High-Temperature Superconducting Non-Insulation Closed-Loop Coils for Electro-Dynamic Suspension System

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Abstract: The null-flux electro-dynamic suspension (EDS) system is a feasible high-speed maglev system with speeds of above 600 km/h. Owing to their greater current-carrying capacity, superconducting magnets can provide a super-magnetomotive force that is required for the null-flux EDS system, which cannot be provided by electromagnets and permanent magnets. Relatively mature high-speed maglev technology currently exists using low-temperature superconducting (LTS) magnets as the core, which works in the liquid helium temperature region (T ⩽ 4.2 K). Second-generation (2G) high-temperature superconducting (HTS) magnets wound by REBa$_2$Cu$_3$O$_{7-δ}$ (REBCO, RE = rare earth) tapes work above the 20 K region and do not rely on liquid helium, which is rare on Earth. In this study, the HTS non-insulation closed-loop coils module was designed for an EDS system and excited with a persistent current switch (PCS). The HTS coils module can work in the persistent current mode and exhibit premier thermal quenching self-protection. In addition, a full-size double-pancake (DP) module was designed and manufactured in this study, and it was tested in a liquid nitrogen (LN2) environment. The critical current of the DP module was approximately 54 A, and it could work in the persistent current mode with an average decay rate measured over 12 h of 0.58%/day.

Keywords: electro-dynamic suspension; HTS magnets; non-insulation; closed-loop coils; persistent current mode

1. Introduction

There are three commonly used suspension technologies in high-speed maglev systems: electromagnetic suspension (EMS), EDS, and HTS flux-pinning suspension [1–6]. EMS uses the electromagnetic attraction between the on-board magnets and ground rails to create suspension, where the suspension height remains at 8 to 10 mm and a highly accurate control system is required. In contrast, as it is generated from the on-board HTS bulks and permanent-magnet ground rails, HTS flux-pinning suspension does not require a control system, but the cost of the ground rails is very uneconomic. EDS is generated from the electric repulsive force between the on-board magnets and the figure-eight-shaped coils, and its suspension height can reach 50 to 100 mm. Compared with EMS, the merits of EDS are that it reduces the accuracy requirements for the guide rails because of the meaningfully higher suspension height, and a complex control system is therefore no longer required. In addition, null-flux EDS results in a significant reduction in the forward resistance and ground rails cost of these systems. The ground rails of the EDS system consist of copper coils and are considerably less costly than that of the HTS flux-pinning suspension system. Afterwards, because of the null-resistance characteristics and high current density, the superconducting magnets can provide a large magnetic momentum, which is necessary for null-flux EDS and cannot be provided using normal conductivity and permanent magnets.
Since the 1970s, the Central Japan Railway Company has been developing a high-speed null-flux EDS system with LTS magnets as its core, which operates in the liquid helium temperature region ($T \leq 4.2$ K) [7]. The LTS magnets are closed-loop coils that are characterized by the self-circulation of the loop current inside of the coils (a function known as the persistent current mode), therefore enabling passive operation while the vehicle is in motion [8,9]. The use of closed-loop coils and operation in passive persistent current mode can overwhelmingly limit the system’s heat loss, and it is the preferred mode for on-board conditions. In 2015, the Yamanashi Maglev Test Line (YMTL) set a world record of 603 km/h for a crewed vehicle equipped with LTS closed-loop coils. In addition, 2G HTS magnets wound with REBCO tapes can operate at above 20 K. Compared with the LTS magnets, the cooling cost of the HTS magnets is considerably reduced, and liquid helium is not required, which is a non-renewable and scarce resource on Earth [10–12]. The HTS Open-loop magnets based on conduction cooling have been developed, but the 2G HTS closed-loop magnets are not yet practical, mainly owing to the immaturity of superconducting PCS technology, joint technology, and quenching protection. In recent years, researchers at the Railway Technical Research Institute have attempted to manufacture the HTS insulated closed-loop coils; however, owing to the large daily decay rate of the coils’ current, there are still difficulties in producing the on-board HTS closed-loop magnets for the EDS system [13–16].

This study presents the fabrication of a prototype HTS magnet that can be applied to an EDS system and loaded onto a maglev trial vehicle with the schematic structure shown in Figure 1. The core of this prototype is the non-insulation closed-loop HTS coils module wound with REBCO tapes without any insulation material between the turns of the tapes. Compared with insulated coils, non-insulation coils have the advantage that when thermal quench occurs, the loop current of the coils can pass between the turns, thus bypassing the hot point and providing good self-protection [17]. The HTS coils module operates in a solid nitrogen (SN2) environment with an operating temperature of 20 to 30 K. In the actual working conditions of this EDS system, offline operations use SN2 as the thermal battery [18] (i.e., the refrigeration system does not work and the temperature of the SN2 chamber remains below 30 K). In this study, a full-size DP module was successfully designed and fabricated, and it was excited using a thermal-control PCS in a LN2 environment. After excitation, the DP module can operate in the persistent current mode, and the average decay rate was 0.58%/day for 12 h, which meet the design requirements of such a system and provides a foundation for the fabrication of the prototype HTS magnets.

![Figure 1. Schematic structure of a prototype HTS magnet.](image-url)
2. Design of The HTS Coils Module

2.1. Design Requirements and Basic Structure

Based on the requirements of EDS systems, it is necessary to calculate the basic parameters of the HTS coils module and ground coils, including the turns, magnetic momentum, and geometric dimensions. The levitation and guidance loads of the EDS system depend on the magnetic field at the surface of the linear motor stator (figure-eight-shaped coils) and total magnetic momentum of the on-board magnets [2,19]. To achieve the desired levitation and guidance loads, the total magnetic momentum of a single pole of an on-board HTS magnet must reach 360 kA, and the HTS coils module should be racetrack-shaped. Additionally, the axial magnetic flux at the central line 90-mm from the bottom surface of the HTS coils module and the axial magnetic flux at the central line of the figure-eight-shaped coils’ surface must exceed 0.7 and 0.9 T, respectively. Therefore, the central lengths of the linear edge and arc edges are determined to be 140 and 125 mm, respectively, and Figure 2 shows a 2D plot of the HTS coils module. The prototype consists of a pair of poles, positive and negative, respectively. The topology of the poles used for the maglev trial vehicle is presented in Figure 3, with eight poles in total. Every single pole consists of three DP modules with 600 turns and operates at 200 A; thus, the magnetic momentum of a single pole is 360 kA. Considering the consistency of the EDS system, the decay rate of the HTS coils module designed to be less than 1%/day in the persistent current mode. The requirements of the EDS system and parameters of the HTS coils module are listed in Table 1.

Using the finite element method (FEM), the electromagnetic properties of the HTS coils module were simulated. Figures 4 and 5 depict the axial magnetic flux distribution on the central line and surface, respectively, which are both located 90-mm from the bottom surface of the HTS coils module, and the peak value is 0.73 T. Figures 6 and 7 depict the axial magnetic flux distribution on the central line and surface of the figure-eight-shaped coils, respectively, and the peak value is 0.96 T. These results adhere to the design requirements of the EDS system.

![Figure 2. 2D plot of the HTS coils module.](image-url)
Figure 3. Topology of the HTS poles for the maglev trial vehicle (the four central poles do not exist in actual usage, and the provided topology indicates the positional relationship of the poles).

Table 1. Requirements of the EDS system and parameters of the HTS coils module.

| Parameters                                                                 | Values                                      |
|----------------------------------------------------------------------------|---------------------------------------------|
| Magnetic momentum of a single pole                                         | ≥360 kA                                    |
| Axial magnetic flux at the central line 90-mm from the HTS coils module’s bottom surface | ≥0.7 T                                     |
| Axial magnetic flux at the central line of the figure-eight-shaped coils’ surface | ≥0.9 T                                     |
| Decay rate                                                                | ≤1%/day                                     |
| Poles                                                                      | 8 (4 for each side)                         |
| Number of DP modules for a single pole                                    | 3                                           |
| Turns of a DP module                                                      | 600                                         |
| Operation current                                                         | 200 A                                       |
| Single-pole dimensions (Central line)                                     | 390 mm · 250 mm · 66 mm                    |
| Spital distance of the poles                                              | 540 mm                                      |

Figure 4. Axial $B$ distribution on the central line 90-mm from the bottom surface of the HTS coils module.
Figure 5. Axial $B$ distribution on the surface 90-mm from the bottom surface of the HTS coils module.

Figure 6. Axial $B$ distribution on the central line of the figure-eight-shaped coils’ surface.

Figure 7. Axial $B$ distribution on the figure-eight-shaped coils’ surface.
2.2. Load Factor Prediction and REBCO Tapes Selection

Considering that the HTS coils module cannot quench in the persistent current mode, this study limits the maximum value of the load factor to below 0.6. The critical current of the 2G HTS tapes exhibits typical anisotropy and is related to the actual operating temperature, known as $I_{c} - B - \theta - T$. The $I_{c} - B - \theta - T$ characteristics of the tape A (Shanghai Superconductor Technology Co., Ltd., TE0133-RRI, Shanghai, China) are shown in Figure 8, where $\theta$ represents the angle between the external magnetic flux and the normal direction of the REBCO tapes. Owing to the different manufacturing processes, the quality and the $I_{c} - B - \theta - T$ characteristics of the tapes vary between different types and batches, thus posing difficulties for simulation analysis and actual tapes selection. This study proposes a method for quickly prediction of the $I_{c} - B - \theta - T$ characteristics of different batches of tapes of the same type. For instance, multiplying the $I_{c} - B - \theta$ characteristics curve of tape A at 30 K by a discount factor $k$ (0.73 for example), the $I_{c} - B - \theta$ characteristics curve of Pa1533-A (denoted as tape B) at 30 K can be produced, which has relatively low performance. Because tape A and B are similar in terms of production process element composition of REBCO layer, their $I_{c} - B - \theta$ characteristics are supposed to be with a similar proportional relationship. This curve is compared with the actual measured $I_{c} - B - \theta$ characteristics curve of tape B, as shown in Figure 9, and they are in good agreement.

![Figure 8. $I_{c} - B - \theta$ characteristics curve of tape A.](image)

The above prediction method can improve the simulation of the distribution of the load factor of the HTS coils module and help guide the selection of tapes in practice. For instance, the $I_{c} - B - \theta$ characteristics curves of tape A and B are used as input quantities and solved using FEM to obtain the distribution of the load factor of the arc edge of the HTS coils module, as shown in Figure 10. Owing to the special racetrack-shape of the HTS coils module, the arc edge is the location of the maximum load factor; therefore, this is used as the indicator area of the load factor of the HTS coils module. By comparing Figure 10a with Figure 10d, Figure 10b with Figure 10e, respectively, it can be concluded that the inner-located DP modules of the single pancake and the single pancake wound with higher performance tapes exhibit a smaller loading factor. Moreover, even if the two middle single pancakes are wound with lower-performance tape B, the load factor is still less than 0.5, as shown in Figure 10c. The above results can guide the actual coils winding using lower-performance tapes for the innermost DP module and higher performance tapes for other DP modules, therefore achieving a more economical system while ensuring the safety of the HTS coils module operation. In practice, three separate tapes are connected in series for each single pancake through low-resistance joints due to limitations of the
tape length. Table 2 indicates that the maximum load factors on different locations and segments of a single pole wound with tape A and B are less than 0.6, therefore meeting the design requirements of this EDS system.

Figure 9. Estimation and verification of different type of HTS tapes’ \( I_c - B - \theta \) characteristics.

Figure 10. Load factor distribution on the arc edge of the single pole at 30 K. Tape B: (a) six single pancakes; (b) four central single pancakes; (c) two central single pancakes. Tape A: (d) six single pancakes; (e) four central single pancakes.
Table 2. Maximum load factors on different locations and segments of a single pole.

| Location and Segment                      | Turns: 201–300 | Turns: 101–200 | Turns: 1–100 |
|-------------------------------------------|----------------|----------------|--------------|
| The two outside pancakes (tape A)         | 0.47           | 0.51           | 0.51         |
| The two middle pancakes (tape A)          | 0.36           | 0.39           | 0.41         |
| The two central pancakes (tape B)         | 0.43           | 0.45           | 0.46         |

3. Fabrication and Experiment of the DP Module

3.1. DP Module Fabrication

A full-size non-insulation closed-loop DP module for the prototype HTS magnets was fabricated using a batch of REBCO tapes produced by Shanghai Superconducting Technology Co., Ltd., Shanghai, China. Figure 11 shows a physical drawing of the DP module with a thermal-control PCS on it. The DP module is racetrack-shaped, and the number of turns of each single pancake is close to 300 turns, and the total inductance was measured as approximately 160 mH. Table 3 lists the parameters of the DP module.

![Figure 11](image)

Figure 11. DP Module: (a) non-insulation winding; (b) front view; (c) oblique view; (d) lateral view.

Table 3. Parameters of the DP module.

| Parameters                             | Values                                      |
|----------------------------------------|---------------------------------------------|
| Turns                                  | 290 and 293 for each single pancake         |
| Inductance                             | ~160 mH                                     |
| Encapsulation layer thickness          | 75 µm copper for each side                  |
| Tape width/thickness                   | 5.75 mm/0.24 mm                             |
| REBCO layer width                      | 4.75 mm                                     |
| Equivalent turn-to-turn resistivity    | 1.3 µΩ·cm²                                  |
The $I_c - B - \theta$ characteristics of the tapes used for winding were measured experimentally at 77 K, as shown in Figure 12. Using FEM, the characteristics curve is used as the input quantity to simulate the electromagnetic characteristics and the load factor distribution of the DP module (see Figure 13). Figure 13 shows that the load factor does not exceed 0.6 when the DP module is operated at a current of 43 A. In addition, the FEM calculates the critical current of the DP module to be approximately 62 A.

![Figure 12. The $I_c - B - \theta$ characteristics of the tapes winding the DP module at 77 K.](image1)

The DP module is discharged under open-loop conditions, and Figure 14 shows the normalized decay curve of the magnetic flux of the DP module under open-loop condition, where $B_0$ corresponds to the magnetic flux value measured at the end of the discharge process. The time constant of the decay of the DP module can be calculated from this curve, and the equivalent turn-to-turn resistance can be calculated based on its total inductance. Finally, the equivalent turn-to-turn resistivity was determined to be 1.3 $\mu\Omega$·cm$^2$. 

![Figure 13. Load factor distribution on the arc edge of the DP Module at 77 K.](image2)
3.2. Excitation Experiments under Closed-Loop Condition

To quickly test the performance of the DP module, the DP module was tested in a LN2 environment, and a thermal-control PCS was used to excite the DP module. The PCS is an essential component of the HTS tapes with a layer of rigid extruded polystyrene foam (XPS) used for thermal insulation wrapped around the outside of the tapes. The quenching process of the PCS can be controlled by heating the heating film inside of the XPS insulation [20]. Figure 15 shows the relationship between the measured resistance by four-lead method and the temperature of the PCS when different heating currents (0.4 to 0.9 A) are applied. The higher the temperature inside of the PCS, the higher the PCS resistance, the shorter the relaxation time of the loop current, and the higher the excitation rate.

Figure 14. Normalized decay curve of the magnetic flux of the DP module under open-loop condition.

Figure 15. Relationship between the measured resistance and the temperature of the PCS at various currents.
Figure 16 shows the typical variation in the operating temperature of the PCS during test. The PCS was continuously heated until quenched, and the temperature was maintained after 1000 s. After approximately 5000 s, the decrease to 77 K in the temperature of the PCS and the restoration of the superconducting state were obtained. In the actual excitation process, the vibrations of the output current of the power supply and the magnetic flux measured by the Hall sensor during the excitation process are shown in Figure 17. After 1500 s, the output current from the power supply has reached the preset threshold, but the magnetic flux of the DP module continued to increase, because there is a certain inductive resistance of the DP module, which makes the coil turn-to-turn and the PCS shunt occur. Therefore, the loop current of the DP module required time to be fully saturated.

![Figure 16. Typical variation in the operating temperature of the PCS during test.](image)

![Figure 17. Output current from the power supply, as well as the measured magnetic flux and the calculated loop current of the DP module.](image)

Regarding the 2G HTS open-loop non-insulation coils, there is a well-established simplified circuit model that represents a series-parallel model of inductance and resistance,
so that the charging and discharging characteristics of the coils can be simulated [21]. A PCS branch is added to the set of the circuit model to simulate the excitation process of the closed-loop coil, as shown in Figure 18. Here, \( R_{\text{ct}} \) represents the turn-to-turn contact resistance, \( L \) is the total coil inductance, and \( R_{\text{mt}} \) and \( R_{\text{sc}} \) are the matrix resistance and equivalent REBCO layer resistance, respectively. Based on the circuit model, the loop current curve of the DP module can be simulated, as shown in Figure 17. This model also yields values for the turn-to-turn resistivity and PCS resistance of 1.8 \( \mu \Omega \cdot \text{cm}^2 \) and 1.0 m\( \Omega \), respectively, where the turn-to-turn resistivity is close to the value measured in the open-loop experiment.

\[ \text{Figure 18. Circuit model of the HTS closed-loop coils.} \]

\[ \text{3.3. Persistent Current Mode} \]

When the excitation process is completed, it is extremely crucial that the DP module can operate in the persistent current mode, which depends mainly on the coil joint resistance. The solder method is adopted to create the low-resistance joints required for closed-loop coils, in which the superconducting surfaces of two tapes are stacked and filled with a relatively low-melting-point solder as the jointing agent, and the REBCO tapes are bonded together via heating and pressurizing [22]. The \( V-I \) curve of a typical joint produced in this study is shown in Figure 19, and its resistance is 4.6 n\( \Omega \), as measured by the four-lead method.

\[ \text{Figure 19.} \ V-I \ \text{curve of a typical joint.} \]
Figure 20 shows the natural decay curve of the magnetic flux of the DP module measured by the Hall sensor in the persistent current mode, and it can be seen that the DP module reached an index loss when the magnetic flux outstrips approximately 148 mT. This occurs because the loop current of the DP module is close to the critical current, therefore generating a large internal resistance, and the resulting heat loss causes the entire coil to dramatically lose energy. Therefore, the loop current and the corresponding magnetic flux decrease exponentially. The measured value of 148 mT corresponds to a loop current of approximately 54 A in the DP module, indicating that the actual critical current of the coil at 77 K is smaller than the simulation value (62 A). This result was obtained mainly because the critical current of the tapes is not uniformly distributed, and a low critical current point exists. These findings indicate the necessity of setting the load factor to be no more than 0.6 in the design of this EDS system so that a large safety margin is achieved.

![Figure 20. Natural decay curve of the magnetic flux of the DP module.](image)

When the magnetic flux of the DP module is lower than 148 mT, the corresponding internal resistance is sufficiently small, and the decay rate is completely determined by the joints resistance. The experimentally measured average decay rate of the DP module during 12 h in the persistent current mode was approximately 0.58%/day. A lower daily decay rate is a decisive factor in the commercialization of the closed-loop coils.

4. Conclusions

The HTS non-insulation closed-loop coils module was designed and applied to an EDS system, which was excited using a thermal-control PCS and could operate in the persistent current mode with good self-protection. The magnetic field and load factor distribution of the HTS coils module were simulated, and a full-size non-insulation closed-loop DP module was fabricated and tested in a LN2 environment. The following main conclusions were obtained: (1) When using the PCS for excitation, the internal resistance value determines relaxation time of the loop current in the DP module, and the resistance value of the PCS was approximately 1.0 mΩ; (2) The experimental critical current of the DP module was approximately 54 A lower than the simulated value. This occurs because there is a low critical current point in the used REBCO tapes. Therefore, a suitable load factor margin needs to be considered in the design process; (3) After the end of the excitation process, the DP module functioned stably in the persistent current mode, and the average decay rate was 0.58%/day as measured in 12 h.
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