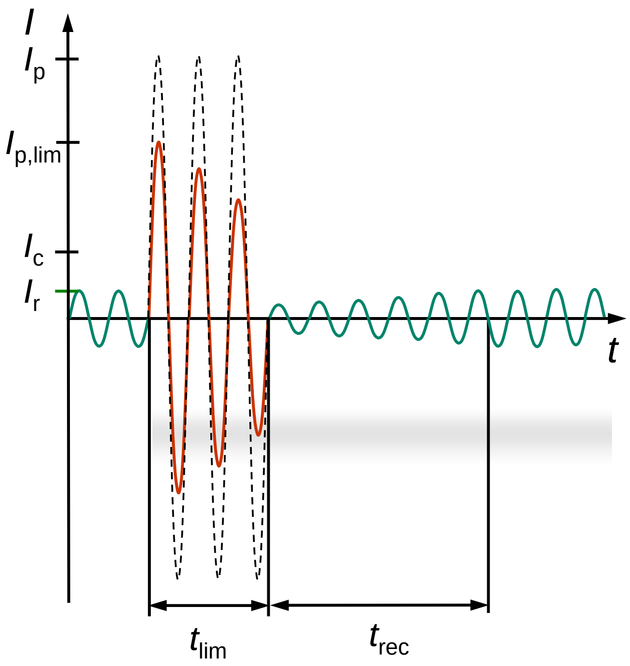
- Compact and lightweight (~50 % Reduction)

Environment and Marketing

- Energy savings (~50 % Reduction)
- 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



Enables new class of transformers.

Transformers – State-of-the-Art

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1996 – First superconducting transformer in grid operation in Switzerland

9 8 7 6 5 4 3 2 1

- Power 630 kVA
- Voltages 18.720 V / 420 V
- Dyn11
- Frequency 50 Hz
- Short-circuit imp. 4.6 %
- Currents 11.2 A/ 866 A
- BSCCO
- Cooling LN_2 at 77 K
- Losses at rated power 337 W @ 77 K

Zueger et.al, Cryogenics 38 (1998) 1169–1172

Experimental proof of concept

2000 2005 2010 2015 2020 2025

Transformers – State-of-the-Art

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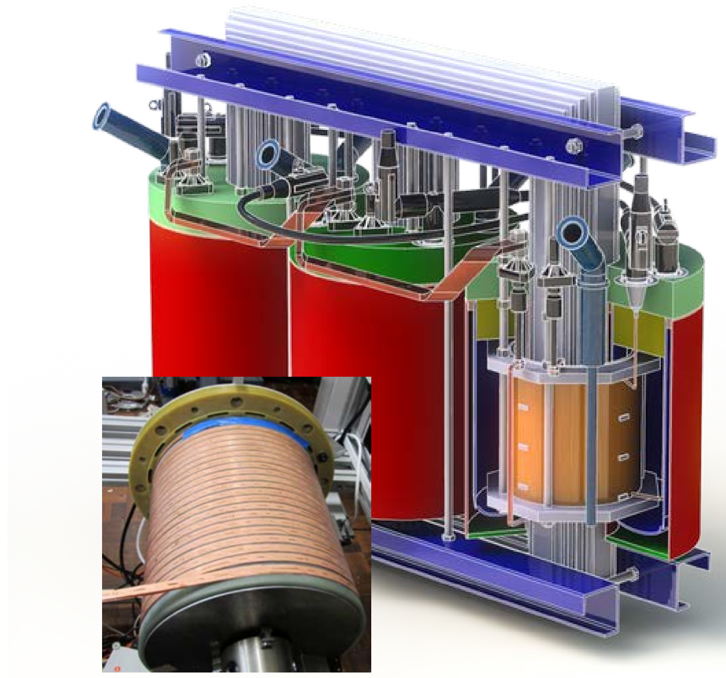
2012 – First superconducting transformer with HTS Roebel winding in New Zealand

9 8 7 6 5 **4** 3 2 1

- Nominal Power 1 MVA
- Voltage ratio 11 kV/415 V
- Current 30 A/1390 A
- Op. Temp. 70 K, LN2
- Cryogenic heat load 936 W at 70 K
- YBCO tape
- Total mass 2800 kg



Glasson et. al, IEEE TASC VOL. 23, NO. 3, JUNE 2013
Doi 10.1109/TASC.2012.2234919

Technology validated in lab

2000 2005 2010 2015 2020 2025

Transformers – State-of-the-Art

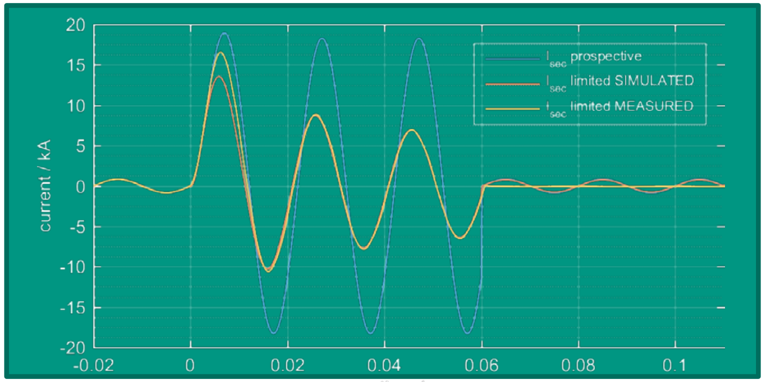
2017 – 1 MVA fault current limiting transformer demonstrated in laboratory at KIT

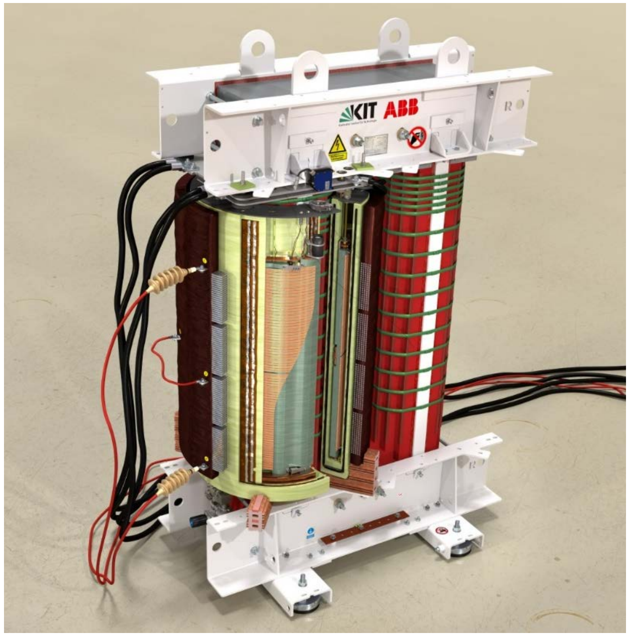
Nominal Power 577 kVA

Voltage ratio 20 kV/1 kV

Fault duration 60 ms

YBCO tape





Hellmann et. al, IEEE TASC Vol. 29 (Nr. 5),8675321, 2019

Experimental proof of concept

9 8 7 6 5 4 3 2 1

2000 2005 2010 2015 2020 2025

Superconducting Transformers State-of-the-Art (> 500 kVA)

In bold field test

Country	Inst.	Application	Data	Phase	Year	HTS
Switzerland	**ABB**	**Distribution**	**630 kVA, 18.4 kV/420V**	**3**	**1996**	**BSCCO**
Japan	Fuji Electric	Demonstrator	500 kVA, 6.6 kV/3.3 kV	1	1998	BSCCO
USA	Waukesha	Demonstrator	1 MVA, 13.8 kV/6.9 kV	1	-	BSCCO
USA	Waukesha	Demonstrator	5 MVA, 24.9 kV/4.2 kV	3	-	BSCCO
Japan	Fuji Electric	Demonstrator	1 MVA, 22 kV/6.9 kV	1	2001	BSCCO
Germany	Siemens	Railway	1 MVA, 25 kV/1.4 kV	1	2001	BSCCO
Korea	U Seoul	Demonstrator	1 MVA, 22.9 kV/6.6 kV	1	2004	BSCCO
Japan	Fuji Electric	Railway	4 MVA, 25 kV/1.2 kV	1	2004	BSCCO
Japan	Kuyshu Uni.	Demonstrator	2 MVA, 66 kV/6.9 kV	1	2004	BSCCO
China	**IEE CAS**	**Demonstrator**	**630 kVA, 10.5 kV/400 V**	**3**	**2005**	**BSCCO**
Japan	U Nagoya	Demonstrator	2 MVA, 22 kV/6.6 kV	1	2009	BSCCO/YBCO
Australia	Callaghan	Demonstrator	1 MVA, 11 kV/415 V	3	2012	YBCO
China	IEE CAS	Demonstrator	1.25 MVA, 10.5 kV/400 V	3	2014	BSCCO
Germany	KIT/ABB	Demonstrator	577 kVA, 20 kV/1 kV	1	2017	Cu/YBCO

Not many activities so far to develop prototypes for field tests.

How Transformers meet Power System Challenges

- Increase energy and resource efficiency.
  - Less volume, less material
- For superconducting transformers with active current limitation see fault current limiters.
- Enables new class of transformers with very high voltage ratio.

1) Ensure stable, reliable and economic operation by e.g. balancing fluctuating generation and volatile consumption.
2) Extension of energy infrastructure to better integrate storage and renewables.
3) Development of acceptable energy and resource efficient technology solutions and processes to reduce CO_2 emissions.

Table of Content

- Major Challenges in Power Systems
- **Power Applications**
  - Cables
  - Fault Current Limiters
  - Rotating Machines
  - Transformers
  - **SMES**
- Summary

(Power applications:)

Benefits

Development of the State-of-the-Art

How this meets Power Challenges

Benefits of SMES

- Short reaction time (ms)
- Fast charge and discharge
- 0-100 % charging possible
- Independent supply of active and reactive power
- High efficiency
- No degradation
- Environmentally friendly

Attractive benefits but limited energy storage capacity.

LTS SMES – State-of-the-Art

2001 – AMSC commerializes D-SMES

9
8
7
6
5
4
3
2
1

Capacity 3 MJ per stack

Up to 8 stacks

BSCCO in CLs

NbTi in SMES

Out of 2001 AMSC Yearly Report "We had sold 11 D-SMES systems worldwide as of May 31, 2001"

System complete and qualified

2000 2005 2010 2015 2020 2025

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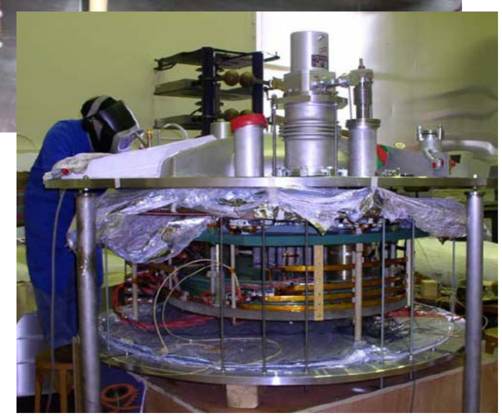
HTS SMES – State-of-the-Art

2008 – 800 kJ HTS SMES for military application

9
8
7
6
5
4
3
2
1

- Capacity 800 kJ
- Current 315 A
- BSCCO2212
- 26 'pancake' coils
- Cryogenfree cooling
- Temperature 20 K

Tixador et.al. IEEE TASC VOL. 17, NO. 2, JUNE 2007



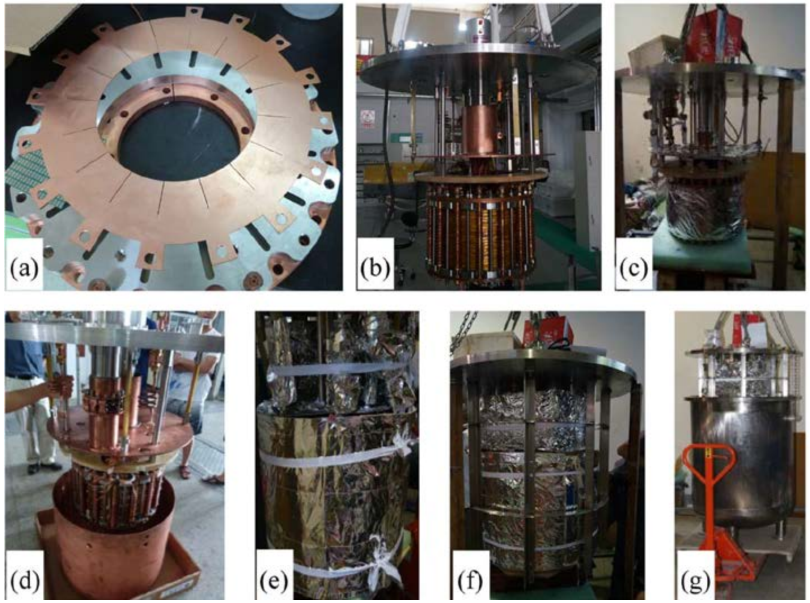
Technology validated in lab

2000 2005 2010 2015 2020 2025

HTS SMES – State-of-the-Art

2014 – 100 kW, 150 kJ movable HTS SMES

- Nominal Power 100 kW
- Capacity 150 kJ
- Max. Current 183 A
- BSCCO and YBCO coils
- 17 coils
- Temperature 20 K
- Max. Field 4.7 T



Li Ren, et.al. Development of a Movable HTS SMES System, IEEE TASC, VOL. 25, NO. 4, AUGUST 2015

9 8 7 6 5 4 3 2 1

Technology validated in relevant environment

2000 2005 2010 2015 2020 2025

HTS SMES – State-of-the-Art

Lead Institution	Country	Year	Data	Super-conductor	Application
Chubu	Japan	2004	1 MVA, 1 MJ	Bi 2212	Voltage stability
CAS	China	2007	0,5 MVA, 1 MJ	Bi 2223	-
KERI	Korea	2007	600 kJ	Bi 2223	Power-, Voltage quality
CNRS	F	2008	800 kJ	Bi 2212	Military application
KERI	Korea	2011	2.5 MJ	YBCO	Power quality
HUST	China	2014	100 kW, 150 kJ	YBCO/BSCCO	Power conditioning
U Bologna	Italy	2020	300 kJ, 100 kW	MgB_2	Hybrid energy storage

High TRL achieved but commercialization challenge due to high investment cost.

How SMES meet Power System Challenges

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- Compensate fast fluctuating changes in generation and/ or load
- Provide peak power
- Ideal for hybrid energy storage

1) Ensure stable, reliable and economic operation by e.g. balancing fluctuating generation and volatile consumption.
2) Extension of energy infrastructure to better integrate storage and renewables.
3) Development of acceptable energy and resource efficient technology solutions and processes to reduce CO_2 emissions.

Table of Content

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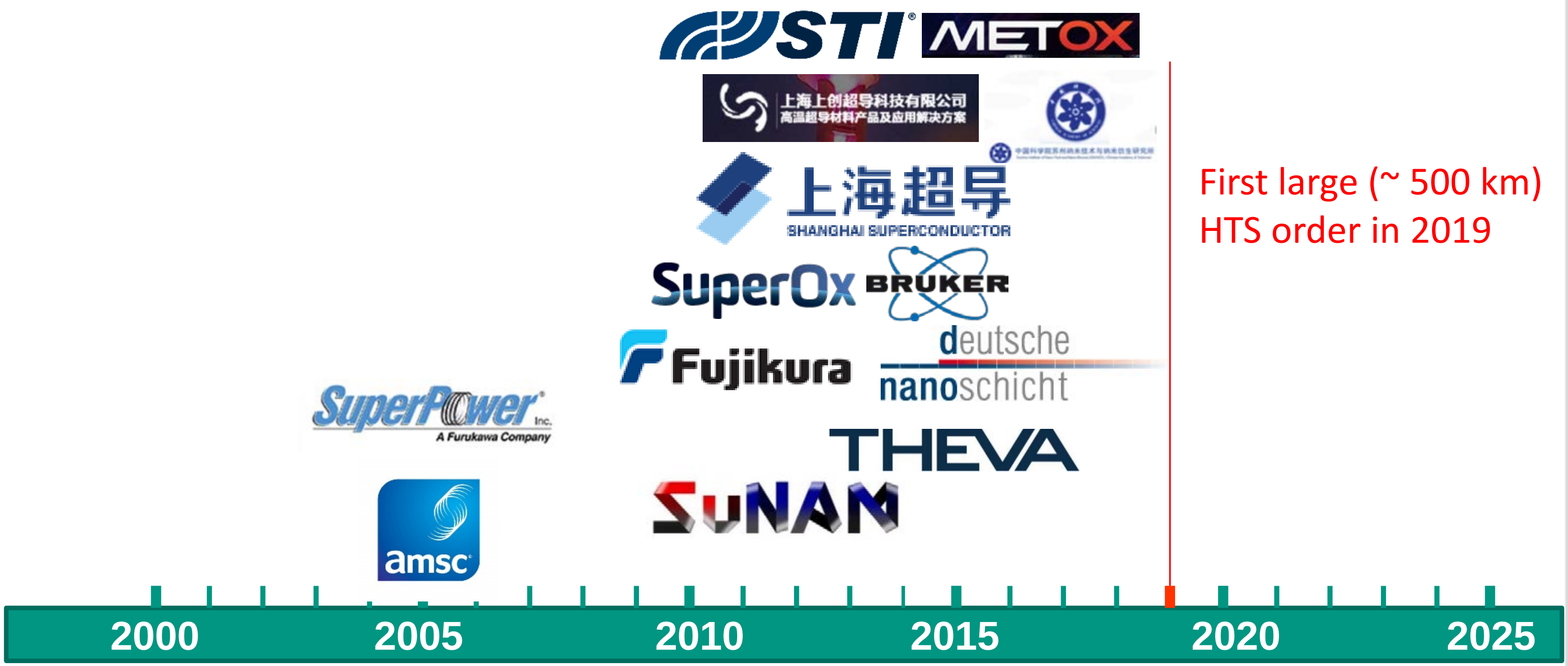
Benefits

Development of the State-of-the-Art

How this meets Power Challenges

Availability of YBCO tapes

Year of first significant manufacturing or delivery of YBCO tapes



Between 2005 and 2015 more and more companies developed pilot production lines for YBCO tapes.

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Plenary presentation PT-1 given at ACASC/Asian-ICMC/CSSJ Joint Conference, 6-9 January 2020, Okinawa, Japan.

Summary – State-of-the-Art

	Low TRL			Medium TRL			High TRL		
	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
AC MV Cables						X			
AC HV Cables						X			
DC High Current					X				
DC High Voltage					X				
SFCL MV Resistive Type							X		
SFCL HV Resistive Type						X			
Ship Propulsion Motor				X					
Wind Generator					X				
Electric Aircraft Generator		X							
Traction Transformer				X					
Utility Transformer				X					
LTS SMES								X	
HTS SMES					X				

Most of the applications need to move from medium to high TRL.

Summary – State-of-the-Art

○ Status 2000
○ Status 2010

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	Low TRL			Medium TRL			High TRL		
	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
AC MV Cables			Status 2000		Status 2010	X			
AC HV Cables		Status 2000			Status 2010	X			
DC High Current				Status 2010	X				
DC High Voltage				Status 2010	X				
SFCL MV Resistive Type				Status 2000	Status 2010		X		
SFCL HV Resistive Type		Status 2000	Status 2010			X			
Ship Propulsion Motor		Status 2000		Status 2010, X					
Wind Generator		Status 2010			X				
Electric Aircraft Generator		X							
Traction Transformer				Status 2010, X					
Utility Transformer			Status 2000, Status 2010	X					
LTS SMES								Status 2000, Status 2010, X	
HTS SMES			Status 2000	Status 2010	X				

Summary – What needs to be done?

- For applications with TRL progress in the past develop more prototypes and perform more long term field tests.
- For applications with no TRL progress in the past check if economic viability can be achieved or try „out of the box“ appraoch.
- For applications with low TRL develop first large scale demonstrators and prototypes.

Many thanks for your attention!