Electro-Thermal Modeling of HTS Power Lines for Cryogenically-Cooled Electric Aircraft Design

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***Abstract*— Emission reduction goals for the aviation industry have led to new research and development efforts in fully electrified propulsion. In the fully-electric aircraft concept currently under development by the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA), the envisioned power system is cryogenically cooled with many novel components, including high-temperature superconducting (HTS) cables [1]. Creating a physical prototype for a cryogenic power system is costly and difficult, with limited opportunities for testing. Hence, to understand the potential advantages and requirements when using cryogenically cooled systems of these novel components in a more efficient manner, well-defined simulation models are essential before building physical prototypes. Object-oriented, equation-based modeling and simulation technologies allow for the "virtual" implementation of the novel technologies being developed through CHEETA, e.g. HTS models. This allows us to study system responses under various operating conditions, cooling medium, and fault conditions. The cryogenic component models have been created using the object-oriented modeling language, Modelica, as it offers interoperability and portability for multi-domain modeling in the thermal and electrical domains. The presentation shows how the models developed can represent the functional behavior of an HTS line compared to physical experiments, on how the thermal behavior using liquid hydrogen cooling provides good thermal properties with substantial improvements in current carrying capacity.**

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[1] Podlaski, M., Vanfretti, L., Nademi, H., Ansell, P. J., Haran, K. S., and Balachandran, T., Initial Steps in Modeling of CHEETA Hybrid Propulsion Aircraft Vehicle Power Systems using Modelica. https://doi.org/10.2514/6.2020-3580 ,
URL https://arc.aiaa.org/doi/abs/10.2514/6.2020-3580.

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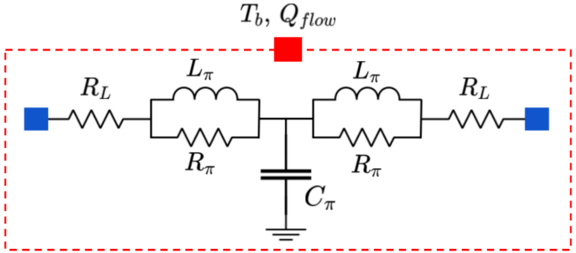

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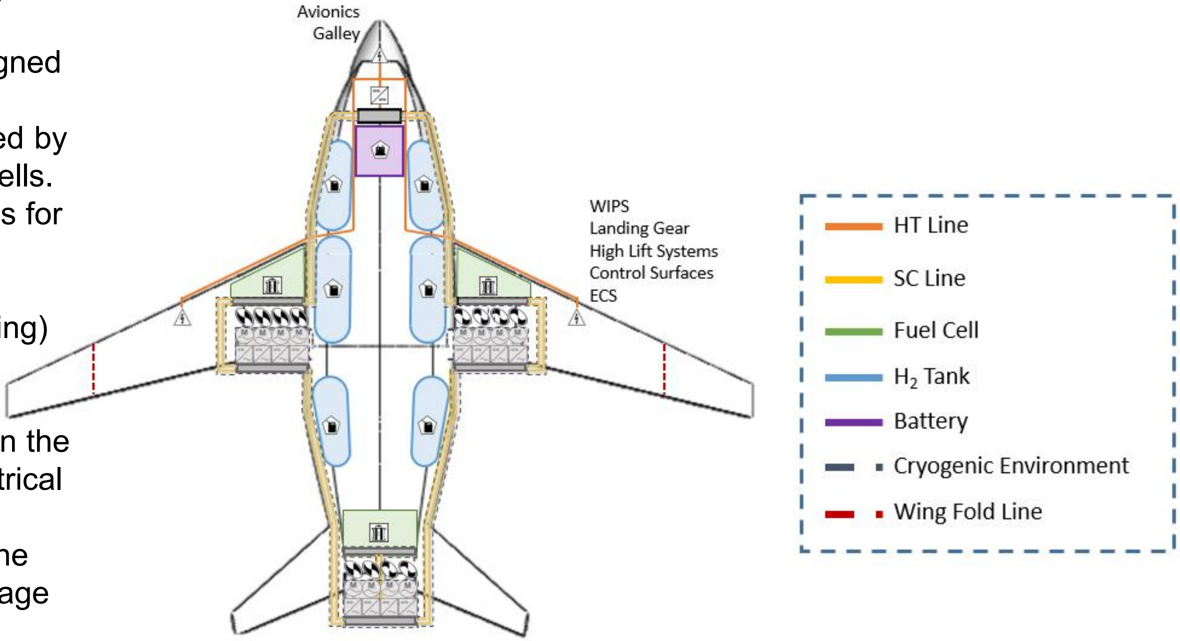
Outline

- **Introduction**
- **CHEETA Electrical System Architecture**
- **Multi-Domain Modeling for High Temperature Superconducting Power lines**
- **Validation Results**
- **Conclusions and Next Steps**
    - Modeling of bus bars, current leads, and integration with the rest of the system

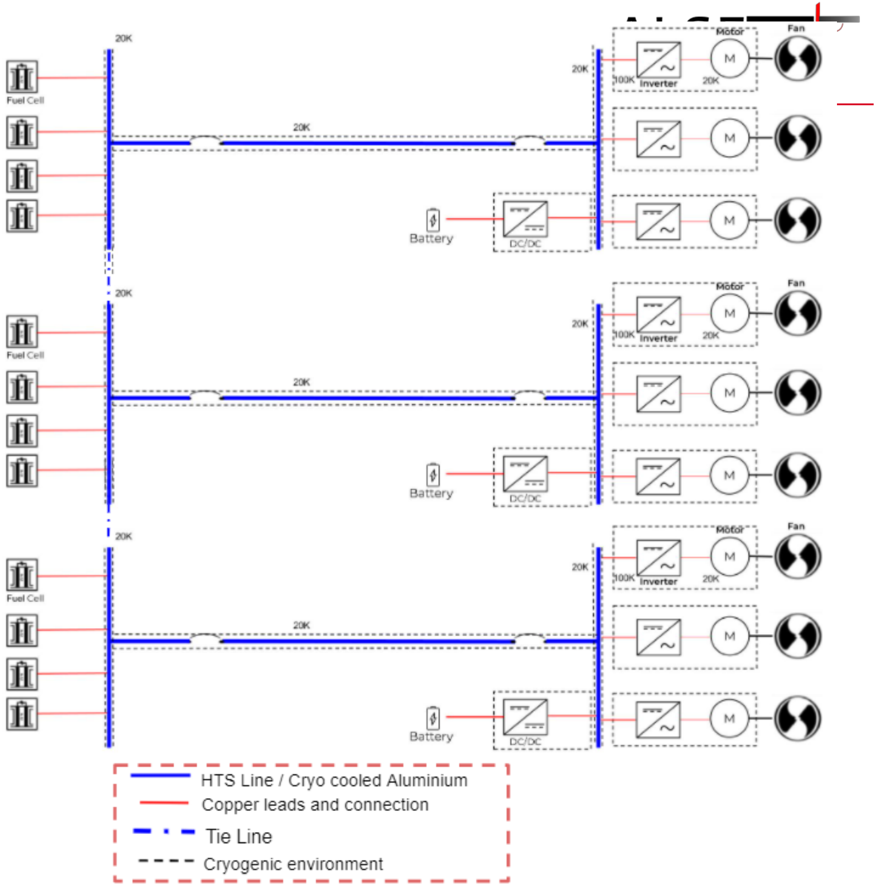
CHEETA Aircraft Overview and Layout

- CHEETA explores future technologies in electrified aircraft.
    - Aircraft components are designed to be cryogenically cooled.
    - Hybrid electric aircraft powered by batteries and hydrogen fuel cells.
- Aircraft consists of multiple domains for modeling:
    - Electrical
    - Thermal (liquid and gas cooling)
    - Mechanical/aerodynamics
    - Control signals
- This presentation mostly focuses on the modeling of the **HT line** in the electrical and thermal domains
    - The model was made using the Modelica programming language



Electrical System Architecture

- Hybrid centralized and distributed electrical architecture
  - Three different areas for propulsion: two on the wings and one on the body
- Added reliability from having the batteries connected at the motor bus
- More balanced aircraft weight with the batteries located in the wings
- Tie line between the fuel cells adds reliability to balance power between generation



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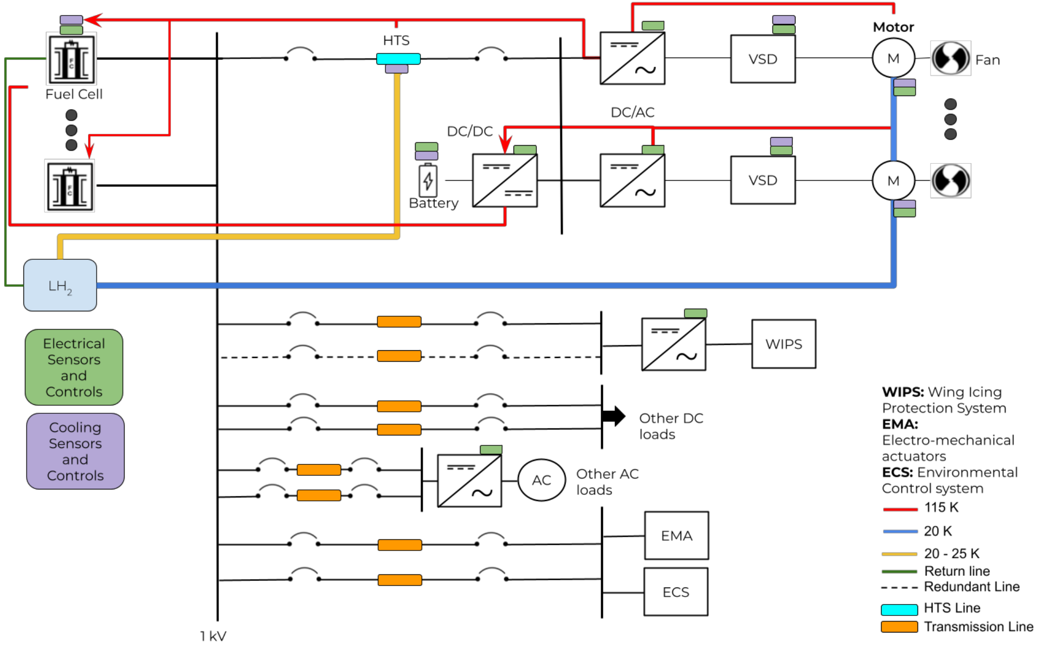
Electrical System Architecture: Cooling System

- HTS lines and bus bars are cooled separately from the drivetrains and fuel cells
  - Ensures a stable, constant temperature applied to components
  - Protects system to ensure maximum capability to remove heat during fault
  - Motors, power electronics, and current leads contribute to most of the heat generation



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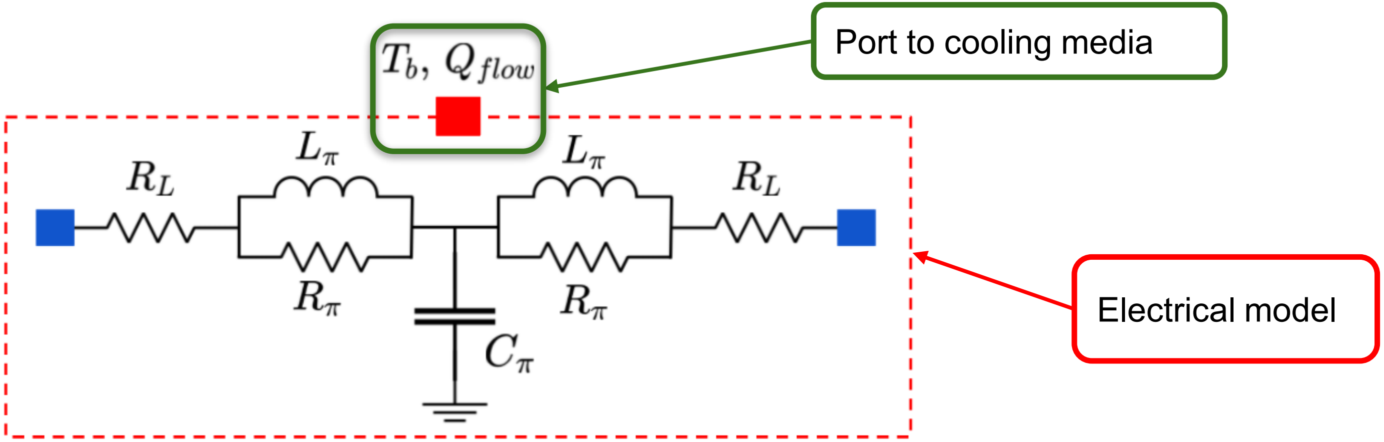
Multi-Domain Modeling of HTS Power Lines

- Multi-domain transmission line represented as co-axial model with a thermal model to dictate the surface temperature of the line
  - The resistances of the line are dependent on the surface temperature of the line and cooling bath temperature
  - Temperature of line is held constant by a fixed boundary condition that specifies ideal temperature of cooling system



Port to cooling media

Electrical model

Multi-Domain Modeling of HTS Power Lines

I = Current flowing through the cable (A)
I_C = Critical current (A)
I_{C0} = Critical current at 20K (A)
T_C = Critical temperature of the superconductor (K)
T_l = Temperature of the surface of the line (K)
ρ = Resistivity of HTS cable $(\Omega \cdot \mathrm{m})$
E = Electric field (V/m)
E_0 = Reference electric field for the critical current (V/m)
A_{cu} = Cross-sectional area of copper portion of line (m^2)

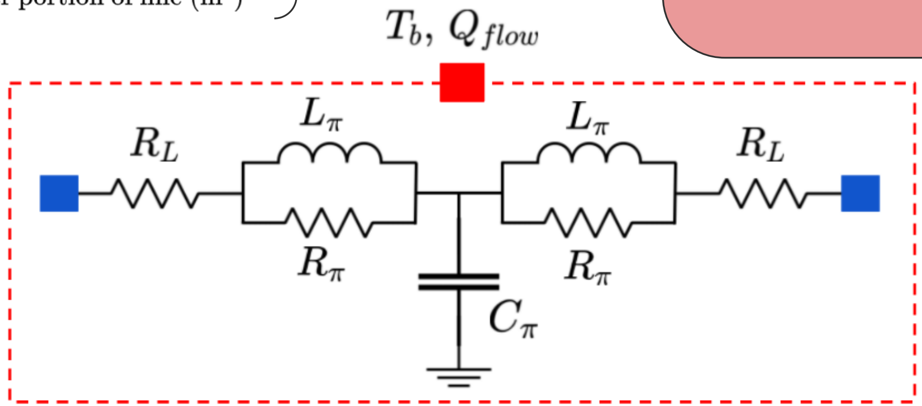
$$I_C = I_{C0}\left(1 - \frac{T_l}{T_C}\right)$$

$$\rho = \frac{E * A_{cu}}{I_C}$$

$$E = E_0\left(\frac{I}{I_C}\right)^n$$

Line is modeled using equations for cold-end cooling

- First need to determine the maximum current rating of the line, resistivity, and electric field



Multi-Domain Modeling of HTS Power Lines

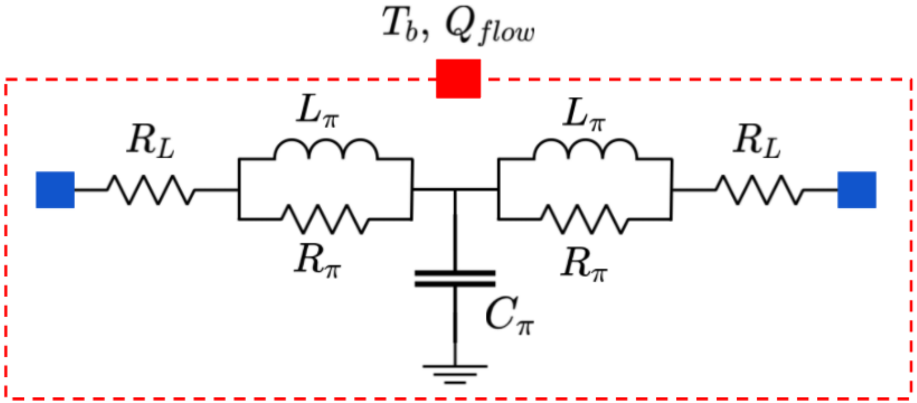
I = Current flowing through the cable (A)
I_C = Critical current (A)
ρ = Resistivity of HTS cable ($\Omega \cdot \mathrm{m}$)
E = Electric field (V/m)
a = Inner radius of the HTS annular electrical cable (m)
b = Outer radius of the HTS electrical conductor (m)
n = Index value of superconductor (unitless)
ϵ = Permittivity of tape material (unitless)
μ = Permeability of tape material (unitless)
R_π = Permeability of tape material (Ω)
C_π = Capacitance of pi-line capacitor (C)
L_π = Inductance of the pi-line inductor (H)
R_L = Current lead resistance (Ω)

$$R_\pi = E_0 * \frac{\left(\frac{I}{I_C}\right)^n}{I}$$

$$L_\pi = \frac{\mu}{2\pi}\log\left(\frac{b}{a}\right)$$

$$C_\pi = \frac{2\pi\epsilon}{\log\left(\frac{b}{a}\right)}$$

Pi-line resistance, inductance, and capacitance all vary depending on the line’s temperature and carrying current



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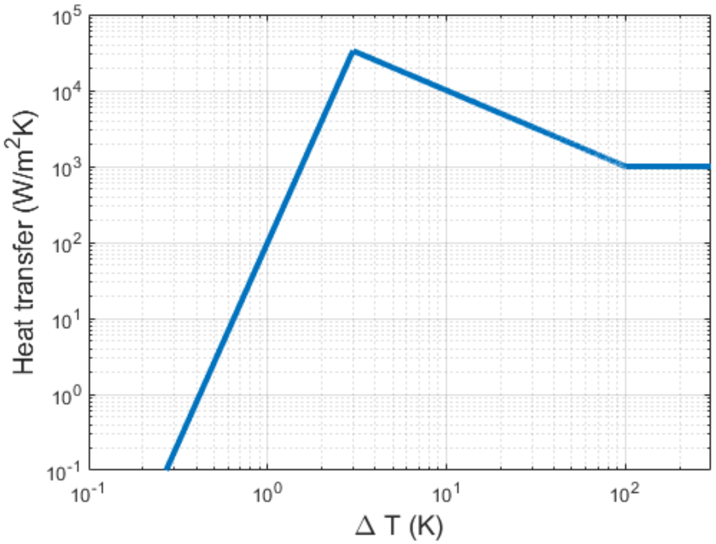
Liquid hydrogen heat transfer model

Heat transfer coefficient of the line is a function of the nucleate boiling curve for liquid hydrogen

- Determines the heat generated by the line (h = Q/ΔT_ρ)
- This helps determine if the line will remain in the cryogenic cooling region

$$h = \begin{cases} 100(\Delta T_\rho)^{5.3} & \Delta T_\rho < 3 \\ \frac{10^5}{\Delta T_\rho} & 3 \leq \Delta T_\rho < 100 \\ 1000 & \Delta T_\rho \geq 100 \end{cases}$$

h = Heat transfer coefficient (W/m^{2}K)
ΔT_ρ = Difference in temperature between cable and cooling media (K)
Q_{flow} = Heat flow generated by the cable (W)



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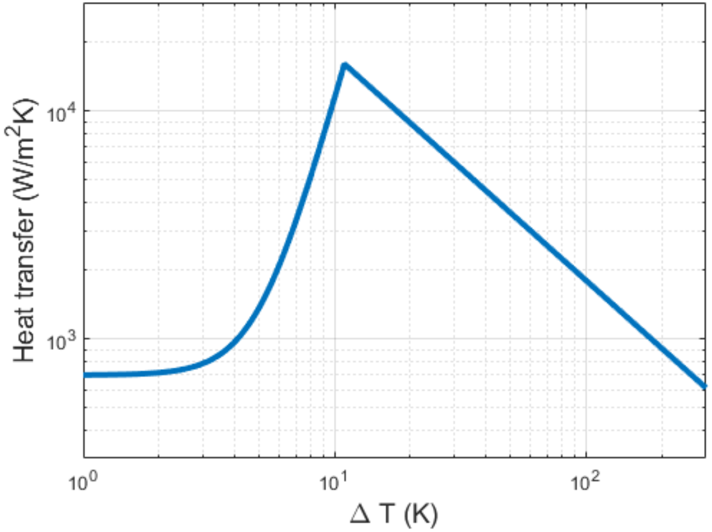
Liquid nitrogen heat transfer model

Heat transfer coefficient of the line is a function of the nucleate boiling curve for liquid nitrogen

- Determines the heat generated by the line (h = Q/ΔT_ρ)
- This helps determine if the line will remain in the cryogenic cooling region

$$h = \begin{cases} 1000\left(0.6953 + 0.001079\Delta T_\rho^4\right) & \Delta T_\rho < 11 \\ 1000\left(\frac{-5.787-0.155\Delta T_\rho}{1-0.546\Delta T_\rho}\right) & \Delta T_\rho \geq 11 \end{cases}$$

h = Heat transfer coefficient (W/m^{2}K)
ΔT_ρ = Difference in temperature between cable and cooling media (K)
Q_{flow} = Heat flow generated by the cable (W)



HTS model thermal functions - liquid cooling

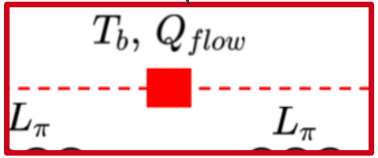
The cooling functions for the rest of the cable is shown accordingly, which relate to the interfacing between the thermal junction to the cooling media.

$h =$ Heat transfer coefficient $(\mathrm{W/m^2K})$
$\Delta T_\rho =$ Difference in temperature between cable and cooling media (K)
$Q_{flow} =$ Heat flow generated by the cable (W)
$Q_{ce} =$ Cold end cooling of cable
$G_d =$ Heat due to a potential additional fault (W)
$I_C =$ Critical current (A)
$\rho =$ Resistivity of HTS cable $(\Omega \cdot \mathrm{m})$
$\kappa =$ Average, effective, radial thermal conductivity of electrical cable $(\mathrm{W/mK})$
$T_b =$ Temperature of cooling media bath (K)
$P =$ Perimeter of cable (m)
$A_{cu} =$ Cross-sectional area of copper portion of line $(\mathrm{m^2})$

$$\Delta T_\rho = \frac{\left(\frac{\rho I_C^2}{P A_{cu}} + G_d\right)}{h}$$

$$Q_{flow} = h \Delta T_\rho + Q_{ce}$$

$$Q_{ce} = T_b \sqrt{2 \kappa A_{cu} P h}$$



HTS model thermal functions - gas cooling

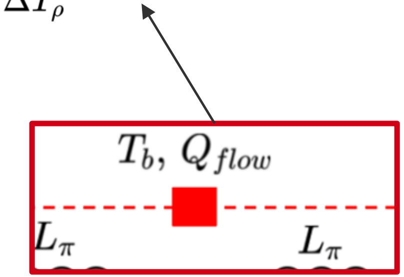
The cooling functions for the rest of the cable is shown accordingly, which relate to the interfacing between the thermal junction to the cooling media.

C_{pv} = Heat capacity of gas coolant (J/K)
h = Heat transfer coefficient (W/m^{2}K)
Q_{ce} = Cold end cooling of cable
Q_{flow} = Heat flow generated by the cable (W)
R_C = Inner radius of cable (m)
R_0 = Outer radius of cable (m)
T_{inlet} = Temperature of cooling media bath (K)
v = Velocity of gas coolant (m/s)
z = Distance from gas coolant inlet (m)
ΔT_ρ = Difference in temperature between cable and cooling media (K)
ΔT_z = Difference in temperature between cable and cooling media from gas inlet (K)
ΔT_{total} = Total temperature jump at interface between cryogen and HTS surface in gas cooling (K)

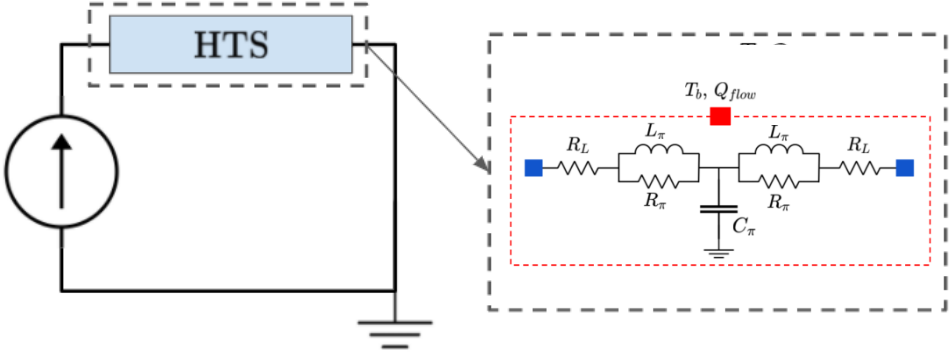
$$< T(z) > \; = T_{inlet} + \frac{Q_{flow} * z}{v * C_{pv} * 2\pi (R_C - R_0)^2}$$

$$\Delta T_z = \; < T(z) > \; - T_{inlet}$$

$$\Delta T_{total} = \Delta T_z + \Delta T_\rho$$



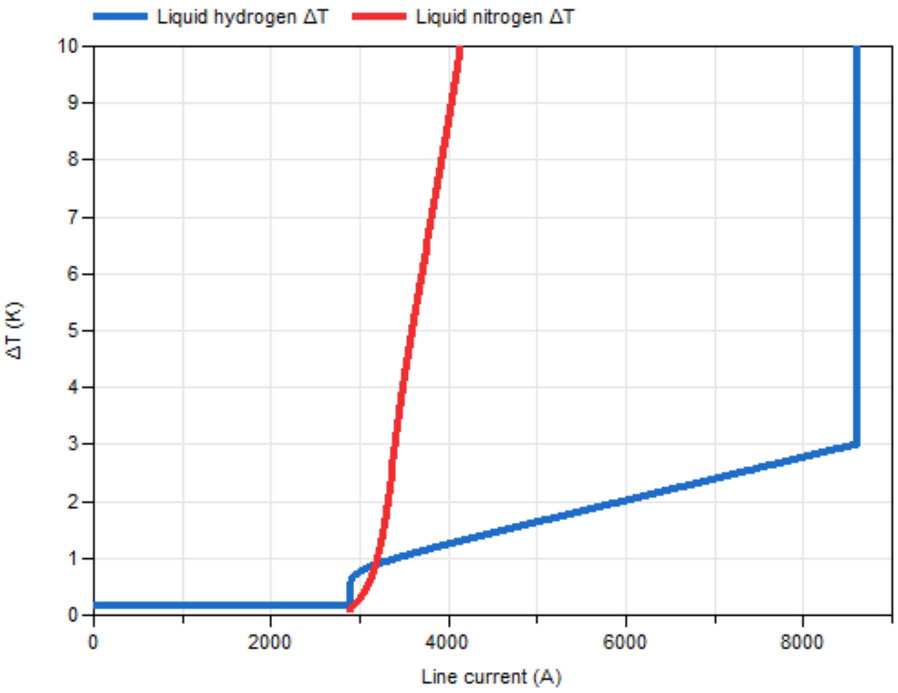
Validation Results



A circuit was set up to match the experiments run on previous HTS tapes to validate the model’s behavior

- Apply a current source to the HTS line, where the current ramps from 0 to twice the value of Ic (critical current)
- Tested line for liquid hydrogen, liquid nitrogen, and gas hydrogen

Validation Results



Applied a current that ramped from 0 to 2*Ic to determine where thermal failure would occur for each cooling media

- The lines have a critical current of 3.7kA
- The liquid hydrogen cooled line remained in cryogenic cooling region until nearly twice the value of Ic
- The liquid nitrogen cooled line enters film boiling when the current in the line is at 3.7kA

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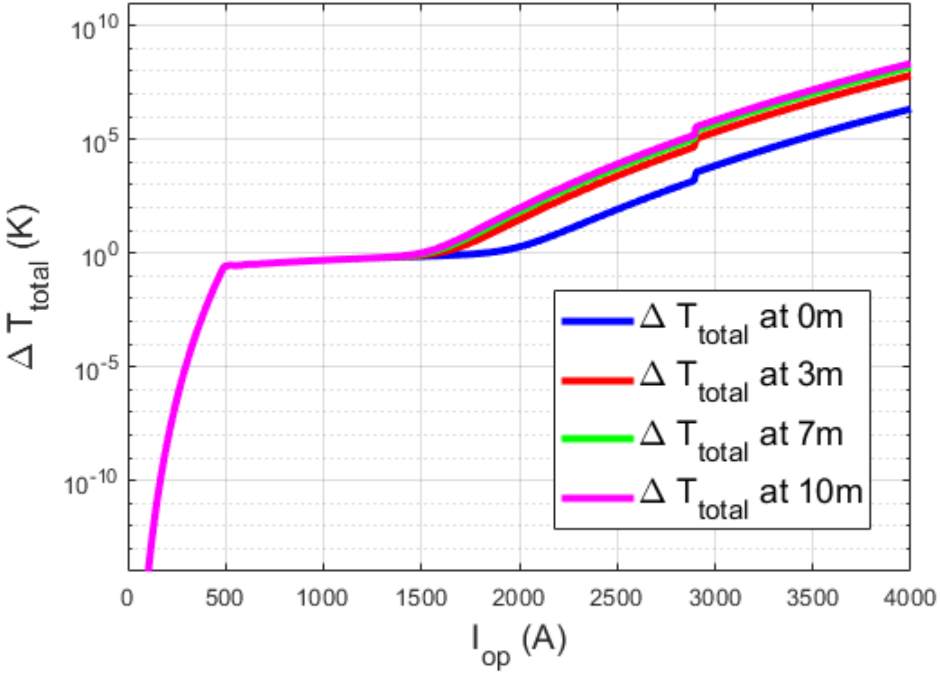

Applied a current that ramped from 0 to 2*Ic to determine where thermal failure would occur for each cooling media

- The lines have a critical current of 3.7kA
- Based on the rapid heating of the gas cooled line prior to Ic, we cannot use the media for an aircraft application

Conclusions and Next Steps

HTS component modeling:

- Given an electrical architecture focused on cryogenic cooling, we have defined mathematical models for HTS components that can be coupled to other multi-domain models for other portions of the aircraft
- Enables integration of thermal management/cooling system (thermo-fluidic network).
- Allows for design driven by mission profiles.

Next Steps and Lessons Learned:

- Early integrated system models can be helpful at early stages of the development of new propulsion concepts:
    - Allows to identify domain boundaries and delineation of responsibilities for different components/subsystems
    - Help to identify original concept gaps and technology needs and aid in communication between experts in different disciplines, and enables early discussion on concept principles
- Next goal is to develop the models for the bus bars
    - Bus bars will be made of cryogenic metal to minimize size and weight
    - Integrate the bus bar and transmission line models to the rest of the power system
- Need to couple the HTS transmission line model with dynamic fluid media model
    - Instead of assuming a constant temperature applied to the cooling media bath, we will couple the model to a dynamic fluid model

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