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ANALYTICAL ESTIMATION OF THE THERMAL STABILITY OF HTS MAGNETS DURING SUDDEN DISCHARGE

ANALITIČNA OCENA TOPLOTNE STABILNOSTI HTS-MAGNETOV MED NENADNIM PRAZNENJEM

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Abstract

Since the advent of 2nd-generation high-temperature superconducting (HTS) tapes, which show great features on critical temperature, critical current density, and critical magnetic field, many researchers have been trying to generate ultra-high magnetic fields using HTS coils. One more promising technology is a no-insulation (NI) winding technique. This technique suppresses the possibility of thermal runaway and burning-out of HTS coils drastically. The interest in compact nuclear fusion magnets wound with HTS conductors has been increasing rapidly during the last five years. The simulation of such magnets larger than MRI/NMR HTS magnets takes an unfeasibly long time. Therefore, we present a simple expression of the coil temperature rise under a simple assumption derived from the simple coil model, to investigate the stability of large-scale magnets.

The method's advantages are simplicity, versatility, and nearly no computation, enabling a time reduction in the first-cut design.

Povzetek

Od pojava superprevodnih trakov druge generacije, ki delujejo pri visokih temperaturah (HTS) in ki izkazujejo izjemne značilnosti v smislu kritične temperature, gostote kritičnega toka in kritičnega magnetnega polja, si številni raziskovalci prizadevajo za generiranje ultravisokih magnetnih polj

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z uporabo HTS-tuljav. Obetavna tehnologija na tem področju je tehnika navijanja brez izolacije (NI). Ta pristop znatno zmanjša tveganje za termični preboj in izgorevanje HTS-tuljav. V zadnjih petih letih opažamo večje zanimanje za kompaktne magnete jedrske fuzije, ki so naviti s HTS-prevodniki. Simulacija takih magnetov, večjih od HTS-magnetov, uporabljenih v MRI-/NMR-napravah, zahteva neizvedljivo dolg čas. Zato v tem članku predstavljamo preprost izraz za opis dviga temperature tuljave, ki temelji na preprosti predpostavki, izpeljani iz osnovnega modela tuljave, s ciljem raziskovanja stabilnosti magnetov velikih dimenzij. Glavne prednosti predlagane metode so njena preprostost, univerzalnost in minimalna potreba po računskih operacijah, kar omogoča skrajšanje časa začetnega načrtovanja.

1 INTRODUCTION

Towards the future of nuclear fusion power, our group is trying to establish a way to simulate and evaluate the thermal stability of superconducting magnets to generate ultra-high magnetic fields. Superconducting magnets wound with high-temperature superconductors (HTS), especially Rare-Earth Barium Copper Oxide (REBCO) [1], are considerably promising for the magnetic confinement of plasma. HTS tapes, such as REBCO-coated conductors, can maintain superconductivity in high magnetic fields (> 20 T). In 2011, Hahn et al. proposed a no-insulation (NI) winding technique for HTS pancake coils [2], where there is no insulation between the winding turns. The NI winding technique improves the thermal stability of HTS pancake coils greatly, solving the long-lasting thermal instability for high magnetic field generation [3], [4]. The mechanism of the high thermal stability is explained as follows [5]: a hot spot, which potentially causes a thermal runaway, appears in an NI HTS coil. The operating current can flow into the adjacent turns through the turn-to-turn contact surfaces, avoiding the hot spot. The consequent Joule heat dissipation is less than the case of a conventionally turn-insulated HTS coil.

As a matter of fact, a metal-insulation winding technique, which is categorized as one of the no-insulation winding techniques, was adopted to generate 20 T for a nuclear fusion coil at MIT [6]. The electromagnetic, thermal, and mechanical behaviors of NI HTS coils are complicated, and the simulation takes a long time, even to evaluate the thermal stability [7]. Furthermore, a fine simulation of such a large-scale NI HTS magnet is complex. Several researches and developments have been made on NI HTS magnet simulation methods; however, a fast and easy way to evaluate thermal stability is still necessary as a fundamental step of thermal stability designs.

This paper proposes a simple analytical expression of NI HTS coil temperature. It is useful in the first-cut conceptual design. The formulation is given in the paper, and an arbitrary NI REBCO coil was investigated with different parameters. The maximum temperatures reached were checked as a function of the radial turn-to-turn resistance. For such a large magnet, a cooling effect is not negligible due to the long time constant. The timescale of heat dissipation and cooling effect is also discussed in the paper. The proposed expression for thermal evaluation enables the parameter survey as well. This helps clarify the thermal stability boundary, which will be addressed in the future.

2 MODEL AND FORMULATION

2.1 Circuit Model

Fig. 1 shows an electrically equivalent circuit of an NI HTS magnet. The NI HTS coils are stacked and connected in series, forming the NI HTS magnet. The NI HTS magnet has the self-inductance L.

The introduction mentions that each NI HTS coil has a radial current path through the turn-to-turn contact surfaces. The resistance in the radial direction is expressed as a radial resistance R_{r} connected in parallel with the magnet inductance L. The current source is not shown in the equivalent circuit, because only the cases of sudden discharge tests are evaluated (mentioned later).

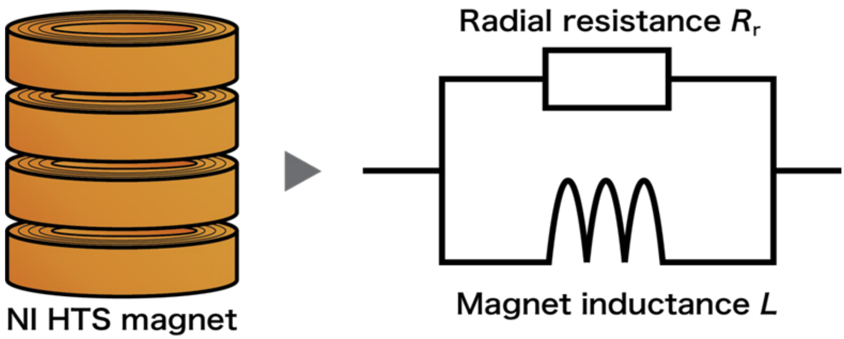

Figure 1: *Electrically equivalent circuit of an NI HTS magnet*

2.2 Formulation of Coil Temperature

From the above-shown electrically equivalent circuit model, we derived the current and temperature of the NI HTS magnet, considering the cooling effect. Here, the NI HTS magnet was assumed to be disconnected from a power source as the worst scenario, commonly called a sudden discharge test. The magnet is immersed in a coolant such as liquid helium. The magnet current I during discharging decays exponentially; the following Equation expresses it:

$$I = I_{\mathrm{m}} e^{-\frac{t}{\tau_{\mathrm{e}}}} \tag{2.1}$$

where I_{m} and t are the initial operating current and the time, respectively. It is noted that τ_{e} is the magnet time constant defined by

$$\tau_{\mathrm{e}} = \frac{L}{R_{\mathrm{r}}} \tag{2.2}$$

Using Equation (2.1), the magnet temperature T is governed by the Equation below:

$$C\frac{\mathrm{d}T(t)}{\mathrm{d}t} = R_{\mathrm{r}} I^2 - H\{T(t) - T_{\mathrm{i}}\} \tag{2.3}$$

Here, C, H, and T_{i} are the magnet thermal capacity [J/K], the thermal transfer coefficient [W/K], and the initial magnet temperature [K], respectively. Now, solving Equation (2.3), and the analytical expression of temperature T after disconnection of the power source is derived as follows:

$$T(t) = \frac{L I_m^2}{H\tau_e - 2C}\left(e^{-\frac{2t}{\tau_e}} - e^{-\frac{t}{\tau_t}}\right) \tag{2.4}$$

where τ_{t} is the thermal time constant, and it is calculated by

$$\tau_t = \frac{C}{H} \tag{2.5}$$

3 ANALYTICAL RESULTS

The current and temperature transitions of large-scale NI HTS magnets were investigated in this Section. Table 1 shows the magnet specifications. The magnet generates approximately 10 T at the magnet center. It was assumed that the magnet was immersed in liquid helium, and the heat could only move through the magnet surfaces in contact with the liquid helium. The heat is transferred according to Newton's law of cooling. The heat transfer coefficient was also assumed constant at 100 W/(m^2·K) [8].

The current profiles after the power shutdown at t = 0 s are shown in Fig. 2 in the cases of radial resistances 10, 50, and 100 μΩ as a design parameter. The magnet current decays exponentially, and the time constant shortens as the high radial resistance. The magnet is heated with the Joule heat by the current passing through the radial current.

Fig. 3 shows the magnet temperature in the three cases of different radial resistances. The temperature increases rapidly, and reaches a maximum after the power shutdown due to the cooling. In the case of radial resistance 100 μΩ, the maximum temperature is 172 K. It is noted that the lower the resistance is, the lower is the reached maximum temperature. This is because a low resistance results in a long time constant, i.e., a long time for energy dissipation and sufficient cooling.

Table 1: *Magnet specifications*

Parameter	Value
inner diameter [m]	0.50
outer diameter [m]	1.0
height [m]	0.3
magnet inductance [mH]	70
mass density [kg/m3]	9000
specific heat [J/(kg·K)]	100
heat transfer coefficient [W/(m2·K)]	100
magnetic energy [MJ]	56
initial current [kA]	40
operating temperature [K]	4.2

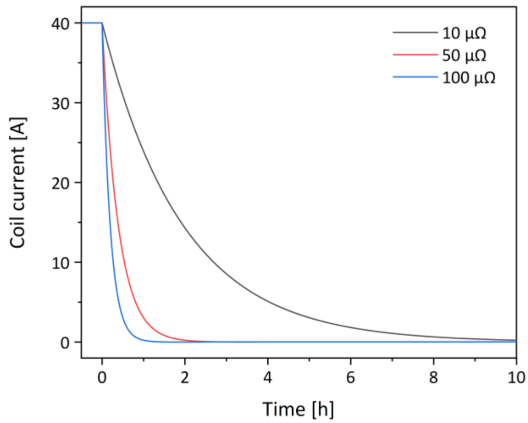

Figure 2: *Coil current of an NI HTS coil with different radial resistance by Equation (2.1)*

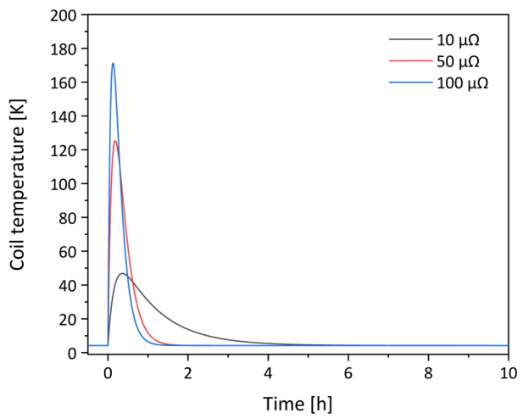

Figure 3: *Temperature of an NI HTS coil with different radial resistance by Equation (2.4)*

Next, the maximum reached temperatures were investigated as a function of the radial resistances. The result is shown in Fig. 4. The maximum temperature increased monotonically and saturated at ~352 K. In the thermal stability view of NI HTS magnets, the increased temperature should be within 300 K to prevent coil performance degradation [8]. The reference line is also drawn in the Figure. When the radial resistance is beyond 1 mΩ, the increased temperature exceeds 300 K. The electrical time constant τ_e is also shown in Fig. 4. It is evident that the low resistance led to the long electrical time constant, and the consequent temperature rise was low.

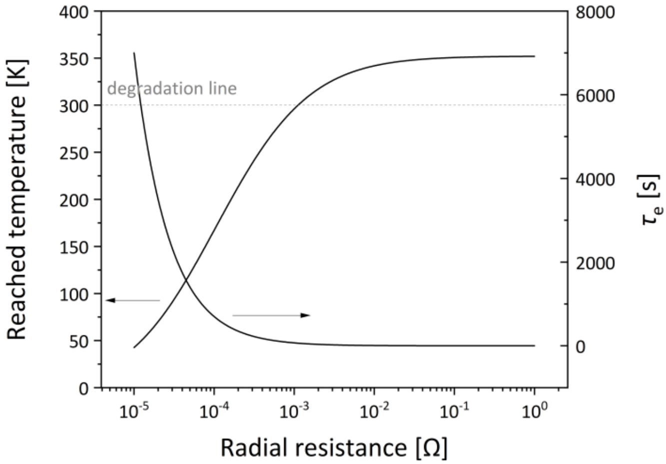

Figure 4: *Reached temperature of HTS magnet as a function of radial resistance*

It is shown that the balance of the timescale of energy dissipation and cooling affects the thermal stability significantly . Now, we introduced the ratio of the electrical time constant to the thermal time constant, α, as below:

$$\alpha = \frac{\tau_t}{\tau_e} \tag{3.1}$$

The ratio computed as a function of the radial resistance is shown in Fig. 5. Here, it is noted that the thermal time constant τ_t remained constant at 614 s. The ratio increased linearly as the electrical time constant τ_e decreased. The high ratio α means the heat dissipation occurred within a short time so as not to cool the magnet effectively. It is shown that the ratio α is one at around 0.1 mΩ. Whereas the ratio α is ~100 at 10 mΩ; i.e., the cooling effect is 1/100 times better from the viewpoint of Joule heat dissipation. Around the region of α = 100, the reached maximum temperature is fully saturated in Fig. 4. In such a large-scale NI REBCO magnet with a long time constant, the radial resistance plays a significant role in thermal stability, and must be designed meticulously.

4 CONCLUSIONS

In the paper, we have proposed the simple stability-evaluation expression of no-insulation (NI) high-temperature superconducting (HTS) magnets. The formulation is shown of the magnet temperature during sudden discharging. It can be used to evaluate the thermal stability of large-scale NI HTS magnets. Several parameter surveys were also conducted using the proposed formula. The results showed that the radial resistance should be low to suppress the high temperature rise by enabling long Joule heat dissipation, whereas the time constant is long. Optimizing the radial resistance is needed [9], [10]. Further analysis is ongoing using the proposed formula.

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