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Studies on the features of characteristic resistance of a no-insulation superconducting coil in energizing and de-energizing processes

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ABSTRACT

A coil wound with no-insulation (NI) winding technique can present enhanced electrical/thermal stability and more compact structure but poorer energizing/de-energizing instantaneity as compared to an insulated counterpart. The above features of a NI coil are resulted from its turn-to-turn contact resistance, namely, the characteristic resistance R_c. R_c is a rather important parameter of a NI coil, and it is greatly influenced by winding tension, more intrinsically, the compactness of coil winding pack. Alone with the winding tension, Ampere's force that is induced by coil current and magnetic flux density, may also apply on each turn of a NI coil to influence the compactness of coil winding pack, and further the R_c and electrical behaviors of the coil. This paper explores the aforementioned influences caused by Ampere's force through energizing and de-energizing tests. Experimental results show the R_c decreases as charging current increases. Meanwhile, simulation results indicate the Ampere's force applied on each coil turn has a compressive effect and the force is proportional to the square of charging current. Furthermore, a step-rising energizing method together with a modified circuit model are proposed to calculate instantaneous current-dependent R_c. And precise prediction of coil electrical behavior is acquired. Totally, the Ampere's force do have influence on coil electrical behavior especially when the operation current and flux density are large.

1. Introduction

MAGNETIC levitation vehicle (Maglev), which provides a possible opportunity for higher demand of speed over 600 km/h, is developed rapidly [1–2]. With support from the High-tech Projects of Technology Innovation Action Plan in Shanghai, the new generation ultrahigh-speed Maglev is going to be built with target operating speed over 600 km/h and even 1000 km/h in the near future. Its propulsion system is made of a long-stator linear synchronous motor (LSM) with a train-carried mover made of no-insulation (NI) high-temperature superconducting (HTS) magnets. The NI-HTS magnet can provide technical solutions not only generating rather high flux density while keeping itself more compact and more efficient than permanent or resistive magnets, but also remaining enhanced electrical and thermal stability and self-protecting features [3–13]. However, due to part of the transport current "leaks" between no-insulation neighboring turns, a NI-HTS magnet appears much slower energizing and de-energizing rate as compared to an insulated counterpart. It is a trade-off between its electrical/thermal stability and current ramping. The trade-off is depicted by characteristic resistance R_c, and the R_c is almost the sum of the contact resistances between every neighboring turns. Generally, the higher R_c will lead faster energizing and de-energizing time [8,13–14] but poorer electrical and thermal stability.

Since the anisotropy of the current paths (i.e. the current around the coil and "leaking" between turns), which originate from no-insulation neighboring turns and are determined by R_c, will induce Ampere's force. And in turn, the Ampere's force that applied on each turn will inference the contact condition between turns, and further the R_c and electrical behavior of the NI magnet. The induced Ampere's force is non-negligible especially when operation current and flux density of the magnet are large. To ensure the NI HTS magnet as a successful solution for the development of ultrahigh-speed Maglev train, it is necessary to investigate the influence brought by Ampere's force. However, few studies have investigated it. In this paper, the influence of the Ampere's force on the electrical behavior of the NI coil was explored based on simulation and experiment of energizing and de-energizing tests. This paper is organized as follows: In Section II, experimental setups of the tested NI coil are described, and simulation model of the coil and Ampere's force calculation are established for further comparison. Then in Section III, results of the experiments and simulations are analyzed in

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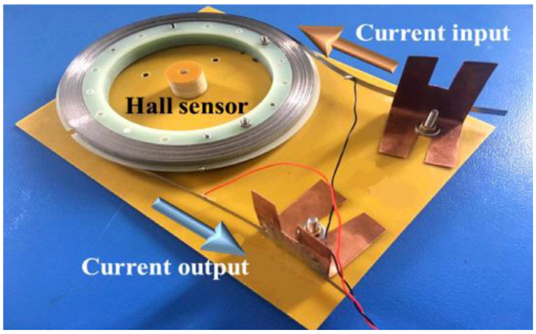

Fig. 1. The NI DP coil used in experiment.

detail. Meanwhile, a modified circuit model and calculation of instantaneous current-dependent characteristic resistance are proposed. Finally, in Section IV, conclusions of this study are summarized.

2. Experimental setups and modeling calculations

2.1. Experimental setups

The HTS tape used in this paper is YBCO coated conductor (CC) with its laminated layer made of stainless steel. A NI-HTS double pancakes (DP) coil wound with this kind of YBCO CC tape is shown in Fig. 1. Its winding tension is controlled by a winding machine at a constant value of 5 N in order to assure repeatable characteristic resistance. Tables 1 and 2 summarize the specifications of the YBCO CC tape and the NI DP coil, respectively. Fig. 2 is the testing *U-I* curve of the NI DP coil with voltage criterion of 1 μV/cm. The curve rises at the beginning of the test is the result of induced voltage generated by "leakage" current and R_c, as described in Part I. To minimize the induced voltage, slow ramp rate of coil current is required. In this test, the ramp rate of coil current is 0.2 A/s, and the induced voltage is ~500 μV, which will not really affect the determination of critical current *Ic* since near *Ic* the voltage rise per ampere is much larger than the induced voltage. Furthermore, liquid nitrogen bath (LN_2, 77 K) is selected as experimental environment in this paper in order to avoid unexpected burn out during experiment. Source current is generated by Agilent 6680 A power supply and controlled by a Labview program. Besides, a hall sensor (Lakeshore HGCA-3020) is inserted in the coil axial center to continuously monitor the magnetic flux density through a gaussmeter (Lakeshore Model 425 with resolution of 0.01 mT).

2.2. FEM model of the NI DP coil

To acquire precise analysis of the Ampere's force applied on each coil turn, a 2D asymmetrical DP coil model is built in a finite element method (FEM) simulation software with all the model parameters are set as same as those in the real NI DP coil, as shown in Fig. 3. The modeling plane in Fig. 3 is the cross section of the winding pack. The outmost upper turn (upper layer turn #57) is set as input current terminal, and the outmost lower turn (lower layer turn #57) is the terminal of current output. Azimuthal current, namely, the current flowing in YBCO CC turns in a circular path around the coil, is assumed

Table 1
Specifications of YBCO CC tape used in NI DP coil.

Specifications	Values or description
Manufacturer	Shanghai superconductor technology co., ltd.
Tape width/ Thickness	4.1 mm/ 0.20 mm
I_c / *n*-value (@77 K, self-field)	150 A/ 36 ~ 37
Stabilizer / Thickness	Ag/ 4 μm
Resistance in normal state	~90 mΩ/m

Table 2
Specifications of the NI DP coil.

Specifications	Values or Description
Inner/ Outer radius	55 mm/ 66.5 mm
Coil type	No-insulation double pancake coil
Total height	8.3 mm
Total # Turns	114 (57 turns per pancake)
Gap between two pancake coils	1 mm
Total tape length consumed	44.60 m
Winding tension	5 N
I_c / *n*-value (@77 K, self-field)	97 A / ~25
Coil self-inductance	2.618 mH
Flux density constant @ coil center	~1.225 mT/A
Driven mode	Current mode
Operation temperature	77 K

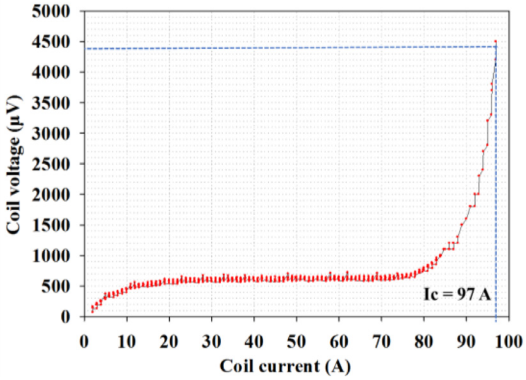

Fig. 2. *U-I* curve of the NI DP coil with voltage criterion of 1 μV/cm.

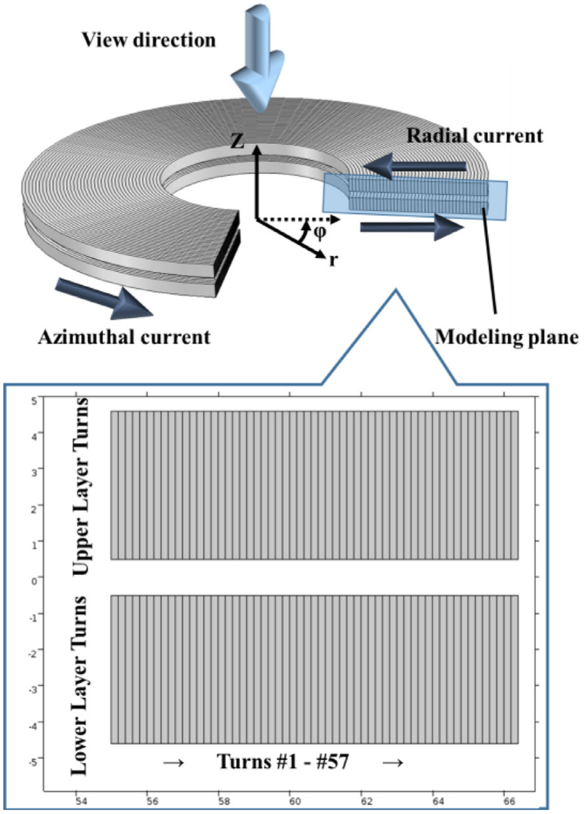

Fig. 3. Schematic drawings of the coil built in a FEM simulation software.