Fault Current Limiters for Distribution and Subtransmission Electricity Networks

5. Braunschweiger Supraleitungsseminar
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Corporate Development
Zenergy Power plc, London/Rheinbach
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Topics
- Enhancing Networks
- Inductive FCL
- Field Testing of FCL 15kV
- FCL Development Path
- FCL 138kV
- FCL 15kV
- Roadmap
- Appendix: Company Profile
Fault Current Limiter – Surge Protector for Power Grids
Challenges in T&D networks

*Increased Power Transfer Capability* – In order to meet the ever increasing electricity demand, utilities have been upgrading their systems for higher power transfer capability resulting in higher fault currents.

*Meshed Networks* – Present networks are getting more interconnected for the purpose of enhancement of reliability and flexibility in the power transmission. A more closely coupled system not only exhibits reduced source impedance values from parallel paths but also an increased number of sources possibly contributing to a fault.

*New Generation* – The addition of new conventional and distributed generation (thermal solar power and photovoltaic systems, wind generators, fuel cells, microturbines, combustion turbines etc.) to existing generation is constantly increasing. The addition of distributed generators results in increased fault currents throughout the distribution system.

From EPRI 1012419 Nov. 2006
Application of FCL:
Network reinforcement, DG connection, power quality
Application of FCL: 110kV Network Coupling
Effect of the Fault Current

Mechanical force $F = f(i_p)$

Thermal Energy: $P \sim \int i(t)dt$

FCL after app. 3 ms
Circuit breaker after app. 100 ms
Fault Current Management Solutions
Only the Fault Current Limiter (FCL) has almost no performance down-side under normal condition and under fault condition

<table>
<thead>
<tr>
<th>Solutions to manage increasing fault current levels</th>
<th>Self-triggered</th>
<th>Recovery under load</th>
<th>Re-settable</th>
<th>Current limitation</th>
<th>Power losses</th>
<th>Voltage stability</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchgear upgrade</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Fuse (Is-Limiter)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Reactor</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+/0</td>
</tr>
<tr>
<td>Resistive SFCL</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+/-0</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Inductive FCL</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+/-0</td>
<td>+</td>
<td>0</td>
</tr>
</tbody>
</table>
FCL Projects

Worldwide Utility Installations are gaining momentum

- Germany, 10 kV
- China, 10.5 kV
- China, 35 kV
- USA, 12.5 kV
- Germany, 12 kV
- England, 11 kV
- Spain, 11 kV
- USA, 115 kV
- USA, 138 kV
- Korea, 22.9 kV
- USA, 13.8 kV

= commission date
= Zenergy project or bid
Competitive Products
Protection Range: Rated Line Current versus Line Voltage

Line Voltage [kV]

Line Current [A]

ABB’s Is-Limiter
Nexans’ FCL 12-800
Zenergy’s FCL 15

Nexans FCL 12 kV
Is-Limiter 12 kV
ZEN FCL 15 kV
Is-Limiter 15 kV

ZEN FCL 33 kV
Is-Limiter 33 kV
ZEN FCL 138 kV
Is-Limiter 40.5 kV
Principle Function of ZEN’s Inductive Fault Current Limiter
Operating principle: saturable iron-core

Configuration for single phase FCL.
Application of an Inductive Fault Current Limiter

The FCL can be placed **in-line**, like a traditional CLR (Current Limiting Reactor).

The FCL impedance is **non-linear**.

The CLR impedance is constant.
Inductive Fault Current Limiter

Think of an Inductive FCL as a Source-Voltage that opposes the main source during a fault. The Back emf is a non-linear function of the instantaneous line current (i)

\[
\text{Back}_\text{emf}(t) = f(i, t) \frac{di(t)}{dt}
\]
INDUCTIVE FCL CHARACTERISTIC CURVE

Fault Current Limiting Capability

FCL back emf [kV]

Limited Current [kA]

FCL Gain - K

6X1 Measured 120A DC 1% Insertion impedance

25.06.2010

FCL summary

12
Zenergy´s Patented FCL Solution

The inductive FCL (with superconducting DC magnet)
… reduces large-scale fault current
… appears “invisible” in the grid until needed

- self-triggered (inherently fail-safe)
- resettable - immediate recovery under load
- immediate response to multiple faults
- current limitation – no interruption
- bi-directional – reverse power load let-through
- (almost) no power losses
- no degrading of net voltage stability
- separation of HV AC line current from HTS DC magnet – no thermal-mechanical stress on HTS components
Inductive Fault Current Limiter

Notice that the FCL is **bi-directional** and independent of the fault location. Its impedance toggle is a function of the line current amplitude. The FCL can be used in both **bus-tie and feeder applications**.

**Application 1 Dual Bus**
Five-Transformer Distribution Substation
Heavy Industry Load
Nexans FCL 12-800 at Vattenfall Powerstation Boxberg, DE: auxiliary power supply

FCL 12-800 protects the internal auxiliary power supply network from fault current arising from coal mill motor.
Testing the First Full-Scale HTS FCL at Powertech Laboratories 2008
Fault current limiting

TEST RESULTS 13.1kV – 23kA

23 kA PROSPECTIVE
X/R = 44

18.6 kA rms w/ FCL
20%

23kA Prospective
FCL IN
MULTIPLE, SUCCESSIVE FAULTS

TEST 77 - DOUBLE FAULT SEQUENCE - 20kA X/R=22, FCL IN

20kA double fault in 2 seconds
Extra long fault

20kA Endurance fault
82 cycles
FULLY TESTED

IEEE Std C57.16-1996 IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors
IEEE Std C57.12.01-1998 IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid-Cast and/or Resin-Encapsulated Windings

The following standards are applicable in the relevant parts to the individual components of the FCL:

1. IEC 60076 Power Transformers: Part 1, General
2. IEC 60076 Power Transformers: Part 2, Temperature Rise
3. IEC 60076 Power Transformers: Part 3, Insulation Levels, Dielectric Tests and External Clearances in Air
4. IEC 60076 Power Transformers: Part 4, Guide to Lightning Impulse and Switching Impulse Testing - Power Transformer and Reactors
5. IEC 60076 Power Transformers: Part 5, Ability to Withstand Short Circuit
6. IEC 60076 Power Transformers: Part 6, Reactors
7. IEC 60076 Power Transformers: Part 7, Loading Guide for Oil-Immersed Power Transformers
8. IEC 60076 Power Transformers: Part 8, Application Guide
10. IEC 62271 High voltage Switchgear and Controlgear: Part 1 - Common Specifications
11. IEC 62271 High voltage Switchgear and Controlgear: Part 200: AC Metal Enclosed Switchgear and Controlgear for Rated Voltages Above 1 kV and up to and including 52 kV
12. IEC 60060-1 High Voltage Test Techniques: Part 1, General Definitions and Test Requirements
13. IEC 60270 High Voltage Test Techniques - Partial Discharge Measurements
14. IEC 62271-100 High voltage Switchgear and Controlgear: Part 100: High Voltage Alternating-Current Circuit-Breakers
15. BS 7671:2008 Requirements for Electrical Installations (IEE Wiring Regulations, 17th edition)
16. BS 7671:2008 Requirements for Electrical Installations (IEE Wiring Regulations, 17th edition)
17. EATS 37-2 LV distribution fuseboards
18. BS 7888 LV and MV accessories for power cables with rated voltage from 0.6/1 kV up to and including 20/36 kV
19. British Standard BS6626: Code of practice for maintenance of electrical switchgear and controlgear for voltages above 1 kV and up to and including 35 kV.
20. BS 4142 Method for rating industrial noise affecting mixed residential and industrial areas.
23. BS 4278: Specification for eyebolts for lifting purposes
The CEC HTS FCL in the SCE Shandin Substation, San Bernardino, California

- Serving 1400 commercial and residential customers
- On-line March 9, 2009; collecting data continuously since installation
SIEMENS PLC NETWORK

Features:
- SMS Warning Text Messages
- SCADA Control via Wonderware
- Data Archiving via Wonderware
- Modbus Interface for SCE

Text Message

GSM Text Modem
3G GSM Data Modem
Siemens PLC
Modbus Interface

Cell Tower
Separate Ethernet Port

W.W.W.
Wonderware Servers

ZP PC
SCE SCADA
FCL CONTROL AND MONITORING

Control:
- Power Supplies
- Compressors
- Cold-Head Temperatures

Monitor:
- AC Status
- DC Status
- Cryo Status
- Aux. Power
- Control DC
Summary of operating experience - FCL at Southern California Edison, USA

- FCL has operated continuously since Mar 2009 and it will be decommissioned in Dec 2010.

- Operating in a harsh environment
  - Maximum ambient temperature reached was **108°F** in Summer 2009 (**42°C**)
  - Minimum ambient temperature - low 30’s (<-1°C)
  - Heavy winds and dusty area

- Experienced one loss of DC Bias with consequent “resonance” condition (see IEEE paper)
- Successful integration with automatic bypass switch

- Experienced one event with multiple faults in quick succession (14 January 2010)

- Experienced two “Auxiliary power failures”
  - Effective bypass of FCL and shut-down of the HTS coil (as expected)
  - “Auxiliary power failures” caused by grid disturbances not on Avanti circuit
  - Instantaneous bypassing sought by SCE
- Performed routine maintenance on cryogenics compressors
14.01.2010 Fault event - FCL at Southern California Edison

Event Details/Waveforms

three seconds

Event #3 at 01/14/2010 09:56:05.216
Alarm Normal To High  
Threshold crossed: 1200
Zenergy FCL history
The First Full-Scale HTS FCL Prototype

• Built at Delta Star, Inc. in 2007
• Tested at Pacific Gas and Electric Laboratories, San Ramon, California, October 2007
• Tested at Powertech Laboratories, Surry, British Columbia, Canada December 2007
Assembling of FCL 15kV Class in 2008
First FCL 15kV Class on the US Grid: Southern California Edison 2008-2009-2010
Magnet Technology
FCL COMPACT full-scale prototypes 2008-2009
Decoupling High Voltage from Cryogenics Simplifies 138 kV Design
Validation of FCL compact design at Powertech, Vancouver in July 2009
SHORT CIRCUIT TEST RESULTS – POWERTECH July 2009

32% FAULT CURRENT REDUCTION of a 15kArms PROSPECTIVE

COMPACT FCL - 15kArms PROSPECTIVE FAULT LIMITED TO 10.7kArms - 32% REDUCTION
SHORT CIRCUIT TEST RESULTS – POWERTECH July 2009

46% FAULT CURRENT REDUCTION of a 25kArms PROSPECTIVE

25kArms PROSPECTIVE FAULT LIMITED TO 13.5kArms - 46% REDUCTION

* FCL Terminal Voltage in Blue
SHORT CIRCUIT TEST RESULTS – POWERTECH July 2009

AC to DC DECOUPLING during FAULTS

FCL, 120ADC Bias

5%, 20 cycles/330 ms

30kA Peak
### The Compact HTS FCL – An Improved Design Evolution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>FCL # 1</th>
<th>FCL # 2</th>
<th>FCL # 3</th>
<th>FCL # 4</th>
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<tbody>
<tr>
<td>Line-to-Line Voltage</td>
<td>kV</td>
<td>12.47</td>
<td>12.47</td>
<td>12.47</td>
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<tr>
<td>Number of Phases</td>
<td>#</td>
<td>3</td>
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<td>1</td>
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<tr>
<td>Line Frequency</td>
<td>Hz</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
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<tr>
<td><strong>Prospective Fault Current</strong></td>
<td>kA</td>
<td>35</td>
<td>46</td>
<td>80</td>
<td>25</td>
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<tr>
<td>Limited Peak Fault</td>
<td>kA</td>
<td>27</td>
<td>30</td>
<td>40</td>
<td>18</td>
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<tr>
<td>Prospective Fault Current RMS Symmetrical</td>
<td>kA</td>
<td>20</td>
<td>20</td>
<td>40</td>
<td>11</td>
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<td>Limited Symmetric Fault Current</td>
<td>kA</td>
<td>15</td>
<td>11.5</td>
<td>18</td>
<td>6.5</td>
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<td><strong>Load Current Steady-State RMS</strong></td>
<td>A</td>
<td>1,250</td>
<td>1,250</td>
<td>1,250</td>
<td>2,500– 4,000</td>
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<tr>
<td>Voltage Drop Steady-State Maximum</td>
<td>%</td>
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<td>1</td>
<td>1</td>
<td>2</td>
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<td>Line-to-Ground Voltage</td>
<td>kV</td>
<td>6.9</td>
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<td>8.0</td>
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<td>Asymmetry Factor</td>
<td>#</td>
<td>1.2</td>
<td>1.6</td>
<td>1.4</td>
<td>1.6</td>
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<tr>
<td>Source Fault Impedance</td>
<td>Ohms</td>
<td>0.346</td>
<td>0.346</td>
<td>0.173</td>
<td>0.724</td>
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<tr>
<td><strong>Fault Reduction</strong></td>
<td>%</td>
<td>25</td>
<td>43</td>
<td>55</td>
<td>41</td>
</tr>
</tbody>
</table>

25.06.2010

FCL summary
Current FCL Projects for MV and HV Distribution Networks
Q4 2010 – Installation at CE Electric Substation in UK

Customer: ASL
Operator: CE Electric, UK

12 kV Voltage Rating
3-Phase, 50 Hz
1.25 kA Nominal Current
17 kA_{peak} prospective fault
Reduce fault by 23% = 13.25 kA_{peak}

Recovery Under Load
AEP Tidd Substation, Ohio, USA: 138kV Feeder
American Electric Power Project: Tidd Substation, Steubenville, OH

Requirements Summary

- 138 kV
- $1300 \text{ A}_{\text{rms}}$
- $\sim 20 \text{ kA}_{\text{rms}}$ prospective fault
- Reduce fault by 50%
- Recovery Under Load required
- Fault test single phase late 2010
- Install 3-phase device late 2011
Example 110 kV distribution grid with FCL interconnection

Summary of FCL Concept

Circuit Parameters
- FCL in interconnection
- nominal voltage 110kV and load current 2,000A
- maximum prospective unlimited fault current: 80kA peak and 30kA symmetric

Preliminary FCL Design
- max. 2% voltage drop at rated current
- > 40% fault current reduction

Source: Supraleitende Strombegrenzer im 110 kV-Netz/13.05.2009, Dr.-Ing. Kathrin Steinke, Vattenfall Europe
Simulation of Fault Current Limiting by Inductive FCL 110kV
Preliminary FCL 110kV design specs

- **Electrical Specs**
  - 110 kV
  - 2,000 A\text{rms}
  - ~ 35 kA\text{rms} prospective fault
  - fault reduction by 43%
  - recovery under load

- **Dimensions**
  - 1-phase length app. 3,000mm
  - 1-phase diameter app. 1,700mm
  - 3-phase footprint LxWxH 3x6x3 meters
  - 3-phase weight app. 75,000kg

- **Auxiliaries**
  - 10” container
  - power consumption app. <150kW

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**Figure 7:** FCL Limited vs. Prospective Current for Phase A to Ground Fault
Summary: Roadmap to Commercial Product

Path to 15 kV and 36 kV class products

- Design freezed
- Commercial Offers: Products for sale from 2010

Path to 160 kV class products

- Design
  - 1-phase module A
  - HP tests in 2010
  - design review
  - 1-ph modules B+C
  - Retrofit module A
  - HP tests
  - Installation/commng.

Commercial Offers: Product for sale from 2012

Current status:
in production

ASL / CE, UK
12 kV / 1,250 A

Compact 12 kV

15 kV class

Current status:
in specification

36 kV class

160 kV class

AEP
138 kV / 1,300 A

Current status:
on SCE grid

FCL summary
25.06.2010
45
Thank you for your attention.

We keep the lights on.

Grid Protection: Inductive Fault Current Limiters
Inherently fail safe and self healing fuse for electric utilities
APPENDIX: COMPANY PROFILE
The Superconductor Energy Technology Company

June 2010
Zenergy's Core Component Strategy

Expertise in superconductive materials

- Next generation low cost wire (2G)
- In-house coiling of superconductor wire

Expertise in products and services

- Coils for Generators
  - Image Courtesy of Converteam
- Fault Current Limiter (‘FCL’)
- Magnetic Billet Heater

End market

- Low-cost large-scale Renewable Energy Generation
- Smart Grid Hardware
- Industrial Heating of Metals
Zenergy Power – World’s Only Superconductor Pure-Play

- **Zenergy Power Plc**
  - Admitted to London AIM (ZEN.L) 2006
  - Market Cap ~ £90m
  - Employees ~ 100

- **Entities incorporated**
  - Germany 1999 (MBH, wires, coils, magnets)
  - USA 2004 (fault current limiters)
  - Australia 1987 (fault current limiters)
  - UK 2005 (finance, investor relations)

- **Intellectual Property** – Over 170 patents and applications
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