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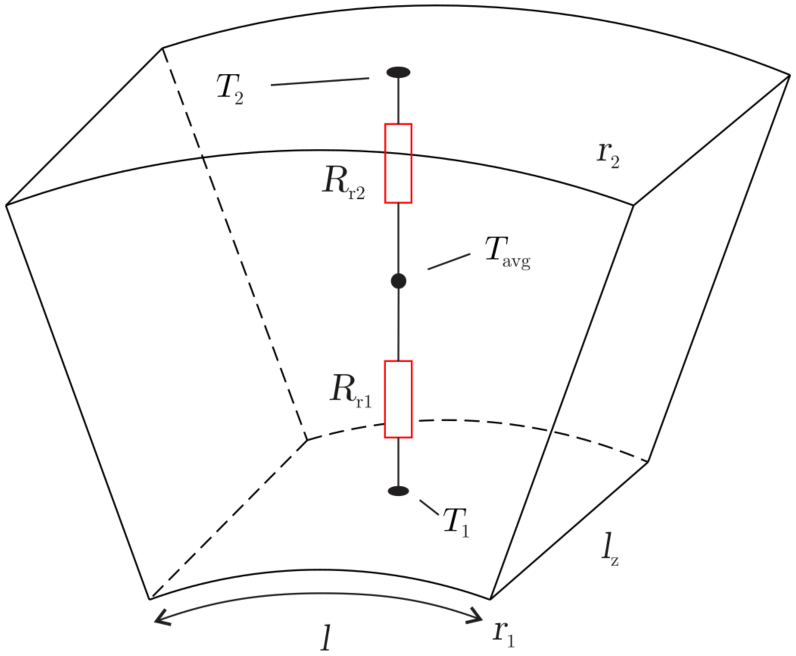
Transient Simulations for HTS Cables

Development of a Lumped Thermal Model

de Sousa, W.T.B.



SuperLink - The longest HTS Cable in the World

Karlsruhe Institute of Technology

Stromtransport: Das längste Hochspannungs-Supraleiterkabel der Welt

In München soll das längste Supraleiterkabel der Welt realisiert und wirtschaftlich eingesetzt werden. Das KIT ist an dem Projekt beteiligt.

Die Wissenschaftlerinnen und Wissenschaftler am KIT konzipieren mit den Projektpartnern effiziente und leistungsstarke supraleitende Dreileiterkabel (Abbildung: NKT Cables Group)

Im Stromnetz der Zukunft müssen große Mengen elektrischer Energie aus erneuerbaren Quellen in dicht bebaute städtische Lastzentren geleitet werden. Mit Supraleitern kann Strom ohne Widerstand und Verlust transportiert werden. „Die Leitung soll perspektivisch insgesamt zwölf Kilometer lang werden und kann eine bestehende 380 Kilovolt Leitung im regulären Betrieb ersetzen“, sagt Mathias Noe, Direktor des Instituts für Technische Physik am KIT. „Wir nutzten ein Hochtemperatur-Supraleiterkabel, das sich durch extreme Kompaktheit und hohe Leistung auszeichnet.“

Gemeinsam möchte das Konsortium innerhalb von zwei Jahren alle notwendigen technischen Voraussetzungen erfüllen und die wichtigsten Komponenten entwickeln; hierzu gehören ein 200 Meter langes Kabelteilstück, Endverschlüsse und die Kühlung. Nach erfolgreichem Abschluss des Projektes sollen dann die zwölf Kilometer angegangen werden. Die Forschungsarbeiten des KIT umfassen vor allem die komplexe Simulation des elektromagnetischen und thermischen Verhaltens des Kabels.

Die Forschungen sind Teil des vom Bundesministerium für Wirtschaft und Energie geförderten Projekts „SuperLink“. Dem Projektkonsortium gehören neben dem KIT und der Fachhochschule Südwestfalen die Stadtwerke München sowie die Unternehmen THEVA, NKT Cables Group und Industriegase-Konzern Linde an.

SWM

NKT

THEVA

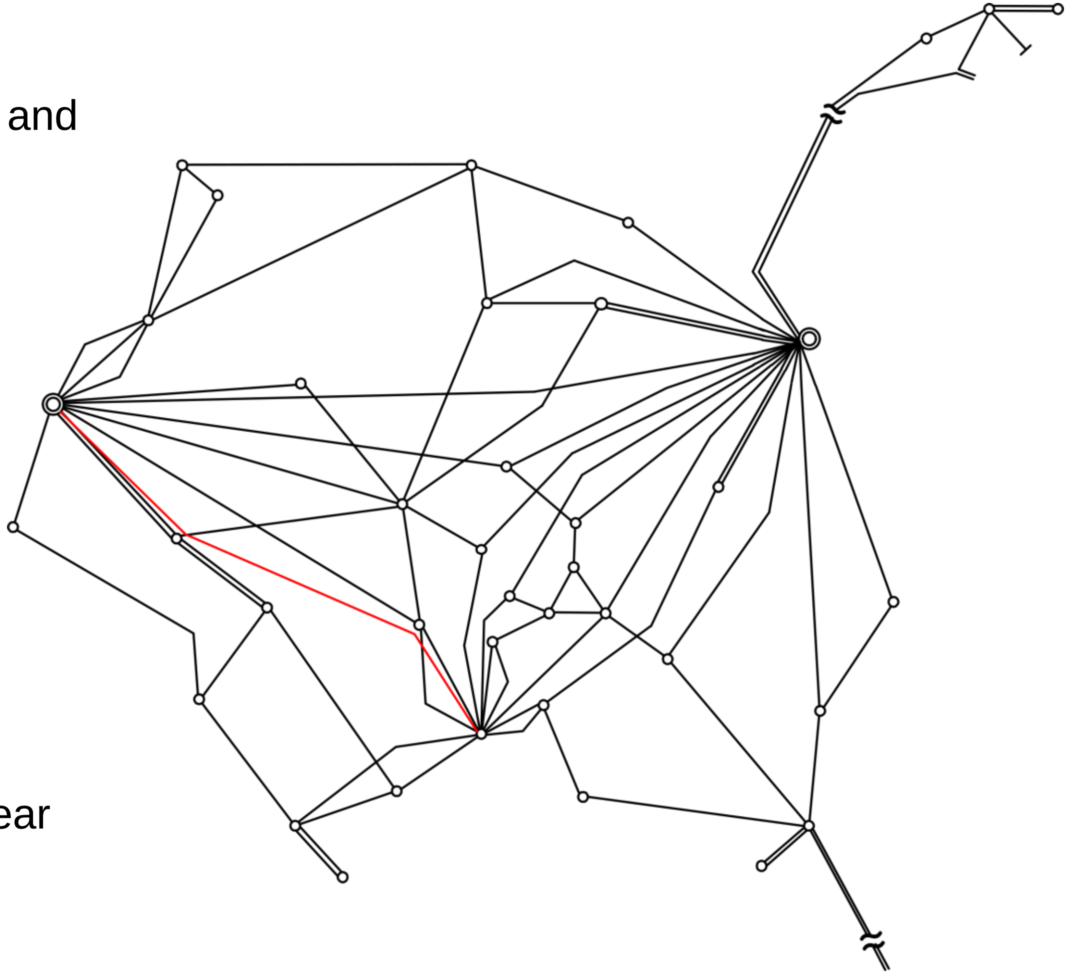
Fachhochschule Südwestfalen
iversity of Applied Sciences

Linde

KIT
Karlsruhe Institute of Technology

Gefördert durch:
Bundesministerium
für Wirtschaft
und Klimaschutz

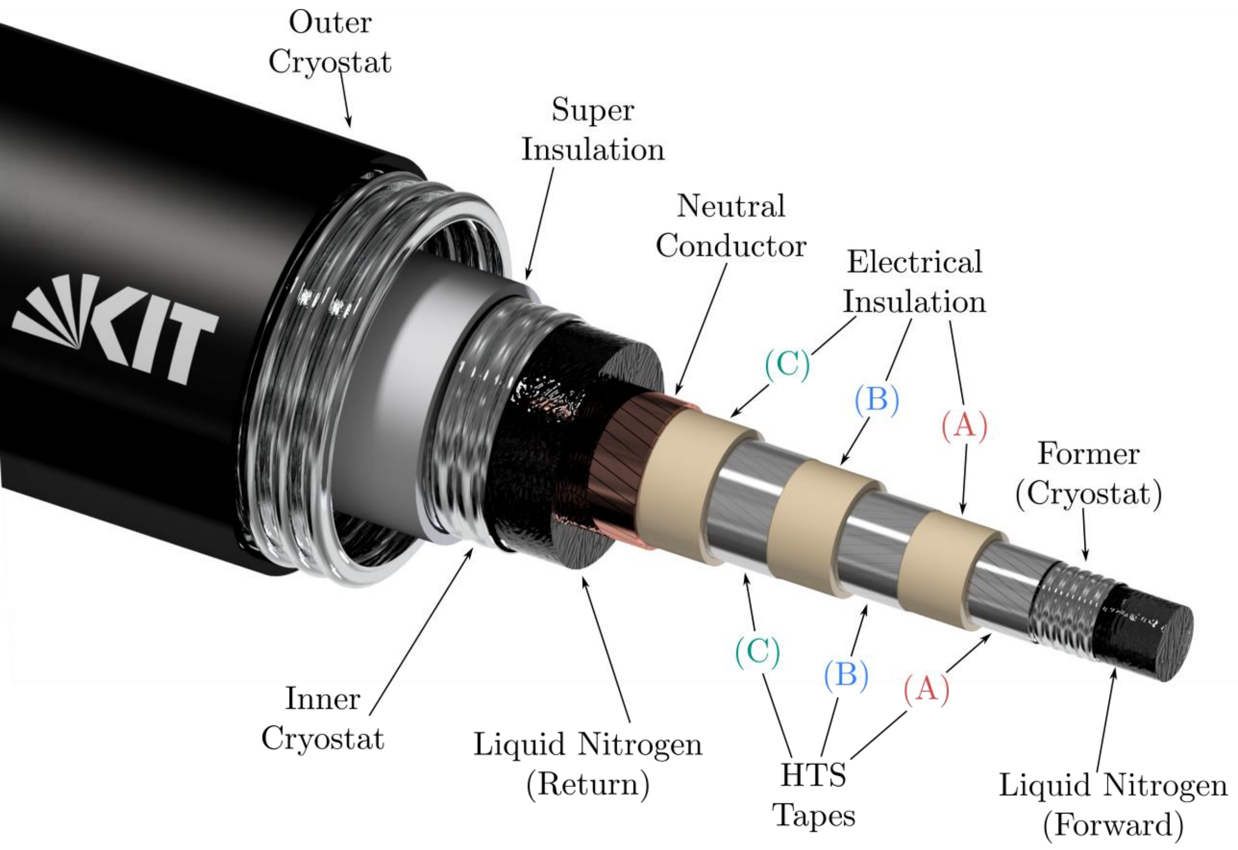
SuperLink Project - Goals

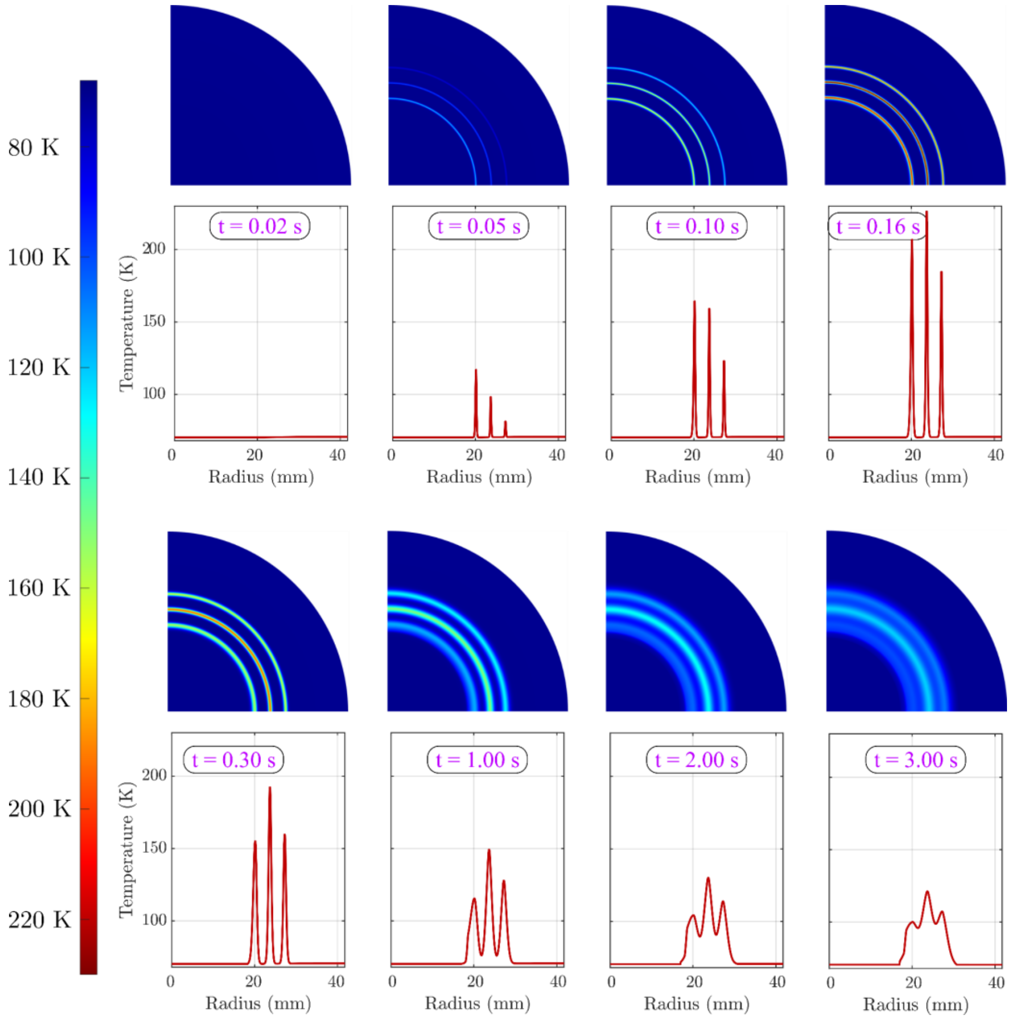


- Development of a commercial, long, high-power HTS cable
  - Design concept for a 15 km long 110 kV cable line with all components and auxiliaries
  - Capacity 500 MVA in a compact single cable (three-in-one)
  - Closed cooling cycle & distributed cooling over 15 km
  - Modeling HTS cable’s impact on the surrounding grid
    - It is highly desirable the development of fast and reliable models to investigate HTS cables in electrical networks
      - Analytical methods – not possible! HTS material are very non-linear materials
      - Numerical lumped schemes – may be a solution…

The 2D Finite Difference-Model (FDM)

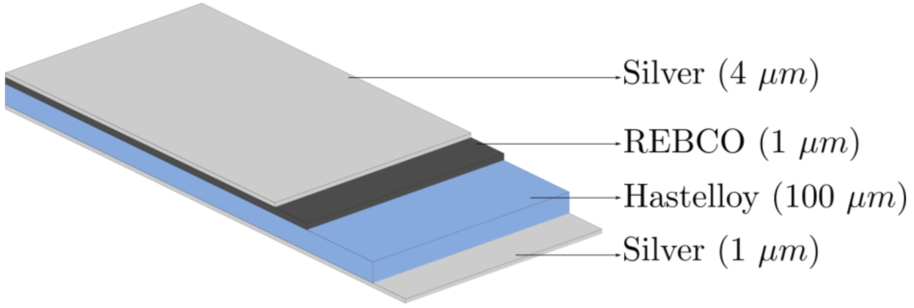
- Not good for power systems simulators





W. T. B. de Sousa et al 2021, 'An open-source 2D Finite Difference Based Transient Electro-thermal Simulation Model for Three-phase Concentric Superconducting Power Cables' Supercond. Sci. Technol. 34 015014

Lumped-Parameter Model – Thermal-Electrical Analogy

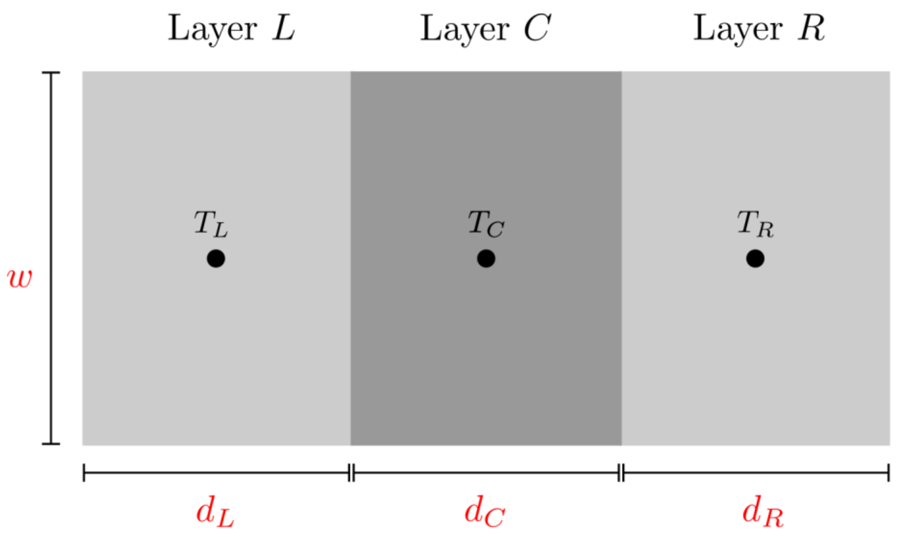


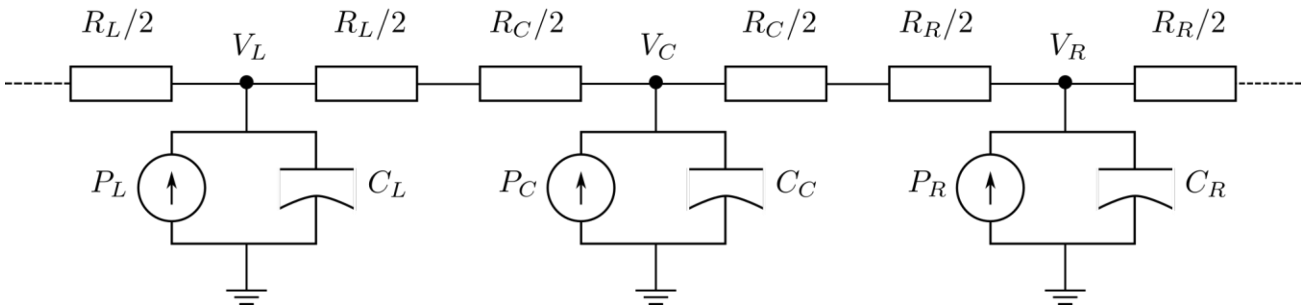
- Cartesian Coordinates

$$R_i = \frac{d_i}{k_i \cdot A_i}$$

$$C_i = \rho_i \cdot c_i \cdot d_i \cdot A_i$$

$$A_i = d_i \cdot w$$





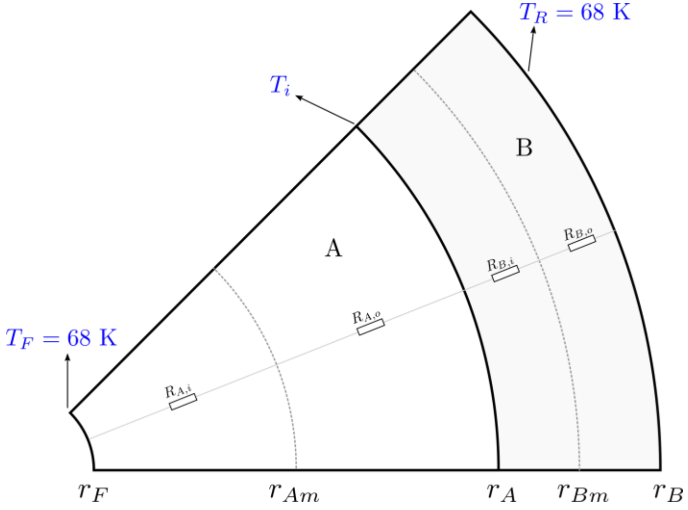
Such schema has been very successful for simulations of SFCLs !

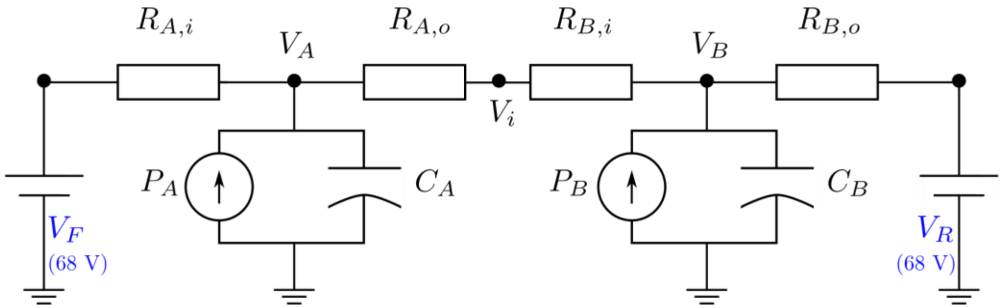
Lumped-Parameter Model – Thermal-Electrical Analogy

- Cylindrical Coordinates

$$Ri_L = \frac{\log(r_{Lm}/r_i)}{2 \cdot \pi \cdot k_i \cdot \ell}$$

$$Ro_L = \frac{\log(r_L/r_{Lm})}{2 \cdot \pi \cdot k_i \cdot \ell}$$

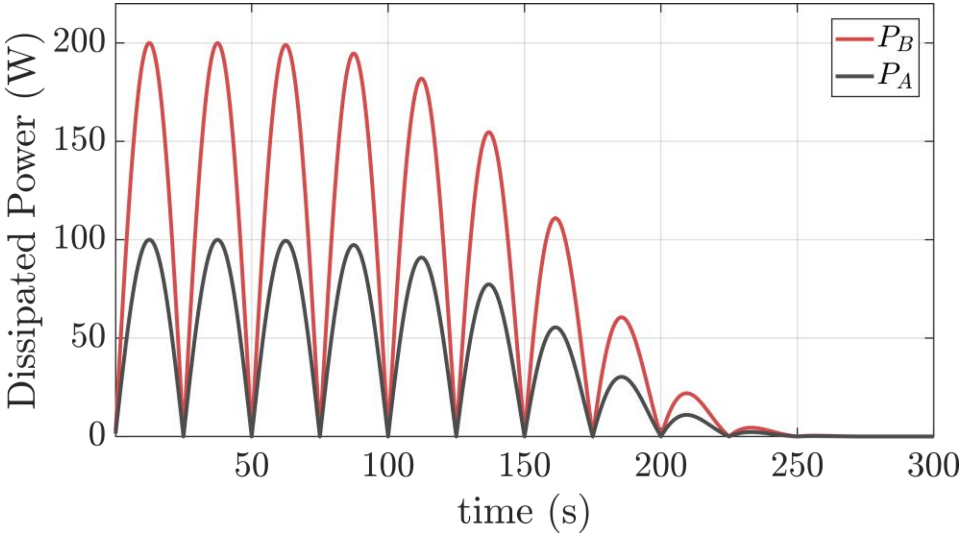




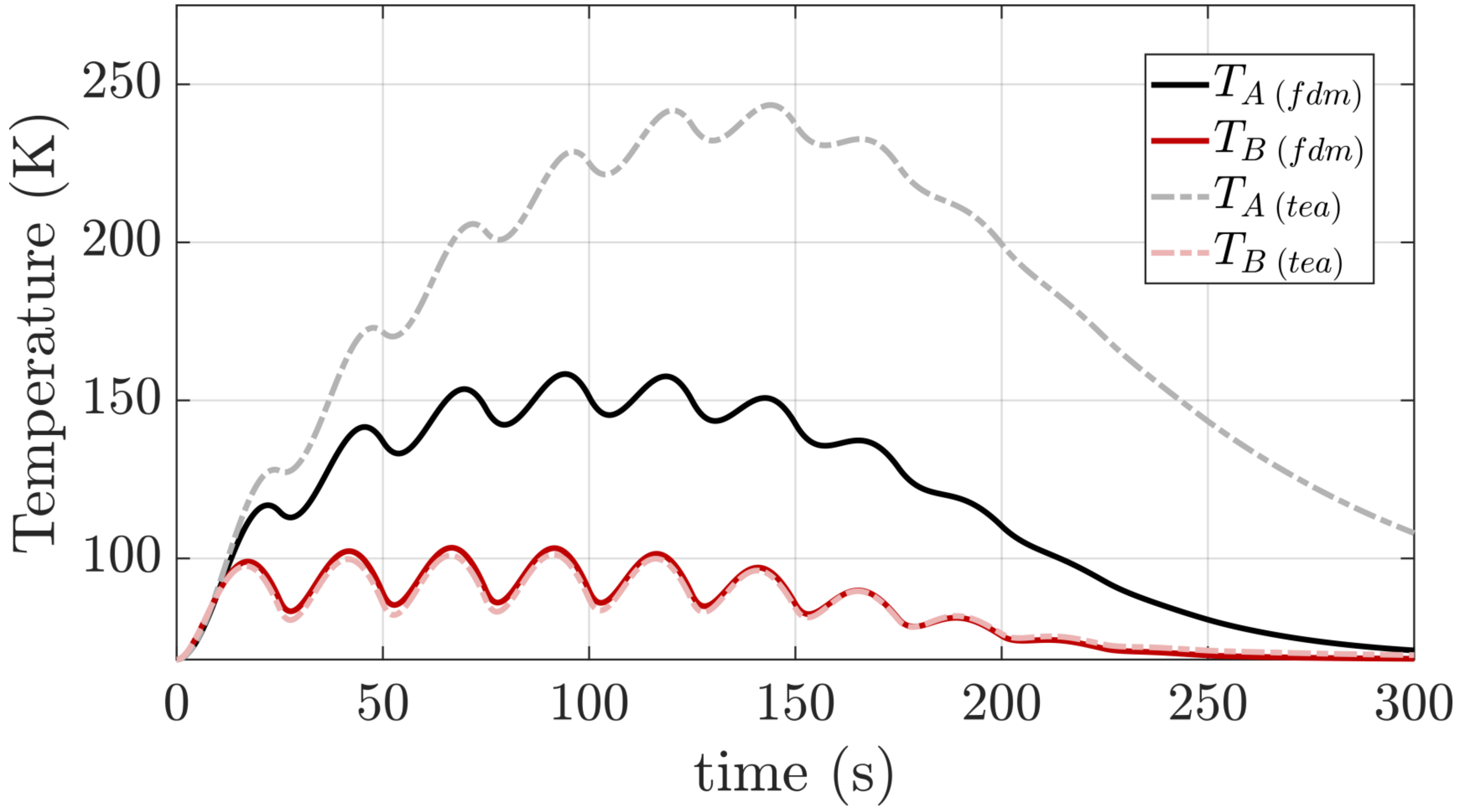
$$C_L = \rho_L \cdot c_L \cdot \pi \cdot \left(r_L^2 - r_i^2\right)$$

Layer	Thermal Conductivity
A	0.15 W/mK
B	500 W/mK

Study case

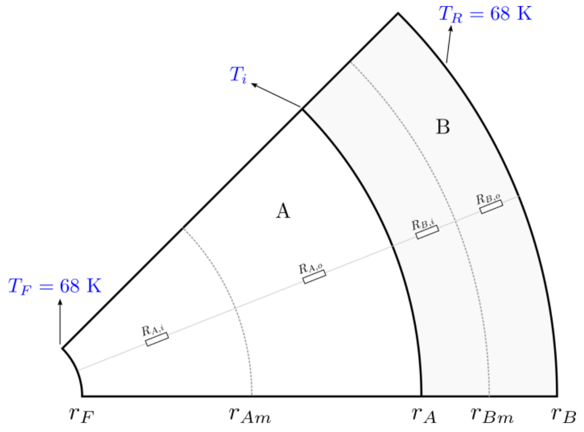


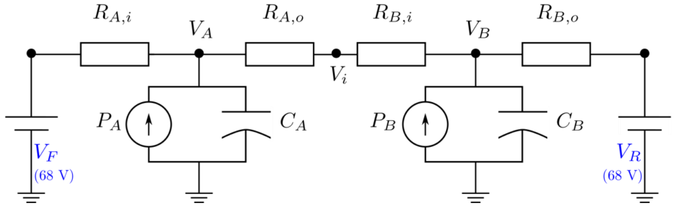
Lumped-Parameter Model – Study Case



Comparison

FDM x Lumped





Lumped-Parameter Model

- The proposed schema does not provide good results
  - Method not suitable for designs with internal heat generation.
  - Distributed losses can not be lumped into a single heat flux source.
- A modification in the analogue circuit is required to suit our problem’s characteristics.
  - Derivation of lumped cylindrical components based on mean temperature values shows that the internal heat generation is indeed applied correctly.

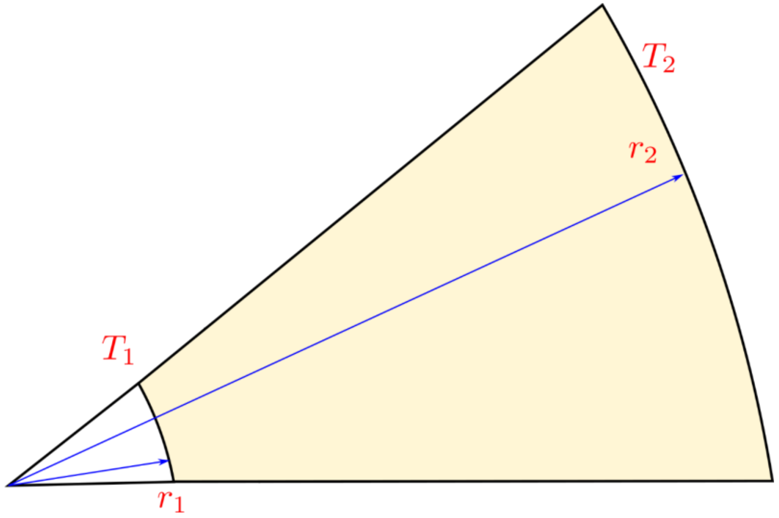
Lumped-Parameter Model – Mean temperature values

- Considering radial heat flow conduction:

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{d^2T}{dz^2} + \frac{g}{k} = 0$$

- General analytical solution:

$$T(r) = a \cdot \ln(r) + \frac{g}{4k}r^2 + b \qquad a = \frac{1}{\ln\left(r_2/r_1\right)}\left[T_2 - T_1 + \frac{g \cdot \left(r_2^2 - r_1^2\right)}{4k}\right]$$



- Calculating the mean temperature value T$_m$

$$T_m = \frac{2}{r_2^2 - r_1^2}\int_{r_1}^{r_2} T(r) \cdot r \cdot dr$$

$$T_m = T_2\left[\frac{r_2^2}{\left(r_2^2 - r_1^2\right)} - \frac{1}{2\ln\left(r_2/r_1\right)}\right] + T_1\left[\frac{1}{2\ln\left(r_2/r_1\right)} - \frac{r_1^2}{\left({r_2}^2 - r_1^2\right)}\right] + g\left[\frac{\left(r_1^2 + r_2^2\right)}{8k} - \frac{\left(r_2^2 - r_1^2\right)}{8k \cdot \left(\ln\left(r_2/r_1\right)\right)}\right]$$

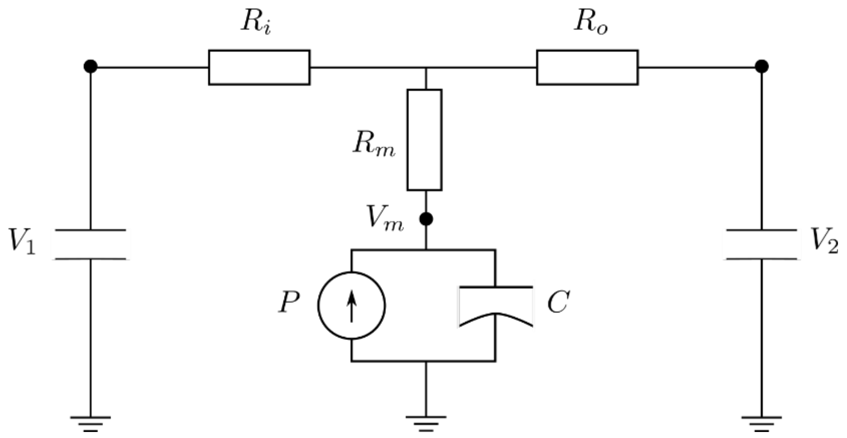
Lumped-Parameter Model – Mean temperature values

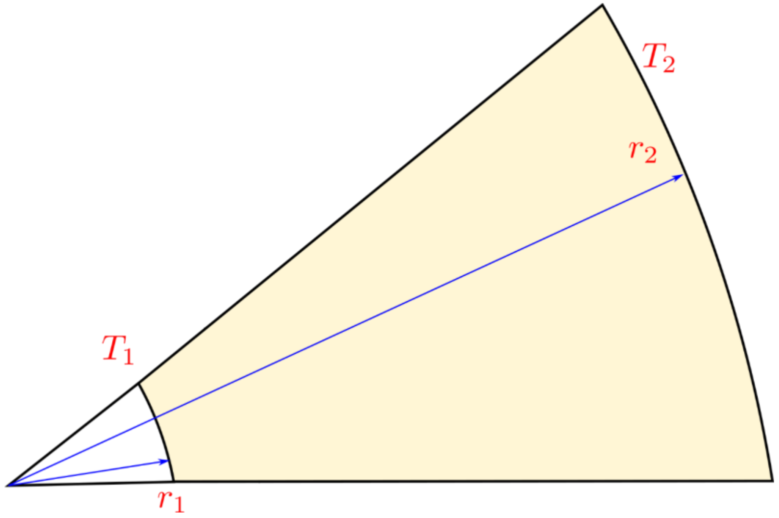
- Electrical Analogy

$$G_o = \frac{1}{R_o}$$

$$G_i = \frac{1}{R_i}$$

$$g = \frac{P}{V}$$





$$V_m = V_2\left[\frac{G_o}{G_o+G_i}\right] + V_1\left[\frac{G_i}{G_o+G_i}\right] + P\left[\frac{1}{G_o+G_i} + R_m\right]$$

- Mean temperature value T_m

$$T_m = T_2\left[\frac{r_2^2}{(r_2^2-r_1^2)} - \frac{1}{2\ln(r_2/r_1)}\right] + T_1\left[\frac{1}{2\ln(r_2/r_1)} - \frac{r_1^2}{(r_2{}^2-r_1^2)}\right] + g\left[\frac{(r_1^2+r_2^2)}{8k} - \frac{(r_2^2-r_1^2)}{8k\cdot(\ln(r_2/r_1))}\right]$$

Lumped-Parameter Model – Mean temperature values

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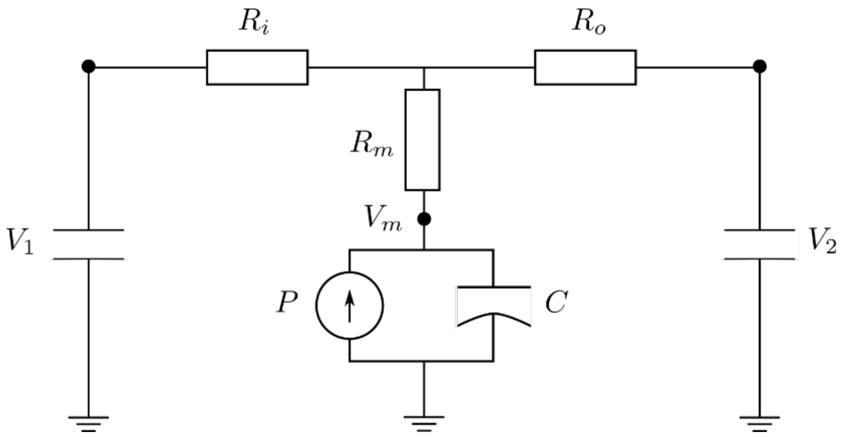

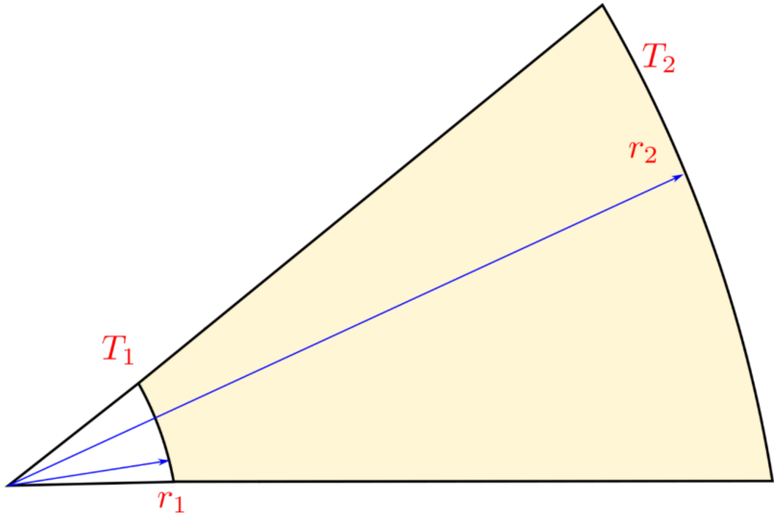

$$R_i = \frac{1}{4\pi k\ell}\left[\frac{2r_2^2\ln\left(r_2/r_1\right)}{\left(r_2^2-r_1^2\right)} - 1\right] \qquad R_o = \frac{1}{4\pi k\ell}\left[1 - \frac{2r_1^2\ln\left(r_2/r_1\right)}{\left(r_2^2-r_1^2\right)}\right]$$

$$C = \rho\cdot c\cdot\pi\cdot\left(r_2^2-r_1^2\right)$$

$$R_m = \frac{-1}{8\pi\left(r_2^2-r_1^2\right)k\ell}\left[r_2^2+r_1^2-\frac{4r_2^2r_1^2\ln\left(r_2/r_1\right)}{\left(r_2^2-r_1^2\right)}\right]$$

Lumped-Parameter Model – Thermal-Electrical Analogy

- Cylindrical Coordinates

$$Ri_L = \frac{\log(r_{Lm}/r_i)}{2 \cdot \pi \cdot k_i \cdot \ell}$$

$$Ro_L = \frac{\log(r_L/r_{Lm})}{2 \cdot \pi \cdot k_i \cdot \ell}$$

$$C_L = \rho_L \cdot c_L \cdot \pi \cdot \left(r_L^2 - r_i^2\right)$$

Layer	Thermal Conductivity
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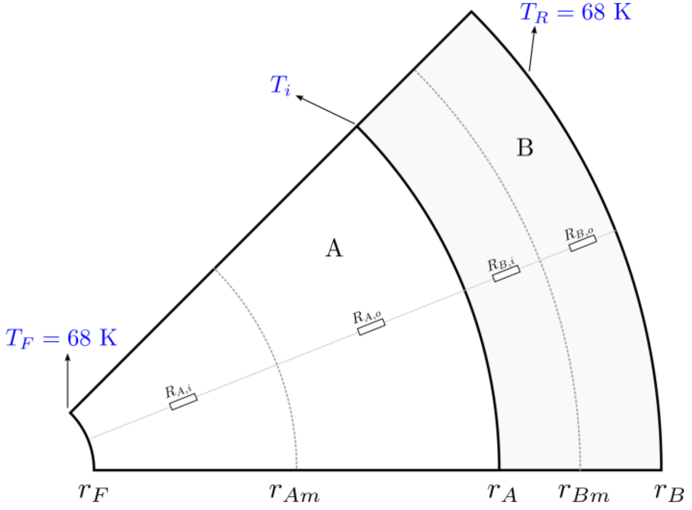
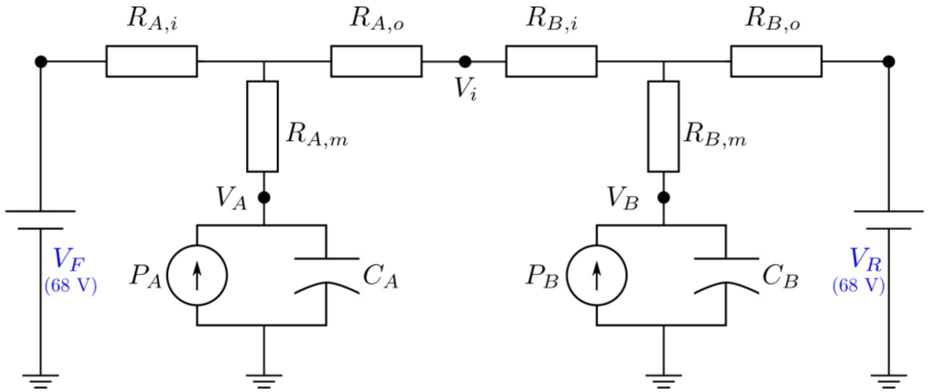
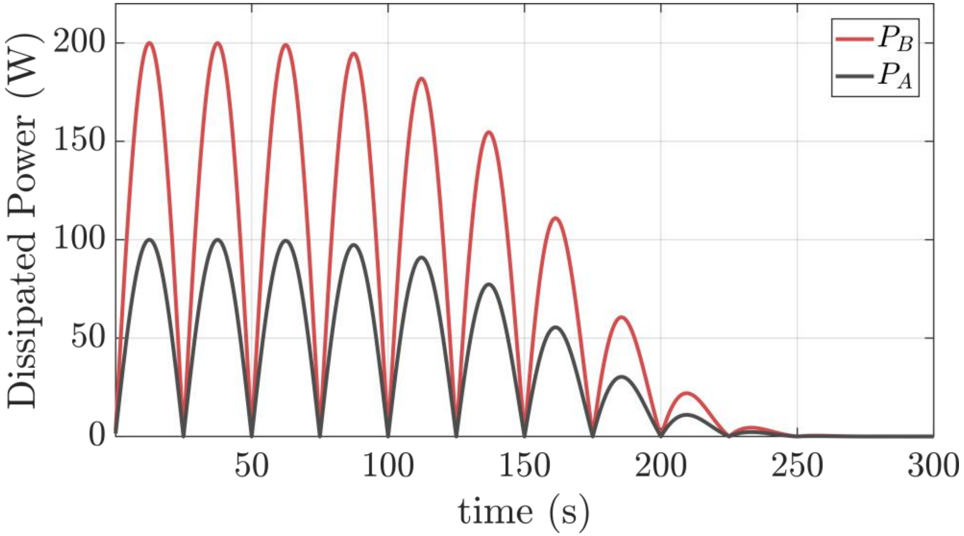
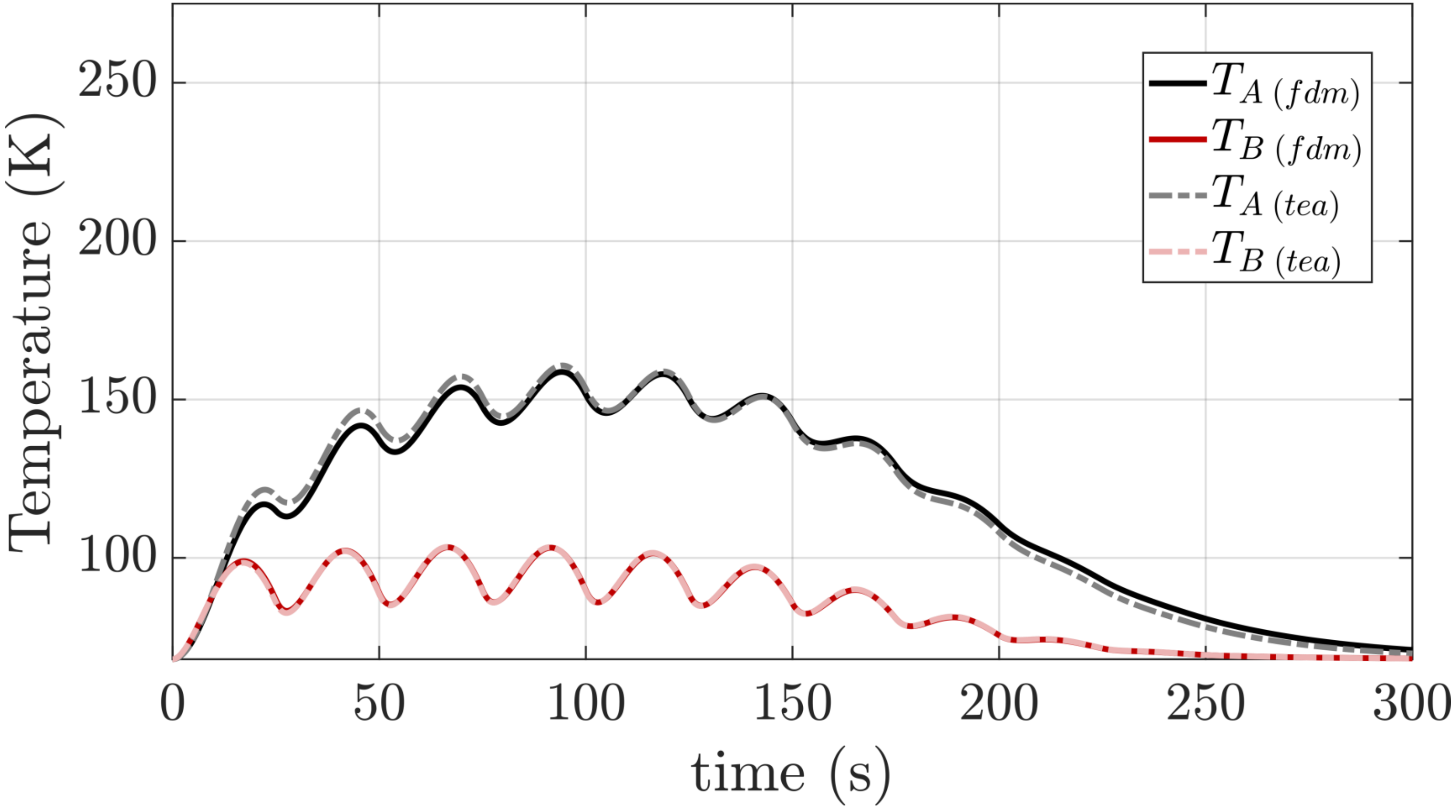




Study case



Lumped-Parameter Model – Study Case



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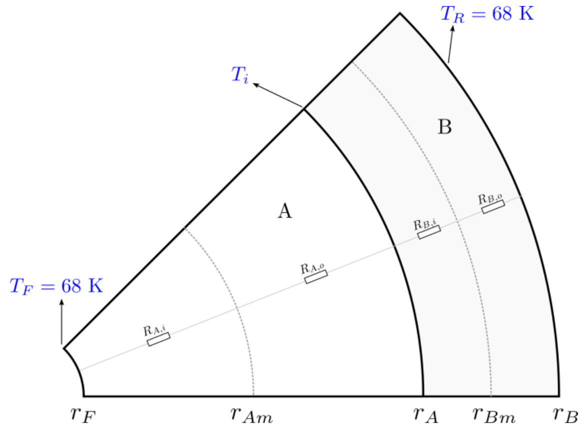
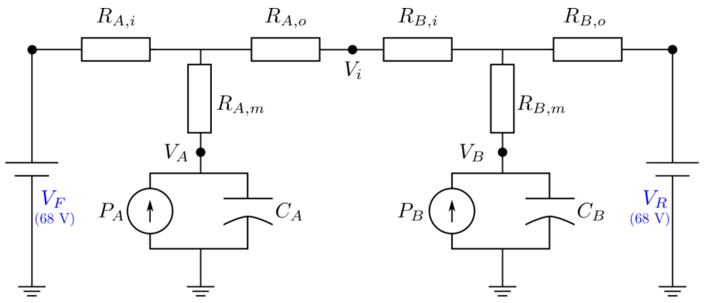
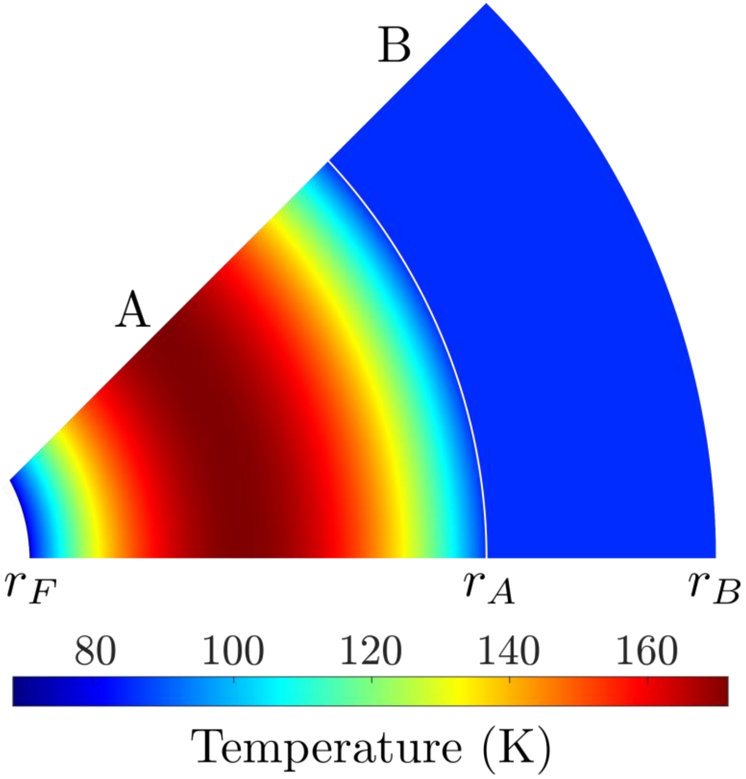


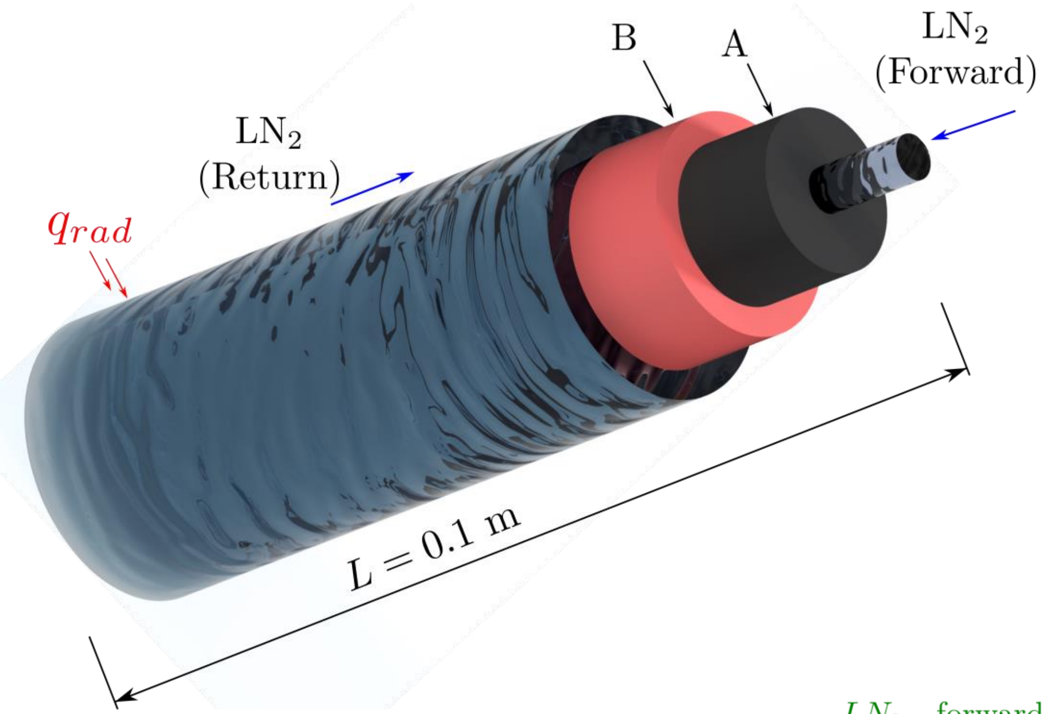


Lumped-Parameter Model – Multilayer Concept

- First results indicates a stable and reliable model, however..
- Its limits must be known!
  - Model based on mean values, thus high temperatures gradients inside the material leads to discrepancies
    - Although the discrepancies between the models are not harsh, such a behavior tends to become worse in cases were several layers and different materials are considered
    - **Possible solution**: split the layers into smaller parts



Lumped-Parameter Model – Cooling



- Convective Heat Transfer

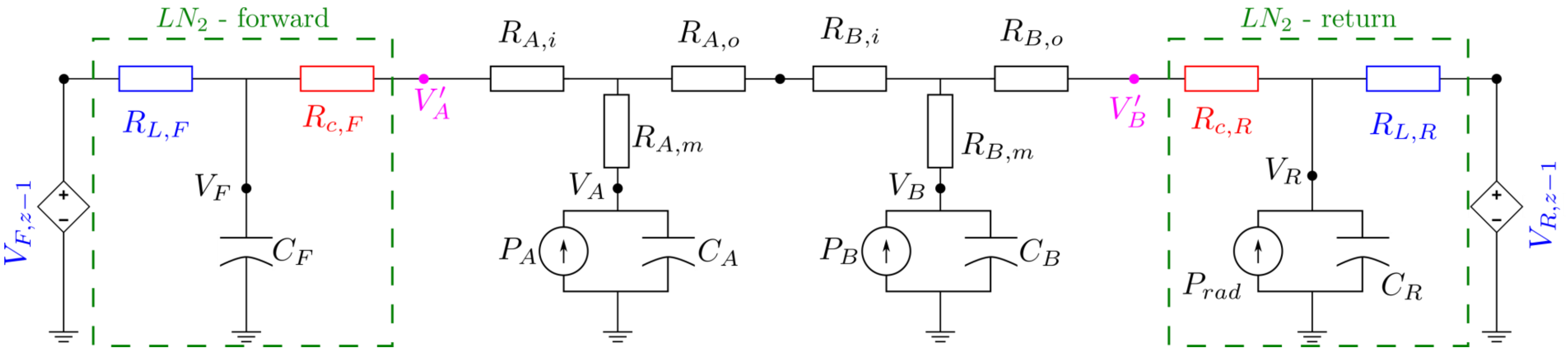
$$\dot{Q} = h_c \cdot A \cdot (T_s - T_f)$$

- LN_2 forced flow (Forward and Return)

$$\rho c \frac{dT_R}{dt} - \rho c v_R \frac{dT_R}{dz} = \frac{h_c \cdot U_R \left(T'_B - T_R\right)}{A_R} + \frac{q_{rad}}{A_R}$$

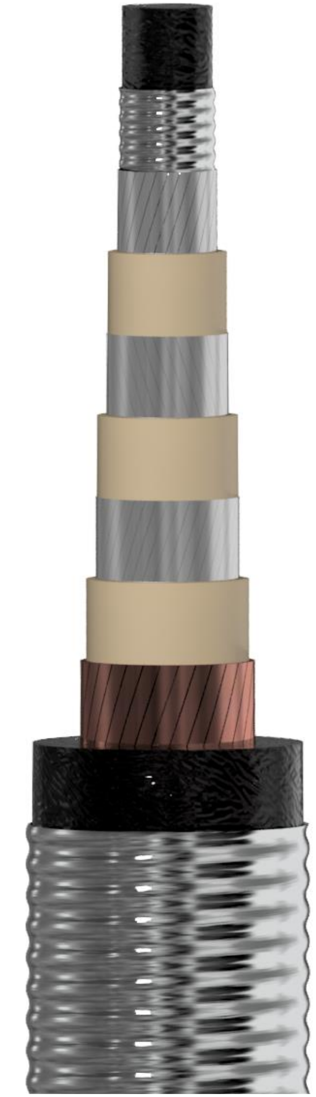
$$R_c = \frac{1}{h_c \cdot A_c}$$

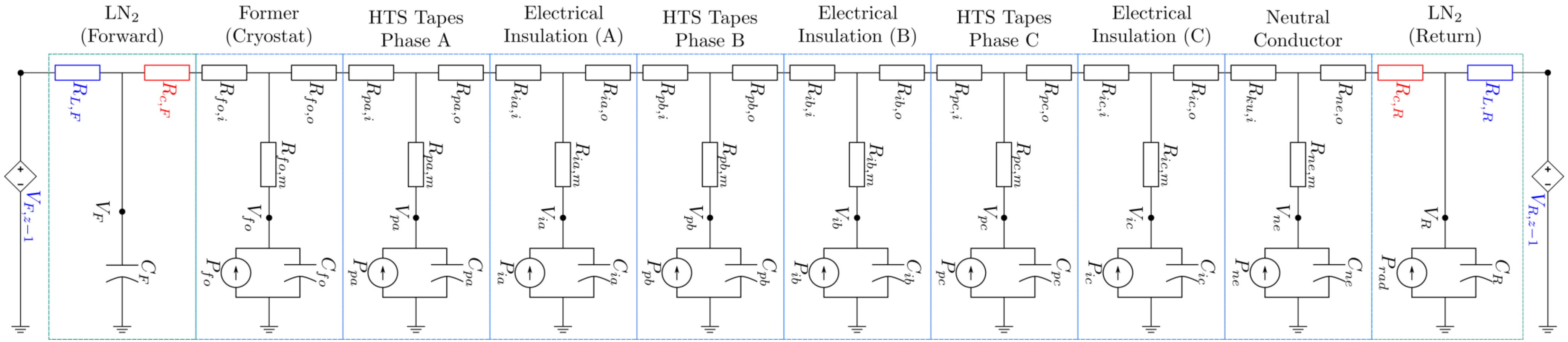
$$R_L = \frac{1}{\dot{m} \cdot c}$$



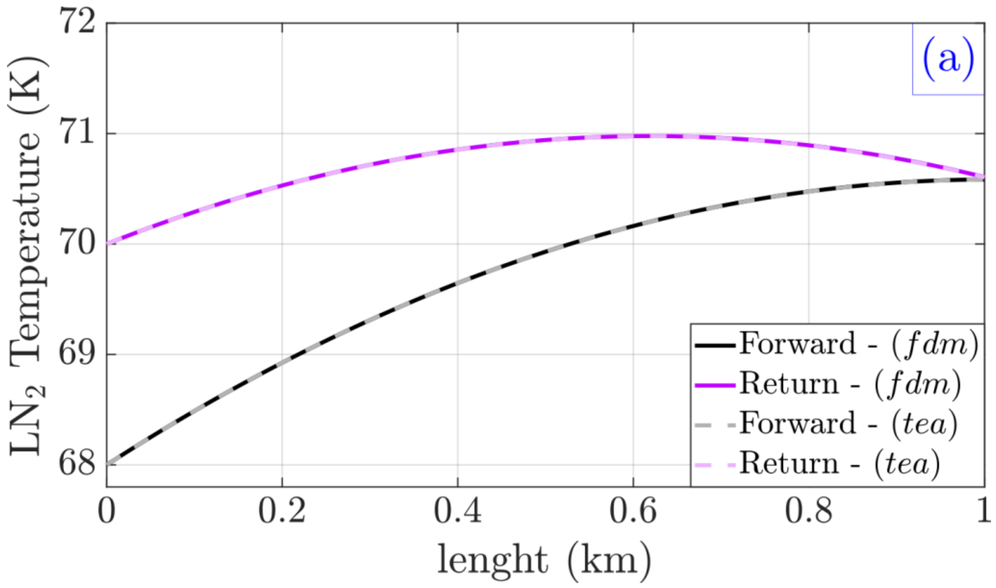
Lumped-Parameter Model

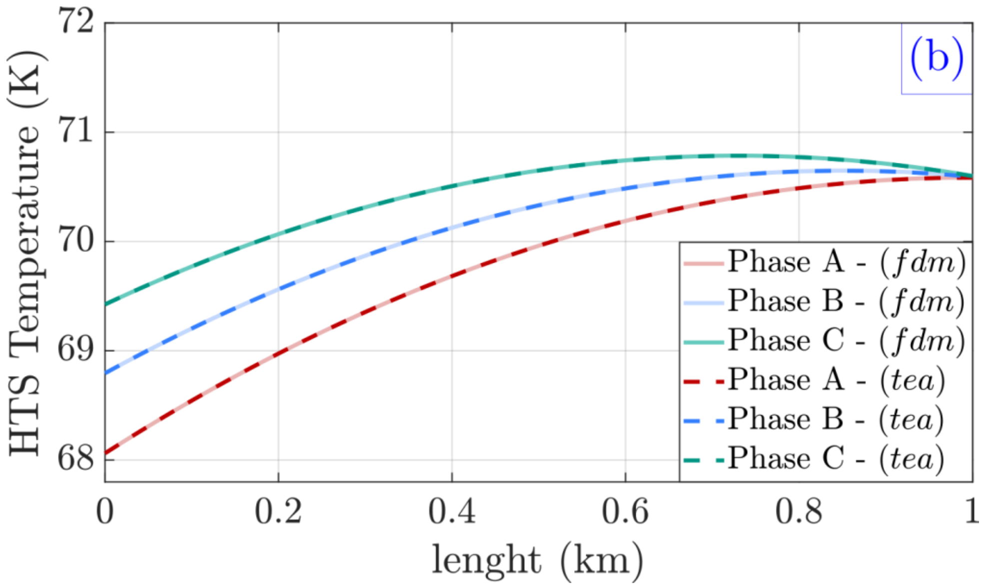
Material	Thickness	Thermal Conductivity	FDM (1160)	Lumped (26)
Former	2.50 mm	15.0 W/mK	125	8
HTS Tapes	0.21 mm	150 W/mK	30	1
Isolator (PPLP)	3.40 mm	0.15 W/mK	450	15
Copper	3.70 mm	534.2 W/mK	555	2

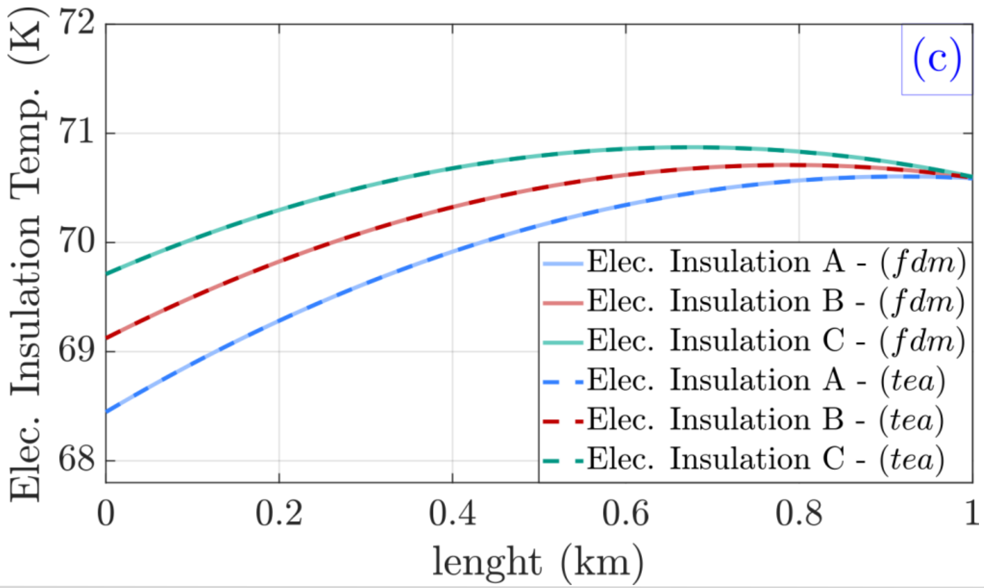




Results – Steady State

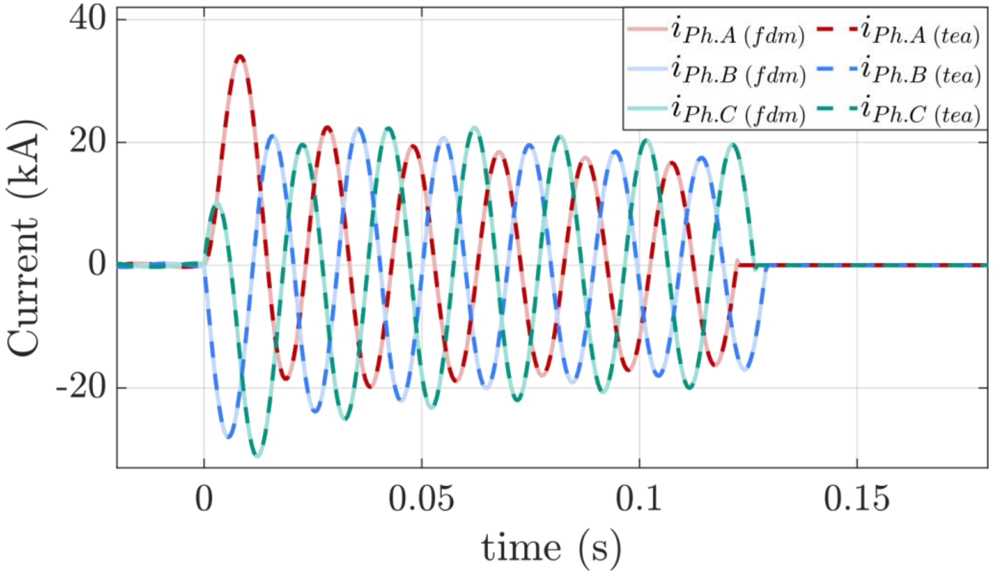


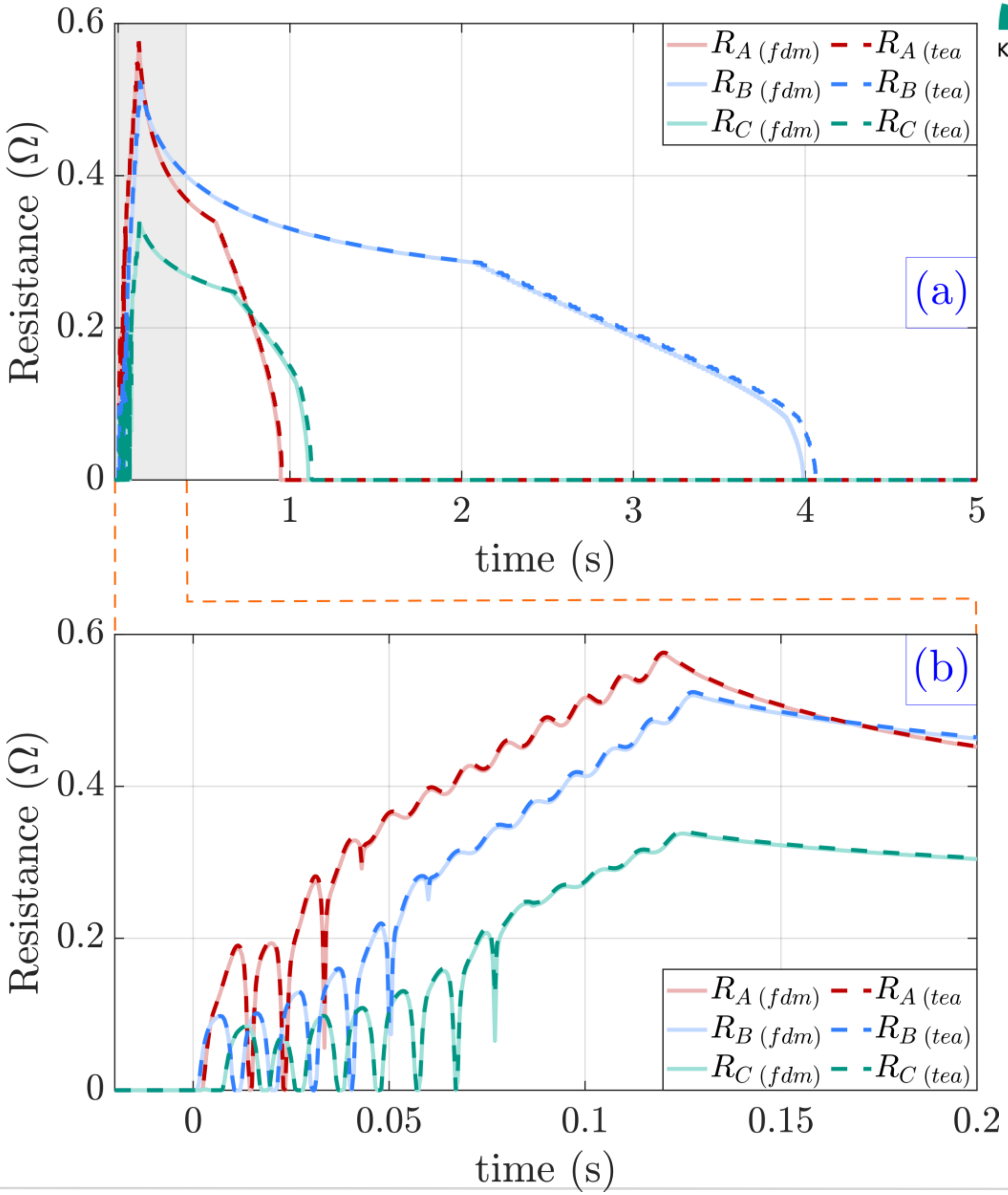




- No major deviation has been identified during the steady AC regime
  - *Deviations are smaller than 0.5 %*

Results – Transient Regime (Current and Resistances)

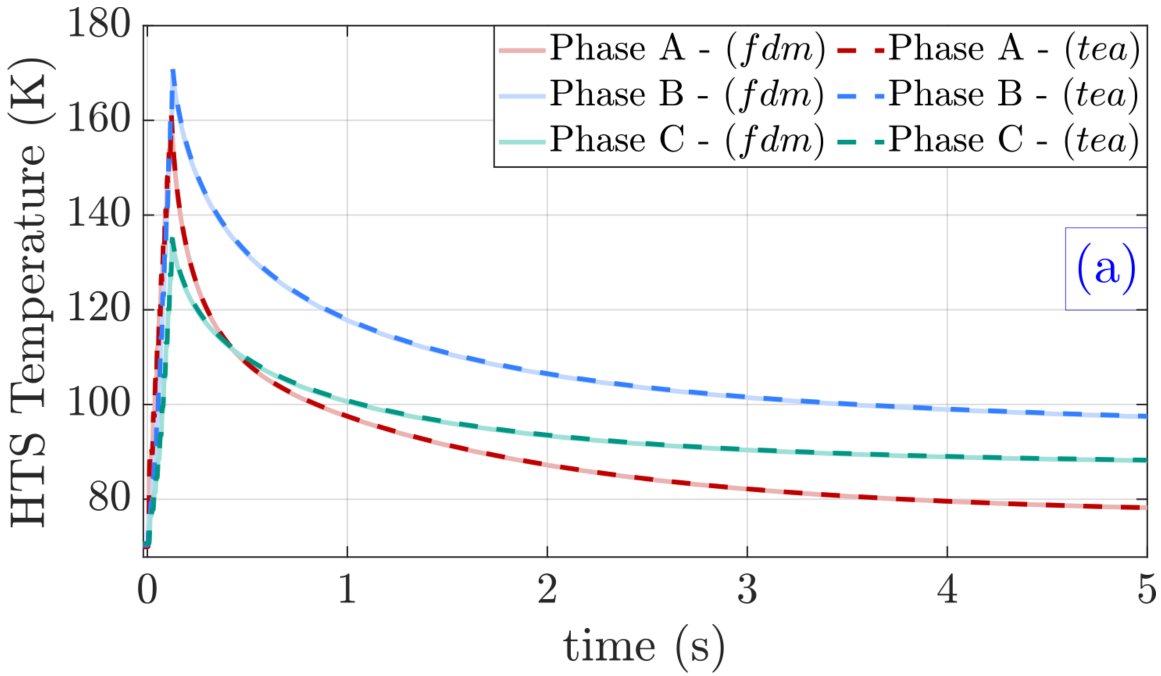


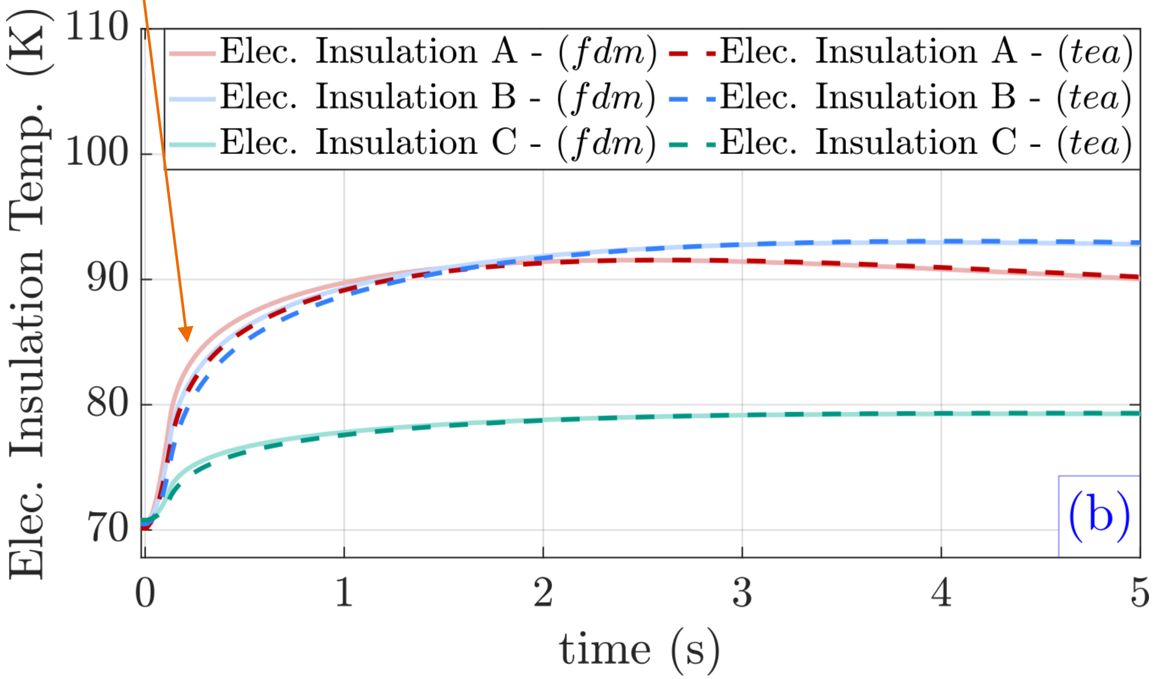


- Deviation of about 8% for R_B during the recovery process
  - *Not that critical however….*

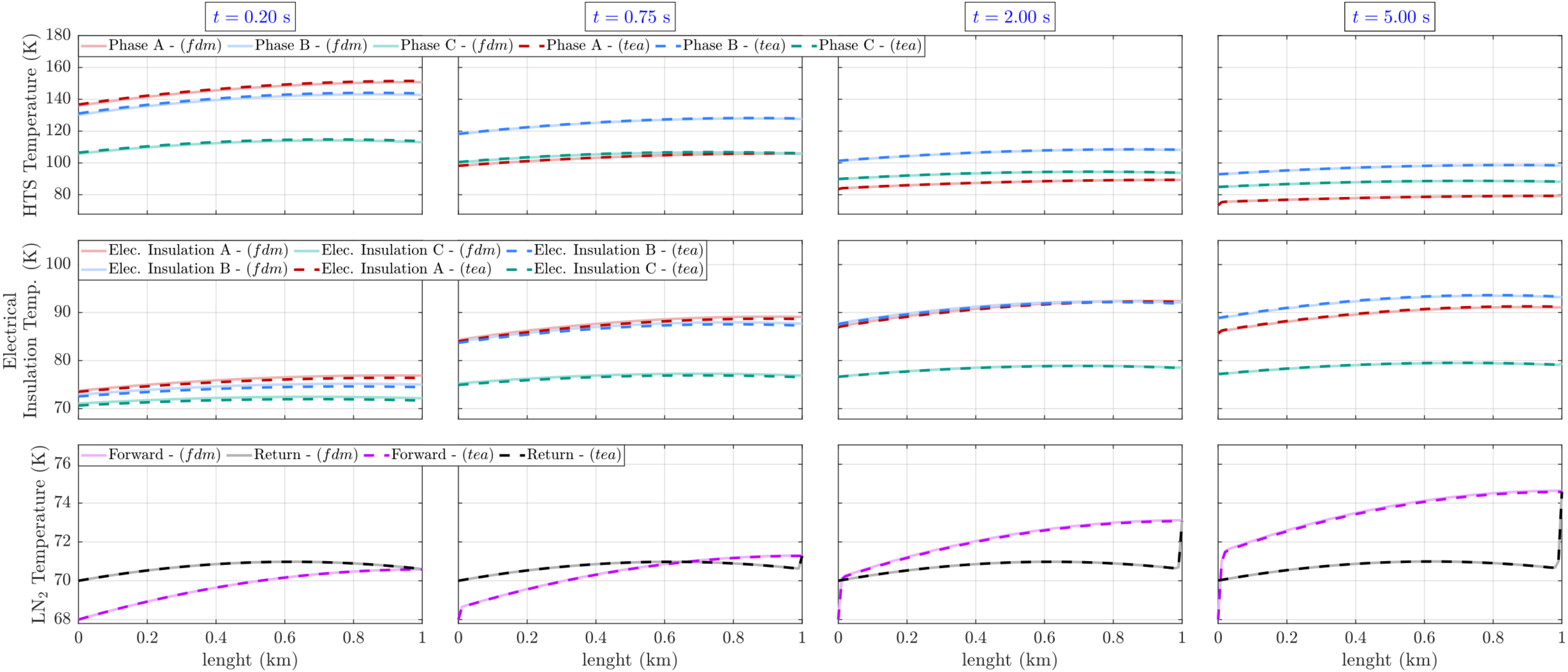
Results – Transient Regime (Temperatures)

- Temperature at half length of the cable (@500 m)
  - *3% deviation at the beginning of the transient period*





Results – Transient Regime (Temperatures)



Lumped-Parameter Model – Performance and Summary

- **Summary**
  - Lumped parameter model requires less computational efforts
  - Easier to code;
    - Boundary conditions between interfaces are automatically included
    - Layered materials can be generated by functions
  - Tests in power system simulators must still be carried out.
  - Further improvements are still possible

Model	time
fdm	21 min
tea	2.0 min