Solid-cryogen-stabilized, cable-in-conduit (CIC) superconducting cables

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Abstract. This paper considers the use of a solid cryogen as a means to stabilize, both mechanically and thermally, magnesium diboride (MgB₂) superconducting strands within a dual-channel cable-in-conduit (CIC) cable for use in AC applications, such as a generator stator winding. The cable consists of two separate channels; the outer channel contains the superconducting strands and is filled with a fluid (liquid or gas) that becomes solid at the device operating temperature. Several options for fluid will be presented, such as liquid nitrogen, hydrocarbons and other chlorofluorocarbons (CFCs) that have a range of melting temperatures and volumetric expansions (from solid at operating temperature to fixed volume at room temperature). Implications for quench protection and conductor stability, enhanced through direct contact with the solid cryogen, which has high heat capacity and thermal conductivity (compared with helium gas), will be presented. Depending on the cryogen, the conductor will be filled initially either with liquid at atmospheric conditions or a gas at high pressure (~100 atm). After cooldown, the cryogen in the stranded-channel will be solid, essentially locking the strands in place, preventing strand motion and degradation due to mechanical deformation while providing enhanced thermal capacity for stability and protection. The effect of cryogen porosity is also considered. The relatively high heat capacity of solid cryogens at these lower temperatures (compared to gaseous helium) enhances the thermal stability of the winding. During operation, coolant flow through the open inner channel will minimize pressure drop.

1. Introduction
Cable-in-conduit (CIC) superconductors have been used since 1975, when they were developed for large, high-current plasma fusion magnets [1-3]. Figure 1a shows a Nb₃Sn based CIC with two partially separated channels; the outer channel contains a multi-stage superconducting cable, while the inner channel provides a low-pressure-drop flow path for the supercritical helium coolant [4]. The side length of the square conductor shown in Figure 1a is 51 mm. A spiral, or perforated, tube is often used for LTS-based CIC to facilitate coolant exchange between the cable space and central cooling channel.

More recently, the CIC concept has been adapted to lower current, single-stage cable applications such as fast-ramped particle accelerator magnets [5, 6]. These miniature CICs were designed to be cooled with supercritical helium cooling; the central cooling channel is retained to provide adequate coolant flow to manage the high anticipated ac loss.
2. Assumed conductor configuration

Since its discovery more than a decade ago, the intermetallic compound, MgB₂, has been aggressively developed for a wide range of applications including research magnets, MRI magnets, power transmission cables, and rotor coils for wind turbines [7, 8]. The 39 K critical temperature of MgB₂ permits low-field operation in the 20–30 K temperature range where the Carnot cooling efficiency is markedly higher than that for more conventional LTS-based applications. In this paper we consider the possible use of MgB₂-based conductors for moderate frequency AC applications, such as the stator winding for a fully-superconducting motor or generator.

For this study, we investigated the design of a stator winding for a high-speed, two-pole electric generator operating at 20 K and 7000 RPM, for which the typical magnetic flux density at the conductor is in the range from 0.5 T to roughly 1.0 T. We adopted the CIC configuration for the MgB₂-based conductor to accommodate the relatively high AC conductor loss anticipated in this application. We assumed relatively modest power output, in the range from 10 MW to 15 MW, and a peak phase current on order of 2 kA; these values were used to estimate the nominal conductor length and cross-sectional area. The stator output current of 2 kA was also used to limit the cooling power required by the stator output current leads. Machine and conductor performance parameters were estimated by use of ANSYS finite element modeling. MgB₂ was chosen for this study, because it is a filamentary, round conductor with low critical current anisotropy.

The CIC conductor design (shown in Figure 1b) for this application was designed iteratively. The time variations of the magnetic flux density at the conductor and of the phase current were determined by use of the ANSYS model. The required strand area was determined using the peak magnetic field, the critical current density vs. local magnetic flux density plot shown in Figure 2, and an assumed superconductor fill factor of 15% [9] so that the peak phase current was equal to 60% of the conductor critical current. Other component area fractions in the strand were set to: roughly 30% Cu30Ni matrix, 15% copper stabilizer, 35% Monel sheath, and roughly 5% filament diffusion barrier. This composition is roughly similar to that for Hyper Tech’s 36-CM strand [9]. The strand, cable, and conductor configuration are summarized in Table I. The assumed strand parameters of 10 µm filament diameter, 10 mm twist pitch, and 10⁻⁶ Ohm-m matrix resistivity have been attempted in prototype 1st generation Hyper Tech strand development, but have not yet made it into routine production [10]. The anticipated AC loss in the conductor was calculated based on magnetization hysteresis, coupling current, and transport current losses [11]. Depending on machine configuration, the calculated AC loss from the ANSYS simulation typically ranges from 30 W to 60 W over the roughly 15 m conductor length needed for a stator winding.

The central cooling channel diameter in the CIC was determined based on thermohydraulic considerations. The conductor cooling design assumes inlet conditions of 20 atm, 20 K helium gas, 0.5 atm pressure drop, and 3 K temperature rise along the conductor length. Because of the low mass density of helium gas at 20 K, there would be virtually no flow through the cable space for the chosen pressure drop, if the cable space were connected to the flow channel. Any helium gas in the cable space is essentially stagnant. The 4.1 mm cooling channel i.d. listed in Table I is based on an average AC loss heat load of 56 W. Preliminary cooling channel design was performed using standard analytic solutions and average value of the inlet and outlet helium gas properties [12], and confirmed by subsequent CFD (FLUENT) analysis. The helium properties needed for this analysis were obtained from the software package REFPROP [13]. Nominal cooling channel flow...
parameters include: a mass flow of 3.2 g/s, Reynolds number of 2.2x10^5, and average heat transfer coefficient of 3580 W/m²-K.

To complete the CIC design, the diameter of the MgB₂ strand was freely varied to best fill the annular gap between the outer diameter of the cooling channel and inner diameter of the conductor jacket. The 33% void fraction in the cable space minimizes the free space between strands while minimizing strand deformation. A two-stage cable design was used, based on 1st stage triplets that were helically wrapped around the cooling channel to form the 2nd cable stage. A solid wall tube was used for the cooling channel. The wall thickness for both cooling channel and jacket were chosen to permit pressurization of the cable space to at least 100 atm, without risk of either cooling channel collapse or jacket rupture. Potential overpressure of the conductor in case of localized melting and evaporation of the solid cryogen was a concern that drove some of the design options. For example, in the case of fully dense solid nitrogen, the potential for a 700 volumetric expansion (from liquid to gas at STP) in the event of rapid loss of cooling could rupture the jacket or buckle the inner channel.

### Table I. MgB₂ strand, cable and conductor design parameters.

| Item                        | Value       | Item                        | Value       |
|-----------------------------|-------------|-----------------------------|-------------|
| Strand diameter (mm)        | 0.256       | Strands per Cable           | 90          |
| Filament diameter (µm)      | 10          | Cable pattern               | 30 x 3      |
| Strand twist pitch (mm)     | 10          | Cooling channel ID/OD (mm)  | 4.1 / 4.6   |
| Matrix resistivity (Ohm-m)  | 10⁻⁶        | Jacket ID/OD (mm)           | 5.5 / 6.3   |
| Fraction of critical current | 0.6         | Peak operating temperature (K) | < 25       |
| Peak strand current (A)     | 22          |                             |             |

![Figure 2. Critical current density vs. local magnetic flux density used in the conductor design. Figure from [9].](image)

**3. Thermal Model (Radial temperature distribution in the cable space)**

Figure 3 shows a simple 2D model used to calculate the thermal behavior of the cable. The convective heat transfer coefficient to the inner channel helium gas stream was given previously as 3580 W/m²-K, whereas the outside of the cable is assumed to be insulated due to the vacuum environment.

![Figure 3. Simple model of solid-cryogen filled cable-in-conduit conductor (CICC).](image)

In this new concept, solid cryogens are used to fill the voids in the cable space, serving three distinct purposes: (1) to mechanically stabilize, i.e. “lock,” the strands in place within the CIC structure, (2) to improve the effective thermal conductivity in the cable space, decreasing the temperature of the strands, and (3) to enhance the thermal stability of the cable using the high heat capacity of the solid cryogen.

3.1 Steady-State Analysis
First, a simple steady-state analysis was performed taking into account only the AC loss heat load on the conductor. Assuming a thermal conductivity of ~1 W/m-K for a typical solid cryogen [14], this model predicts a radial temperature gradient rise well within 2K as shown in Figure 4a. Figure 4a indicates that the heat transfer to the cold helium gas on the inside of the cable, along with the thermal conductivity of ~1 W/m-K, is sufficient to maintain an acceptable temperature rise of ~0.4 K under AC loss heating.

By contrast, for the conventional case in Figure 4b where the annular space is filled with stagnant cold helium gas with a thermal conductivity of only ~25 mW/m-K [13], the temperature rise becomes ~1.2 K, which decreased the thermal margin for the MgB2 cable. Therefore, for this design, in addition to providing mechanical stability, the solid cryogen provides a significantly better temperature margin during steady state operation.

3.2 Transient Analysis
Next, the transient quench behavior of the cable was analyzed. The enthalpies for several solid cryogens are plotted as functions of temperature in Figure 5 [15]. A summary of some pertinent data for these cryogens is provided in Table II.

During quench, the current in each strand is transferred from the MgB2 filaments to the copper stabilizer which comprises ~15% of the strand cross-sectional area. The objective of this analysis was to determine the time at which cryogen vaporization started to occur. Once vaporization occurs, there would be a corresponding localized pressure rise which could damage the cable by either rupturing the jacket or buckling the cooling channel; therefore, the goal is to determine the time before vaporization occurs, in order to avoid this situation.

The results are provided in Figure 6. These results take into account the increase in copper stabilizer resistivity, which increases the Joule heating, as the temperature increases. The results show only marginal improvement in time response using argon or nitrogen, as opposed to methanol or propane. Also, both methanol or propane have much higher vaporization temperatures; therefore, the overall response time is ~3 times longer, since the allowable final temperature can be higher.
Figures 5. Enthalpy vs temperature curves for select solid cryogens.

Table II. Data for selected cryogens.

| Cryogen      | Density @ 20 K [g/cc] | Thermal conductivity @ 20 K [W/m-K] | Melting point @ 1 atm [K] | Heat of Fusion [J/cc] | Boiling point @ 1 atm [K] | Density @ 298 K [g/cc] | Porosity @ 20 K [%] |
|--------------|-----------------------|-------------------------------------|----------------------------|------------------------|---------------------------|-------------------------|-----------------------|
| Argon (Ar)   | 1.71 (solid)          | 1.8*3* (slope)                      | 83.8                       | 41                     | 87.2                      | 0.17 (gas @ 100 atm)   | 90                    |
| Helium gas (He) | 0.015 (@ 6.5 atm)    | 0.032* (slope)                      | n.a.                       | n.a.                   | 4.2                       | 0.015 (gas @ 100 atm)  | n.a.                 |
| Nitrogen (N\textsubscript{2}) | 1.02 (solid)         | 0.4* (slope)                        | 63.1                       | 20                     | 77.4                      | 0.11 (gas @ 100 atm)   | 89                    |
| Methanol (CH\textsubscript{3}OH) | 1.03 (solid)         | 0.12* (slope)                       | 151                        | 10                     | 337                       | 0.79 (liquid @ 1 atm)  | 23                    |
| Propane (C\textsubscript{3}H\textsubscript{8}) | 0.73 (solid)         | 1"1.5" (slope)                      | 84.5                       | 39                     | 231                       | 0.49 (liquid @ 1 atm)  | 30                    |

Figures 6. Temperature vs. time plot for a quench event.
4. Discussion
The ideal condition of fully dense solid cryogen is unlikely to be achieved in practice due to safety concerns, as the cryogen would need to be continually supplied during cooldown. A safer procedure is to fill the system initially near room temperature, seal it off and then cool to the operating temperature of 20 K.

At standard temperature and pressure, nitrogen (or argon) is a gas; therefore, it is necessary to fill the cable with high pressure nitrogen gas, in an effort to maximize its initial mass. If the cable were filled with 100 atm nitrogen gas, upon cooldown to 20 K, the resulting solid nitrogen will have a porosity of > 80%. The resulting high void fraction significantly reduces the effective of the solid nitrogen on both steady-state radial temperature gradient across the cable and transient temperature rise during quench.

Conversely, if either propane or methanol were used, the system could be initially filled with liquid, at atmospheric pressure in the case of methanol, or at about 8-10 bar in the case of propane. Upon cooldown to 20 K, the resulting solid has a porosity of only ~25%. In this case the solid cryogen can significantly reduce the radial temperature gradient across the cable space. However, due to their limited cryogenic enthalpies, neither solid has significant impact on the transient temperature rise during quench. Assuming either propane or methanol were used, the following cooldown procedure could be used

1. Fill stator winding with selected liquid or gas.
2. Start cooldown with cold nitrogen gas flowing through the cooling channel until reaching ~100 K.
3. Start circulating cold helium gas through system until reaching 20 K.

5. Conclusion
We investigated the use of solid cryogens to improve both the thermal and mechanical stability of a cable-in-conduit conductor used in the MgB2 stator windings of a superconducting generator. We modeled both transient and steady-state behaviors of CIC conductors partially filled with solid nitrogen, argon, propane and methanol. Due to their higher vaporization temperatures and reduced densification, and therefore lower porosity upon cooldown to the 20 K operating temperature, either propane or methanol is preferable to nitrogen or argon.

The thermal conductivity of a solid cryogen is about 1 order of magnitude greater than that for gaseous helium at 20 K. Thus, a solid cryogen is significantly more effective at removing the ac loss power from the strands, useful in applications where there is substantial heating, such as in AC applications.

Given that methanol is somewhat less flammable than propane, methanol is the solid cryogen of choice to meet the design objectives of maintaining the steady-state temperature of ~20 K, increasing thermal response time during quench and also mechanically stabilizing the MgB2 strands within the CICC cable.

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