Multi-Domain Modeling for High Temperature Superconducting Components for the CHEETA Hybrid Propulsion Power System

Meaghan Podlaski, Abhijit Khare, and Luigi Vanfretti
Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY, USA
{podlam, kharea, vanfrl}@rpi.edu

Michael Sumption
Department of Materials Science and Engineering, Ohio State University, Columbus, OH, USA
sumption.3@osu.edu

Phillip Ansell
Department of Aerospace Engineering, University of Illinois Urbana-Champaign, Urbana, IL, USA
ansell1@illinois.edu

As the aviation industry focuses on increasing the sustainability of its technologies, fully electrified propulsion concepts are further explored and developed. One particular area of interest is in the development of hybrid propulsion aircraft using cryogenic cooling and components in the power system. This paper presents the modeling of the high temperature superconducting (HTS) transmission lines used in the power system of the Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETA). These are novel components, so a mathematical model for both the electrical and thermal domains are provided in the paper. To this end, the development of these models allow for trade-off studies for different operating power capabilities, cooling mediums, and operational modes.

I. Nomenclature

A_{cu}	=	Cross-sectional area of copper portion of line (m^2)
a	=	Inner radius of the HTS annular electrical cable (m)
b	=	Outer radius of the HTS electrical conductor (m)
CHEETA	=	Center for High-Efficiency Electrical Technologies for Aircraft
C_π	=	Capacitance of pi-line capacitor (C)
E	=	Electric field (V/m)
E_0	=	Reference electric field for the critical current (V/m)
G_d	=	Heat due to a potential additional fault(W)
h	=	Heat transfer coefficient (W/m^2K)
HTS	=	High-temperature superconductor
I	=	Current flowing through cable (A)
I_c	=	Critical current (A)
I_c0	=	Critical current at 20K (A)
LH_2	=	liquid hydrogen
L_π	=	Inductance of the pi-line inductor (H)
n	=	Index value of superconductor (unitless)
P	=	Perimeter of cable (m)
Q_{ce}	=	Cold end cooling of cable (W)
Q_{flow}	=	Heat flow generated by the cable (W)
R_π	=	C (Ω)
T_b	=	Temperature of cooling media bath (K)
T_c	=	Critical temperature of superconductor (K)

T_l	=	Temperature of surface of the line (K)
ΔT_ρ	=	Difference in temperature between cable and cooling media (K)
ρ	=	Resistivity of HTS cable (Ω m)
ϵ	=	Permittivity of tape material (unitless)
μ	=	Permeability of tape material (unitless)
ω	=	Frequency of AC system (rad/sec)
κ	=	Average, effective, radial thermal conductivity of electrical cable (W/mK)

II. Introduction

A. Motivation

Emission reductions in transportation require advances in aviation technologies which has 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 liquid hydrogen using 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, especially because the aircraft is still in a conceptual phase. Well-defined, reliable models are essential for the development, testing, and validation of these novel components. Object-oriented equation-based modeling and simulation technologies allow for the implementation of technologies in the novel CHEETA power system architecture, e.g. HTS models, which in turn allows system responses to be studied under various operating conditions and response times. The models have been created using the object-oriented modeling language, Modelica, as it offers interoperability and portability for multi-domain modeling. In this work, multi-domain models were created for the HTS lines within the power system focusing on the thermal and electrical domains. This paper introduces the multi-domain modeling and analysis of cryogenically cooled HTS lines. Opportunities for trade-off studies for cooling methods of the HTS cables are also discussed.

B. Paper Contribution

This paper focuses on the multi-domain modeling of HTS transmission lines and components in the CHEETA power system. The thermal and electrical domains are modeled; this allows for trade-off studies for different operating power capacities and cooling mediums. In this work, the term “domain” refers to each engineering problem, e.g. all electrical variables in this model are modeled according to Ohm’s Law, Kirchoff’s Laws and other electrical principles. The thermal system is modeled such that all variables and equations obey the laws of thermodynamics. The two domains are interfaced at the equation-level, allowing to compute the thermal performance under different electrical configurations and cooling media.

C. Related Works

This paper builds off of the power system conceptualized in [1], which introduced the power system architecture for the CHEETA aircraft and initial component modeling using the Modelica computer-based modeling language. The power system is cryogenically cooled using liquid hydrogen, which requires mathematical modeling of all components since their losses and operational behavior changes from the conventional behavior in traditional power systems at ambient temperature. As a result, multi-engineering domain models are required to study the system.

Previous electrified and hybrid aircraft designs do not utilize cryogenic cooling and the corresponding components in their power system designs. Electric aircraft configurations modeled in [2] and [3] utilize the same first-principles, multi-domain modeling techniques used in modeling the HTS lines and other components in the CHEETA power system; however, HTS components are less studied, and have not been modeled or studied for aircraft applications. Other HTS components have been modeled and experimentally validated, such as in [4], however these studies primarily focus on strict partial differential equation models that only study the HTS material. This paper focuses on modeling and application for HTS materials in the form of electrical components and the impact of the cooling media for the component with the goal of enabling integrated system analysis of the HTS lines as part of a aircraft power system.

D. Paper Layout

Section III introduces the CHEETA power system architecture, the system layout, and cooling system hierarchy to provide background on the application of the HTS models. The mathematical model of the HTS cable is explained in Section IV, showing the modeling for both the electrical and thermal domains. The HTS cable is tested in a simple circuit in Section V to show the trade-off between cooling via liquid hydrogen and liquid nitrogen in terms of line current carrying capability and cryostability.

III. CHEETA Electrical System Architecture

A. Multi-Domain Modeling Approach

The models developed for the CHEETA aircraft are created using the object-oriented, equation-based modeling language, Modelica. Modelica provides flexibility to implement and interface models from different engineering domains by developing physically-meaningful equation-based interfaces between them. In the case of the HTS components introduced in this paper, the term 'domain' refers to an engineering problem. All electrical variables are modeled according to Ohm's Law, Kirchoff's Laws, and other electrical principles. The thermal variables are modeled according to the laws of thermodynamics. Given the layout of the aircraft in Figure 1, it is necessary to create interfaces and models to connect all sub-systems and sub-domains together to study the system. The orange lines in Figure 1 represent the HTS cables, which are modeled for both electrical and thermal representations. The other sub-systems in the aircraft in Figure 1 are the cooling lines carrying liquid and gas hydrogen in orange, the fuel cells in green, liquid hydrogen storage tanks shown in blue, and the batteries in purple. The cryogenic environment is contained within the grey dashed lines, and the red dashed lines represent the wing fold lines.

B. Power System Architecture Overview

The CHEETA power system consists of a series of liquid hydrogen fuel cells and batteries, power electronics (i.e. inverters), and other components that supply electrical power to motors that drive the fans for aircraft propulsion [1]. The overall CHEETA power system architecture is shown in Figure 2. Each group of four fuel cells is connected via

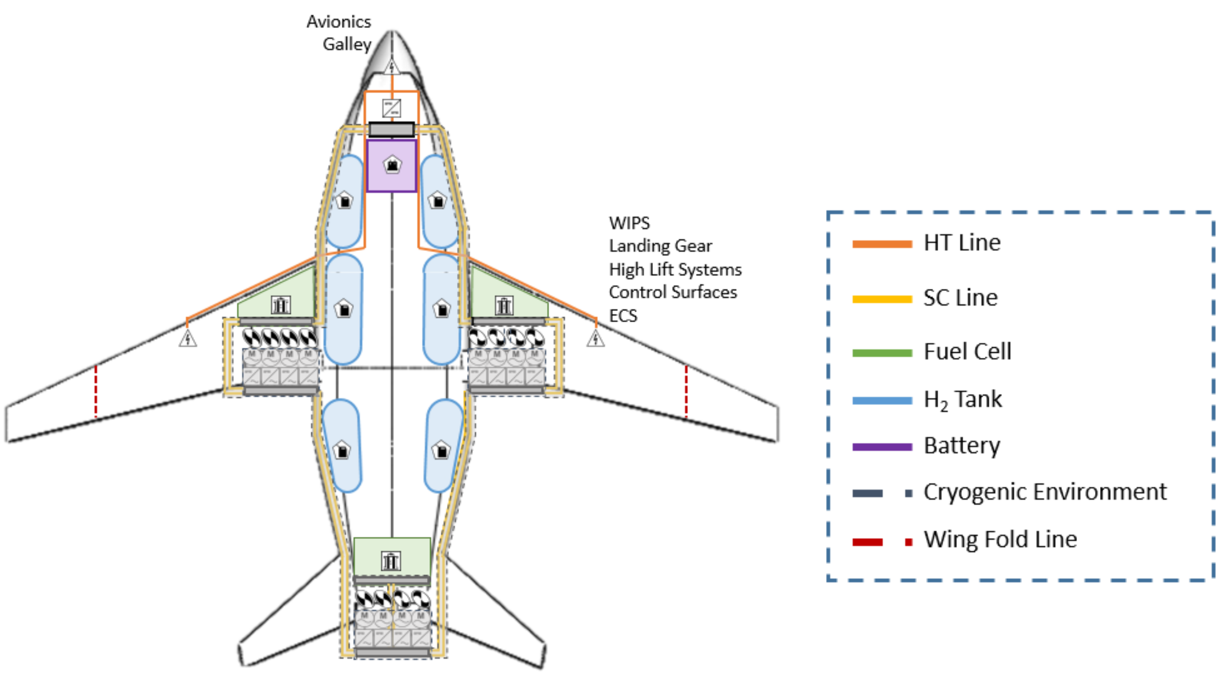

Fig. 1 Power system architecture layout inside of proposed CHEETA aircraft in terms of sub-systems and sub-domains to demonstrate the physical placement of components.

HTS transmission line to a distribution bus containing eight machines, inverters, and a battery that provides extra power when necessary. The two fuel cell buses are connected with a tie line for reliability. The 'additional loads' in Figure 2 consist of the wing icing protection system, electromechanical actuators, environmental control system, and other AC and DC loads. They all operate at ambient temperature, so they are simplified into one block in the system architecture.

All of the bus bars and transmission lines are encapsulated by a cryogenic environment, as designated by the blue portion of the system in Figure 2. The system is modeled to operate at a voltage of 1kV DC with each motor providing 1.6625MW of power for a total of 26.6MW. In traditional power systems, normally the current in a system is minimized to limit the I^2R losses on the line, resulting in an operating voltage that is considerably higher than the current. HTS components provide negligible losses when subject to cryogenic cooling, allowing for a system to operate at a much higher current and lower voltage. The HTS line is cooled separately at a temperature of 20-25 K from the rest of the cryogenic components. The transmission lines and bus bars are the components most vulnerable to failure due to uncontrollable heating, so it is crucial that the temperature is controlled in its own loop.

Figures 3 and 4 show the cooling architecture for the power system, where Figure 3 shows a portion of one branch of the fuel cell/drivetrain circuit shown in Figure 2. The HTS transmisson lines and bus bars are cooled separately from the drivetrains and other components to ensure stable, constant temperature applied to the cryogenic components. This is necessary because the HTS cable needs to be constantly cooled at 20K to avoid film boiling, which will protect the system in case of a fault as it will have maximum ability to remove heat [5]. These components heat the hydrogen from liquid to gas to be applied to the power electronics, motors, and current leads in the drivetrains. The heated hydrogen gas from the power electronics is then sent to a heater to control the fuel cell cooling temperature. The fuel cell operates at ambient temperature.

IV. Multi-Domain Modeling of High Temperature Superconducting Components

HTS transmission lines can electrically be represented as a pi-line model, similar to a standard co-axial cable model as shown in Figure 5. The electrical behaviors of the line are dependent on the temperature of the cooling media surrounding the line, which can affect the lines behavior, and thus, needs to be controlled to a prescribed temperature range. In the model, this temperature is held constant by a fixed boundary condition that specifies the ideal temperature that the cooling system should maintain. The blue boxes in Figure 5 represent the electrical connections to the rest of the electrical system. In Figure 2, this would connect the fuel cells to the motors and batteries. The red box in Figure 5 represents the thermal connection to the cryogenic cooling media, where the line is fully submerged in a cooling bath and cooled on all surfaces. The current leads are modeled as R_L in Figure 5; currently they are represented by a constant resistance, but in future models they will be modeled as a resistive current lead subject to vapor cooling.

The HTS line is mathematically modeled using the equations outlined in [5, 6] for cold-end cooling. The HTS line's critical current I_c is calculated using Equation 1. It is the maximum current rated for the cable, is a function of the temperature of the media that the line is submerged in and a critical temperature T_c. The resistivity of the line is dependent on this critical current, shown in Equation 2.

$$I_c = I_{c0}(1 - \frac{T_l}{T_c}) \tag{1}$$

$$\rho = \frac{E * A_{cu}}{I_c} \tag{2}$$

$$E = E_0 \left(\frac{I}{I_c} \right)^n \tag{3}$$

The line is a pi-line model with resistive, inductive, and capacitive components that vary depending on the line temperature and carrying current. Equations 1, 3, and 2 are then used to calculate the values of the pi-line electrical model. In these equations, μ is the permeability of free space and ϵ is the permittivity of the dielectric.

$$R_\pi = E_0 * \frac{\left(\frac{I}{I_c}\right)^n}{I} \qquad \Omega\text{ /m} \tag{4}$$

$$L_\pi = \frac{\mu}{2\pi} \log\left(\frac{b}{a}\right) \qquad \text{H/m} \tag{5}$$

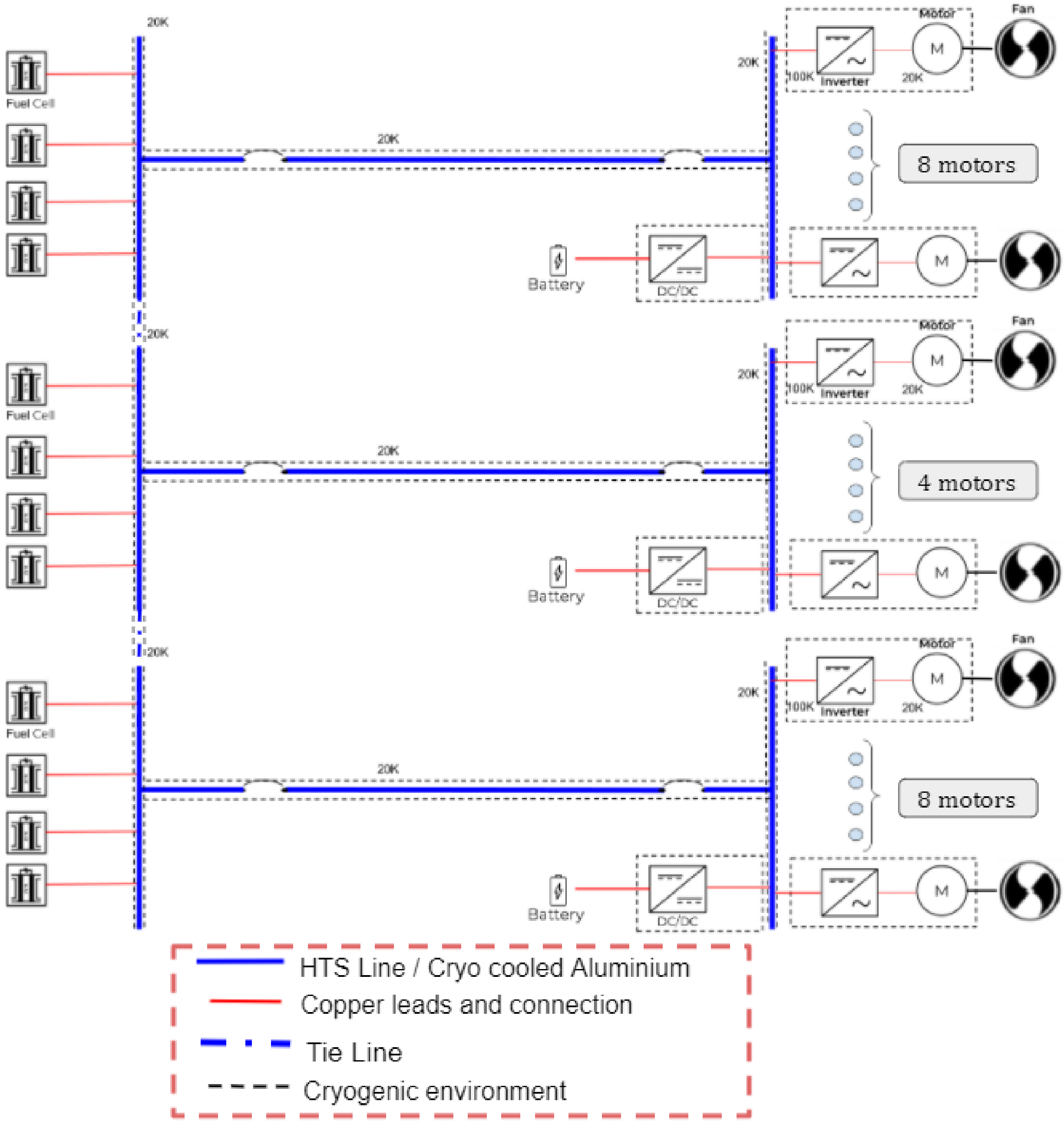

Fig. 2 The CHEETA electric aircraft architecture configured to show the electrical wiring scheme for the system. This schematic focuses on the electrical components; all cooling and thermal components are omitted. This representation only shows the go portion of the circuit, the return lines will also have the same structure.

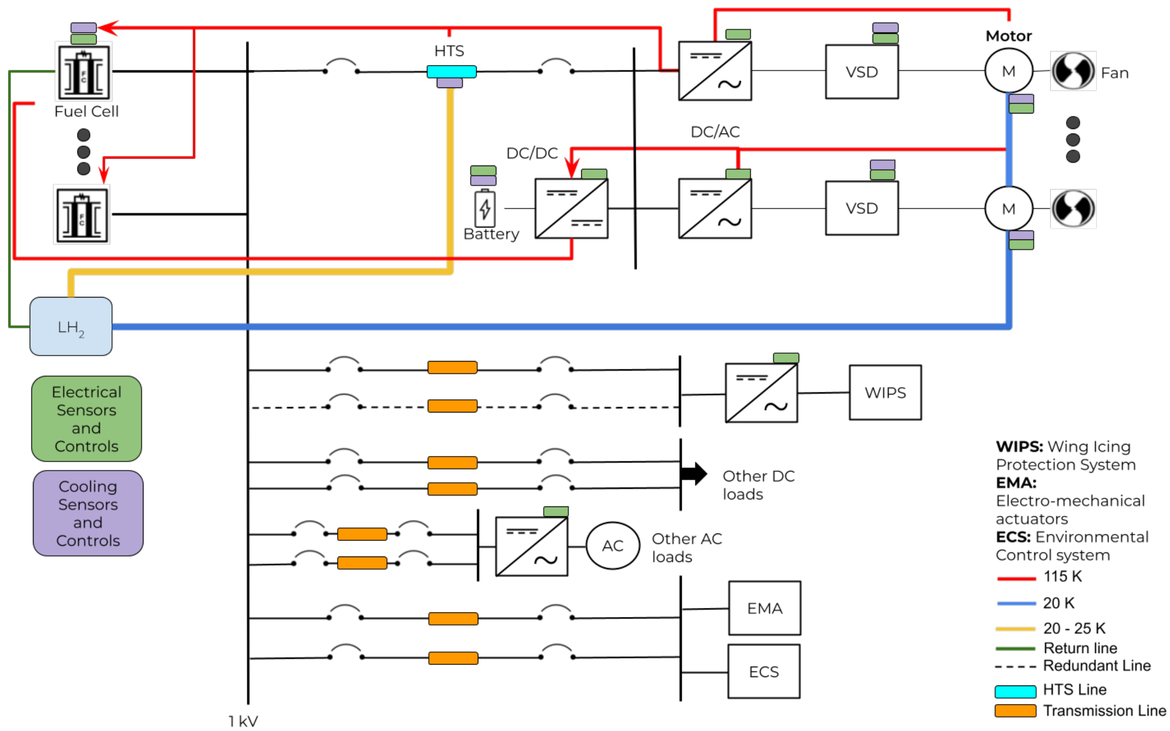

Fig. 3 Cooling system concept for the power system. This schematic shows the flow of liquid hydrogen and hydrogen gas between components in the electrical system, neglecting the controlled heating components. This also only shows one branch of the system in Figure 2.

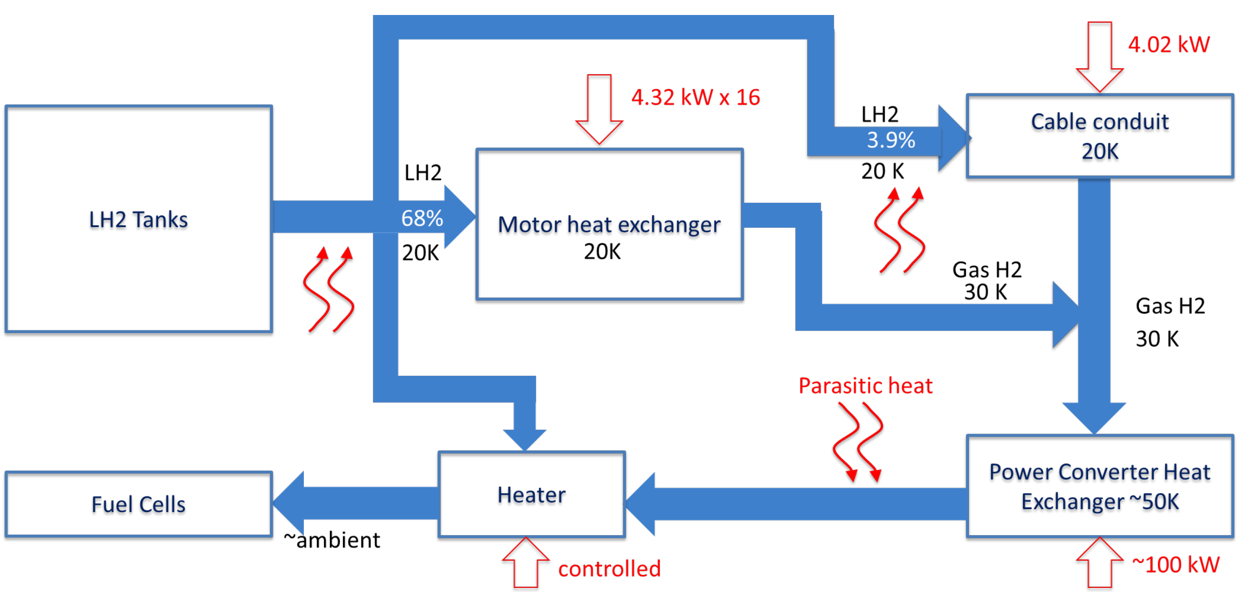

Fig. 4 Cooling system flow chart for the power system with losses and operating temperatures for each component in the aircraft. The blue lines represent the liquid and gas hydrogen cooling to each component, while the read lines represent the parasitic heat and the heat generated by the component.

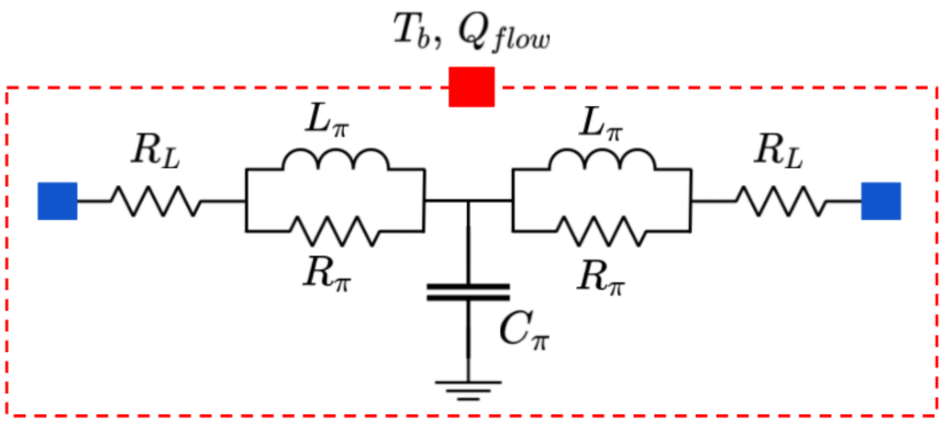

Fig. 5 HTS pi-line model schematic. When the line is modeled using Modelica, it is a multi-domain model consisting of thermal (red) and electrical (blue) behavior as all electrical components are temperature dependent.

$$C_\pi = \frac{2\pi * \epsilon}{\log\left(\frac{b}{a}\right)} \qquad \text{F/m} \tag{6}$$

When the HTS line is submerged in a LH_2 cooling bath, so the thermal response of the model is defined by Equations 7 and 9. These functions are derived from the relationship that the heat transfer coefficient is the result of the heat transfer divided by the change in line temperature, $h = Q/\Delta T_\rho$. In this case, ΔT_ρ is measured at the surface of the HTS line as the difference between the coolant temperature and line surface temperature.

In addition, if the line is cooled by LH_2, the heat transfer coefficient in Equation 7 is a piece-wise function based off of the nucleate boiling curve in [7]. The piece-wise function is defined such that the line will remain in the cryogenic cooling region for any change in temperature in the cooling bath less than 3 K, the the line will enter the nucleate boiling region after the change in cooling bath temperature is instantaneously greater than 3 K. Because the line model follows the cold-end cooling outlined in [5], the cold end cooling is modeled using Equation 11 as a function of coolant temperature T_b. The heat transfer function for liquid nitrogen in shown in Equation 8

$$h = \begin{cases} 100(\Delta T_\rho)^{5.3} & \Delta T_\rho < 3 \\ \frac{10^5}{\Delta T_\rho} & 3 \leq \Delta T_\rho < 100 \\ 1000 & \Delta T_\rho \geq 100 \end{cases} \tag{7}$$

$$h = \begin{cases} 1000(0.6953 + 0.001079(\Delta T_\rho^4)) & \Delta T_\rho < 11 \\ 1000\left(\frac{-5.787 - 0.155\Delta T_\rho}{1 - 0.546\Delta T_\rho}\right) & \Delta T_\rho \geq 11 \end{cases} \tag{8}$$

$$\Delta T_\rho = \frac{\left(\frac{\rho I_c^2}{P * A_{cu}} + G_d\right)}{h} \tag{9}$$

$$Q_{flow} = h * \Delta T_\rho + Q_{ce} \tag{10}$$

$$Q_{ce} = T_b\sqrt{2\kappa * A_{cu} * P * h} \tag{11}$$

V. High Temperature Superconductor Component Validation Results

The thermal behavior of the HTS transmission line needed to be validated against the data provided by the experimental work of [5]. To reproduce the laboratory experiments in simulation, the HTS transmission line model is connected to a current source that will ramp up to twice the critical current value, I_c, as shown in Figure 6. Since the line is submerged in LH_2, the material could remain in the nucleate boiling or cryogenic region until approximately the current applied to the line is twice the value of I_c. This is due to the properties of LH_2 [7], as the line is the same temperature at all points on the surface of the line.

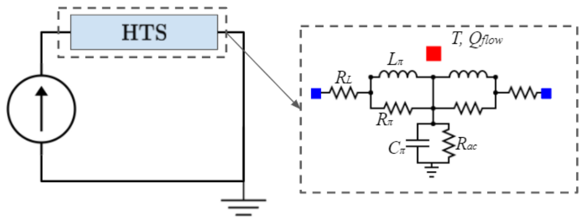

Fig. 6 Circuit consisting of HTS line and current source. The current source is a ramp to make sure the HTS line is simulated in the cryogenic region, nucleate boiling, and film boiling.

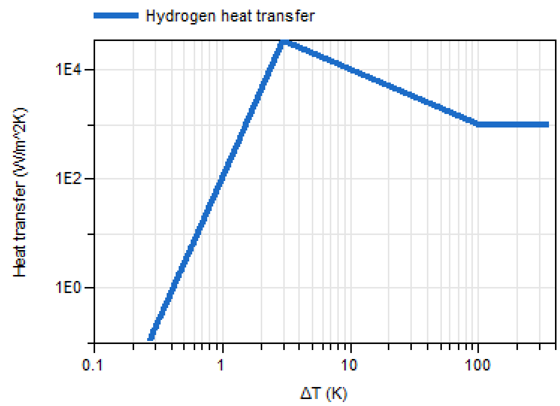

Fig. 7 Heat transfer characteristics as a function of change in temperature for the line submerged in a liquid hydrogen cooling bath. This behavior matches the expected behavior for LH_2 in [7].

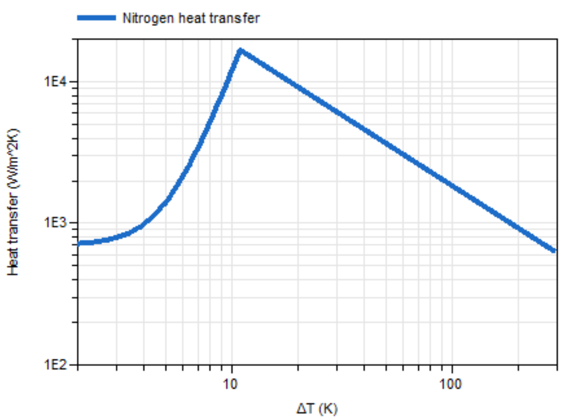

Fig. 8 Heat transfer characteristics as a function of change in temperature for the line submerged in a liquid nitrogen cooling bath. This behavior matches the expected behavior for LN_2 in [8].

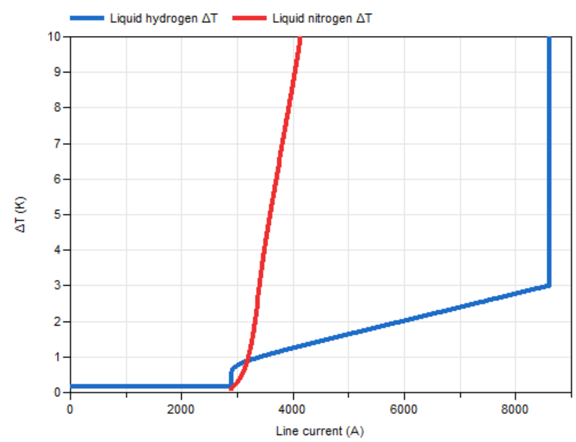

Fig. 9 Comparison between the difference in temperature of the surface of the transmission line and cooling both media, where liquid hydrogen (blue) and liquid nitrogen (red), as a function of line current.

The HTS transmission line's thermal behavior was compared against the data in [7] to verify that the same heat transfer curve can be produced as that from experimental data. The thermal behavior was also compared to liquid nitrogen, which is a common coolant for cryogenic applications, in Figure 8 to provide a reference when fault and stability studies are conducted on the power system [5, 8].

Two different simulation scenarios are configured, one for liquid hydrogen and one for liquid nitrogen cooling according to the circuit in Figure 6. The same ramp input is applied to each line, which varies the line's current from 0 to 10 kA over a 15 second period. The lines have a critical current I_{c0} of 3.7 kA. In Figure 9, the liquid nitrogen cooled line starts entering the nucleate boiling region once the applied current exceeds the critical current I_{c0} at 3.7kA. The liquid hydrogen cooled line stays thermally stable until 8.5 kA is flowing through the line and then it enters the film boiling region. This shows that liquid hydrogen cooling will provide good thermal properties with substantial improvements in current carrying capacity that are critical power system design, as the properties of liquid hydrogen protect the system during faults and current surges without having to scale up the power capacity of the line.

VI. Conclusion

The HTS transmission line has been modeled for both liquid hydrogen and nitrogen cooling. The liquid nitrogen cooling gives a baseline for comparison to show that liquid hydrogen cooling is a better option for the aircraft. Liquid hydrogen cooling would allow for a smaller HTS cable to be used since the media would enter film boiling at a higher current than liquid nitrogen. For a system like an aircraft where weight is a significant consideration, it is crucial to keep component weight minimal where possible. This behavior allows the system to have protection built into the cooling media itself to prevent overheating instead of adding weight to the system by including protection devices. Instead, the HTS cables can be sized to remain thermally stable for high currents caused by other component failures. This sizing will be done in the future by analyzing different faults and component failures to predict maximum current that would be carried by the HTS cables.

In the future, the line will be studied under various operational conditions including fault conditions. The line will also be integrated with the fuel cell, battery, power electronic converters and drive train models at varying levels of modeling fidelity for each of the components. This will enable the study the effects of the HTS line on those components operation and to derive cooling requirements for the cooling system. This analysis will be conducted in three fundamental steps.

A. Developing Bus Bars

The bus bars for the power system will also need to be cryogenically cooled to prevent the conductor from melting from the heat produced by the high currents flowing through the node. The weight and size of the bus bars will be vastly reduced by using cryogenic cooled metal.

B. Coupling the HTS transmission line with a fluid media model

The operation of the HTS transmission line is dependent on the temperature of the LH_2 cooling bath that the component is submerged in. The thermal system is modeled such that the line is dependent on heat flow and temperature of the LH_2, but changing pressure of the media will need to be considered when the line is coupled with the rest of the CHEETA power system in [1].

C. Integration of bus bar and transmission line models to electrical system

The bus bar and transmission line will be coupled with the remaining components in the power system model in Figure 2. These components, such as the inverter and drive train, fuel cell, and batteries, will be modeled at varying levels of detail. For example, the power electronics will be modeled as both averaged and switched models to study the effects of switching on the system, but those models are computationally expensive to run together with thermal sub-systems, hence, different levels of representation are needed. After the models are integrated, the system will be studied to ensure that the system is stable for transient overload conditions, such as the ones outlined in [9] and [10].

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