Electrical faults in high temperature superconducting power cables for MVDC power systems of all-electric ships

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Abstract. High temperature superconducting (HTS) power cables are expected to be used in the future in electric ships that will have integrated power and energy systems (IPES). There have been a few studies on understanding electrical faults in power systems consisting of HTS cables; however, there are no comprehensive studies on the response of HTS cables for various types of electrical faults. We have recently initiated a research project on understanding various electrical faults in shipboard medium voltage direct current (MVDC) power systems and the duration of the fault, maximum voltage, and maximum current that the HTS cables will encounter during the fault. This paper presents investigations on the potential cable architectures being developed for MVDC power systems, and the type of faults that HTS cables will encounter in such systems. The paper will assess the relative merits of these architectures in terms of their suitability for accommodating the limitations of cryogenically cooled HTS cables and offer design suggestions for resilient power systems. Electrical and cryogenic thermal models of HTS cables that are suitable for assessing the response of HTS cables for electrical faults, as well as HTS cable designs that can endure electrical faults without catastrophic damage will also be discussed.

1. Introduction
Future all-electric ships are expected to carry substantially higher power loads compared to current ships due to the integration of the power loads of the propulsion and ship service systems. Along with these projected power demands, future ships must meet the ambitious targets of energy efficiency, power density, and resiliency to electrical faults for this shipboard power system (SPS). In order to help achieve these targets, future ship designs plan to use an integrated power and energy system (IPES). This IPES must meet the strict targets set for the SPS, with a primary consideration involving the type of cables and power system architecture used in the design. After extensive research, many research groups have accepted the 10-20
kV medium voltage direct current (MVDC) notional system as one of the most promising candidates for the power distribution architecture to utilize on all-electric ship designs [1].

In order to meet the weight benchmark of the all-electric ship IPES, and achieve the targeted power density, high temperature superconducting (HTS) cable technology is being developed to replace some of the conventional copper cables. The HTS cable technology has the potential to reduce the weight of the cable system by a factor of 5–10, depending on its operating conditions [2]. Figure 1 depicts two potential steady-state power cable configurations. As seen in Figure 1 (a), one cable configuration involves utilizing a bipolar cable design: \(+\frac{1}{2} V_{dc}\) applied to one pole and \(-\frac{1}{2} V_{dc}\) applied to the other. The other cable configuration shown in figure 1 (b) utilizes a two-multipole HTS cable design configuration. Even at the lower weight, the bipolar HTS cable system would be able to deliver currents up to 10 kA at the 10-20 kV voltage level of the MVDC system [2]. The current density of these HTS cables is a function of their temperature: so by adjusting these parameters according to operating demands, the HTS cable’s current carrying capacity could effectively be managed to meet the demands of the system. Because of this flexibility of varying the power rating that conventional cables do not have, HTS cables also have easy adaptability to different rated current levels of a system.

One of the greatest challenges in designing the MVDC shipboard power system is in protecting the system from potential electrical fault scenarios. It is crucial to design these power systems to be stable, reliable, and resilient even in faults. The SPS are susceptible to sudden load changes based on the operational mode of the ship. Additionally, the SPS is more vulnerable to electrical faults than a typical terrestrial power system because the components of the system are tightly coupled and the systems are ungrounded [3]. With this vulnerability, fault currents injected into the system propagate to the entire system more quickly than in long-distance transmission systems. Even minor faults conditions could cause catastrophic system failure on a tightly coupled system if effective protection systems are not included. Therefore, the SPS must be designed to accommodate for these quickly propagating fault conditions and be able to fully and quickly recover to normal operation from the impacts of the faults. Zonal and compartmental survivability have been set as a target for this IPES design. Zonal survivability is the ability of the distributed system to protect loads in un-faulted zones from electrical faults experienced in other zones. In other words, if an electrical fault occurs in one zone of the IPES, then other zones must remain in their normal operating conditions. Compartmental survivability ensures that there is a safe method for restoring faulted loads to normal operating conditions after sustaining and surviving damage [4]. Satisfying these two targets would satisfy the IPES design target of system resiliency.
2. MVDC Fault Study

2.1. Overview of DC Fault Types in the SPS
When designing a HTS cable for MVDC power systems, it is essential to consider some of the possible electrical fault scenarios that HTS cables must tolerate. This paper will focus specifically on electrical faults that can occur on the HTS cable system of a MVDC architecture in a SPS. In spite of the same arcing phenomenon in most cases, these faults can be broadly classified into two types: namely series faults and parallel faults. A series fault, which could be either caused by a totally disconnected cable or by a partially disconnected conductor, may result in a high-impedance arc channel. In this situation, the fault current is lower than the nominal current. Therefore, the series fault current may not trigger the corresponding protection device. Due to the arc discharge, dielectric breakdown induced by temperature rise inside the cable may lead to catastrophic damage to system components [5]. On the other hand, parallel faults occur when the arc is in parallel with the load. These types of faults are caused by insulation failures and cause a short circuit in the system. Most probable faults in the DC systems are pole-to-pole and pole-to-ground faults. Fault path between positive and negative lines is the cause of pole-to-pole faults, while fault path between the positive or negative line to ground is responsible for pole–to-ground faults. The magnitude of the fault current can be determined as a short circuit measurement. To calculate the current injected into the system by a fault, first convert the system to a Thévenin equivalent circuit. Then, the fault current can be calculated by:

\[ I_{\text{fault}} = I_{\text{sc}} = \frac{V_{\text{th}}}{Z_{eq}} \]

A pole-to-pole fault study was selected as it poses the greatest potential to influence the thermal and electrical stability of a HTS cable. The resulting fault currents and voltages for the PGM simulations are shown in figure 2. As expected, the voltage and current after the fault increased and decreased, respectively with an increase in fault impedance.

![Figure 2. Fault current and voltage profile with an increase in fault impedance [6].](image)

The possible DC parallel fault scenarios which can occur on the HTS cable system in monopole and dipole configurations are represented in figure 3. This figure illustrates pole-to-ground, pole-to-pole, and pole-to-pole-to-ground fault scenarios. Typically, for conventional systems, pole-to-pole faults are the most severe case, which releases the maximum fault current compared to other faults. However, for a HTS cable system, it is necessary to understand that not only energy released from pole-to-pole faults may cause issues with the cryogenic system, but also a pole-to-ground fault can transition into a pole-to-pole-to-ground fault in the case of the dipole configuration. This pole-to-pole-to-ground fault is even more devastating than the pole-to-pole fault, in that even more current is released due to the fault. Especially in the dipole cable
configuration, this transition may consequently cause an insulation issue and a localized temperature increase which decreases the dielectric strength of gaseous helium (GHe) and the dielectric strength of the other pole. Therefore, understanding the relationship between the energy released from every fault and local temperature increase has to be studied in greater detail. The multilevel modular converters (MMC) are considered the best configuration for controlling the extent of fault current and simplifying fault management and detection because this power converter architecture releases the least amount of energy during electrical fault scenarios in the MVDC power system compared to other converter topologies [6]. In addition, this converter topology allows for an easier controlling of voltage regulation compared to the other three designs [7].

2.2. Electrical Fault Considerations for HTS Cables

Implementation of HTS cables in the MVDC SPS requires additional considerations to be accounted for in the system design. Fault currents create an additional risk factor of cable quenches in HTS cables systems. Since the critical surface of HTS materials are determined by temperature \( T_c \), current density \( J_c \), and magnetic field \( H_c \), the HTS cable must be placed inside of a cryostat to maintain proper thermal insulation to maintain the necessary cryogenic operating temperature. The integrated cooling system of HTS cables creates additional concerns for the electric fault potential of the cable system because now the system is critically reliant on both electrical and thermal conditions rather than just electrical conditions.

As stated above, not only the electrical fault itself, but also the consequence of the fault will bring about a dielectric breakdown which could cause insulation failure. Because of this threat to the cable system, one of the most important factors in HTS cable design is the dielectric strength of the chosen electrical insulation for the cable. The dielectric strength of the insulation is dependent on the insulation material installed in the cable. For cables utilizing gaseous cryogens, the dielectric strength is dependent on the mass density of the gas, which is impacted by the pressure and temperature of the cable.

According to studies on the dielectric strength of gaseous cryogens and insulations for superconducting cables, it has been demonstrated both theoretically and experimentally that an increase in the mass density of a gas has a direct impact on an increase in its dielectric strength. Similarly, as the mass density of a gas is decreased, its dielectric strength also decreases [8]. Although temperature and pressure themselves have a negligible effect on the dielectric strength of a gas for a given mass density, temperature and pressure both have an impact on the mass density of gas [9]. Because the mass density of a gas is directly affected by its temperature and pressure, pressure and temperature gradients inside the cryostat of HTS cable systems that utilize gaseous cryogens or insulations could cause potential concerns for unexpected dielectric breakdowns. The electric field intensity that a HTS cable system can withstand is only as high as its weakest point, in this case being the gas at the lowest pressure and highest temperature of the system. Therefore, a temperature increase and pressure drop in one location of the cable could have an impact on the entire cable system. In extreme cases, a large increase in cable temperature could even cause a quench of the cable.

Specifically, a pole-to-pole-to-ground fault is the worst fault scenario that could be seen by a dipole HTS cable design in this MVDC SPS. This scenario would cause substantial levels of current and energy to be released to the system if not isolated and mitigated quickly. The released energy would cause temperature increase, which effectively would decrease the dielectric strength of the other pole. The release of energy is dependent on how quickly the fault current is mitigated, and thus how quickly the cable can re-enter its superconducting state. In addition to sudden resistive losses, HTS cables can potentially sustain
permanent damage by sudden energy spikes. Although they are able to sustain a finite amount of energy without significant degradation, if the energy absorbed by a HTS cable exceeds a threshold, the current rating of the cable could be permanently reduced by a significant factor as seen in [10]. In this experiment, after a HTS tape sustained as little as 186.1 J, its critical current permanently reduced to about 5% of its original critical current rating. In the same experiment, even when an energy spike of 48.4 J was applied to a HTS tape, its critical current permanently reduced to about 80% of its original value. Even in systems utilizing current-limiting power electronics such as a MMC with a quick fault mitigation time of 7 ms and a bolted grounding system (no impedance), released energy during an electrical fault scenario could potentially even surpass the energy levels (186.1 J) that caused substantial permanent damage to the HTS tape [6]. This shows the importance of developing energy-protection designs when utilizing a HTS cable system. Although thermal and electrical impacts caused by series faults on the cable might be less than parallel faults, studies should also be considered and verified for the thermal and electrical condition of HTS cable system. Typically, series faults could occur in the following cases: single HTS tape failure, single joint failure, and complete break. In the case of a single HTS tape failure caused by a defective YBCO section or a snapped tape, arcing may not occur or occur momentarily when a current carrying tape snaps. A failure in a solder joint is similar to a snapped tape, but it involves different anode and cathode materials. In these types of faults, the required voltage for sustaining an arc may vary depending on the material itself and thus the arcing may be prevented by controlling the material. Furthermore, a complete break could cause arcing through a conductive channel and increase the local temperature. The increased temperature could potentially quench the cable and alter its dielectric strength locally. The arcing characteristics will be different from conventional power cables due to the factors such as surrounding medium, anode/cathode materials, dielectric materials, and surrounding structure.

3. Potential HTS Cable Architectures

3.1. Cable Dielectric Design
The dielectric design of a HTS cable has a significant impact on its expected performance in the MVDC power system. Electrical breakdowns are the most common cause of electrical faults that are expected for a MVDC power system utilizing HTS cables. Therefore, it is crucial to take utmost consideration of the different insulation designs that are available for HTS cables and to take into account the tradeoffs that the varying designs have to offer. HTS cables can utilize a traditional solid insulation such as lapped tape, or a gas insulation design which utilizes a gas as both the dielectric medium and the cryogen of the cable [10-12].

While lapped tape insulation designs for HTS cables have been proven to have a sufficient dielectric strength for both MVDC and HVDC applications [11], if a dielectric breakdown was to occur, the lapped tape could sustain permanent physical and chemical degradation along the path of discharge. This degradation could cause a significant reduction of the dielectric strength of the lapped tape, which is why it would be essential to de-energize and replace the insulation of the cable immediately in this breakdown event. On the other hand, gases do not permanently degrade in the event of an electrical breakdown, and therefore, gas-insulated superconducting cable (S-GIL) designs have an important design feature of resiliency [10]. At the expense of the insulation being able to immediately recover after an electrical breakdown event is a lower dielectric strength for the cable compared to a cable utilizing lapped-tape insulation due to the low dielectric strength of GHe. However, the ability for an S-GIL cable to recover without replacing the insulation of the cable could be a significant advantage for this MVDC power system design over the higher dielectric strength of lapped tape designs because these cables would still have a dielectric strength high enough to be suitable for this MVDC power system. Research is being conducted to improve the dielectric strength of S-GIL cables, so it is likely that in the future the dielectric strength of S-GIL cables could be improved to be suitable for medium voltage power system designs [11], [12]. Along with dielectric strength being an important design consideration for fault-tolerant HTS cables, the chosen cable and cryostat design are important design factors that could not only reduce weight, but also address the redundancy benchmark of the system design. This would help in avoiding potential power interruption.
3.2. Cable & Cryostat Configuration

As HTS cable technology is being developed, it is important to ensure its reliability, resiliency and robustness are comparable to that of conventional power cables from a system-level perspective. This is especially significant when considering shipboard applications and the consequences of HTS cable failure while in service. The deeply-coupled cryogenic thermal and electrical aspects of HTS cable system also add additional risks and modes of failure which needs to be addressed to ensure system-level reliability and meet the system redundancy benchmark of a SPS to help avoid potential power interruptions or system failure. These benchmarks are especially important in a SPS compared to typical transmission systems because in shipboard applications, there are constantly changing operating conditions that may require sudden changes in power demands. In this case, the ship may need full operational capability of the system, so the system must be able to meet all necessary power demands at any given moment.

Figure 4 represents a schematic of 4 kA cable and cryostat configurations, which were drawn to scale using data from [14] and [15]. This schematic demonstrates that a single HTS cable satisfies the required current capability while having a diameter of only between 5 and 7 mm, compared to the conventional design of utilizing several copper cables that have much larger total diameter to carry the same current. Although the current capability of one single HTS cable is equivalent to that of a bundle of conventional cables, implementing single outage contingency should be taken into consideration in each configuration. One of the main design considerations for HTS cables being implemented to the SPS is the type of cable and cryostat configuration used. In order to satisfy all the design targets, such as weight and power density, two types of configurations are being considered: a monopole design and a dipole design. In a monopole cable design, each cable pole (positive and negative) is installed in an individual cryostat. Because of this design, for every DC cable section, two individual cryostats must be used. In a dipole HTS cable design, on the other hand, both poles are placed in a same cryostat. To reduce the burden of terminations (losses) and cryogenic equipment (weight and space) of HTS systems on the power density of the entire system, it is more advantageous to use a dipole HTS cable system, as seen in figure 4 (c), instead of a monopole system (figure 4 (b)). In addition, when it comes to meeting system reliability, the dipole design is the better option because one HTS cable of dipole configuration can still supply power even if the other HTS cable encounters a failure.

The physical parameters of the HTS cables in figure 4 are for a cable rated for 12 kV DC. However, it should be noted that the insulation thickness only varies by a few millimeters between DC 1-30 kV [12]. Therefore, these cable designs could easily be adapted to be rated for a different system voltage in that range. The HTS cables in figure 4 do not specify the type of electric insulation used in the HTS cables because this is still an active area of research. In the case of the HTS cables utilizing a solid electrical insulation, the process of changing from a monopole to a dipole HTS cable would just require an additional cable to be installed within the cryostat. However, when considering a gas insulated HTS cable, a completely new design and configuration needs to be developed. From this information, it is evident that if the S-GIL design is to be adopted into a MVDC system, a dipole S-GIL design would be the most suitable cable and cryostat configuration to implement to the system.

![Figure 4. Theoretical 4 kA cable and cryostat configuration utilizing: (a) conventional Cables, (b) monopole HTS cables, and (c) dipole HTS cables (drawn to scale using data from [13], [14], [15]).](image)
4. Discussion
The efforts of this research form a basis for an upcoming series of research studies on how HTS cables handle the effects of electrical faults in the MVDC SPS, and how fault-resistant HTS cables could be designed. Further research with modeling, simulations, and experiments will have to be conducted with the end-goal of creating a HTS cable design that can tolerate electrical faults, and produce greater confidence that HTS cables can be implemented into MVDC power systems of all-electric ships without causing greater risks for system damage or failure. If fault-resistant HTS cables are designed, this would be an additional benefit for selection of HTS technology in the SPS on top of their superior power density compared to the conventional copper cable and their weight and space savings. In addition, a fault-resistant HTS cable would offer a greater confidence in its selection to fill cable routes in the SPS despite its known impacts to the system if permanent damage is caused to it by a fault.

Due to the possibility that a fault in a HTS cable leads to temperature increase, research must focus on studying the extent of increase in local temperature during an electrical fault to assess whether or not HTS cables do indeed introduce an increased threat of electrical faults in the system over conventional cables. There are many design considerations that would influence the added possibility of the threat of this pole-to-pole-to-ground electrical fault scenarios that HTS cables could introduce. These considerations include different cryogenic gas mixtures that increase dielectric strength, as studied by [10], different insulating spacers used to keep the HTS cable concentric in the cryostat as studied by [16], and creating a HTS cable system that has a high enough temperature margin and safeguards to prevent faults from occurring. Detailed models and experiments will need to be performed to study both the electrical and thermal impacts that electrical faults have on HTS cable systems, and to determine what kind of HTS cable designs would be best suited for the MVDC shipboard power system.

As outlined by this paper, HTS cables can benefit power system designs if the added complexity of the cryogenic cooling system and added cost can be outweighed by the HTS cable’s high power density to save on weight and space in the power system. Further research needs to be performed on system and device-level optimization to determine the necessities of the cryogenic cooling system, and more specific HTS cable needs so that more accurate weight and space saving quantifications can be estimated when replacing conventional copper cables with HTS cables. After applying the criteria of [2], it was clear that nearly half of the conventional cables in the 4-zone notional IPES design studied in [6] would be of benefit to replace with HTS cables. Therefore, in order to create the most optimal shipboard power system in terms of weight, space, power density, and resiliency, it is crucial that HTS cables are designed with safeguards implemented.

5. Conclusion
By describing potential electrical faults, HTS cable design factors, and the MVDC power system for shipboard applications, this paper identified the potential risks that electrical faults pose on HTS cables in the MVDC SPS. While these potential threats for HTS cables were introduced, the substantial power density and weight and space saving benefits of replacing conventional cables with HTS cables were also highlighted. One of the key points of this study was to demonstrate the numerous benefits of replacing conventional cables with HTS cables that outweigh the greater design complexities involved with implementing these HTS cables systems such as the cryogenic cooling system, and the possibility of cable quenches. However, in order to give a greater confidence in selecting these cables for certain cable routes over conventional copper cables, HTS cables need to be developed to be fault tolerant, and thus be able to recover from potential damage from faults. In addition, these HTS cables need to be designed so that the likelihood of electrical faults is not more than when using conventional cables, especially pole-to-pole-to-ground faults. As a result of this study, it is clear that further research needs to be carried out to be able to quantify the likelihood of electrical faults, including series faults created by HTS cables and analyze how these scenarios can be effectively eliminated.
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