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Analytic equation to energy conversion between electromagnetically coupled superconducting and copper coils

Soobin An, Kibum Choi, Jeseok Bang, Uijong Bong, and Seungyong Hahn*

Department of Electrical and Computer Engineering, Seoul National University, Seoul, 08826, South Korea

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Abstract

This paper presents an analytic method to calculate energy conversion between electromagnetically coupled high-temperature superconducting and copper coils. The energy transfer from one coil to the other is commonly observed during quench of a no-insulation (NI) high temperature superconductor (HTS) magnet. Proper understanding of this phenomenon is particularly important to protect an NI HTS magnet, especially to avoid any potential mechanical damages. In this paper, analytic equations are obtained to estimate the energy transfer between the NI and copper coils. The well-known lumped-parameter circuit model is adopted provided that key parameters of the coils are given.

Keywords: HTS coil, no-insulation, quench analysis, electromagnetically coupled coils

1. INTRODUCTION

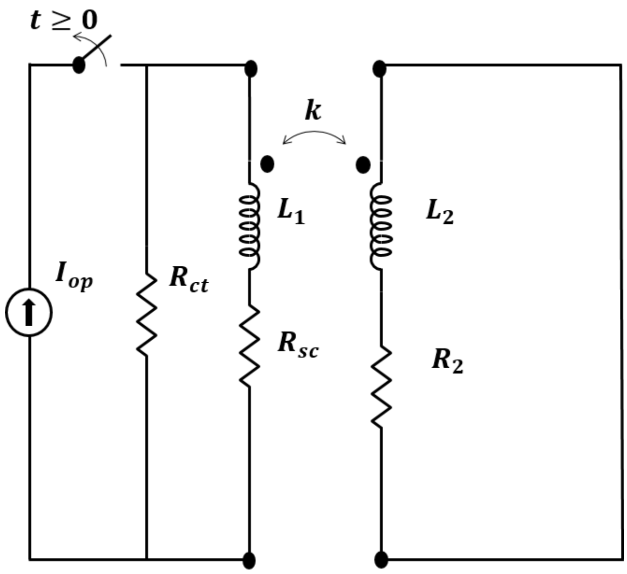
Since the first publication in 2011 [1], remarkable progress has been made in the no-insulation (NI) high temperature superconductor (HTS) winding technique [2–8]. Up to now, a number of NI HTS magnets have been designed, constructed, and successfully operated without experiencing burn-out upon quench [9–21], but mechanical damages in some high field NI HTS magnets due to large current during quench were reported. To precisely analyze the non-linear NI behaviors like this, a lot of numerical simulation approaches and analytic solutions have been reported [22–32]. In addition, we now propose a method which can analyze the stored energy transfer between electromagnetically coupled coils.

If most of the energy can be transferred to the outside of the NI HTS magnet, the damages due to the large current can be prevented. In this paper, we propose a coil coupled with the NI magnet which can absorb the energy. The energy transfer from one coil to the other is commonly observed during quench of an NI HTS magnet, but for the better understanding of the energy transfer between magnet and coil, analytic calculations were performed for an NI HTS double pancake coil whose key parameters were experimentally measured in National High Magnetic Field Laboratory (NHMFL) [33]. The analysis is performed in two steps: (1) Analytic equations are obtained assuming some conditions and using the well-known lumped parameter circuit model [34]. For analytic simplification, the coils have constant coil parameters, and the system is operated in isothermal condition (4.2K). (2) By the equations, approximate values of induced current, transferred power, and energy are calculated. According to these steps, the validity of the coil is verified. Finally, a virtual case of an electromagnetically coupled coil is presented and its performance is established.

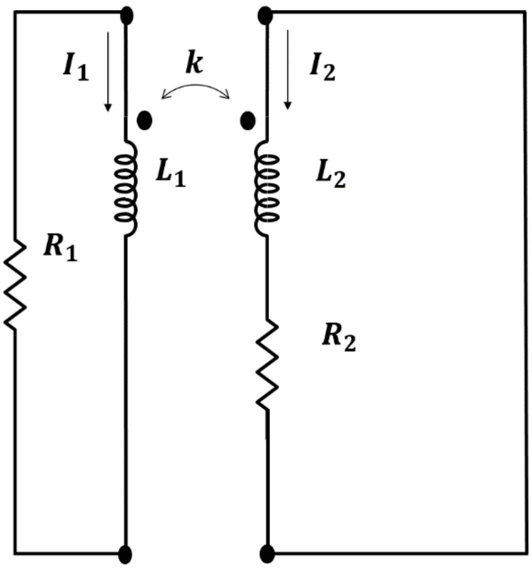
2. ENERGY TRANSFER BETWEEN COILS

In this part, the proper design condition to transfer energy is estimated analytically. For analytic simplification, all the circuit parameters are assumed to be constant. Fig. 1(a) shows an electric circuit of NI HTS double pancake coil with electromagnetically coupled copper coil using lumped-parameter circuit model, where I_{op}, R_{ct}, R_{sc}, and L_1 are operating current, contact resistance, superconductor resistance, and inductance. In fact, the index model is usually used to represent the superconductor resistance. In this analysis, because the parameters are assumed to be constant, and we are only interested in the transient state of the system after quench, the superconductor resistance is represented as the copper stabilizer resistance, R_{st}, when the current only flows through the copper stabilizer of HTS tape after quench. L_2 and R_2 are inductance and resistance of the copper coil. For calculating the transferred energy only from double pancake coil, not the current source, when quench occurs at $t = 0$, it is detected immediately, and the switch opens. By these assumptions, applying the Laplace transformation, transient state of the circuit after quench can be simply calculated. The circuit model of this system is represented in Fig. 1(b), where R_1 is sum of R_{ct} and R_{st}. By applying the Kirchhoff's voltage law, voltage relationships between the two closed loop currents are represented as (1) and (2):

* Corresponding author: hahnsy@snu.ac.kr



(a)



(b)

Fig. 1. (a) Electric circuit of NI HTS coil with electromagnetically coupled coil using lumped parameter circuit model and (b) disconnecting current source after quench detection.

$$L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} + i_1 R_1 = 0 \quad (1)$$
$$L_2 \frac{di_2}{dt} - M \frac{di_1}{dt} + i_2 R_2 = 0 \quad (2)$$

, where i_1, i_2, and M are double pancake coil current, coupled coil current, and mutual inductance between the coils. To analyze the currents of each coil in transient state, Laplace transformation is applied to (1) and (2):

$$sL_1 I_1 - L_1 i_1(0) - sMI_2 + I_1 R_1 = 0 \quad (3)$$
$$sL_2 I_2 + M i_1(0) - sMI_1 + I_2 R_2 = 0 \quad (4)$$

, where I_1, I_2, and $i_1(0)$ are double pancake coil current, coupled coil current at Laplace domain, and initial value ($t = 0$) of HTS coil current. From (3) and (4), I_1 and I_2 at Laplace domain can be represented as (5) and (6).

$$I_1(s) = \frac{i_1(0)(L_1 - M^2 s)}{(1-k^2)s^2 + (L_1 R_2 + L_2 R_1)s + R_1 R_2} \quad (5)$$
$$I_2(s) = \frac{i_1(0) M R_1}{(L_1 L_2 - M^2)s^2 + (L_1 R_2 + L_2 R_1)s + R_1 R_2} \quad (6)$$

If the two coils are close enough to each other, the magnetic coupling coefficient and mutual inductance can be represented as (7).

$$k \cong 1, \quad M \cong \sqrt{L_1 L_2} \quad (7)$$

Applying (7) to (6), The coupled coil current, I_2 can be represented as (8).

$$I_2(s) = \frac{i_1(0) M R_1}{(L_1 R_2 + L_2 R_1)s + R_1 R_2} \quad (8)$$

Applying inverse Laplace transformation to (8), the induced current after quench ($t \geq 0$) in coupled coil, $i_2(t)$ can be represented as (9).

$$i_2(t) = \frac{i_1(0) M R_1}{L_1 R_2 + L_2 R_1} e^{-\frac{R_1 R_2}{L_1 R_2 + L_2 R_1} t} \quad (t \geq 0) \quad (9)$$
$$i_{2,max} = \frac{i_1(0) M R_1}{L_1 R_2 + L_2 R_1} \quad (10)$$

By (9), the total consumed energy in copper coil can be calculated as (11):

$$\begin{aligned} E_{loss,R_2} &= \int_{t=0}^{\infty} i_2^2 R_2 dt \\ &= \left[-\frac{(i_1(0) M R_1)^2}{2(L_1 R_2 + L_2 R_1) R_1} e^{-\frac{2 R_1 R_2}{L_1 R_2 + L_2 R_1} t} \right]_0^{\infty} \\ &= \frac{(i_1(0) M R_1)^2}{2(L_1 R_2 + L_2 R_1) R_1} \\ &= \frac{L_1 i_1^2(0)}{2} \frac{1}{\frac{L_1 R_2}{L_2 R_1} + 1} \end{aligned} \quad (11)$$

, where E_{loss,R_2} is dissipated energy by Joule loss at the coupled coil resistance R_2. The time constant of dissipated energy, τ is represented as (12):

$$\tau = \frac{\frac{L_1}{R_1} + \frac{L_2}{R_2}}{2} \quad (12)$$

, which means that 63% of energy is dissipated in the coupled coil for τ s after quench. In (11), the transferred energy can be expressed as a product of the stored energy in HTS double pancake coil and a term related to time constants of two coils. This means that the amount of transferred energy is related to the time constant of the copper coil. When the time constant relationship between two coils is represented as (13), most of the stored energy can be transferred to the coupled coil.

$$\frac{L_1}{R_1} \ll \frac{L_2}{R_2} \quad (13)$$

For energy transfer to the coupled coil, the above condition should be satisfied.

TABLE I
COIL PARAMETERS.

Specifications		Value	
		NI HTS	Coupled
Winding		NI HTS	Copper
Winding dimension (Width, Thickness)	[mm]	4.1×0.12	2.7×0.27
Inner Diameter	[mm]	40	
Outer Diameter	[mm]	221.68	
Turns		757	1000
Inductance	[mH]	246	107
Mutual inductance	[mH]	139	
Coupling coefficient		0.85	
Copper resistance	[mΩ]	101.1	10.8
Contact resistance	[mΩ]	15.3	
Operating current	[A]	99.6	

3. CASE STUDY: AN NI HTS DOUBLE PANCAKE COIL

The above equations were applied on a coil coupled with an NI HTS double pancake coil which was used in 35-T REBCO magnet, and its performance was estimated in this section. The copper stabilizer thickness of HTS tape was assumed to be 1/4 of the total thickness. Its material properties were obtained, and all of the coil inductances were calculated from our in-house code which has been used in NHMFL. It was assumed that the superconductor resistance switches from the index model with the index value $n = 15$ to the stabilizer resistance when quench occurs. All quench behaviors were analyzed at isothermal condition, 4.2 K.

Table 1 presents the NI HTS double pancake and the coupled coil key parameters. The NI coils were wound with 4.1 mm REBCO tapes. ID, OD, turns, and operating current are 40 mm, 221.68 mm, 757 per pancake, and 99.6 A. The copper stabilizer resistance is 101.1 mΩ, and the contact resistance is calculated as 15.3 mΩ from measured characteristic resistance, 170 $\mu\Omega \cdot \mathrm{cm}^2$. The coupled coil is designed to satisfy the assumed condition (7) and the condition (13). For strong magnetic coupling, the coupled coil has the same ID and OD as the double pancake coil, and is located 1 mm above the double pancake coil. It was wound with a copper wire which has 0.27 mm thickness and 2.7 mm width. The turns and resistance are 1000 and 10.8 mΩ. The inductances of double pancake and coupled coil are 246 mH and 107 mH. The mutual inductance between the two coils is 139 mH. The coupling coefficient k is 0.85, can be assumed to be 1. The stored magnetic energy in double pancake coil is 1220 J.

4. RESULT AND DISCUSSION

The analytic equations between an NI HTS coil and copper coil upon a quench are obtained by using Laplace's transform with some assumptions: (1) the current source is disconnected right after the quench occurs ($t = 0$); (2) the two coils are close enough to each other. By the equations, the copper coil should have larger time constant than the NI HTS coil. This is applied to an NI double pancake coil case, and the transferred energy to the copper coil is calculated as 1006 J. About 82 % of stored energy can be transferred, and 63 % of the transferred energy is delivered for 6 s. During the quench, the maximum induced current is 105A, and its current density is calculated as 144 $\mathrm{A/mm^2}$. Because the coupling coefficient is assumed to be 1, the transferred energy may be overestimated. The copper resistance is kept low due to the isothermal condition, also. Because of this condition, the time constant of the copper coil and induced current become too large, and the current flows for a long time. Considering the change in copper resistance due to the heat, the current conduction time is much reduced, and the coupled coil can be prevented from electric burn-out. It means that the magnetically strongly coupled coil which has a larger time constant than the NI HTS coil can effectively prevent the over-current inducing and mechanical damages in NI HTS coil.

5. CONCLUSIONS

We studied the energy transfer between the NI HTS double pancake coil and an electromagnetically coupled coil. Using some assumptions, the equations about induced current, transferred energy, and transfer time can be obtained, and the conditions between coils for energy transfer were shown. Applying these conditions, a virtual case has been studied with a coil coupled with the NI HTS double pancake coil. By the analytic equations, the performance of the coupled coil was estimated. Finally, we obtained the magnetically coupled coil which can consume about 80% of the stored magnetic energy in the NI HTS coil.

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