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Design and Modelling of Superconducting FCL

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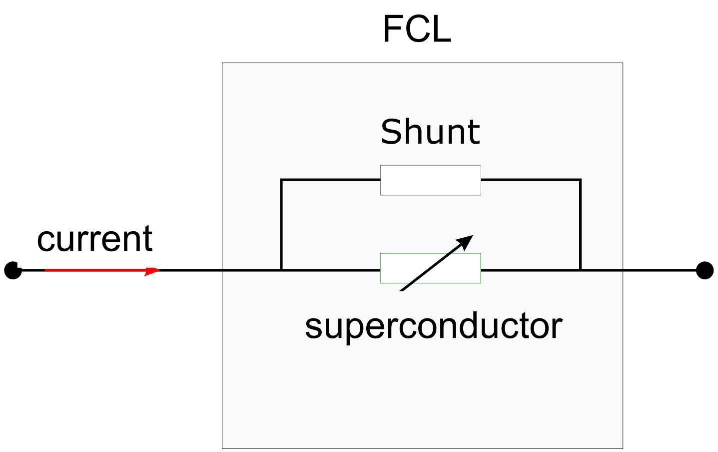
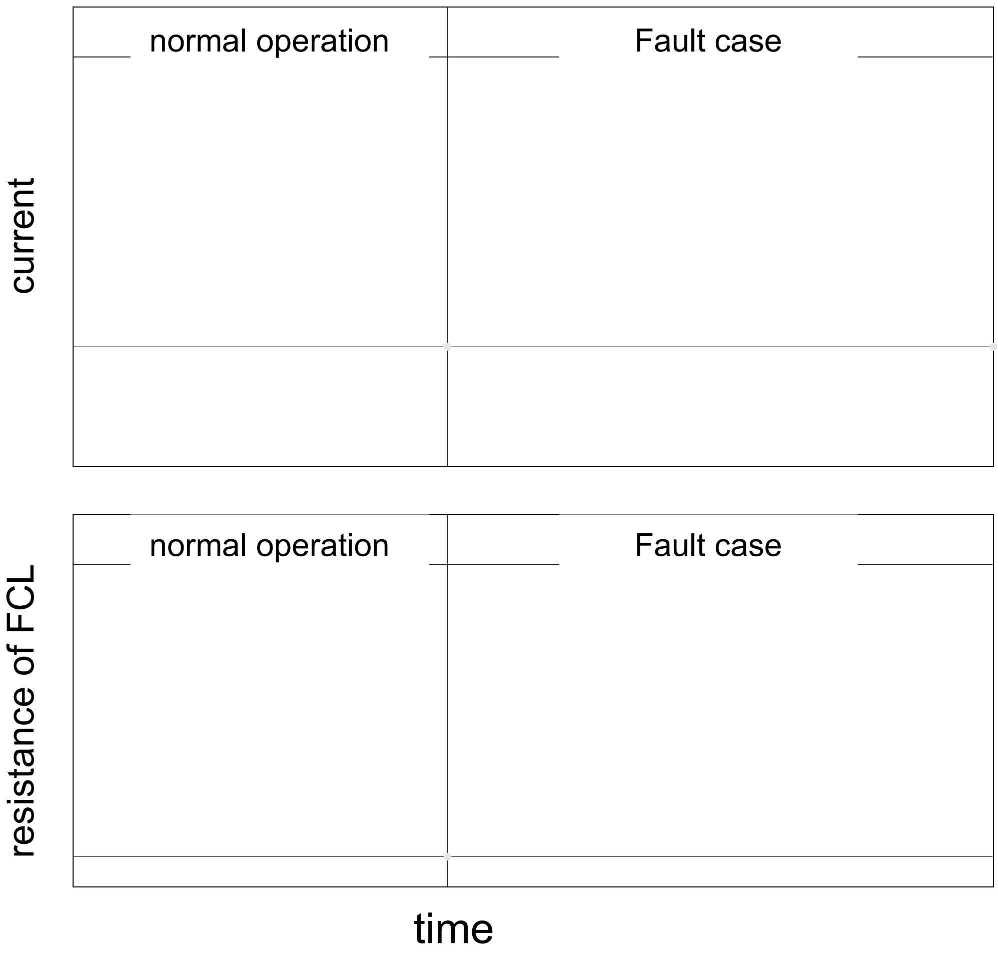
Simulation of superconducting fault current limiter

- The integration of a superconducting fault current limiter (FCL) in power systems appears as a powerful solution against increasing short-circuit currents levels that endanger the safety of electrical equipment
- Simulation methods are part of the development of all new electrical equipment
- Standard network analysis software does not include suitable models for FCLs
  - DigiSILENT PowerFactory, MATLAB Simulink, EMTP-ATP, PSCAD, ANAREDE, etc…

Basic concept of superconducting fault current limiter

- Superconducting fault current limiter are a safety measure that can quickly and efficiently reduce the fault current in an electrical power supply





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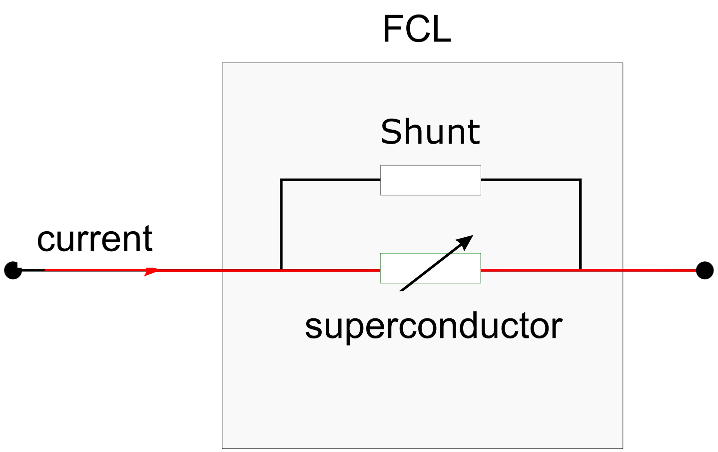

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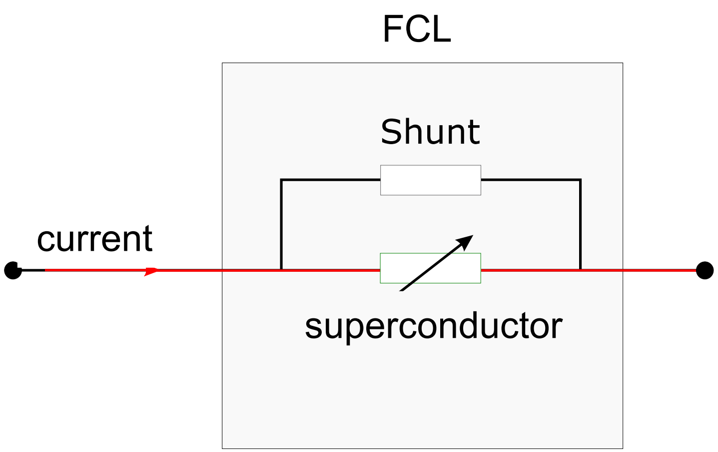

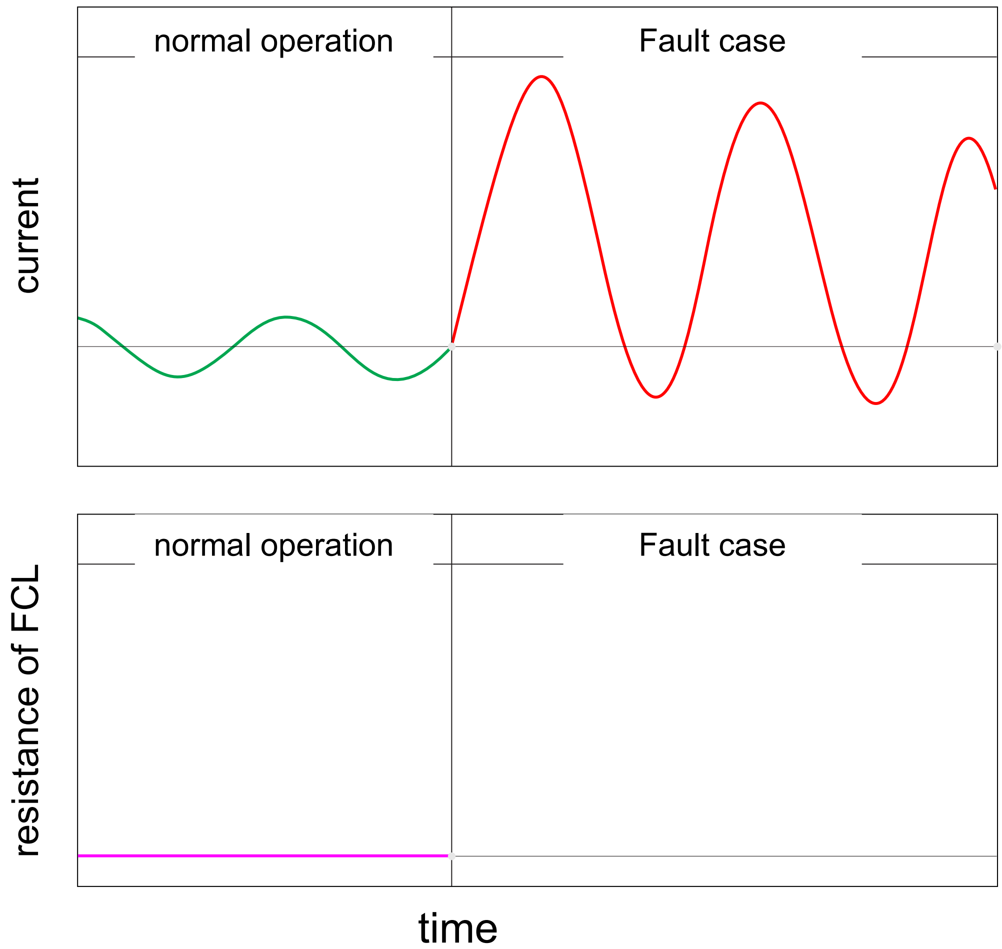

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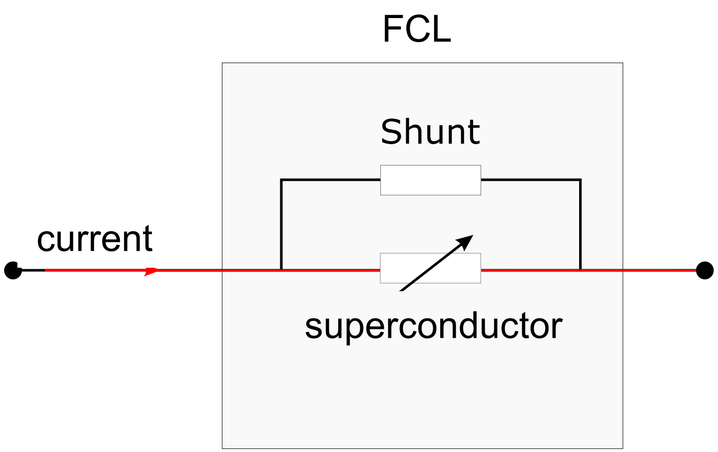

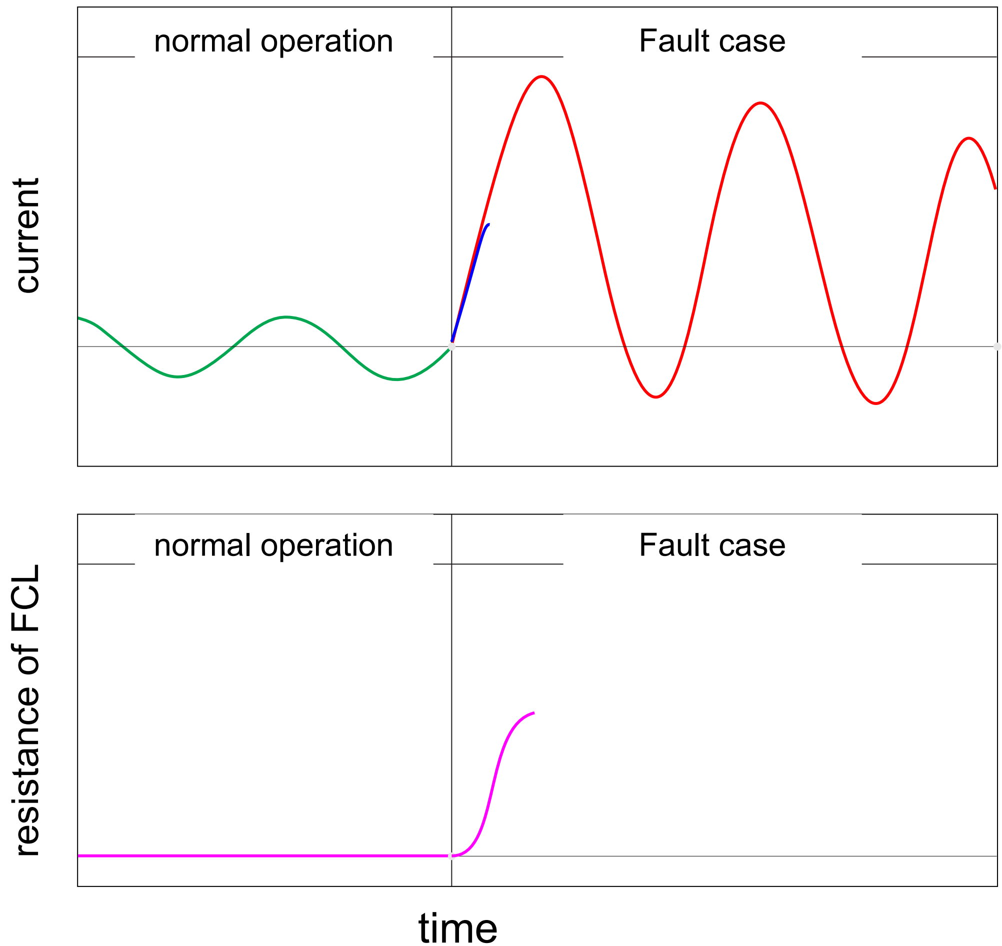

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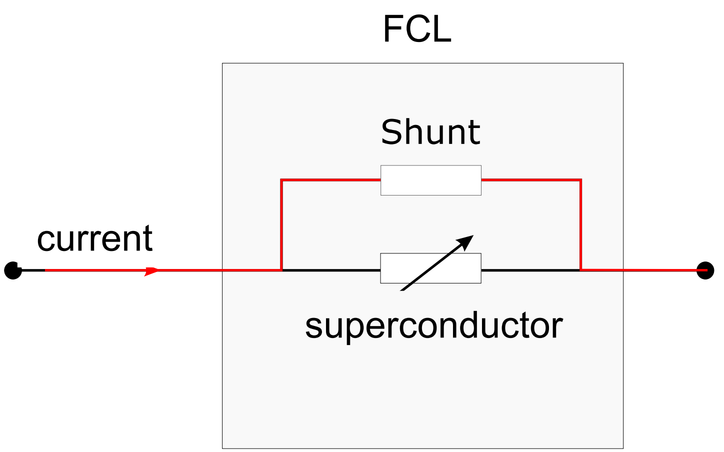
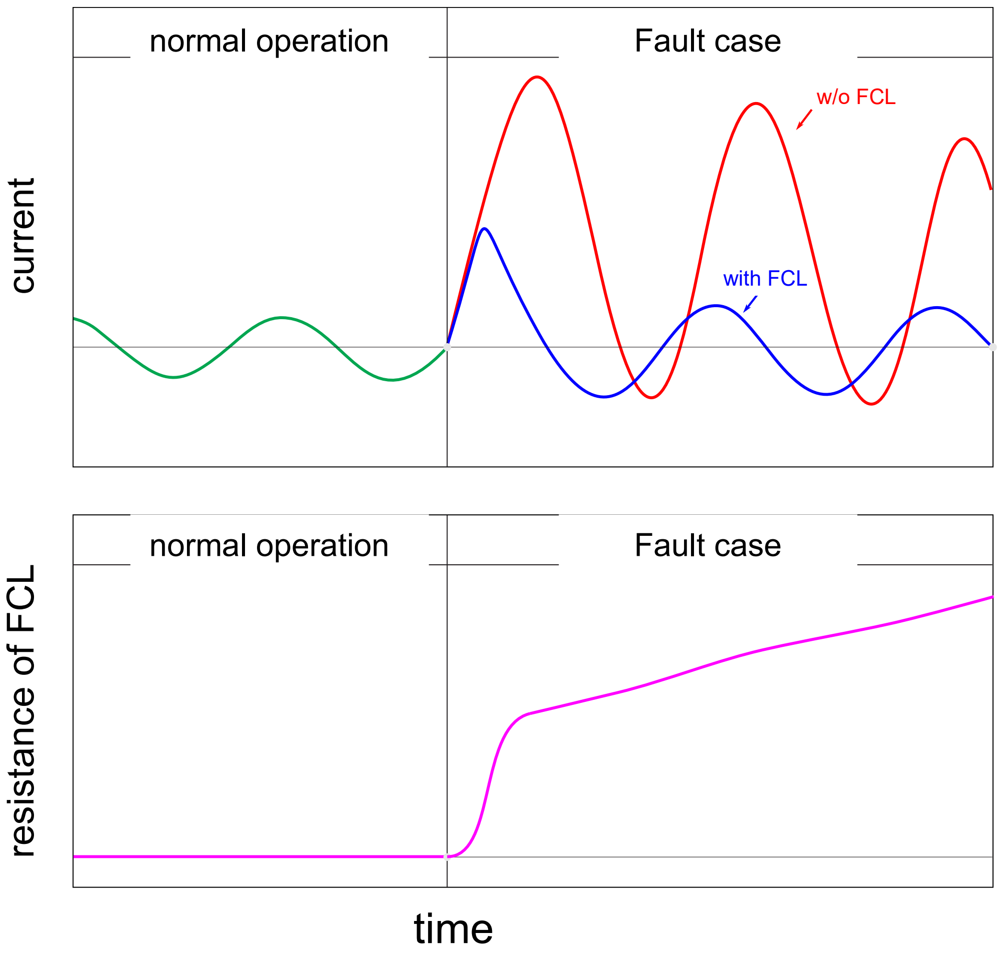




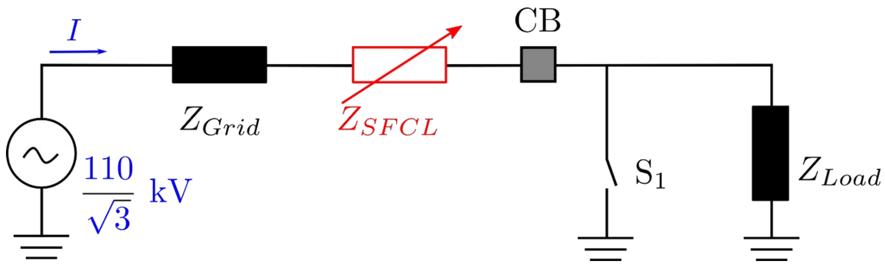
Basic Designing Concepts

- Voltage Drop along the SFCL during fault period:

$$U_{SFCL} = \frac{U_N}{\sqrt{3}} - I_F \cdot Z_{Grid}$$

- Total lenght of one single HTS tape:

$$\ell_{tape} = \frac{U_{SFCL}}{E_{hts}}$$



- Total lenght of tapes in the SFCL (per phase):

$$\ell_{Tot} = \ell_{tape} \cdot n_p$$

$$n_p = \frac{\sqrt{2} \cdot I_N}{k \cdot I_c}$$

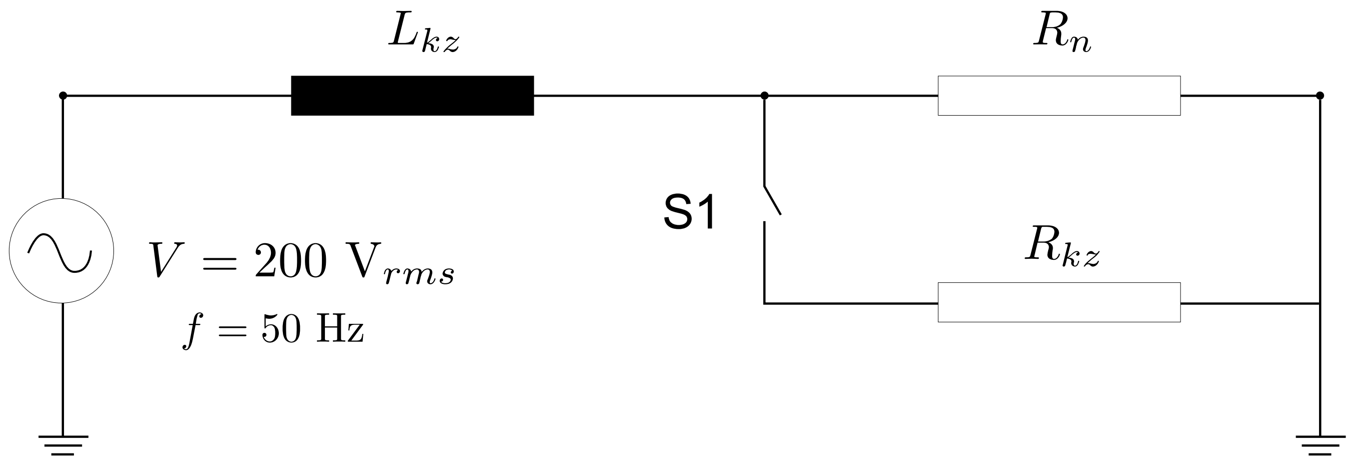
$$E_{hts} = 0.2 \ldots 0.5\ \mathrm{V/cm}$$

$$k = 0.9 \ldots 1.0$$

- T_{MAX} = 360 K

Determination of the network parameters

- The first step is to set the network parameters. For example, take the following electrical circuit



- Without current limiter

$$L_{kz}\frac{di}{dt} = V - R_{kz}i$$

State Equation

$$R_n = 2.0\ \Omega$$

$$I_n = 100\ A_{rms}$$

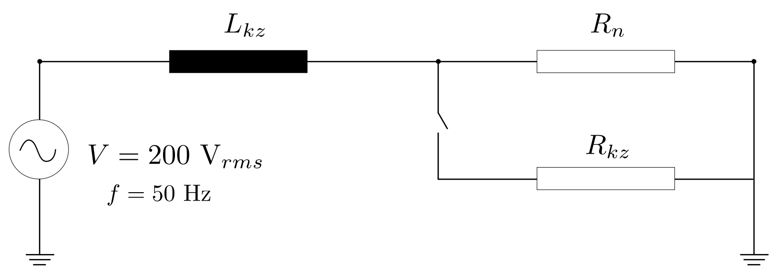
$$L_{kz} = 0.02\ mH$$

$$R_{kz} = 0.6\ m\Omega$$

$$R_n = 2.0\ \Omega$$

$$I_{kz} = 40\ kA_{rms}$$

Runge-Kutta method



$$L_{kz}\frac{di}{dt} = V - R_{kz}i$$

- The Runge-Kutta method is a explicit iterative method to solve initial value problems (ordinary differential equation) numerically.

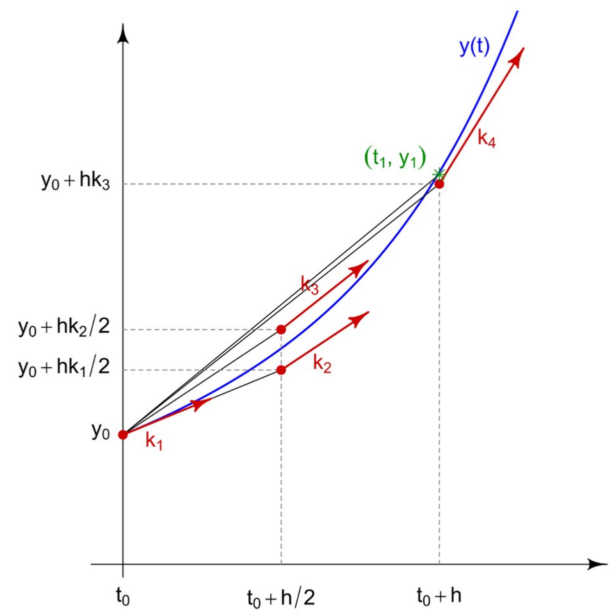
$$k_1 = \frac{1}{L_{kz}}A\sin(\omega t) - R_{kz}i_o$$

$$k_2 = \frac{1}{L_{kz}}A\sin\left[\omega\left(t+\frac{h}{2}\right)\right] - R_{kz}\left[i_o + k_1\frac{h}{2}\right]$$

$$k_3 = \frac{1}{L_{kz}}A\sin\left[\omega\left(t+\frac{h}{2}\right)\right] - R_{kz}\left[i_o + k_2\frac{h}{2}\right]$$

$$k_4 = \frac{1}{L_{kz}}A\sin\left[\omega\left(t+h\right)\right] - R_{kz}\left[i_o + k_3 h\right]$$

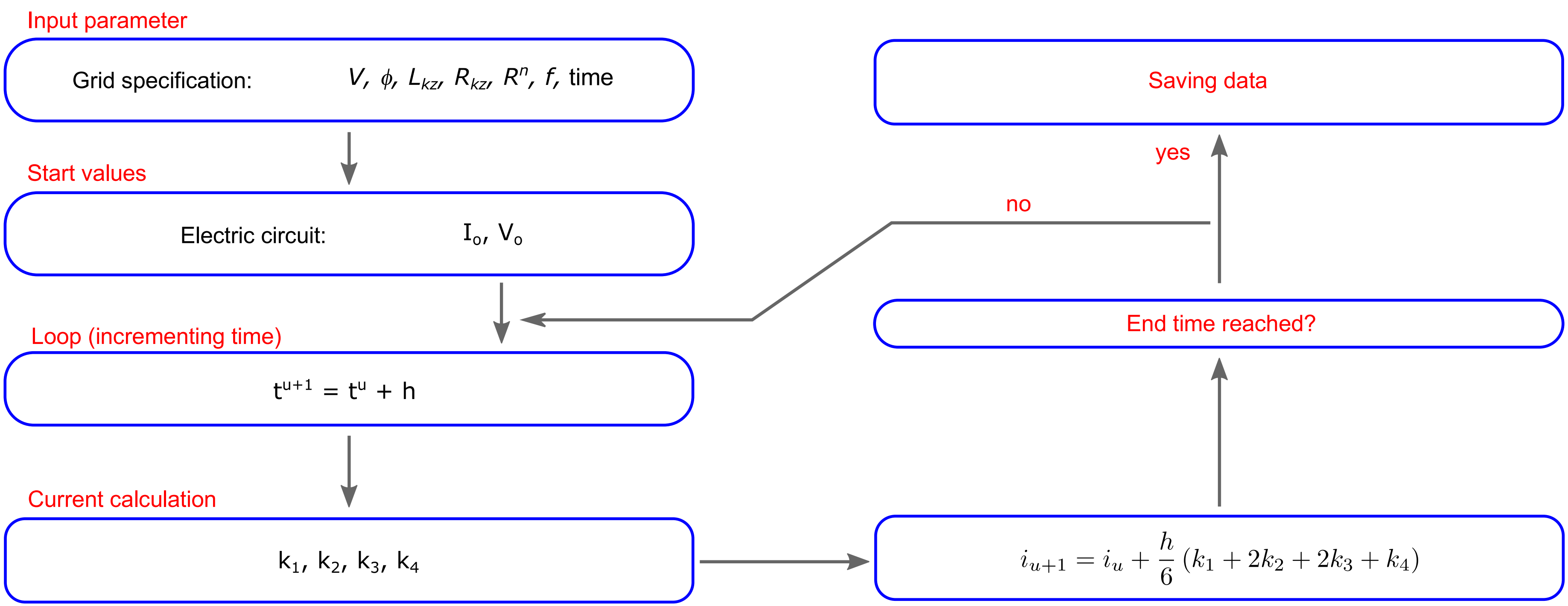
$$i_{u+1} = i_u + \frac{h}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right)$$



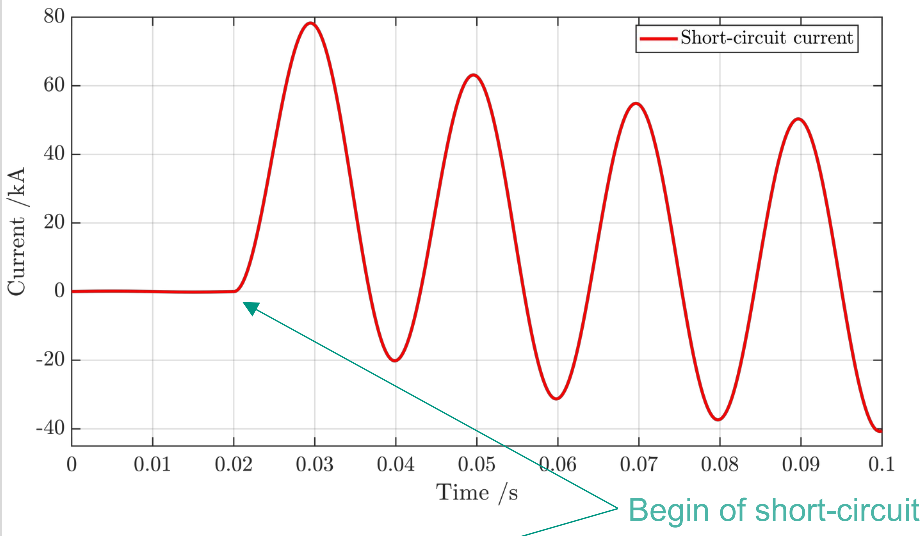
Picture: Wikipedia

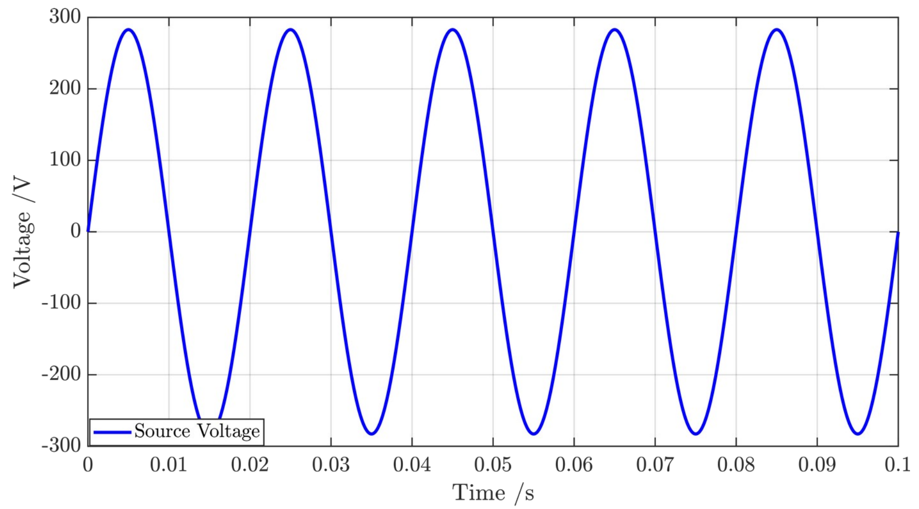
Simulation sequence – short-circuit current

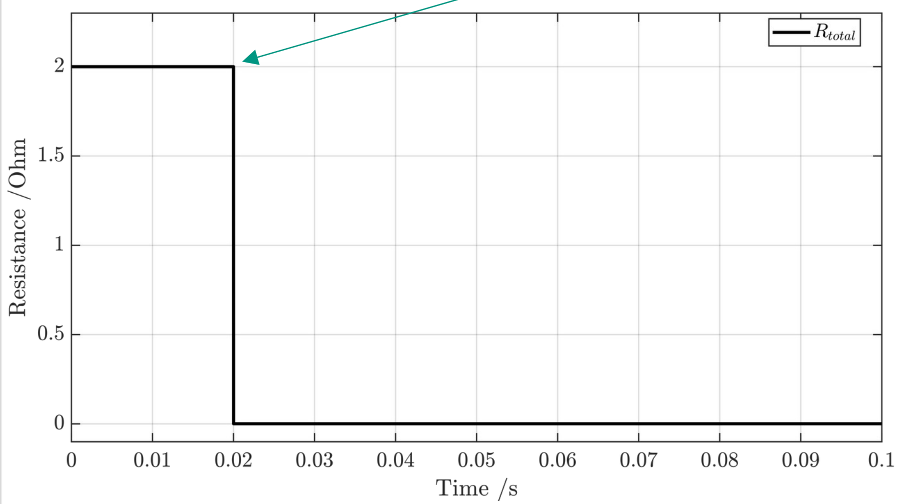
- Flowchart for the simulation of the transient behaviour of short-circuit current

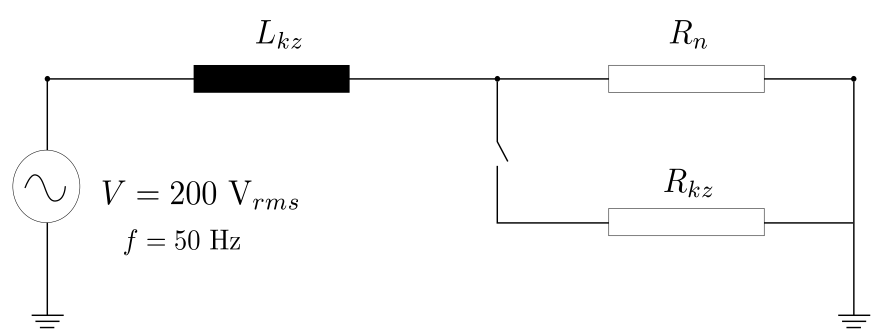


Results – Short-circuit current – Example 01



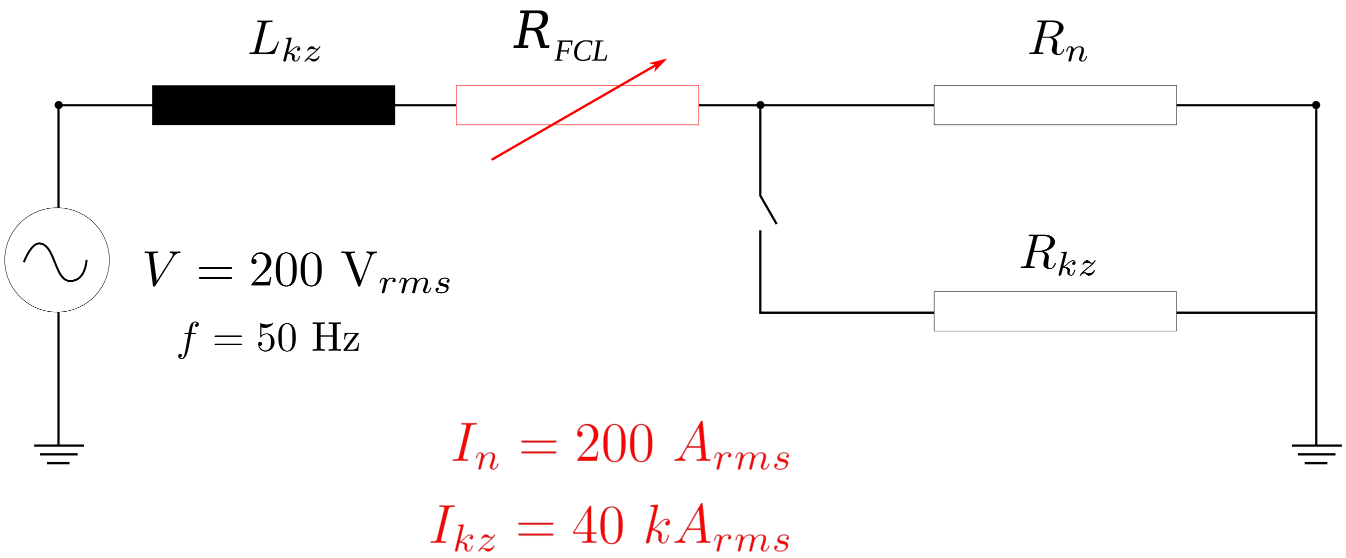






Determination of network parameter

- Simulation of the network with FCL (temperature dependent)



- With fault current limiter

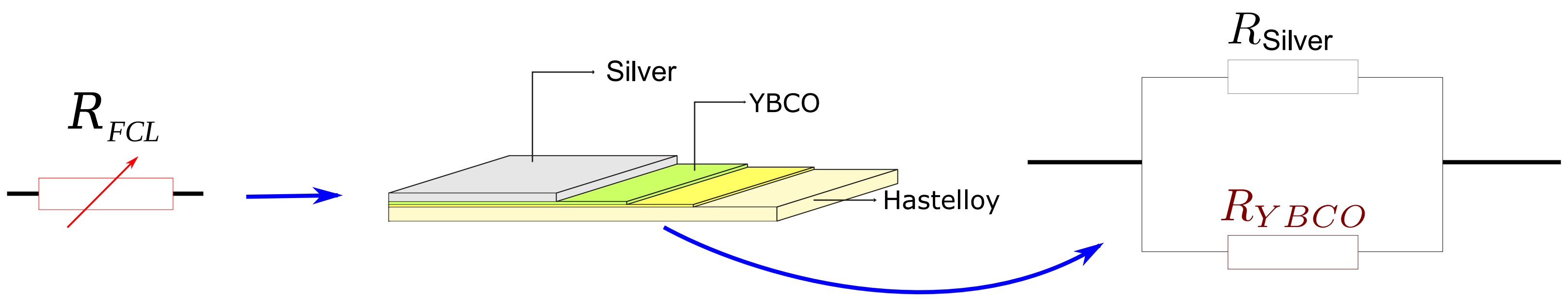
$$L_{kz}\frac{di}{dt} = V - [R_{kz} + R_{FCL}(T)]i$$

- In this model, the resistance of the FCL no longer depends on time, but on the temperature of the materials involved.

Electrical and thermal model

- **Electrical Model**

$$\frac{1}{R_{FCL}} = \frac{1}{R_{YBCO}} + \frac{1}{R_{\text{Silver}}}$$



- **Thermal Model**

$$C_v \frac{\partial T}{\partial t} = R_{FCL} \; i^2$$

Euler-method

$$T_{(u+1)} = T_{(u)} + h \left[\frac{R_{FCL} \; i^2_{(u)}}{C_v} \right]$$

$$C_v = C_{\text{Silver}} + C_{Hastelloy} + C_{YBCO}$$

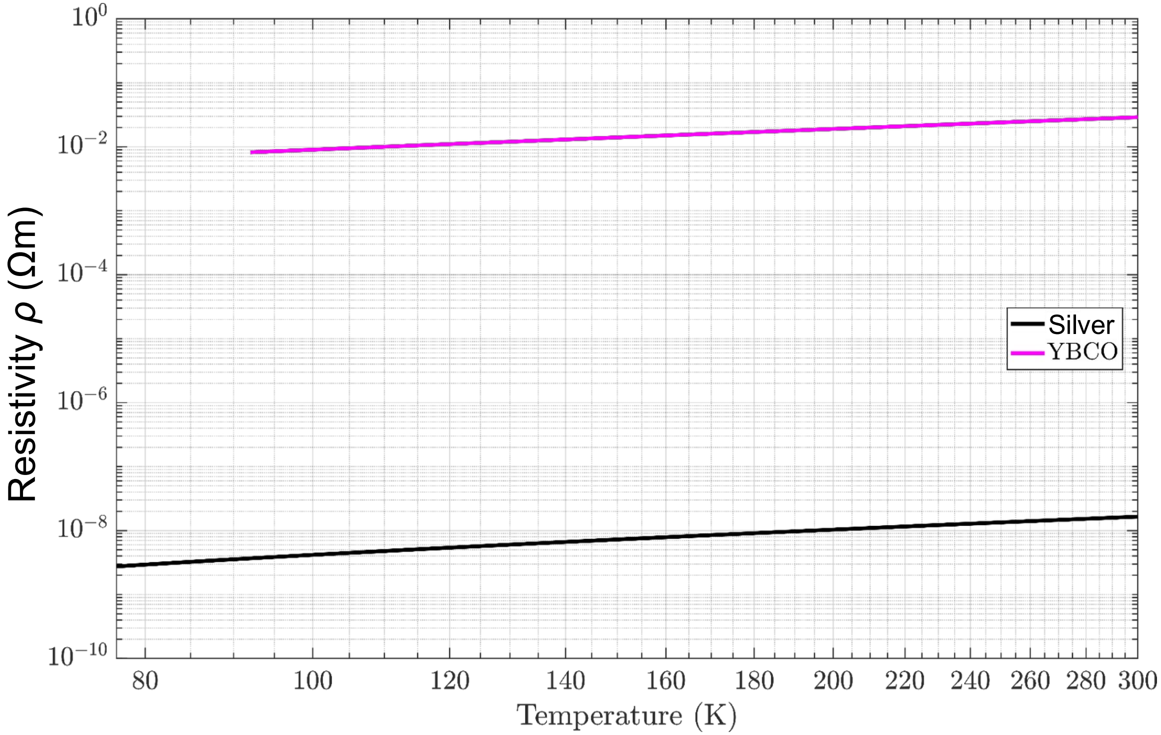
Temperature dependance of specific resistance

- Resistivity ρ of Silver and YBCO over T_c:

$$\rho = mT + z$$

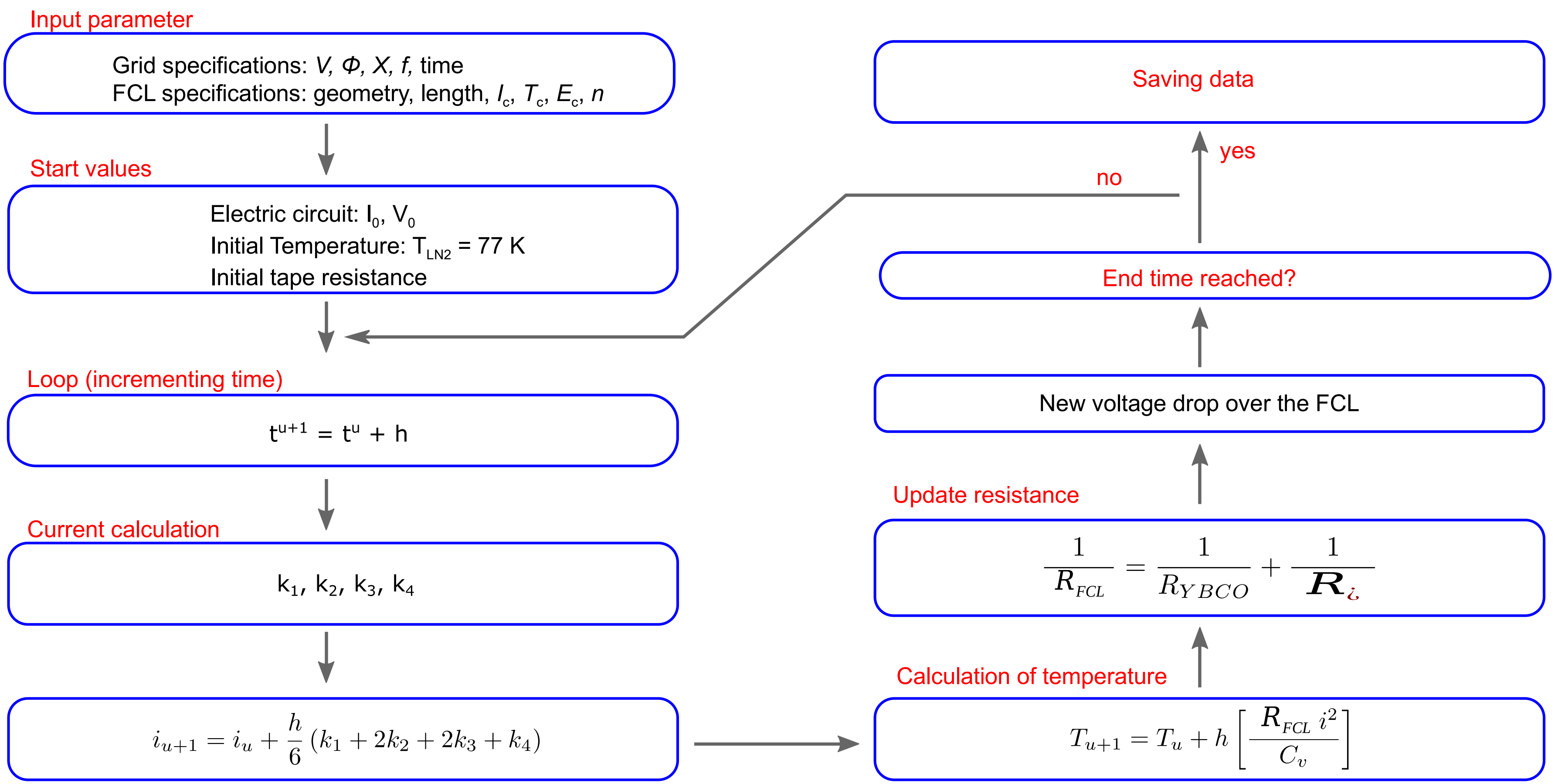
- Below T_c:

$$\rho_{YBCO} = \rho(T_c)\left[\frac{T}{T_c}\right]^n$$



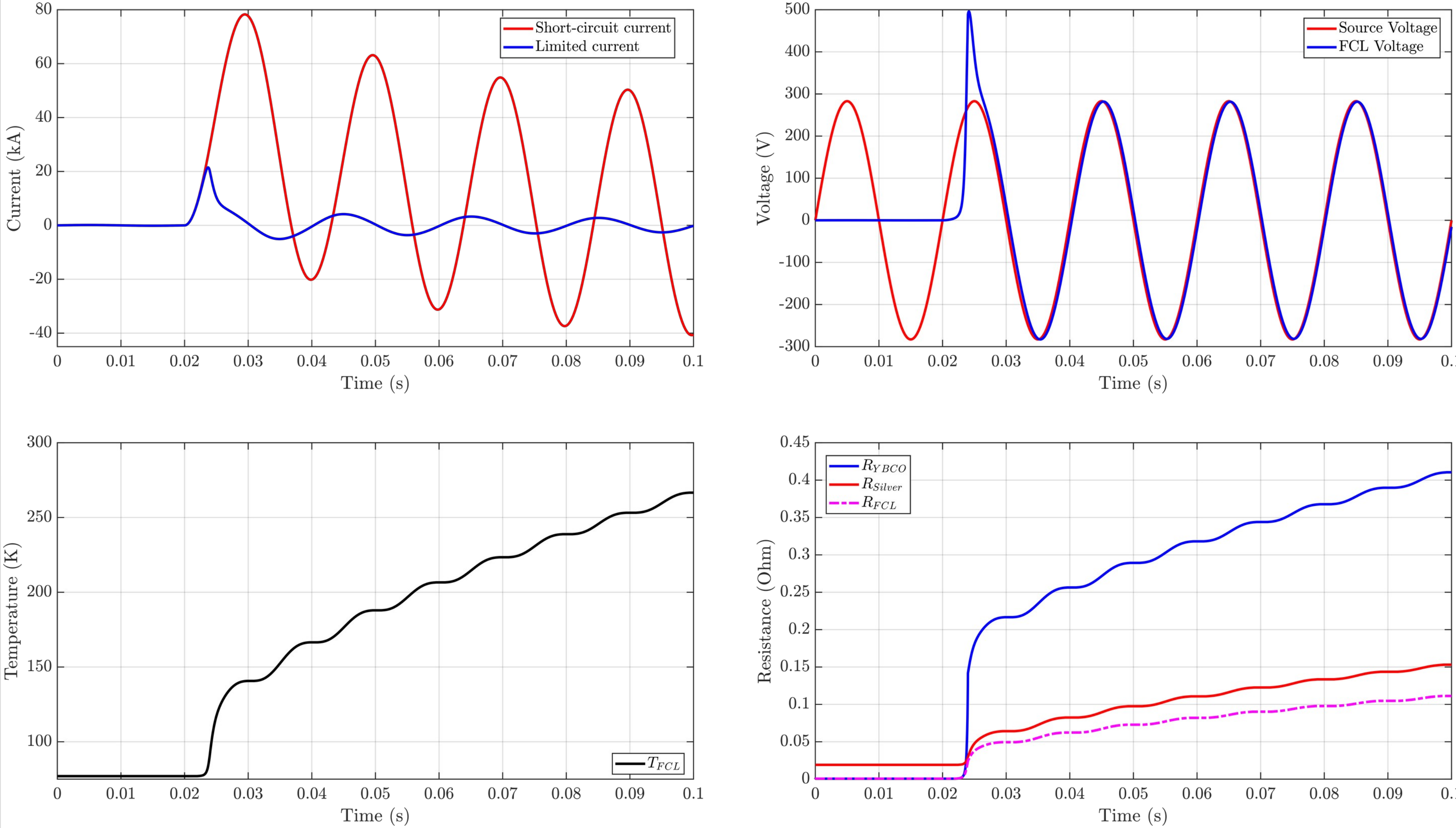
Simulation Sequence - FCL

- Flowchart for the simulation of the limiting behavior of a temperature-dependent FCL.



Result – FCL temperature dependent transient behavior

Karlsruhe Institute of Technology



Your Task

- **Design a SFCL**
  - 10 kV
  - 2 kA (Nominal Current)
  - Fault Current = 40 kA_{rms} (X/R = 10)
    - Determine number of HTS tapes
    - Find the total lenght of HTS material
    - Perform transient simulation and verify if maximal temperature is under 360 K