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# Modeling and numerical analysis of resistance network for non-insulated superconducting magnet

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ABSTRACT

Non-insulated (NI) superconducting magnet may enhance transient stability of magnet coils and improve the self-protection ability, in which the resistance of adjacent turn-to-turn contact plays an important role. A resistance network model of NI superconducting magnet has been established in this paper. The equivalent total resistance has been numerically analyzed by using EDA software, and the influences of the total layer number and the turn number in each layer on the resistance value have been studied. By simulating the resistance network, we have acquired the variation trend of the equivalent total resistance when the total layer number is odd or even and found that the simulation results are basically consistent with the experimental results. The results show that when the total layer number of coils is odd, the total resistance first decreases down to the minimum and then increases with the increase of the layer number, and when the total odd layer number is lower than 9, the total resistance is greatly influenced by the turn number in each layer. When the total layer number is even, the total resistance increases with the increase of the layer number. However, whether odd or even, when the total layer number exceeds 25, the total resistance is little influenced by the turn number in each layer, and the total resistance is about a few multiples of the adjacent turn-to-turn contact resistance. These numerical analysis results will provide theoretical basis for the design of NI superconducting magnet.

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## 1. Introduction

Most superconducting magnets are insulated magnets, that is, the adjacent superconducting wires are insulated in the magnet coils. But the quench phenomenon accompanying insulated superconducting magnet will cause potential harm to the magnet. Compared with low temperature superconducting coils, high temperature superconducting coils have extremely low self-protection ability because of low normal zone propagation velocity [1,2]. The high temperature rise caused by local quench would damage superconducting magnet coils and the induced high voltage between adjacent turns might cause a breakdown of the insulation material. This large problem obstructs the commercial application of HTS. Therefore various design methods have been adopted to solve the quench problem in insulated superconducting magnet [3–5]. The concept of non-insulated (NI) superconducting magnet is proposed with respect to insulated superconducting magnet, that is, the adjacent turn-to-turn contact is not insulated in magnet coils [6–8]. Once the coil quenches, the operating current might bypass the Joule's heating region into the adjacent turns or layers. Thus serious damage of superconducting coils may be avoided before discharging. NI superconducting magnet has good thermal conductivity leading to faster normal zone propagation. Compared with insulated superconducting magnet, NI superconducting magnet has great advantages in quench protection ability and thermal stability [9,10]. Although some researchers have been studying the technique and properties of NI superconducting magnet coils [11–13], the research on equivalent resistance of NI superconducting magnet in charge–discharge has not been reported so far. The main purpose of this paper is to establish the resistance network model of an NI superconducting magnet coil and to clarify the variation of total resistance value with the number of turns and layers in the magnet coil. These research results would provide theoretical basis for the design and fabrication of NI superconducting magnet.

## 2. Equivalent resistance network model of NI superconducting magnet

Equivalent circuit model of NI superconducting magnet has been reported in Ref. [6], as shown in Fig. 1. It mainly consists of three components: $L$, $R_\theta$ and $R_C$, where $L$ and $R_\theta$ are the two parameters related to superconducting wire. $L$ is the self inductance. $R_\theta$ is the azimuthal resistance of the superconducting wire matrix metal and the superconductor flux-flow represented by $n$ index. When the operat-

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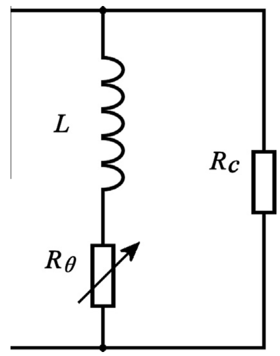


**Fig. 1.** Equivalent circuit model of the NI superconducting magnet.

ing current is significantly lower than the critical current, $R_\theta$ can be ignored because its value is so tiny that it can hardly influence the equivalent total resistance. $R_C$ is the contact resistance of turn-to-turn and layer-to-layer. Theoretical calculation of the resistance $R_C$ value is very complicate, thus this paper is focused on numerical calculation of $R_C$ by using simulation software. The structure sketch of NI superconducting magnet coils with 3 layers is shown in Fig. 2(a), where bold line represents superconducting wire, the resistance in horizontal direction is the contact resistance of adjacent turns in the same layer; the resistance in vertical direction is the contact resistance of adjacent turns in different layers. When NI superconducting magnet is working normally and the current is stable, the current only flows through the superconducting wire. When NI superconducting magnet is in charge–discharge and the current ramping rate is large enough, the current will chiefly flow through the turn-to-turn and layer-to-layer contact resistance. Fig. 2(a) can be simplified to the pure resistance network as shown in Fig. 2(b), in which the equivalent total resistance value is almost equal to $R_C$ shown in Fig. 1. When the total layer number of superconducting magnet coils is even, current flows out from $I_e$ side, and when the total layer number of superconducting magnet coils is odd, current flows out from $I_o$ side, as shown in Fig. 2. It can be seen from the Fig. 2(b) that the influence of the even–odd of the total layer number on the total resistance $R_C$ value would be remarkable. The magnitude orders of $R_C$ would directly impact the operating stability and self-protection ability of NI superconducting magnet. In order to study the influences of the turn number and the layer number on the $R_C$ value and the relationship between the total resistance and the adjacent turn-to-turn contact resistance, the numerical calculation of the total resistance $R_C$ for the NI superconducting magnet resistance network will be performed.

## 3. Numerical analysis of the resistance network

The equivalent total resistance of the resistance network shown in Fig. 2(b) is very difficult to be obtained using theoretical formula calculation. However, this problem can be solved using Altium Designer, which is an EDA software solution that provides the designer with the tools they need to solve engineering problems. The software has the function of circuit simulation and can conveniently analyze the proposed resistance network model as shown in Fig. 2(b). In the simulation, the draw interface of the resistance network is shown in Fig. 3. Numerical analysis process is as follows: firstly, the total current and the individual resistance value are set respectively. Then through numerical analysis and calculation, the electric potential difference across the two nodes can be obtained. Lastly, the equivalent total resistance is calculated by Ohm's law.

To judge the validity of the numerical simulated software, we performed practical test to the two sets of resistance networks with 4 layers–4 turns and 5 layers–5 turns, respectively. And then the experimental results were compared with those results of the software simulation. In the experiment, each resistance value of resistance networks was 50.5 Ω. Through testing, the total resistance value of resistance networks with 4 layers–4 turns and 5 layers–5 turns was 81.61 Ω and 108.02 Ω, respectively. While, using the software to simulate the same networks as the experiment, equivalent resistance value was 81.5878 Ω and 107.89 Ω, respectively. Thus it can be considered that the results of practical measurement and numerical simulation are approximately equal in the range of error. It shows that the numerical analysis approach is effective and reliable. Therefore we adopt the numerical simulation to investigate the total resistance problem of the multi-layer and multi-turn coils of NI superconducting magnet.

In the process of numerical simulation, each resistance value in Fig. 2(b) is assumed to be 1 Ω and the total current is set to 1000 A. The electric potential of any node on the resistance network can be directly read by using the simulation software. Thus the equivalent total resistance can be easily obtained, which is the total voltage value divided by the total current value.

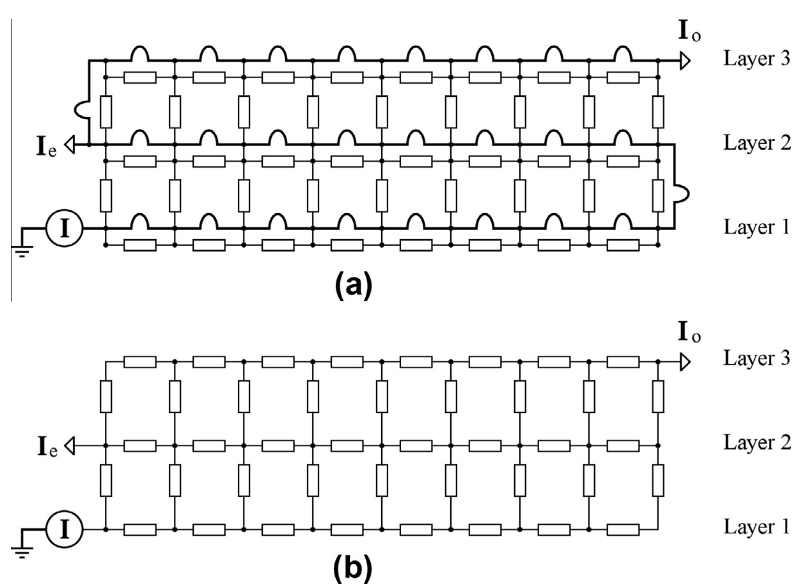


**Fig. 2.** (a) The structure sketch of NI superconducting magnet and (b) the pure resistance network of NI superconducting magnet.

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