Models for Design and Analysis of Superconducting Power Systems Cooled with Cryocoolers

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ABSTRACT

Thermal network models (TNM) to evaluate combined electrical and cryogenic thermal behavior of high temperature superconducting (HTS) power systems are discussed. The models were applied to study a few potential configurations of an integrated cryogenic system for multiple HTS power devices. The usefulness of the TNM models in designing the HTS power system is discussed using a hypothetical system consisting of a HTS propulsion motor, an HTS generator and an HTS power cable cooled by an integrated cryogenic system. The transient behavior of the integrated system under contingencies such as a cryocooler failure and the cryogenic gas circulation impeller failure are discussed. The effect of increasing the thermal mass of the cryogenic components of HTS devices and their effect on the rate of rise of temperature of the system and the time to reach the maximum allowed operating temperature of the HTS system are discussed. The benefits of adding solid nitrogen as cryogenic thermal storage is studied as a way to increase the time to reach the maximum allowed temperature for the HTS system during the contingencies.

INTRODUCTION

High temperature superconducting technology is a potential option for applications that require high power densities for lightweight and compact solutions for electric aircraft and all-electric Navy ships [1-6]. Future US Navy ships are being planned with multiple large electric loads [7-9]. NASA and several aircraft manufacturers are investing in electric propulsion for aircraft, some with several HTS devices [10-12]. For some of these applications, power devices with variable power rating that offer tunability and high efficiency at a broad range of speeds would be beneficial. Superconducting machines offer high efficiencies even at low speeds and thus address the design challenges of future all electric ships and aircraft. It is also vital to reduce the size and weight of the ships or aircraft to increase fuel economy and operational effectiveness [6] [13]. The two competing interests can be met with innovative designs and integrated power systems. HTS Technology has the potential to satisfy the design goals and also to provide operational flexibility. Superconducting devices have zero resistance and high current density that depends on the operating temperature. The current density of an HTS device can be increased up to 10 times by lowering the operating temperature by 40 K. Gaseous helium (GHe) can be used as the cryogen in conjunction with cryocooler technology which allows the wide operating temperature window of

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10-77 K for HTS power devices. The benefits of using gaseous helium over liquid nitrogen (LN2) as the cryogen have been demonstrated and research in this area is continuing [14-18].

Several individual HTS power devices have been successfully demonstrated for shipboard applications [5] [13] [19-21]. However, the real benefit lies in providing the system level design flexibility and operational advantages with an integrated cryogenic system. A centralized cryogenic cooling technology is being explored to serve multiple HTS devices in a closed loop system. This provides high efficiency and permits directing the cooling power to where it is needed depending on the mission at hand which provides operational flexibility. HTS power devices offer power rating tenability via control of the operating temperature and the integrated cryogenic system allows to control the operating temperature of individual HTS devices based on the mission by directing the additional cooling power as required. An integrated cryogenic system also allows energy savings by operating the cryogenic plant at just enough capacity and any additional capacity can be directed to cryogenic storage [22].

HTS devices are finding it difficult to penetrate the larger market due to their design complexity, capital and operational costs involved in providing the required cryogenic environment. Design optimization, risk mitigation and the operational characteristics under various conditions need to be studied to increase the confidence level in HTS technology. Development of simpler and cost-efficient cryogenic systems are essential to make HTS systems attractive. Detailed electrical and cryogenic thermal models of the devices are also necessary to understand the risks in HTS power systems and to devise mitigation techniques for all the potential failure modes. As the thermal and electrical characteristics of HTS devices are intertwined, coupled thermal and electrical models are necessary to perform system level studies. To enable versatile and fast models, the thermal network method was recently introduced as a useful tool [23]. The effectiveness of the modelling technology was demonstrated using case studies of multiple HTS devices in a closed loop cryogenic helium circulation system connected in different configurations to access the relative merits of each configuration [24].

Studies of transient behavior of HTS systems are also important to understand the response of a large HTS system after one of the components fails. These studies are essential to understand the risks and potential options in the design or in operations to mitigate some of the risks. Thermal network models developed in this study are also useful to study the temperature evolution along the whole system as a function of time after a component fails. The models are useful in exploring the design options to extend the time of operation of a device such as a HTS cable after the failure of the cryogenic system.

HTS systems require combined electrical and cryogenic thermal models to properly represent their behavior because electrical properties of HTS systems are temperature dependent. Additionally, electrical resistivity and contact resistance of various components change significantly as the cryogenic temperature changes. Heat capacities and thermal conductivities of most structural materials are also temperature dependent. The primary characteristic of HTS cables that is relevant for electric power applications is their critical current, which is a strong function of temperature. Typically, a change of 1 K in operating temperature will cause a 10% change in the current carrying capacity of HTS cables. Owing to all the temperature dependencies of the components involved, HTS system studies require combined electrical and thermal models. This paper presents a simplified thermal network method for faster simulations of combined electrical and thermal models of HTS systems with multiple power devices cooled with an integrated centralized cryogenic system. The simplifications in the model sacrifice the details of the local temperature information within the individual components of the system, but serve as a powerful tool for analyzing various potential design possibilities and operational contingencies suitable for tradeoff studies. The paper explores and discusses various ways to extend the operational time after a failure of cryogenic system component and the time-dependent temperature evolution at various locations of the system using the developed thermal network models.

MODELLING OF HTS POWER SYSTEM

An effective modelling methodology, based on the thermal network methods, to simulate the electrical and thermal performance of an HTS power cable was previously developed [23]. However, the tool needed to be simplified for studies of larger systems containing multiple HTS devices and their associated cooling systems for faster simulations. The simulation of multiple HTS devices is based on steady state analysis of the system. Transient analysis can be accomplished by a repetitive successive iterations of the model using temperature dependent cryogenic thermal properties of various components.

System Components in Thermal Network Model

The thermal network model (TNM) is based on the analogy between thermal and electric fields. The models use Ohm's law, Kirchhoff's law and superposition principle on a system that consists of thermal resistors, thermal capacitors, heat sources and temperature potentials [25]. This can be modelled using a circuit simulation software package which accounts for the inter-dependencies between the electrical and thermal characteristics such as Joule heating in the electrical model that leads to heat influx in the thermal model, which in turn changes the material properties in both the sub-models. TNMs have been used for the design of conventional power equipment [25].

The HTS power system simulated in this study is hypothetical, but realistic in terms of heat loads and operating temperatures. The hypothetical system is used to demonstrate the modelling methodology. The simulated power system consists of a closed loop cryogenic helium circulation system that provides the cryogenic environment for a HTS ship propulsion motor, HTS generator and HTS power cable along with the terminations on either side of the cable. The hypothetical system includes a 36.5 MW motor, a full-size ship propulsion motor similar to the one that was successfully tested at the Naval Surface Warfare Center in Philadelphia in 2007 [20]. GHe cooled HTS power cables included in the system are similar to the kind demonstrated recently by our research group at the Center for Advanced Power System (CAPS) [26]. The system also includes a HTS generator.

The heat loads produced by each of the three HTS devices are dependent on their respective operating temperatures. Similarly, the cooling capacity of the cryogenic system is also dependent on the operating temperature. The heat loads and the cooling capacity are defined as polynomials based on our own experimental data and the data taken from the published literature on the recent demonstrations of HTS devices and associated cryogenic circulation systems [27] [28]. For the purpose of the model, the heat load of the HTS motor is defined as

$$Q_{motor} = -1.07*T + 433.3 \text{ (W)} \tag{1}$$

The HTS generator has a relatively higher load due to a stronger magnetic field and the associated AC losses in the stator. Also for the same reasons, to obtain high power density, the generator in the model is restricted to operate in the temperature range of 30-50 K with a heat load of

$$Q_{gen} = -0.54*T + 782.0 \text{ (W)} \tag{2}$$

for the HTS power cable, a 100 m long cable with a heat load of 1 W/m of cryostat loss and 120 W for each of the terminations are considered based on the typical values from the cryostat manufacturer specifications and estimated from experiments [13]. The cable's operating load of 3 kA and the corresponding heat load due to Joule heating from the resistive components present in the terminations is calculated in the model using the temperature dependent resistivities and the heat capacities were calculated using the component masses based on the dimensions of one of the actual terminations used for HTS cable demonstrations at CAPS. The operating temperature for the HTS cable is set as 40-77 K. The operating temperature ranges and heat loads of the three HTS devices in the system are listed in Table 1.

Table 1. Operating temperature and heat load ranges of the three HTS power devices in the power system used for the models.

HTS Power Device Operating	Temperature (K)	Heat load range (W)
Motor	40-60	370-390
Generator	30-50	750-765
Power Cable	40-77	481-555

Cryogenic System Design

The cryogenic system consisted of one or multiple cryocoolers and circulation fans. The cryogenic system used in the model is based on Stirling cryocoolers [29]. GHe is the cryogen operating at 1.7 MPa and a flow rate of 20 g/s. The pressure and the mass flow rate are similar to those used in our recent HTS demonstration studies [18], [24]. The heat capacity at constant pressure, C_p in J/g/K, of helium is temperature dependent and is approximated to be

$$C_p = -0.0012T^3 + 0.306\,T^2 - 27.511\,T + 6077 \text{ (J/g/K)} \quad (3)$$

the cooling power of the cryocoolers decreases as the operating temperature is lowered. In a cryogenic helium circulation loop, actual cooling power transferred by gaseous helium to the cryocooler through the heat exchanger attached to the cold head is also a function of the mass flow rate. This relationship was determined empirically in our previous experimental studies for a single cryocooler unit and is approximated to be

$$Q/\dot{m} = 3.97T - 171.92 \text{ (W/(g/s))} \quad (4)$$

where Q is the cooling power in Watts transferred to the GHe, $\dot{m}$ is the mass flow rate of GHe in g/s.

For configurations consisting of multiple HTS power devices, the required cooling power is transferred using multiple cryocoolers connected in series. The cooling capacity curve is scaled accordingly based on the number of cryocoolers used in the system to meet the required cooling power. For the purpose of the model, where multiple cryocoolers are used, the total cooling power is a multiple of that of an individual unit, maintaining similar dependencies on operating temperature. For a system with multiple devices, there are small additional heat loads in the transfer lines between the cryogenic system and HTS devices. The heat leak is assumed to be from 50-100 W between the devices depending on length and mass flow rate of each transfer line. The heat leak through the transfer lines results in a temperature gradient of about 0.5-1 K along the length of the transfer line. It is important to note that the hypothetical relationships used in the model can be replaced by the actual relations for the HTS devices and cryogenic systems to obtain realistic results of any system. The model uses the relationships as input parameters and hence the model does not need to change to be useful for other systems with different load or device characteristics.

CASE STUDIES

Several configurations of the system consisting of the three HTS devices and the cryogenic system have been discussed in our previous work [18]. The results in the previous study focused on maintaining each of the HTS devices in their respective operating temperature window with the minimum required cooling power. The case studies are discussed in this paper to demonstrate the usefulness of the modelling technique. The goal of the modeling exercise presented here is to assess the effectiveness of the modelling methodology and to demonstrate its usefulness in the system design and in developing operational protocols through parametric studies.

Case 1: Integrated Cryogenic Cooling System with the Three HTS Devices in Serial Configuration

In this configuration, the three HTS devices are connected in series with a single integrated cryogenic system as shown schematically in Figure 1. This case is used as the baseline to compare with other possible configurations. A scaled cryocooler (equivalent to 9 times of a single Stirling cryocooler) is used in the case. The cryogenic system needed has to provide a total cooling power of 2080 W at a flow rate of 20 g/s to support the required inlet temperatures for each of the three devices as shown in Figure 1.

Case 2: Local Cryogenic Cooling System with the Three HTS Devices in Parallel Configuration

In this configuration, three HTS devices are connected in parallel with each branch having its own cryogenic system as shown in Figure 2A. The mass flow rate of helium is maintained at 20 g/s. Variation of the load in each branch requires different cooling power supplied by the corresponding cryogenic system. The cryogen flow rate is divided based on the cooling power requirement and the capacity of the cryocoolers for each branch controlled by valves in each branch. For the given heat

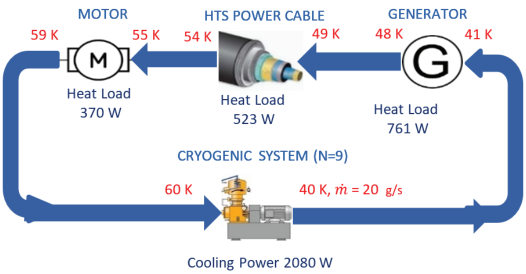

Figure 1. Case 1: A schematic of closed loop cryogenic circulation with a single cryocooler serving all three HTS devices. The figure shows the inlet and outlet gas temperatures of each device.

load, upon numerous iterations, optimum distribution of mass flow rate and number of cryogenic systems are arrived at for each branch. For the given configuration, mass flow rate is divided in the ratio of 65:19:16 to satisfy the operating temperature of each HTS device connected. Although this configuration requires more number of cryocoolers, the total cooling power required is lower than that in Case 1.

Case 3: Hybrid System with Local and Shared Cooling System in a Parallel Configuration

Some HTS power devices do not require their own cryogenic systems due to the relatively low cooling requirement. Thus, the motor and the power cable are placed in series and share a cryogenic system while the generator has its own cryogenic system placed in parallel to the other two devices, as shown in Figure 2B. Since the generator has a relatively high heat load and needs to be operated below 50 K, the mass flow rate is divided in the ratio of 7:3 while the generator gets a GHe flow rate of 14 g/s and motor and power cable get flow rate of 6 g/s. This configuration requires 6 cryocoolers and has an effective total

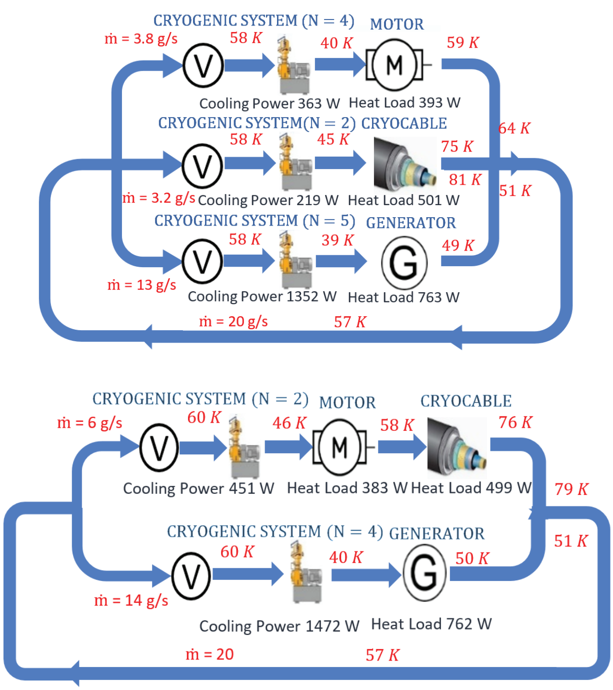

Figure 2. 2A (top) CASE 2: A schematic of a closed loop cryogenic circulation with a local cryocooler serving each of three HTS devices in a parallel configuration. 2B (bottom) CASE 3: A schematic of a closed loop cryogenic circulation in a hybrid (series and parallel) configuration with a local cryocooler serving each HTS device.

Table 2. Total cooling power required for different configurations of multi-device HTS.

Case	Cooling System	Device Configu- rations	Cooling Power (W)	Figure Number
1	Integrated	Series	2080	1
2	Local	Parallel	1930	2A
3	Local/Shared	Hybrid	1920	2B

cooling power of 1920 W, which is lower than all the cases considered previously. For the system with the three devices, this configuration is optimum with the lowest total required cooling power.

The case studies discussed are examples of possible configurations that can be used for the system with the three HTS devices. There are additional possible configurations depending on the tradeoffs. Table 2 summarizes the required cryogenic cooling power and the number of cryocoolers for the case studies considered. As seen from the data, the total cryogenic cooling capacity varies with the configuration and thus optimal configuration needs to be decided based on the design constraints such as total cooling power, number of cryocooler units, or the cost. In a shipboard system, the design constraints could be, total available installed cryogenic capacity, targeted efficiency of the overall HTS power system, or operational flexibility.

TRANSIENT BEHAVIOR DURING THE FAILURE OF A COMPONENT

In the event of a failure in the cryogenic system, there will not be any continuing cooling power available and the heat capacity of the cold mass of the total system and the heat load determine the temperature evolution as a function of time. Contingencies such as failure of the cryocooler, failure of the cryogen circulation impeller make it necessary to shut down the HTS system at the right time to prevent potential damage to the HTS devices. Models to understand the system behavior in such scenarios is essential to make the necessary operational decisions on the time available to turn off the system and/or to activate the contingency plan.

Failure of the Cryocooler

One of the potential contingencies of HTS power systems is the failure of one or more of the cryocoolers. Although, it is unlikely that all the cryocoolers fail at the same time, the potential condition was studied as the worst case scenario. The test case considered for this system was a HTS cable termination module cooled by a cryogenic system. The HTS cable termination module is assumed to be under a load current of 3 kA. Figure 3 shows the transient response of the system with the temperatures when the cryocooler failure occurs at time, $t = 1000$ s. Since the maximum allowed operating temperature of the HTS termination is 80 K as shown in Table 1, the time at which the temperature of termination

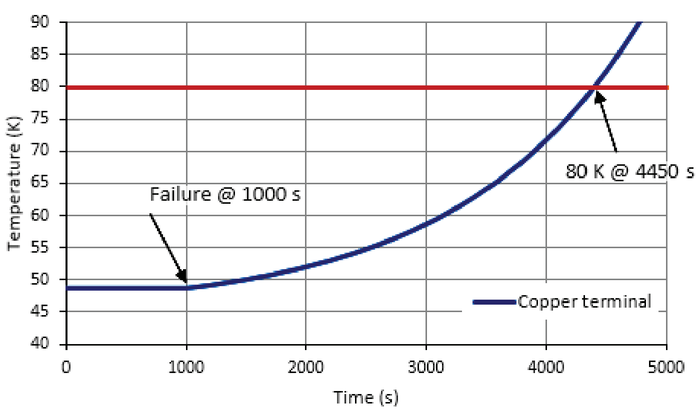

Figure 3. Transient response of the HTS cable termination upon cryocooler failure at t=1000s

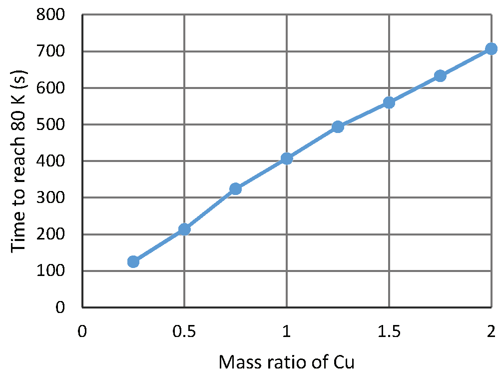

Figure 4. Effect of mass ratio of copper on the time available before reaching the maximum allowed temperature of 80 K in the HTS cable termination after the circulation failure.

reaches 80 K was determined as the point of failure time for the system. Upon simulation, it was seen that the system reaches 80 K at 4450 s. Hence, upon failure of the cyrocooler, the time required for the system to reach 80 K is 3450 s or 58 minutes.

Failure of the cryogenic gas circulation impeller

Another mode of failure in a helium gas cooled HTS cable system is failure of the gas circulation pump, leading to the helium circulation stoppage. The rate of rise in the temperature would be higher in this case than in the case of failure of the cryocooler because the heat propagation is not efficient in a stagnant gas medium and the local temperature in the termination where the heat load is highest would start rising faster than in the rest of the system. The termination is carrying a 3 kA load current when the circulation fan fails. The simulations of this failure mode include assessing the system behavior for different masses of copper in the termination module and determining the rate of rise of temperature. The cold mass of the total system determines the temperature evolution as a function of time. A large cold mass is beneficial, but to minimize the total weight of the system, it is necessary to conduct trade-off studies to relate the operational requirements with a weight minimization constraint. The weight of cold mass for the base design of the termination module is 8.9 kg. Various mass ratios relative to the base design have been simulated to check the behavior of the

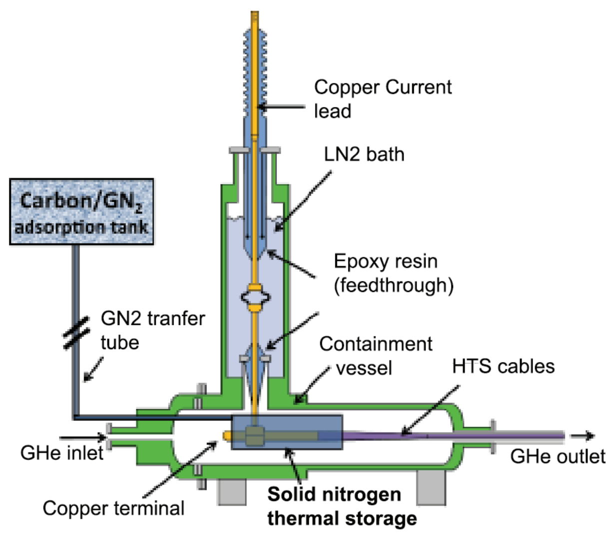

Figure 5. Solid nitrogen as the thermal storage buffer in HTS termination.

system under the failure condition. Figure 4 shows the guide to appropriate cold mass based on the needs on time to switch to maintenance mode at failure condition.

Modeling the Benefit of Cryogenic Thermal Storage Buffer in the Form of Solid Nitrogen

The time available before the HTS device reaches 80 K after the failure of the cryocooler needs to be long enough to allow sufficient time for the operators to activate the contingency plans and to make the system resilient. The time available can be extended by adding a cryogenic thermal storage buffer within the device which increases the heat absorption capacity for the device without a temperature increase. The possibility of using solid nitrogen (SN2) for HTS applications in conjunction with a pressure controlling gas adsorption system was proposed previously [30]. Here we discuss a HTS termination system consisting of SN2 as a thermal storage buffer by analyzing its benefit using the modeling tools developed.

The SN2 block modeled is thermally anchored to the copper terminal within the HTS cable termination. This block is connected to an external buffer gas chamber filled with activated carbon creating a self-contained system as shown in Figure 5. The carbon is used to adsorb the gaseous nitrogen at room temperature and to prevent the pressure build up during the event of an unexpected heat load. It is important to keep the pressure in SN2 chamber close to 1 bar because higher pressure raises the boiling point of nitrogen and hence will not be able to maintain the temperature of the termination at or below 77 K. During the normal operation of a HTS device such as the termination, the buffer gas is solidified and stored as SN2 in the buffer volume that is thermally anchored to the heat producing elements of the termination. In the event of a loss of cooling due to the cryocooler failure, the solid nitrogen will absorb the heat and maintain the temperature of the termination for some time. It is preferred that the thermal storage buffer stays at constant atmospheric pressure of 0.1 MPa during the time when the SN2 becomes liquid and eventually vaporizes. The system was modeled and analyzed using lumped analysis for different masses of SN2 to explore the effect of thermal mass on the time required to reach the maximum allowed operating temperature of the HTS device.

The time at which the copper components in the termination reaches 80 K is considered to be the maximum operating time of the device under the failure condition. It is important to note that the operating time under failure condition is also dependent on the steady state temperature of the system under operation before failure. Naturally, if the steady state temperature is high, the operating time will be short. Thus, one way to increase the operating time is to operate system at lower steady state temperature and increase the margin. However, operating the system at lower than the required temperature is costly. Another way to increase the operating time is by increasing the cold mass of the system. The cold mass of 8.9 kg is considered as the base design for the termination in this study. The case of the SN2 storage chamber consisting of 3 kg of nitrogen was modeled and analyzed under

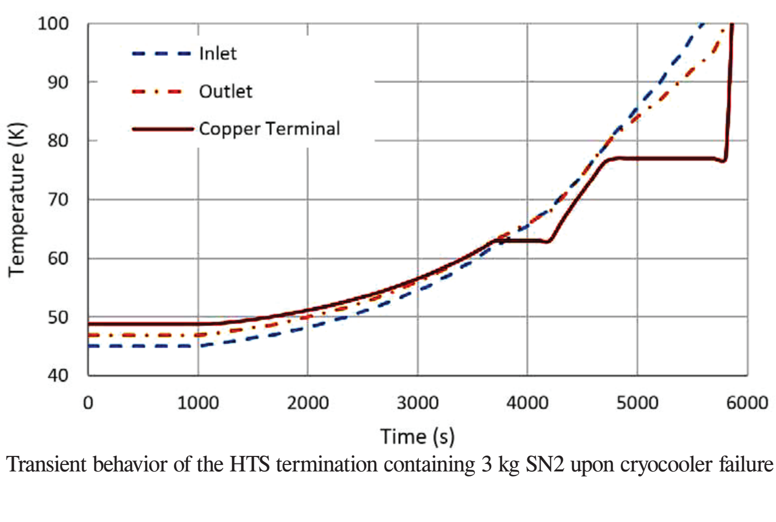

Figure 6. Transient behavior of the HTS termination containing 3 kg SN2 upon cryocooler failure at 1000s.

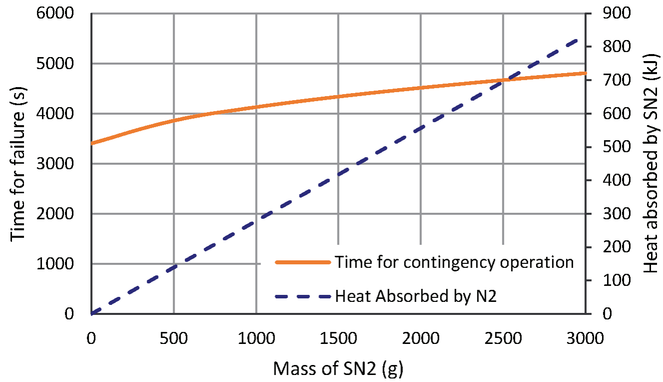

Figure 7. Time available for continued operation for HTS termination system upon cryocooler failure as a function of the mass of SN2.

cryocooler failure. The results of the model are shown in Figure 6. The temperatures at the copper terminals are monitored after the incidence of failure. The steady state temperature before failure is 49 K. In steady state operation, the cryogen GHe provides the cooling to SN2 chamber and makes SN2 which will also be at 49 K in normal operation. Upon failure of the cryocooler at 1000 s, GHe is no longer cooled by the cryocooler and the temperature would start rising in the absence of the storage buffer. The SN2 thermal storage starts providing the cooling when the SN2 chamber is at a lower temperature than GHe. When the SN2 reaches 63 K at around 3700 s, the copper terminal is maintained at the temperature for about 500 s after which the SN2 starts changing into liquid. Again, when LN2 reaches 77 K, LN2 phase change from liquid to gas can hold the temperature of copper terminal for about 1000 s. After all nitrogen becomes gas, the low heat capacity of GN2 causes sudden increase in temperature of copper terminal. Hence, the time to reach 80 K upon failure when SN2 cryogenic storage is used is 4808 s giving an additional operation time of 81 minutes to the HTS termination system after the cryocooler failure, which can be valuable to either for continued operation to provide power to the critical loads or safely shutting down of the HTS system.

The model developed was used to study the effect of the mass of SN2 in the cryogenic thermal storage buffer from 0 – 3 kg in the increments of 0.5 kg and the corresponding operational time available after the cryocooler failure. The results are shown in Figure 7. The operational time available after the failure obviously increases with the mass of SN2 in the thermal storage. For example, 3 kg of SN2 storage buffer increases the additional operational time by 81 minutes. This is an increase of operational time of 24 minutes compared to the HTS cable termination model without SN2 as the storage buffer. This time can be utilized for either maintenance or controlled shut down of the whole system. The total heat that can be absorbed by different masses of SN2 in the chamber is also shown in the Figure 7. It can be seen that for a system having fixed cold mass, the heat absorbed by the SN2 increases linearly, hence increasing the time for failure of the system. As seen in the graph, for a fixed cold mass of the system, the time for failure can be varied by changing the amount of SN2 used. Due to high mass density of the SN2, the volume occupied by this chamber is small allowing it to be used as a design feature to increase resiliency and if the loads served are critical. Appropriate mass of SN2 is a design feature that can be selected based on the operational need for HTS cable system.

CONCLUSION

A versatile modeling technique, based on thermal network methods, was developed and used for the power system with multiple HTS power devices to aid in design studies and in the operations. The system level benefits of integrating multiple HTS devices and their necessary cryogenic circulation systems in a closed loop configuration are presented. The integrated approach allows system level optimization and enables taking advantage of the tunable power rating of HTS devices.

The integrated approach also allows to direct the cooling power as needed for the particular mission on hand. The versatility of the models is demonstrated with a few case studies. The cases involving cryogenic system failure are analyzed using the models. The benefits of adding solid nitrogen as the thermal storage buffer is discussed as a way to increase the operation time after a cryogenic system failure. It was shown that incorporation of a 3 kg SN2 as cryogenic thermal storage buffer in HTS cable termination allows the system to operate for 81 minutes after the failure adding critical resilience to the system.

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