Multi-scale model of rSFCLs in EMTP-RV power system transient simulator

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WHY MULTI-SCALE?
The EU-funded ECCOFLOW project targets developing a multi-purpose SFCL providing flexibility for a range of power grid applications. Nexans acts as coordinator and device partners. The ECCOFLOW design is based upon YBCO coated superconductor modules. The SFCL's power rating is 24 kV at 1 A, its design allows inrush currents of up to 4.1 kA.

Modular Design

The superconducting part of Nexans SFCLs consists of series- and parallel-connected modules for each current phase. “Stacking” these units provides the system with the specific fault current limiting capacities, which can be pre-defined in keeping with the power rating of the grid’s technical infrastructure. The system is intrinsically fail-safe and automatically returns to its passive operating state after a fault incident. Ageing permits internal MV supply switchgear to be downsized to standard component level and thus affords a substantially lower investment requirement.

Towards a Standard Solution:

“Stacking” these units provides the system with the specific fault current limiting capacities, which can be pre-defined in keeping with the power rating of the grid’s technical infrastructure. The system is intrinsically fail-safe and automatically returns to its passive operating state after a fault incident. Ageing permits internal MV supply switchgear to be downsized to standard component level and thus affords a substantially lower investment requirement.

Materials and basic wires

Assemblies (e.g. coils)

Devices

Systems

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© Nexans

© Nexans

© Nexans

µm to km length scales!

World-Class Engineering


3
Critical phenomena must be taken into account → Here: hot spots!

FEM is convenient, but not ideal to couple with system equations


The EU-funded ECCOFLOW project targets developing a multi-purpose SFCL providing flexibility for a range of power grid applications. Nexans acts as coordinator and device manufacturer in the ECCOFLOW consortium which involves five European power utilities and eight scientific and industrial partners. The ECCOFLOW design is based upon YBCO coated superconductor modules.

Combined with inductive or resistive shunts, the SFCL limits conductor modules. The SFCL's power rating is 24 kV at 1 A, its design allows inrush currents of up to 4.1 kA. Essentially, SFCL deployment permits internal MV supply switchgear to be downsized to standard component level and thus affords a substantially lower investment requirement. This permits internal MV supply switchgear to be downsized to standard component level and thus affords a substantially lower investment requirement.

In 2009, a Nexans SFCL based upon BSCCO-2212 bulk superconductor modules was deployed at the power plant for Boxberg Power Plant (I), (Vattenfall, D). In 2011, a Nexans SFCL based upon YBCO coated conductor modules replaced the first device and was commissioned after successful testing. The YBCO based SFCL combines further improved energy efficiency with a faster response to fault currents and stronger initial limitation: 63 kA peak short-circuit protection of house load including lignite crushers. Protective testings were successfully completed.

With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds. With a nominal current rating of 800 A, its design allows inrush currents of up to 4.1 kA immediately and to about 7 kA after 10 milliseconds.

Local temperature elevation in SFCL vs. fault impedance

Simulink model

Mixture of micro and macro

1) Co-simulation (horizontal)
   - Requires an interface between device and system simulators
   - Exchange of data between two commercial codes is difficult
   - Inclusion of more than 2 length scales hardly possible

2) System equations in device simulators (bottom-up)
   - Challenging because of heterogeneity/complexity of system equations
   - Few commercial codes offer this flexibility

3) Device equations in system simulators (top-down)
   - Challenge: write a device simulator within a system simulator
   - Option available in many commercial codes (dynamic-link lib.)
   - If well done, no limit on level of detail: true multi-scale!
MULTI-SCALE MODEL: OPTIONS

- Tool selected: EMTP-RV

- Features:

  - Power system transient simulator for large-scale systems
  - Nearly 50 years of model and code developments behind it
  - Typical types of problems investigated:
    - Insulation coordination
    - Switching surges
    - Ferroresonance
    - HVDC
    - Protection
    - Shaft torsional stress
    - Synchronous machines
    - Power electronics and FACTS
    - Wind generation
    - Lightning surges
    - Network analysis
    - Series compensation
    - Switchgear
    - Short-circuits & fault currents

Major users in industry / rich library / open env.
EMTP-RV: EXAMPLES OF APPLICATIONS

- Switching transients on transmission lines
EMTP-RV: EXAMPLES OF APPLICATIONS

- Insulation coordination upon lightning strikes

**Insulation Coordination of a 765 kV GIS**
- Backflashover Case
- Impulse Footing Resistance of the strucken Tower may be represented by $R_i = f(l)$
- Usage of ZnO model based on IEEE SPD WG
- Frequency-Dependant Line modeling

200 kA 3/100 us Lightning Stroke

Network ↔ 765 kV Line ↔ Air-Insulated Substation

30 km 300 m 300 m

To eliminate undesirable reflexions

CVT 588 kV Zno Gas-filled Bushing

**EMTP-RV**
The reference for power systems transients

EMTP-RV: EXAMPLES OF APPLICATIONS

- Power electronics for voltage regulation
GENERAL CONSIDERATIONS

- EMTP-RV: not the only choice, but a good one for us since:
  - Used by many major utilities and device manufacturers
    - Good vector to promote superconducting device models
  - Optimized to solve large-scale networks (more than 100,000 components!)
  - Rich device libraries
    - Cables, transformers, machines, control devices, etc.
    - Many types of nonlinear elements
  - Relatively “open environment” that allows creation/addition of new library elements by
    - assembling existing elements;
    - writing user codes (dynamical-linked library - DLL)

- Main development realized in Polytechnique Montreal (!)
THE MODEL

- Electro-thermal model of an HTS tapes
  - including all interfacial effects, symmetries, etc.
  - inductive effects neglected (OK in rSFLCs)

\[ \nabla \cdot \left( \sigma(T, \nabla V) \nabla V \right) = 0 \]

\[ \rho_m C_p(T) \frac{\partial T}{\partial t} = \nabla \cdot (\kappa(T) \nabla T) + Q_J \]

Coupling variables:

- $T = \text{Temperature}$
- $Q_J = \text{Electrical losses} \left( \vec{E} \cdot \vec{J} \right)$

Boundary conditions and constraints
THE MODEL

- Discretization approach: **old good resistor network**
  - Directly compatible with a circuit simulator
  - Dimensionality easy to adjust

*In appearance, similar to the finite difference method*

*In fact: closer to a finite volume method (laws of conservation)*
THE MODEL

- Our building block in EMTP-RV
  - Basic 3-D (or less) electro-thermal element
  - All resistors and capacitors are nonlinear (!)

Electrical model

\[ R_{el} = f(I, T) \]

Electrical analogy of thermal model

\[ R_{th} = f(T) \]
\[ C_{th} = f(T) \]
\[ R_c = f(T_s - T_0) \]
THE MODEL

Electrical model

\[ R_{el} \]

Thermal model

\[ Q_J(t) \]

\[ T(t) \]

\[ R_{th} \]

\[ C_{th} \]

\[ Q_c \]

\[ 2\Delta z \]

\[ 2\Delta y \]

\[ 2\Delta x \]

Interfacial resistance

Buffer layers

Hastelloy substrate

Silver layers

(RE)BCO
THE MODEL

Basic electro-thermal element

Electrical model
Electrical analogy of thermal model

\[ Q(t) = \frac{1}{2} I(t)^2 R_{el} \]

\[ T(t) = \frac{1}{C_{th}} \int Q(t) dt \]

Basic electro-thermal element (cf Fig. 2)

Equivalent circuit of rSFCL

1/4th of the tape (cf Fig. 6)

Hastelloy (RE)BCO resistance
Silver substrate
Interfacial layers
Buffer layers
Interfacial resistance
Hastelloy substrate
Silver layers
THE MODEL

Basic electro-thermal element

Connection of big blocks with small blocks:

Kirchhoff laws do all the work!
Connection of elements of different lengths:

For instance: one element of 100 m with elements of 50 microns
THE MODEL

- Periodic conditions & symmetry planes handled through controlled voltage and current sources
  - Saves a huge amount of computation time

In this example:
only 25% of original model is simulated
THE MODEL

- Implementation of interfacial effects

"0.5-D component"  
Electrical/thermal resistance  
Electrical/thermal insulation
THE MODEL

- Implementation of nonlinear resistances in EMTP-RV

\[ I_n = I_p + g(V_n - V_p) \]

\[ I_0 = I_p - gV_p \]

\[ I_n = I_0 + gV_n \]

Newton method

EMTP-RV element: Nonlinear admittance (Y)

Y=1/R
THE MODEL

- Implementation of nonlinear resistances in EMTP-RV

\[ I_n = G V_n \]

\[ G = I / V \]

Fixed-point method

EMTP-RV element: Nonlinear admittance (Y)

\[ Y = 1 / R \]
The Model

- Temperature dependant elements: fixed point-method and use of control blocks
THE MODEL

- Our building block in EMTP-RV
  - Basic 3-D (or less) electro-thermal element

\[ L = \Delta x \]
\[ S = (2\Delta y)(2\Delta z) \]

Electrical model

Electrical analogy of thermal model

\[ T(t) \]
\[ Q_J(t) \]
\[ Q_c \]
THE MODEL

- Temperature dependant elements: fixed point-method and use of control blocks

\[ S = (2\Delta y)(2\Delta z) \]
**THE MODEL**

- Temperature dependent elements: fixed point method and use of control blocks

\[ T \Rightarrow f(T) \]

\[ S = (2\Delta y)(2\Delta z) \]

\[ L = \Delta x \]

\[ \rho(T) = f(T) \]
- Temperature dependant elements: fixed point method and use of **control blocks**

\[ \Delta x \]
\[ L = \Delta x \]
\[ R_x(T) = \rho(T) \frac{L}{S} \]

\[ S = (2\Delta y)(2\Delta z) \]

\[ \rho(T) = f(T) \]
THE MODEL

- Temperature dependant elements: fixed point method and use of **control blocks**

\[ R_x(T) = \rho(T) \frac{L}{S} \]

\[ G = 1/R = Y \]

\[ \Delta x \]

\[ L = \Delta x \]

\[ \Delta y \]

\[ S = (2\Delta y)(2\Delta z) \]

\[ \rho(T) = f(T) \]
THE MODEL

- Temperature dependant elements: fixed point method and use of control blocks

\[
\begin{align*}
R_x(T) &= \rho(T) L/S \\
\rho(T) &= f(T)
\end{align*}
\]

\[
S = (2\Delta y) (\frac{1}{R})
\]

\[
Y = \frac{1}{R}
\]
THE MODEL

- Superconductor elements
  - Control block approach proved to be very unstable
  - Reason:
    - Control blocks introduce a delay of 1 time step
    - with high nonlinearity, very small time steps (ns range!) might be required to converge
- Alternative approach:
  - Integrate a user-code in the form of a DLL file (Dynamic-Link Library)
  - The code has to be written in Fortran or C++
  - Pre-compiled once, then materials parameters can be changed from the GUI of EMTP-RV
THE MODEL

- **Superconductor model**

\[
\rho_{PL}(J, T) = \frac{E_c}{J_c(T)} \left( \frac{|J|}{J_c(T)} \right)^{n-1}
\]

\[
J_c(T) = J_{c0} \left( \frac{T_c - T}{T_c - T_0} \right)
\]

\[
\rho_N(T) = \rho_{Tc} + \alpha (T - T_c)
\]

\[
\rho_{SC}(J, T) = \frac{\rho_{PL}(J, T) \times \rho_N(T)}{\rho_{PL}(J, T) + \rho_N(T)}
\]

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<th>Description</th>
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<td>1 (\mu V/cm)</td>
<td>Critical electric field criterion</td>
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<td>(J_{c0})</td>
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<td>Self-field critical current density</td>
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<td>(n)</td>
<td>15</td>
<td>Power law exponent</td>
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<td>(\rho_{Tc})</td>
<td>30 (\mu \Omega.cm) (^\dagger)</td>
<td>Normal state resistance at (T_c)</td>
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<td>(\alpha)</td>
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<td>Temperature coefficient</td>
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<td>(T_c)</td>
<td>90 K</td>
<td>Critical temperature</td>
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<tr>
<td>(T_0)</td>
<td>77 K</td>
<td>Temperature of LN(_2) bath</td>
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\(^\dagger\) Deduced from Friedmann *et al.* [23] by averaging the normal state resistivity along the \(a\) and \(b\) crystallographic axes.

\[
R_{SC}(I, T) = \rho_{SC}(J, T)L/S
\]
**THE MODEL**

- **Superconductor model**

\[
\rho_{PL}(J, T) = \frac{E_c}{J_c(T)} \left( \frac{|J|}{J_c(T)} \right)
\]

\[
\rho_N(T) = \rho_{Tc} + \alpha (T - T_c)
\]

\[
\rho_{SC}(J, T) = \frac{\rho_{PL}(J, T) \times \rho_N(T)}{\rho_{PL}(J, T) + \rho_N(T)}
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\[R_{SC}(I, T) = \rho(J, T) I / S\]

\[\rho = \rho_{SC}(J, T)\]


World-Class Engineering
THE MODEL

- Our building block in EMTP-RV
  - Basic 3-D (or less) electro-thermal element
  - All resistors and capacitors are nonlinear (!)

Control blocks or DLL

Electrical model

Electrical analogy of thermal model

$$R_{el} = f(I, T)$$
$$R_{th} = f(T)$$
$$C_{th} = f(T)$$

$$R_c = f(T_s - T_0)$$

$$Q_c$$

$$Q_J(t)$$

$$T(t)$$

$$x$$

$$y$$

$$z$$

$$2\Delta y$$

$$2\Delta z$$

$$2\Delta x$$
THE MODEL

- Nonlinear thermal capacitors
  - Temperature dependence of specific heat is VERY important in rSFCLs
  - In the electric analogy, $C_{th}(T) = C(V)$
  - But there is no nonlinear capacitor in most circuit simulators! (especially in power system simulators)
- Solution:
  - Another DLL code!
  - Main features:
    - Trapezoidal integration
    - Look up table for $C(V)$
    - Table read from a file (no need to recompile to change material properties)
### THE MODEL

- Nonlinear convection cooling
  - Critical aspect for assessing thermal stability of rSFCLs
  - Modelled with control blocks as described above
  - For instance:

\[
R_c = \frac{1}{h(T-T_0)S}
\]

THE MODEL

- Our building block in EMTP-RV
  - Basic 3-D (or less) electro-thermal element
THE MODEL

- Our building block in EMTP-RV

- Unused blocks can be disabled (reduction of dimensionality)

\[ Q_J = 6 \times R_{el} \]

\[ C_{th} = 6 \times R_{th} \]
THE MODEL

- Our building block in EMTP-RV
THE MODEL

Basic electro-thermal element

Equivalent circuit of rSFCL (cf Fig. 6)

Length

Width

I/2

V/2

I/2
THE MODEL

Equivalent circuit of rSFCL (cf Fig. 6)

Final rSFCL block!
APPLICATION EXAMPLES

- rSFCL in simple radial power system

**Schematic:**

**EMTP-RV model:**
VERIFICATION OF MODEL

- Heavily compared against finite element method
  - Fault current limitation → Macroscopic effect

![Graph comparing EMTP-RV, COMSOL, and EMTP-RV (homogenized) current values over time.](image)
VERIFICATION OF MODEL

- Heavily compared against finite element method
  - NZPV calculations → Microscopic effect

![Graphs showing temperature vs. time for COMSOL and EMTP-RV simulations.](image)

- Hot spot & normal zone propagation

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<th>Temperature (K)</th>
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<tr>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
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<td>110</td>
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<td>20</td>
<td>120</td>
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<tr>
<td>25</td>
<td>130</td>
</tr>
<tr>
<td>30</td>
<td>140</td>
</tr>
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![Graphs showing temperature vs. time for COMSOL and EMTP-RV simulations.](image)
VERIFICATION OF MODEL

- Heavily compared against finite element method
  - Impact of interfacial resistance on NZPV \rightarrow Microscopic effect

```
\begin{align*}
\text{Interfacial resistance} (\mu\Omega \cdot \text{cm}^2) & \quad \text{NZPV (cm/s)} \\
\text{EMTP-RV} & \quad \text{COMSOL}
\end{align*}
```

[Graph showing comparison of NZPV with EMTP-RV and COMSOL against interfacial resistance]
VERIFICATION OF MODEL

- Required discretization
  - Highly function of your needs!
  - Example below for NZPV calculations:

![Graph showing NZPV calculations](image)

EMTP-RV vs COMSOL for NZPV calculations.

\[ L_{\text{fine}} = 5 \text{ mm} \]
Validation of the popular “homogenized model” of an rSFCL

In low over-current regimes, the homogenized model can induce a very important delay in triggering the limitation (not a hot spot issue!)

\[ I_{\text{peak}} = 1.6I_c \]

With heat diffusion

Homogenized

\[ \approx D \]

160 ms!
APPLICATION EXAMPLES

- More involved: rSFCL & transformer energization

**EMTP-RV model:**

![EMTP-RV model diagram](image-url)

APPLICATION EXAMPLES

- More involved case: rSFCL impact on common power system transients

*Peak due to energization* vs *Peak due to fault*

- **Prospective**
- **SFCL**
- **Limited**
- **Shunt**

Current (A) vs Time (ms)
More involved case: rSFCL impact on common power system transients

Peak due to energization

Impact of stabilizer thickness

Voltage across hot spot (V)

Time (ms)

Current (A)

-2,000  -1,500  -1,000  -500   0   500   1,000   1,500   2,000   2,500

-0.2  -0.1   0.0   0.1   0.2   0.3

2 µm silver stabilizer
3 µm silver stabilizer
4 µm silver stabilizer
5 µm silver stabilizer

Prospective
SFCL
Limited
Shunt
More involved case: rSFCL impact on common power system transients

- On-load recovery after transient over-current
- Min and max temperature along tape
- Etc.
PERSPECTIVES

- Multi-scale models + professional power system transient simulator opens a world of possibilities
  - Optimization of tape architecture under realistic network operating conditions
    - Various type of stabilizers
    - Tapes with accelerated NZPVs
    - $I_c$ inhomogeneities
    - etc.
  - Robustness of rSFCLs under various transients
  - Investigation of the impact of rSFCLs in AC and DC power systems with realistic device behaviour
  - etc.
POSSIBLE IMPROVEMENTS

- Model still heavy in terms of number of components
  - many control blocks and nonlinear devices

- Would be desirable to integrate more components into the DLL file

- An hierarchy of models of increasing complexity would help to enable optimal multi-scale modelling
CONCLUSIONS

- A true multi-scale model of rSFCLs have been developed in the EMTP-RV software

- The model has been heavily verified against FEM
  - Proper discretization remains a delicate issue

- Multi-scale models are of interest for both
  - Manufacturers (and researchers)
  - Power system engineers

- Implementation in a major commercial code bridges a gap between these two worlds
  - A public version should be released within a few months