

Received October 7, 2021, accepted October 27, 2021, date of publication October 29, 2021, date of current version November 8, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3124247

Simulation and Test of Energy Consumption of High-Tc Superconducting Coils in Electromagnetic Levitation System

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This work was supported in part by the National Natural Science Foundation of China under Grant 51825703 and Grant 51690181, and in part by the Natural Science Foundation of Hubei Province under Grant ZRMS2020000185.

ABSTRACT In order to evaluate the energy consumption of the superconducting magnetic levitation system with real-time control, the methods of simulation and test were used to study the AC plus DC loss of the superconducting coil. The simulation established a 2D finite element model in COMSOL, which was based on the H equations method with simple form and fast calculation speed. The test was carried out on a new type of measurement system, which adopted the electrical method with high sensitivity, simple operation and easy implementation. The results of simulation and test showed that, under normal working conditions, the levitation current in the form of AC plus DC produced a relatively small energy loss below $1mW$ per meter. This conclusion is helpful for the promotion and application of superconducting magnetic levitation control system.

INDEX TERMS Energy consumption, electrical measurement, HTS coil, maglev control, numerical simulation.

I. INTRODUCTION

High-Tc superconducting magnetic levitation is a novel and promising research direction. It uses superconducting tapes to completely replace normal wires to wind the excitation coils of levitation electromagnets, and through real-time control of the current in superconducting coils to achieve the stable levitation of the system [1]–[3]. It can effectively solve the shortcomings of the normal-conducting magnetic levitation system, such as heating of the magnet, saturation of the magnetic field, limited carrying capacity, small levitation gap, and high rail cost [4]. This type of technical scheme has important practical significance for improving the performance of current maglev system and reducing its energy consumption.

In our previous published work [5], we designed and built a set of high-Tc superconducting magnetic levitation test system based on Bi-2223/Ag tape, which achieved stable levitation without quenching under the conditions of 77K and current $\geq 20A$, as shown in Fig. 1. This system not only verified the feasibility of using HTS tape to completely

replace the normal wire for winding maglev coils, but also its current-carrying index has been greatly improved compared with previous experimental systems, reaching the level of engineering application for the first time. However, no in-depth study of its loss characteristics.

Broadly speaking, the superconducting magnetic levitation system is an AC application of superconducting magnets, and there should be a certain degree of AC loss, but it is different from the AC equipments such as superconducting motors [6]–[8], superconducting transformers [9], accelerator magnets [10], etc. When the system is normally suspended, although the control current inside superconducting coils is constantly changing, it actually superimposes a relatively small dynamic component on a large steady-state DC component, which is also generally called AC plus DC. In theory, the loss of AC plus DC should be less than the pure AC loss of the same level. However, the loss under this special working condition still needs to be studied. If the loss is too large, the advantages of superconducting tapes used in electromagnetic levitation systems cannot be reflected.

Regarding AC plus DC loss, some scholars have proposed some theoretical calculation methods [11]–[13], but these

The associate editor coordinating the review of this manuscript and approving it for publication was Guido Lombardi¹.

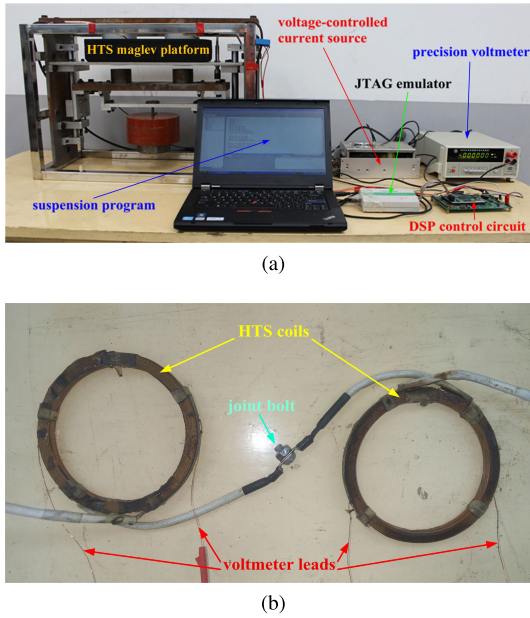


FIGURE 1. High-Tc superconducting magnetic levitation test system: (a) test site; (b) HTS coils.

methods have made varying degrees of assumptions and simplifications in their derivation process, not only the accuracy is not high, but the scope of application is limited. For this reason, this article focuses on the study of the AC plus DC loss of the superconducting magnetic levitation system from the perspective of simulation and test, and compares and discusses the energy consumption and total cost of superconducting and normal-conducting levitation systems.

In addition, some issues need to be emphasized. A suspension system, in which the internal current of superconducting coils can be adjusted in real-time by an active control method, is a brand-new suspension system. Therefore, the current research on this type of suspension system, including design, loss, modeling, control, etc., are very few. This article focuses on the aspect of loss. Because it is different from the DC current in superconducting coils, this kind of suspension system will inevitably produce AC loss in the superconducting coils. If the loss is too large, it will restrict its subsequent application and promotion, so qualitative evaluation is urgently needed. Therefore, this article is not to propose a set of new theories or solve the engineering problems encountered, but to use simulation and test methods to study and analyze the energy consumption level of the suspension system according to its special working conditions, and evaluate the applicability of the system. The research conclusions can lay the foundation for follow-up research.

II. SIMULATION

A. MATHEMATICAL PROBLEMS IN SIMULATION

For high-Tc superconductors, the finite element method (FEM) is a very effective simulation analysis method to study its electromagnetic characteristics and calculate its AC

and DC losses. As for the mathematical calculation behind FEM, the H equations method with simple form and fast calculation speed is usually adopted [14]. The main feature of H equations method is that magnetic field intensity \mathbf{H} is the independent variable, and its derivation process from Maxwell's equations is as follows. Firstly, the differential form of Maxwell's equations is shown as:

$$\begin{cases} \nabla \times \mathbf{H} = \mathbf{J} \\ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \cdot \mathbf{J} = 0 \end{cases} \quad (1)$$

In the solution domain, the relationships of magnetic flux density \mathbf{B} versus magnetic field intensity \mathbf{H} and electric field intensity \mathbf{E} versus current density \mathbf{J} are shown in (2) and (3), respectively.

$$\mathbf{B} = \mu_0 \mathbf{H} \quad (2)$$

$$\mathbf{E} = \rho \mathbf{J} \quad (3)$$

In (2) and (3), μ_0 represents the permeability of the vacuum. ρ represents the resistivity of the substance. For the liquid nitrogen region, ρ is a constant; for the superconducting region, it is necessary to calculate the equivalent resistivity of the superconductor according to the E - J index model, i.e.

$$\rho_{sc} = \frac{E}{J} = \frac{E_0(J/J_c)^n}{J} = E_0 \frac{J^{n-1}}{J_c^n} \quad (4)$$

In (4), E_0 represents the critical electric field intensity, which is also called the quench judgment standard of superconductors; According to international standards, the value is generally $1\mu V/cm$. J_c represents the critical current density in A/m^2 . The value of n is used to describe the quench change rate of high-Tc superconductors, which is related to the inherent characteristics of superconducting materials. It needs to be noted, ρ_{sc} is only a hypothetical intermediate variable, and does not represent the actual current density distribution of the superconductor.

Substituting (2), (3) and (4) into the first two formulas in the system of equations (1), one can get the H equations used to solve the electromagnetic characteristics in the superconducting region, shown as

$$\begin{cases} \nabla \times \mathbf{H} = \mathbf{J} \\ \nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t} \\ \mathbf{E} = \rho_{sc} \mathbf{J} \\ \rho_{sc} = E_0 \frac{J^{n-1}}{J_c^n} \end{cases} \quad (5)$$

The three variables \mathbf{H} , \mathbf{E} and \mathbf{J} can be solved by equations (5), and then \mathbf{E} and \mathbf{J} can be integrated to obtain the loss value \mathbf{Q} , namely (the subscript scr of the integral represents the region where the superconductor is located)

$$\mathbf{Q} = \int_{scr} \mathbf{E} \cdot \mathbf{J} \quad (6)$$

TABLE 1. Principal parameters of Bi-2223/Ag tape and HTS coil.

Critical Temperature of Single Tape	105K
Critical Current of Single Tape (77K, 0T)	120A
Critical Current Density of Single Tape (77K, 0T)	12000A/cm ²
Dimension of Single Tape	4.2mm×0.23mm
Min. Bending Radius of Single Tape (decay 5%)	30mm
Max. Tensile Stress of Single Tape (decay 5%)	100MPa
Min. Diameter of HTS Coil	80mm
Number of Turns of HTS Coil	50turns
Nominal Current in HTS Coil	20A

B. SIMULATION MODEL AND RELATED SETTINGS

The multiphysics coupling analysis software COMSOL was adopted, and in order to reduce the amount of calculation, a 2D simulation model of multi-layer tapes stack was established. In the calculation of electromagnetic heating, for taking into account the magnetic field between each layer of the superconducting coil, we subdivided the cross section of the coil, which was divided into multi-turns, and each turn represented a double-cake single layer, as shown in Fig. 2(a). The principal parameters of Bi-2223/Ag tape and HTS coil are shown in Tab. 1.

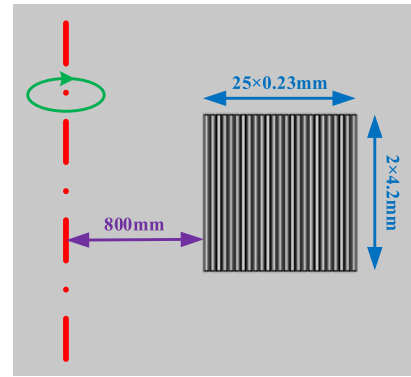
In order to improve calculation efficiency, the simulation model was further optimized: 1) mesh the superconducting coil area according to a more regular quadrilateral; 2) coarsen the triangular mesh of the liquid nitrogen area. The improved model meshing is shown in Fig. 2(b).

C. TEST AND FITTING OF THE E-J MODEL OF SUPERCONDUCTING COIL

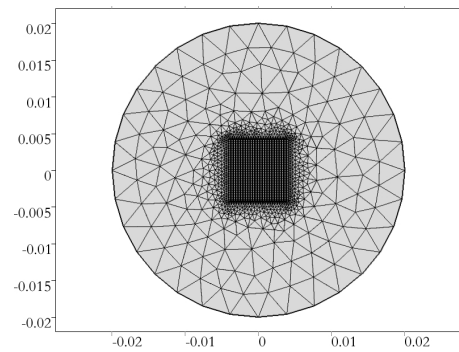
As known from Section 2.1, the E-J model of superconducting coil is needed in the simulation. Generally, different superconducting materials have different E-J models. In addition, the critical properties of superconducting materials are affected by various factors such as temperature, magnetic field and mechanical deformation. Even for the same superconducting sample, the results of its E-J model measured at different times may be different. Therefore, in order to improve the authenticity of the simulation, we firstly carried out experimental measurements on the critical characteristics of the superconducting coil, and obtained its true E-J exponential relationship through data fitting, as shown in Fig. 3.

In Fig. 3, the abscissa I represents the current input into the superconducting coil through a constant current source; the ordinate U represents the steady-state voltage at both ends of the coil measured by a precision voltmeter. In fact, the meaning of U here and E in the previous equations are essentially similar, but the E in the equations has universal meaning and can represent superconductors of different shapes. Since the total length of the tape in a single superconducting coil is 13.5m, if E₀ = 1μV/cm is used as the quench criterion, the result of the fitting function is

$$U = E_1 \times \left(\frac{I}{I_c}\right)^n = 1.35 \times \left(\frac{I}{48.36}\right)^{8.39} \quad (7)$$



(a)



(b)

FIGURE 2. 2D simulation model of superconducting coil: (a) geometry structure; (b) meshing result.

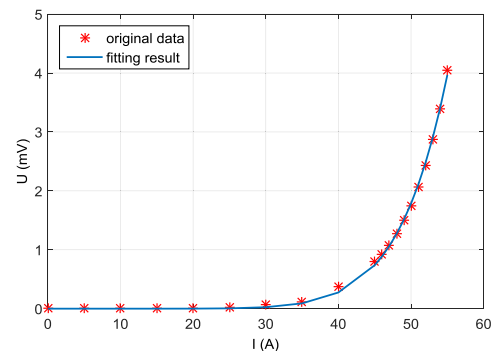


FIGURE 3. Measured result of the E-J model of superconducting coil.

Considering that the cross-sectional area of the tape is 4.2mm × 0.23mm, which is 9.66 × 10⁻⁷ m², its critical current density can be calculated as J_c = 5.01 × 10⁷ A/m². Then, the E-J model of the superconducting coil is

$$U = E_0 \times \left(\frac{J}{J_c}\right)^n = \left(\frac{J}{5.01 \times 10^7}\right)^{8.39} \mu V/cm \quad (8)$$

The superconducting coils were made of Bi-2223/Ag tape produced by Innova Superconductor Technology Co., Ltd. Their researchers have previously measured the n values of different lengths (5cm-1m) of superconducting tapes, the results obtained were 8.1-15.5. However, after the

superconducting tape is wound into a coil, the value of n will be attenuated to a greater extent, so the 8.39 we got here is consistent with their results. In addition, different superconducting coils have different values of n under different conditions, here we only measured the n value required by the simulation model.

D. LOSS UNDER THE GIVEN WORKING CONDITIONS

When the superconducting levitation system is in a steady state, its excitation current is in the form of AC plus DC, which can be approximated by the following formula (where I_d represents the DC component, I_a represents the amplitude of the AC component, and f represents the frequency of the AC component):

$$I = I_d + I_a \sin(\omega t) = I_d + I_a \sin(2\pi f t) \tag{9}$$

When a current is applied to a high-Tc superconductor, the distribution of current density is not uniform, and with the passage of time, the distribution of current density will also change, which makes the loss of the superconductor at different moments different. In order to observe this phenomenon, we first selected a set of typical parameters for simulation, namely $I_d = 20A$, $I_a = 5A$, $f = 50Hz$. This set of parameters is closest to the steady-state operating conditions of the superconducting levitation system. The simulation step length is 1/10 cycles, and the total simulation time is 5 cycles, which we found is enough to analyze the data after a lot of simulation tests. At different times in the first cycles, the change trend of the current density distribution inside the superconducting coil is shown in Fig. 4(a)-(d).

As can be seen from Fig. 4, in the initial stage of the current flowing into the coil, the areas with higher current density are mainly distributed inside the outermost and innermost tapes and at the two ends of the middle tapes; As it progresses, current begins to penetrate into the inner area of the coil. At the same time, the area with the largest current density gradually concentrates on the four corners of the coil section, and the value of current density gradually decreases. In addition, it can be seen that starting from the second cycle, the current density distribution inside the superconducting coil gradually tends to a stable state.

Based on the simulation model and the given working conditions, the relationships between the coil loss Q_t and the three parameters I_d , I_a and f were analyzed, as shown in Fig. 5(a), (b) and (c) respectively. These three parameters were not randomly selected, and were mainly based on the real maglev train system. When the maglev train runs stably, its steady-state levitation current is generally around 20A, the dynamic adjustment current is generally less than 5A, and its adjustment frequency is not greater than 100Hz. However, in order to cover more data and it is easier to operate than the experiment, the range of parameters was expanded in the simulation.

As can be seen from Fig. 5, the total loss Q_t of superconducting coil increases with the increasing of DC component I_d , AC component I_a and frequency f . In addition, the loss

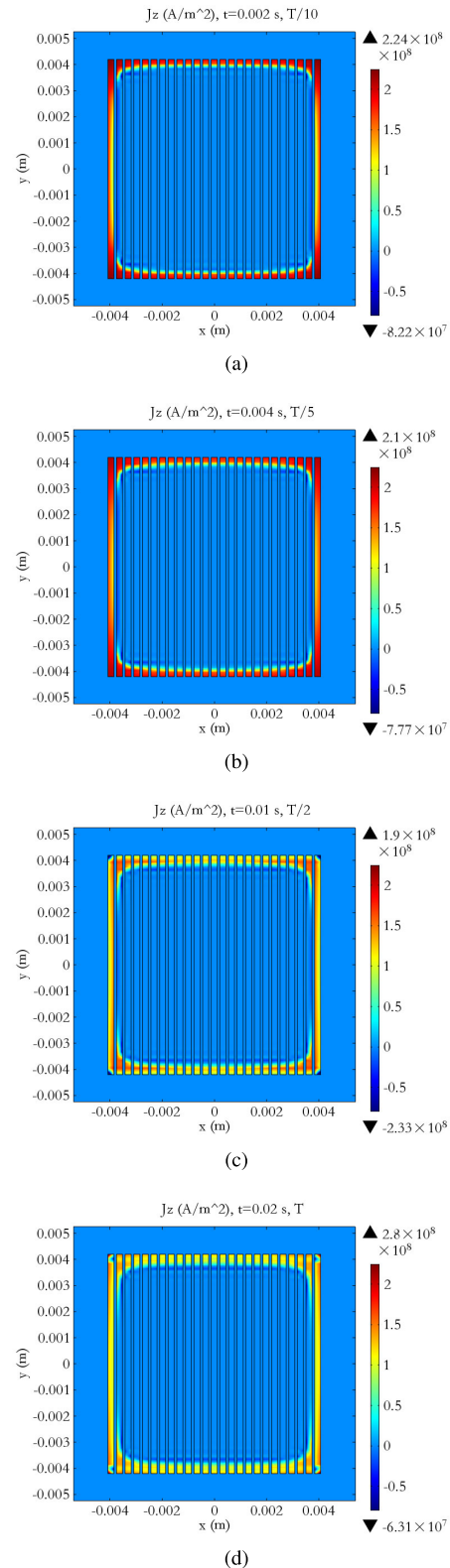


FIGURE 4. Change trend of current density distribution inside superconducting coil. (a) 1/10 cycle, (b) 1/5 cycle, (c) 1/2 cycle, (d) 1 cycle.

value of superconducting coil is relatively low. As for a typical operating condition, the power loss of a single superconducting coil is only about 0.04W.

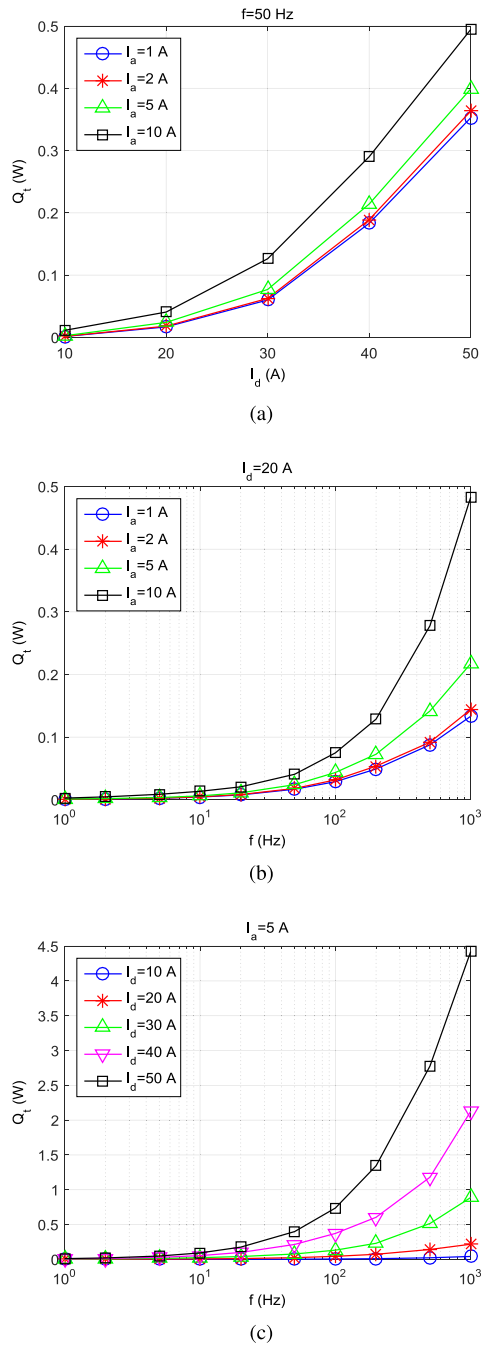


FIGURE 5. Superconducting coil loss Q_t vs I_d , I_a and f . (a) $f = 50\text{Hz}$, I_d and I_a change; (b) $I_d = 20\text{A}$, I_a and f change; (c) $I_a = 5\text{A}$, I_d and f change.

III. TEST

A. TEST SYSTEM AND ITS OPERATING PRINCIPLE

Considering the small size and low loss of the superconducting coil, the loss test was carried out on a new type of measurement system, which adopts the electrical measurement method with high sensitivity, simple operation and easy implementation. Its principle diagram is shown in Fig. 6.

The working process is as follows: 1) firstly adjust the function generator to obtain the required AC and DC compo-

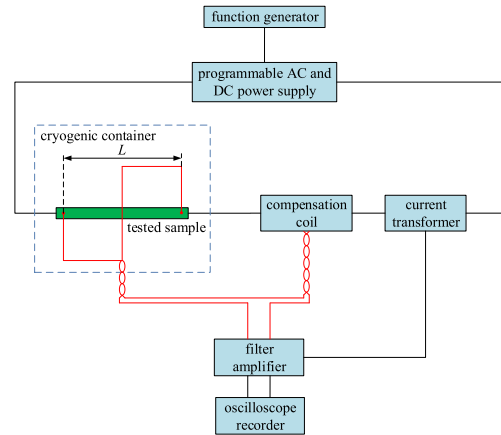


FIGURE 6. Principle diagram of the electrical measurement method for loss test.

nents, frequency and period of the current waveform output by the programmable AC and DC power supply; 2) then input the current into the superconducting sample to be tested, and collect the voltage at both ends of the sample and the current inside it through voltage leads and current transformer respectively; 3) finally send the voltage and current signals to the filter amplifier, after filtering and amplifying, to the oscilloscope recorder. In addition, for the superconducting coil, because the voltage signal contains inductive components and its phase leads the current signal by 90 degrees, it is necessary to use a compensation coil with a better inductance value to compensate it. Multiply the compensated voltage and current and after integrating, one can get the loss value of the sample.

The test was completed at the Superconducting Research Center of Shanghai Jiaotong University. The test platform and test site are shown in Fig. 7(a) and (b), respectively.

B. LOSS RESULTS OF THE TESTED SUPERCONDUCTING COIL

We conducted a lot of experiments, data collection and post-processing, and revised the simulation model based on the test results. In order to form a simple and intuitive comparison with simulation, only a part of the typical working conditions of a single superconducting coil were selected and divided into three cases: 1) set $I_a = 5\text{A}$ and $f = 50\text{Hz}$, then adjust $I_d = 5, 10, 15, 20, 25, 30\text{A}$; 2) set $I_d = 20\text{A}$, $f = 50\text{Hz}$, then adjust $I_a = 5, 7.5, 10, 12.5, 15\text{A}$; 3) set $I_d = 20\text{A}$, $I_a = 5\text{A}$, then adjust $f = 25, 40, 50, 60, 75\text{Hz}$. The measured loss of the above three cases and compared with their corresponding simulation results after model correction are shown in Fig. 8(a), (b) and (c) respectively.

As can be seen from Fig. 8, the measured data and the simulated data are in good agreement with the change trend, but the simulation results are slightly higher than the measured results in value. The reason may be that the measured loss is only the transmission loss, and the simulation results not only include the transmission loss, but also part of the magnetization loss caused by the changing magnetic field. However, the loss value of the superconducting coil is low,

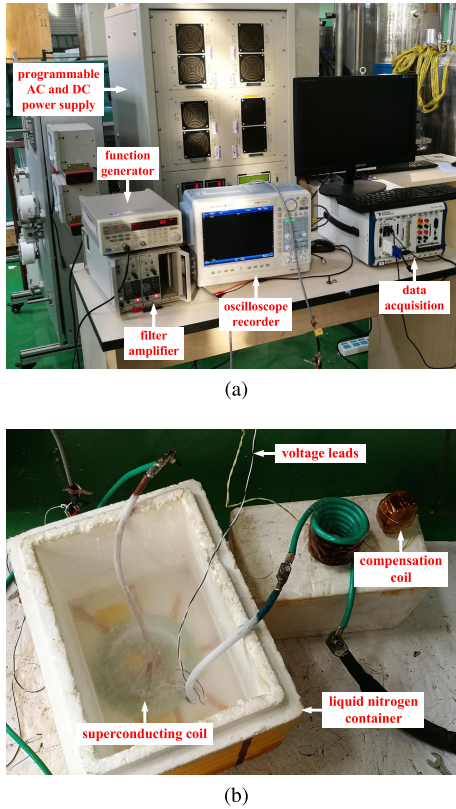


FIGURE 7. Electrical measurement system for the loss of superconducting coil: (a) test platform; (b) test site.

and the power loss of a single superconducting coil under normal working conditions is only about 0.04W.

IV. DISCUSSION

A. LOSS UNDER THE ACTUAL WORKING CONDITIONS

In order to make the simulation results closer to the actual working conditions of superconducting levitation system, we collected several current data during the experiment, which represent the start floating, start landing, stable levitation and square-wave interference of the system, as shown in Fig. 9(a), (b), (c) and (d) respectively.

Input the four actual levitation current into the simulation model of superconducting coil, the corresponding loss data can be obtained after calculation, as shown in Fig. 10(a), (b), (c) and (d) respectively. In fact, the simulation model in COMSOL does not reject any type of suspension current, whether it is an equivalent formula or the test data, the simulation model can calculate the corresponding loss.

As can be found from Fig. 10, under the four actual working conditions, the loss value generated by the superconducting coil is not large, and the maximum power loss of a single coil is less than 0.02W; In addition, the area with large loss generally occurs at the moment when the levitation current fluctuates sharply.

However, the energy consumption of maglev trains mainly occurs in long-term steady-state operation, the loss generated

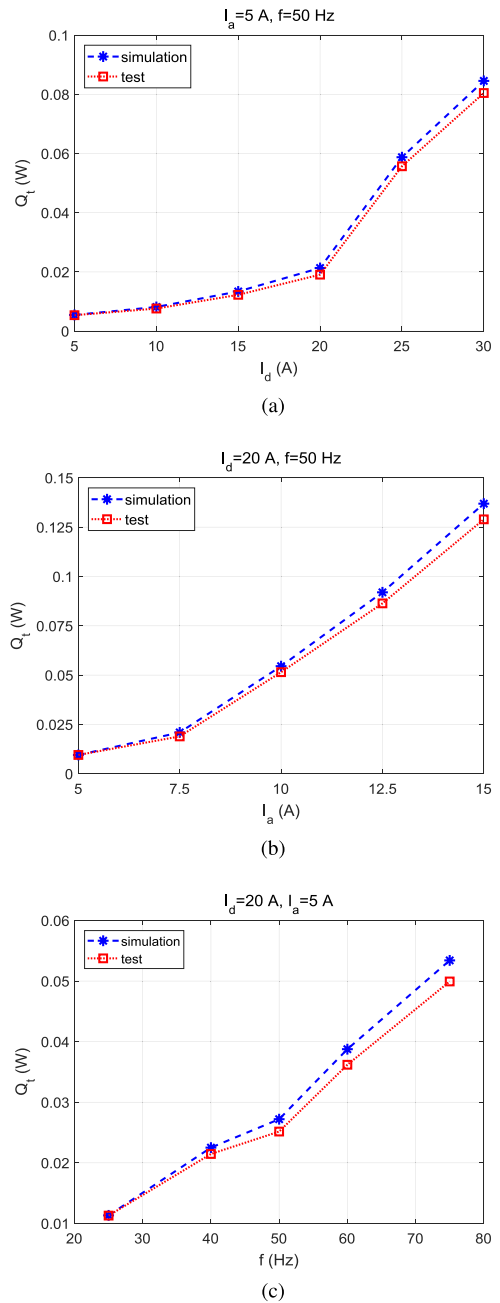


FIGURE 8. The measured loss of superconducting coil and compared with simulation: (a) Q_t vs I_d ; (b) Q_t vs I_a ; (c) Q_t vs f .

by higher frequency and transient conditions can be negligible in the total energy consumption when considering long-term accumulation.

B. ENERGY CONSUMPTION AND TOTAL COST OF TWO LEVITATION SYSTEMS

Under normal levitation conditions, i.e. the rated current is about 20A, the current fluctuation is about 5A, and the frequency range is 50-200Hz, the total loss of the superconducting levitation system with two coils is less than 0.1W. If aluminum wire (its resistance per unit length is

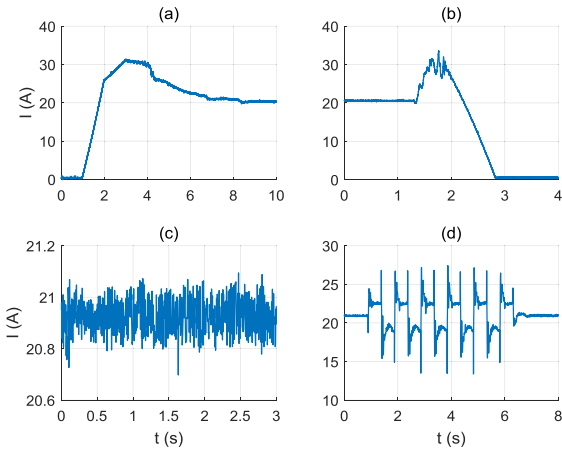


FIGURE 9. Levitation current under four actual working conditions: (a) start floating; (b) start landing; (c) stable levitation; (d) square-wave interference.

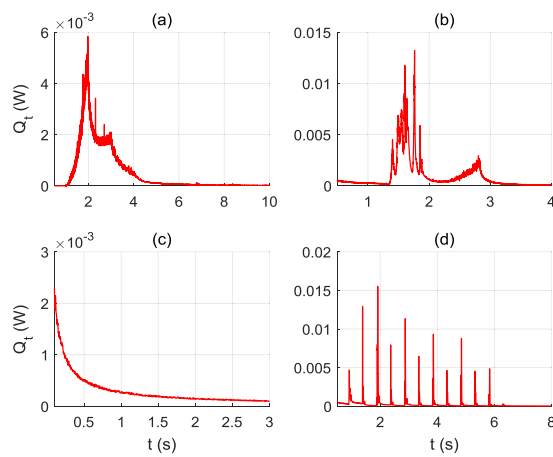


FIGURE 10. Coil loss under four actual working conditions: (a) start floating; (b) start landing; (c) stable levitation; (d) square-wave interference.

$1.35 \times 10^{-3} \Omega/m$) is used to wind a normal conducting levitation electromagnet, the total resistance of the two coils is 0.0365Ω , and the resistive power loss is $14.58W$, which is 145.8 times the loss of superconducting levitation system. In addition, considering the cooling efficiency of liquid nitrogen is about $1/15$, the energy consumption of the superconducting levitation system using Bi tapes is about $1/10$ of that of the normal conducting levitation system.

However, one disadvantage of superconducting tape is that it is more expensive. Its price in Chinese market is about $150 \text{ Yuan}/m$ ($23 \text{ Dollars}/m$), which is about 15 times the price of aluminum wire. Besides, this is only the basic cost proposed by the manufacturer, including the tape itself and the winding coil, other content and factors such as the additional hardware requirements are not taken into consideration. Therefore, in order to save the amount of superconducting tape, a feasible solution is to increase the current of single-turn coil to reduce the number of coil turns. However, as the current increases, the loss generated by

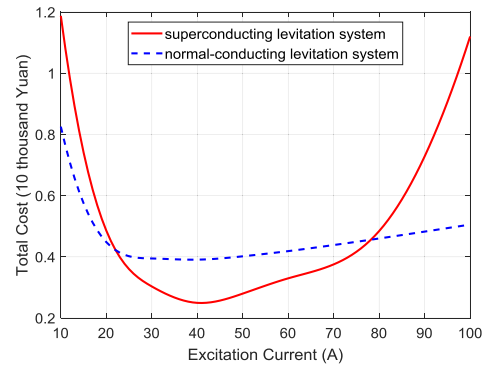


FIGURE 11. Total cost versus excitation current of superconducting and normal-conducting levitation systems.

superconducting levitation system also increases, so a compromise between loss and price needs to be made.

Assuming that the price of aluminum wire is $10 \text{ Yuan}/m$, the superconducting levitation system runs for 10 hours a day for 10 years, and the price of electricity is $1 \text{ Yuan}/kWh$, then the total cost versus excitation current of superconducting and normal-conducting levitation systems is shown in Fig. 11.

As can be seen from Fig. 11, when the excitation current is in the range of $22-78A$, the total cost of the superconducting levitation system is less than that of the normal-conducting levitation system, and the excitation current corresponding to the lowest cost is about $40A$.

One point worthy of special mention: due to the small size of the platform [5] and the low consumption of liquid nitrogen during the test, we stored the liquid nitrogen in an open foam dewar and used a liquid nitrogen pump to manually replenish the liquid nitrogen in real time. Because this method can effectively guarantee the normal operation of the test, we have not carried out research on the relevant thermal management system. However, we are currently planning to build a larger 1:1 test platform. The above method will no longer be applicable. We will learn from some schemes or examples in the application of HTS cables [15] to design and manufacture an enclosed liquid nitrogen cycle refrigeration system, to ensure the safe, automatic and stable operation of the system. The related thermal management research will be elaborated in a follow-up presentation.

V. CONCLUSION

In order to evaluate the energy consumption, economy and applicability of the superconducting magnetic levitation system, this article used the methods of simulation analysis and experimental measurement to study the AC plus DC loss of the superconducting coil, and compared with the normal-conducting magnetic levitation system based on the results of simulation and test. The main conclusions are as follows:

- 1) The loss will increase with the increasing of the DC component, the amplitude and frequency of the AC component.

2) Under normal working conditions, the excitation current in the form of AC plus DC produces relatively small loss in the superconducting magnetic levitation system, and the order of magnitude is below $10^{-3} W/m$.

3) For the superconducting magnetic levitation system, only when its excitation current is placed in a certain range (the special case of this article is 22-78A), it has the advantages of energy consumption and total cost compared with the normal-conducting magnetic levitation system.

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