Resiliency Analysis of Cryocoolers Based Large Scale Superconducting Distribution Networks of Electric Transport Systems

S. Telikapalli, P. Cheetham, C. H. Kim, and S. V. Pamidi

FAMU-FSU College of Electrical Engineering, Florida State University
Center for Advanced Power Systems, Florida State University
Tallahassee, FL 32310

ABSTRACT

The need for intelligent cryogenic circulation system designs to maintain the resiliency of high temperature superconducting (HTS) power system components of large electric transportation systems is emphasized. The requirements of cryocoolers characteristics to support electric transportation systems are discussed. Thermal Network Models were developed and used to study the temperature profiles along the length of HTS cables. The selection and location of cryocoolers and the design of cryogenic flow systems are shown as critical to achieve overall system efficiency and resiliency. It is also shown that the flows of electricity and cryogenic fluid have to be designed together to incorporate the tightly couple the thermal and electrical aspects of HTS power system components. The use of two different cryocoolers and their influence on the temperature profile of the electrical distribution network is discussed to emphasize the importance of the choice of cryocoolers in achieving the necessary resiliency of electric transport systems.

INTRODUCTION

Rapid depletion of fossil fuels and increasing awareness of their adverse effects on the environment has accelerated the development of clean and sustainable transportation systems. There have been significant developments in reducing the dependence of transport systems on fossil fuels [1]. For automobile applications, the most economical solution currently is to use batteries to store the energy to run the electric motors. This is viable due to the low power density requirements of the automobile systems [2]. Depending exclusively on energy storage is not feasible for the electrification of large transport systems such as electric ships or electric aircraft. The challenge arises due to the large power ratings needed for the large transportation systems. The estimated electric loads of an electric ship and an aircraft are 100 MW and 40 MW, respectively [3].

For transport systems to be efficient and economical, the space and weight of the power system are major factors. Several studies have concluded that the optimal power distribution for electrification of large transport systems is achieved by using medium voltage direct current (MVDC) distribution grids operating between 10-20 kV [4]–[7]. To achieve the target power ratings of tens of MW using MVDC architecture would require the current rating of the power distribution cables to be at several kA range. The use of copper or aluminum cables in such distribution systems would make the power systems prohibitively bulky and heavy for large transport applications [8].

Cryocoolers 21, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller
© International Cryocooler Conference, Inc., Boulder, CO, 2021

High temperature superconducting (HTS) power cables have a significantly higher power density compared to their copper counterparts and have no electrical loss in DC applications. Therefore, they are a natural choice to replace conventional copper technology in large MVDC power systems. It is envisioned that DC systems that incorporate HTS cables would have the reduced losses, smaller size, and lower weight MVDC distribution networks resulting in efficient overall power systems of large electric transportation platforms [9].

Liquid nitrogen (LN2), the most commonly used cryogen for large scale demonstrations of HTS technologies [10], is not suitable for large transport applications. This is due to the risk of over pressurization and asphyxiation associated with LN2 [11] and the limited operating temperature range of 65-77 K. Cryogens such as gaseous helium (GHe) and liquid hydrogen (LH2) are being explored as alternative cryogens. LH2 is being considered both as the fuel and the cryogen for electric aircraft by NASA in the N3-X, an all-electric superconducting aircraft [12], [13]. Airbus has announced a plan to use LH2 in near future aircraft [14]. For electric ships, GHe is used as the cryogen to cool HTS motors, power cables, and other devices in a closed-loop circulation system [11], [15], [16]. The use of GHe as a cryogen allows lower operating temperatures, thus resulting in higher power densities in HTS cables than can be achieved using LN2.

For electric transport applications, the reliability of the power system is crucial. The total failure of electric propulsion and essential systems must be avoided at all costs. Due to the deeply coupled nature of cryogenic thermal and electrical systems in HTS devices, there is a need to understand the resiliency of the system from a cryogenic systems failure along with the electrical faults. The superconducting electrical system can perform only if the necessary cryogenic system is operational. The selection and design of the cryogenic system are thus of great importance, and both the electrical and cryogenic systems must be designed together. Failure in either the electrical and/or thermal system can affect the reliability and performance of the power system. Power systems must be designed to operate in the event of a device failure or during the routine maintenance of the components.

Cryocoolers with attached heat exchangers are an integral part of the cryogenic system for GHe cooled HTS power cables. The cryocoolers designed for transport systems have certain additional requirements compared to their terrestrial counterparts. They must be compact and lightweight to fully utilize the benefits of HTS technology. The cryocoolers have to be highly efficient in their refrigeration cycles so that the total loss in the system is considerably smaller than the total ohmic losses incurred when using copper cables. Finally, they should be easy to maintain and be capable of running for long durations between the maintenance cycles.

Along with the generation of cooling power, additional challenges are involved in the distribution of cooling power to the cryogen and circulation of cryogen in large HTS systems. There is a need for efficient designs for a heat exchanger that transfers the cooling power from the cold head of the cryocoolers to the circulating cryogenic medium. High-speed gas circulators that generate a large volumetric flow and have a little to no chance of failure in events of a sudden change of thermal loading have to be developed [10].

The type of cryocooler used plays an important role in the resiliency and the feasibility of the system. For example, if the envisioned lowest operating temperature that the HTS cables are subjected to is approximately 70 K, we can make use of high efficiency and low maintenance reverse turbo Brayton (TB) cycle cryocoolers to achieve provide very high cooling power. TB refrigerators provide up to 40% Carnot efficiency and have a Mean Time Between Failure (MTBF) of 105,000 hours. The time between maintenance cycles is around 5 years. Commercially available TB coolers are capable of producing a cooling power of 7.5 – 150 kW at 77 K [17].

For applications that require lower than 70 K operating temperature, the choice of the cryocooler depends on many factors including, the operating temperature range, the cooling power required, the refrigeration cycle, the efficiency of the refrigeration cycle, the size and weight of the cryocooler, the commercial availability of cryocooler specific heat exchangers, the compatibility with gas cooled circulation systems, the time between maintenance cycles, the MTBF, and finally the cost of the cryocooler. The choice of cryocoolers also depends on the architecture of the ship or aircraft. It might be preferable to have multiple smaller cryocoolers rather than one large cryocooler. This is to efficiently utilize all the space available on the platform. Stirling cycle and Gilford-McMahon cycle are some of the examples of refrigeration cycles available in large capacity commercial cryocoolers. Both have a maintenance cycle of approximately 10,000 hours and can produce between 350 and 400 W at 50 K, respectively [18], [19]. High efficiency, very low-temperature free-piston Stirling cryocoolers for Navy HTS applications are being developed by Infinia Technology Corporation [20]. These cryocoolers are capable of producing over 400 W at 50 K and have a maintenance cycle of around 100,000 hours. These cryocoolers are soon to be commercially available. Finally, each type of cryocooler has its advantages and disadvantages. The choice of the cryocooler is application-specific and has to be made after careful consideration. For our model, based on the estimates for heat load and expected operating temperatures, we have selected SPC-4 and SPC-1 Stirling cryocoolers to understand the temperature profile of the HTS cables within a notional power system for electric transportation systems, using the electric ship as an example.

Another important factor to consider when incorporating HTS cables in transport systems is that unlike in traditional power systems where cables often run point to point, electric transport applications are likely to consist of multiple HTS cables connecting at common nodes. Using single cable terminations at every junction would increase the weight and size of the HTS cable system significantly. There is a need to develop "cryogenic nodes" that are capable of housing multiple HTS cables. A cryogenic node would have multiple HTS cables and disconnect switches at the cryogenic temperature inside it. A cryogenic node would serve as the beginning and end of a cooling loop for multiple cables. Additionally, a cryogenic node would be capable of rerouting the flow of both electricity and cryogenic fluid independently. Developing and utilizing cryogenic nodes gives the opportunity for the cryogenic system to be optimized to achieve overall system efficiency.

It is also necessary to ensure that the desired changes in operating current and associated heat loads are accounted for by the cryogenic system without causing the HTS cable to quench. This is for both the normal operation and contingency conditions. The contingency operation includes partial failures to both the electrical and/or cryogenic systems. It is, therefore, necessary to also understand how to develop the cryogenic system in a power-dense manner whilst ensuring the failure within the cryogenic system does not affect the power system. The resiliency in the cryogenic network of the power system has to be achieved at both the system level and device level.

This paper explores a notional shipboard power system rated for 100 MW and utilizing HTS cables for the main DC bus operating at 12 kV. The power system uses a radial fed cable architecture and zonal based cryogenic system. The paper provides an overview of both the electrical and cryogenic systems architectures and the development of thermal network models to estimate the required cooling power of cryocoolers to enable the power system to be resilient and power-dense. The paper discusses the difference in the temperature profiles of the system when using two different types of cryocoolers.

NOTIONAL MVDC MICROGRID INCORPORATING HTS CABLES

Cryogenic Node

The notional power system developed for a 100 MW electric ship consists of eight cable cryostats each approximately 100-m in length. Each cryostat houses 3 dipole HTS cables that are cooled by circulating GHe. Each dipole cable terminates at a unique destination within the power system via a cryogenic node. The cryogenic node contains a thermal break as part of the system, which allows each cable section to be cooled by different cooling loops if required. A schematic of the layout of one of the cryostats is shown in Figure 1.

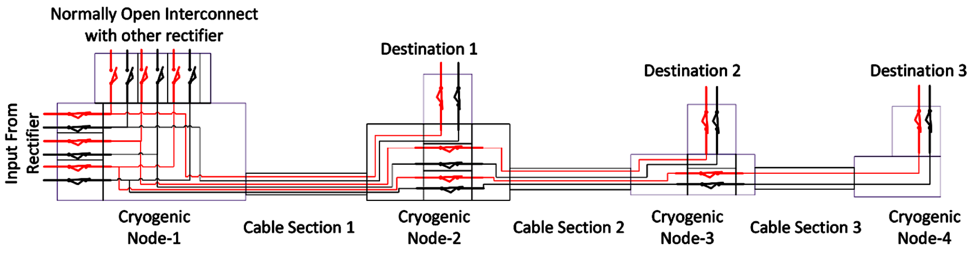

Figure 1. Cryogenic nodes that can reroute the flow of electricity and cryogenic fluid.

Figure 1 shows the cryogenic node that has twelve current/terminal leads, six of these are closed during the normal operation and the remaining six are closed only in case of a contingency when the HTS cable has to operate at a higher current. There are multiple cryogenic disconnect switches housed inside the cryogenic node. These disconnect switches act as a means to reroute the electrical power and also act as fault current limiters working along with the power electronics in the generator and the motor. It is worth noting that, currently a cryogenic disconnect switch does not exist and has to be developed. Although using switchgear at cryogenic temperature introduces additional heat load into the cooling loop, it would considerably decrease the footprint of the system compared to using conventional circuit breakers and cable terminations to tap into the HTS cable. Additionally, having spare terminal leads will add additional heat load into the cryogenic node even in regular operation. This additional heat seep into the cryogenic cooling loop is through conduction from copper terminal leads. Having the switchgear operating at cryogenic temperatures reduces the thermal gradient along the copper lead which reduces the heat load onto the cryogenic system as it allows the potential of two-stage cooling to be implemented when terminating an HTS cable to ambient. The remaining cryogenic nodes only have two terminal leads which connect to ambient as this allows for simpler terminations and reduced heat loads compared to having all cables terminate at each location.

Heat Loads Influencing the HTS Cable Systems

For each cryostat, it is necessary to understand all the heat loads that influence the temperature gradient along its length. The heat loads on the cryostat are the ambient heat seep through the cryogenic nodes and along the length of the cryostat; the heat load introduced by the current leads; the heat load of the disconnect switches; and the ohmic losses at the cable joints. In electric transport applications a typical cable section length is less than 100 m, and assuming a heat seep of 1 W/m, the heat load would be at most 100 W [21]. This suggests that the majority of the heat load is produced at the cryogenic nodes. The heat load at a cryogenic node varies from 100 – 500 W, depending on the number of terminal leads, the operating current, and the heat leak from ambient. The heat load at the disconnect switch is assumed to be a notional value of 5 W per switch.

Increasing/decreasing the operating current from the design current of the terminal lead will result in higher than optimal heat loads because the current leads are typically optimized for minimum heat load at normal operating current using the McFee process [22], [23]. It is therefore necessary to understand the permissible operating currents of HTS cables. The flexible current rating of HTS cables means there is a potential for HTS cables to operate at higher current levels during peak load times or to mitigate failures of another HTS cable within the system. However, this is only possible if the additional heat load is handled by the cryogenic system. Additional heat load being introduced into the cryogenic system has the potential to reduce the safety margin between the critical current and operating current of the HTS cable. One of our previous publications concluded the operation of HTS cables in parallel to keep the operating current of the system between 1-2 kA with adequate margin between operating and critical currents of the HTS cable [24]. In that study, a single Stirling SPC-1 cryocooler was assumed to provide the cooling power to each HTS cable section. Building upon the research we are investigating the ability to cool multiple HTS cables in parallel as well as the possibility to decouple the electrical and thermal system from one another and have a zonal-based cryogenic cooling.

The architecture of the cable system causes an HTS cable to come across multiple cryogenic nodes throughout its length. Aided by the long lengths of cables (approximately 100 m), the temperature gradient along the length of the cable could be significant. A large temperature gradient is detrimental because the critical current of a cable is dictated by its hottest point. In case of a contingency operation, where higher currents are run through the cable to mitigate the loss of a cable/component, we need to make sure to consider the temperature gradient to avoid the cable from quenching. Furthermore, the cooling loops have to be designed in such a way that the temperature gradient along the length of a cable is minimized.

Notional Electrical Schematic of the Ship

A schematic of the electrical system of the ship is shown in Figure 2. As seen in Figure 2, each 25 MW generator (PGM 1 - 4) is dual wound and supplies two rectifiers rated for 25 MW each. This setup allows the entire current of the generator to be supplied through one of the cryostats if needed in case of failure of

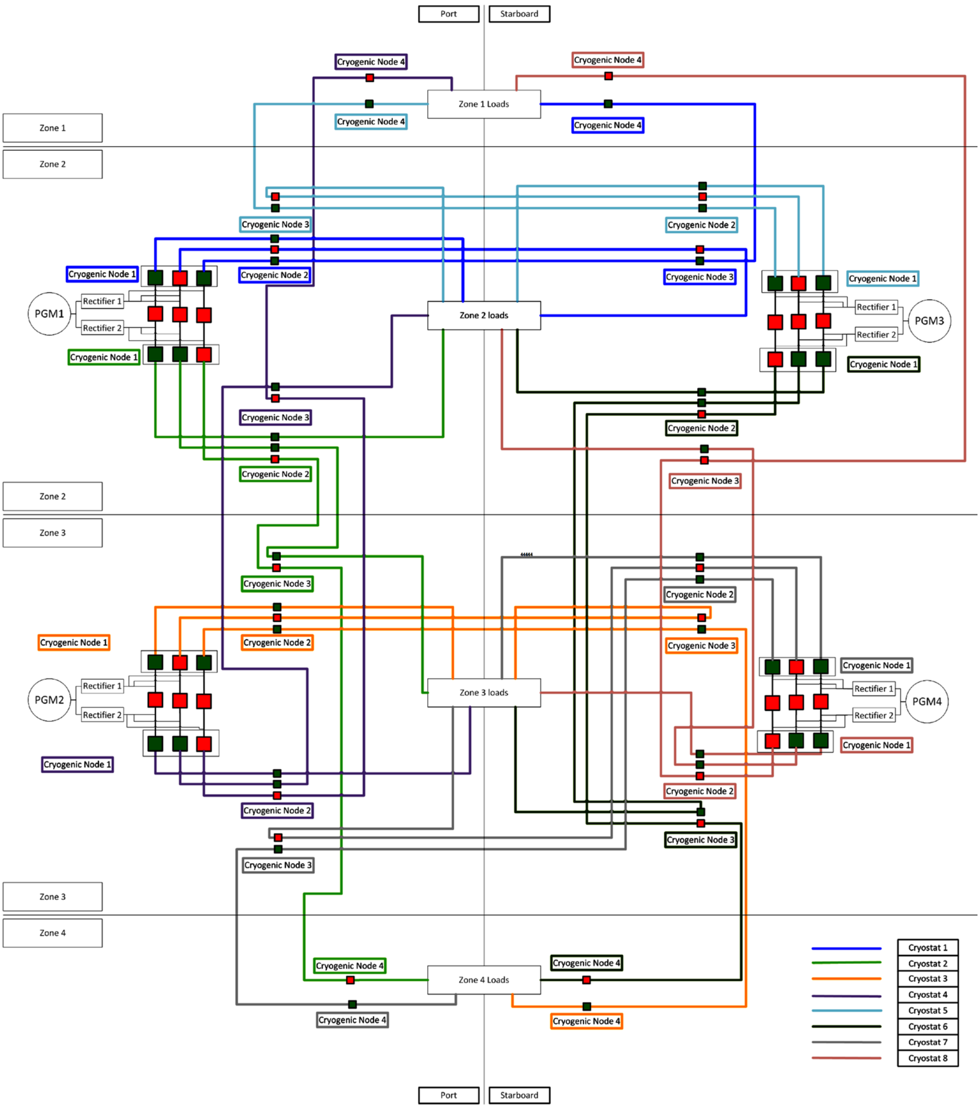

Figure 2. Notional electrical schematic of an electric ship.

a rectifier. HTS cables originating at cryogenic nodes at the rectifiers pass along the length of the ship and supply power to loads spread across Zones 1-4. In this architecture, the electric propulsion is situated in zones 2 and 3. Accordingly, they have a higher load rating than zones 1 and 4. The electrical loadings assumed for this model are 5, 45, 40 and 10 MW for Zones 1, 2, 3, and 4, respectively. The architecture was built to have extreme resiliency and redundancy. It is envisioned that the power system can sustain failures in generators, rectifiers, cables, and cooling systems without total loss of power to the loads. The cable layout is symmetrical which means that a cable failure in an even number of cryostats will have similar results to one another. The same is true for odd number cryostats. The electrical and the thermal schematics were built simultaneously to ensure system-level redundancy in the cryogenic system and to fully utilize the temperature-dependent critical current nature of HTS cables to add in additional redundancy in case of fault on one of the cables or the components.

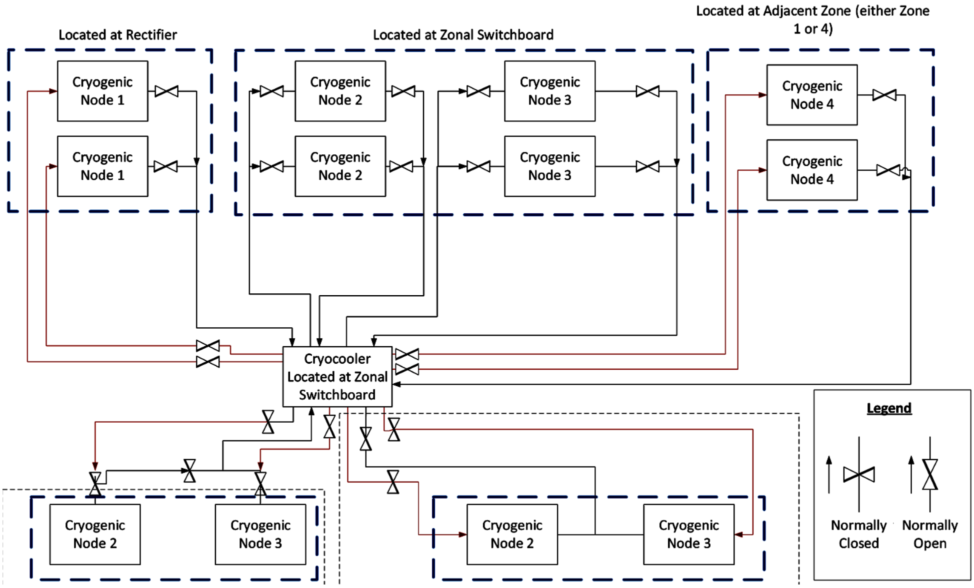

Figure 3. Cryogenic circulation system showing the cooling loops for most resilient operation.

Table 1. Cooling loops in central zones (2/3)

Cooling loop	Heat load 1	Heat load 2	Heat load 3
1	HTS cable (15m)	Termination 1 (Z2P R1)	Transfer line (15m)
2	HTS cable (15m)	Termination 1 (Z2P R2)	Transfer line (15m)
3	Transfer Line (5m)	Termination 2 (C1-1)	Transfer Line (5m)
4	Transfer Line (5m)	Termination 2 (C2-1)	Transfer Line (5m)
7	Transfer Line (5m)	Termination 3 (C4-2)	Transfer Line (5m)
8	Transfer Line (5m)	Termination 3 (C5-2)	Transfer Line (5m)
9	HTS cable (57m)	Termination 4 (C4-3)	Transfer Line (57m)
10	HTS cable (57m)	Termination 4 (C5-3)	Transfer Line (57m)
11	HTS cable (30 m)	Transfer line (30 m)	Termination 2
12	HTS cable (38 m)	Transfer line (38 m)	Termination 2
13	Transfer line (30 m)	Termination 3	HTS cable (30 m)
14	Transfer line (38 m)	Termination 3	HTS cable (38 m)

Cryogenic Fluid Circulation System

The required cryogenic environment of the HTS system is maintained by multiple cooling loops that start at the cryocoolers located at the zonal switchboards of Zone 2 and Zone 3 on both the port and starboard sides of the ship. Figure 3 and Table 1 show the cooling loops pertaining to HTS cables originating from one generator. Due to the symmetrical nature of the system, understanding the cryogenic circulation system for one set of cables can be extended to the remaining three.

Cryogenic node 1 (cooling loop 1 and 2), is located next to the rectifiers (ZP2-R1 and R2). This node consists of 12 current leads, 6 normally open and 6 normally closed. In the first model, we have used one SPC-1 cryocooler for each HTS cable dipole, and in the second model, we have assumed one SPC-4 cryocooler per zone. As seen in Table 1, the cryogen flows to the HTS cable first and to the cryogenic node next to make sure the temperature of the HTS cable remains low and is not influenced by the large heat load introduced at the node.

Cryogenic nodes 2 and 3 (cooling loops 3-8) supply the cooling power to the cryogenic nodes and HTS cables that serve the zonal loads at the port and starboard sides of the craft. Nodes 2 and 3 have two current leads each and similar to node 1 have one SPC-1 per node in the first case. For the second case, one SPC-4 serves both nodes.

Cryogenic node 4 (cooling loops 9 and 10) supply the cooling power to HTS cables and the cryogenic node is situated in adjacent low load zones such as Zone 1 or Zone 4. These are the longest spans of cables, with a length of about 57 m. The redundancy in this loop is not provided at this level, in case of failure of a cryogenic equipment or HTS cable in this cryostat, the loads in the zone are supplied through a different channel.

Cooling loops 11-14 are normally open. They are closed in case of a failure of the cryogenic circulation system that normally serves the cryogenic nodes 2 and 3 of the adjacent zone. This is to build additional redundancy into zones 2 and 3 in case of failure of cooling systems. This is important as in our architecture, the most essential loads such as propulsion and radar systems are located in Zones 2 and 3.

The model we have developed does not consider the difference in electrical and thermal time constants. Electrical time constants are in the μs to ms timescales while the thermal time constant could be anywhere from a few seconds to a few minutes. However, this would not decrease the accuracy of the model significantly when studying the response of the thermal system to electrical studies. The reason for that is the built-in heat capacities of the system. Most cryogenic devices have a large heat capacity associated with them and do not change their temperature instantaneously. To further increase the resiliency of the thermal systems to faults, we have previously looked at introducing a solid nitrogen buffer to the cable terminations, improving the operation time of the system after failure of a cryocooler to a maximum of 90 mins [25]. Even without the buffer, the system engineer would have enough time to respond to the failure and redirect power as necessary before the cables quench. However, the major challenge is in real-time monitoring of the state of the system and to ensure the authenticity of the data obtained to the control unit.

MODEL RESULTS AND DISCUSSION

Figures 4 and 5 show the results of the Thermal Network Models using SPC-1 and SPC-4 Stirling cryocoolers. The main purpose of these models is to aid in the system design process. These models act as

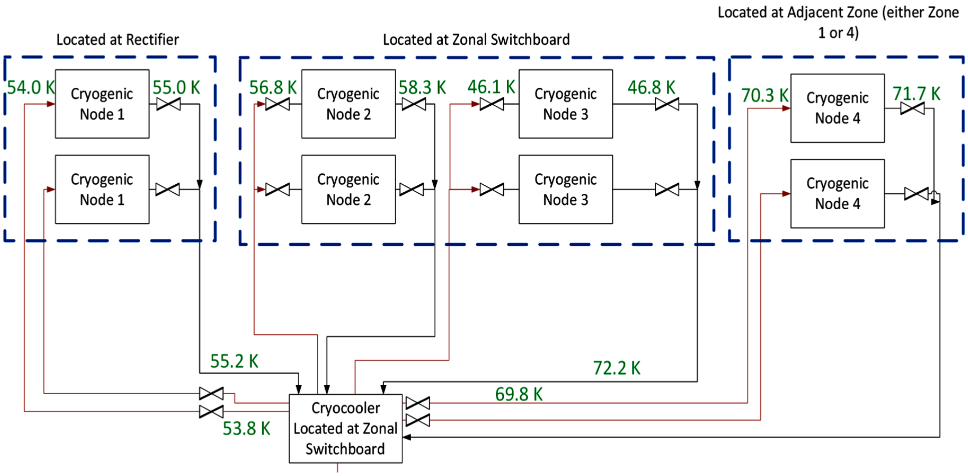

Figure 4. Temperature profile of the HTS cable system when using two SPC-1 Cryocoolers.

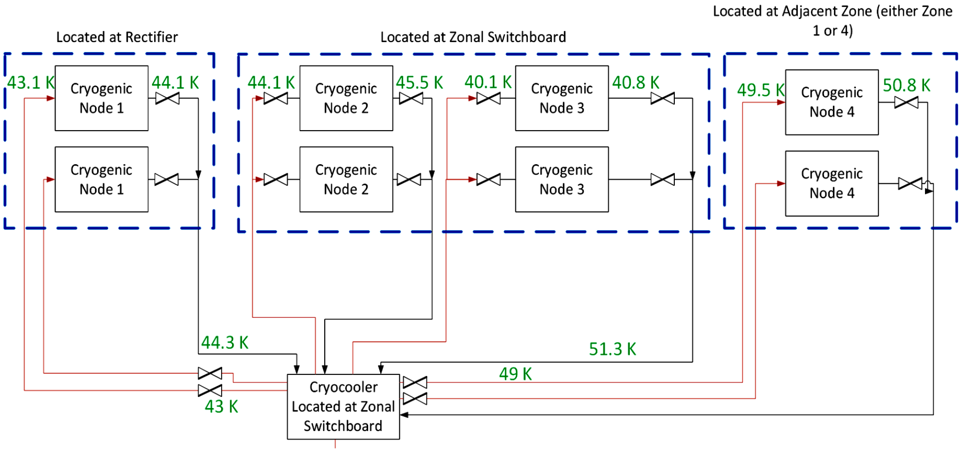

Figure 5. Temperature profile of the HTS cable system when using one SPC-4 Cryocooler.

tools in designing the cryogenic system that is supporting the electrical distribution system of ships. The advantages of TNM models would become apparent when conducting fault studies on the system. However, the response of the electrical and thermal systems to a fault and the control strategies is beyond the scope of this paper. The results presented here are to gain an understanding of the temperatures and temperature gradients along the important components in the HTS system.

In the case of SPC-1, two cryocoolers which are located at the zonal switchboard work in parallel. The heat exchanger connecting the cold head to the cooling loops was assumed to have multiple outlets to which each cooling loop can tap in for heat transfer. SPC-4 was modeled in a similar fashion, however, instead of two cryocoolers, we have considered only one cryocooler to be present at the switchboard. The cooling power available in the cryocooler is assumed to be equally divided into each cooling loop. This is not true in practice, however, due to the notional nature of the system, the exact dimensions of the system are not available. Therefore, the results we have presented here are reasonably accurate and serve the purpose of supporting the electrical network to get an idea of how a resilient MVDC microgrid with HTS cables incorporated into it would work.

The cooling power provided by an SPC-4 cryocooler is approximately four times that of SPC-1. However, the weight is only twice as much. So, choosing SPC-4 over SPC-1 would appear like a better solution. The reasoning behind choosing an SPC-1 cryocooler that has lower cooling power to weight ratio, is that from a design standpoint accommodating two lighter cryocoolers could improve the weight and space distribution of the ship's power system. Also, there is an added redundancy in the system as the loss of a cryocooler does not result in the total loss of the cryogenic system.

Figures 4 and 5 respectively show the temperature profiles of the HTS cable systems when two SPC-1 and one SPC-4 are used. As listed in Table 1, the transfer lines for nodes 2 and 3 are only 5 m in length, and hence the temperature gradient along the length to and from the nodes to the cryocooler is small. The lengths of HTS cables between the cryocooler and the nodes 1 and 4 are 15 and 57 m, respectively. This creates a temperature gradient which depends on the length. As seen in Figures 4 and 5, the longer the transfer line/HTS cable, the higher the delta T.

As predicted, due to the higher cooling power available by using SPC-4, the temperature of the cable is lower. The highest temperature in the system is 51 K. Similarly, due to lower cooling power in SPC-1 cryocoolers, the maximum temperature attained is 72 K.

The cooling loops 11-14 have not been shown in Figures 4 and 5 because under normal operation those valves are typically open, and therefore, no cryogen would flow in these loops from the cryocoolers(s). The results for contingency operation are not included in this paper as the primary focus of this paper is on introducing the cryogenic system challenges of the notional MVDC architecture of the ship, the resilient cryogenic designs, but not on the model itself. The results of the contingency study would be included in a future publication.

The goal for this work was to design a cryogenic circulation system that would keep the temperature profile of the system under 77 K under both normal operation and contingency operations. The results from the model show that under normal operation the use of any cryocoolers configuration would maintain the desired temperature of the system.

As part of our ongoing research on this topic, we plan to use the models created in this paper to better understand how temperature variation along the HTS cables changes for contingency operations. Additional studies to be performed also include understanding how the operating temperature of the HTS cable can influence the number of HTS conductors required per cable. Reducing the number of HTS conductors is one potential strategy to reduce the cost of the HTS power system due to the inherently high cost of HTS conductor.

ACKNOWLEDGMENT

This work was supported by the Office of Naval Research (ONR). Grant number N00014-18-1-2693 and N00014-16-1-2956

REFERENCES

[1] A. Tintelecan, A. Constantinescu-Dobra, and C. Martis, "LCA Indicators in Electric Vehicles Environmental Impact Assessment," *2019 Electr. Veh. Int. Conf. EV2019*, 2019, doi: 10.1109/EV.2019.8892893.

[2] A. Ajanovic and R. Haas, "An economic, ecological and energetic assessment of battery electric, hybrid and fuel cell cars," *Asia-Pacific Power Energy Eng. Conf. APPEEC*, no. 3, pp. 4–7, 2013, doi: 10.1109/APPEEC.2013.6837311.

[3] S. Satyanarayana, "Florida State University Libraries Combined Electrical and Thermal Models for Integrated Cryogenic Systems of Multiple Superconducting Power Devices," 2018.

[4] G. Bathurst, G. Hwang, and L. Tejwani, "MVDC-the new technology for distribution networks," *IET Semin. Dig.*, vol. 2015, no. CP654, pp. 1–5, 2015, doi: 10.1049/cp.2015.0037.

[5] Z. J. Shen, G. Sabui, Z. Miao, and Z. Shuai, "Wide-bandgap solid-state circuit breakers for DC power systems: Device and circuit considerations," *IEEE Trans. Electron Devices*, vol. 62, no. 2, pp. 294–300, 2015, doi: 10.1109/TED.2014.2384204.

[6] G. L. Kusic, G. F. Reed, J. Svensson, and Z. Wang, "A case for medium voltage DC for distribution circuit applications," *2011 IEEE/PES Power Syst. Conf. Expo. PSCE 2011*, pp. 1–7, 2011, doi: 10.1109/PSCE.2011.5772478.

[7] N. Doerry and John V. Amy Jr., "Design Considerations for a Reference MVDC Power System," *Naturwissenschaften*, vol. 30, no. 16, p. 240, 2015, doi: 10.1007/BF01486360.

[8] P. A. Klaudy and J. Gerhold, "Trials," vol. M, no. 3, 1983.

[9] R. E. Hebner, A. L. Gattozzi, S. M. Strank, S. P. Pish, and J. D. Herbst, "Electrical and thermal system considerations for MVDC superconducting distribution on navy ships," *2017 IEEE Electr. Sh. Technol. Symp. ESTS 2017*, pp. 592–597, 2017, doi: 10.1109/ESTS.2017.8069342.

[10] C. H. Kim, J. Kim, and S. V Pamidi, "Cryogenic Thermal Studies on Cryocooler-Based Helium Circulation System for Gas Cooled Superconducting Power Devices," *Cryocoolers 18*, ICC Press, Boulder, CO (2014), pp. 504–513.

[11] P. Cheetham, W. Kim, C. H. Kim, L. Graber, H. Rodrigo, and S. Pamidi, "Enhancement of Dielectric Strength of Cryogenic Gaseous Helium by Addition of Small Mol% Hydrogen," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–5, Jun. 2017, doi: 10.1109/TASC.2016.2642539.

[12] M. J. Armstrong *et al.*, *Architecture, Voltage, and Components for a Turboelectric Distributed Propulsion Electric Grid(AVC-TeDP)*, no. July. 2015.

[13] K. Davies, P. Norman, C. Jones, S. Galloway, and M. Husband, "A review of Turboelectric Distributed Propulsion technologies for N+3 aircraft electrical systems," 2013, doi: 10.1109/UPEC.2013.6714885.

[14] Cheetham Peter, S. Telikapalli, C. H. Kim, and S. Pamidi, "A Comprehensive Guide to Superconductivity - Chapter 1 - Superconducting Power Devices for the Electrification of Transportation," in *A Comprehensive Guide to Superconductivity*, 2020.

[15] S. S. Kalsi, "HTS ship propulsion motors," 2004, doi: 10.1109/pes.2004.1373238.

[16] M. J. Gouge, J. A. Demko, P. W. Fisher, C. A. Foster, J. W. Lue, J. P. Stovall, U. Sinha, J. Armstrong, R. L. Hughey, D. Lindsay, and J. Tolbert, "Development and testing of HTS cables and terminations at ORNL," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 2341-2354, 2001.

[17] "Air Liquide Turbo-Brayton Machines." https://advancedtech.airliquide.com/turbo-brayton-cryogenic-systemshttps://advancedtech.airliquide.com/turbo-brayton-cryogenic-systems.

[18] "Stirling Cryocoolers." https://www.stirlingcryogenics.eu/en/products/cryocoolers.

[19] "CRYOMECH Cryocoolers." mech.com/cryocoolers/.

[20] J. G. Schreiber, "Developmental considerations on the free-piston stirling power converter for use in space," *Collect. Tech. Pap. - 4th Int. Energy Convers. Eng. Conf.*, vol. 1, no. May, pp. 157–183, 2006, doi: 10.2514/6.2006-4015.

[21] Nexans, "CRYOFLEX ® Transfer Lines for Liquid Gases," 2012. .

[22] L. Bromberg, P. C. Michael, J. V. Minervini, and C. Miles, "Current lead optimization for cryogenic operation at intermediate temperatures," *AIP Conf. Proc.*, vol. 1218, no. 2010, pp. 577–584, 2010, doi: 10.1063/1.3422405.

[23] R. McFee, "Optimum input leads for cryogenic apparatus," *Rev. Sci. Instrum.*, vol. 30, no. 2, pp. 98–102, 1959, doi: 10.1063/1.1716499.

[24] S. Telikapalli, P. Cheetham, C. H. Kim, and S. V. Pamidi, "Power Dense HTS Cable Microgrids – Designs for Contingencies and Resiliency (Submitted)," 2020.

[25] S. Satyanarayana, Z. Zhang, C. H. Kim, and S. Pamidi, "Models for Design and Analysis of Superconducting Power Systems Cooled with Cryocoolers," *Cryocoolers 20*, ICC Press, Boulder, CO (2018), pp. 427–437.