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Superconducting thermo-magnetic-mechanical energy conversion machine

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Abstract

This paper presents a superconducting thermo-magnetic-mechanical (STMM) energy conversion process. This energy conversion concept revolves around of utilizing a cryogenic coolant, e.g., liquid nitrogen, as a thermal energy facilitator to cool down the superconductor to below the critical temperature. Then, utilizing the mixed state, i.e., Meissner effect and weak vertex - which leads to partially shielding the magnetic field - an external magnetic field is used to apply force on the superconductor and create motion. The concept proposed is demonstrated using thorough Multiphysics understanding i.e., thermal, magnetic, and mechanical. The proof of concept is completed by using a combination of analytical and numerical simulations and calculations, and measurements. Using this concept, a practical automotive drive has been theoretically designed and compared with a counterpart electric drive. The proposed technology has a potential to provide a step change for the sustainable cleaner cost-effective transportation.

1- Introduction

The search for alternatives for the classical propulsion drives has been rising due to the need to move away from fossil fuel and the need for more efficient and sustainable energy conversion systems. Apart from electric drives, there have been a few possible alternatives with the promising capability to replace classical propulsion drives¹.

This article proposes a superconducting thermo-magnetic-mechanical (STMM) energy conversion process. The energy conversion process consists of reducing the temperature of the superconductor to a temperature lower than the critical temperature in the presence of an external magnetic field. Once the critical temperature is reached the superconductor will achieve the superconducting state and due to the presence of an external magnetic field it will result in achieving the mixed state i.e., Meissner effect and

weak vertex. Therefore, the superconductor will partially shield the external magnetic field thus resulting in a force applied on the superconductor which will move the superconductor resulting in motion.

Once the motion has happened, the superconductor temperature will be increased from the critical temperature, hence achieving the normal state by losing the superconducting state. This would result in the removal of the force that has been generated/applied by the external magnetic field due to the magnetic shielding. Hence, the superconductor can move back to the original position with the help of a mechanical arrangement.

The paper presents an illustration of the proposed energy conversion system and provides a detailed explanation of the process. Furthermore, a measurement has been conducted to experimentally measure the equivalent relative permeability of the superconductor under the superconducting state. Finally, a practical system that utilizes the STMM energy conversion system has been proposed and theoretically designed. This system shows a suitable performance, i.e., torque and speed, for a direct-drive marine propulsion application. The proposed system has the advantages of longer running time as compared to the conventional electric machine drive used in such application. This is because the consumption of the liquid nitrogen, i.e., energy facilitator, in the proposed system is around five times lower than the electric power in the conventional electric machine drive.

2- Flux expulsion (shielding) in superconductors

Below lower critical field B_{c1} (full shielding)

Based on the literature on Type II superconductors, a full shielding occurs below the lower critical field due to the exhibition of Meissner effect. The lower critical field of

some Type II superconductors around the critical temperature of -196°C can be as high as 0.05T^2 . Thus, at such field, a superconductor completely expulses the magnetic field independent of the size of the superconductor³, whether the superconductor field cooled or zero-field cooled⁴.

Above lower critical field B_{c1} (partial shielding)

A partial shielding can be achieved with an external field above the lower critical field. The magnitude of partial shielding would depend on the operating temperature along with factors mentioned herewith. The shielding then depends on the size of the superconductor and depending on whether the superconductor is field cooled or zero-field cooled⁵. This effect can be presented in the form of the equivalent.

3- Superconductor thermal states

The critical temperature of the superconductor is the threshold where the state changes from normal to superconducting. From the literature, the change in the resistance of the superconductor from the maximum value to zero occurs over a few degrees Celsius, e.g., from -175°C to -168°C a difference of 10°C .

It can also be interpreted as, the change in the magnetic susceptibility of a superconductor occurs over a few degrees Celsius when the superconductor is zero-field cooled. However, when the superconductor is field cooled, the magnetic susceptibility change occurs over a relatively wider range, e.g., from -190°C to -210°C a difference of 20°C ⁶. Fig. 1 presents an illustration of the superconducting state change with temperature.

Fig. 1 Illustration of the superconducting state change with temperature.

4- Concept of superconductor-thermo-magnetic-mechanical (STMM) energy conversion

Fig. 2 presents an illustration of the superconductor thermos-magnetic energy conversion process. A magnetic circuit consists of a permeant magnet, permeable material shaped C structures and a superconductor. In the normal state, the superconductor behaves like a reluctance gap with an equivalent relative permeability of one and therefore the magnetic field flows through the circuit, i.e., ‘on state’, shown in Fig. 2 (a). In the superconducting state, the equivalent relative permeability of the superconductor reduces to zero if the magnet field is below the lower critical. Hence, the reluctance of the superconductor becomes infinite and block the flux from passing, as shown in Fig. 2 (b). However, if the external magnetic field is above the lower critical field, the reluctance of the relative permeability of the superconductor is between 0 to 1, hence large reluctance. Depending on the level of the applied external field and temperature, the superconductor partially blocks the magnetic field leading to a reduced magnetic field passing through the circuit, as shown in Fig 2 (c).

Therefore, by applying a cyclic change of the superconductor temperature, the flux passing the magnetic circuit will experience a cyclic increase and decrease. Thus, it opens two possibility of energy conversion a) by winding a coil around the core. The rate of change of magnetic flux that is achieved due cyclic variation of reluctance (achieved by temperature cycling that can be obtained used controlled flow of liquid nitrogen) would result in the induction of voltage based on Faraday's fundamental principle; b) by allowing the superconductor to move vertically which would lead to the existing magnetic field exert force on conductor creating linear motion (potentially can be converter to rotatory motion by making suitable mechanical arrangement). Similarly, allowing the superconductor to move vertically leads to the magnetic field creating a force on the superconductor, leading to linear motion.

Fig. 2 Magnetic circuit illustrating the superconductor-thermo-magnetic energy conversion. a, The magnetic circuit in normal state (non-superconducting). **b,** The magnetic circuit in superconducting state with flux below lower critical field. **c,** The magnetic circuit in superconducting state with flux above lower critical field.

5- Numerical and analytical design of superconductor-thermo-magnetic-mechanical energy conversion drive

To use the concept of superconductor-thermo-magnetic-mechanical in a practical system to generate mechanical power, a proposed system is shown in Fig 3. The proposed system consists of three main parts, 1) the rotating machine, 2) the thermal control reservoir and 3) the tank (energy storage). To mathematically evaluate the performance of the system, each part will be analysed separately.

Fig. 3 Illustration of the superconductor-thermo-magnetic-mechanical energy conversion system.

The rotating machine

At first, to understand the concept to generate mechanical power, an illustration of the force generated on a superconductor is presented. Using the layout presented in Fig. 4 where the flux source produces a flux below 0.1T (the lower critical field), thus, superconductor relative permeability is set to zero. The force acting on the superconductor does not change with the increase in the thickness of the superconductor. Using finite element analysis (FEA), the layout presented in Fig. 4 has been rigorously analysed. In the study, the superconductor thickness changed from 1mm to 10mm with an interval of 2mm. The force versus the distance of the superconductor to the source is calculated and presented in Fig. 5. With the variation of the thickness of the superconductor no change is observed. Therefore, theoretically, the force produced is independent of the thickness of the superconductor.

Fig. 4 Layout presents magnetic force generated on superconductor. **a**, Magnetic circuit and magnetic flux lines illustration. **b**, FEA set-up of the layout

Fig. 5 Below the lower critical field, magnetic force acting on the superconductor with different thicknesses.

On the other hand, above the lower critical field, the change in the external magnetic field leads to different flux vertices and therefore varying the equivalent relative permeability of the superconductor accordingly. The same layout in Fig. 4 has been used to study the effect of the equivalent relative permeability on the exerted force. A magnetic field of the magnetic field source has been increased to 0.5T and a superconductor relative permeability of 0.2 has been used⁷. Fig. 6 presents the force versus the distance of the superconductor with a relative permeability of 0.2.

It is worth noting that modelling superconductor in FEA requires taking into account the effect of the London equation and using a formulation such as T-A⁸. However, equivalent relative permeability can also be used to simulate the superconductor in FEA with good accuracy^{7, 9-13}.

Fig. 6 Above the lower critical field, magnetic force acting on the superconductor with different thicknesses.

A rotating machine topology can be made by utilizing the exerted force on the superconductor. Fig. 7 (a) presents a proposed rotating topology utilizing the concept. The topology consists of a ring of superconductor made of 45 degrees segments, and a permanent magnet set to produce magnetic flux with a ferromagnetic material to enhance the magnetic circuit. Fig. 7 (a) presents the FEA setting for the rotating topology. The outer diameter of the topology is 45mm, the axial length is 25mm and the airgap between the superconductor ring and magnets is 0.5mm. As illustrated in Fig. 7 (a), the superconductor segments above the X-axis are set to a normal state, i.e., relative permeability of 1, and the segments below the X-axis are set to superconducting state with a relative permeability lower than 1. The rotor, shown in Fig. 7 (a) is set to rotate a

cycle of 45 degrees. Different relative permeability values of the superconductor were analysed, in order to predict the influence on the torque production. Table 1 presents the average torque of the different investigated cases of relative permeability, and Fig. 7 (b) presents magnetic flux lines and magnetic flux density in the rotating machine.

Fig. 7 STMM rotating topology. a, Topology layout. **b**, Magnetic flux lines and equipotential of the rotating topology with 0.2 relative permeability of the superconductor segments in superconducting state

Table 1 Average torque of the rotating topology with different equivalent relative permeability

Permeability	≈ 0	0.01	0.05	0.1	0.3	0.5	0.7	0.9
Average torque (Nm)	4	2.75	1.5	1.1	0.6	0.4	0.22	0.07

The thermal control reservoir

The thermal reservoir is the section where the temperature of the superconductor is cyclically changed above and below the critical temperature to maintain the rotation. It consists of a liquid nitrogen reservoir covering half the superconductor ring - which is the cool-down section - and a heat dissipation mechanism, which is the heat up section. Fig. 8 presents an illustration of the thermal control reservoir.

Fig. 8 Illustration of the thermal control reservoir.

Initially, the temperature of the superconductor is reduced from room temperature (20°C) to the liquid nitrogen boiling temperature of -196°C . Subsequently, the thermal cycle consists of increasing the temperature by the difference required to change the superconductor from the superconducting state to normal state, e.g., from -196°C to -166°C (30°C) for YBCO superconductors. This cycle consists of two states: 'heat up' and 'cool down'. The first is when the superconductor temperature is raised from below to above critical temperature ('heat up'), i.e., from -196°C to -166°C . The second stage is when the temperature is reduced from above to below the critical temperature 'cool down', i.e., from -166°C to -196°C . Fig. 9 presents an illustration of the cool-down condition.

Fig. 9 Cool down condition.

To estimate the time required to switch the superconductor from normal to the superconducting state and vice versa, a numerical approach using transient finite element

analysis (FEA) has been used. The ‘cool down’ condition consists of the superconductor in complete contact with the coolant (liquid nitrogen) with a boiling temperature of -196°C . Assuming a superconductor has a relatively smooth surface, the thermal contact between the superconductor and the liquid nitrogen can be assumed to be perfect, i.e., negligible thermal resistivity. Calculations used the thermal properties of YBCO superconductor, the properties are the mass density of $5900(\text{kg}/\text{m}^3)$, the thermal conductivity of $15(\text{W}/\text{m } ^{\circ}\text{C})$ and specific heat capacity of $(\text{J}/\text{kg } ^{\circ}\text{C})^2$. Different superconductor thicknesses were considered. Table 2 presents the time required to bring down the temperature from -166°C to -196°C .

Table 2 Time (seconds) to cool down (change from -166 to -196) YBCO superconductor with different thicknesses

Superconductor Thickness	2mm	4mm	6mm	8mm
Time (s)	0.1	0.38	1	1.7

On the other hand, the ‘heat up’ condition can be made by natural convection of the superconductor to the environment. However, to reduce the time for the heat up, four different mechanism were investigated. Fig. 10 presents an illustration of the different mechanism: (a) is the natural convection method, (b) a heat dissipation surface near the superconductor with a small airgap, (c) a heat dissipation surface with direct contact with weak contact conductance and (d) a heat dissipation spinning mechanism with direct contact with high contact conductance. Table 3 presents the heat up time of the YBCO superconductor using the different considered mechanisms.

Fig. 10 Temperature changing methods. **a**, Heat up, neutral convection. **b**, Heat up, heat source with airgap. **c**, Heat up, heat source with direct contact. **d**, Heat up, heat source with directly contacted free to spin wheel.

Table 3 Time (seconds) to heat up (change from -196°C to -166°C) YBCO superconductor with different thicknesses

	2mm	4mm	8mm	16mm
A	11.5	22	47	90
B	7.33	13.5	31	61
C	0.25	0.5	1.2	2.6
D	0.15	0.3	0.47	1.2

The calculation shows that for a thin layer of 2mm superconductor exposed to liquid nitrogen, the cooled-down time is 0.1s, and the same layer heat-up using the mechanism, Fig. 10 (d), is 0.15s. Therefore, allowing a half cycle for cool-down and heat up, the estimated time can be converted to a rotation for each half cycle. Completing half a cycle at 0.15s allows a 3.33 revolution per second (rps) and hence 200 revolutions per minute (rpm). Increasing the temperature of the heat source allows for faster thermal change. However, the cooling down temperature is the cut-off limit for the system. Therefore, the 2mm superconductor can have a maximum change time of 0.1s, hence a 300rpm.

The tank

In the proposed system, the coolant, e.g., the liquid nitrogen, acts as the energy facilitator. The container that reserves the liquid nitrogen is the fuel tank for the system. This consists of a thermal dewar (flask) to store the liquid nitrogen and insulated pipes to contact the tank to the thermal control reservoir. The thermal dewar and thermal pipes have very high thermal insulation i.e., 0.00104 evaporation rate of millilitres per second. Therefore, the evaporation of the liquid nitrogen through the thermal dewar and thermal pipes will be neglected. As a result, the liquid nitrogen will mostly be consumed by the contact with the superconductor surface. To estimate the consumption time of a finite amount of liquid nitrogen in contact with the superconductor surface, the following equation can be used:

$$\text{Evaporation rate} = (\text{change in temperature} / \text{liquid surface resistance}) / \text{enthalpy}$$

$$\text{Liquid surface resistance} = \text{liquid surface area} / \text{liquid conductivity}$$

Therefore, to maintain the operation for a longer period of time, the temperature difference and the surface area of superconductor needs to be as small as possible. Using the above equations, Table 4 presents the evaporation time of 50 litres of liquid nitrogen at different temperature differences and different superconductor surface areas.

Table 4 Liquid nitrogen consumption time (seconds) according to evaporation equation at different temperature difference and different superconductor surface area

	Temperature difference (ΔT)				
Surface area (m^2)	10	20	30	40	50
0.2	110.55	55.277	36.851	27.638	22.111

0.4	55.277	27.638	18.425	13.819	11.055
0.6	36.851	18.425	12.283	9.2129	7.3703
0.8	27.638	13.819	9.2129	6.9097	5.5277
1	22.111	11.055	7.3703	5.5277	4.4222

From the calculations and results presented in Table 4, the time to fully consume the liquid nitrogen in a 60 litres tank with superconductor surface of 1 square meter and a change in temperature from -196 °C to -166 °C (30°C) is 7.37 hours. This applies to YBCO superconductor with a critical temperature of -196C and a 30°C change to switch between normal to superconducting states.

6- Equivalent permeability measurements

To measure the equivalent relative permeability of the superconductor, a measurements set-up was created, as shown in Fig. 11 (a). The experimental set-up consists of a YBCO-123 disk, a NdFeB magnet to produce the external magnetic field, and a gauss-meter to measure the level of the magnetic field, as shown in Fig. 11 (c). The experiment is conducted in field cooled state, i.e., the superconductor cooled in the presence of the external field, as shown in Fig. 11 (d). The magnetic field passing through the superconductor has been measured when the superconductor is in normal state and is in superconducting state. Fig. 11 (b) presents an FEA simulation of the experiment. The FEA simulation is used to calculate the equivalent relative permeability of the YBCO-123 that matches the experimental values. In normal state, a 60mT magnetic field is measured and the same value has been predicted in the FEA simulation when the superconductor relative permeability is 1. In superconducting state, a 40mT magnetic field is measured and the FEA simulation predicted the same value when the relative permeability of the superconductor is 0.2.

Fig. 11 Measurement of the YBCO-123 superconductor equivalent relative permeability. **a**, YBCO and NdFeB dimensions and measurement set-up. **b**, simulation of measurement set-up. **c**, measurement equipment. **d**, liquid nitrogen boiling (NdFeB magnet under the YBCO disk)

7- Validation of liquid nitrogen evaporation time

Using the thermally insulated cup presented in Fig. 11 (6), the time required for complete evaporation of a finite quantity of liquid nitrogen is validated. The volume of

the cup containing the liquid has been measured, 0.03(litre), and the cup opening surface has also been measured, 0.0028(m²).

Although the insulated cup is not perfect and evaporation through the cup walls is expected, this can be neglected due to the low evaporation rate in comparison to the evaporation through opening of the cup. The cup is then filled with liquid nitrogen and the time required for the liquid nitrogen to fully evaporate is recorded. This is repeated three times. The recorded time for each of the three iterations is 10.2, 10.15 and 10.22minutes, respectively. The temperature above the cup opening and cup wall temperature has been measured through the experiment and it is found to be $\approx 20^{\circ}\text{C}$ and $\approx 8^{\circ}\text{C}$, respectively. Using the equations for evaporation rate (presented in section 5) the time required for the liquid nitrogen to fully evaporate has been calculated. The analytically calculated time required for a 0.03(litre) liquid nitrogen to evaporate through a surface of 0.0028(m²) with an external temperature of 20°C is 10.1 minutes.

8- Practical STMM drive

Since analysis shows that the concept of STMM can produce relatively high torque and low speed, a practical drive targeting application with similar requirements will be theoretically designed. Direct-drive propulsion systems are characterized by their low speed and high torque to meet the power requirement. In marine applications, i.e., ship propulsion, the engine or electric motors used for propulsion normally rotate between 50 to 500rpm. An electric drive system proposed for marine application with speed of 50rpm and torque of around 840Nm has been used as a benchmark¹⁴. Table 5 lists the performance, size and weight of the whole drive including the electric motor, inverter and batteries. The electric motor drive provides the full required power at 50rpm and 20 battery cells provide 1 hour of total operation time. The total weight of the system is 187.6kg and the total volume is 0.129m³. Table 6 presents the performance of the system.

Table 5 Marine electric propulsion system size and weight

Motor	Outer diameter (mm)	Machine length (mm)	Machine weight (kg)	Shaft torque (Nm)	Shaft speed (rpm)	
Value	500	500	150	840	50	
Inverter	Width (mm)	Depth (mm)	Height (mm)	Weight (kg)		
Value	211	252	310	7.6		
Single battery cell	Width (mm)	Depth (mm)	Height (mm)	Weight (kg)	Total weight of 20 cells (kg)	Discharge Time (hours)
Value	38	70	280	1.5	30	1

Table 6 Marine propulsion design targets

	Shaft torque (Nm)	Shaft speed (rpm)	Discharge Time (hours)	Total weight (kg)	Total volume (m ³)
	840	50	1	≈220	≈0.13

Fig. 12 presents a proposed STMM drive which will achieve the performance criteria in Table 6. The drive consists of rotating the superconductor ring sandwiched between two magnet cores modules. Half of the ring is located in a liquid nitrogen container and the second half is partly sandwiched between free-to-spin wheels connected to thermal dissipater. Thermal insulation is located in the middle, between the two halves, to eliminate unnecessary heating of the liquid nitrogen.

Fig. 12 Proposed practical STMM drive layout.

To estimate the performance, the drive rotating machine is analysed using magnetic FEA. The thermal mechanism is analysed using thermal FEA, and the consumption of liquid nitrogen is calculated using the equations in section 5.

The rotating machine consists of NdFeB magnets with a magnetic field of 1.2T, ferromagnetic core with B-H curve, and a YBCO superconductor ring. FEA modelling is used to calculate the torque in the same setting, as presented in section 5. The equivalent relative permeability of the YBCO superconductor under an external field produced by NdFeB magnets is 0.2⁹. Therefore, in the FEA model, the relative permeability of the YBCO in superconducting has been set to 0.2. Fig. 13 presents the FEA layout and results. Maximum torque of 905Nm and average torque of 860Nm has been predicted.

Fig. 13 FEA Torque calculation. a, FEA model and flux lines and density. b, Torque waveform

The time for the superconductor to heat up and cool down has been estimated using FEA in the same setting as presented in section 5. Fig. 14 presents the FEA layout and results. The heat-up time required to heat a quarter of the ring is 0.2s, leading to 150rpm. The cooling-down for half of the ring is 0.4s leading to a 75rpm.

Fig. 14 Heat change calculations. a, Heat up at 0.2s. b, cool down at 0.4s

Finally, following the calculation in section 5, 60 litres of liquid nitrogen under a thermal change of 30C and exposed surface of 1.256m² (half of the superconductor ring) can provide 5.86 hours of operation. The empty weight of 60 litres of liquid nitrogen thermal flask (dewar) with the needed values, pressure gauges and pump is 36kg and 0.16m³ in volume. A 30 litres liquid nitrogen thermal flask has a weight of 30kg and 0.1m³ in volume and this provides 2.93 hours of operation.

Table 7 presents the performance of the proposed drive. It can be seen that the proposed STMM drive has similar performance compared to the benchmark marine proposition system. However, the size and weight are slightly higher but the operation time is 5.86 (%) times higher.

Table 7 Proposed STMM drive system performance

	Shaft torque (Nm)	Shaft speed (rpm)	Discharge Time (hours)	Total weight (kg)	Total volume (m ³)
60 liters system	≈860	≈50	≈5.86	≈215	≈0.2
30 liters system	≈860	≈50	≈2.93	≈178	≈0.16

9- Conclusion

The STMM energy conversion concept has been illustrated and explained in this paper. The concept consists of utilizing the magnetic flux expulsion (shielding) of the superconductor that occurs at a small temperature difference when the superconducting state changes from normal to superconductor. The superconducting thermo-magnetic-mechanical concept can be utilized to generate electrical power by using a magnetic circuit with winding; mechanical power, by creating a linear motion or rotation, or both. The superconductor coolant, i.e., energy facilitator, and the storage of such coolant, i.e., thermal dewar, is the energy storage of the system. A theoretical design of the system

using numerical and analytical methods demonstrated a promising performance of the system. The proposed practical STMM drive for marine propulsion has a comparable performance to its counterpart electrical drive system, with the advantage of longer duration of operation. The proposed STMM drive can use different coolant, i.e., energy facilitator, with lower boiling temperature such as liquid helium or liquid hydrogen. Using a lower boiling temperature coolant increases the magnetic flux shielding capability of the superconductor and therefore increases the torque production. Similarly, the temperature gradient between the critical temperature and liquid temperature considered in this study is large and therefore higher rotation is expected. This makes such drive suitable operatable by different coolant.

Methods

Experimental methods

To realize the equivalent relative permeability of the YBCO-123, a commercial disk (22mmX2mm) has been used. A NdFeB (grade N42) commercial magnets (10X5X2) has been used. A cryogenic thermal insulation cup has been used to conduct the temperature change by liquid nitrogen. Temperature reading has been conducted using Type T, -200°C - +350°C, thermocouple and thermometer type MM2020, -200°C - +1372°C. The magnetic field has been measured using gauss meter grade WT10A.

Theoretical methods

Numerical calculations have been conducted using finite element analysis. ANSYS software electromagnetic suite and transient thermal have been used for the transient electromagnetic and thermal calculation, respectively. The material properties and the set-up of the finite element models are shown in the main article notes. Analytical

calculations are conducted to estimate the coolant consumption time using general evaporation mathematical equation.

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Author Contribution Statement

Both Mahir Al-ani has contributed to the conception of the idea, design of the work and, acquisition and analysis of the data. Both Mahir Al-ani and Gaurang Vakil have written and reviewed the article.