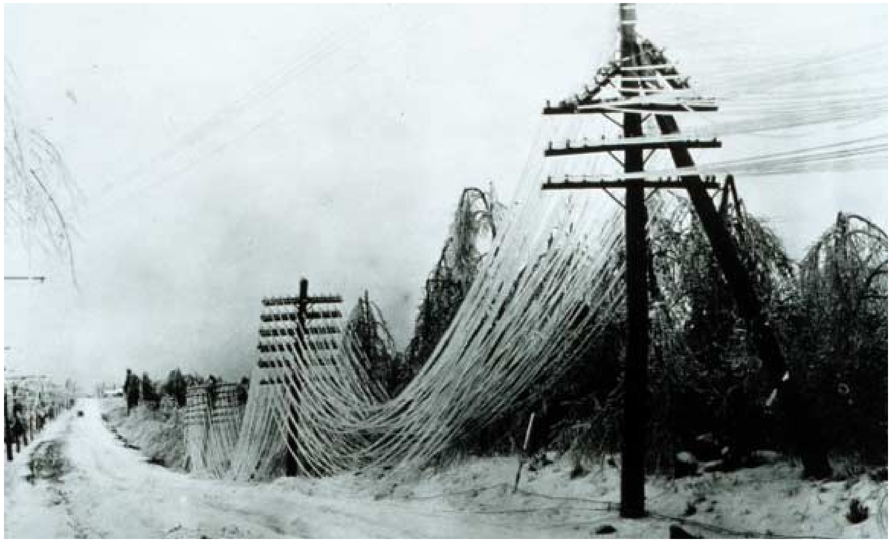
Superconducting Fault Current Limiter

„it is impossible to avoid short-circuits“

Karlsruhe Institute of Technology



Thermal stress due to short-circuit currents

Thermal energy at fault location

$$W_F = \int_0^{t_F} i \cdot v_F \, \mathrm{d}t$$

$$v_F \approx const. \rightarrow W_F \propto i$$

Conventional methods for fault current limiting

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Passive
Impedance increase in normal operation and fault case

Active
Small impedance in normal operation,
Rapid impedance rise in the event of a fault

- Subgrids
- Higher voltage
- Busbar disconnection
- (Sequential switching)

- Impedance of transformer
- Chokes

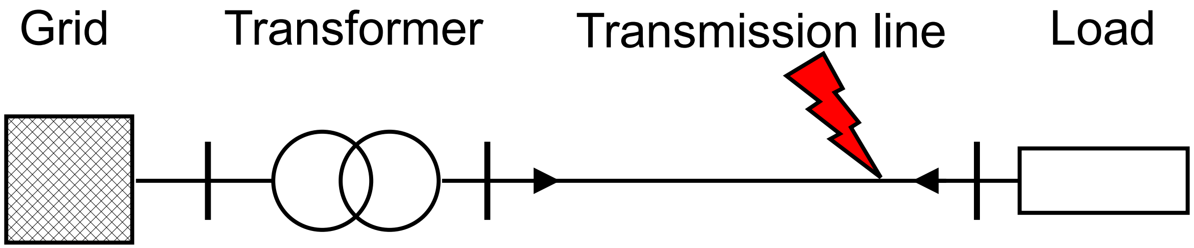
- HH-fuses (< 1 kA, < 36 kV)
- I_S-limiter (< 4 kA, < 36 kV)
- Current limiting switches

New concepts
- Superconductor
- Semiconductor e.g. FACTS
- Hybrid systems

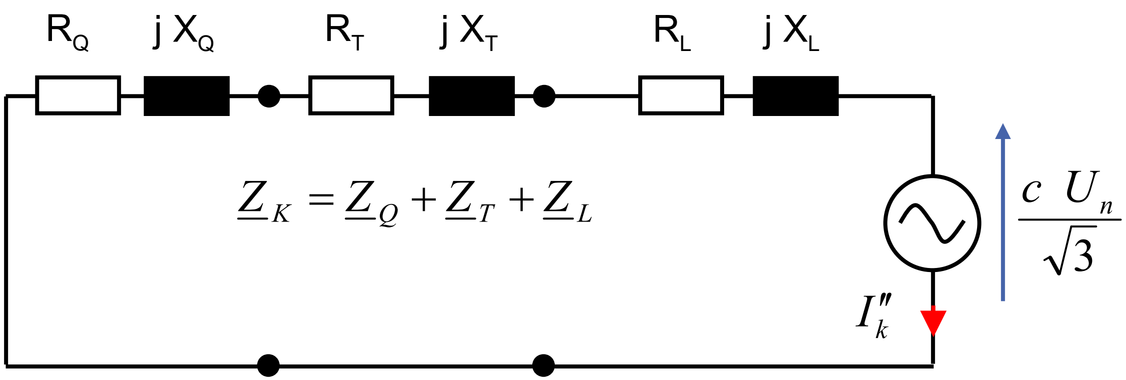
Grid measures

Device measures

Short circuit current calculation



Electrical equivalent circuit (3-phase short circuit)



c=1,1 for high short circuit currents

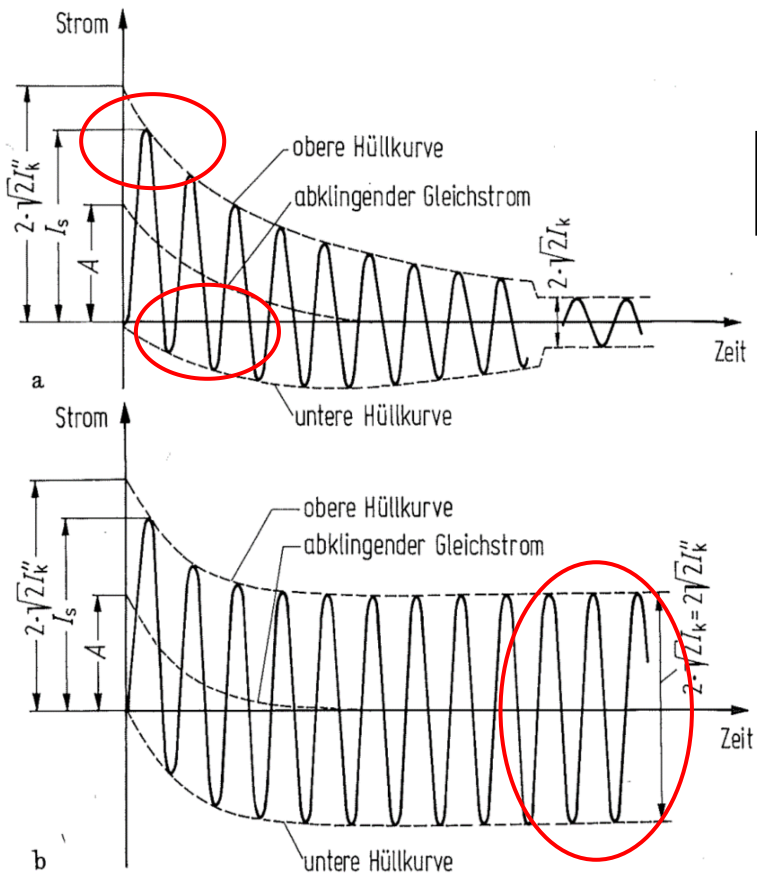
c=1 for lower short circuit currents

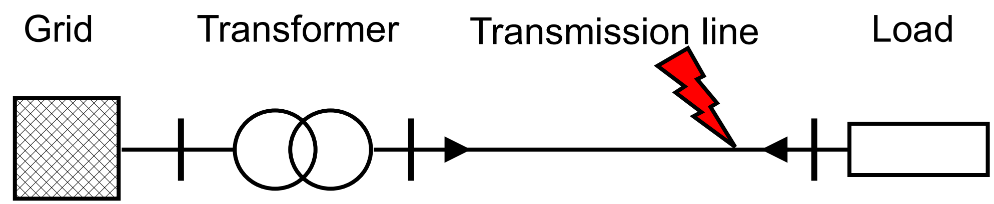
with and we get

Surge short-circuit current $i_p \leq \sqrt{2}\, I_k^{¿}$

Motivation
Short circuit current calculation

Short circuit current calculation according to DIN EN 60909-0 (VDE 0102)



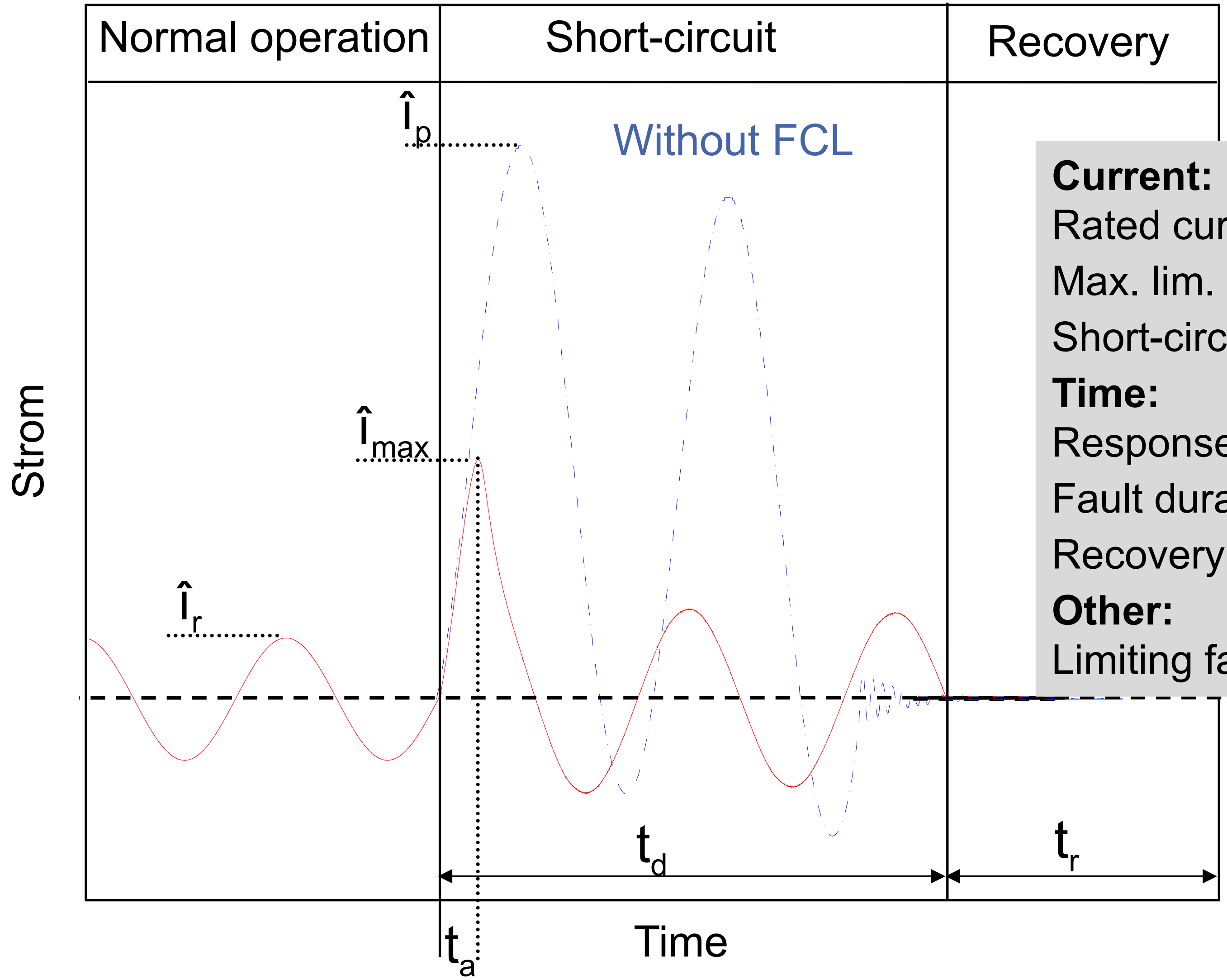


short-circuit near generator

short-circuit far from generator

Superconducting Fault Current Limiter

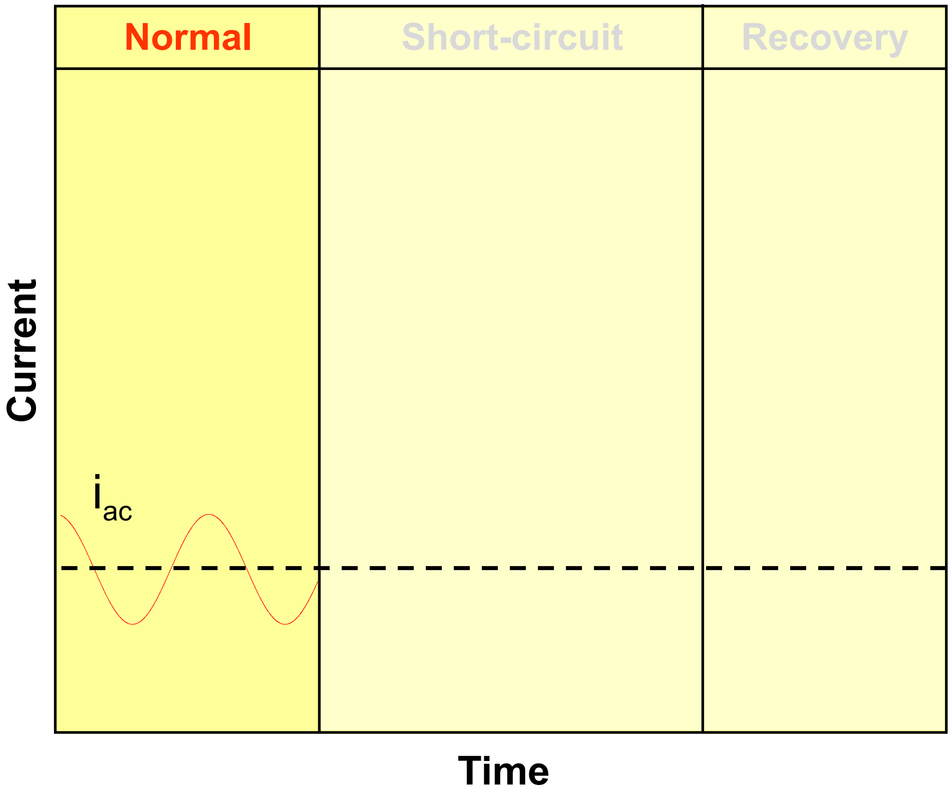
Important parameters



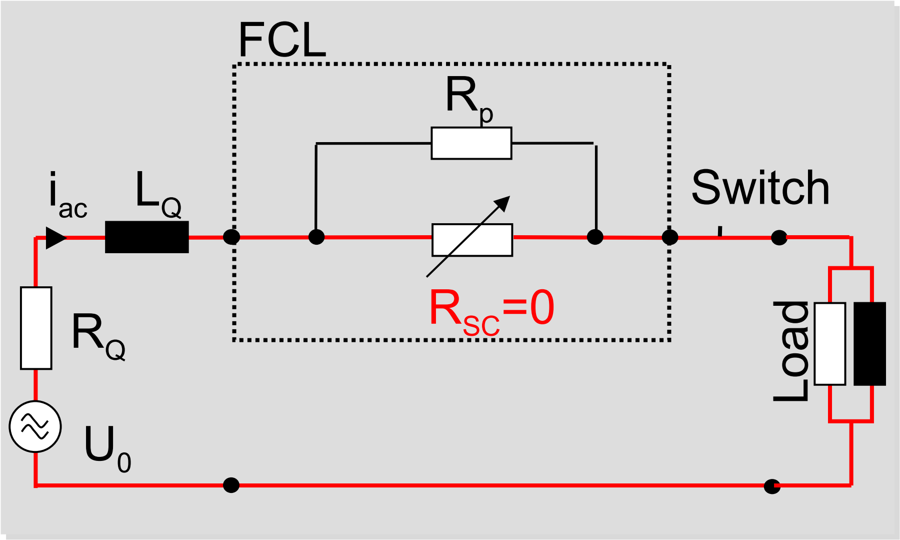
Current:
Rated current i_r, $\hat{i}_r$
Max. lim. current $\hat{i}_{max}$
Short-circuit current $\hat{i}_p$
Time:
Response time t_a
Fault duration t_d
Recovery time t_r
Other:
Limiting factor $\hat{i}_{max}/\hat{i}_r$

Resistive Fault Current Limiter

Operating behavior

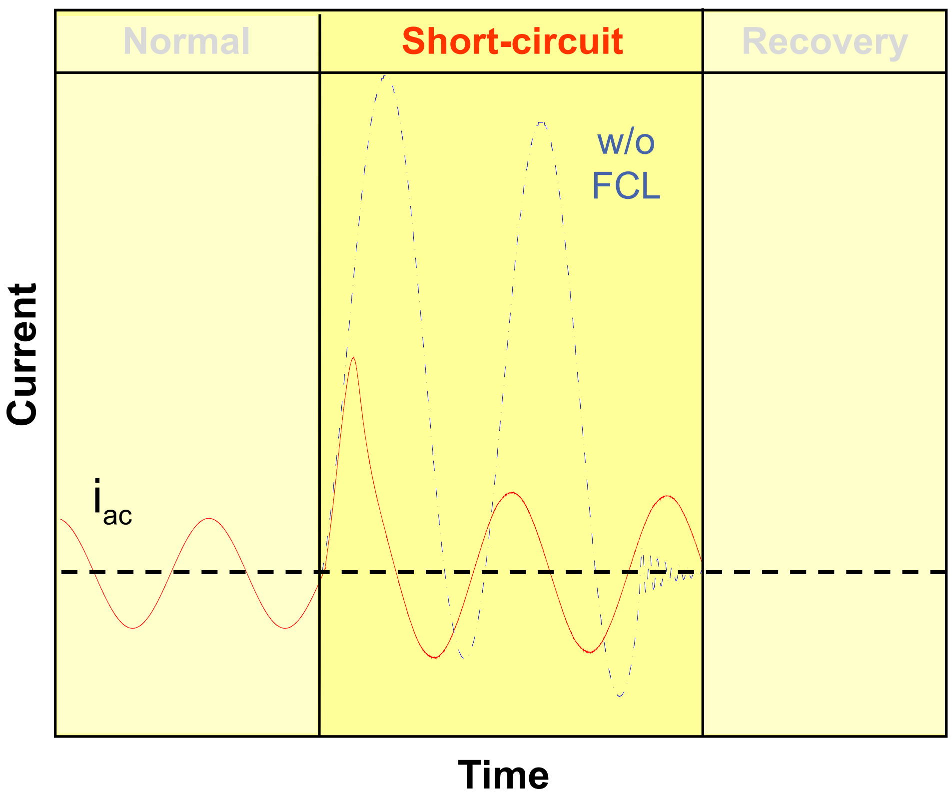


Equivalent circuit

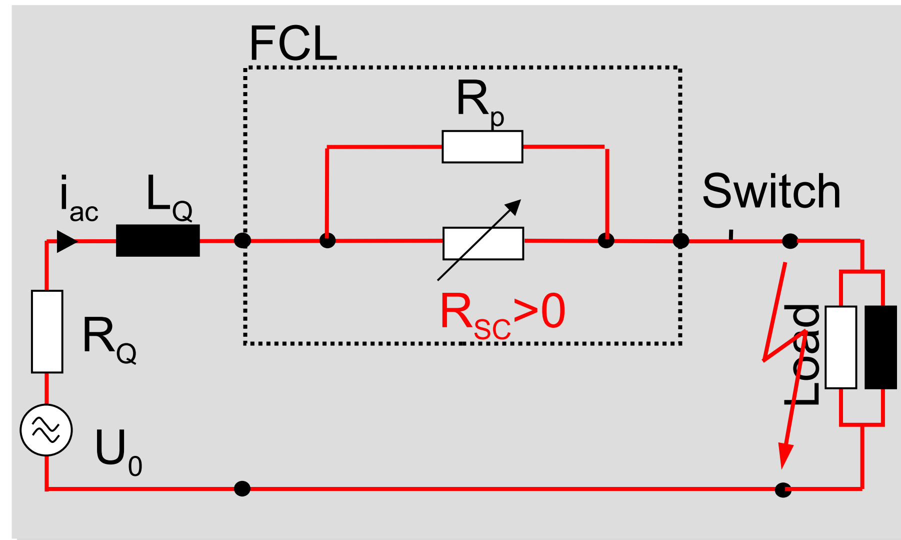


Resistive Fault Current Limiter

Operating behavior

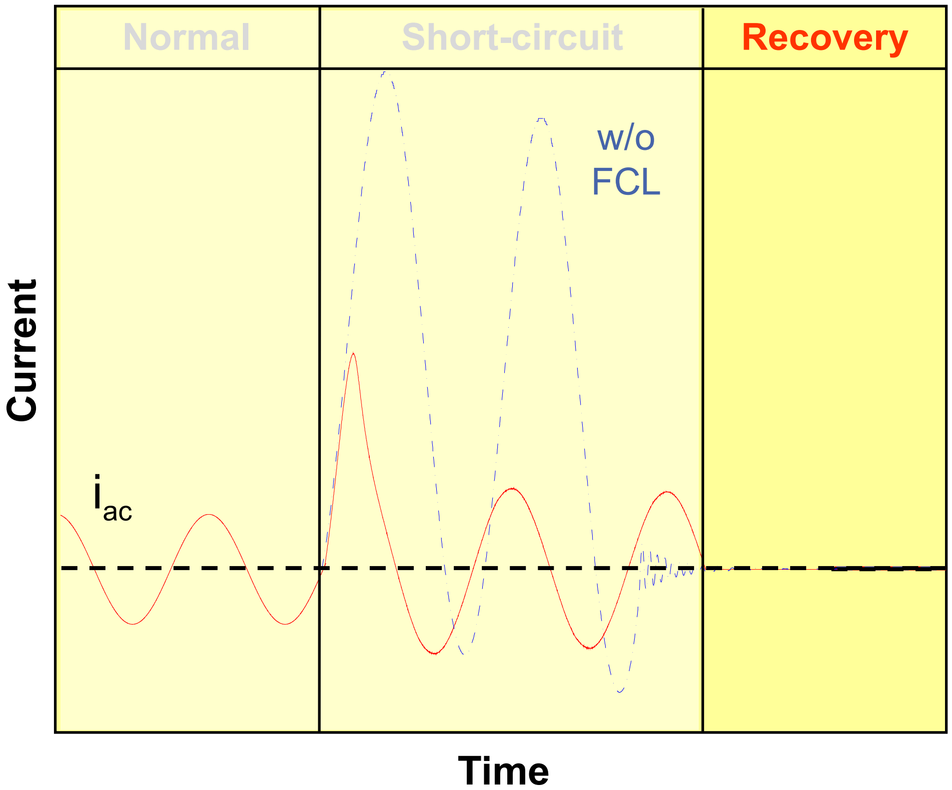


Equivalent circuit

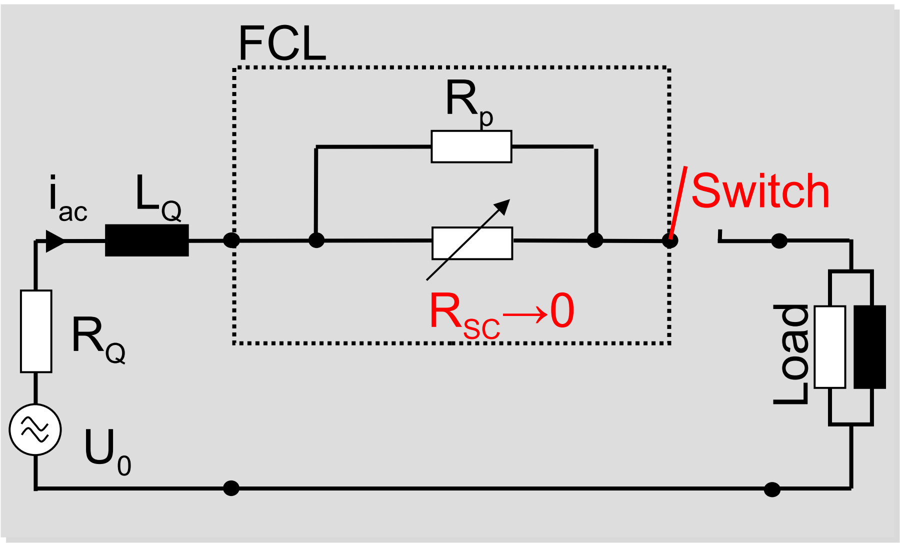


Resistive Fault Current Limiter

Operating behavior

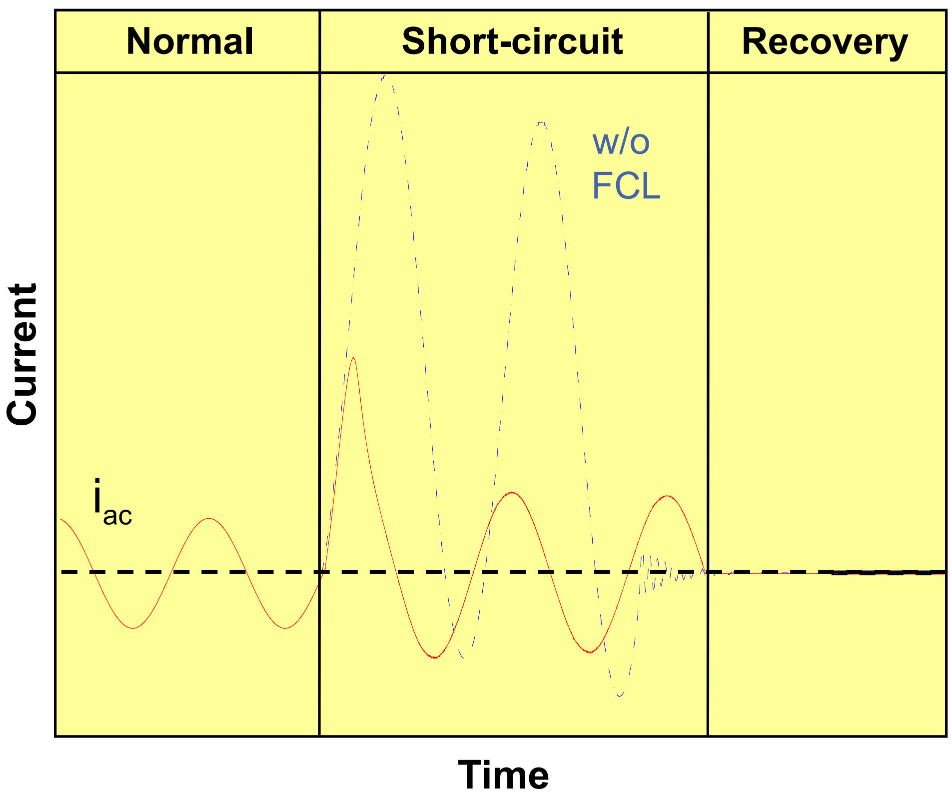


Equivalent Circuit

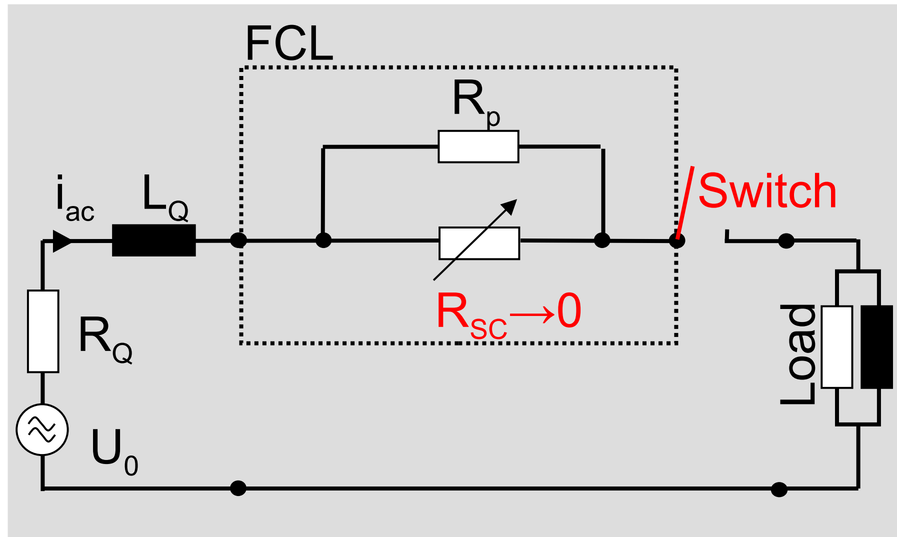


Resistive Fault Current Limiter

Operating behavior



Equivalent circuit



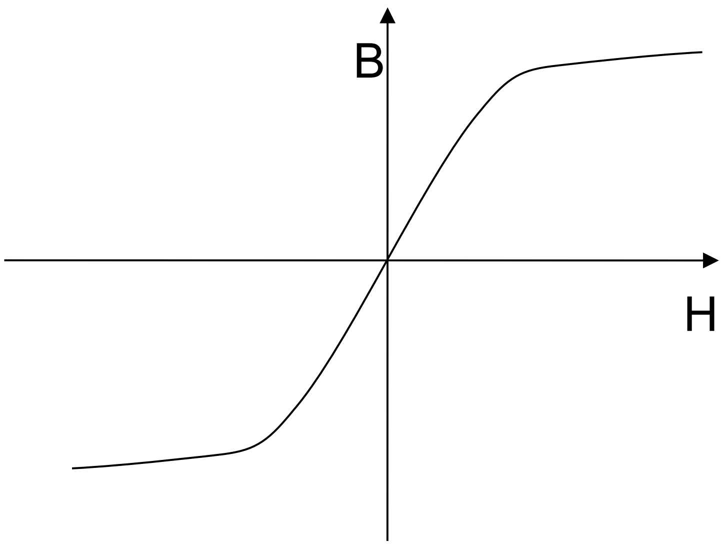
Properties

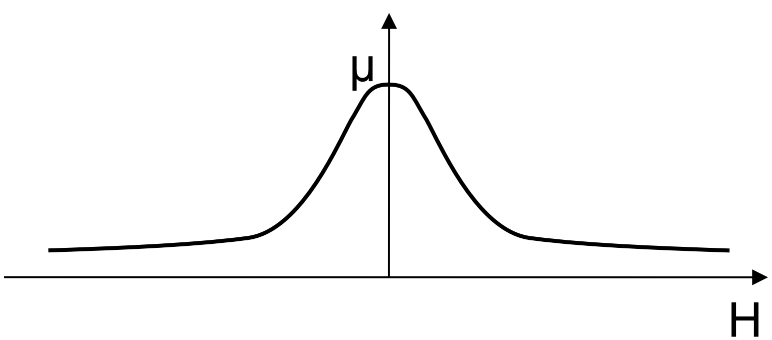
+ compact, light weight
+ intrinsically safe
- current leads to cryogenic temp

Superconducting Fault Current Limiter

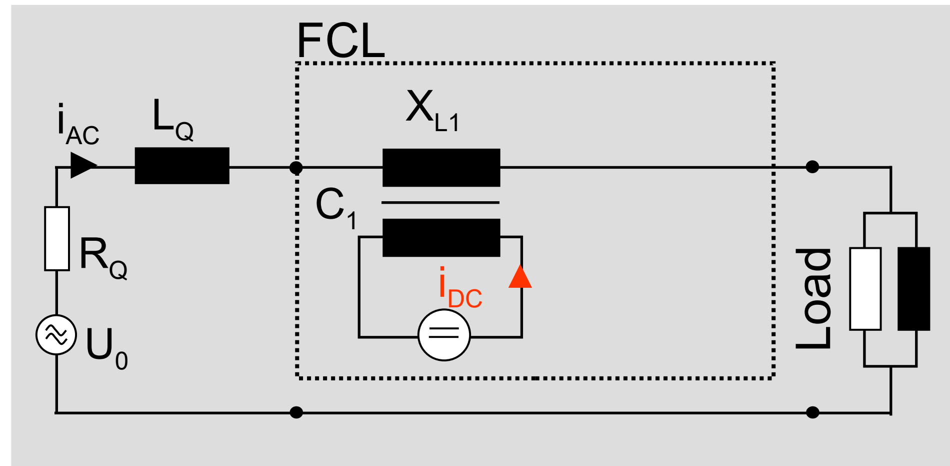
Fault current limiter with Iron core and DC-premagnetisation

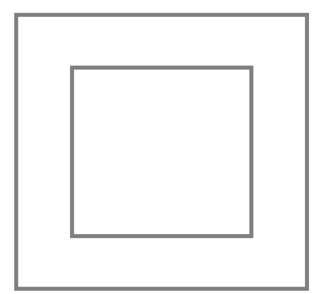
Operating behavior





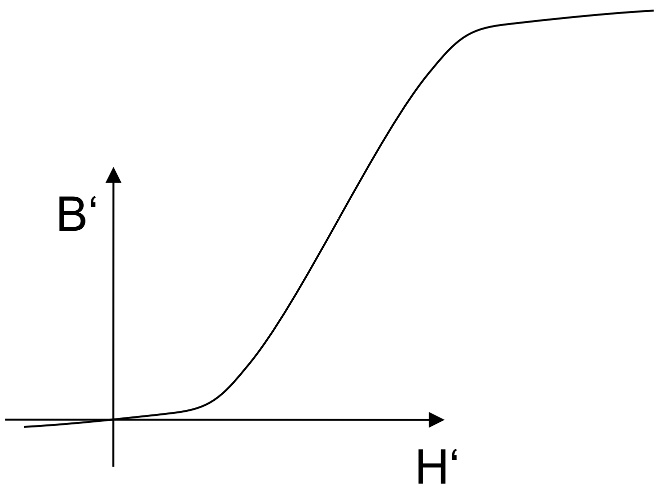
Equivalent circuit

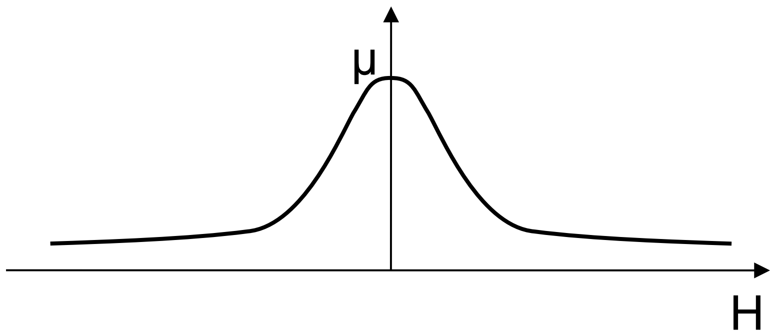




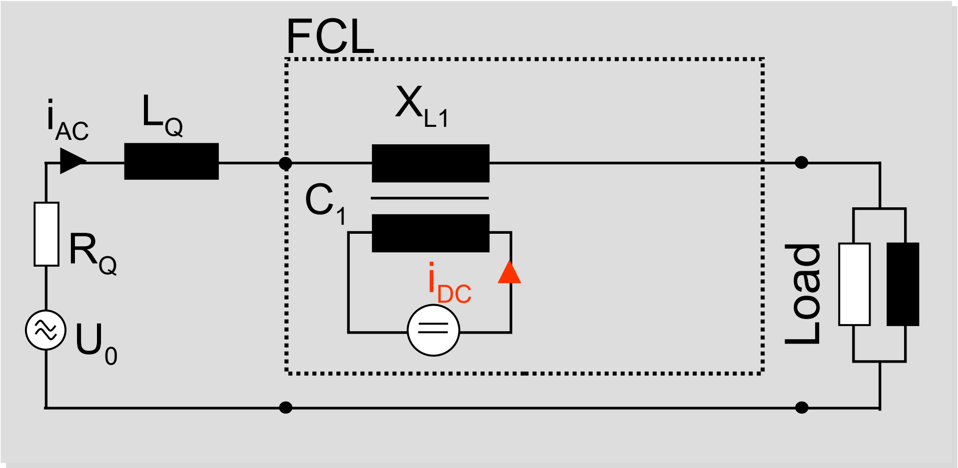
Fault current limiter with Iron core and DC-premagnetisation

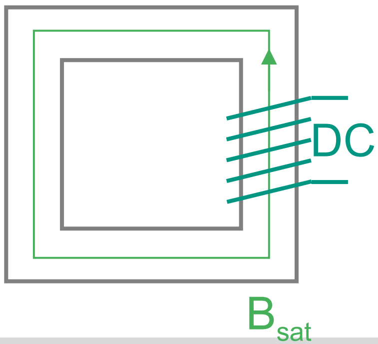
Operating behavior





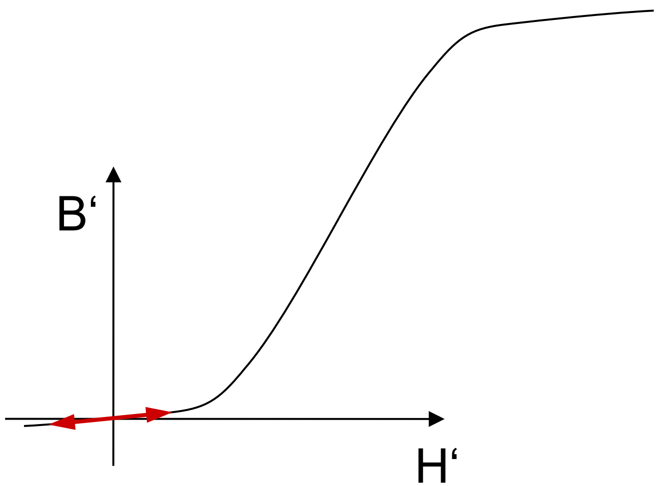
Equivalent circuit

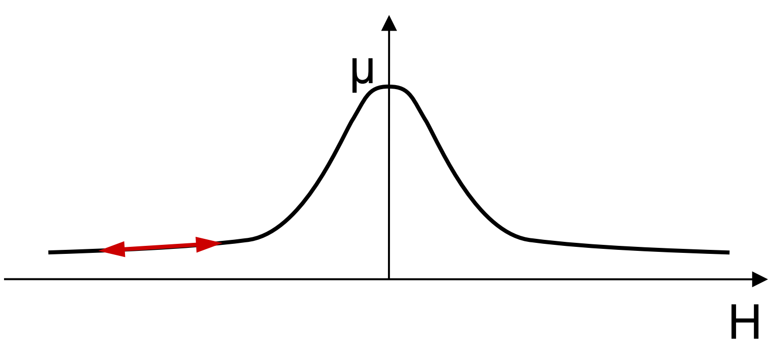




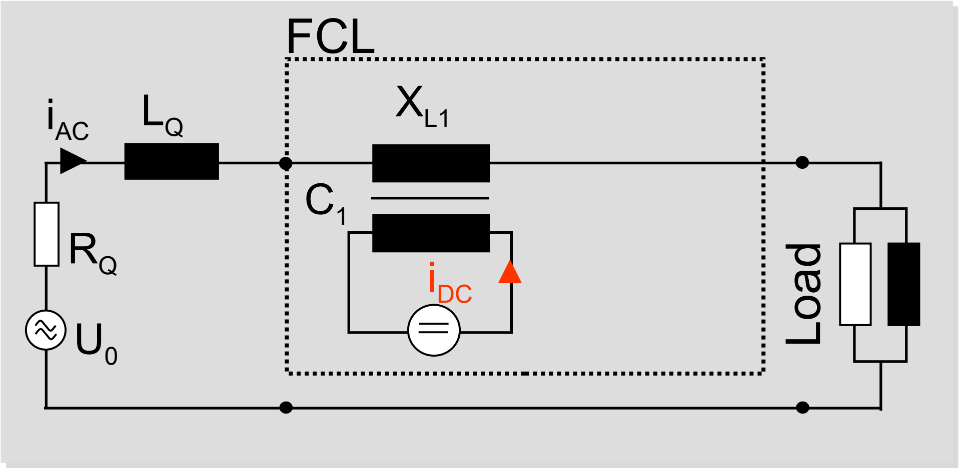
Fault current limiter with Iron core and DC-premagnetisation

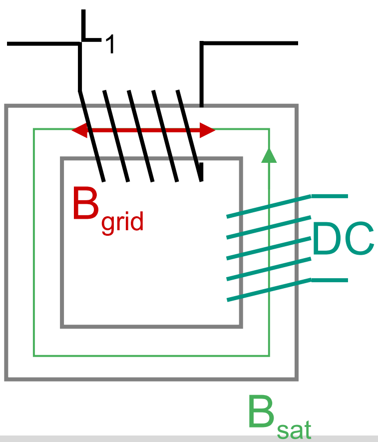
Operating behavior



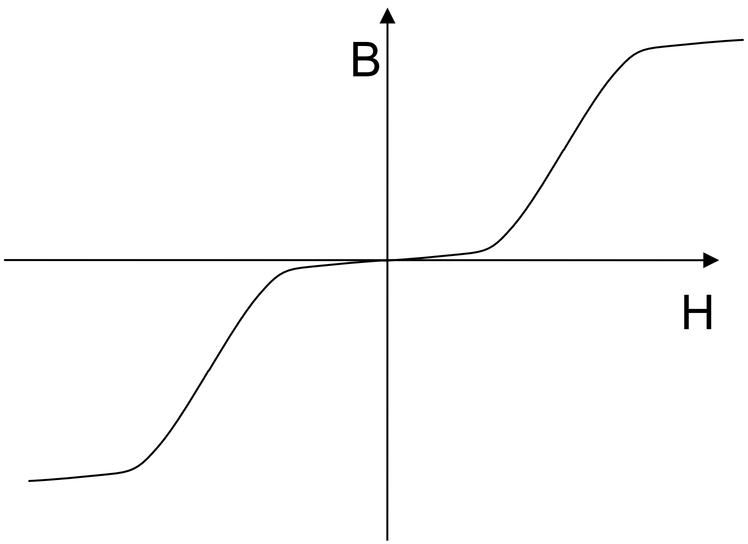


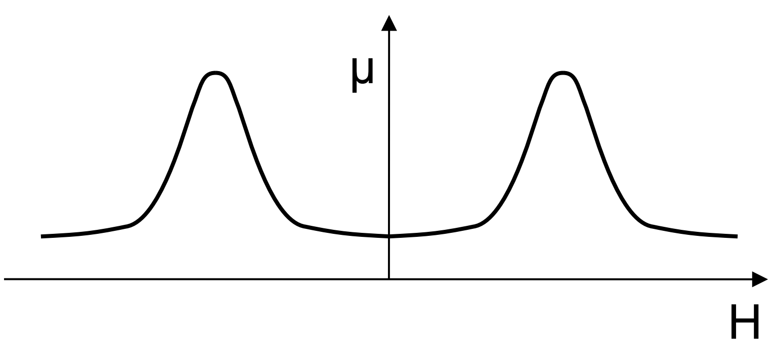
Equivalent circuit



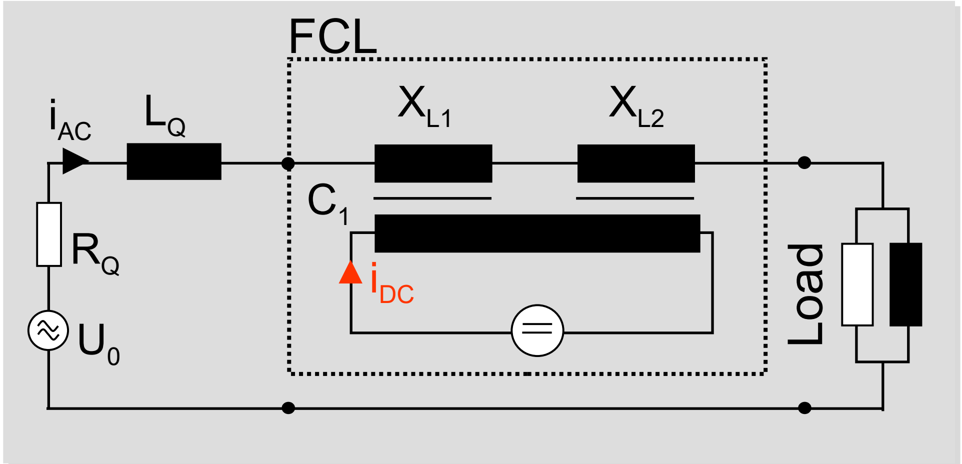


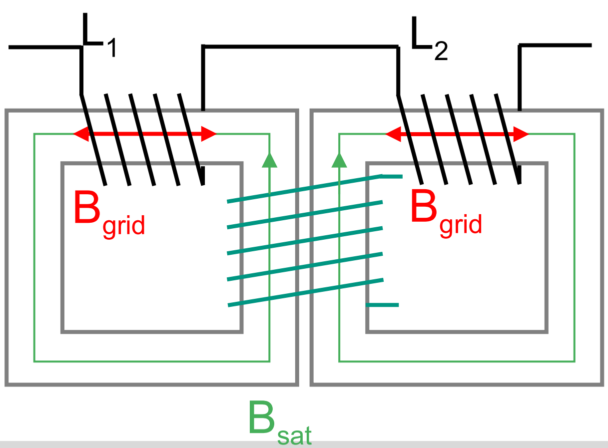
Fault current limiter with Iron core and DC-premagnetisation



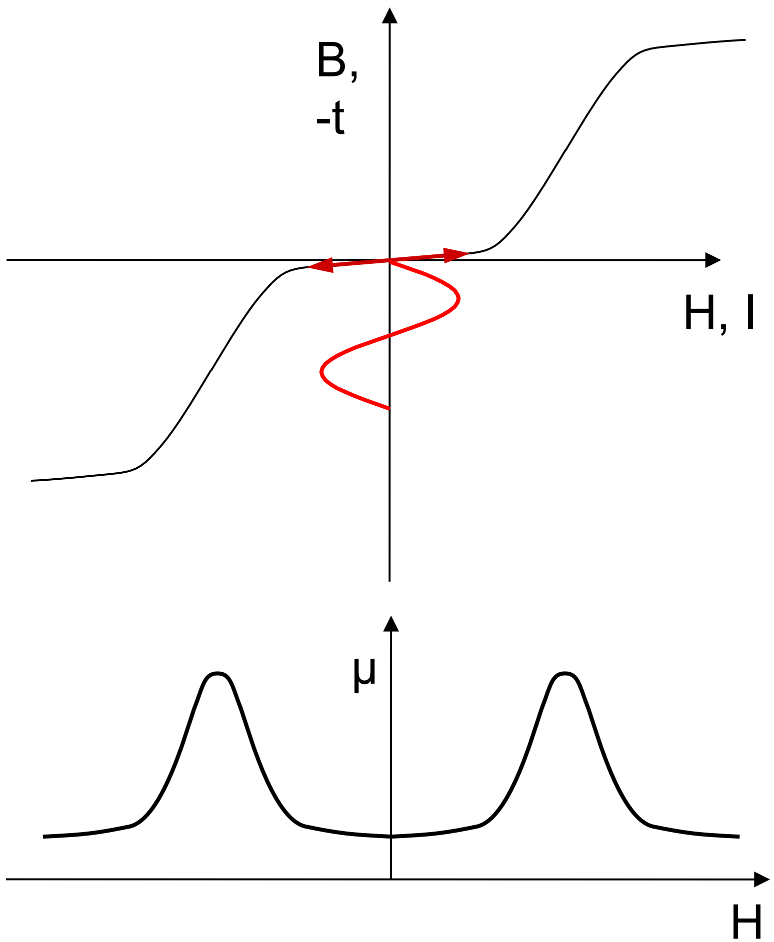


Equivalent circuit

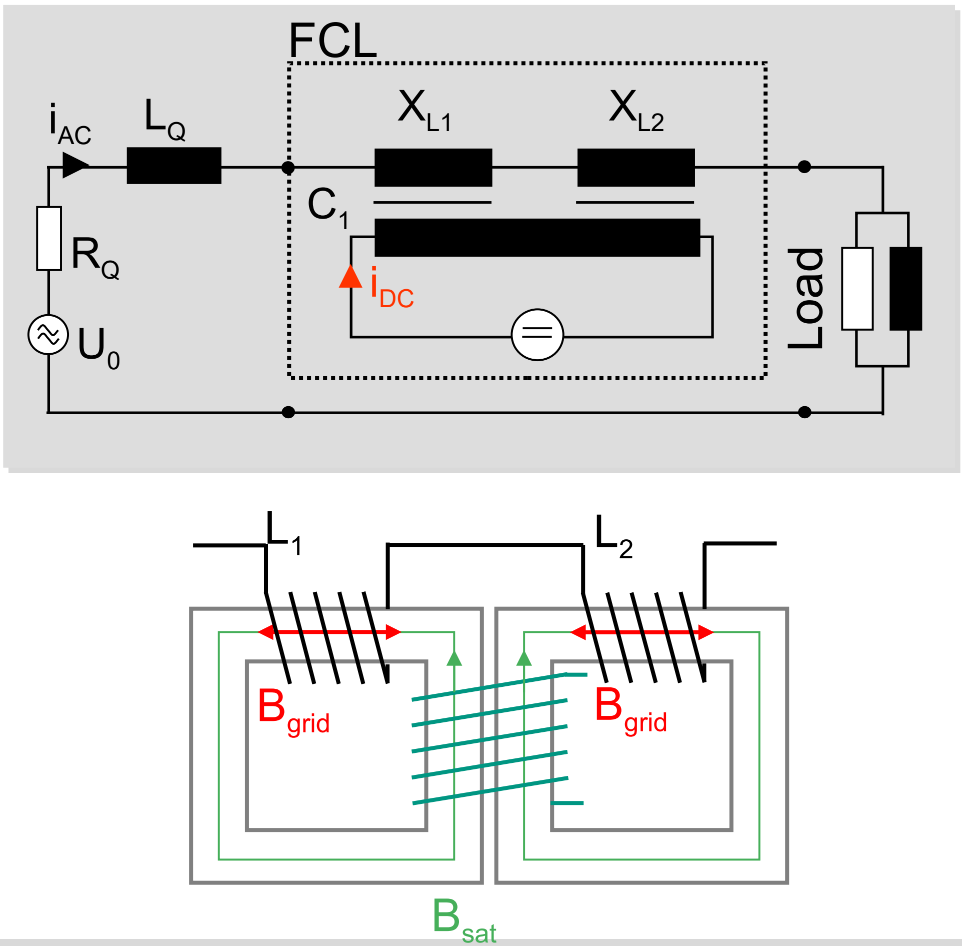




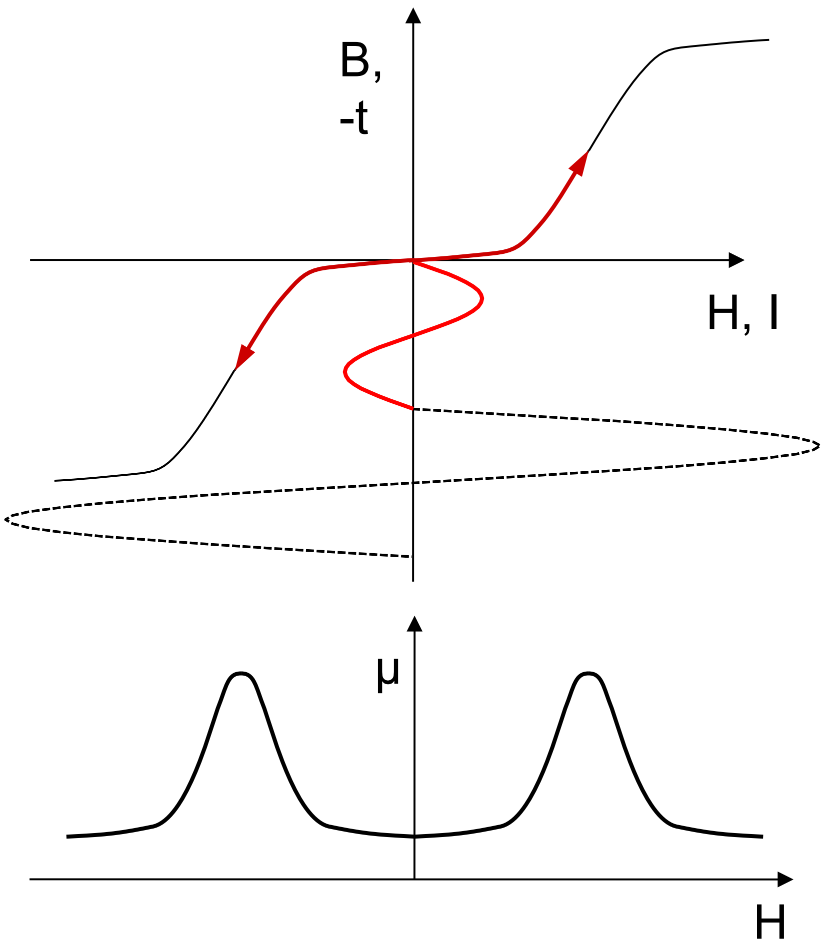
Fault current limiter with Iron core and DC-premagnetisation



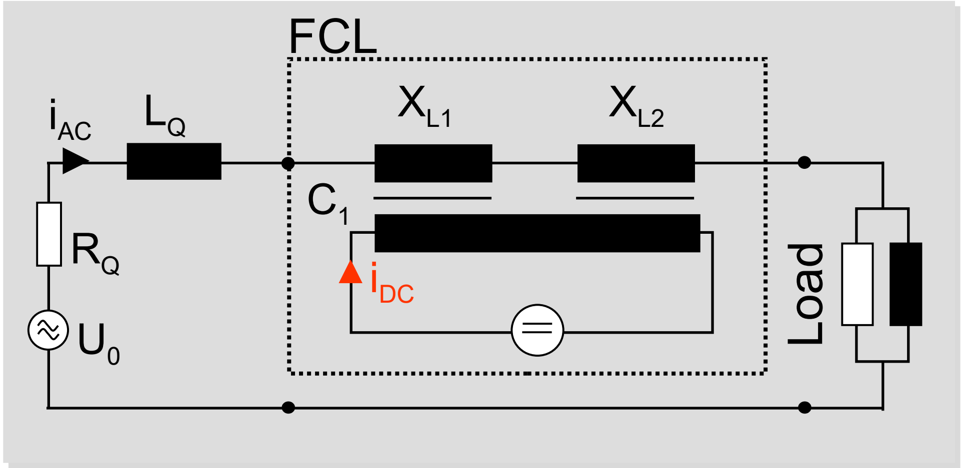
Equivalent circuit

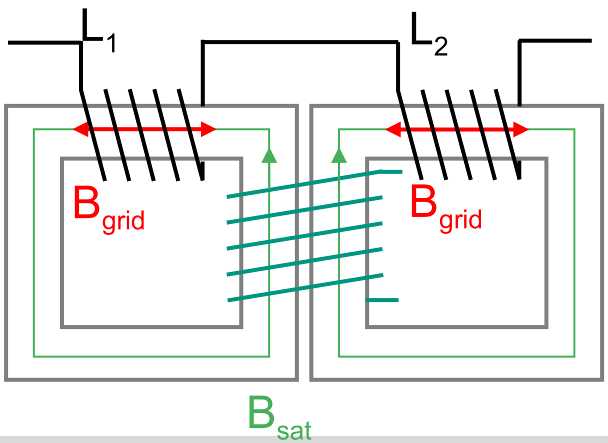


Fault current limiter with Iron core and DC-premagnetisation

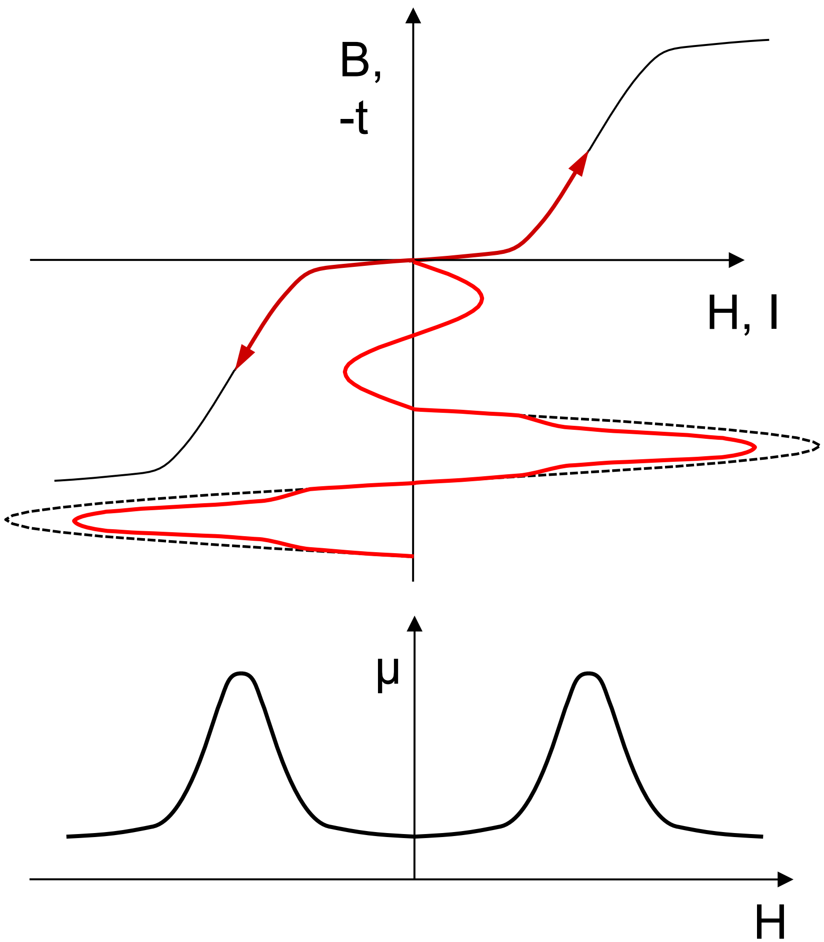


Equivalent circuit

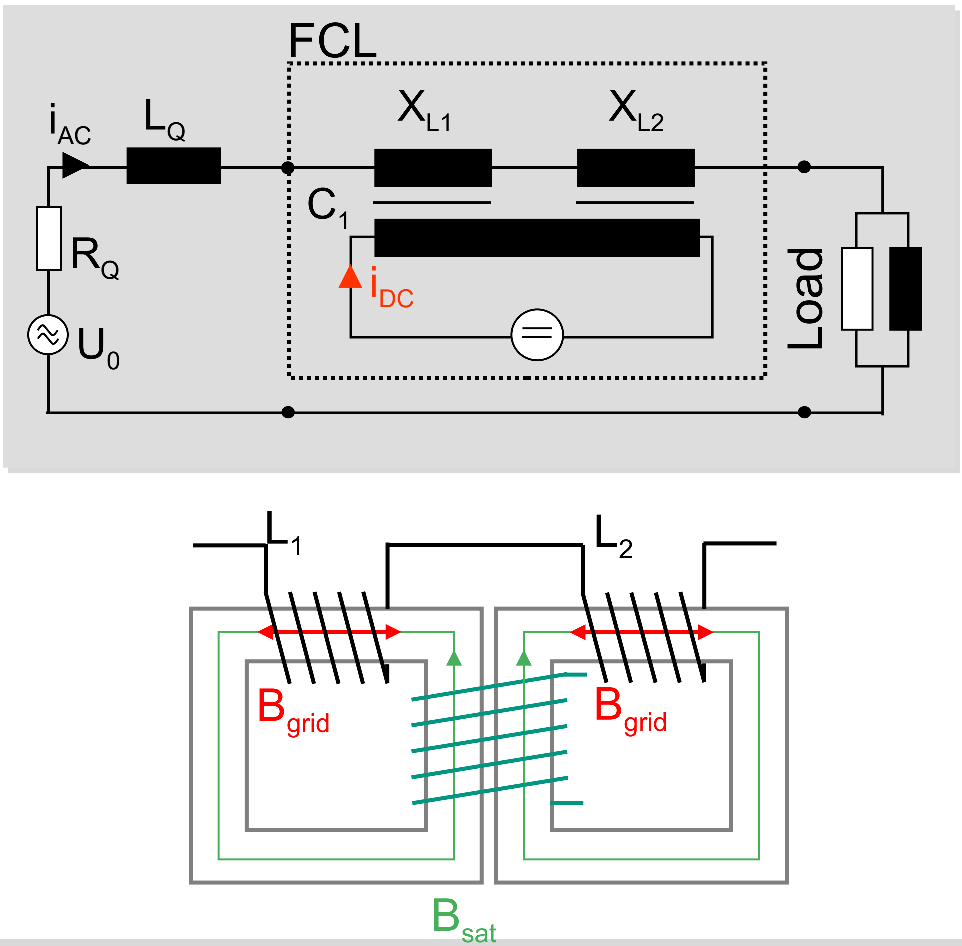




Fault current limiter with Iron core and DC-premagnetisation



Equivalent circuit



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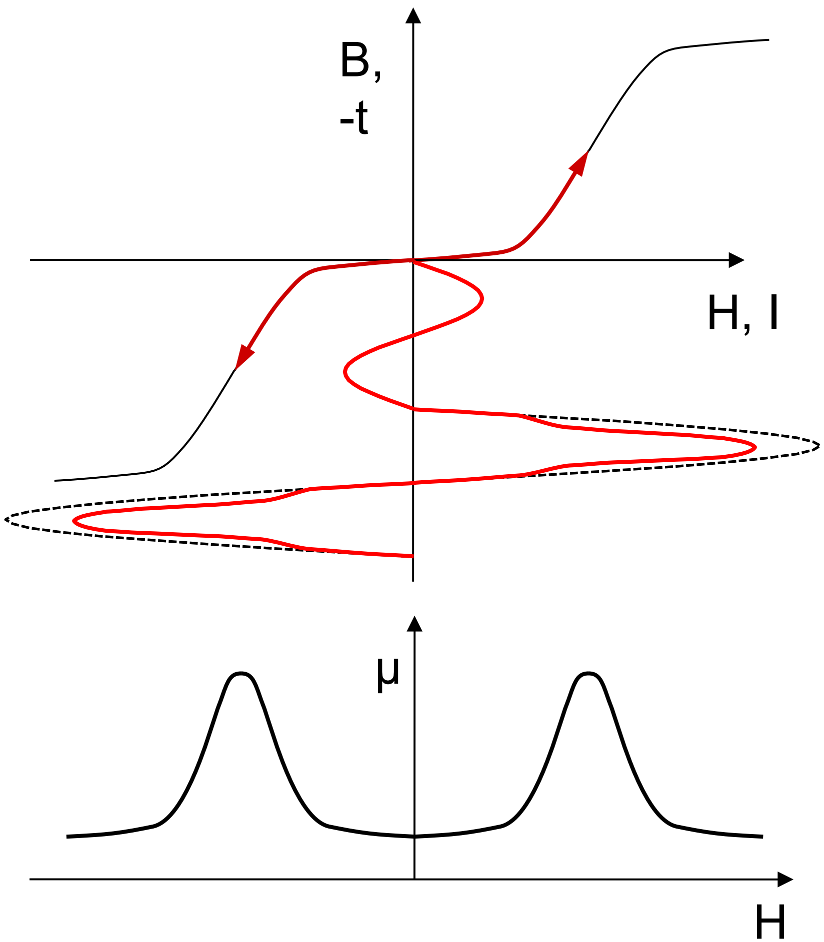

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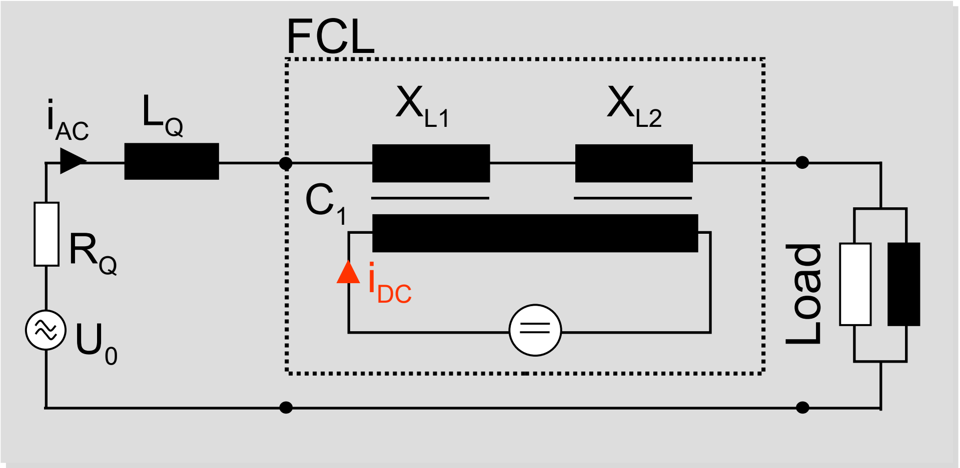


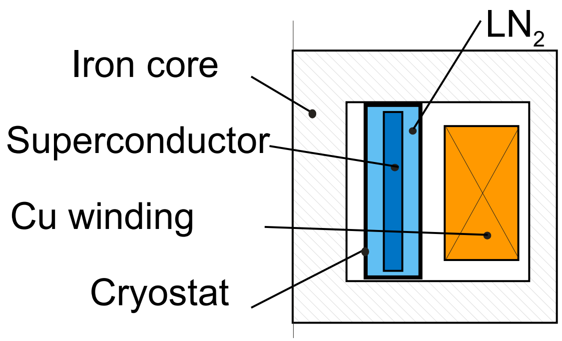
Properties

+ no quench of superconductor
+ immediate readiness for use
+ only DC current in superconductor
+ adjustable trigger current
- High volume and weight
- relatively high impedance

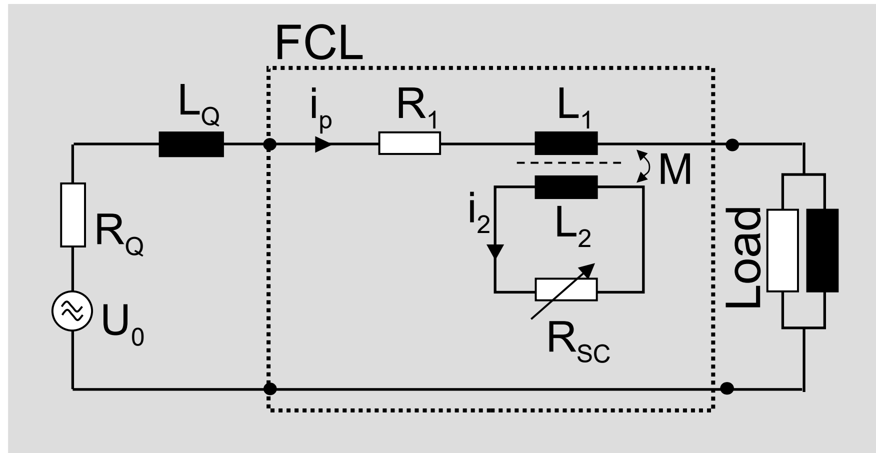
Superconducting Fault Current Limiter

Shielded iron core

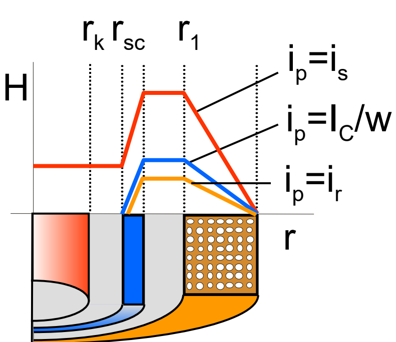
Sketch



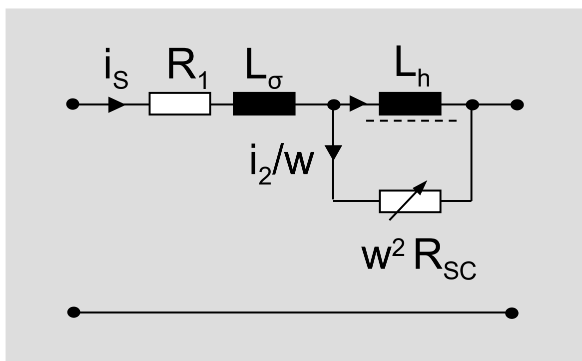
Equivalent circuit



Magnetic field



Equivalent circuit

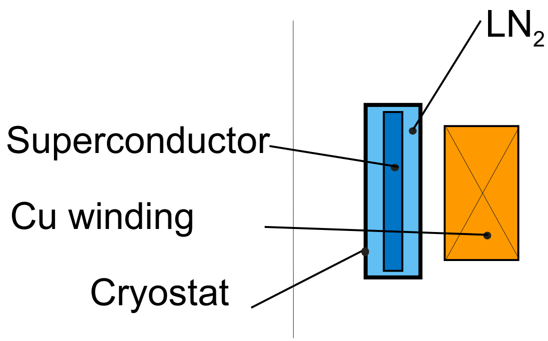


Properties

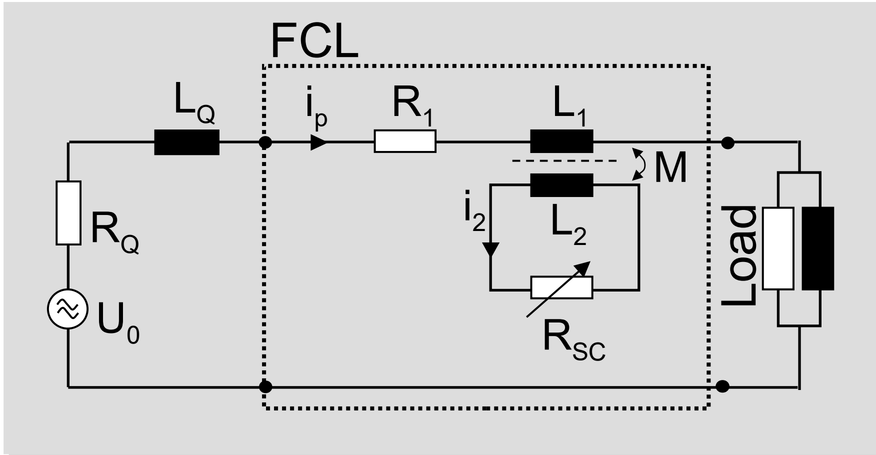
+ no current leads to cryogenic temperatures
+ intrinsically safe
- large volume
- high weight

Smart Coil (KIT Patent)

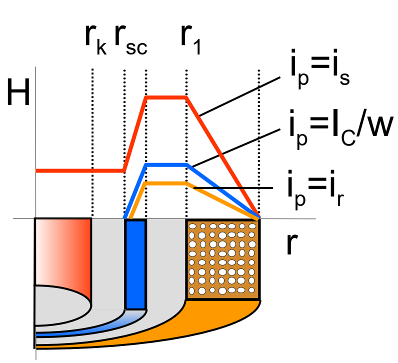
Sketch



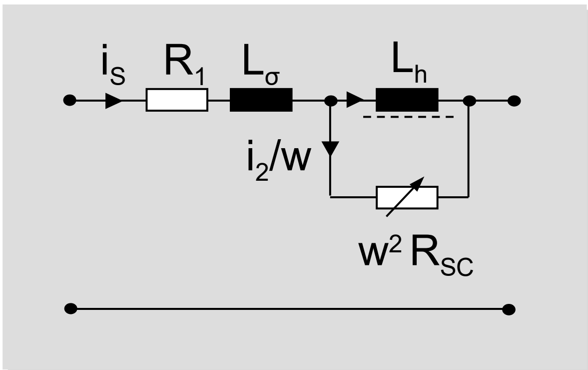
Equivalent circuit



Magnetic field



Equivalent circuit



Properties

- \+ no current leads to cryogenic temperatures
- \+ intrinsically safe
- \- ~~large volume~~
- \- ~~high weight~~

Overview

Semiconductor

- Diode bridge circuit
- Semiconductor switch
- Series resonance link
- Series line compensation
- Fault current controller

Superconductor

- Resistive FCL
- Diode bridge circuit with superconducting coil
- Premagnetized iron core
- Shielded iron core
- Flux lock type

Normal conducting

- I_s-limiter / CLiP
- Transformers / Chokes
- HV-Fuses
- Liquid metal
- Polymer PTC
- Arc circuit breaker

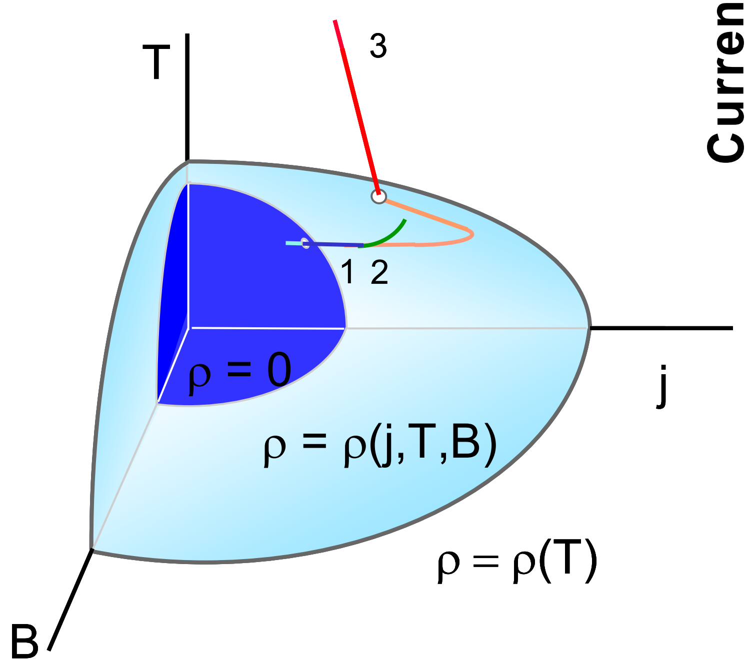
Hybrid Switches

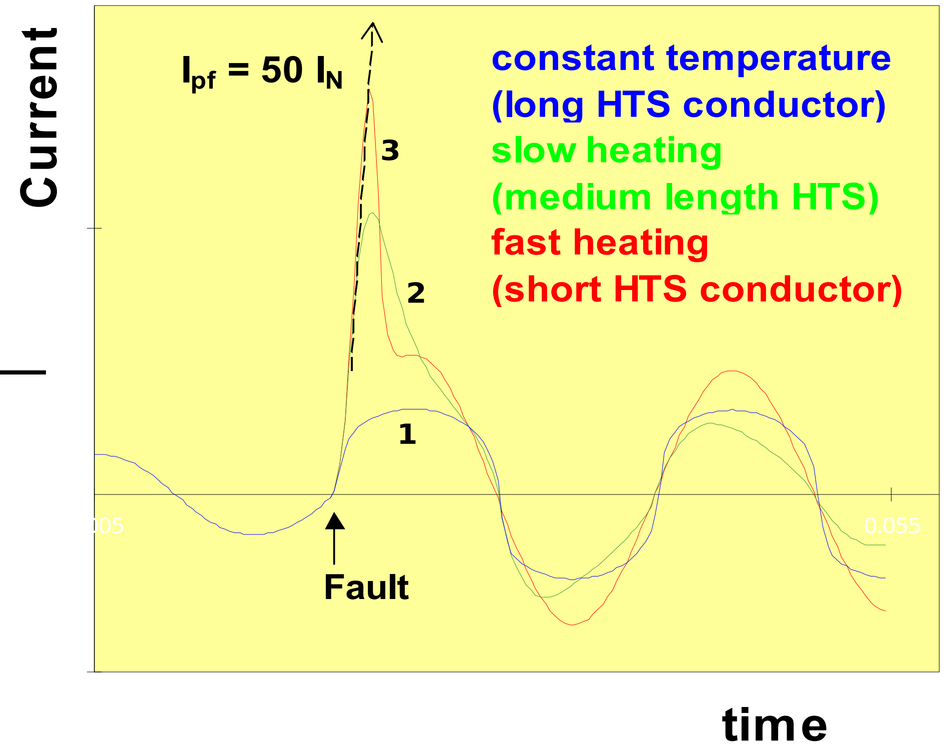
- Mech. Switch / Superconductor / Resistance
- Mech. Switch / Semiconductor / Resistance

Superconducting Fault Current Limiter

Basics of design
Limiting behavior

Influence of the conductor length (max. electric field)

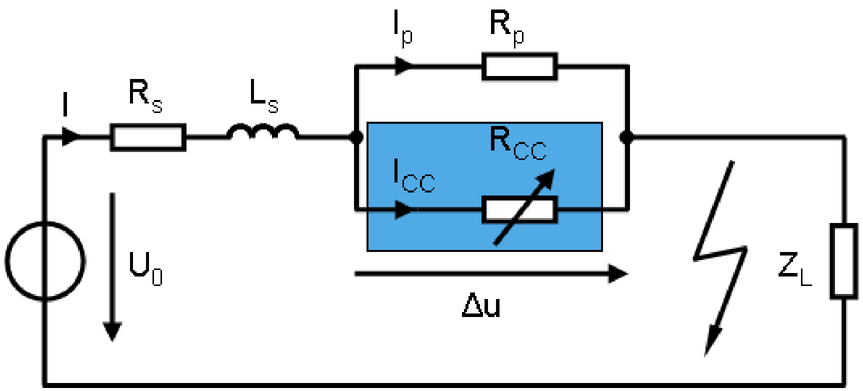




Quelle: W. Paul, et. al, „Fault current limiters based on high temperature superconductors – different concepts, test results, simulations, applications", Physica C, 354, (2001), p. 27-33

Basics of Resistive Current Limiter Design with YBCO tapes

- 1-phase equivalent circuit for a symmetric 3-phase short-circuit



$$R_{cc} \gg R_p$$

① $$i' = \frac{U_0 - R_{total}(T)\cdot i(t)}{L_S}$$

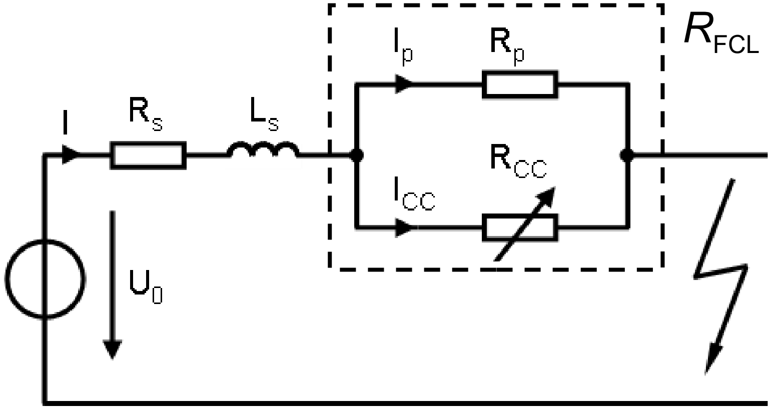
② $$i(t) = \frac{\hat{u}\left[R_{total}\cdot\sin(\omega\cdot t+\gamma) - L_s\cdot\omega\cdot\cos(\omega\cdot t+\gamma)\right]}{L_s^2\cdot\omega^2\cdot R_{total}^2} + C1\cdot e^{-\frac{R_{total}}{L_s}\cdot t}$$

③ $$i_{cc}(t) = i(t)\cdot\frac{R_p}{R_{CC}(T)+R_p}$$

U_0 = source voltage (V)
i = current (A)
γ = fault angle (rad)
t = time (s)
l = coated conductor length (m)
ω = angular frequency (rad)
$C1$ = constant of integration (A)
L_s = system inductance (H)
R_s = system resistance (Ω)
R_p = resistance of the parallel branch (Ω)
R_{cc} = resistance of the coated conductor (Ω)

Basics of Resistive Current Limiter Design with YBCO tapes

- Resistance limits of the current limiter



$$R_{FCL} = \frac{1}{\frac{1}{R_{cc}} + \frac{1}{R_p}}$$

$$= \frac{1}{\frac{w \cdot d_{cap}}{\rho_{cap}(T) \cdot l} + \frac{w \cdot d_{cap}}{\rho_{sub}(T) \cdot l} + \frac{1}{R_p}}$$

Temperature well below T_{max}

$R_{cc} > R_p$ and $\rho_{cap} < \rho_{sub}$

$$R_{FCL,\min} \Rightarrow f(R_p, l, d_{cap})$$

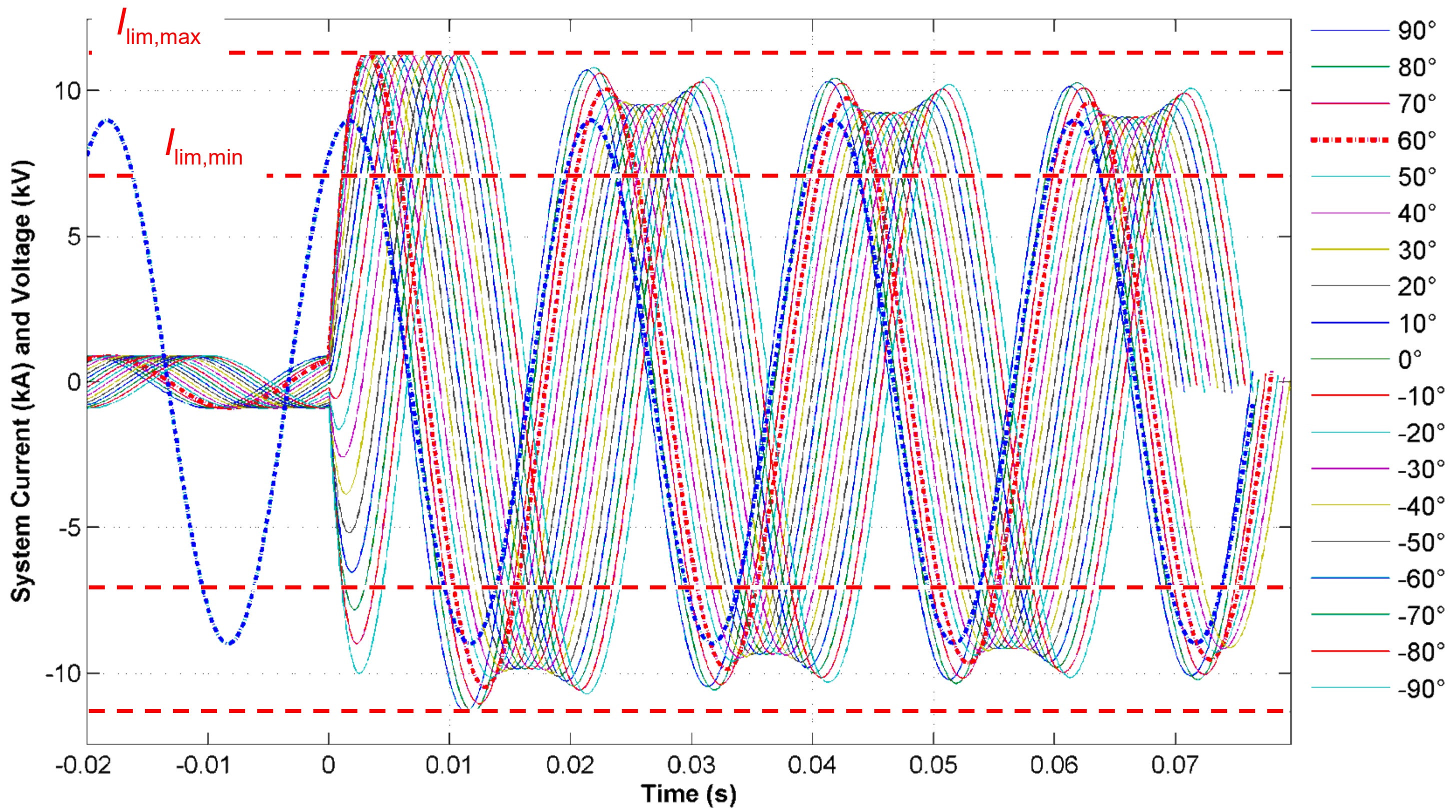
Temperature near T_{max}

$R_{cc} >> R_p$ and $\rho_{cap} \approx \rho_{sub}$

$$R_{FCL,\max} \Rightarrow f(R_p)$$

Basics of Resistive Current Limiter Design with YBCO tapes

- The limited current I_{lim} must comply with the limits $I_{lim,min/max}$ for the entire limitation period and for each switching angle



Basics of Resistive Current Limiter Design with YBCO tapes

- Temperature limits of tapes

$$\Delta T = \Delta Q(T) \cdot C(T)$$

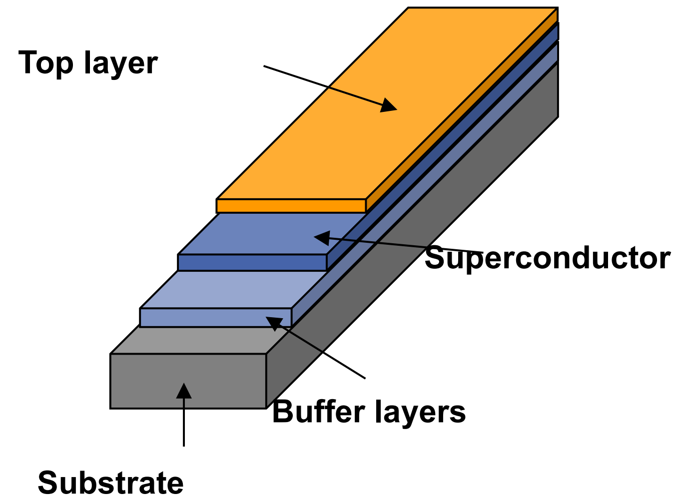
$$\Delta Q = P(T) \cdot \Delta t = \frac{\Delta u^2(T)}{R_{CC,p}(T)} \cdot \Delta t$$

$$\Delta T = \frac{U_0^2 \cdot \Delta t}{C \cdot R_{CC,p}(T)} \cdot \frac{R_{FCL}^2(T)}{\left[R_{FCL}(T) + Z_s\right]^2}$$

Assumption: $Z_s << R_{FCL}$ and $C_{cap} < C_{sub}$

$$\Delta T = \frac{U_0^2 \cdot \Delta t}{l \cdot w \cdot C^* \cdot R_{CC}(T)} = \frac{U_0^2 \cdot \Delta t}{l^2 \cdot C^*} \cdot \left(\frac{d_{cap}}{\rho_{cap}} + \frac{d_{sub}}{\rho_{sub}} \right)$$

$$T_{end} = T_{\max} = const. \Rightarrow l \propto \sqrt{d_{cap} + \beta}$$



Design Parameter:

Tape length l

Thickness of top layer d_{cap}

Parallel resistance R_p

Basics of Resistive Current Limiter Design with YBCO tapes

1. Determination of the number of parallel tapes n_p

$$n_p = \frac{I_{\max} \cdot \sqrt{2}}{I_c \cdot k} = \frac{1kA \cdot \sqrt{2}}{320A \cdot 0.9} = 5 \qquad k = \frac{I_n}{I_{\max}} = \frac{900A}{1000A} = 0.9$$

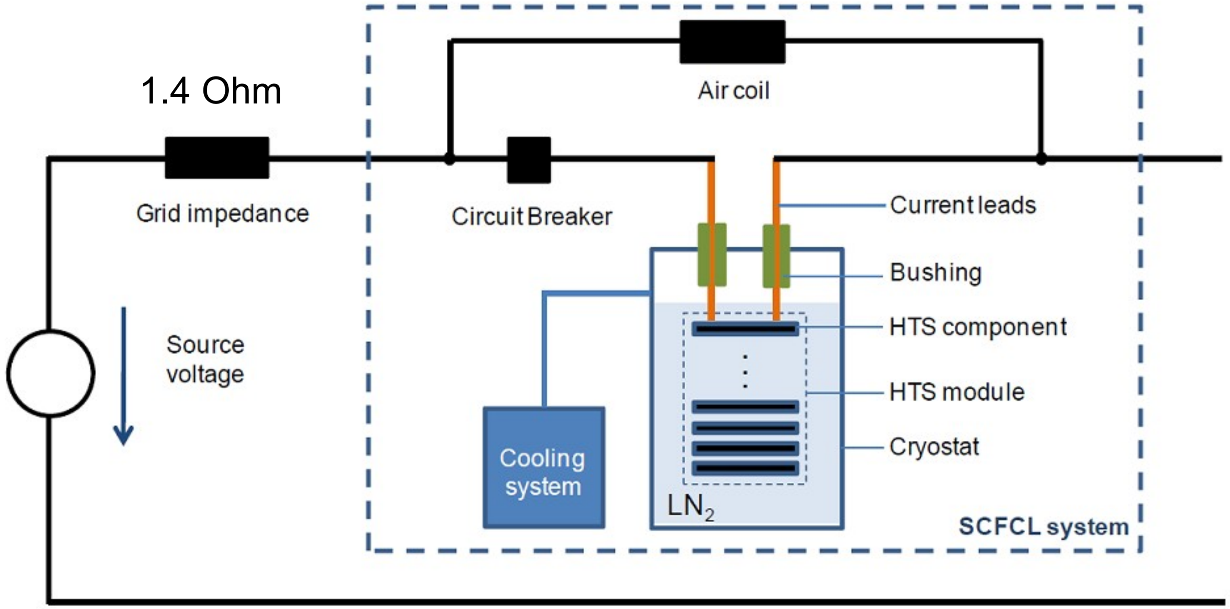
2. Determination of minimum and maximum current limiter resistance $R_{FCL,min}$ and $R_{FCL,max}$ for $I_{lim,min}$ and $I_{lim,max}$

$$R_{FCL,\min} \Rightarrow f(R_p, l, d_{cap}) \qquad R_{FCL,\max} \Rightarrow f(R_p)$$

3. Valid values of the design parameters in compliance with the temperature criterion $T \leq T_{max}$ during limiting period

$$T_{end} = T_{\max} \Rightarrow l \propto \sqrt{d_{cap} + \beta}$$

Exercise - Superconducting fault current limiters
How to calculate the total heat input?



Limitation time	120 ms
Max. short-circuit current cont. (RMS)	4 kA

Superconducting fault current limiters
How much superconducting wire is needed?

How many tapes in parallel?

$$n_p \geq \frac{\sqrt{2} I_r}{I_c} = \frac{1.414 \cdot 1005 A}{275 A} = 5.16$$

Assumption 2011 for 10mm wide YBCO tape at 77K, sf

What is the total tape length?

1) What is the total voltage along the tape during limiation?

$$U_{\lim,RMS} = \frac{24 kV}{\sqrt{3}} - 4 kA \; 1.4 \Omega = 8.25 kV$$

2) Do not overheat the tape during limitation?

For a electrical field of 0,43 V/cm the temperature during limitation time of 120 ms can be kept below 360 K.

$$l_{SC} = 190 m \cdot 6 \cdot 3 = 3420 m$$

Exercise - Superconducting fault current limiters
How to calculate the total heat input?

A	B	C	D
Straight line	Bifilar straight	Monofilar coil	Bifilar coil

Superconducting fault current limiters
How to calculate the heat input?

Current lead heat input?

45 W/kA for uncooled and optimized copper current lead from 300 K to 77 K

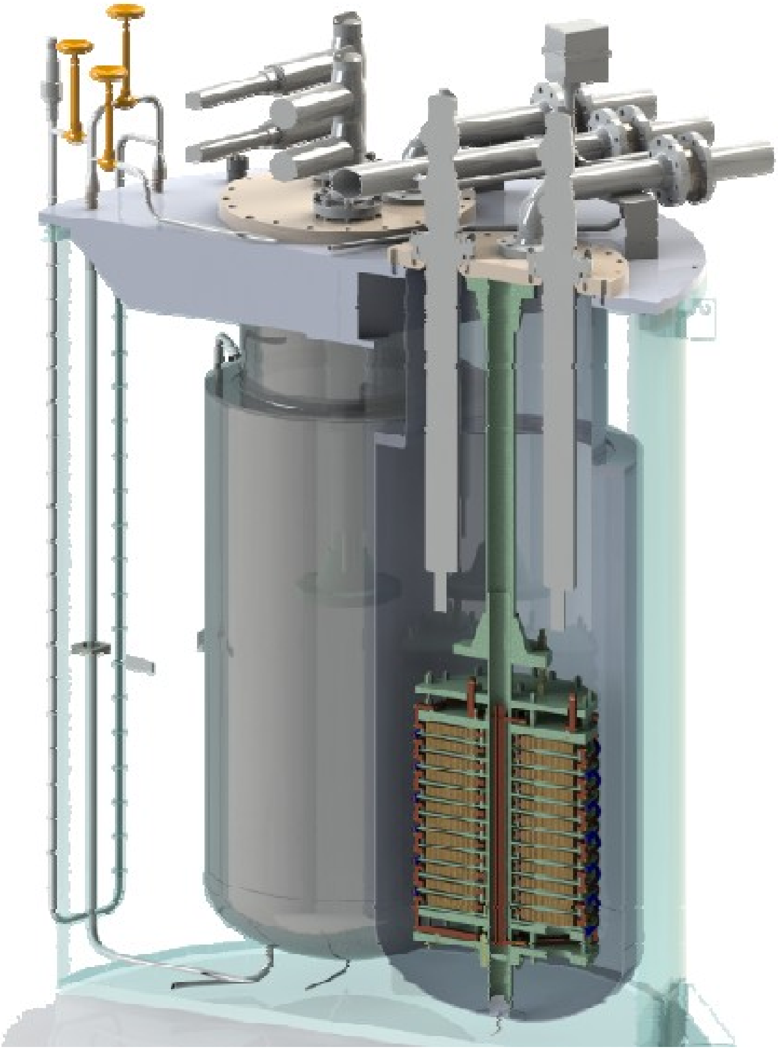
45 W/kA * 1 kA *6=270 W at nominal current

Superconducting fault current limiters
How to calculate the heat input?

Loss of the cyrostat?

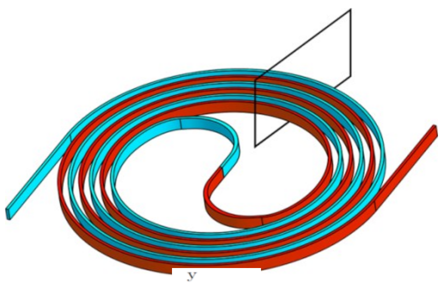
P=120 W

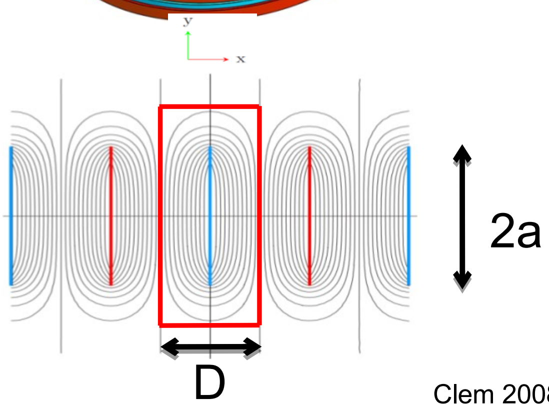
Three LN2 vessels in one vacuum vessel.

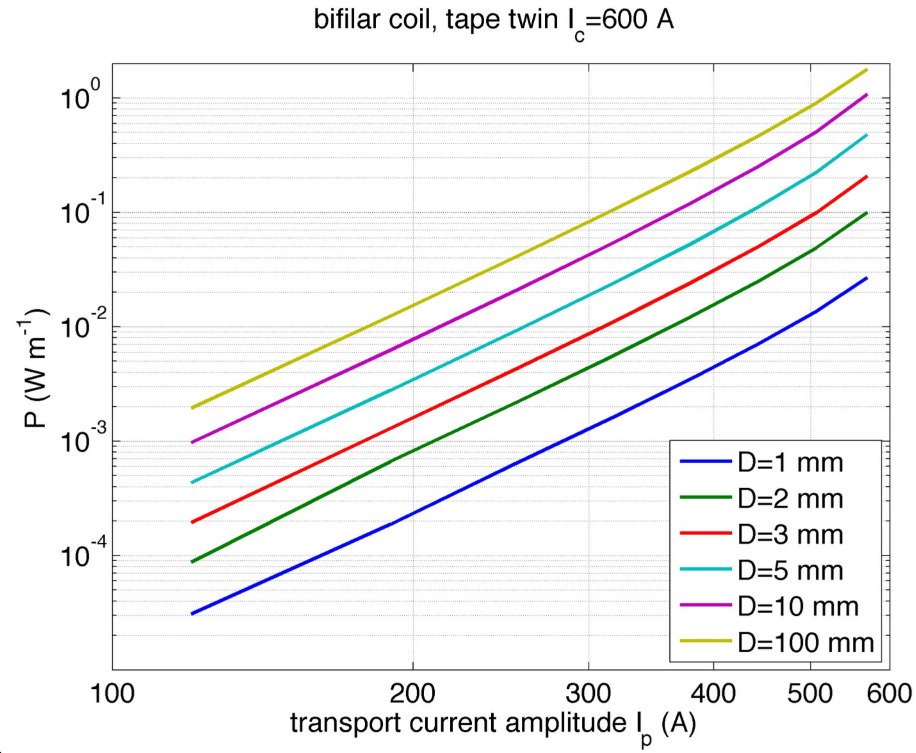


Superconducting fault current limiters
How to calculate the heat input?

AC loss of the superconductor?







Clem 2008 PRB **77** 134506

$$P = f\mu_0 I_c^2 \left[\frac{2}{\pi a^2}\int_c^a (a-x)\tanh^{-1}\sqrt{\frac{\sinh^2\frac{\pi x}{D}-\sinh^2\frac{\pi c}{D}}{\sinh^2\frac{\pi a}{D}-\sinh^2\frac{\pi c}{D}}}\,dx + \frac{d}{12a}\left\{1-\frac{c}{a}+\frac{8}{\pi^3 a}\int_0^c\left[\tan^{-1}\sqrt{\frac{\sinh^2\frac{\pi a}{D}-\sinh^2\frac{\pi c}{D}}{\sinh^2\frac{\pi c}{D}-\sinh^2\frac{\pi x}{D}}}\right]dx\right\}\right]$$

Superconducting fault current limiters
How to calculate the heat input?

Summary of heat input

Loss contribution	Loss at 0.1 I_c	Loss at 0.5 I_c	Loss at 1 I_c
Max. superconductor AC loss [1)]	< 1 W	~ 10 W	150 W
Max. current lead loss [2)]	180 W	~ 220 W	270 W
Cryostat loss [3)]	120 W	120 W	120 W
Max. additional loss [4)]	1 W	15 W	60 W
Max. total loss at 77 K	**~ 300 W**	**~ 365 W**	**600 W**
Max. electric power at RT[5)]	**~ 6990 W**	**8504 W**	**13980 W**

1) According to AC Loss report [2.1.1] Ic=300 A, L=3.4 km
2) Specific current lead loss 45 W/kA [2.6.4]
3) According to Cryostat Design [2.4.1]
4) HTS-Copper-0.5µΩ•12•2/3=4µΩ, Copper connections-2µΩ•12•2/3=16µΩ
5) GM Cryocooler efficiency (GM600) 1/23.3

Superconducting Fault Current Limiter

1. Motivation

2. Different types of fault current limiter

2.1 Resistive fault current limiter

2.2 Fault current limiter with Iron core and DC-premagnetisation

2.3 Other

3. Basics of design

4. Applications

4.1 Overview

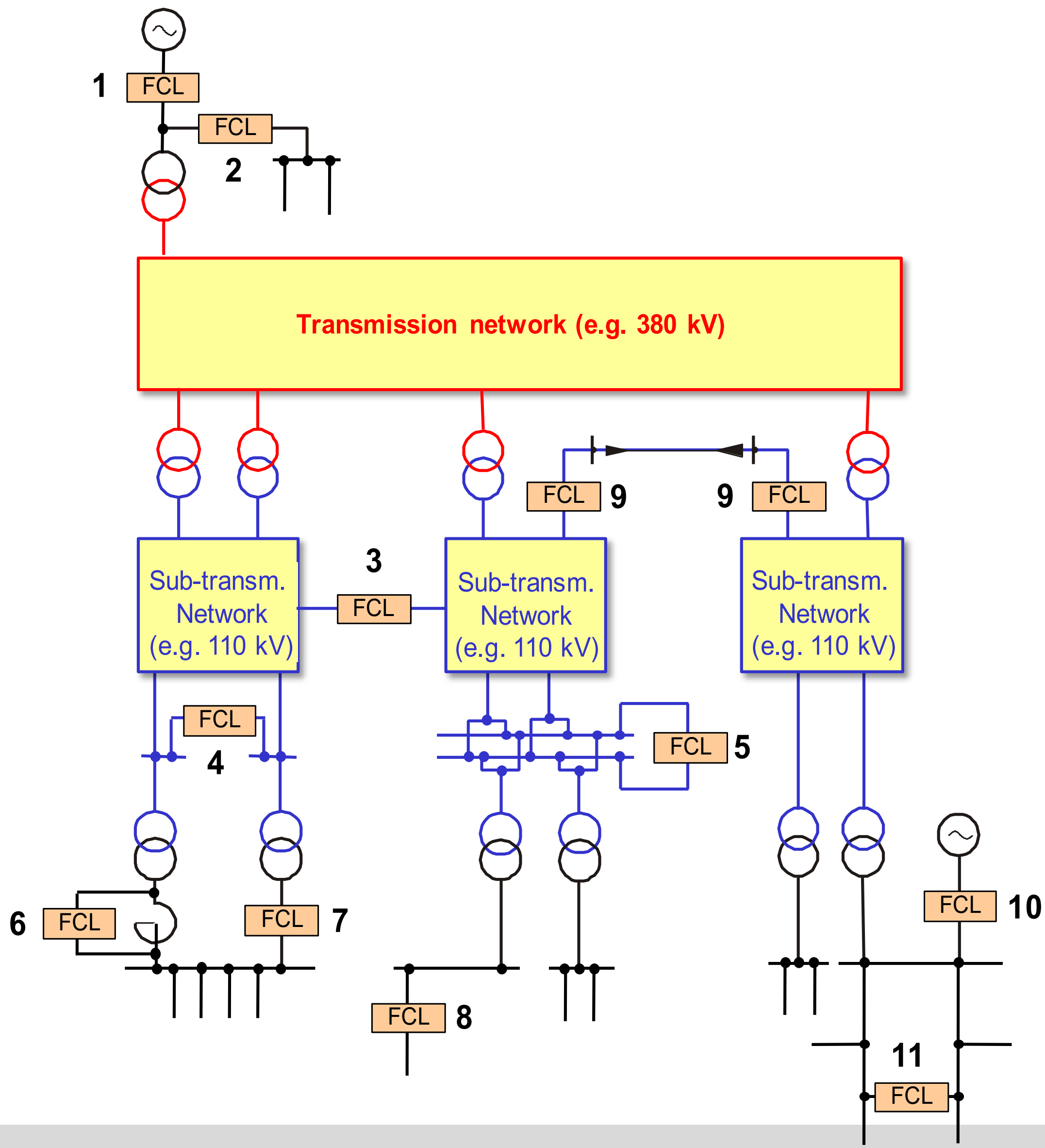
4.2 Application in medium voltage level

4.3 Application in high voltage level

5. History

6. State of the Art and application examples

Applications

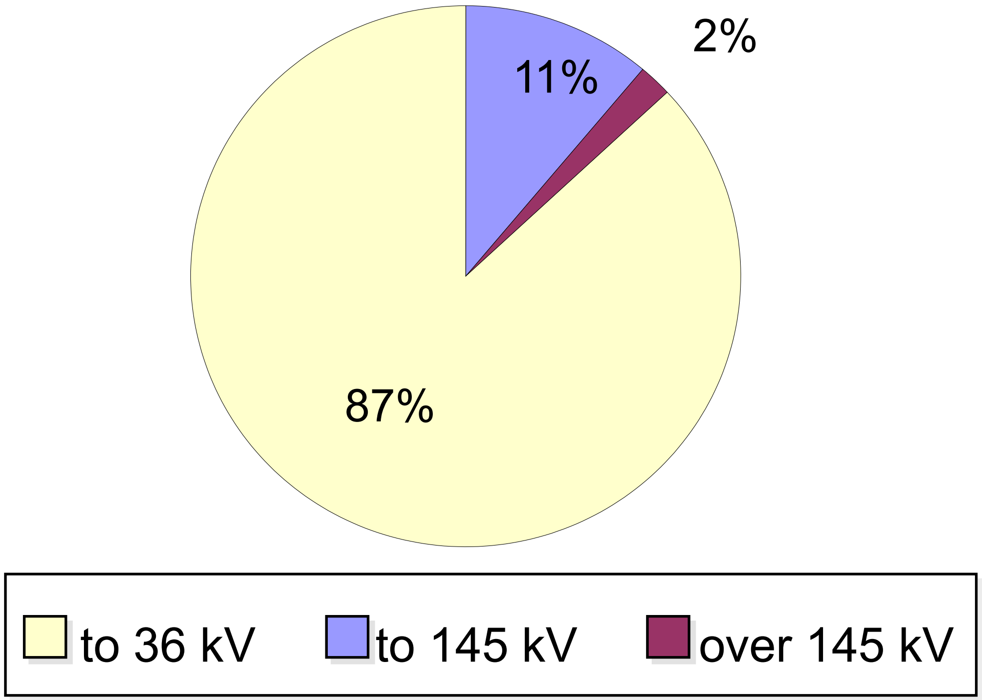


1 Generator feed-in
2 power plant own demand
3 Coupling of sub networks
4,5 Busbar coupling
6 Parallel to chokes
7 Transformer feed
8 Busbar feed
9 Combination with other SC-components
10 Coupling of local generators
11 Connecting of ring lines

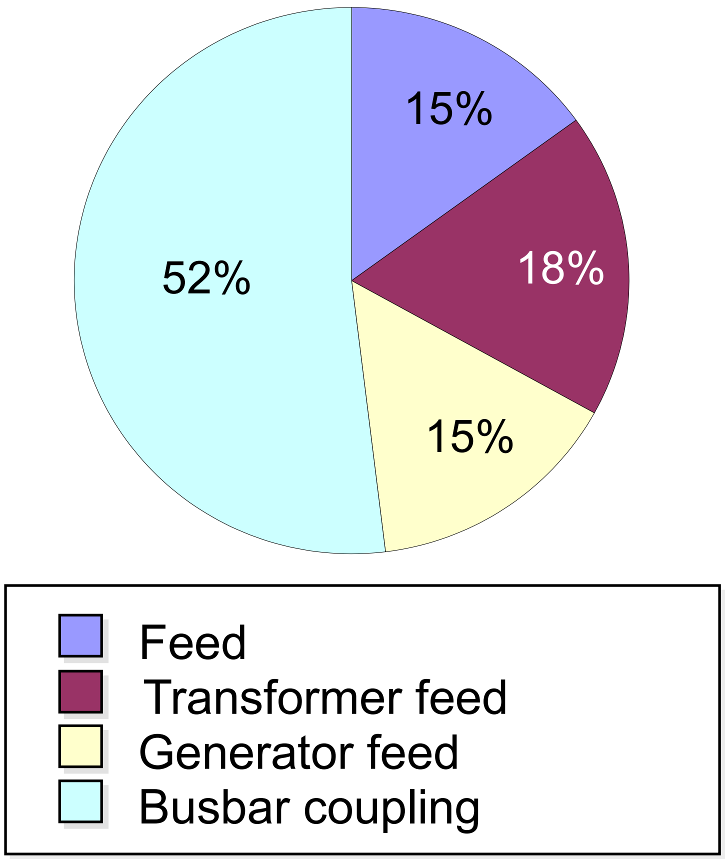
Quelle
Noe, M.; Oswald, B.R., "Technical and economical benefits of superconducting fault current limiters in power systems", IEEE Trans. Appl. Supercon. Vol. 9/2, June 1999, pp. 1347 –1350

Applications

Which voltage level?



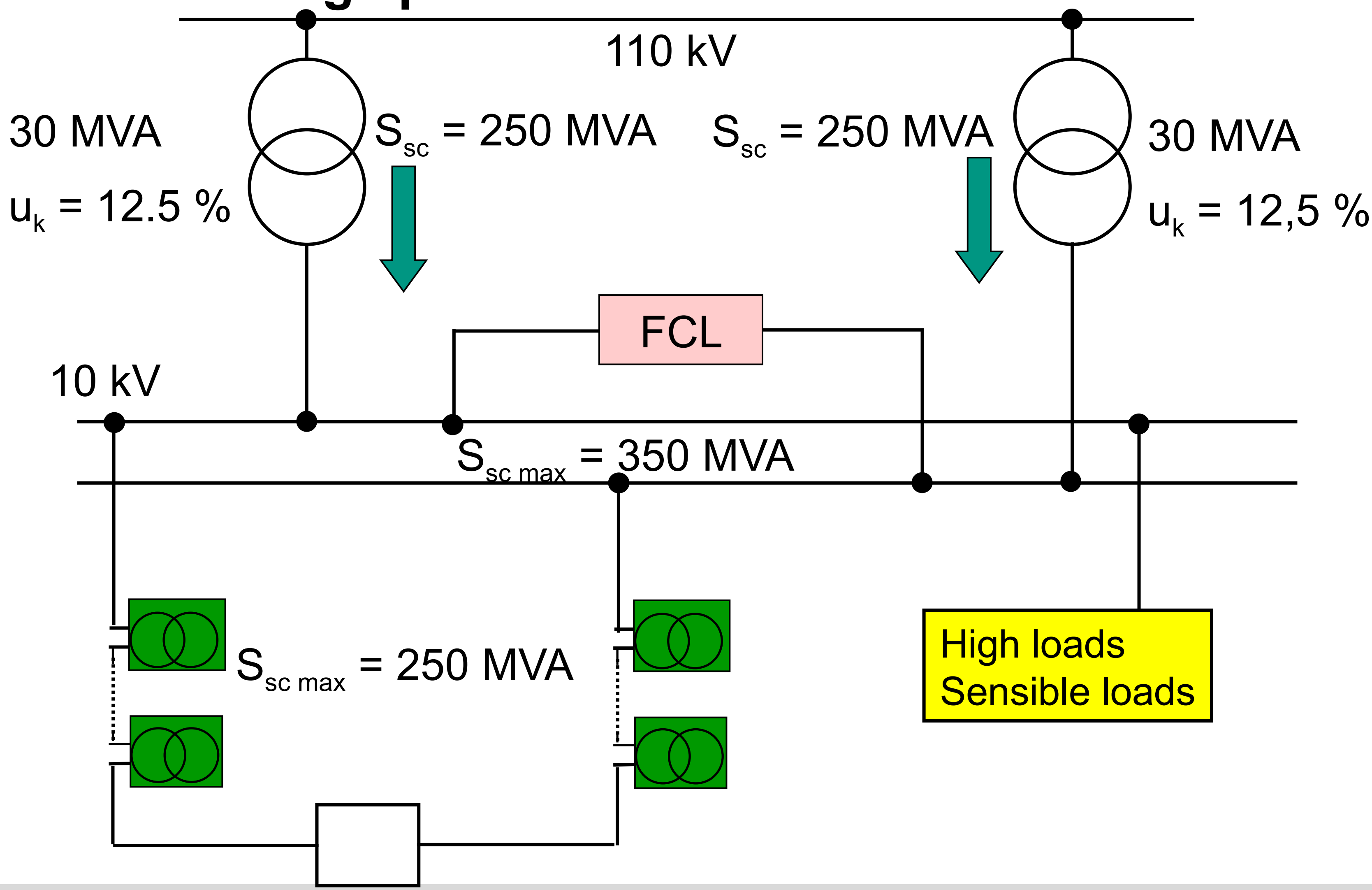
What place of operation?



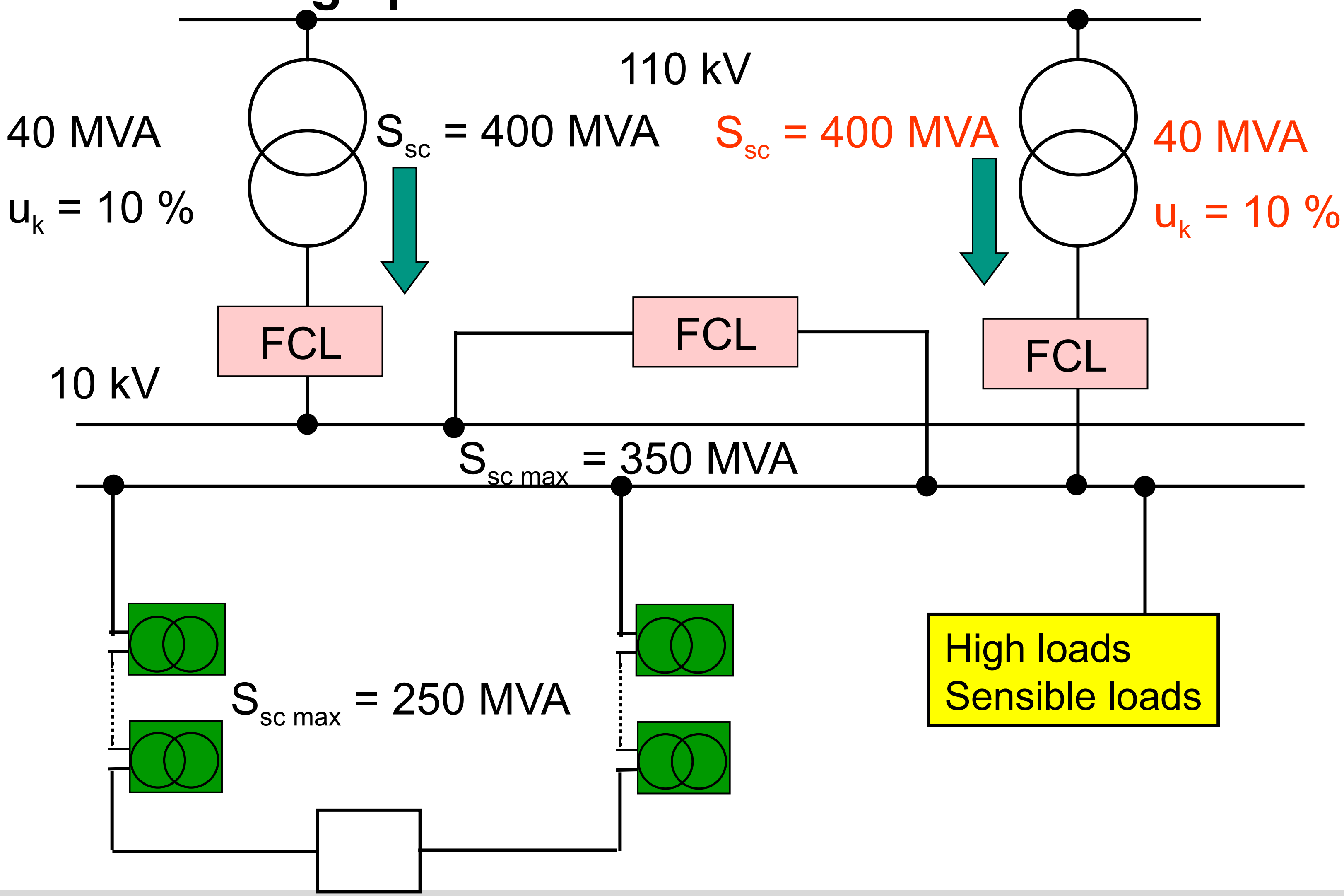
Quelle:
Fault Current Limiters
Report on the Activities of CIGRE WG 13.10
by CIGRE Working Group 13.10 (*), CIGRE Session 2004, Paris

Superconducting Fault Current Limiter

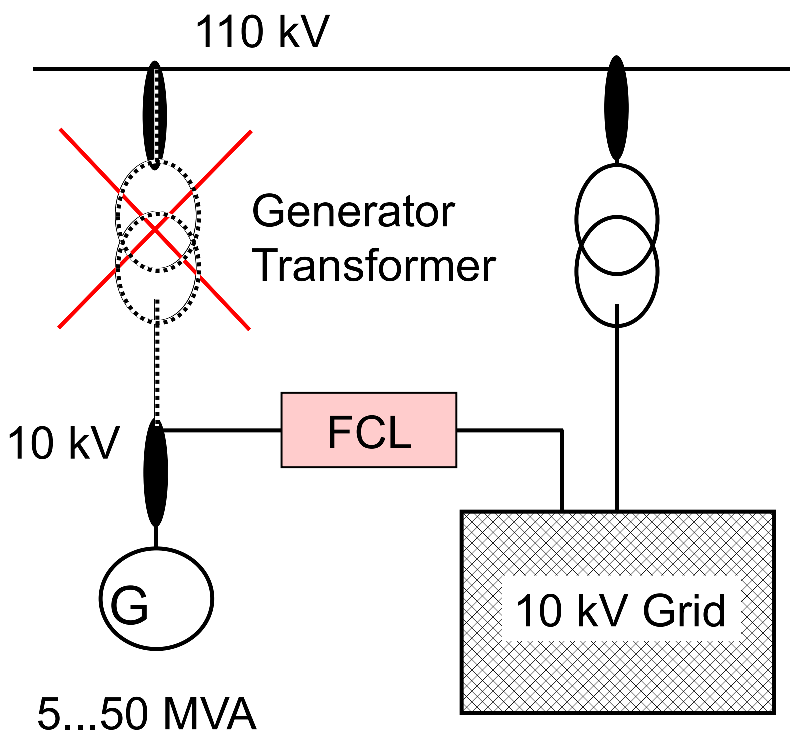
Fault current limiter in Busbar coupling in medium voltage plants



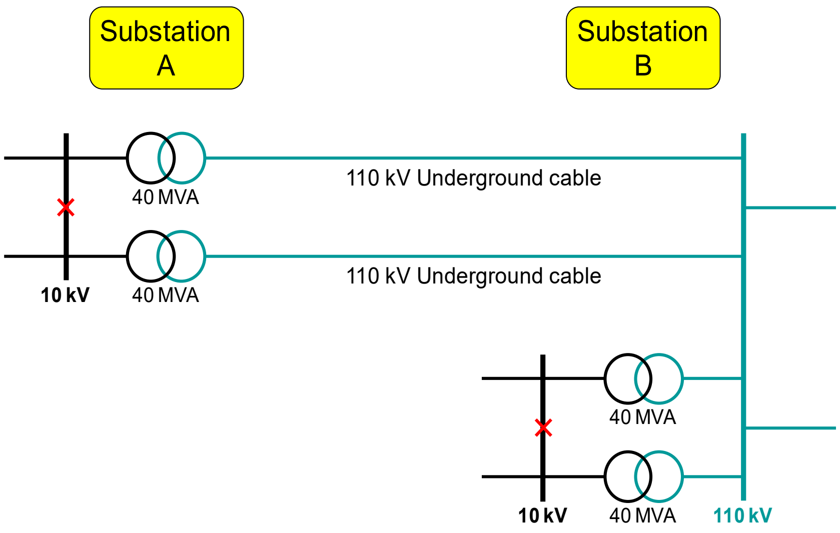
Fault current limiter in Busbar coupling in medium voltage plants

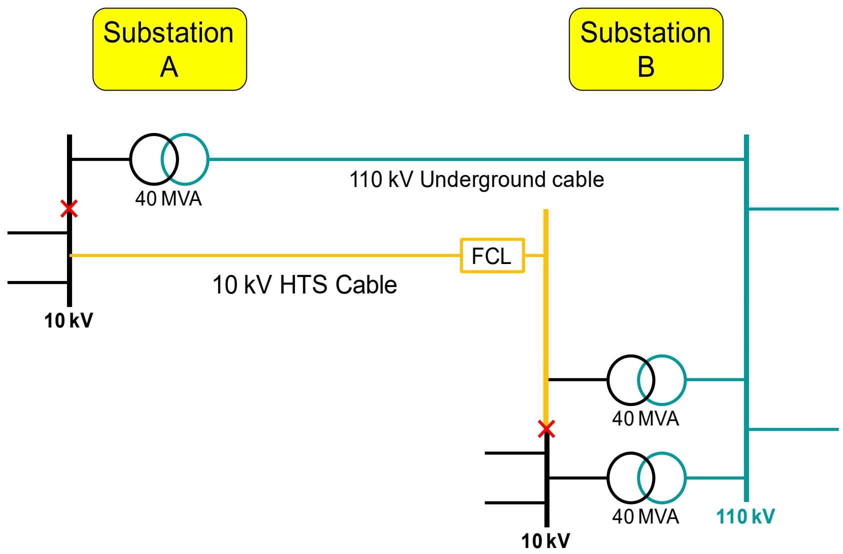


Coupling of decentralized feed-in



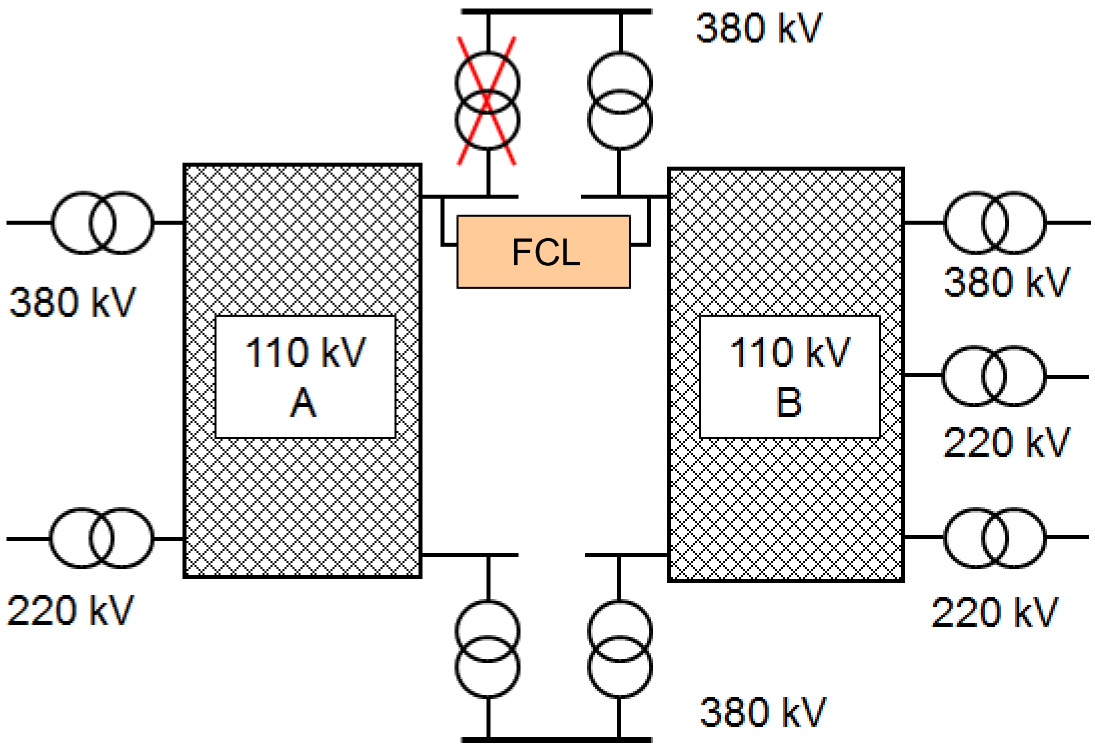
FCL with superconducting cable





Superconducting Fault Current Limiter

Couping of high voltage networks (e.g. RWE)



Für Details: C. Neumann, SCENET Workshop on Superconducting Fault Current Limiters, Siegen, Germany, June 28-29 2004

System advantages of superconducting fault current limiter

Superconductivity enables:

- Novel current limiting by non-linear current-voltage characteristic curve

Advantage of superconducting fault current limiter

- Operation
  - Negligible impedance in normal operation
  - Fast and effective current limiting in the first rise
  - Automatic recovery
  - Intrinsically safe
  - Applicable in high voltage
- Environmentally friendly

There is currently no conventional measure for limiting short-circuit currents with these characteristics

Superconducting fault current limiter

Economical advantages

- Delaying grid expansion or renewal investments
  - e.g. when adding new power plants by adhering to the permissible short-circuit capacity
  - e.g. When feeding in renewable energies by keeping within the voltage band via coupling of MV busbars
- Reduced dimensioning of equipment, systems and power supply units
  - e.g. in the power plant own barf
- Replacement or elimination of equipment
  - e.g. omission of redundant feeders due to partial grid coupling
- Increase in availability and reliability
  - e.g. through coupling of subnetworks
- Lower losses
  - e.g. through equal load sharing of transformers connected in parallel

Superconducting current limiters can achieve savings of several 100 k€ in the medium voltage level and several million € in the high voltage level

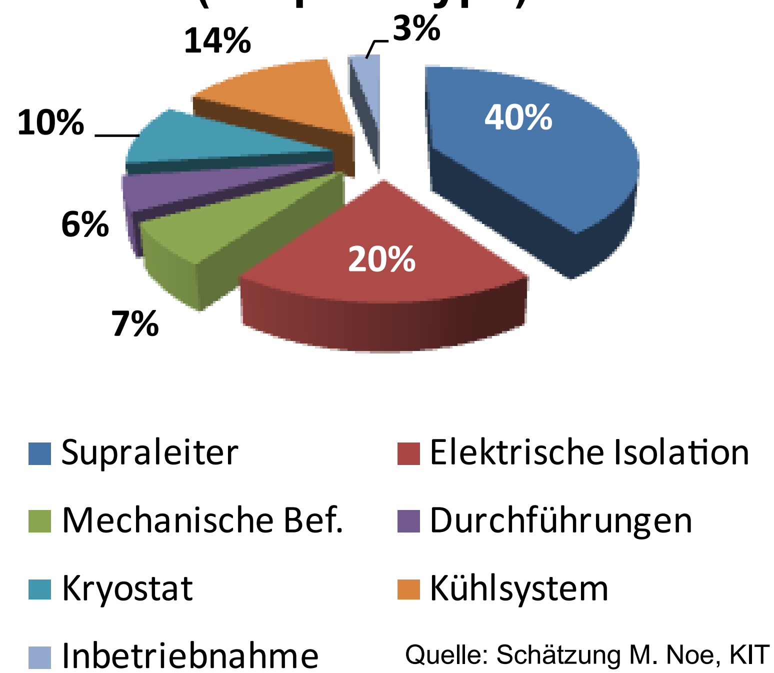
Superconducting fault current limiter

When are superconducting current limiters economical?

Main cost components

- Superconductor
- Insulation
- Mechanical components
- Feedthroughs
- Cryostat
- Cooling system
- Commissioning
- Man hours
- Overhead and profit

Investment cost shares for 40 MVA fault current limiter (1st prototype)



Quelle: Schätzung M. Noe, KIT

Superconducting Fault Current Limiter

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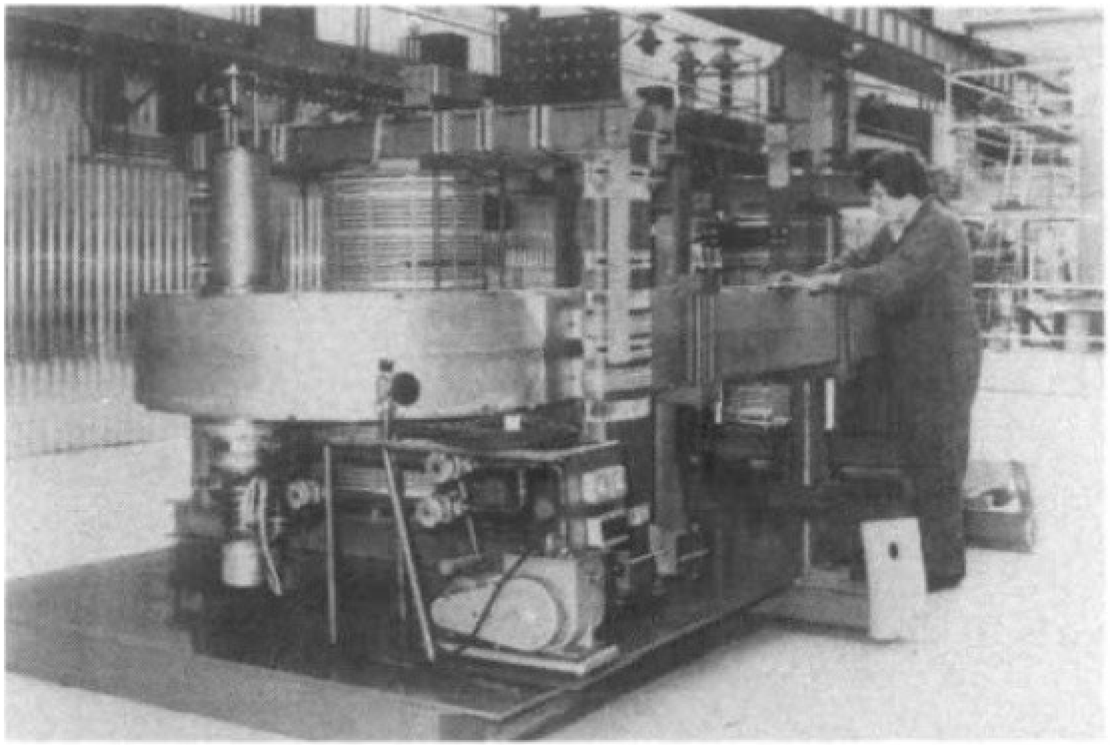
One of the first large superconducting fault current limiters

DC biased iron core type



B.P. Raju, T.C. Bartram; Fault current limiter with superconducting DC Bias, IEEE Proc. Vol. 129, No. 4, July 1982, pp.166

Voltage 3 kV

Frequency 50 Hz

Normal current 556 A_{RMS}

Fault current

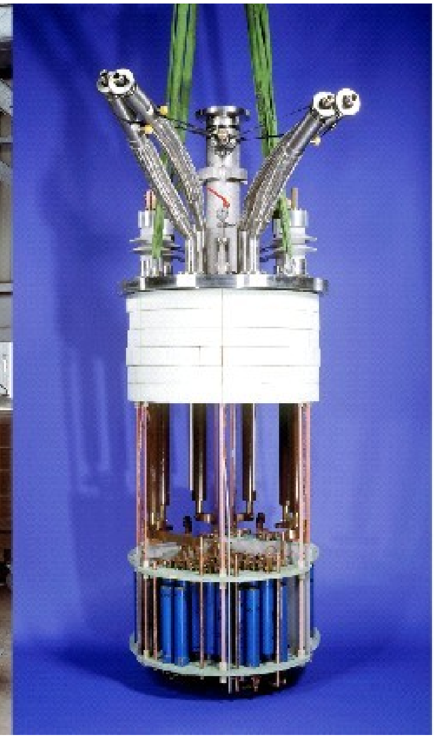
for fault at *V peak* 2900 A_{peak}

for fault at *V zero* 14750 A_{peak}

Normal voltage drop 4.4 %

First field test of a resistive superconducting fault current limiter

BMBF Project CURL10



Voltage	10 kV
Frequency	50 Hz
Normal current	600 A_{eff}
Fault duration	60 ms
Max. lim. current	8,75 kA
Temperature	66 K
Superconductor Massive	Bi 2212

☹ Only one 1-phase short-circuit during operation

Source: R. Kreutz, J. Bock, F. Breuer, K.-P. Juengst, M. Kleimaier, H.-U. Klein, D. Krischel, M. Noe, R. Steingass, and K.-H. Weck, System Technology and Test of CURL 10, a 10 kV, 10 MVA Resistive High-Tc Superconducting Fault Current Limiter, IEEE Trans. On Applied Superconductivity, Vol. 15, No. 2, June 2005

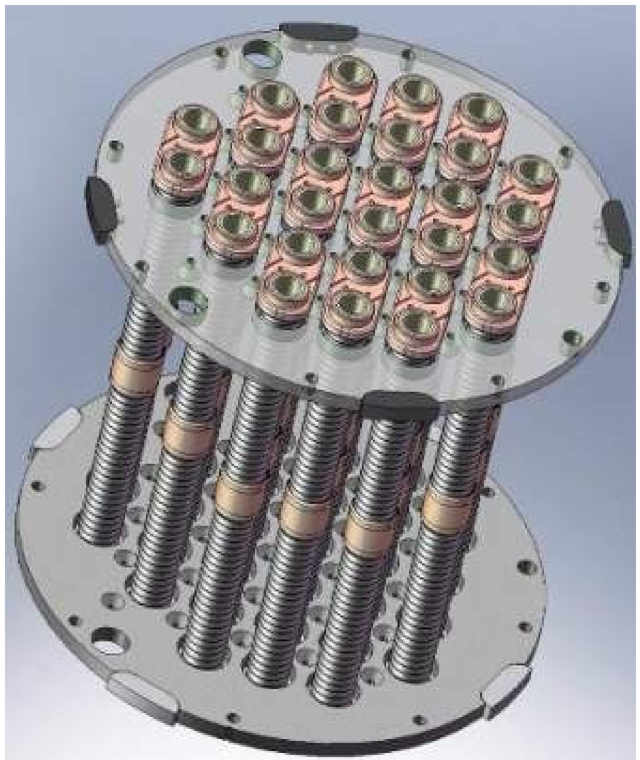
Resistive FCL (Nexans SuperConductors)

In 2009 two grid installations in Europe

Dual component Bi 2212 bulk

Source:
Nexans SuperConductors

Module



Source:
Nexans SuperConductors

Application for one phase

Source:
Nexans SuperConductors

Resistive FCL (Nexans SuperConductors)

In 2009 two grid installations in Europe

12 kV, 800 A installed resistive FCL in the captive grid of a Vattenfall power plant near Cottbus, Germany

Source: Nexans SuperConductors

Rated voltage 12 kV

Rated currend 800 A

Short-term overcurrent 4,1 kA (50 ms)

Max. const. current 1,8 kA (15 s)

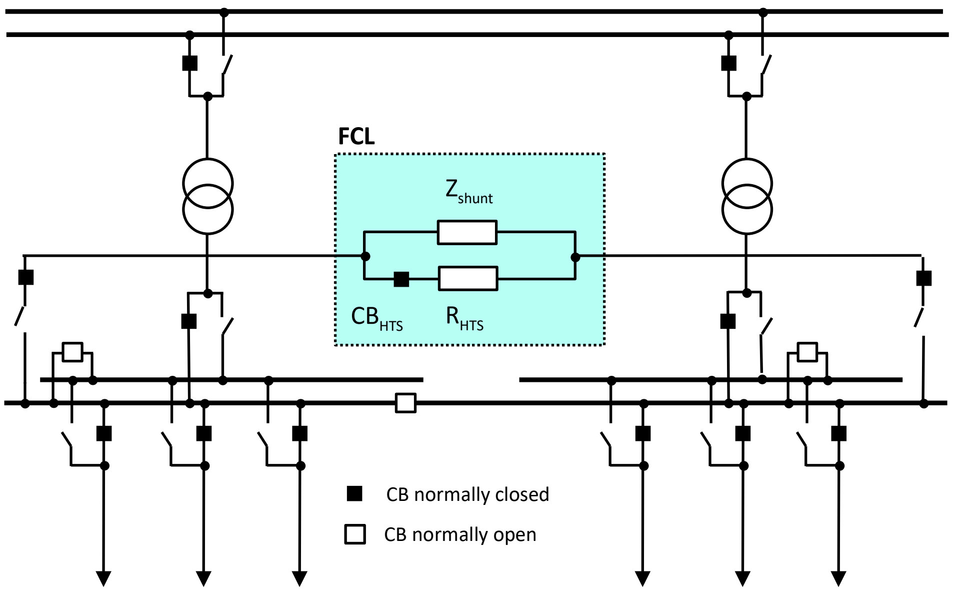
Limiting time 120 ms

Limiting current < 27 kA

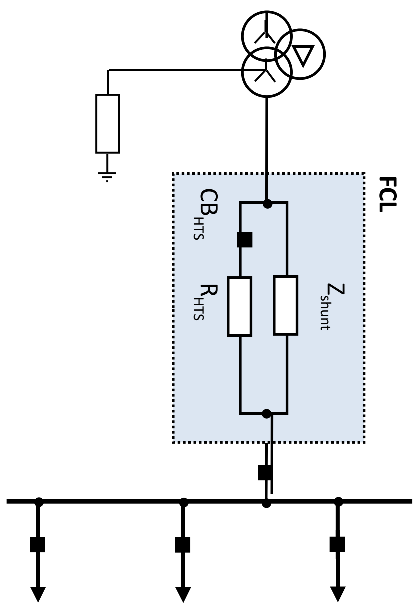
EU Project Eccoflow (2010-2014)

Objective: Development and field test of a resistive FCL with YBCO

Busbar coupling



Transformer feed-in



Unique (1005A,24kV):

- One design for two different applications
- Two field tests
- 5 energy supply companies as partner
- Design as permanent installation

EU Project Eccoflow (2010-2014)

Specification

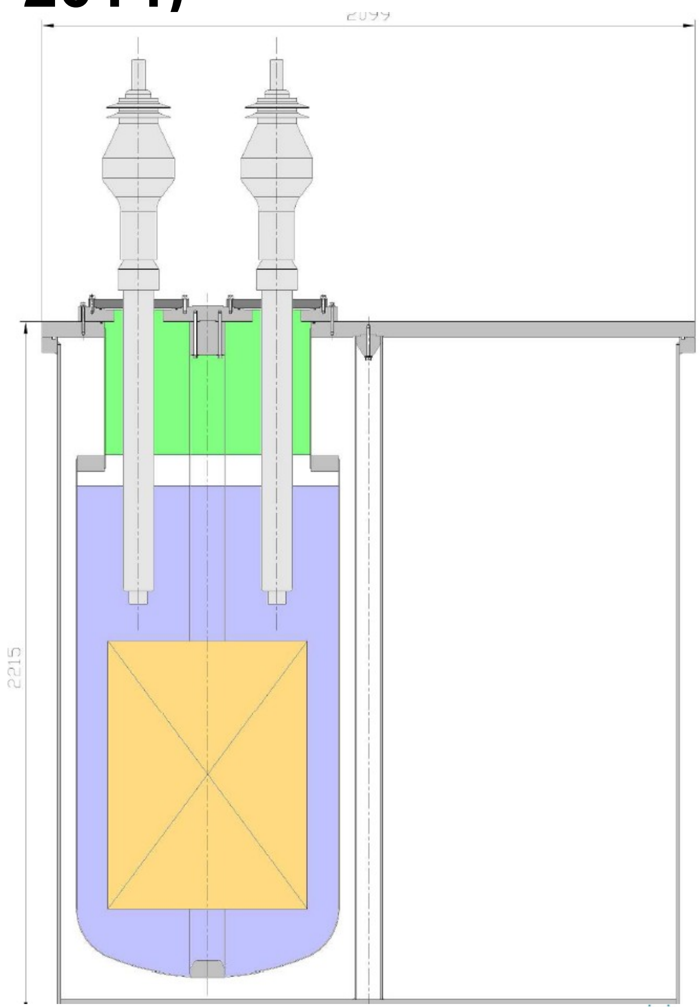
	ENDESA	VSE	ECCOFLOW
Rated voltage	16.5 kV	24 kV	**24 kV**
Rated current	1000 A	1005 A	**1005 A**
max. short-circuit current(peak)	22 kA	26 kA	**26 kA**
max. limited current (peak)	10.8 kA	17 kA	**10.8 kA**
Fault duration	1 s	120 ms	**1 s**
HTS Limiting duration	80 ms	80 ms	**80 ms**
Recovery time	< 30 s	< 30 s	**< 30 s**
AC Voltage	50 kV	50 kV	**50 kV**
Lightning surge voltage	125 kV	125 kV	**125 kV**

Source: Eccoflow Detailed Design Report, 2011

EU Project Eccoflow (2010-2014)

HTS Limiter arrangement

- 12 components per phase in series
- 3 LN_2 vessels, only 1 vacuum vessel
- About 100 W thermal losses
- Liquid nitrogen at 77 K, 2 G-M cryocoolers
- Compact design, close to series production



Source: J. Schramm et. al. „Design and Production of the ECCOFLOW resistive Superconducting Fault Current Limiter “, ASC Conference 2012, Portland USA

„ASSiST“ – SFCL for public 10 kV grid of Stadtwerke Augsburg, Bavaria, Germany

SIEMENS

SFCL based Solution (SFCL+switchgear+control+DAQ) successfully installed and inaugurated in swa Netze

gefördert von
Bayerisches Staatsministerium für
Wirtschaft und Medien, Energie und Technologie

Details

- Collaboration of Siemens EM, CT & Stadtwerke Augsburg
- Integration of MTU's extended testing facility of combined heat and power unit requires reduction of short-circuit current
- Combination of superconducting 15 MVA SFCL with ultrafast breaker and parallel series reactor
- Closed cooling system (cold heads included) – no blow-off during limitation
- Reduction of losses compared to conventional solution
- Increased system stability, no voltage drop
- Large area breaker up-grade dispensable
- Timeline:
  - Apr. 15, 2014: project start
  - Mar. 15, 2016: official inauguration
  - till Jan. 15, 2017: data acquisition & monitoring (to Siemens Erlangen)
  - Continued operation planned after project end

Visitors (IEA) at SFCL site

Installation area


Installed vessels

Inauguration ceremony

SuperOx(2019)

World's first 220 kV high-voltage current limiter successfully used in field test

Voltage 220 kV

Current 1200 A

Max. limited current 7 kA

Fault duration ?? ms

25.2 km, 12mm wide YBCO tape

Picture and information Superox

Projects superconducting fault current limiter

Resistive FCL

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

Learning objectives

Being able to explain the operating principles of the most important current limiter types.

Being able to select and justify a preferred current limiter type for given application examples.

Understand and be able to explain various possible applications

Being able to classify the state of development of superconducting current limiters and describe important milestones.