HTS MODELLING 2016

5th International Workshop on Numerical Modelling of High Temperature Superconductors

Numerical Simulations of an Inductive Type Fault Current Limiter Based on Electromagnetic and Temperature Dependent Parameters

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Bologna, June 16 2016

1. Introduction
2. Problem and Approaches
3. Results and Discussion
4. Conclusions

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Introduction

Motivation

Inductive Type Limiters are commonly simulated in FEM software. For a proper accuracy, both electromagnetic and thermal phenomena must be taken into account.

The properties of high temperature superconducting (HTS) materials, such as electrical resistivity, heat capacity, thermal conductivity, critical current density and n-index, are strongly dependent on temperature values.

Objective

Develop a practical tool for a fast and accurate prediction of the behaviour of inductive type FCLs in electrical grids.

Reverse Engineering Simulations: Matlab/Simulink
FEM Simulations: Matlab/Simulink + Cedrat Flux2D

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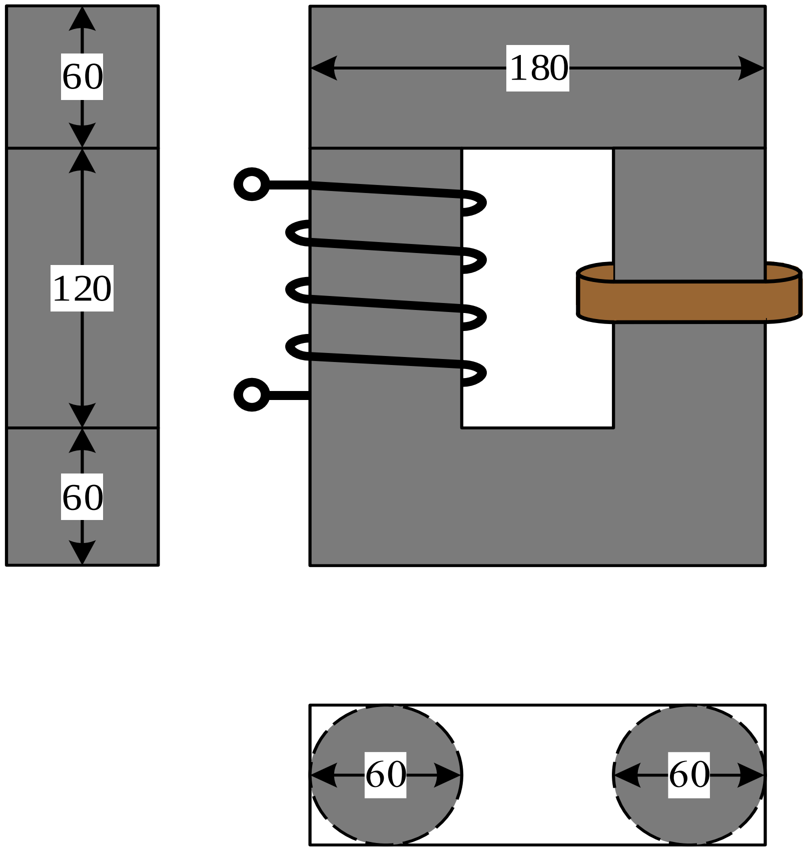
Problem and Approaches

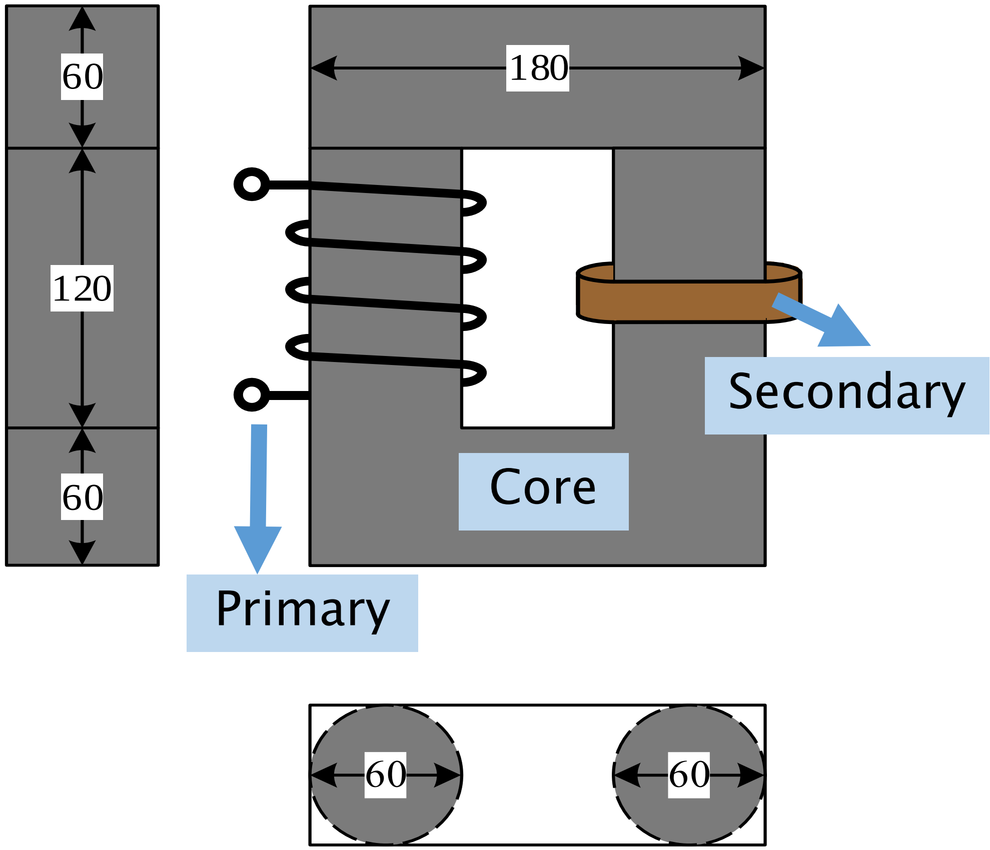
Dimensions



(Dimensions in mm)

Primary winding	
Material	Copper
Number of turns	60
Conductor cross section	1.5 mm^2
Inner radius	32.5 mm
Width	0.7 mm
Height	40 mm
Secondary winding	
Material	Superpower SCS4050
Number of turns	1
Conductor cross section	0.4 mm^2
Critical current density at 77 K	250 $A \cdot mm^{-2}$
Inner radius	40 mm
Width	0.1 mm
Height	4 mm
Cryostat	
Material	Extruded polystyrene
Inner radius	31.5 mm
Outer radius	60.5 mm
Wall thickness	6 mm

Dimensions



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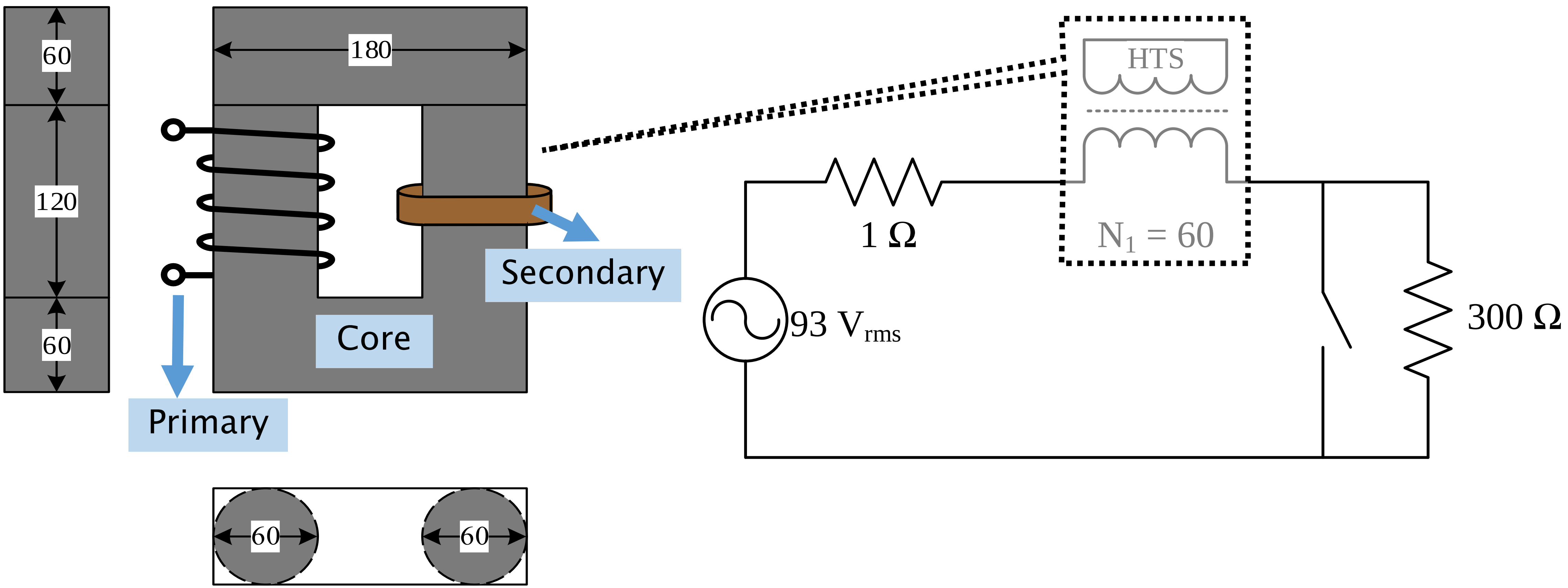
Test Circuit



(Dimensions in mm)

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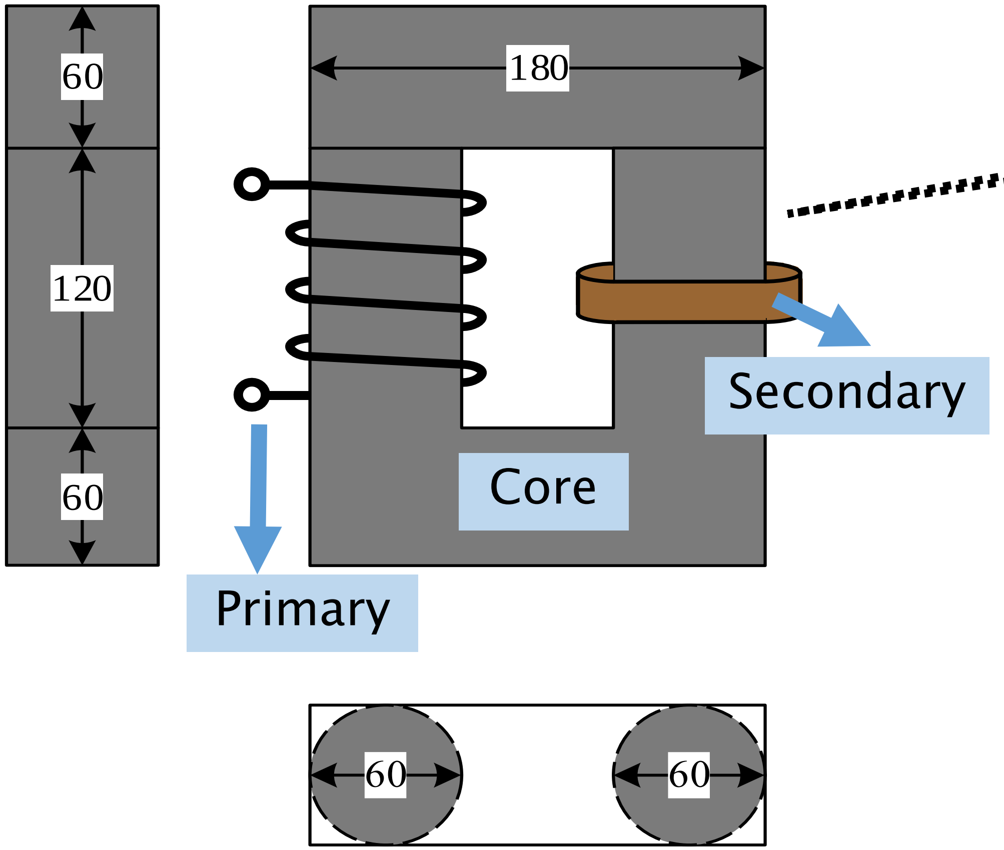
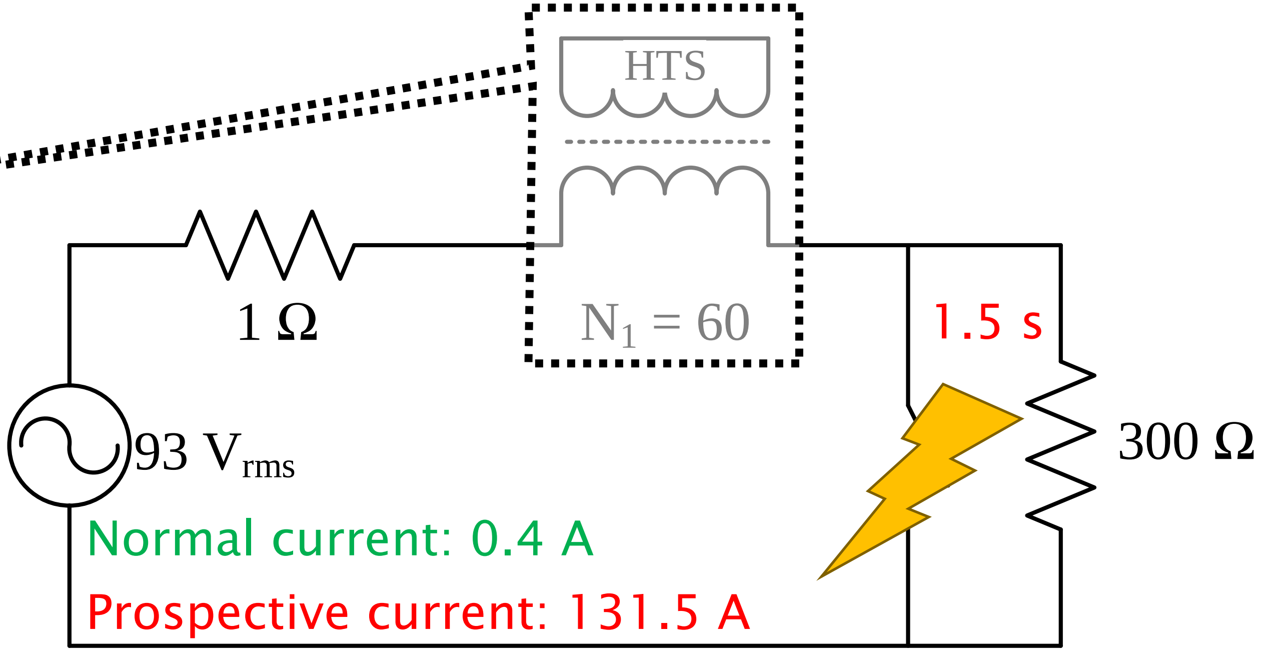


(Dimensions in mm)

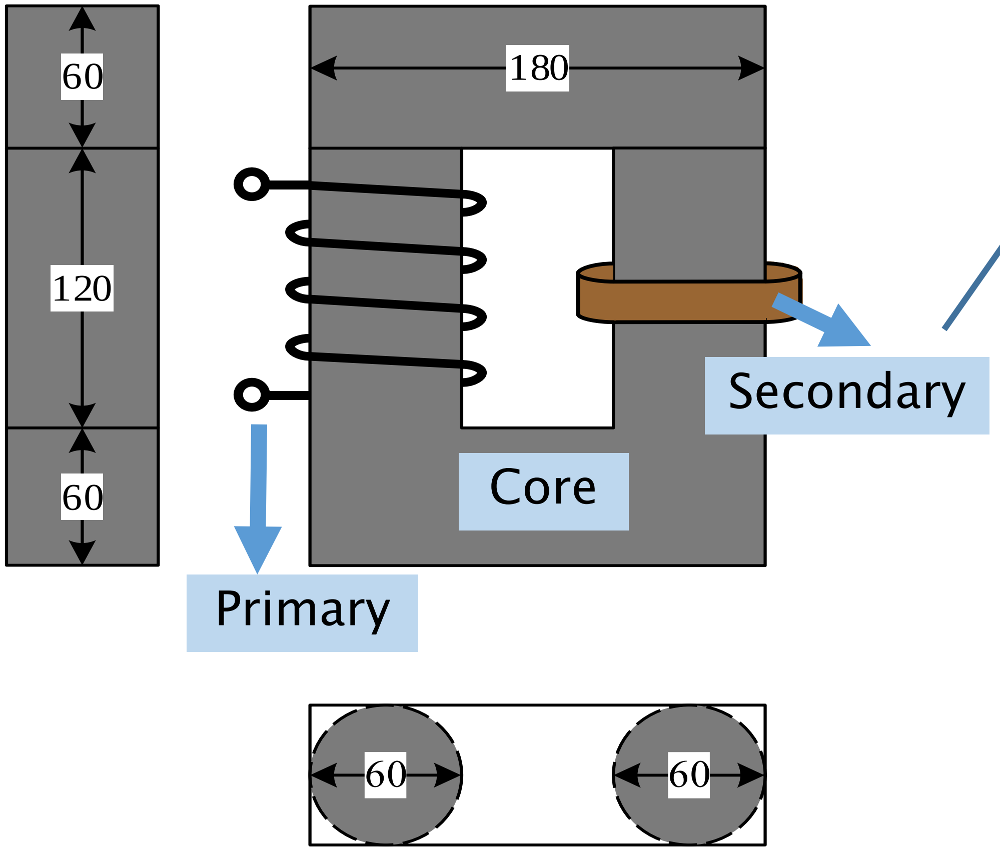


Open : 0.00 s – 1.25 s

Close : 1.25 s – 2.75 s

Open : 2.75 s – 5.00 s

Parameters

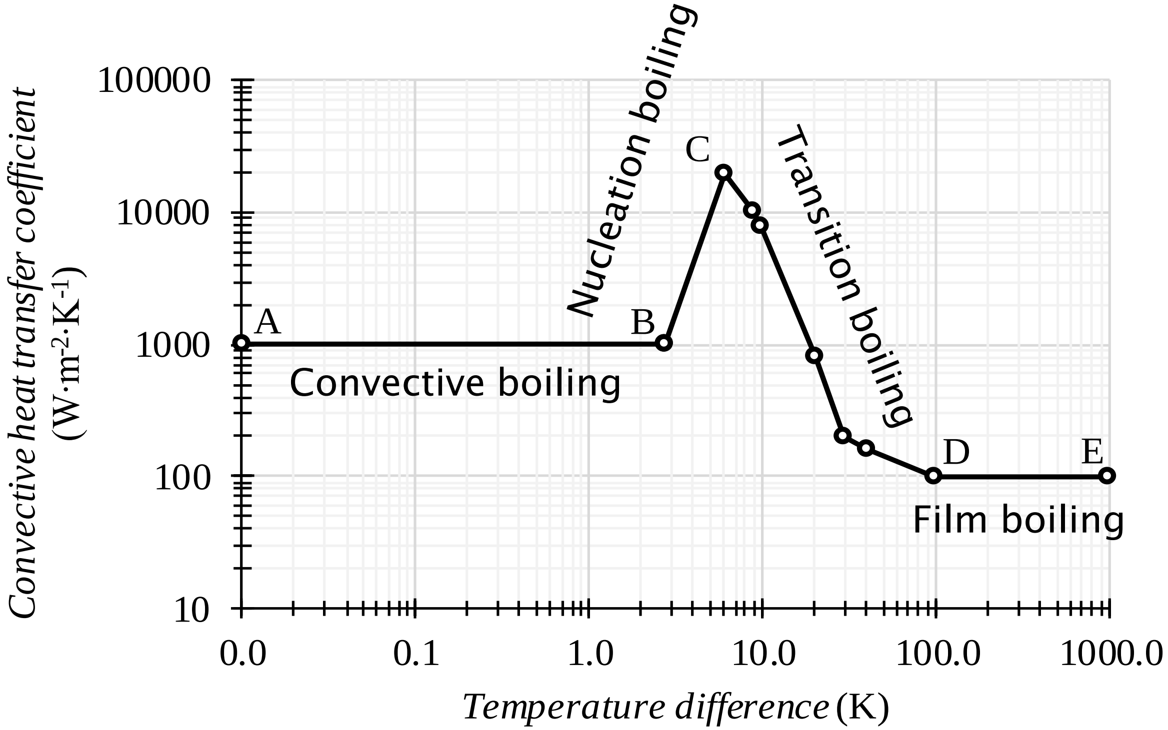


(Dimensions in mm)

Temperature dependent properties:

- Convective heat transfer.
- Critical current density.
- n-value.
- Resistivity of copper, silver, Hastelloy, (Re)BCO.
- Thermal conductivity.
- Heat capacity.

Parameters: Convective Heat Transfer Coefficient



$$h = \frac{Q_h}{\Delta T} \qquad [\mathrm{W \cdot m^{-2} \cdot K^{-1}}]$$

Q_h : Convective heat transfer ($\mathrm{W \cdot m^{-2}}$)

ΔT : Temperature difference (K)

Reference:

- Kaufmann B, Dreier S, Haberstroh C and Grossmann S 2013 Integration of LN2 Multiphase Heat Transfer Into Thermal Networks for High Current Components *IEEE Trans. Appl. Supercond.* **23** 5000104–5000104.

Parameters: Critical Current Density and n−Value

$$J_C(T) = J_C(T_0) \cdot \left(\frac{1 - \left(\frac{T}{T_C}\right)^{\delta}}{1 - \left(\frac{T_0}{T_C}\right)^{\delta}} \right)^{\gamma} \; [\mathrm{A \cdot mm^{-2}}]$$

$$n(T) = n(T_0) \cdot \left(\frac{T_0}{T}\right)^{\kappa}$$

T_0 : LN_2 temperature (77.2 K)

T_C : Critical temperature (93.0 K)

δ : Fitting parameter (−67.09)

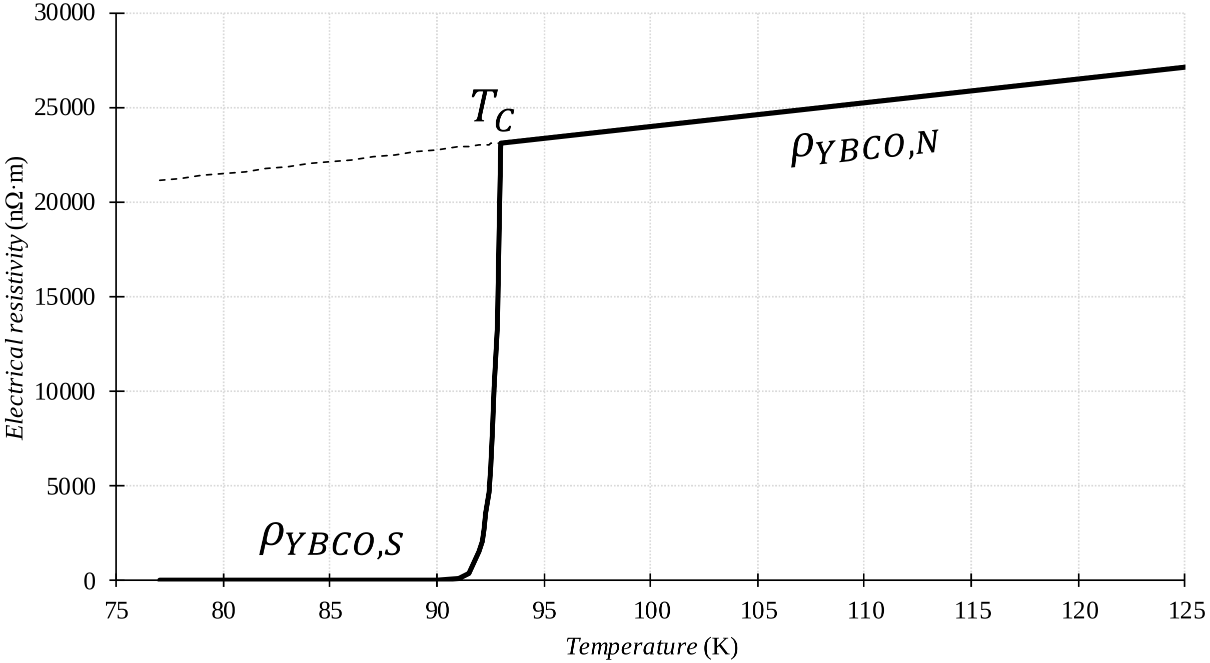
γ : Fitting parameter (0.4107)

κ: Fitting parameter (22.96)

References:

- Lee W S, Nam S, Kim J, Lee J and Ko T K 2015 A Numerical and Experimental Analysis of the Temperature Dependence of the n-Index for 2G HTS Tape Surrounding the 77 K Temperature Range *IEEE Trans. Appl. Supercond.* **25** 1–4.
- Cedrat 2007 Flux 10 User's Guide vol 2.

Parameters: Resistivity of Superconducting Layer



$$\begin{cases} \rho_{YBCO,S}(J,T) = \frac{E_c}{J} \cdot \left(\frac{J}{J_c(T)}\right)^{n(T)} \\ \rho_{YBCO,N}(T) = 1.25 \times 10^{-7} \cdot T + 1.15 \times 10^{-5} \end{cases}$$

$[\Omega \cdot \mathrm{m}]$

E_C : Critical electrical field (1 μ · cm^{-1})

J : Current density (K)

J_C : Critical current density (A·m^{-2})

n : n–value

T : Temperature (K)

Parameters: Resistivity of Copper, Silver and Hastelloy Layers

$$\rho_{Copper}(T) = 6.85 \times 10^{-11} \cdot T - 3.30 \times 10^{-9}$$

$$\rho_{Silver}(T) = 6.11 \times 10^{-11} \cdot T - 1.97 \times 10^{-9}$$

$$\rho_{Hastelloy}(T) = 1.17 \times 10^{-10} \cdot T + 1.25 \times 10^{-6}$$

$[\Omega \cdot \mathrm{m}]$

References:

- Moore J P, McElroy D L and Graves R S 1967 Thermal Conductivity and Electrical Resistivity of High-Purity Copper from 78 to 400 K *Can. J. Phys.* **45** 3849–65.
- Matula R A 1979 Electrical resistivity of copper, gold, palladium, and silver *J. Phys. Chem. Ref. Data* **8** 1147.
- Lu J, Choi E S and Zhou H D 2008 Physical properties of Hastelloy® C-276TM at cryogenic temperatures *J. Appl. Phys.* **103** 064908.

Parameters: Thermal Conductivity

$$\lambda_{YBCO}(T) = 5$$

$$\lambda_{Copper}(T) = 416.3 - 5.904 \times 10^{-2} \cdot T + \frac{7.087 \times 10^{7}}{T^{3}}$$

$$\lambda_{Silver}(T) = 431.4 - 1.817 \times 10^{-2} \cdot T + \frac{1.708 \times 10^{7}}{T^{3}}$$

$$\lambda_{Hastelloy}(T) = 0.0238 \cdot T + 5.896$$

$[W \cdot m^{-1} \cdot K^{-1}]$

References:

- Moore J P, McElroy D L and Graves R S 1967 Thermal Conductivity and Electrical Resistivity of High-Purity Copper from 78 to 400 K *Can. J. Phys.* **45** 3849–65.
- Lu J, Choi E S and Zhou H D 2008 Physical properties of Hastelloy® C276 at cryogenic temperatures *J. Appl. Phys.* **103** 064908.
- Ho C Y, Powell R W and Liley P E 1974 *Journal of Physical and Chemical Reference Data*, Volume 3.

Parameters: Volumetric Heat Capacity

$$C_{YBCO}(T) = 4.05 \times 10^6 - 1.73 \times 10^8 \cdot T^{-0.9747}$$

$$C_{Copper}(T) = -9.463 \times 10^7 \cdot T^{-0.8292} + 4.279 \times 10^6$$

$$C_{Silver}(T) = -1.983 \times 10^8 \cdot T^{-1.23} + 2.643 \times 10^6$$

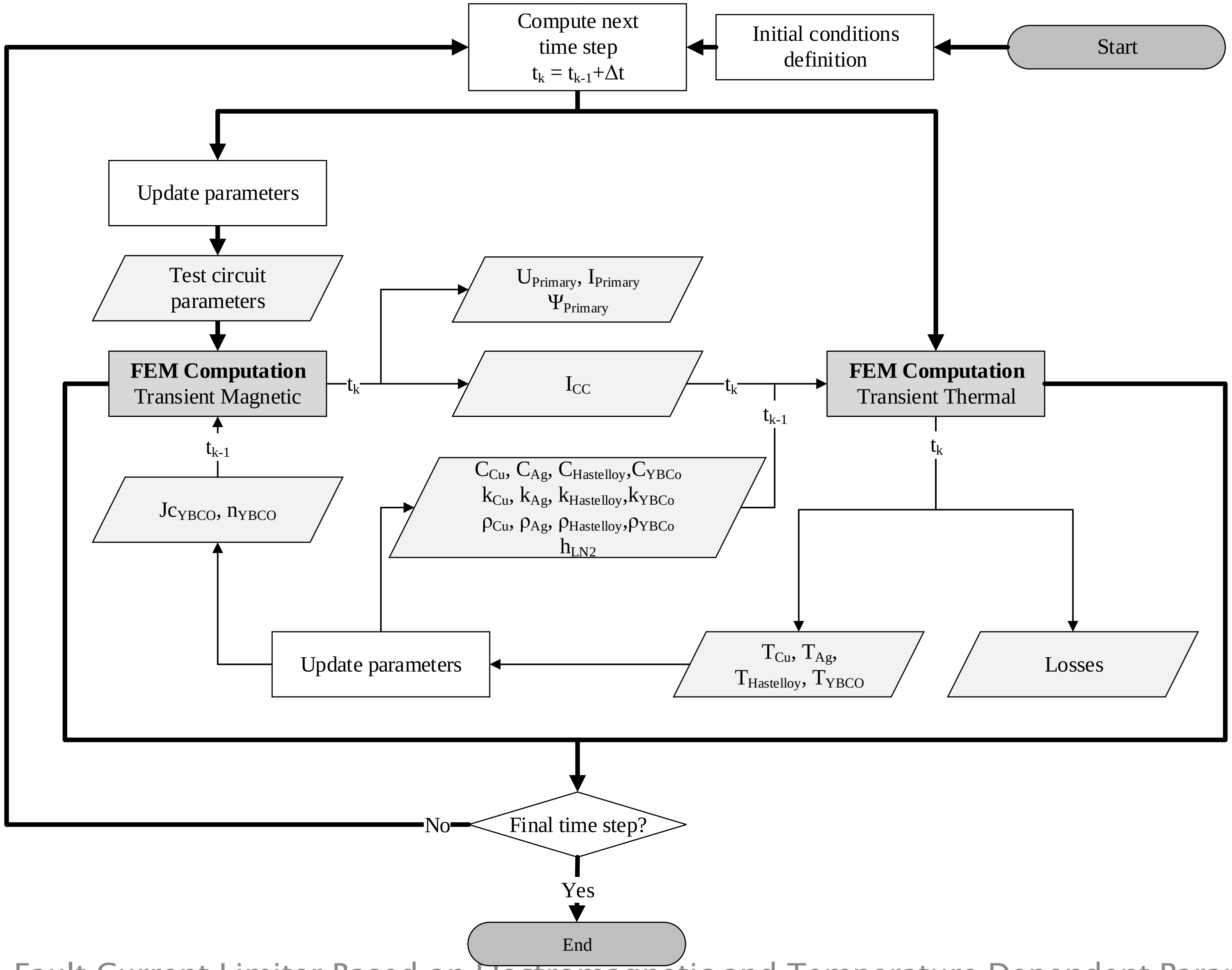
$$C_{Hastelloy}(T) = 4.14 \times 10^6 + \frac{5.92 \times 10^5 - 4.14 \times 10^6}{1 + \left(\frac{T}{120.42}\right)^{2.39}}$$

$[J \cdot K^{-1}]$

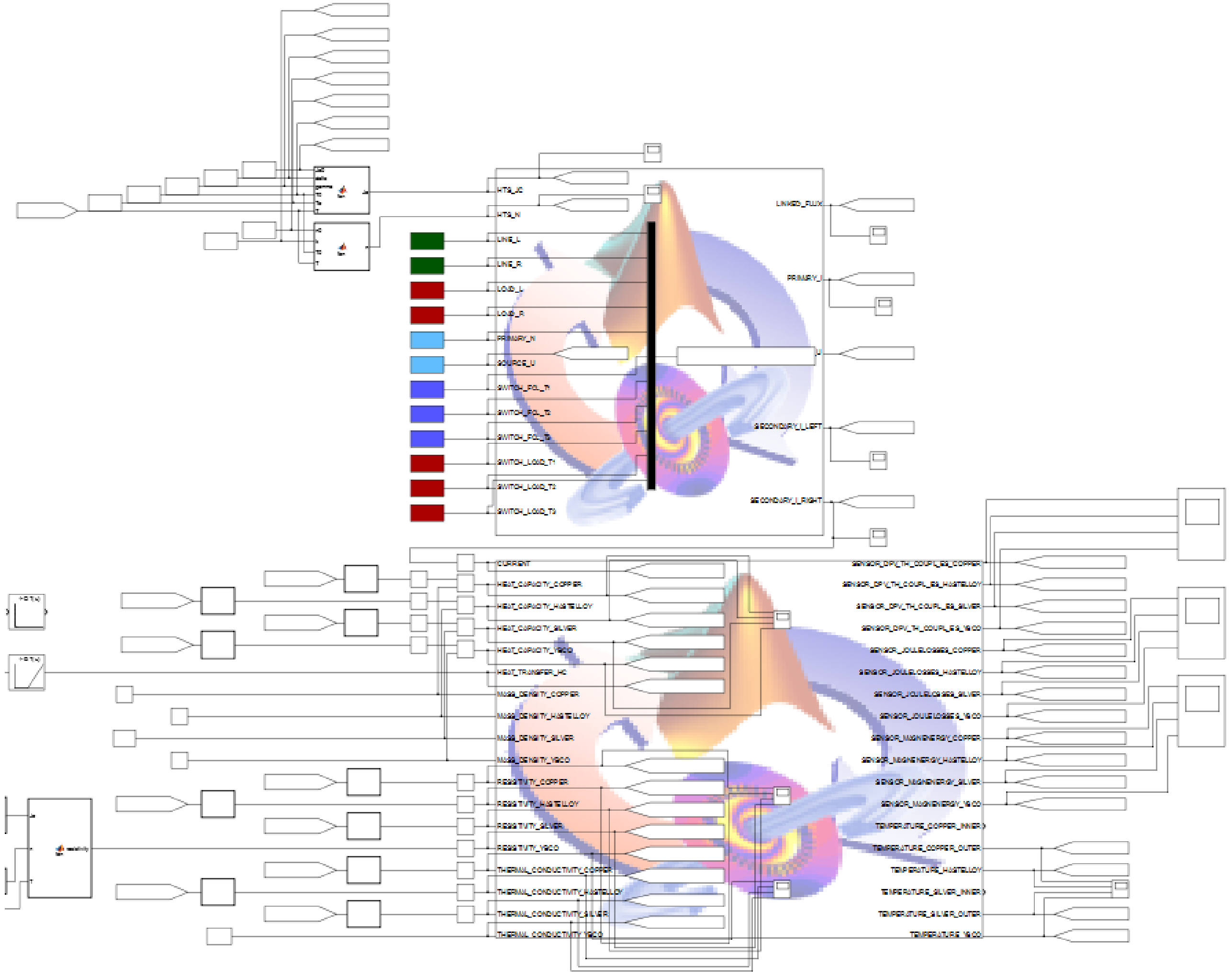
References:

- Lu J, Choi E S and Zhou H D 2008 Physical properties of Hastelloy® C–276TM at cryogenic temperatures *J. Appl. Phys.* **103** 064908.
- Jensen J E, Tuttle W A, Stewart R B, Brechna H and Prodell A G 1980 Specific heat of some solids *Brookhaven National Laboratory Selected Cryogenic Data Notebook, Volume 1.*
- Smith D R and Fickett F R 1995 Low–Temperature Properties of Silver *J. Res. Natl. Inst. Stand. Technol.* **100** 119.

Approach 1: Coupled Electromagnetic–Thermal Simulation

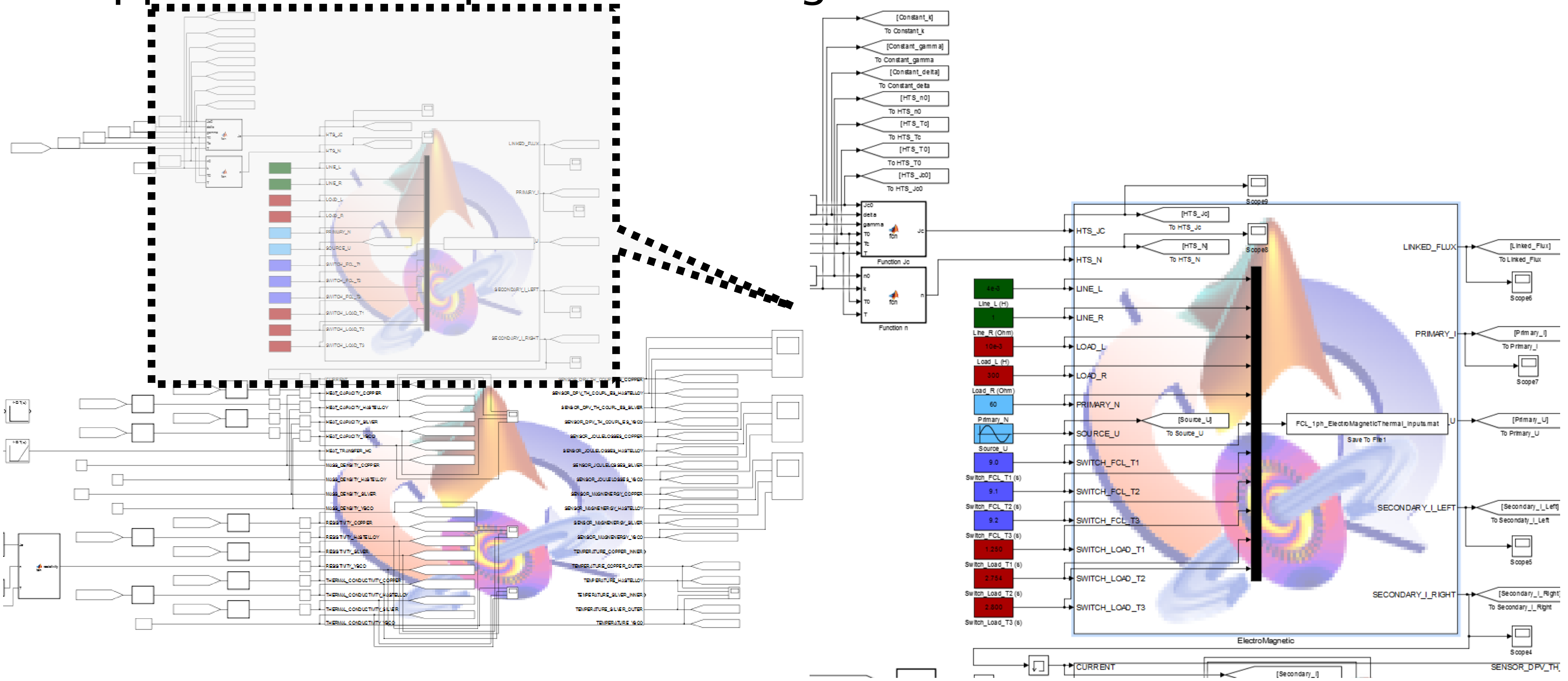


Approach 1: Coupled Electromagnetic–Thermal Simulation



Co-Simulation:
Matlab/Simulink + Cedrat Flux2D

Approach 1: Coupled Electromagnetic–Thermal Simulation



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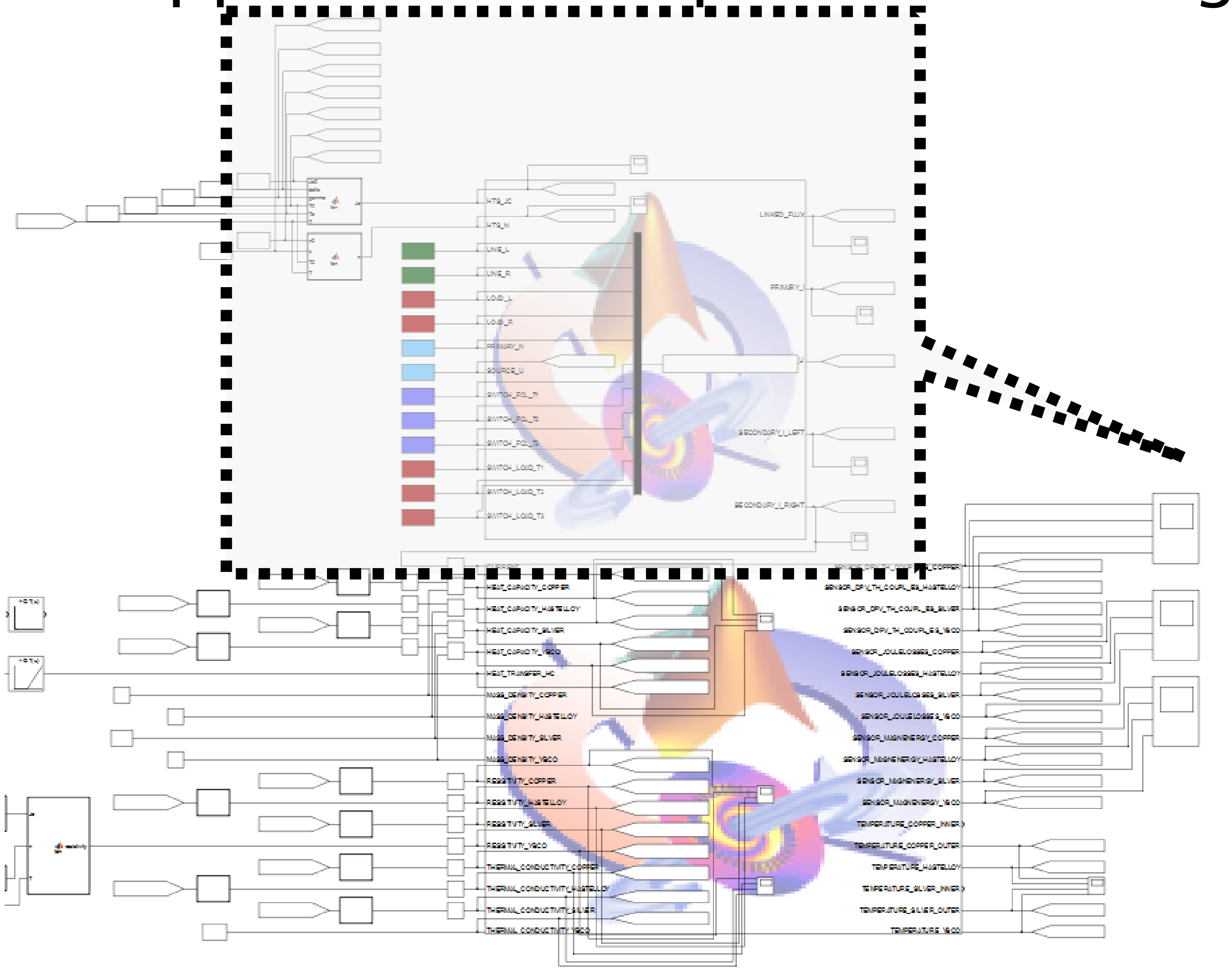

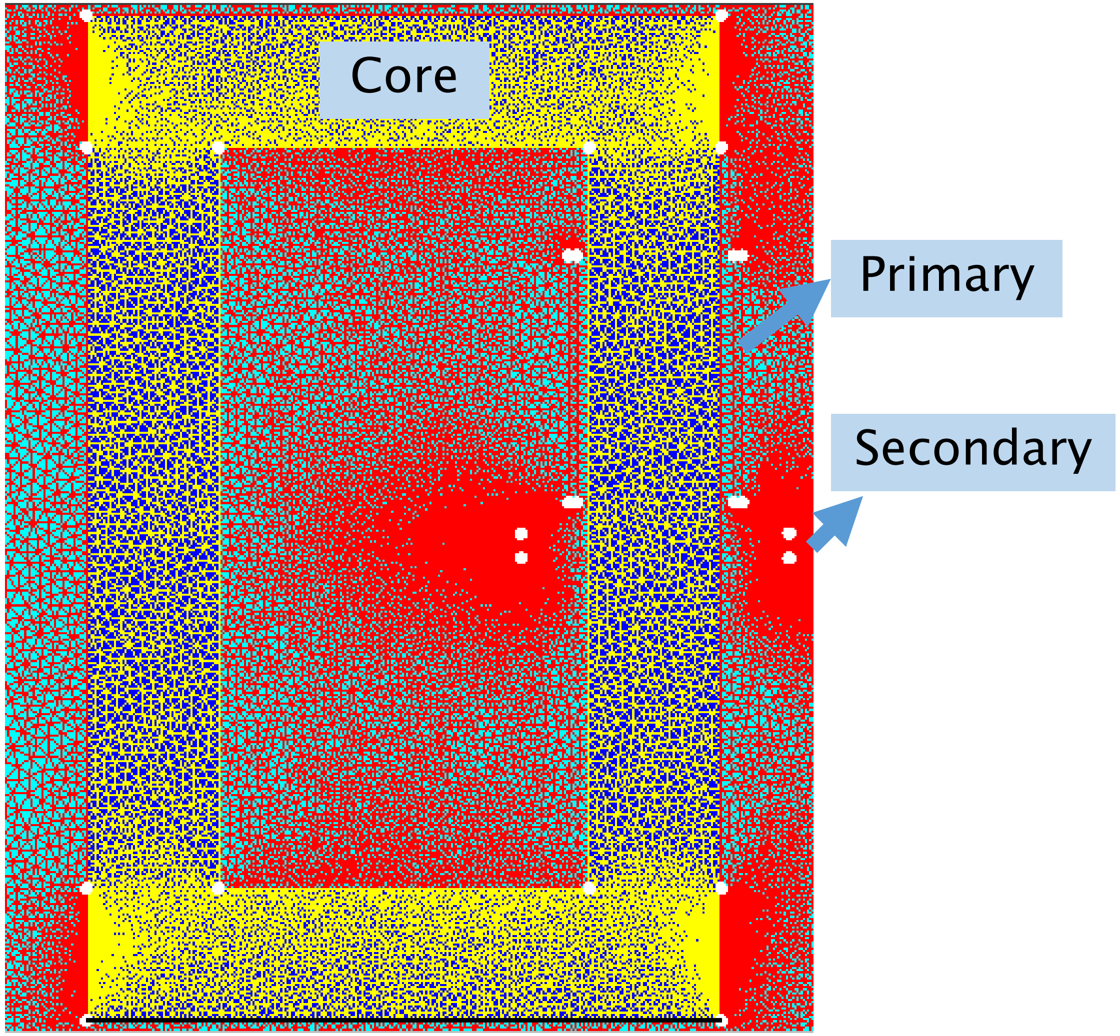

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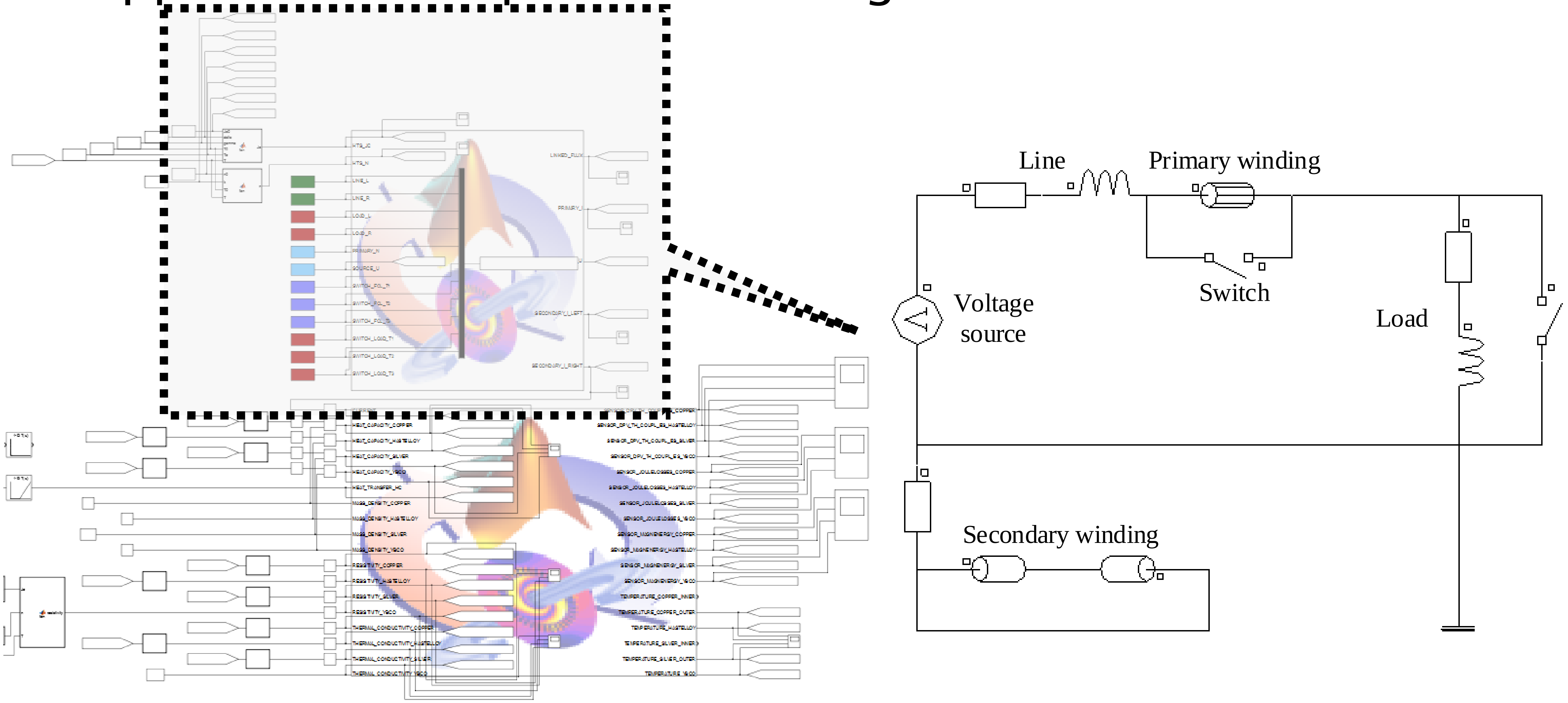

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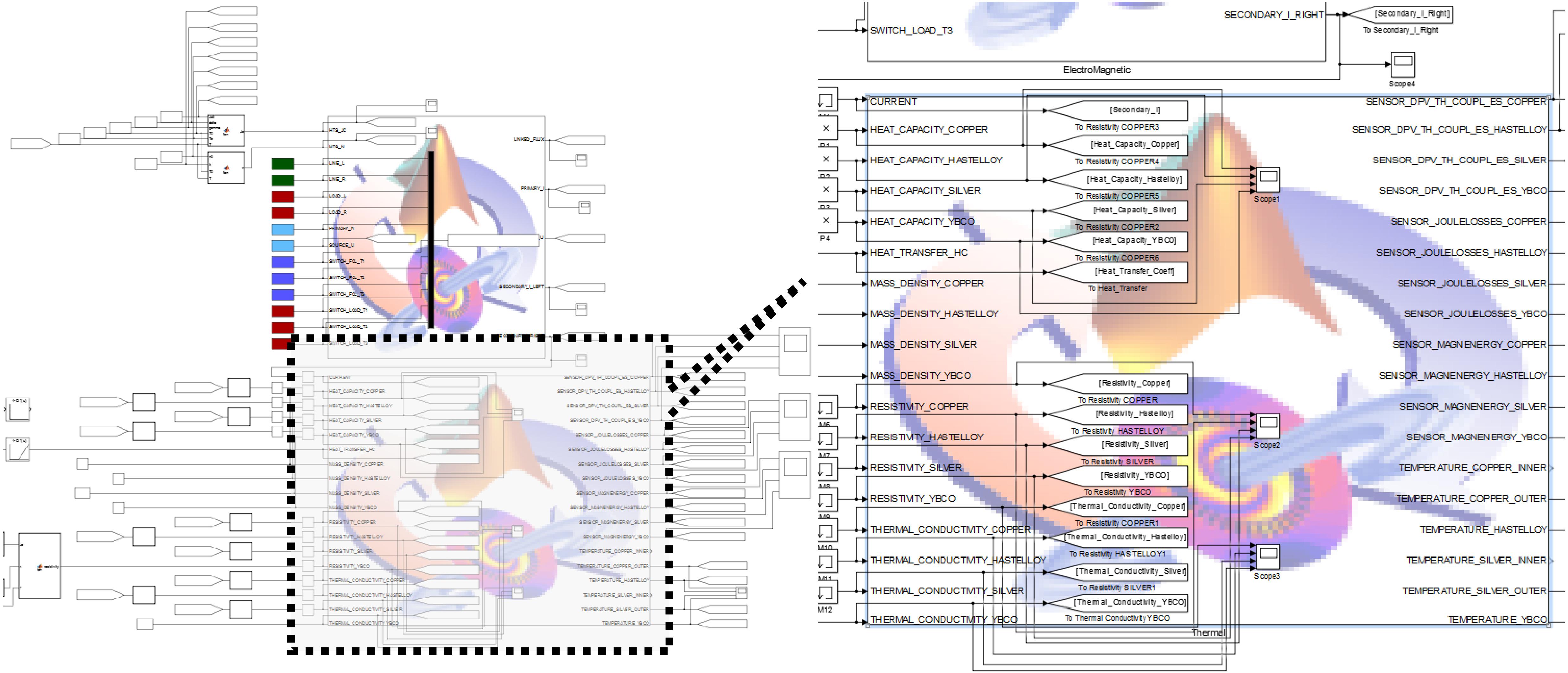

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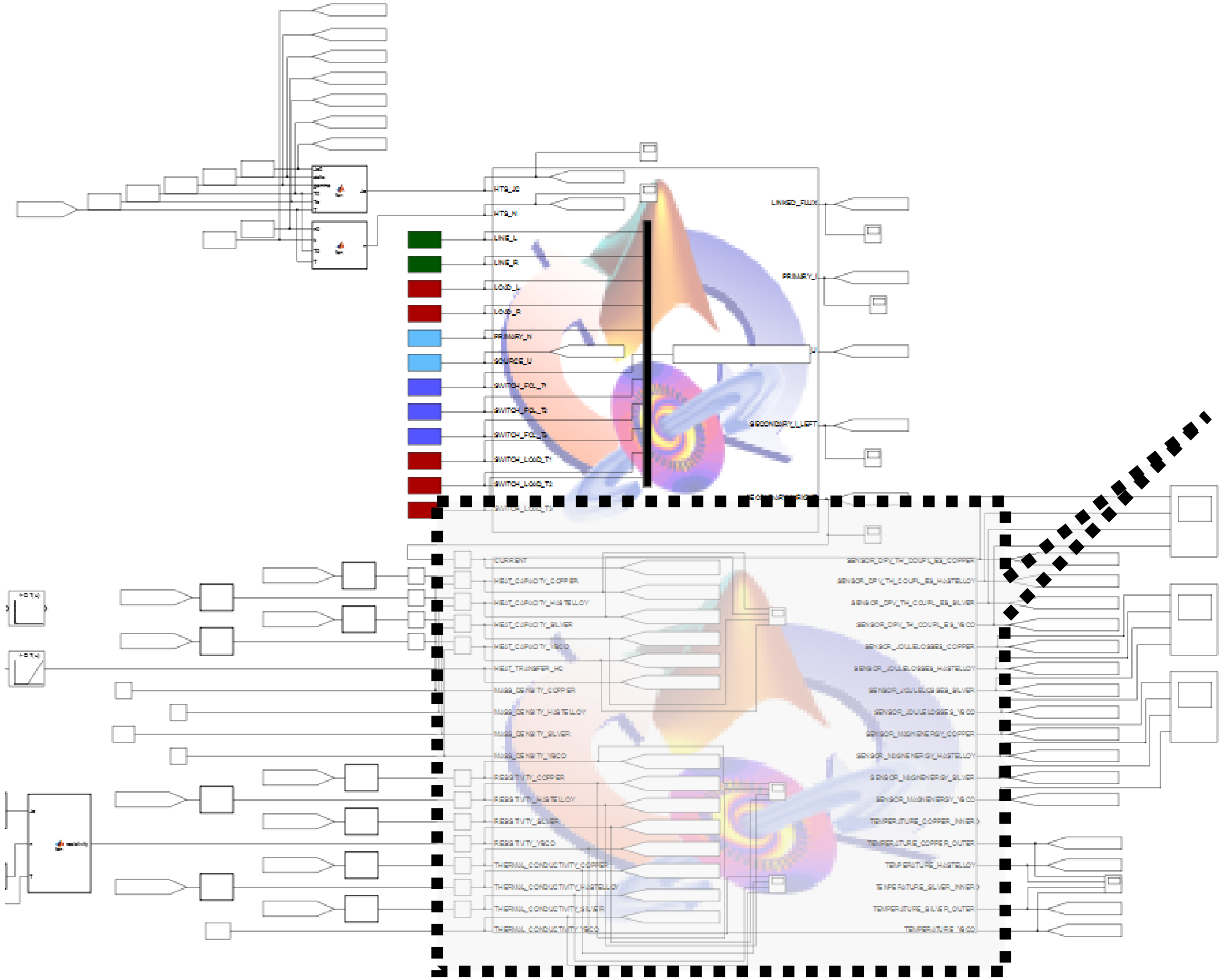
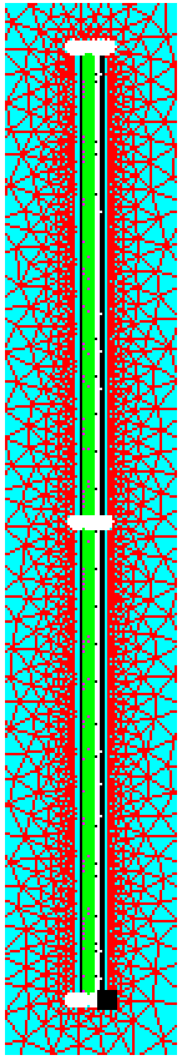
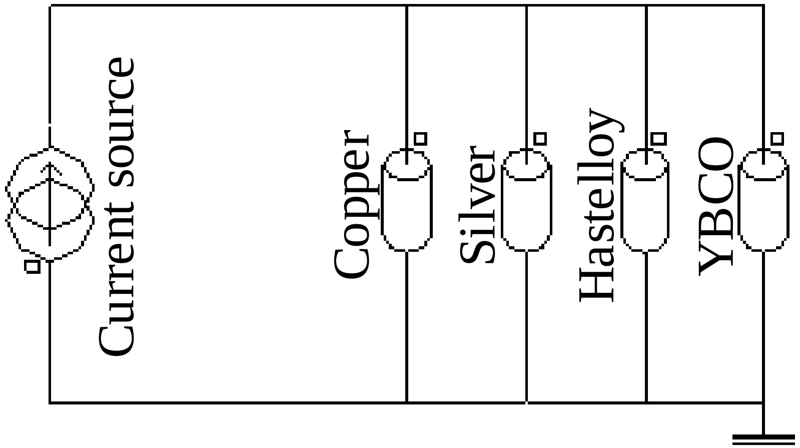
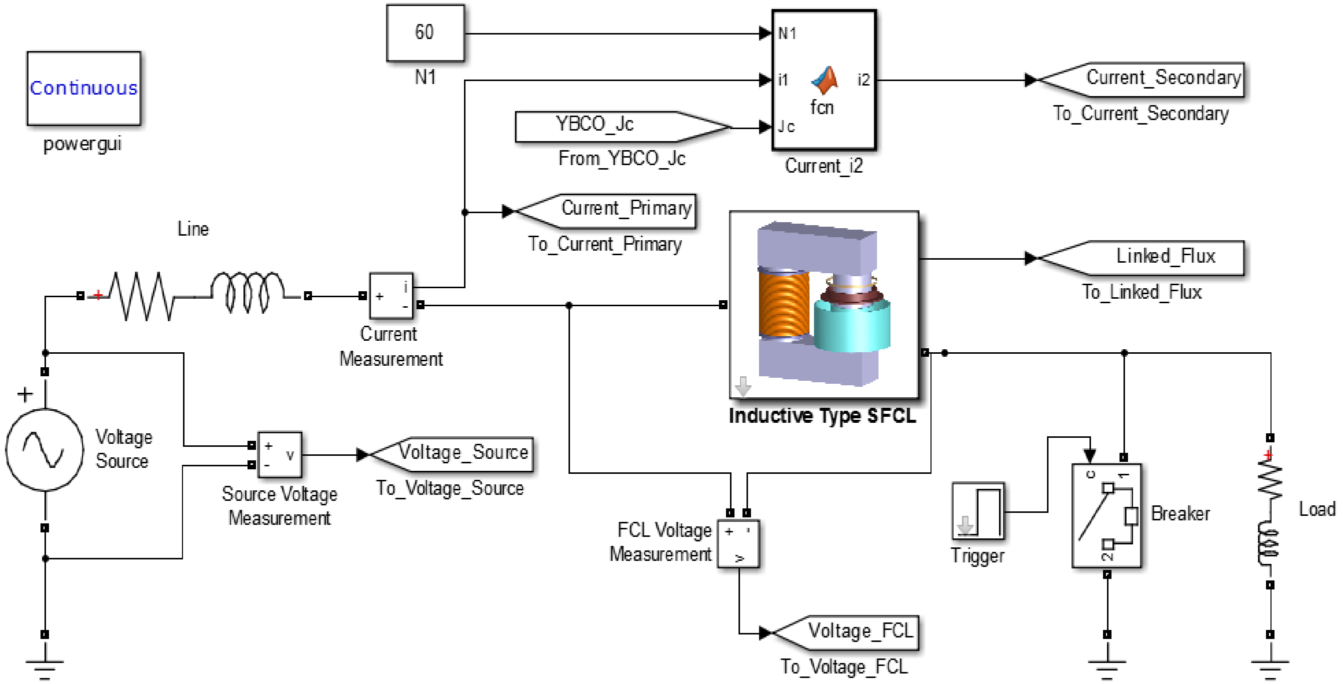




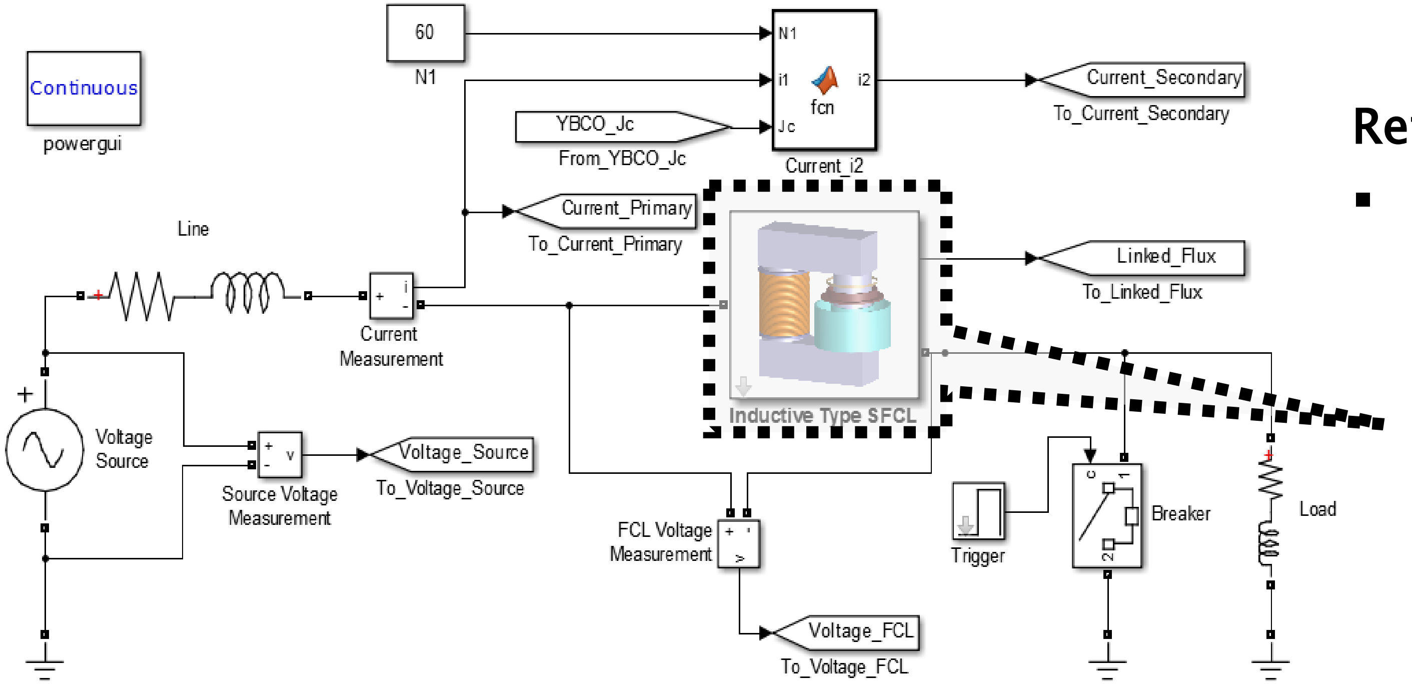


Approach 2: Reverse Engineering Methodology



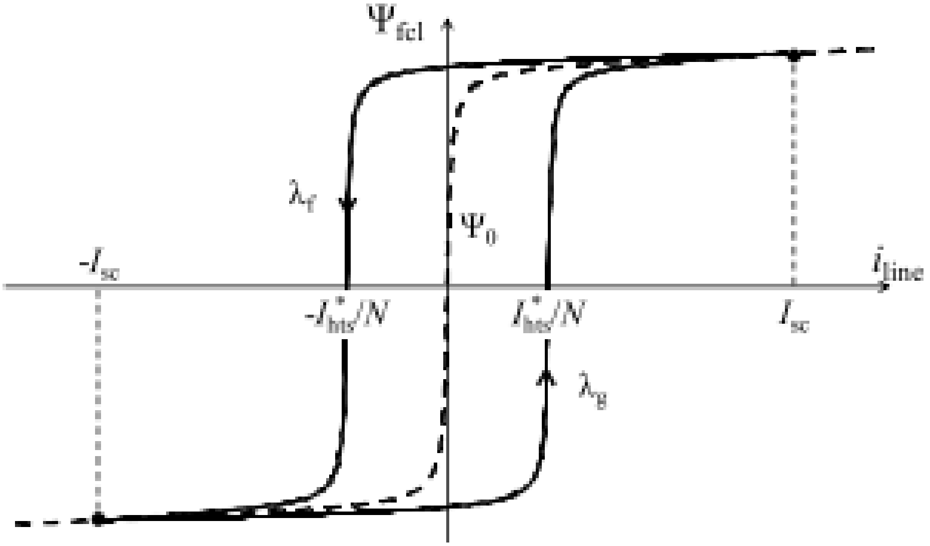
Matlab/Simulink

Approach 2: Reverse Engineering Methodology



Reference:

- Pina J M, Suárez P, Neves M V, Álvarez A and Rodrigues A L 2010 Reverse engineering of inductive fault current limiters *J. Phys. Conf. Ser.* **234** 032047.



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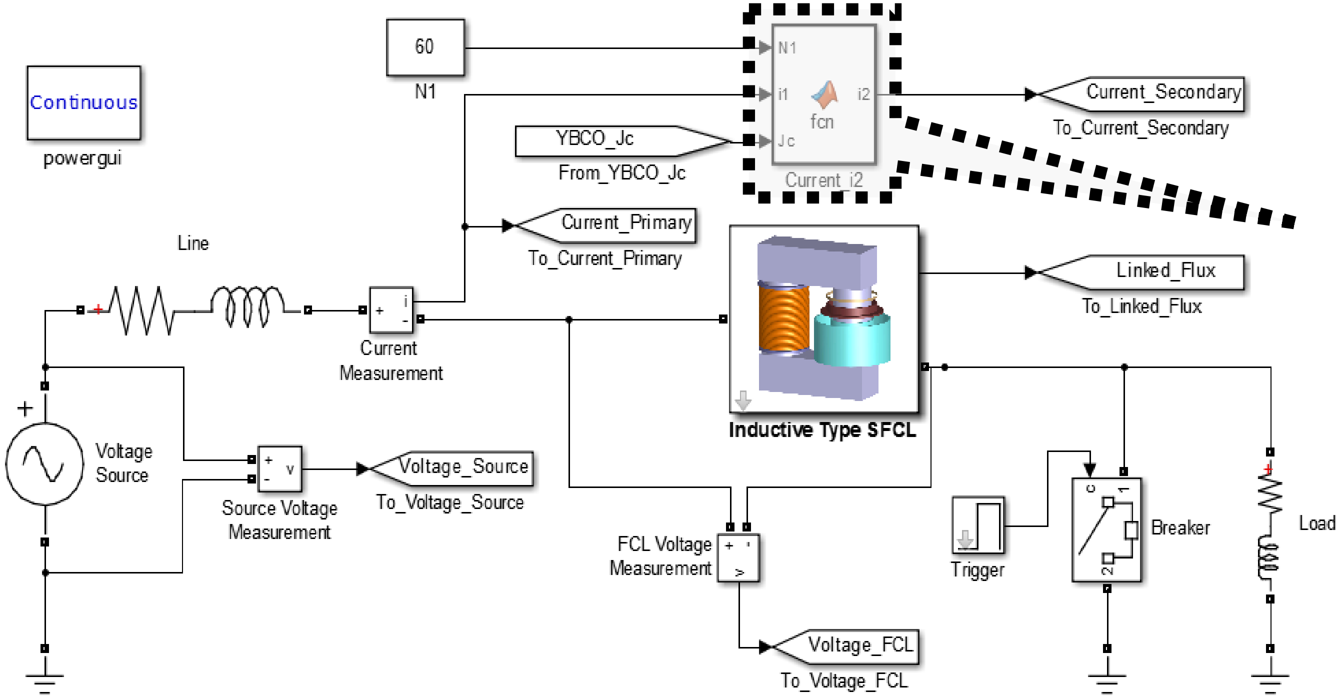
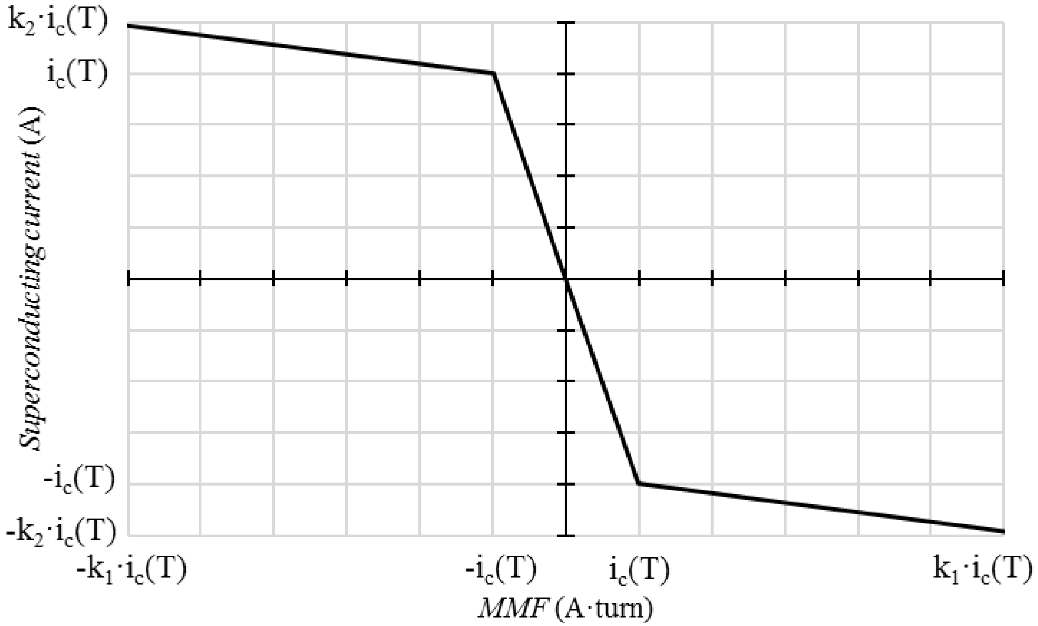


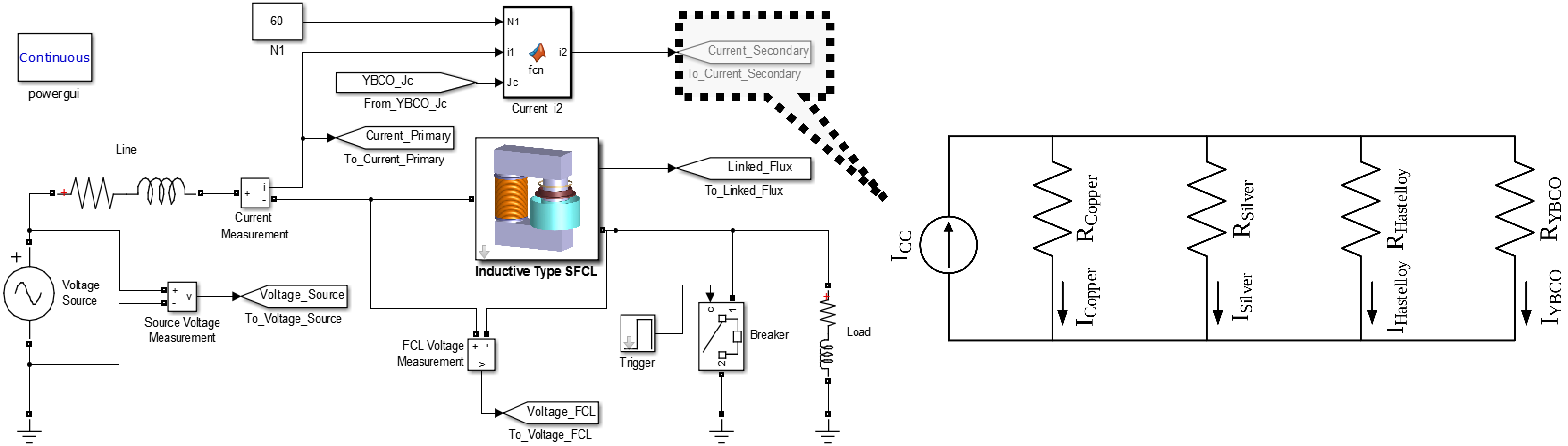


$$
\begin{cases}
i_2 = -N_1 \cdot i_1 & -i_c(T) \le N_1 \cdot i_1 \le i_c(T) \\
i_2 = \dfrac{1-k_2}{k_1-1} \cdot (N_1 \cdot i_1) + \dfrac{k_1-k_2}{k_1-1} \cdot \left(i_c(T)\right) & N_1 \cdot i_1 < -i_c(T) \\
i_2 = \dfrac{1-k_2}{k_1-1} \cdot (N_1 \cdot i_1) + \dfrac{k_2-k_1}{k_1-1} \cdot \left(i_c(T)\right) & N_1 \cdot i_1 > i_c(T)
\end{cases}
$$

$$i_C(T) = J_C(T) \cdot S_{Tape}$$

$$
\begin{cases}
k_1 = 90 \\
k_2 = 3
\end{cases}
$$

Approach 2: Reverse Engineering Methodology



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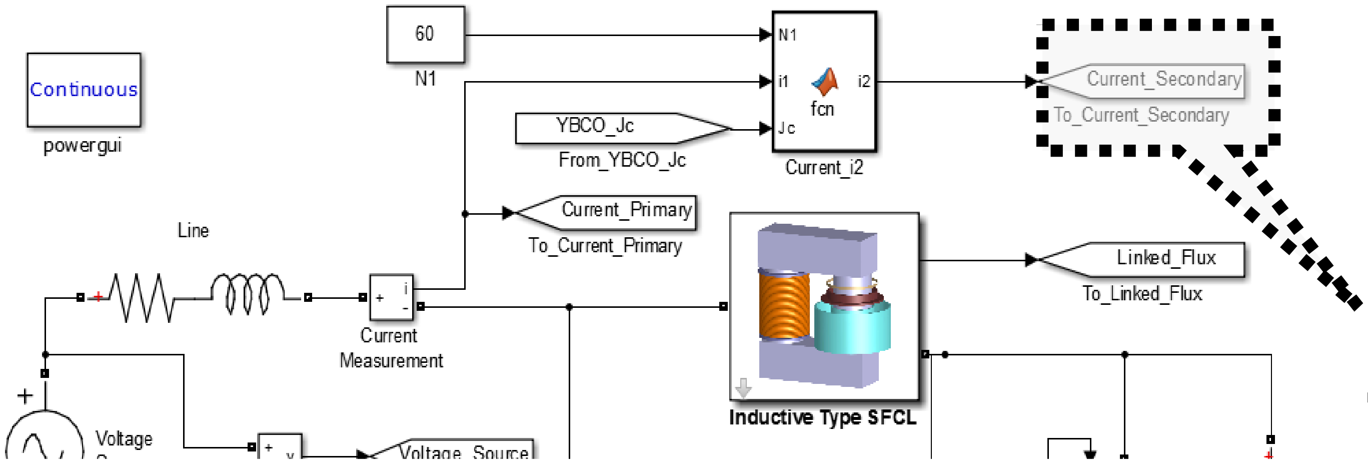
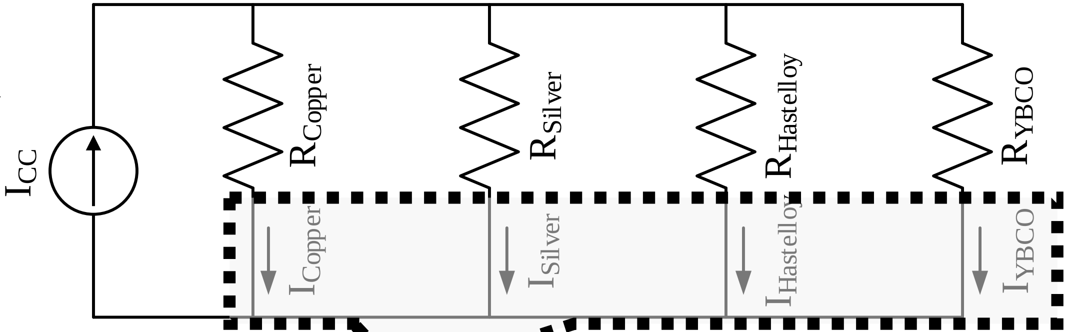
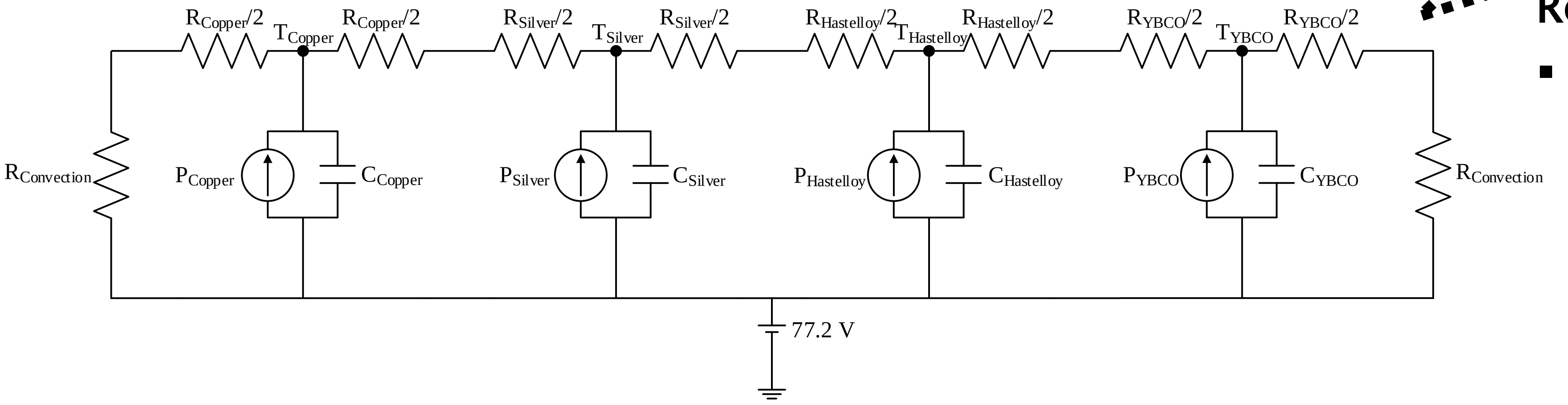




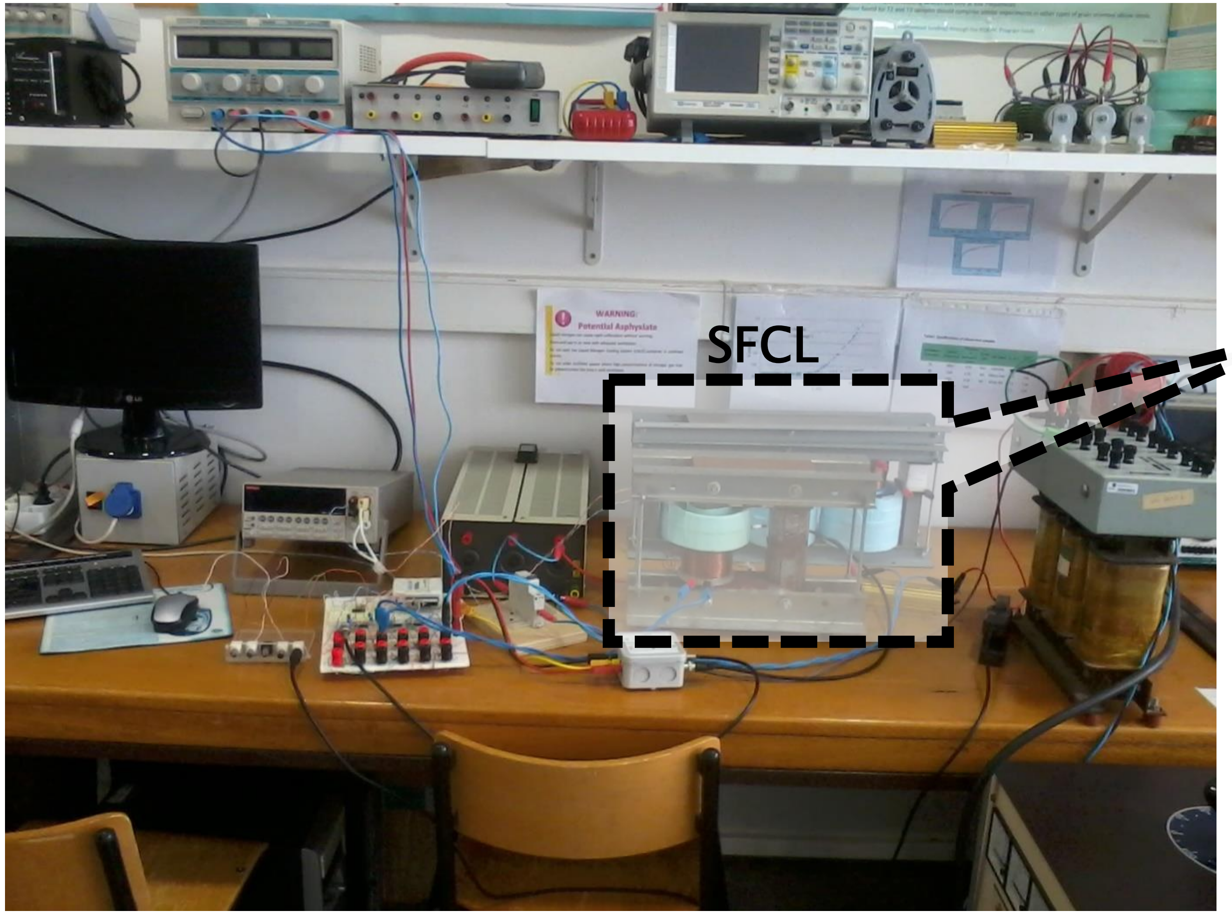


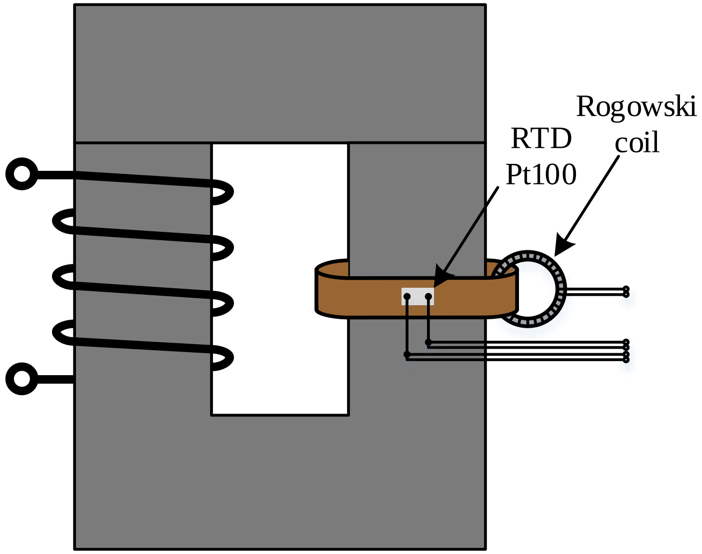
Reference:

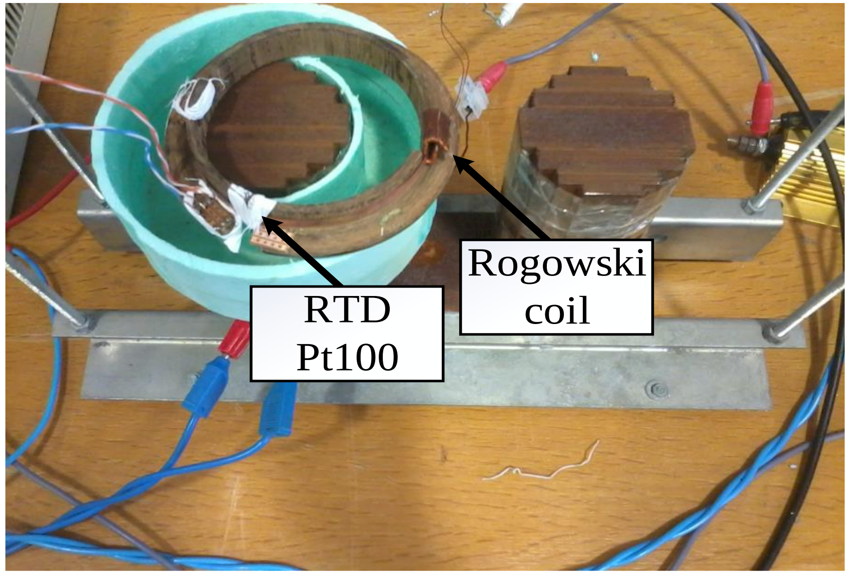
- de Sousa W, Polasek A, Dias R, Matt C and de Andrade R 2014 Thermal–electrical analogy for simulations of superconducting fault current limiters *Cryogenics* **62** 97–109.

Experimental Test Bench

Experimental Test Bench







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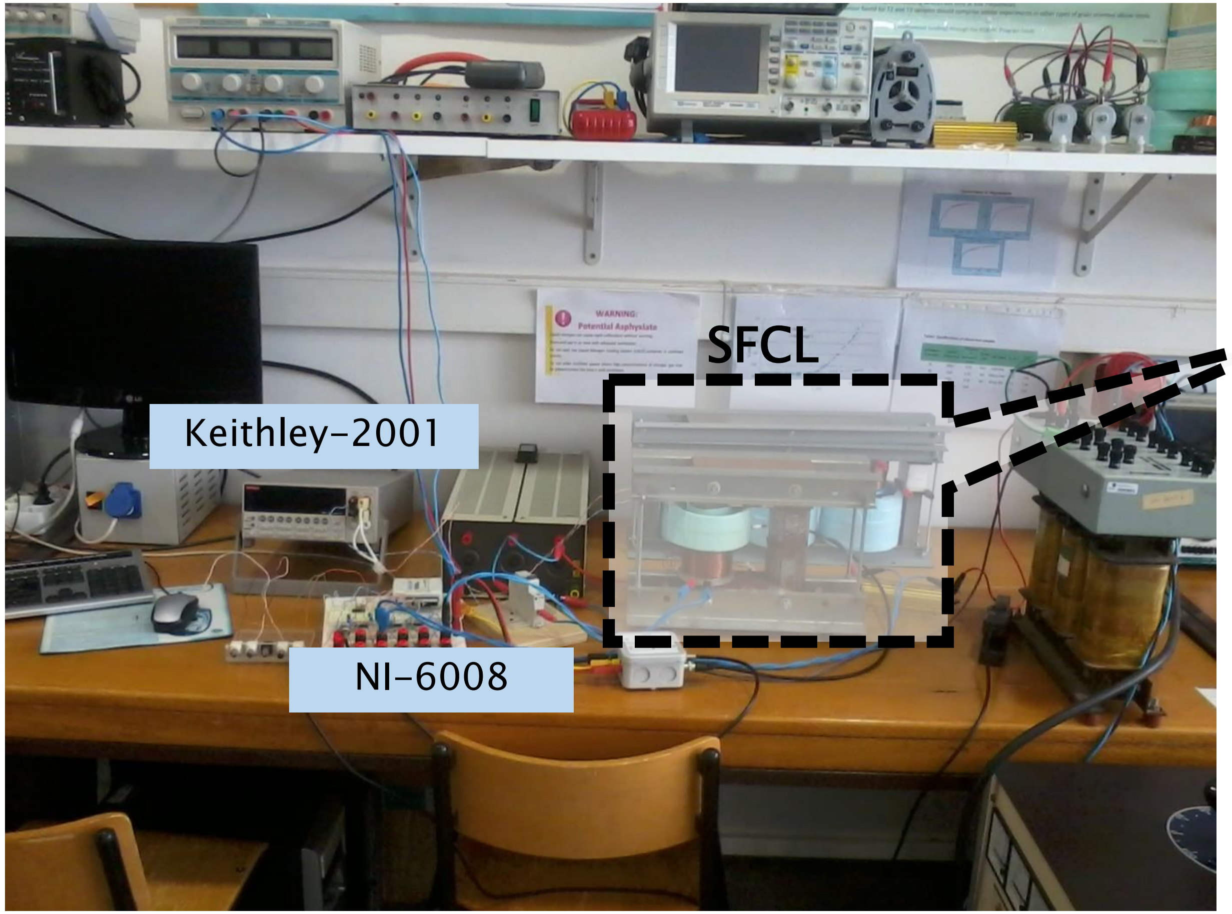
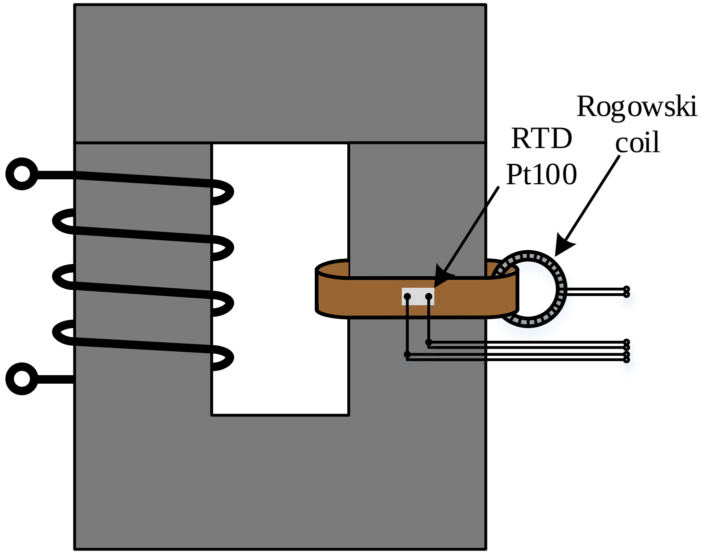
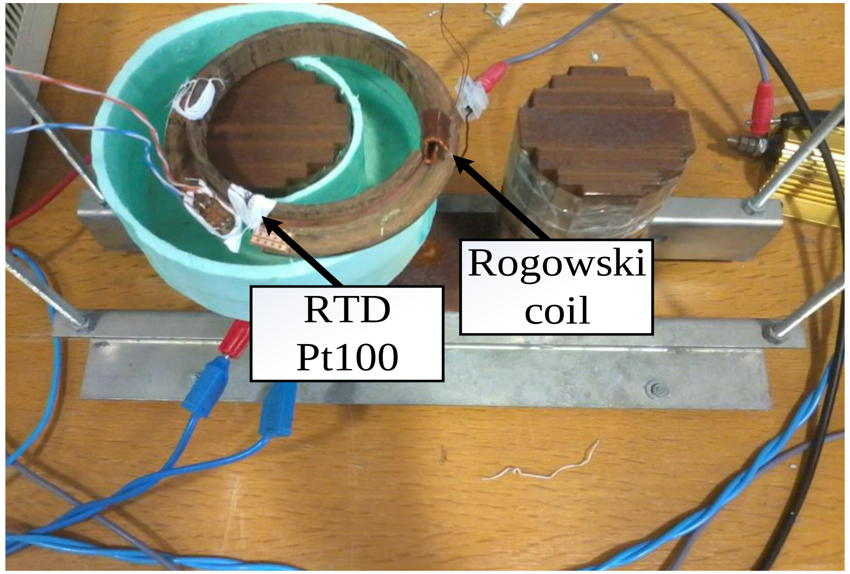
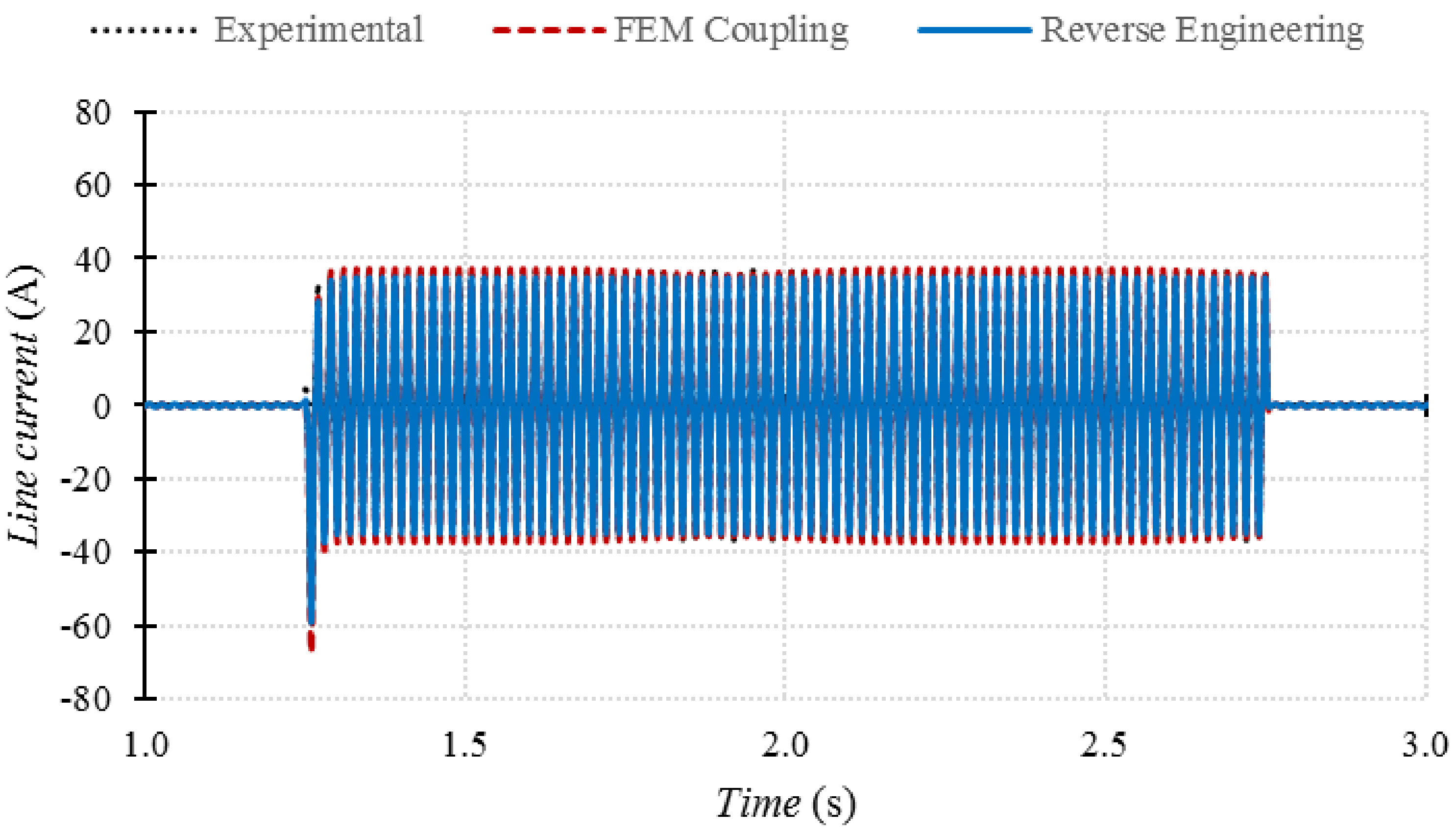






Results and Discussion

Line Current



Prospective current:

- 131.5 A

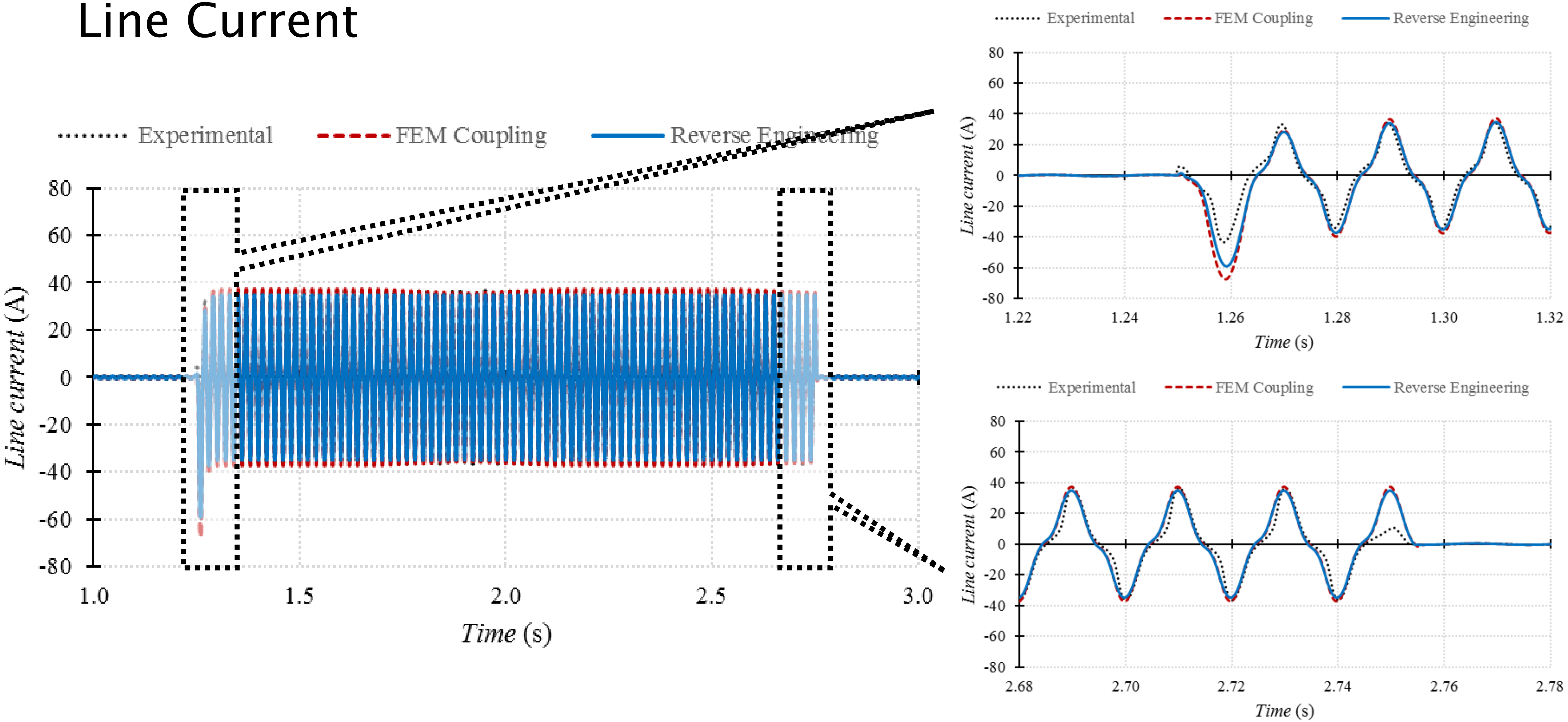
Peak current:

- 43.3 A (Experimental)
- 67.4 A (FEM Coupling)
- 59.0 A (Reverse Engineering)

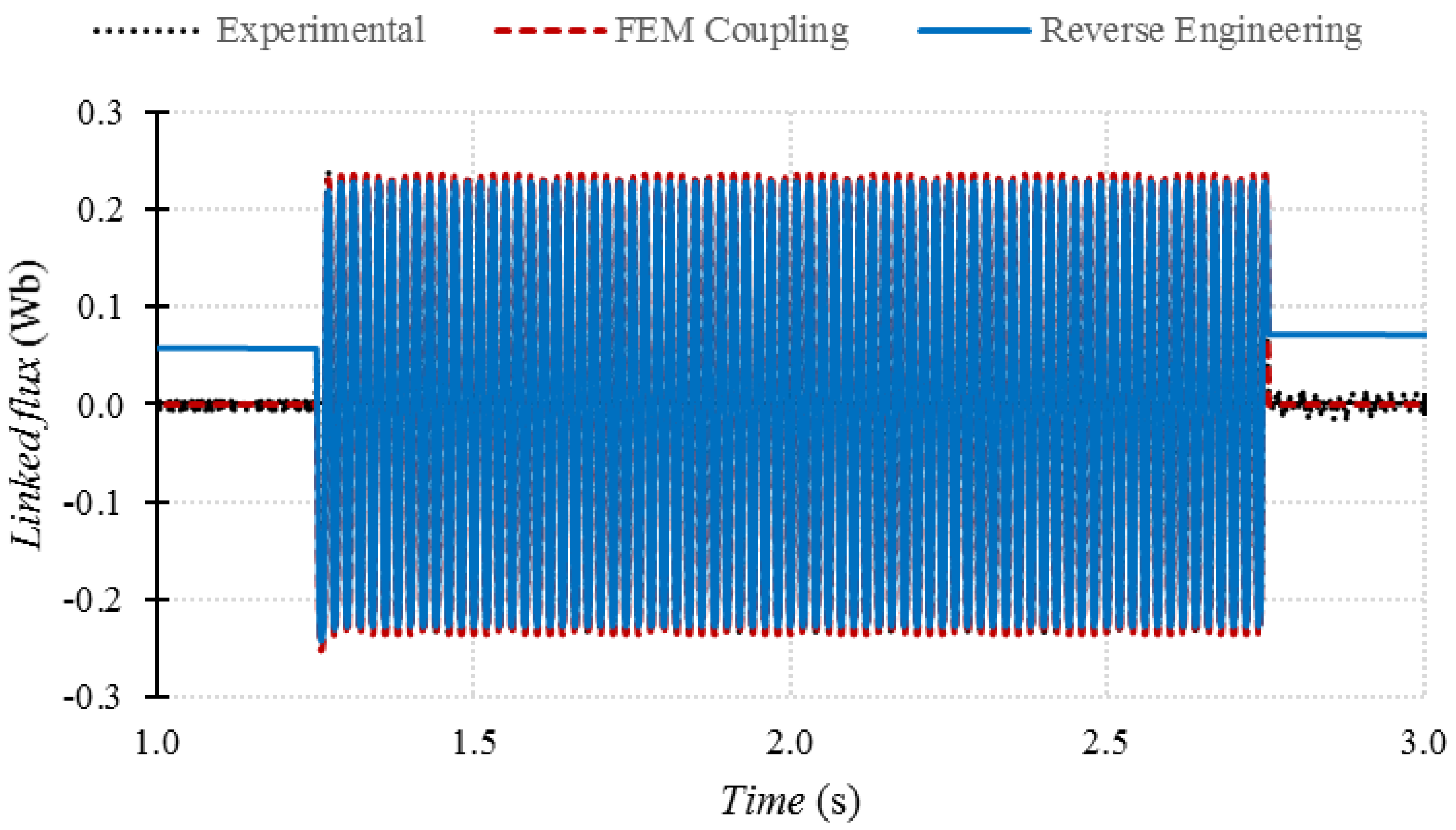
Limited current (excluding 1st peak):

- 36.8 A (Experimental)
- 37.2 A (FEM Coupling)
- 34.9 A (Reverse Engineering)

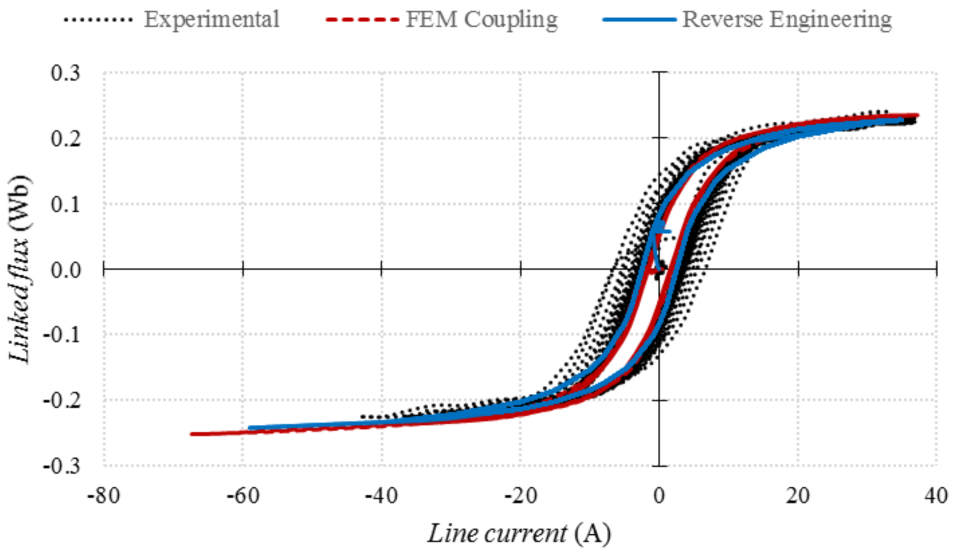
Line Current



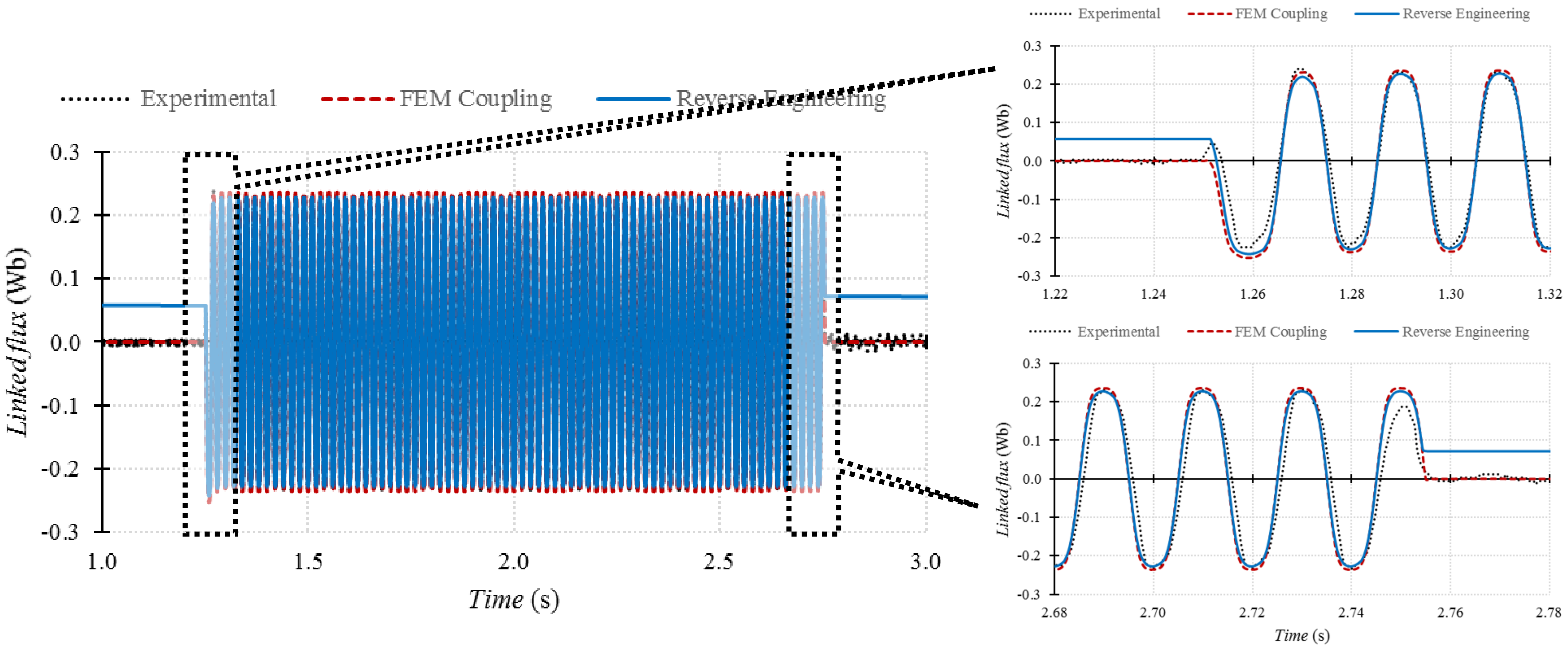
Linked Flux and Hysteresis Loop



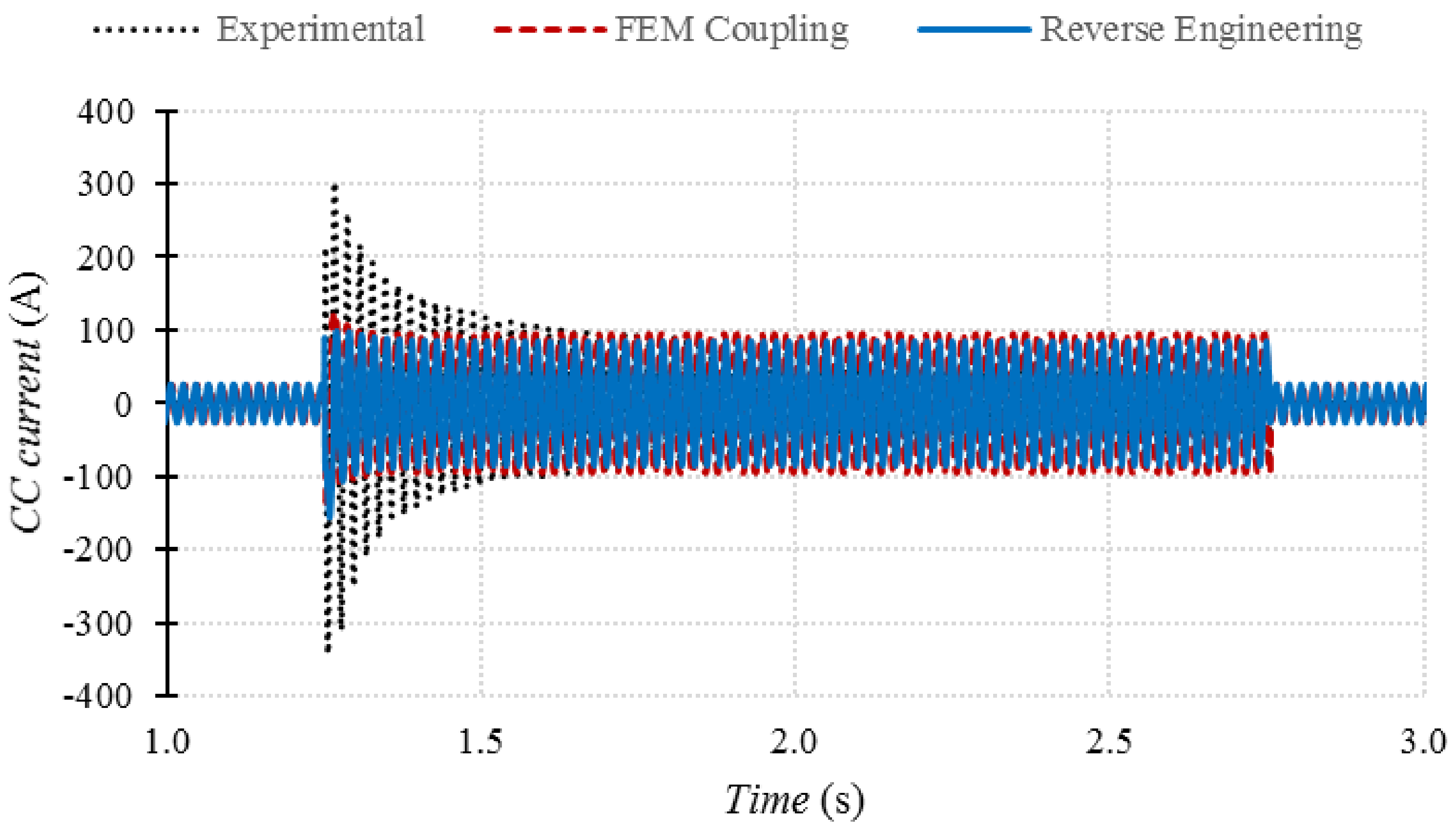
<u>Maximum flux</u>:
- 0.239 Wb (Experimental)
- 0.252 Wb (FEM Coupling)
- 0.242 Wb (Reverse Engineering)



Linked Flux and Hysteresis Loop



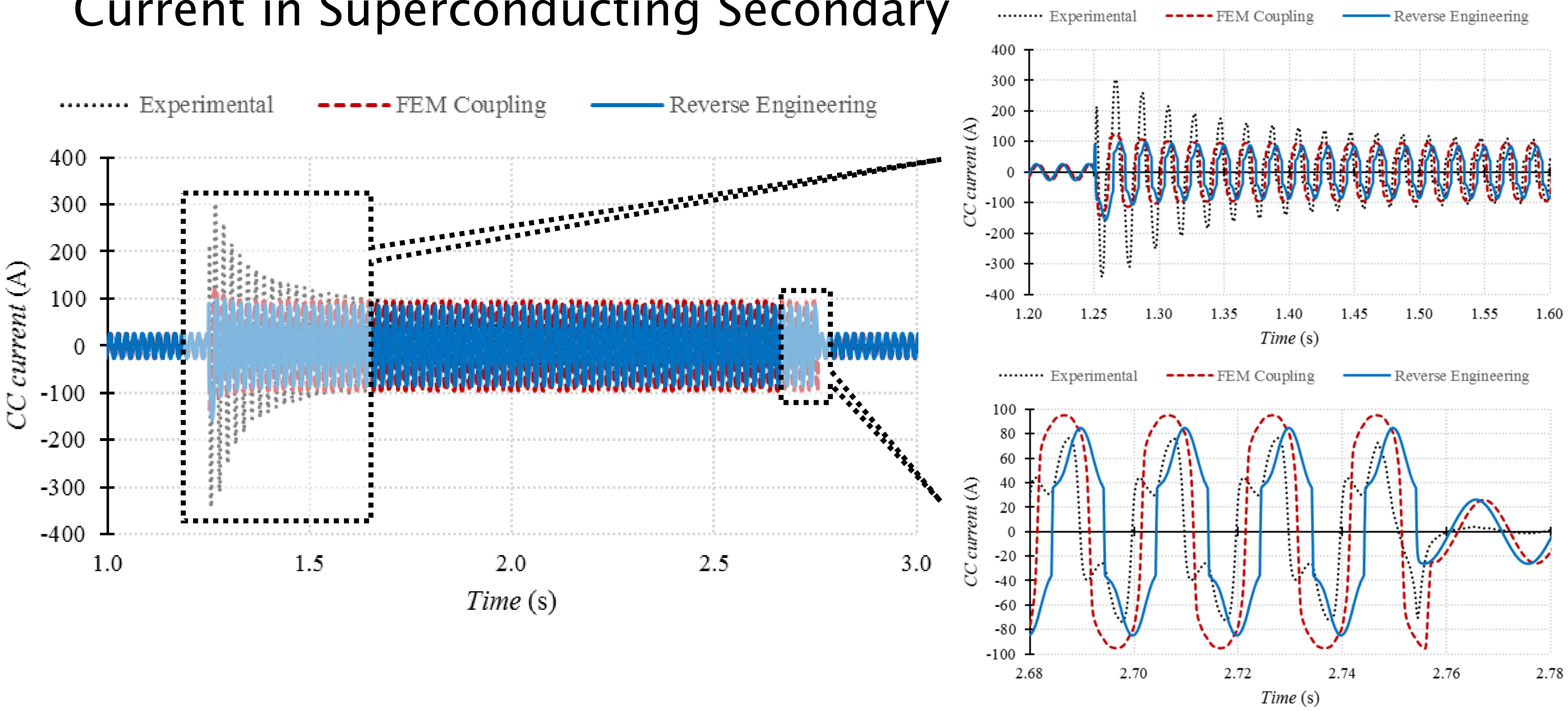
Current in Superconducting Secondary



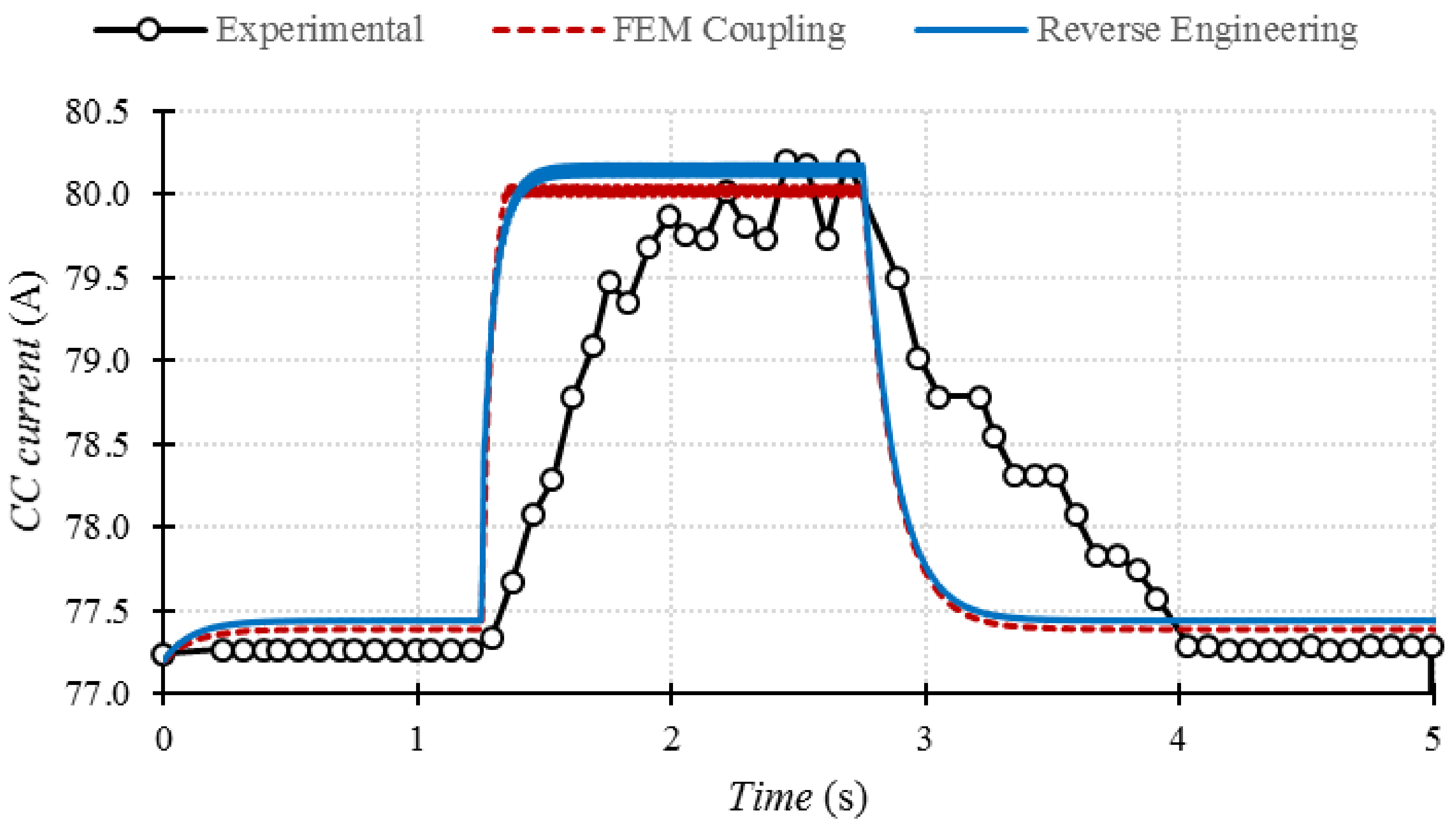
Maximum current (1st peak):
- 342.6 A (Experimental)
- 142.7 A (FEM Coupling)
- 152.0 A (Reverse Engineering)

Maximum current (steady-state):
- 74.2 A (Experimental)
- 95.1 A (FEM Coupling)
- 82.9 A (Reverse Engineering)

Current in Superconducting Secondary



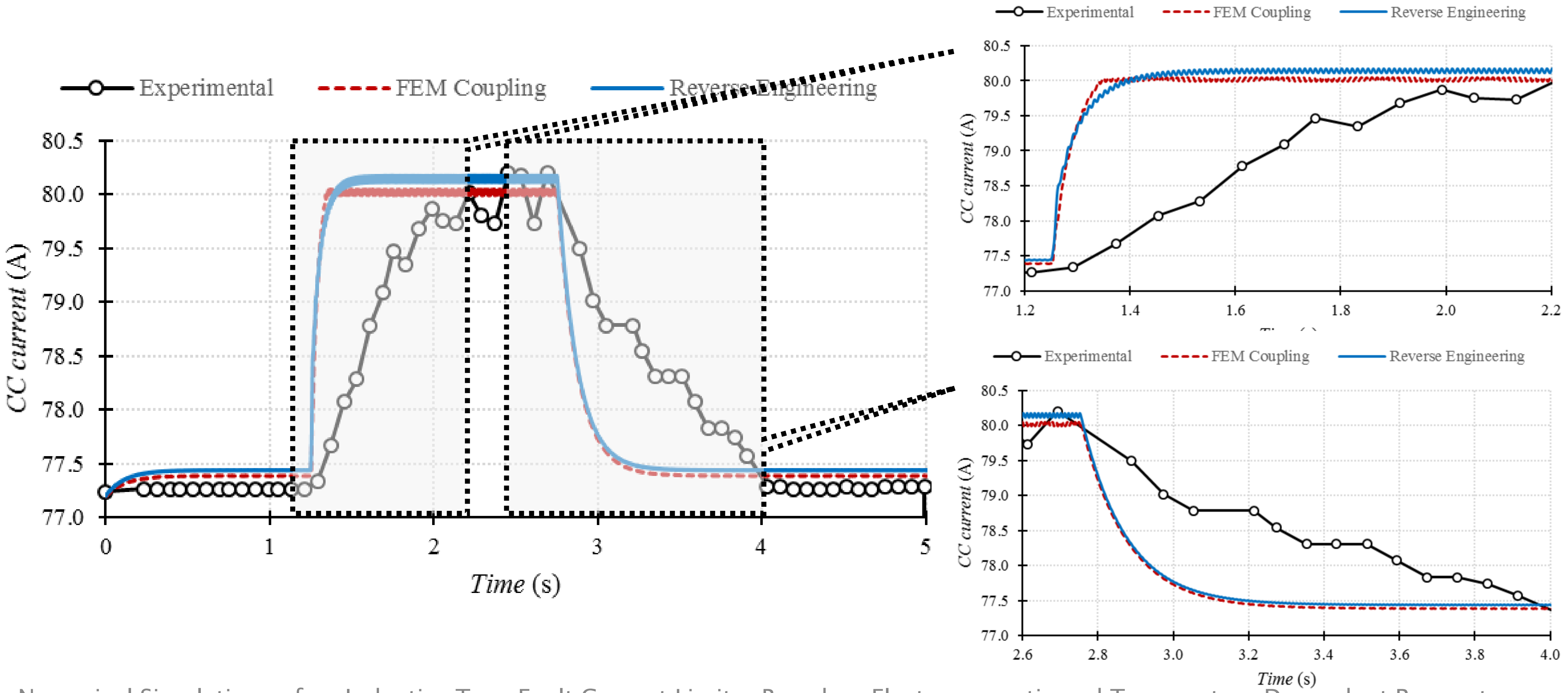
Temperature in Superconducting Secondary



Maximum temperature:

- 80.2 K (Experimental)
- 80.1 K (FEM Coupling)
- 80.2 K (Reverse Engineering)

Temperature in Superconducting Secondary



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Conclusions

Conclusions

Good agreement between experimental and simulations were achieved.

The reverse engineering methodology provides results in **few seconds** while the electromagnetic-thermal coupled simulation based on FEM takes **several days** (5~7 days depending on mesh quality). Furthermore, complex grids can be easily simulated by means of the reverse engineering methodology.

Experimental temperature measurements shows drift due to thermal inertia of the RTD sensor. Ripple during fault occurrence is also observed.

HTS MODELLING 2016

5th International Workshop on Numerical Modelling of High Temperature Superconductors

Thank You!

Pedro Arsénio, PhD Student

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Bologna, June 16 2016