CIGRE SC A3 Tutorials and Colloquium Vienna 2011

Tutorial on Fault Current Limiters

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Content

- **Introduction**
- **Fault Current Limitation**
  - ➔ Why Fault Current Limiters (FCL)?
- **State of the Art**
  - ➔ Different types of FCLs
- **Application**
- **Requirements**
- **Power System Integration Issues**
- **Examples**

Introduction

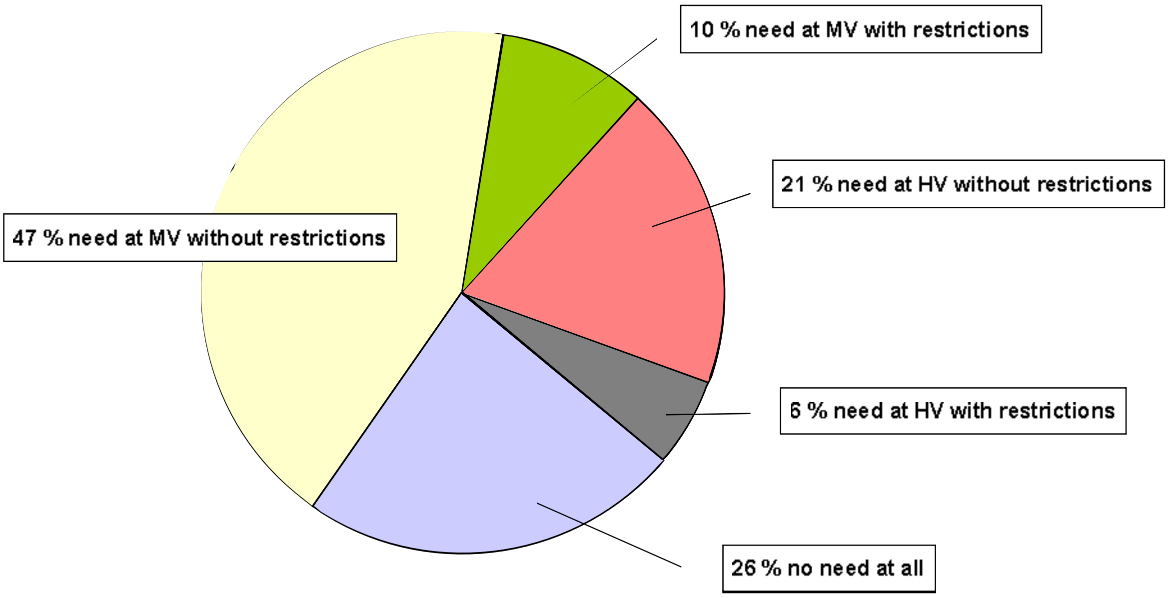
- CIGRE WG 13.10 - „Fault Current Limiters“
  - → Established in 1996
  - → 15 members from 9 different countries
  - → Reports in Electra 2001 and 2003
  - → Technical Brochure „Fault Current Limiters in Electrical Medium and High Voltage Systems“ No. 239, 2003
  - → Work finished and WG disbanded in 2003

Introduction

- CIGRE WG A3.16 - „Fault Current Limiters“
  - → Established in 2003
  - → 11 members from 8 different countries
  - → Report in Electra 2008
  - → Technical Brochure “Guideline on the impacts of Fault Current Limiting Devices on Protection Systems”
    No. 339, 2008
  - → Work finished and WG disbanded in 2008

Potential FCL Application

CIGRE Questionnaire 2003 - **Need for FCL**



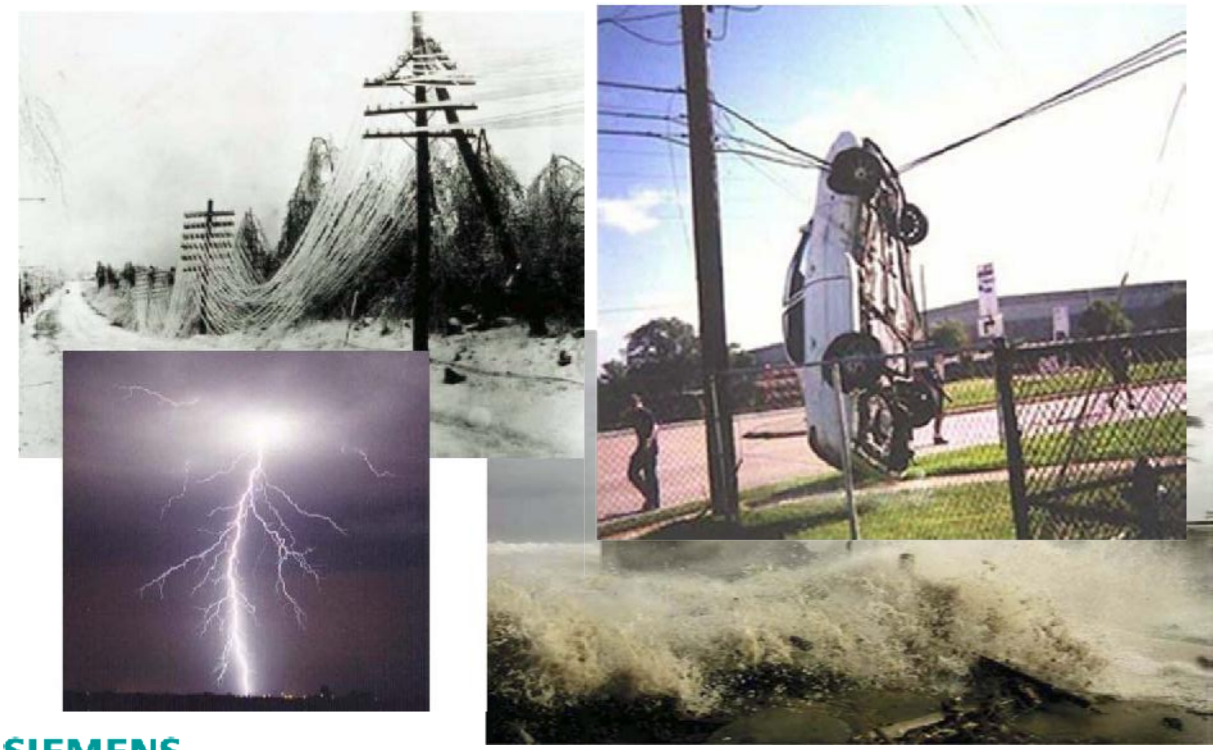
Introduction

- **CIGRE WG A3.23 - „Fault Current Limiters“**
  - **Established in 2008**
  - **25 members from 11 different countries**
  - **Technical Brochure “Application and Feasibility of Fault Current Limiters in Power Systems” in process**
  - **Scheduled to finish the work in 2012**

Introduction

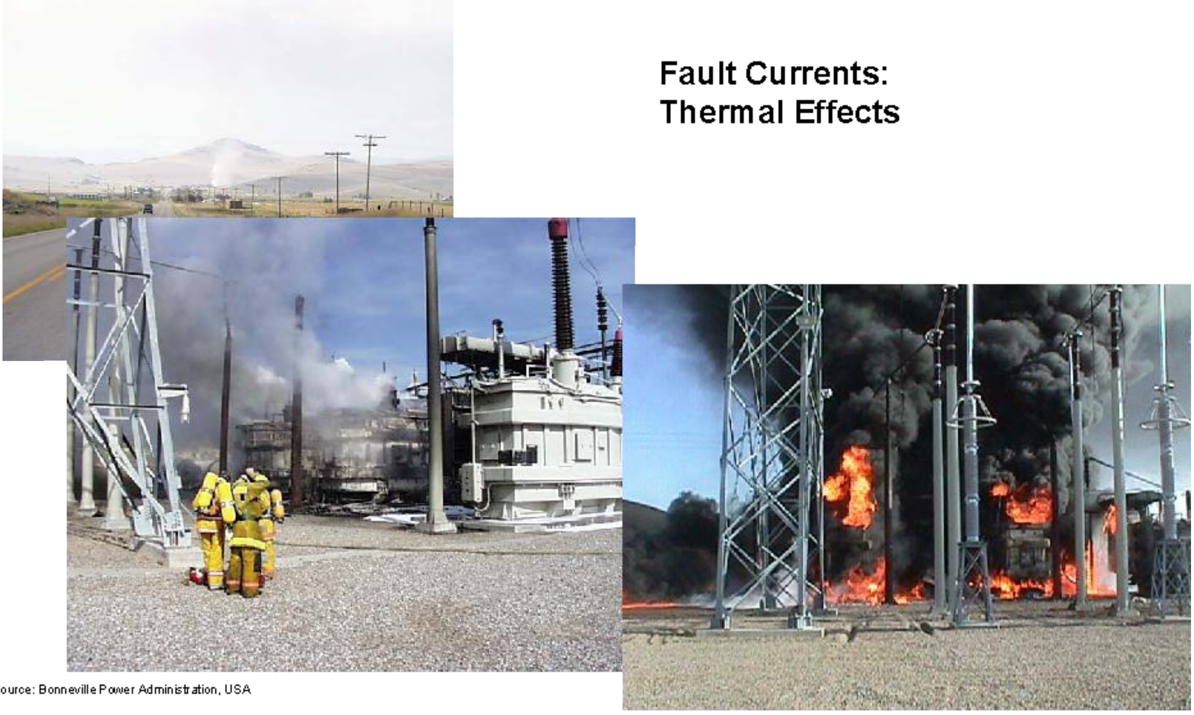
- CIGRE WG A3.23 – Content Technical Brochure
  - ➔ Fault Current Management
  - ➔ Past Experience and State of the Art
  - ➔ Application Considerations
    - Needs and Requirements
    - Impact and Interactions
    - Reliability and Availability
  - ➔ Feasibility and Economic Issues
    - Case Studies
  - ➔ Modeling Aspects

Introduction - Short Circuits are Unavoidable



Introduction

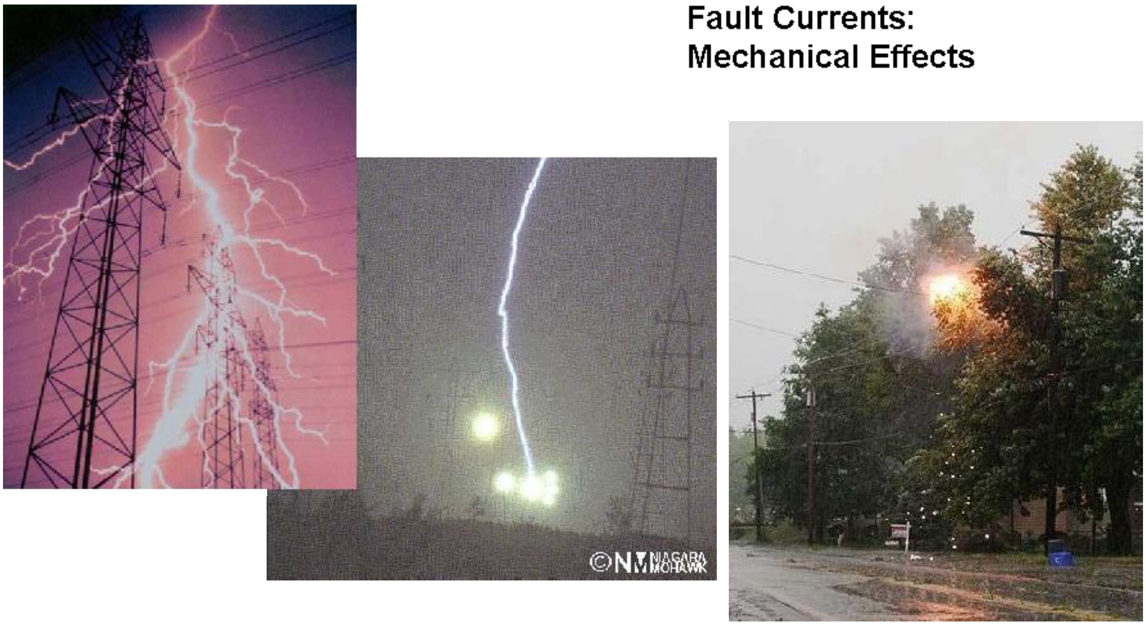
Fault Currents: Thermal Effects



Source: Bonneville Power Administration, USA

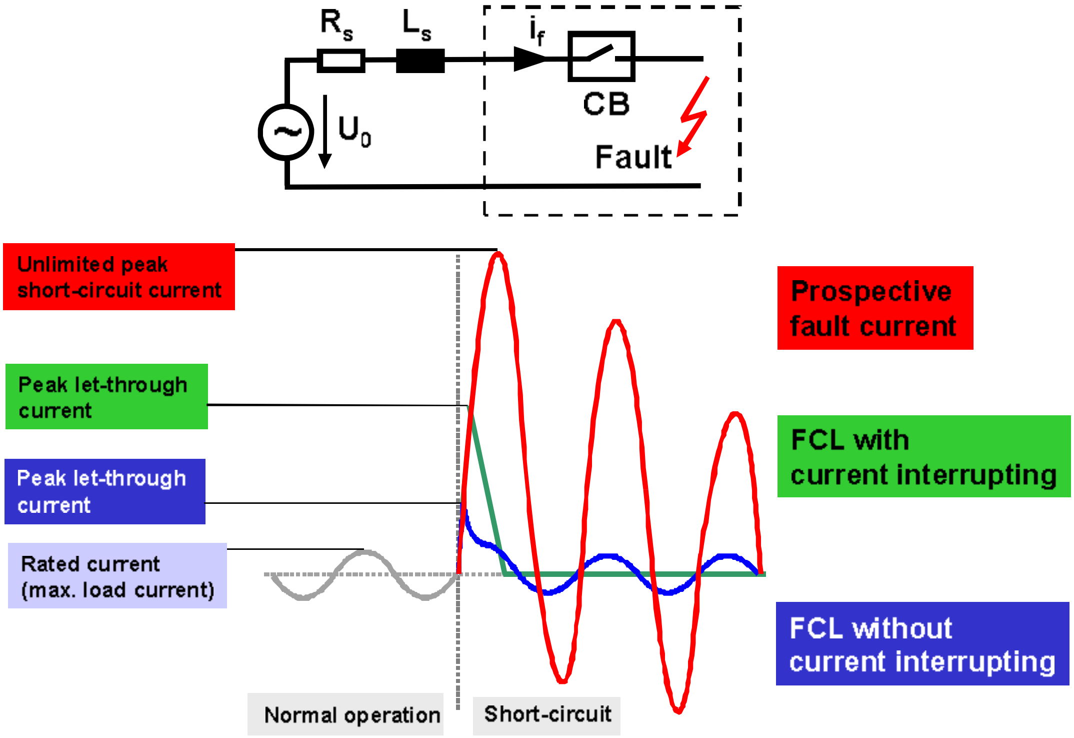
Introduction

Fault Currents: Mechanical Effects

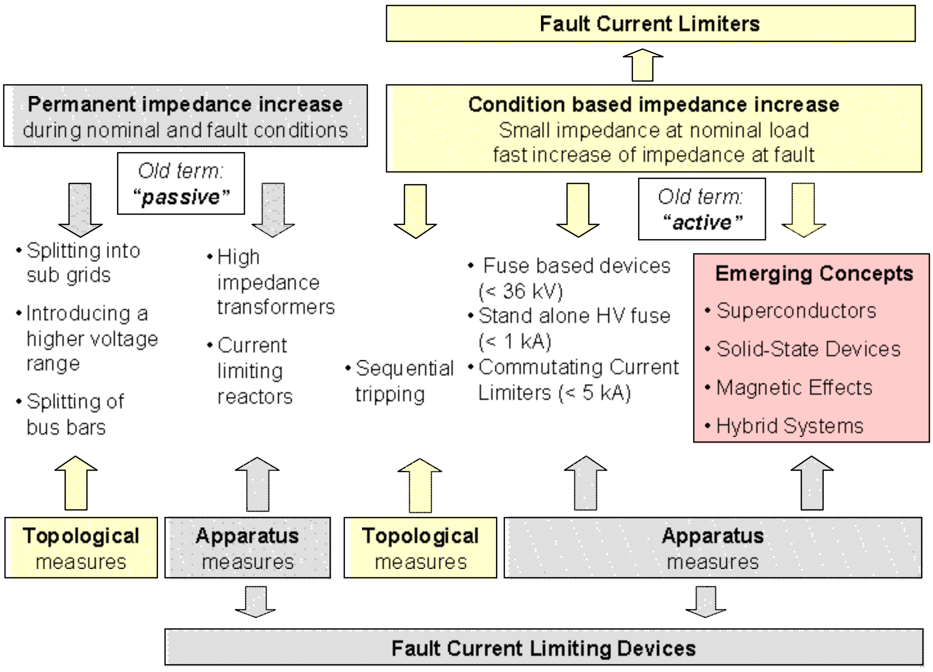


Source: http://www.gaiengineers.com/photos.htm

Fault Current Limitation



Measures to Limit Short-Circuit Currents



Fault Current Limiters

Permanent impedance increase
during nominal and fault conditions

Old term:
"passive"

Condition based impedance increase
Small impedance at nominal load
fast increase of impedance at fault

Old term:
"active"

- Splitting into sub grids
- Introducing a higher voltage range
- Splitting of bus bars

- High impedance transformers
- Current limiting reactors

- Sequential tripping

- Fuse based devices (< 36 kV)
- Stand alone HV fuse (< 1 kA)
- Commutating Current Limiters (< 5 kA)

Emerging Concepts
- Superconductors
- Solid-State Devices
- Magnetic Effects
- Hybrid Systems

Topological measures | **Apparatus** measures | **Topological** measures | **Apparatus** measures

Fault Current Limiting Devices

Conventional Measures to Limit Short-Circuit Currents

		Low Voltage	Medium Voltage	High Voltage
Topological measures	Introduction of a higher voltage level	applied	applied	applied
	Splitting of busbars	no	applied	applied
	Choose or upgrade to higher voltage	no	applied	applied
Apparatus measures	High impedance transformers	no	applied	applied
	Current limiting air coil reactors	applied	applied	applied
	Fuses	applied	applied	no
	Pyrotechnic Fault Current Limiter	no	applied	no

Why Fault Current Limiters ?

Compromise in power systems

High short-circuit capacity during normal operation
(low short-circuit impedance)

- Low voltage drops
- High power quality
- High steady-state and transient stability
- Low system perturbations

Low short-circuit capacity during fault conditions
(high short-circuit impedance)

- Low thermal and mechanical strain
- Reduced breaker capacity

Optimal solution
Fault Current Limiter

- Low impedance during normal operation
- Fast and effective current limitation
- Automatic and fast recovery

Different Types of FCL

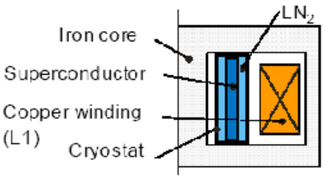
- **Conventional Devices**
  - ➔ **Reactor**
  - ➔ **Transformer**
  - ➔ **Pyrotechnic Fault Current Limiter**

- **Superconducting Fault Current Limiters**
  - ➔ **Shielded Core**
  - ➔ **Saturable Core**
  - ➔ **Resistive FCL**

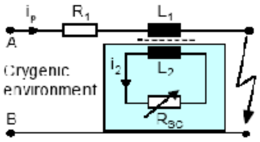
Different Types of FCL

- **Shielded Core**

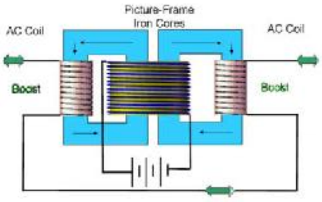
Scheme

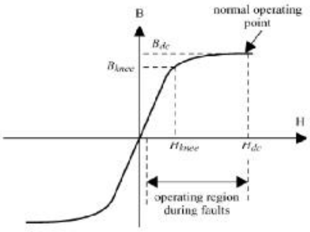


Equivalent circuit



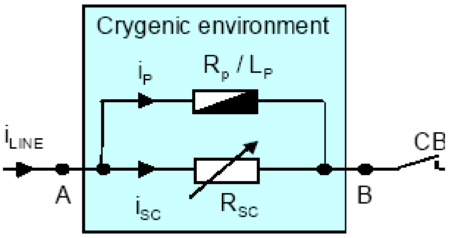
- **Saturable Core**

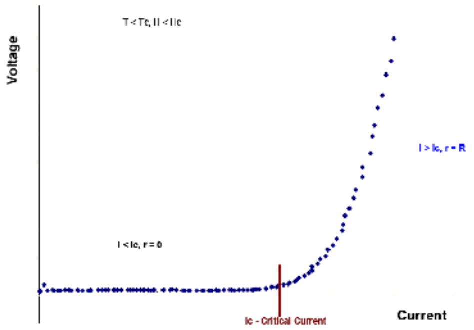




Different Types of FCL

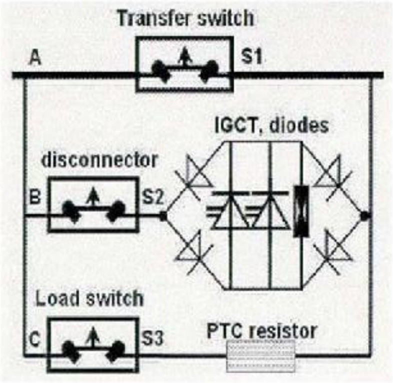
- **Resistive FCL**

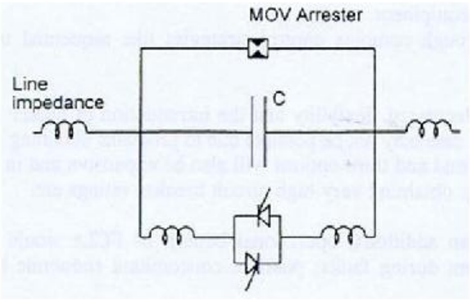




Different Types of FCL

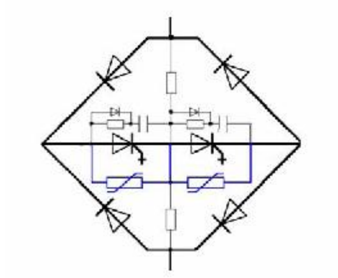
- **Hybrid Systems using fast mechanical switches**
- **Polymer PTC**
- **Resonance Link (Series Compensation)**
- **Driven Arc ("LV-CB concept")**

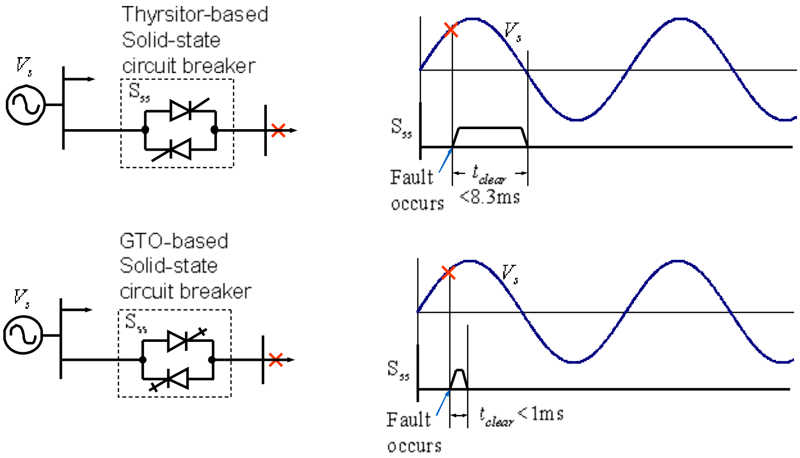




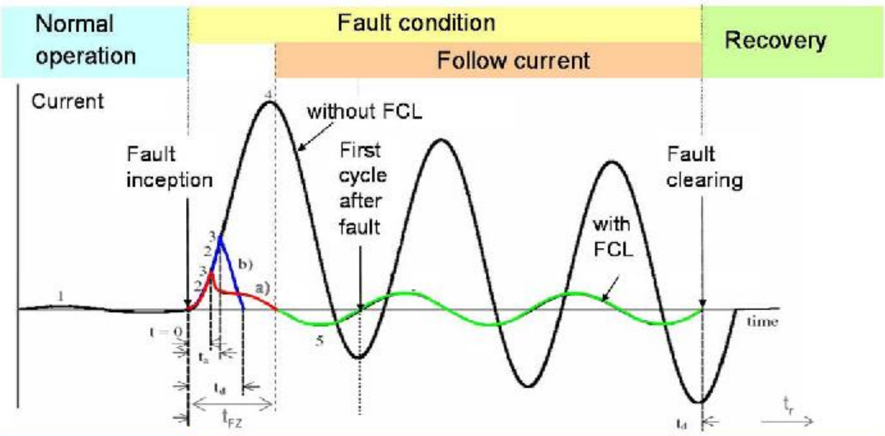
Different Types of FCL

- **Electronic Limiters (Solid State Breaker)**
  - → **Thyristor Technology**
  - → **Self Commutated Device Technology (GTO, IGCT, IGBT) possible**





Limiting Behaviour and Characteristic Terms of FCLs



t_a action time (from t = 0 until 3)
t_d fault duration time (from t = 0 and fault clearing)
t_{FZ} first zero crossing time

1: load current (In)
2 minimum initiating current
3: first peak value of limited current
4: prospective (peak) short circuit current
5: first peak value of the follow current

t_r recovery time (between current interruption and return of the FCL to its low impedance state)

State of the Art of Fault Current Limiters

- **Characterisation**
  - ➔ **„Passive“ Fault Current Limiting Measures**
    - ■ Passive: Increase of Impedance at Nominal and Fault Conditions (Example: Fault Current Limiting Reactor)
  - ➔ **„ Active “ Fault Current Limiters**
    - ■ Active: Fast Increase of Source Impedance at Fault Conditions (Example: Superconducting Fault Current Limiter)
      - With or without Current Interruption
      - Self-triggered or External-triggered
      - „Resetable“ or „Non-resetable“ *)

*) Parts of the fault current limiter need to be replaced after an operation

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State of the Art of Fault Current Limiters

Type	Passive / Active	Triggering Method	Current Interruption	Resetable	Voltage Level
Fault Current Limiting Reactor	Passive	-----	----	----	MV, HV
Transformer with Increased Short-Circuit Impedance	Passive	----	----	----	MV, HV
Current Limiting Fuse	Active	Self	Yes	No	MV
Pyrotechnic Fault Current Limiter	Active	External	Yes	No	MV
Resonance Link (Kalkner Kupplung)	Active	Self	No	Yes	MV, HV

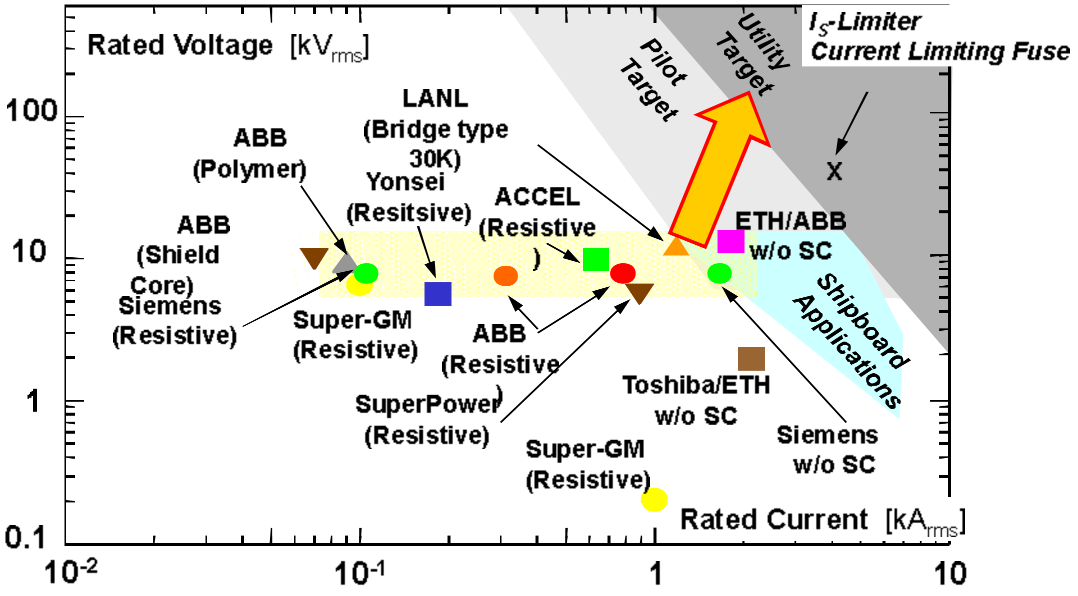
State of the Art of Fault Current Limiters

Novel Approaches

Type	Characteristics				Proto-type
	Passive/ Active	Triggering Method	Current Interruption	Resetable	
Resistive Type SCFCL	Active	Self	No	Yes	MV
Shielded Iron Core Type SCFCL	Active	Self	No	Yes	MV
Saturated Iron Core Type SCFCL	Active	Self	No	Yes	MV
“Current Controller” Type SCFCL	Active	External	Yes/No	Yes	MV
FCL with PTC Resistors	Active	Self	(Yes)	(Yes)	MV
Liquid Metal FCL	Active	Self	No	Yes	MV
Current Limiting Solid-State Switch	Active	External	Yes	Yes	MV
Solid-State Switch with Current Limiting Impedance	Active	External	Yes	Yes	MV
Hybrid FCL with Solid-State Switch	Active	External	Yes	Yes	MV
Current Limiting Circuit-Breaker (with High Arc-Voltage)	Active	External	Yes	Yes	MV
Resonance Link with Switching Device (Solid-State, Vacuum)	Active	External	No	Yes	MV

FCL Projects (Tested)

The “big step“ needed now is towards higher distribution voltages and further on to Transmission voltage levels



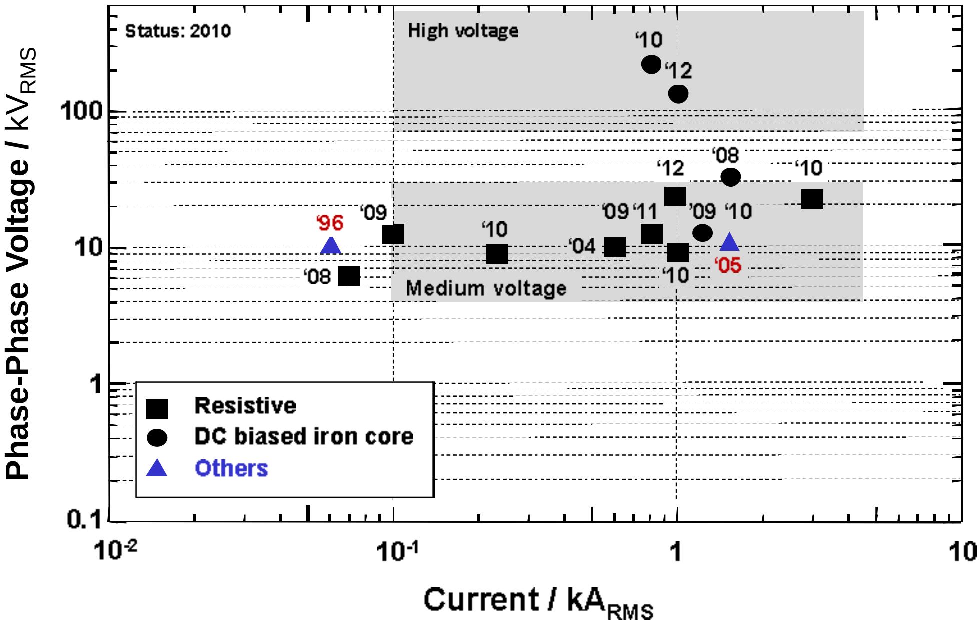
Status: June 2004

Superconducting Fault Current Limiters
State-of-the-Art

Lead Company	Country / Year of test	Type	Data	Phase	Superconductor
ACCEL/NexansSC	D / 2004	Resistive	12 kV, 600 A	3-ph.✓	Bi 2212 bulk
CAS	China / 2005	Diode bridge	10.5 kV, 1.5 kA	3-ph.✓	Bi 2223 tape
CESI RICERCA	Italy / 2005	Resistive	3.2 kV, 220 A	3-ph.	Bi 2223 tape
Siemens / AMSC	D / USA / 2007	Resistive	7.5 kV, 300 A	1-ph.	YBCO tape
LSIS	Korea / 2007	Hybrid	24 kV, 630A	3-ph.	YBCO tape
Hyundai / AMSC	Korea / 2007	Resistive	13.2 kV, 630 A	1-ph.	YBCO tape
KEPRI	Korea / 2007	Res.-hybrid	22.9 kV, 630 A	3-ph.	Bi 2212 bulk
Innopower	China / 2008	DC biased iron core	35 kV, 90 MVA	3-ph.✓	Bi 2223 tape
Toshiba	Japan / 2008	Resistive	6.6 kV, 72 A	3-ph.✓	YBCO tape
Nexans SC	D / 2009	Resistive	12 kV, 100 A	3-ph.✓	Bi 2212 bulk
Zenergy Power	USA / 2009	DC biased iron core	12 kV, 1.2 kA	3-ph.✓	Bi 2223 tape
Zenergy Power	USA / 2010	DC biased iron core	12 kV, 1.2 kA	3-ph.✓	Bi 2223 tape
Nexans SC	D / 2009	Resistive	12 kV, 800 A	3-ph.✓	Bi 2212 bulk
Nexans SC	D / 2011	Resistive	12 kV, 800 A	3-ph.✓	YBCO tape
Innopower	China / 2010	DC biased iron core	220 kV,300 MVA	3-ph.✓	Bi 2223 tape
ERSE	I / 2010	Resistive	9 kV, 250 A	3-ph.✓	Bi 2223 tape
ERSE	I / 2010	Resistive	9 kV, 1 kA	3-ph.✓	YBCO tape
KEPRI	Korea / 2010	Resistive	22.9 kV, 3 kA	3-ph.✓	YBCO tape
AMSC / Siemens	USA / D / 2012	Resistive	66 kV, 1.2 kA	1-ph.	YBCO tape
Zenergy Power	USA / 2012	DC biased iron core	138 kV	3-ph. ✓	Bi 2223 tape
Nexans SC	EU / 2012	Resistive	24 kV, 1005 A	3-ph. ✓	YBCO tape

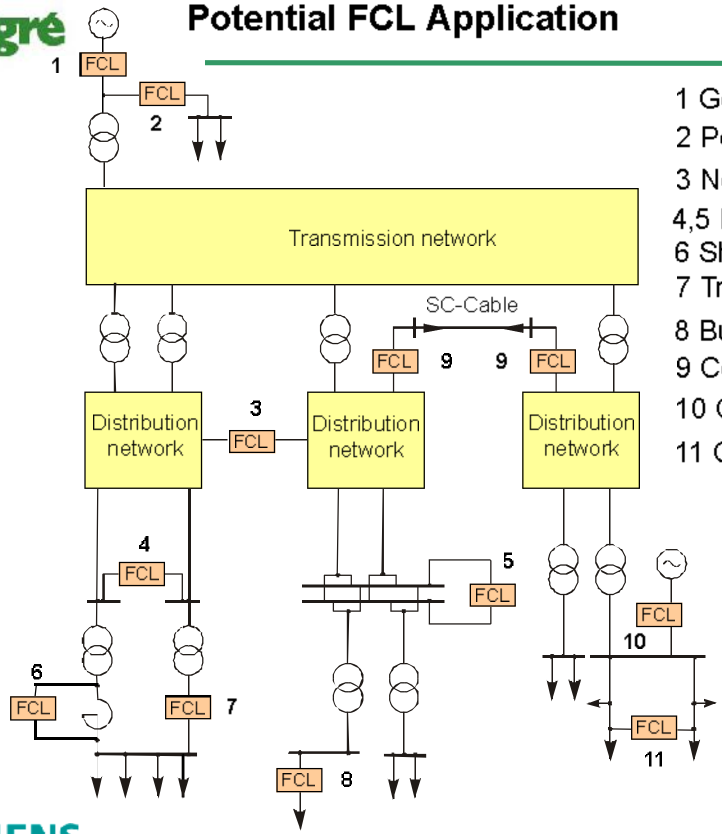
Source: M. Noe, KIT, ASC 2010

Superconducting Fault Current Limiters
SCFCL Field Tests – planned and carried out



Source: M. Noe, KIT, ASC 2010

Potential FCL Application

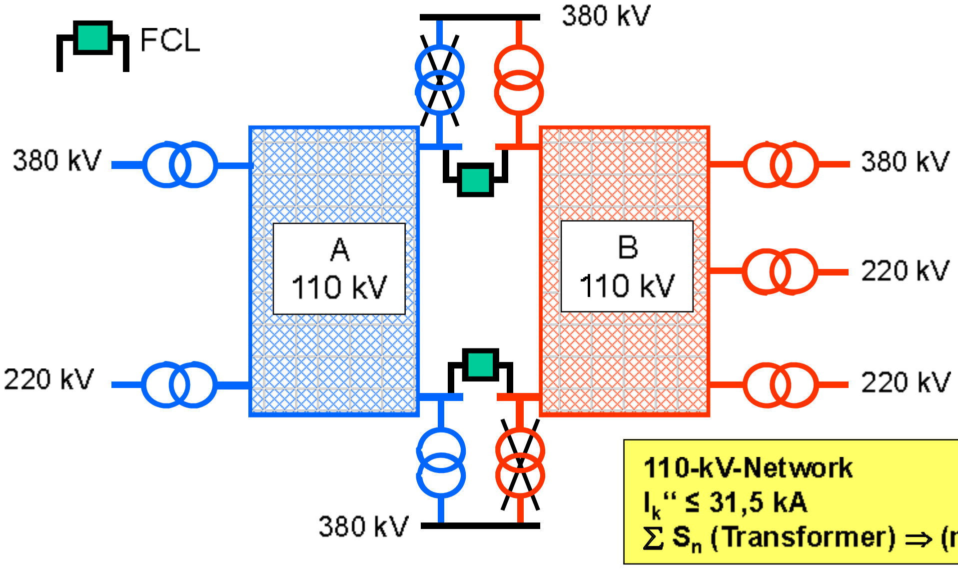


1 Generator feeder
2 Power station auxiliaries
3 Network coupling
4,5 Busbar coupling
6 Shunting current limiting reactor
7 Transformer feeder
8 Busbar connection / feeder
9 Combination with other SC devices
10 Coupling local generating units
11 Closing ring circuits

Source
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

Potential FCL Application

RWE, Germany 110 kV FCL application
Coupling of 110 kV subgrids



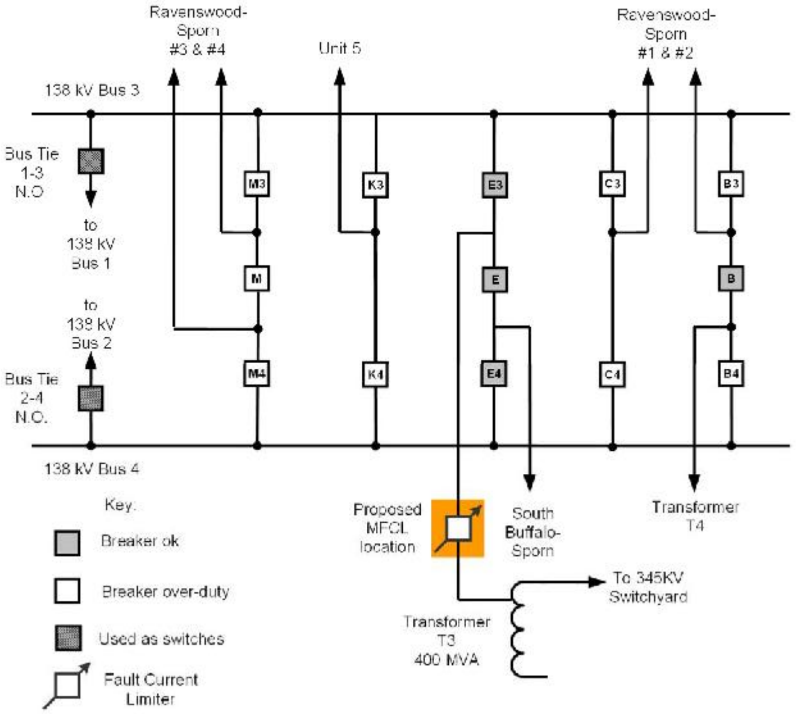
110-kV-Network
I_k" ≤ 31,5 kA
$\sum S_n$ (Transformer) ⇒ (n-1)-Criteria

Potential FCL Application

American Electric Power (AEP) 138 kV FCL application

Reducing fault contribution from transformer feeder

Sequential tripping used to cope with high fault currents on nine existing breakers:
E3 and E trip first if fault on line #1 to #4 generator unit 5



Advantages of the Use of FCLs

	Bus Tie	Incoming Feeder	Outgoing Feeder
Reduction of the Short-Circuit Current of the System	applied	applied	applied
Reduction of the Short-Circuit Current of the Feeder	no	no	applied
Reduction of Voltage Sags and Flicker	applied	applied	applied
Reduction of Harmonics	applied	applied	applied
Higher System Availability	applied	applied	no
Higher Loads in Sub-Systems	applied	no	no
Even Loading of Transformers	applied	applied	no

Requirements for FCL

- Low impedance during normal operation (low voltage drop across device)
- Adequate current limiting performance
- No deterioration of limiting behaviour during the useful life
- Low losses
- Low cost, cost effective operation
- Compact size and low weight
- No risk for operating personnel
- Low impact on the environment

Requirements for FCL

- Technical aspects (rating)
- Rapid and fail safe
- Automatic recovery within short recovery time
- No excess over voltage due to current limitation
- No action due to transient phenomena (motor startup, capacitor energization, etc.)
- Integration into existing installations
- Compatible with existing protection system
- Low maintenance requirements
- High reliability

Power System Integration Issues with FCL

- **Effects of the System on a Fault Current Limiter**
  - → **Undesirable Tripping of Fault Current Limiters**
    - Transient Currents Due to Single Phase-to-Earth Faults
    - Inrush Currents Due to Transformer Switching
    - Inrush Currents Due to Capacitor Bank Switching
    - Starting Currents of Motors
  - → **Ability of Fault Current Limiters to Withstand Fault Currents**
  - → **Fault Duration Depending on Protection System**

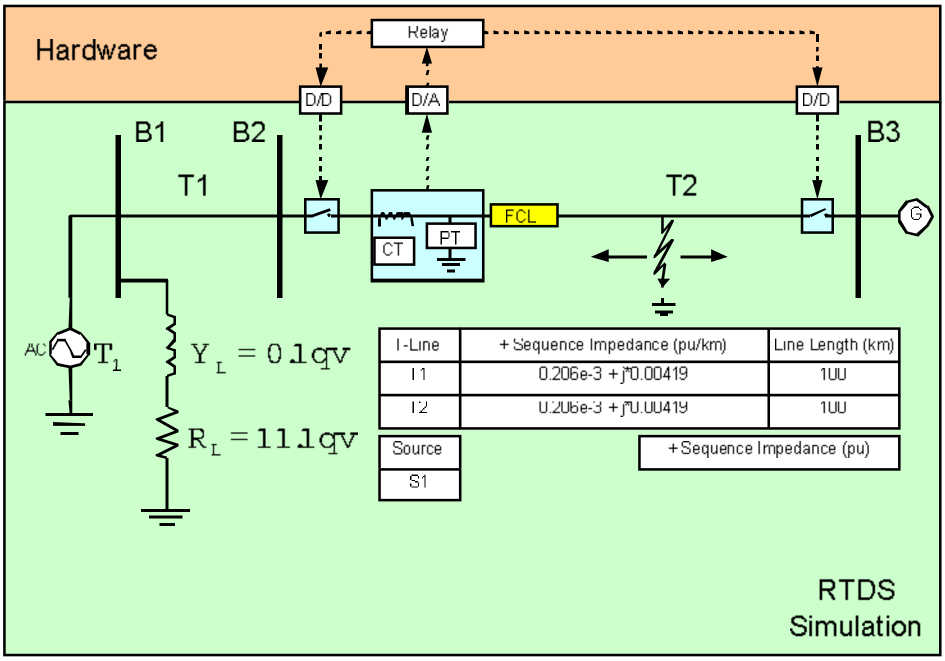
Power System Integration Issues with FCL

- **Effects of a Fault Current Limiter on the System**
  - → **Effects on System Reliability**
    - Reliability of the Fault Current Limiter
    - Effect of a Malfunction of the Fault Current Limiter
    - Behaviour of the Fault Current Limiter in Case of an Internal Fault
  - → **Maintenance Requirements**
    - Maintenance Intervals
    - Maintenance Duration

Power System Integration Issues with FCL

- **Effects of a Fault Current Limiter on the System**
  - ➔ **Effects on Protection Schemes**
    - Relay Settings
    - Selectivity
    - Compatibility with Downstream Fuses
    - Protection Blinding (e.g. in Case of Directional Protection)
  - ➔ **Effects on Conventional Switchgear**
    - Transient Recovery Voltage of Downstream Circuit-Breakers
  - ➔ **Transient Stability**
    - Impact on Rotor Angle Stability

Effects of SC-FCL on Impedance Relay

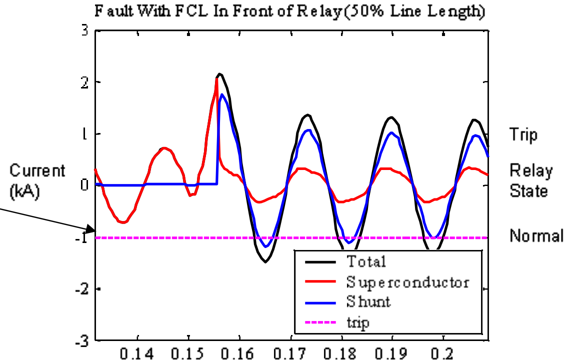


T-Line	+ Sequence Impedance (pu/km)	Line Length (km)
T1	0.206e-3 + j*0.00419	100
T2	0.206e-3 + j*0.00419	100

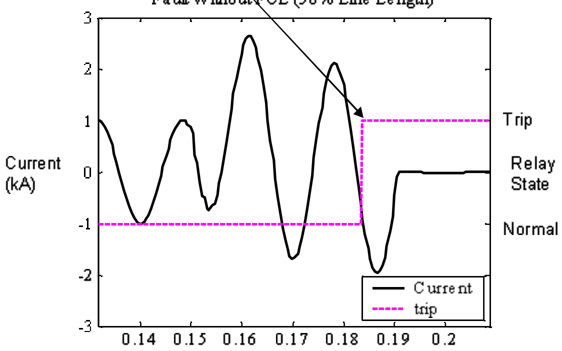
Source	+ Sequence Impedance (pu)
S1	

Results: FCL leads to missing trips

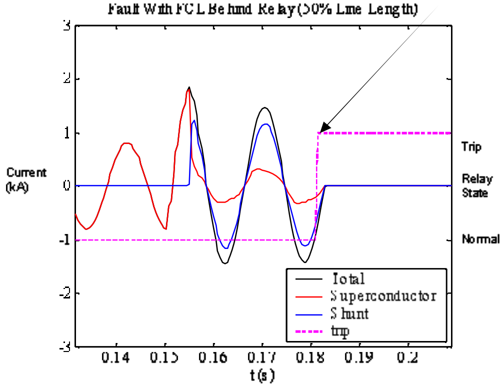
FCL in upstream
of PTs and CTs
=> Relay does not trip



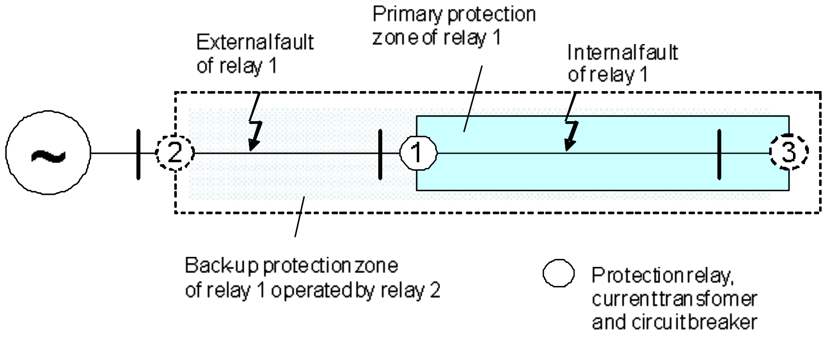
Reference without FCL
=> Relay trips
appropriately



FCL in downstream
of PTs and CTs
=> Relay trips appropriately



Protection Zone Concept



External fault
of relay 1

Primary protection
zone of relay 1

Internal fault
of relay 1

Back-up protection zone
of relay 1 operated by relay 2

○ Protection relay,
current transfomer
and circuit breaker

Protection Zone Concept

- **Sensing**
  - ➔ **Transmission Errors**
- **Pickup**
  - ➔ **Distinction between load and fault condition**
- **Processing**
  - ➔ **Evaluation of measured values**
- **Coordination**
  - ➔ **for selectivity protection relays must be coordinated with each other**

Protection Zone Concept

Protection principles	**Pickup**		**Processing**		**Coordination**	
	FCL Inside	FCL outside	FCL Inside	FCL outside	FCL Inside	FCL outside
Overcurrent 50/51	1 : overcurrent pickup: $I_{SC\ FCL} > I_{Pickup}$		6 : FCL fault duration > processing time, additionally delay due to inverse-time characteristics		12 : current grading, current blinding	13 : source-impedance ratio (SIR) – grading
Directional functionality 67	2 : zone impedance pickup (refer to 3)		6, 7, 8 : range of line phase angles including FCL, signal distortion	6, 8, 9 : determination of direction based on source impedance	No coordination, because the directional stage is added to overcurrent or distance function	
Distance 21	1, 3 : overcurrent pickup, impedance pickup $Z_{Fault} < Z_{Pickup}$	1 : overcurrent pickup, no influence on impedance pickup	3b, 6,8: zone impedance sensing	6, 8, 9 : determination of direction based on source impedance	14 : Inter-in-feed effect	15 : source-impedance ratio (SIR) - accuracy
Differential 87 - Low impedance	1, 4 : Overcurrent pickup or overcurrent guarding		6, 10 : lower fault current, check for sensitivity		16 : No coordination with other types of protection, only some unusual exceptions	
Differential 87 - High impedance	5 : No overcurrent pickup facility, differential current measurement only		6, 11 : lower fault current, check for sensitivity			

Protection Zone Concept

1:

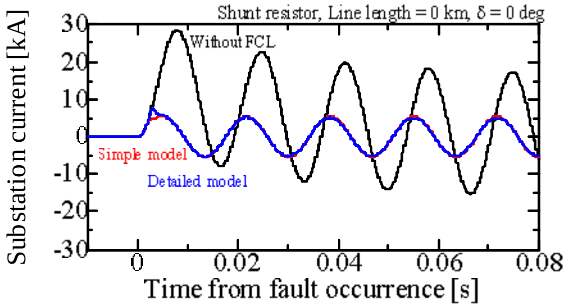
- ➔ No adverse influence as long as the minimum limited fault current measured by the relay, depending on the limitation factor and possible current distortion of the FCL, still exceeds the threshold for pickup current of the overcurrent function.

6:

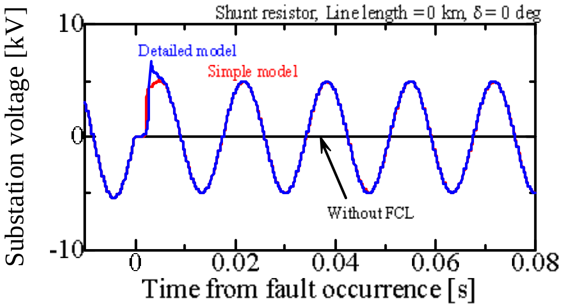
- ➔ The FCL must allow the fault current to flow at least as long as the sum of all processing times and the delay times. This depends on the fault duration time of the FCL.

Modeling Aspects and Simulation

	Detailed model	Simple model
HTS resistance	E-J characteristic HTS temperature	Linear model
Resistance of shunt resistor	Constant	Constant
Inductance of shunt coil	Constant	Constant
Resistance of shunt coil	Depend on temperature	Constant



(a) Substation current



(b) Substation votlage

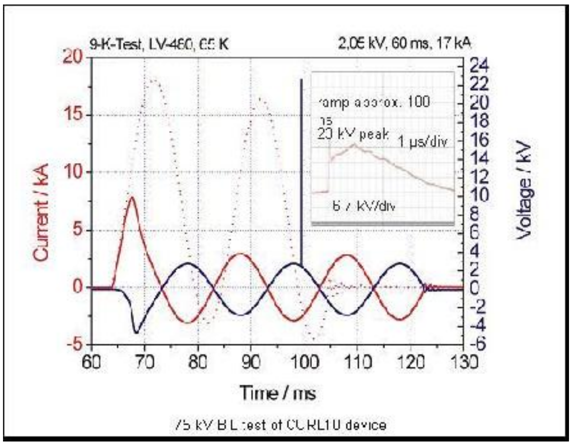
Testing of Fault Current Limiters

- **Existing Standards:**
  - ➔ **Fault Current Limiting Reactors (IEC 60289)**
  - ➔ **High Voltage Fuses (IEC 60282-1)**
  - ➔ **Power Transformers (IEC 60076)**
- **For all other Types of Fault Current Limiters no Standards Exist**

Testing of Fault Current Limiters

No.	Type	Existing IEC Standard
1	Winding resistance	IEC 60076-6
2	Impedance	IEC 60076-6
3	Total losses	IEC 60076-6
4	Temperature rise	IEC 60076-6, IEC 60076-2
5	Applied voltage	IEC 60076-6
6	Insulation power factor	IEC 60076-11
7	Insulation resistance	IEC 60076-11
8	Turn to turn	IEC 60076-11, IEC 60076-3
9	Lightning impulse	IEC 60076-11, IEC 60076-3, IEC 60076-4
10	Chopped wave	IEC 60076-11, IEC 60076-3, IEC 60076-4
11	Partial discharge	IEC 60076-3, IEC 60076-6,
12	Seismic verification via analysis	A new IEC standard will be created, actually IEEE Standard 693 is used

Standard FCL Testing Procedures Needed



75 kV BIL test of CURL10 device

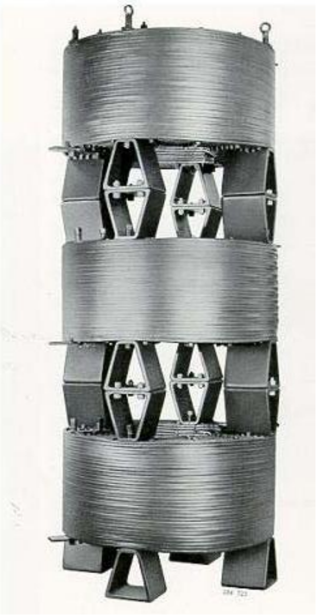
- **In the past: Individual requirements defined by host utility**
- **Voltage impulse test for FCL**
  - **➔ All terminals to ground for FCL open**
  - **➔ Terminal to Terminal one phase**
  - **➔ lightning impulse during FCL action**
- **Short time withstand current testing**
  - **➔ "Active part bridged" for FCLs which inherently do not allow the prospective fault current to flow**
- **"Reclosing"**
  - **➔ Expected duty comparable to circuit breaker (e.g. O-C-O). Is this really required for all applications?**

Power System Integration Issues with FCL

- **FCL characteristics introduce new system dynamics**
  - **➔ Standard testing procedures must be developed**
  - **➔ System protection must be investigated**
    - How to coordinate FCL characteristic with existing protection schemes?
    - New protection schemes are possible with FCL for future systems
  - **➔ Validated models for system simulation studies needed**
  - **➔ New materials for FCL (e.g. Cryogenics)**
    - Utilities/users are not familiar with

Application of Fault Current Limiters - Examples

Limiting Reactor MV

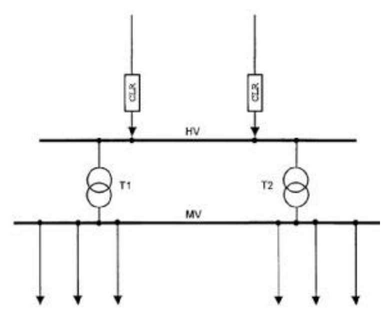


Application of Fault Current Limiters - Examples

Limiting Reactor 110kV

Application of Fault Current Limiters - Examples

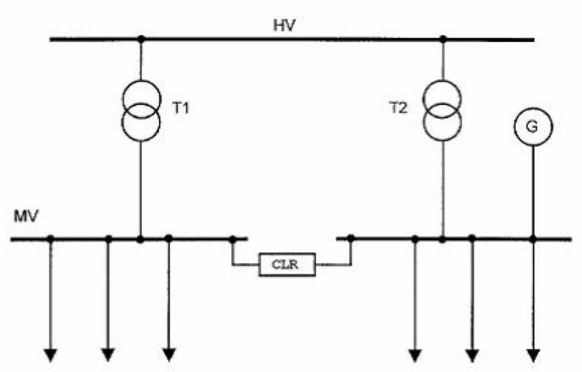
Limiting Reactor 362 kV



SIEMENS

Application of Fault Current Limiters - Examples

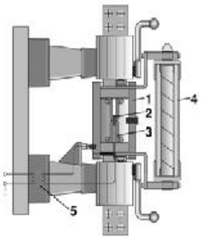
Limiting Reactor 550 kV



SIEMENS

Application of Fault Current Limiters - Examples

Pyrotechnic Fault Current Limiter



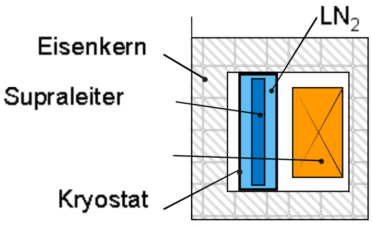
Courtesy G&W

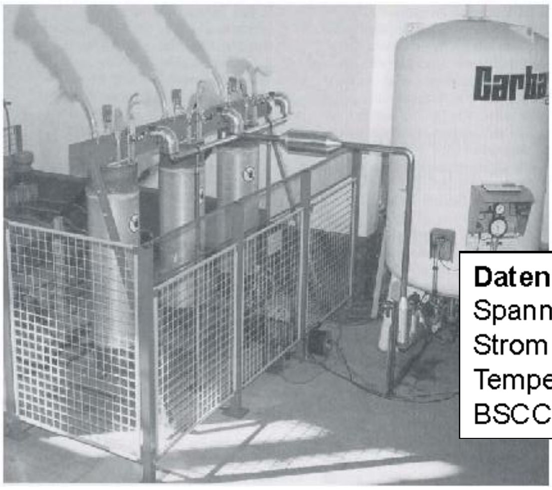
Courtesy ABB

Application of Fault Current Limiters - Examples

Superconducting FCL (Inductive Type) - 1996
(abgeschirmter Eisenkern)

Schema





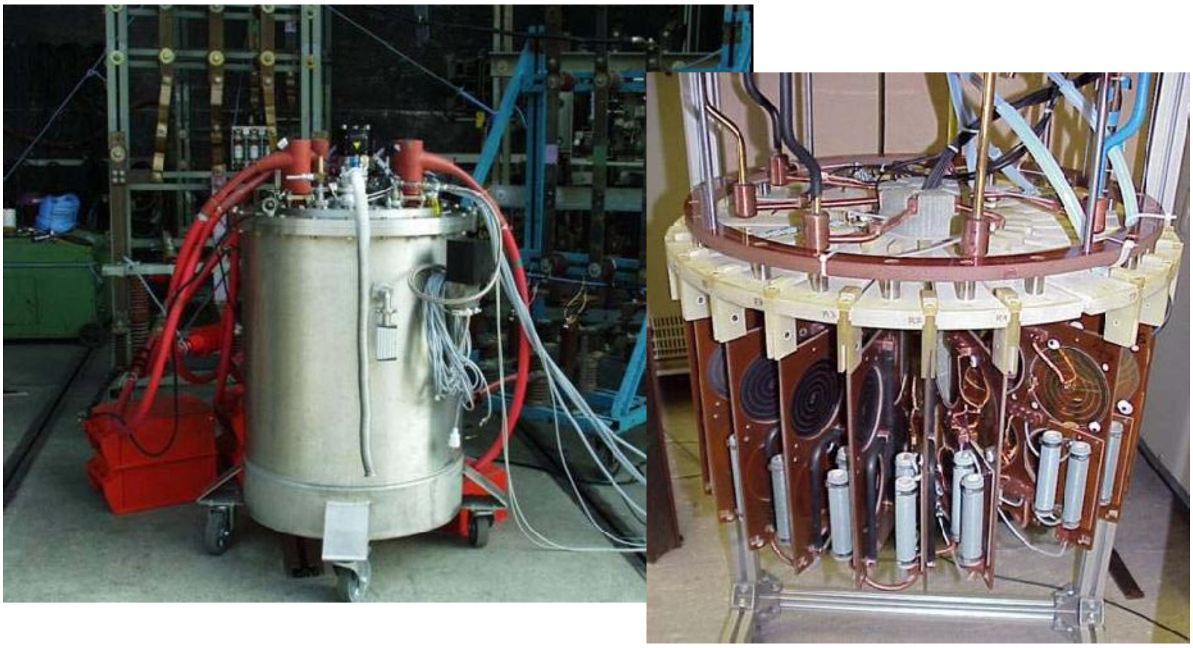
Daten:

Spannung	10 kV
Strom	70 A
Temperatur	77 K
BSCCO2212 Zylinder	

Courtesy ABB

Application of Fault Current Limiters - Examples

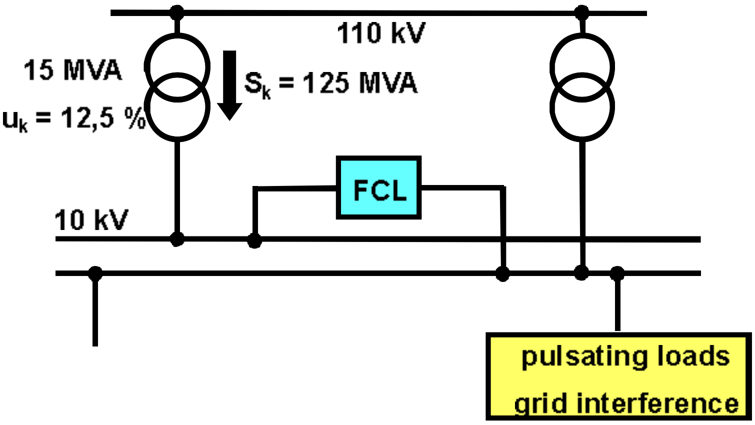
Superconducting FCL (Resistive Type)



Application of Fault Current Limiters - Examples

World wide first resistive SC-FCL field test
at RWE, Germany (field test started April 2004)

Demonstrator application in a 10 kV busbar coupling



Main data:

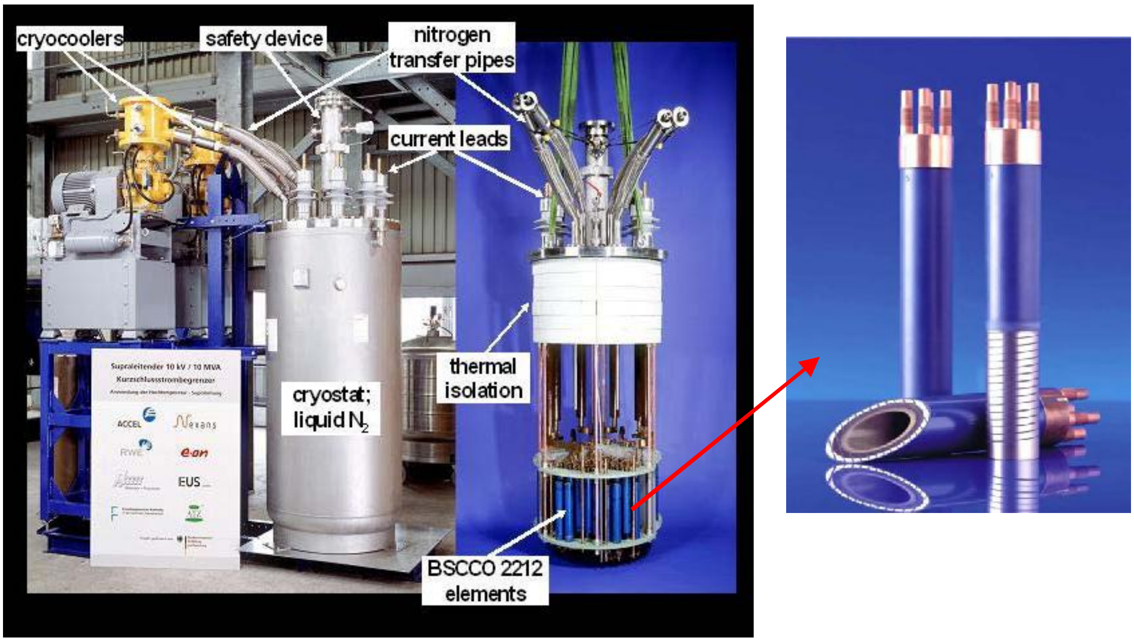
Voltage	12 kV
Current	600 A
Lim. time	60 ms
Max. current	8.75 kA
Temperature	65 K
Max. E-field	0.6 V/cm

MCP-BSCCO2212 bifilar coils

Photo: ACCEL, Germany

Application of Fault Current Limiters - Examples

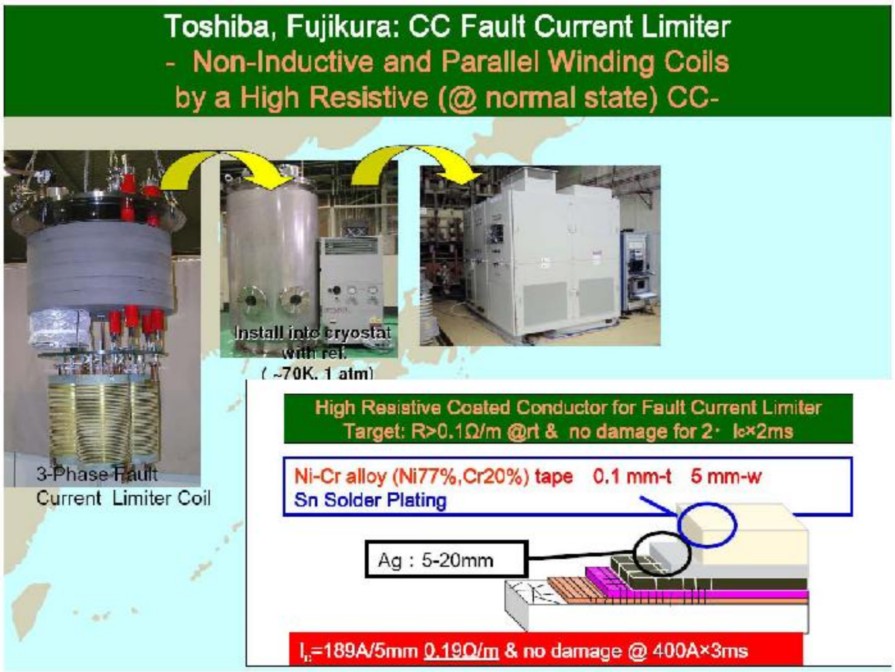
Superconducting FCL (Resistive Type BSCCO) - 2004



Application of Fault Current Limiters - Examples

Superconducting FCL (Resistive Type YBCO) - 2008

Toshiba, Fujikura: CC Fault Current Limiter
- Non-Inductive and Parallel Winding Coils by a High Resistive (@ normal state) CC-



High Resistive Coated Conductor for Fault Current Limiter
Target: R>0.1Ω/m @rt & no damage for 2· Ic×2ms

Ni-Cr alloy (Ni77%,Cr20%) tape 0.1 mm-t 5 mm-w
Sn Solder Plating

I_c=189A/5mm <u>0.19Ω/m</u> & no damage @ 400A×3ms

Source: Yamada, US Doe Peer Review 2008

Application of Fault Current Limiters - Examples

Superconducting FCL – 2009

Source: LSIS

Application of Fault Current Limiters - Examples

Electronic Limiter

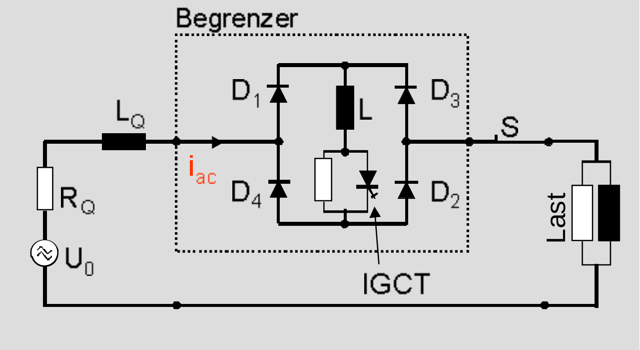
Application of Fault Current Limiters - Examples

Electronic Limiter (Solid State Limiter) - 2004

Application of Fault Current Limiters - Examples

Strombegrenzer mit Diodenbrückenschaltung - 2005

Daten:
Spannung 10.5 kV
Blitzstossspannung 75 kV
Strom 1.5 kA
Spuleninduktivität 6.24 mH

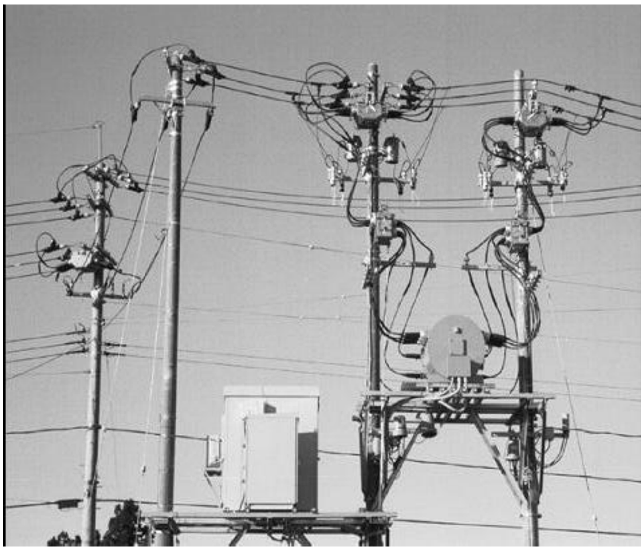


Installation in der Gaoxi Schaltanlage

HTS Spule

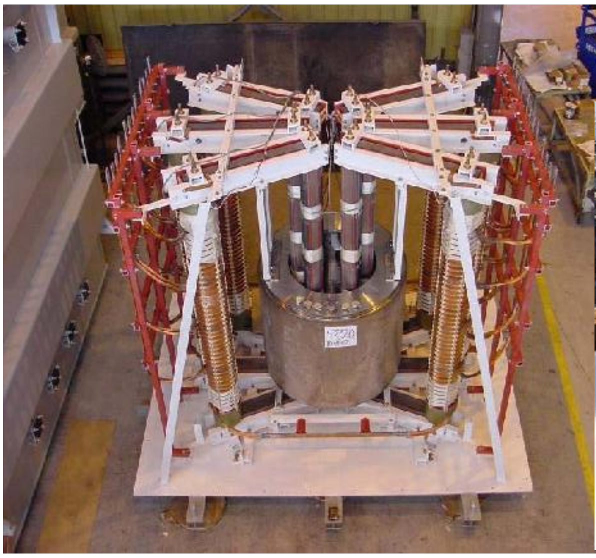
Application of Fault Current Limiters - Examples

Arc Driven FCL



Application of Fault Current Limiters - Examples

Saturable Core (2009)



Installation in the system of Southern California Edison

Prototype 13 kV

Courtesy:
Zenergy Power

Short Circuit Tests at Powertech Labs British Columbia, December 2007

Source: M. Noe, KIT

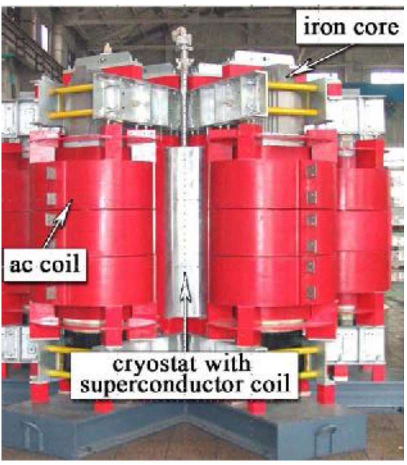
Superconducting Fault Current Limiters State-of-the-Art

Nexans SuperConductors

Courtesy: Nexans SuperConductors

- Resistive Type
- 12 kV, 800 A, 120 ms
- Bi 2212 bulk material
- Power system auxiliary
- Energized 2009
- First commercial system

Innopower



Courtesy: Innopower

- DC Biased Iron Core Type
- 35 kV, 90 MVA
- Bi 2223 tapes
- Substation
- Energized 2008

Zenergy Power

Courtesy: Zenergy Power

- DC Biased Iron Core Type
- 15 kV, 1.2 kA, 60 cycles
- Bi 2223 tapes
- Substation Feeder
- Energized March 9, 2009

Source: M. Noe, KIT, ASC 2010

Thank you for your attention

Tutorial on Fault Current Limitation

The End