High Temperature Superconducting (HTS) Cable Application to Ship Deperming Work

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Abstract. We study a system of high electric current cable laid on the seabed for purpose of naval ship magnetic deperming. Moderate magnetic field over 2400 A/m is to be imposed on the volume equivalent of several thousand tons of ship, with alternately changing direction and gradually decreasing intensity. Cable with conventional conductor needs large power source because of the requirements coming from the cable's resistivity and high decay of magnetic field depending on distance from source. High Temperature Superconducting cable is suitable for this application. We set a requirement of maximum current of the cable as 200 kA and the length as 1200 m set on seabed of 12 m depth. Our recent design of the cable composed of Rare-earth-Barium-Copper-Oxide tape conductor stack, bundled and cooled by helium gas to 50 K. As a next step, cooling to 20 K with the same base concept of cable is shown to mitigate high expense of the tape conductor.

1. History
Magnetic deperming of ship is to reduce permanent magnetization of ship by imposing alternative magnetic field with reducing amplitude. Decreasing magnetization of ship started in World War II (WW II) to avoid heavy casualty caused by sea-mines equipped with magnetic sensors [1]. After the end of WW II, magnetic sea-mines threat continue to exit, sea-mines are resulting to be the top cause of severe damage to large ships by number [2]. As a result, the treatment of demagnetization of ship is conducted in many navies even today. One of the demagnetization methods is to compensate induced magnetization by the Earth’s magnetic field (degaussing) [3], and the other is to decrease remanent magnetization of ship (deperming) [4]. Degaussing treatment is commonly conducted by coils equipped on ships, and imposing magnetic field equivalent to the Earth’s field. For the deperming treatment however, imposing magnetic field is of the intensity sufficient to saturate magnetization of steel of ships, and its level of intensity is typically up to one or two milli Tesla [5]. This magnetic field is generated by the electric current through the cable. Due to the nature of the intensity of magnetic fields, where it reduces inversely with respect to distance from the cable, in addition to the shear size of the ships, the system requirement on the electrical current is high. Deperming treatment has been conducted on naval ships by various methods such as winding cable on ship, driving in cage-type-coil [6] and running through magnetic fields generated by coils in the water [7], while these methods lead to heavy manual loads and large electric power consumption.

Recent development of HTS power transmission cable technology [8] is applicable to ship deperming coil system with high current cable. AC power cable technology is investigated to reduce electromagnetic shielding, AC losses, and precise control of current [9], [10]. Technology of DC
current HTS power cable [11] is available for the deperming cable because of its low rate of change with respect to time. The electric current of these cables is mostly 10 kA while higher current is expected for the deperming cable. We started the feasibility study on ship deperming using HTS cable set on seabed in 2015 [12], and proceeded the study by including the technology of multi-tape conductor by Takayasu [13] and Van der Laan [14].

2. Grand design of deperming system
We designed a deperming cable to form a flat seabed coil and a ship to deperm is to keep its position over the coil while deperming [15]. Magnetic field to deperm the ship is imposed vertically on to the ship. This concept has a couple of key benefits. One is the reduced manual effort required for winding the cable in case of wound-cable type. The other benefit is the elimination of need to accurately control time and position of ship during passing through the coil-setting-type.

This design limits the ship size only by the depth of water where the coil is set, but free from width and height of ships which constrains by cage-type-coil.

The electric current which generates the magnetic field to deperm is higher than those required for wound-cable type and cage-type because of distance from the required position and short length of related line. Zero electric resistivity of superconductor and recently developed High Temperature Superconductor (HTS) cable technology is suitable for this application to reduce power of supply.

2.1. Required magnetic field
Type of steel used for shipbuilding is mostly low-carbon steel. High tensile steel has been applied to naval ships for reduction of weight and volume of ship structure. We measured magnetic flux density with respect to magnetic field (B-H) curve of high tensile steel SM490 and SPFC980Y shown in Figure 1 (a) and (b). Tensile forces of these steel samples are expected as 490 and 980 N/mm², and measured coercive forces are 521 and 1079 A/m, respectively. This result suggests higher tensile force sample have higher coercive force. Japanese NDS standard of steel for naval ship building shows tensile force of up to 1078 N/mm², thus nearly 1187 A/m of coercive force is expected. Magnetic field to saturate magnetization of steel is more than two times of coercive force from the full B-H curves. With this logic, we estimate 2400 A/m is required field for deperming of naval ships.

This hypothetical magnetic field estimated is used only to set the initial requirement and to initiate the design of the depermig coil, and thus this is to be substituted once the actual magnetic field becomes known.

![Figure 1. B-H curves of steel SM490A and SPFC980Y.](image)

2.2. Required volume to deperm
Size of the system is one of the important parameters for the deperming coil design. As target ships, we have considered a Destroyer (248 m L, 38 m W, 23.5 m H, 7.2 m D, 19,500 ton) and a Submarine (86 m L, 9.1 m W, 10.3 m H, 8.5 m D, 2,950 ton) from the JMSDF fleet. Thickness of hull of 0.1 and 0.2 m, respectively, are calculated using single spheroidal shell model [16] assuming high yield steel of HY90 construction throughout the entire ship, and using the same steel's property of permeability
Demagnetization factors of 0.81 and 0.36 for destroyer and submarine under vertical magnetic field are obtained from the calculation [17].

2.3. Deperming coil

Our design of coil consists of ideally infinite length of two straight lines with opposite electric current direction. This design is suitable for lengthier ships. Magnetic field at \( r_0(0,0,0) \) generated by a straight line extended along z-axis (\( z \)) at position \( R(x_s, y_s, z) \) with electric current \( I(0, 0, Idz) \) is expressed by equation (1).

\[
B(R, r_0, I) = \frac{\mu_0(\mathbf{R}(x_s,y_s,z)-\mathbf{r}_0(0,0,0))\times I dz}{4\pi|\mathbf{R}(x_s,y_s,z)-\mathbf{r}_0(0,0,0)|^3} = \frac{\mu_0 I(\mathbf{R}(x_s,y_s,0)-\mathbf{r}_0(0,0,0)) \times z}{2\pi |\mathbf{R}(x_s,y_s,0)-\mathbf{r}_0(0,0,0)|^2} \tag{1}
\]

Because of limit of space, seabed coil to generate saturation magnetic field forms a race-track shape along the length of ship as shown in Figure 2. Additional length equivalent to the width of the coil is added to either end in length-wise direction, extending the straight segment of the coil. This is to achieve uniform magnetic field at both the bow and the stern of the ship. Depth of the water is 12 m to allow 2 degree of pitching of the target ship. Maximum current of the cable is expected to be 200 kA to generate enough field using three coils, which is a balance of achieving uniform magnetic field with the least number of coils in such systems.

![Figure 2](image2.png)

**Figure 2.** Views of target ships and seabed coils.

Magnetic fields to saturate magnetization of ship is estimated at 2400 A/m from our test measurement conducted using a test piece. Destroyer ship is expected to have upper deck with high tensile strength for landings of aircraft. Demagnetization factor for destroyer and submarine, and upper deck of destroyer are considered to be depermed. Minimum width of coil is equivalent to the double the depth of the coil to avoid canceling effect of the two magnetic fields generated by opposing electric currents. Maximum width of coil fits the width of destroyer to impose maximum field at the edge of her upper deck. The total length of the cable is maximum 1200 m (: length), including the 400 m length of cable which covers the length from seabed where the coils are installed back to the ground where the power is provided to the system.

Magnetic fields generated by three coils at central vertical surface is shown in Figure 3, where the required field is divided by demagnetization factor of each ship.

![Figure 3](image3.png)

**Figure 3.** Magnetic field generated at the central x-y surface by three seabed coils.
3. Cable design

Provided that the number of lines each with same current and same orientation are bundled in a circle area, the magnetic field generated by other lines are imposed on to any of the other lines. In order to generate high magnetic field with smaller current supply, all of the lines are connected in series. Therefore, in such case, the maximum magnetic field experienced by any part of this line limits the total electric current to pass. When the cross-sectional size of each line is assumed negligible, electromagnetic shielding between the lines can be neglected. Distributions of lines in circle area are two extreme cases: the case of all the lines are on the circle edge and the case of homogeneous distribution in circle area. Larger number of dividing total current into lines causes increasing maximum magnetic field, and slight increase for the homogeneous distribution case.

Magnetic field generated is proportional to the total current passing through limited area but the inductance is the square product of number of lines, thus the large current in one line is better for the cable design which has time dependent aspects. Because single tape conductor has limited current capacity of several hundred ampere, a line with multi-tape conductors connected in parallel enables conduction of the required amount of current although not to the full extent [18].

Our first design of deperming coil is of a bundle of stacked tape-conductor shown in Figure 4 (a), where self-magnetic field on each tape is calculated. Taking in to account present-day production processes and technologies, the conductor consists of 4 bundles of unit cables is considered. Each bundle contains 6 units of lines and a core, as shown in Figure 4 (b) below. The tape conductor element consists of ReBCO (Rare-earth-Barium-Copper-Oxide) and width is 4 mm in the first design along with other commercially obtainable materials. High expense of HTS material requires reduction of its usage quantity, and also implies higher electric current to be conducted to maintain the same field intensity per unit material used. We set the operational temperature at 20 K where the critical current of ReBCO is drastically increased compared to the current level at higher temperature. Furthermore, other cheaper HTS materials have potential to be applied. In the lower operational temperature, the diameter of the total conductor can be smaller, resulting in the possibility of both the diameter of the cable to set on the seabed and the refrigeration system to be down-sized.

![Figure 4](image.png)

**Figure 4.** Cross-section image of the entire conductor cable by (a) ensemble of whole line elements and (b) bundles of six line-elements in one.

3.1. Internal Magnetic Field

The required magnetic field is 2400 A/m from the discussion above. This means in doubling the capacity from our first design of the cable capable of conducting only 100 kA. We set the required total electric current as 200 kA for the coil design shown in Figure 2, then we designed total conductor with eight bundles of unit cable (Figure 5 (a)) and calculated the maximum internal magnetic fields on all tape elements as shown in Figure 5 (b).
All the surface of stacked tapes in unit line are assumed to be in same orientation for the pessimistic case because the biggest internal field is expected to be imposed on some specific tape. The calculation result shows that conductor with eight bundles of 21 tapes with 4 mm width stacked line is enough to operate at 20 K for ReBCO or BSCCO (Bismuth-Strontium-Calcium-Copper-Oxide). This calculation is based on the electric current for each tape as 198 A \( (= 200 \times 10^3 / (8 \times 6 \times 21)) \), the diameter of unit line as 0.01 m \( (2r) \) and maximum magnetic field as 1.46 T, which is calculated with this conductor cross-section geometry.

The similar results are obtained with MgB\(_2\) where lower expense for cabling is expected [20].

### 3.2. Refrigeration

Our design of the cooling system consists of two circuits. One of which is achieved by the liquid hydrogen flow in conjunction with the radiation shield. This in turn is cooled by the second circuit of liquid nitrogen. The cross-section image of the cable is shown in Figure 6. The maximum diameter of the conductor is 112 mm, those of liquid hydrogen pipe and liquid nitrogen pipe are at this stage of design set to be 120 mm and 30 mm, resulting in the outer most pipe diameter to be less than 300 mm.

First, we considered the heat balance at the stable state in operation which means the temperature of 20 K at conductor and 77 K at the radiation shield. Heat input to the radiation shield through radiation and physical contact is referred from the experimental data of DC power transmission line by Watanabe et al. [21]. The length of the cable in their experiment and our design are similar thus their refrigeration system can be ideally applied to our system. Heat input to the liquid hydrogen pipe is radiation from the radiation shield at 77 K which is calculated as 9.5 \times 10^{-3} W/m from 2 W/m at radiation shield by the calculation of \( (77^4 - 20^4)/(293^4 - 77^4) \). thus, the heat input in full length of 1200 m cable is 11 W. Heat input \( (W_{in} \text{ J/s}) \) to the liquid hydrogen pipe through direct contact is unknown. The temperature rise \( (\Delta T K) \) of liquid hydrogen at the end of the cable from its start versus its supply \( (Q \text{ L/min}) \) is written by \( W_{in} = (Q/ (60 \times 1000)) \times \rho_{H2} \times C_{H2} \times \Delta T \) where liquid hydrogen density is \( \rho_{H2} = \)
0.071 × 10^3 kg/m^3 and heat capacity is \( C_H = 6.89 \times 10^3 \) J/kg/deg. Even with \( W_{in} \) of 500 W, \( \Delta T \) is calculated as 2 K with \( Q = 30 \) L/min, which is acceptable value for the cooling system.

Next, a process to cool conductor from room temperature 293 K to operational temperature of 20 K is considered by flow of liquid hydrogen. Refrigeration path is kept by one refrigerant material to avoid any contamination to the system. Using heat capacity of the conductor (\( Q_{cond} = \rho_{Cu} \times \pi r^2 \times C_{cu} \times 7 \times 8 = 1.512 \times 10^4 \) J/deg/m), evaporation heat of liquid hydrogen (\( Q_{ev} = 891 \) J/mol) and heat capacity of gaseous hydrogen (\( C_{gas} = 28.6 \) J/mol/deg), time rate of the temperature of the conductor (\( T_{cond} \)) dependent on the flow of liquid hydrogen (\( V_{liqH2} \) mol/s) is calculated by equation (2).

\[
q_{cond} \cdot length \frac{dT_{cond}}{dt} = \left[ -\alpha (T - T_{20}) C_{H2gas} V_{liqH2} + C_{H2ev} V_{liqH2} \right] + \epsilon (T_{77}^4 - T_{cond}^4) \cdot length + H_{const}
\]

Where, \( \alpha \) is heat exchange efficiency set as 0.6, \( H_{cond} \) is set as 500 W and \( \epsilon \) is calculated as 2.7 \times 10^{-10} referred the data [21].

As shown this calculation with 30 L/min of 18 K liquid hydrogen in Figure 7, time to cool the conductor to 20 K is 22.9 hours and total quantity of liquid hydrogen is 41 m^3.

4. Discussion and Conclusion

Our idea of the deperming system set flat on seabed is designed based on the requirement of the magnetic field on target ships. Internal magnetic field on each tape conductor is calculated and unit cable design is decided within the critical current with respect to its magnetic field property of ReBCO and BSCCO at 20 K. As a result, operational electric current of 198 A through each tape, and a maximum internal magnetic field of 1.46 T on a tape is obtained. Electromagnetic force on tapes is to be calculated and cable design to support this force may be reconsidered. Because of the large quantity of superconducting tape required to manufacture the conductor of the designed cable, the potential in using other materials with lower expense is currently being explored.

Refrigeration with liquid hydrogen is acceptable from its supply and time to cool to the operational temperature. Methods to reduce the required supply quantity of hydrogen and putting preventive measures against the risk of explosions of the gas are the challenges.

The entire concept of our deperming system has been explained. The procedure of research for the details are as follows

(a) Optimization of cross-section of the cable and conductor by calculation by considering electromagnetic force and refrigeration.

(b) Short cable with dummy conductor fabrication and cooling test.
   • Cable length as 40m.
   • Development of connecting part of the conductor, within the coil, coil to outside leads.
   • Cooling to 20 K not by using liquid hydrogen.
   • Refrigeration system with low expense of hardware.

(c) Short cable with HTS conductor fabrication and coil activation.
   • Power supply and controller.
Full electric current passing through coil at operation temperature confirmed by magnetic field measurement.

Middle length cable with over 100m is to be fabricated and tested following the success of the short cable tests.

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