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Quench simulation of SMES consisting of some superconducting coils

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Abstract

In recent years, many HTS superconducting magnetic energy storage (HTS-SMES) systems are investigated and designed. They usually consist of some superconducting element coils due to storing excessively high energy. If one of them was quenched, the storage energy of the superconducting element coil quenched has to be immediately dispersed to protect the HTS-SMES system. As the result, the current of the other element coils, which do not reach to quench, increases since the magnetic coupling between the quenched element coil and the others are excessively strong. The increase of the current may cause the quench of the other element coils. If the energy dispersion of the element coil quenched was failed, the other superconducting element coil would be quenched in series. Therefore, it is necessary to investigate the behavior of the

HTS-SMES after quenching one or more element coils. To protect a chain of quenches, it is also important to investigate the time constant of the coils. We have developed a simulation code to investigate the behavior of the HTS-SMES. By the quench simulation, it is indicated that a chain of quenches is caused by a quench of one element coil.

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Keywords: SMES; superconducting magnet; stability

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1. Introduction

In recent years, many HTS superconducting magnetic energy storage (HTS-SMES) systems have been investigated and designed [1-3]. They usually consist of some superconducting element coils due to efficiently storing energy. From the viewpoint of flux leakage, a toroid is an ideal structure [3]. Some optimal design methods for the toroidal HTS-SMES have been proposed to reduce the winding volume [4-5]. Moreover, the E - J characteristics depending on the orientation of the magnetic field applied to the HTS tape were taken into account. Thus, the design methods for the HTS-SMES magnet have been advanced. However, the behavior of the quench on the toroidal HTS-SMES has not been investigated on the design stage.

Employing the toroidal structure, the magnetic coupling between the superconducting element coils is so strong, and the magnetic leakage can be reduced. Therefore, if one of the superconducting element coils was quenched, the current of the element coil quenched would be immediately and drastically reduced to prevent the superconducting conductor from burning. As a result, the current of the other element coils, which do not reach to quench, increases according to the magnetic mutual inductance between the quenched coil and the others. The increase of the current may cause the quench of the other element coils. Therefore, even if one of the superconducting element coils reached to quench, the other superconducting element coils would be quenched in series. Therefore, it is important to investigate the behavior of the HTS-SMES after one element coil is quenched. To protect a chain of quenches,

it is also important to investigate the time constant of the decreasing current of the SMES. We have developed a simulation code to investigate the behavior of the HTS-SMES magnet after quenching one element coil. From the viewpoint of the stability of the SMES, it is important to investigate the condition causing the chain of quenches when the HTS-SMES consisting of some element coils are designed.

2. Simulation model

To investigate the chain of quenches, the toroidal HTS SMES magnets, which were designed in Ref. [3], are employed. The numbers of the superconducting element coils are 8, 12, 16, 18 and 24, the storage energy is 72 MJ and Table 1 shows the specifications of them. Fig. 1 shows the schematic view of the 12-toroidal SMES magnet, and Fig. 2 shows the external view of the 8, 12, 16, 18 and 24-toroidal SMES magnets. Here, the operating current I_{op} is 87.5% of the critical current I_c , the safety margin 12.5%. I_c is decided based on the maximum of the magnetic field and its orientation on HTS tape when the current I_{op} flows. In this paper, it is assumed that an element coil reaches to quench immediately after the transport current increases to the critical current. That is, if the operating currents of the other coils increased to 114.3% after quenching one element coil, they would also reach to quench in series. We call the phenomenon ‘a chain of quenches.’ Fig. 3 shows the electrical circuit considered in this paper. R_s is the shunt register, L_k is the self inductance of the k -th superconducting element coil, $M_{l,k}$ is the mutual inductance between the l -th and k -th superconducting

element coils. R_{nk} is the resistance of the k -th superconducting element coil in a normal state, and it is supposed that it appears immediately after the k -th superconducting element coil is quenched. It is also assumed that the temperature of k -th superconducting element coil drastically rises due to a thermal runaway, which is a peculiar phenomenon of HTS tape. When the k -th superconducting element coil is in a superconducting state, $R_{nk} = 0$. In this paper, the resistance of the element coil in the normal state is calculated from the silver resistance. The self and mutual inductances are computed from a numerical analysis, based on the Biot-Savart law. Table 2 shows the resistance of the element coil in the normal state, the self and the mutual inductances.

3. Quench simulation

The quench simulation is performed solving the following equations.

$$L \frac{dI_k}{dt} + \sum_{l=0}^{k-1} M_{k,l} \frac{dI_l}{dt} + \sum_{l=k+1}^{m-1} M_{k,l} \frac{dI_l}{dt} + (R_s + R_{nk}) I_k = R_s I, \quad (1)$$

$$\sum_{l=0}^{m-1} R_s I_l = m R_s I, \quad (2)$$

where m is the number of the superconducting element coils. In this paper, it is assumed that the 0th superconducting element coil wholly transitions into the normal state when $t = 0$, for simplicity, *e.g.* owing to an accident of the cryocooler. Before $t = 0$, the operating current shown in Table 1 flows in every superconducting element coil. When the current I_k of the k -th superconducting element coil increases to the critical

current I_c shown in Table 1, the k -th superconducting element coil transitions into the normal state, and then the normal resistance R_{nk} appears.

The simulation is done with various resistances of the shunt resistor, $R_s = 0.10, 0.50, 0.65, 0.70, 0.75, 1.00$ and 1.50Ω . Table 3 shows the occurrence of the chain of quenches, where the circle mark (o) represents no occurrence of the chain of quenches and the cross mark (x) represents the occurrence.

Figs. 4 and 5 show the coil current and the storage energy of the 8-toroidal SMES with $R_s = 0.10$ and 0.50 , respectively. Here, the current of the 0th to 4th superconducting element coils is plotted because of the symmetrical structure. In the case of $R_s = 0.10$, the current of the element coil next to the quenched element coil increases to the critical current, and then the chain of quenches occurs. On the other hands, in the case of $R_s = 0.50$, the current of the element coil next to the quenched element coil does not reach to the critical current.

Figs. 6 and 7 show the coil current and the storage energy of the 16-toroidal SMES with $R_s = 0.75$ and 1.00 , respectively. Figs. 8 and 9 also show the coil current and the storage energy of the 24-toroidal SMES with $R_s = 0.50$ and 0.65 , respectively.

4. Discussion

When one superconducting element coil transitions into the normal state by any cause, the current of the quenched element coil decreases immediately. However, it induces the current in the superconducting element coils next to the quenched one in

order to maintain the magnetic field since the mutual inductance is large. The current of the next element coils increases to the critical current. Eventually, the chain of the quenches occurs. The appearance of the chain of the quenches is shown from Figs. 4, 6 and 8.

As shown in Table 3, it is easy to occur the chain of quenches in the case of the 16-toroidal SMES. In the case of 8- or 24-toroidal SMES, the chain is difficult to be occurred. When the number of the superconducting element coils is smaller than 16, the current of the quenched element coil slowly decreases due to the long time constant caused by the large self inductance, as shown in Figs. 4 and 5. If the total current decreased before the current of the neighbor element coil reached to the critical current, the chain of the quenches would not occur.

On the other hand, when the number of the superconducting element coils is larger than 16, the SMES magnet has the enough current margin ($I_c - I_{op}$). Therefore, if the energy and the total current were immediately reduced with the shunt resistor before the induced current reached to the critical current, the neighboring element coil would not transition into the normal state.

The possibility of the chain of the quenches is indicated in this paper. The causes of the chain of the quenches are the short time constant of the decreasing current of the quenched element coil, the small current margin ($I_c - I_{op}$) and the small shunt resistance. To protect the chain of the quenches, the large current margin or the large

shunt resistance is required. Otherwise, it is required that the number of the superconducting element coils increases. As the number of the element coils increases, the self inductance of the element coil and the flux leakage decrease. As the result, the stability and the efficiency are also enhanced.

5. Conclusions

The HTS-SMES usually consists of some superconducting element coils due to storing excessively high energy. When one of them is quenched, the current of the neighbor element coils is induced due to the high mutual inductance. If the current of the neighbor element coils increased to the critical current, they would transition into the normal state. Therefore, the chain of the quenches occurs. The occurrence of the chain of the quenches is indicated using the simulation.

It becomes obvious that the causes of the chain of the quenches are the time constant, the current margin and the shunt resistance. To prevent from the chain of the quenches, it is required that the current margin is large or the shunt resistance is large. Moreover, it is required that the number of the superconducting element coils increases, consequently the critical current increases and the high current margin can be taken. As the result, the stability and the efficiency are also enhanced.

In near future, it is necessary to couple the magnetic field analysis and the circuit analysis to take into account the B - J - θ characteristic.

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Tables

Table 1. Specifications of the HTS-SMES designed in Ref. [3]

Table 2. Resistance, self and mutual inductance of each element coil

Table 3. Occurrence of chain of quenches

Figure captions

Fig. 1. The schematic view of the 12-toroidal HTS-SMES. The radius of the toroid, the inner radius, thickness, length of coil are also represented.

Fig. 2. The external view of the 8, 12, 16, 18 and 24-toroidal HTS-SMES designed in Ref. [3] with numbering the superconducting element coil.

Fig. 3. The electric circuit of the m -toroidal HTS-SMES system with the shunt resistors.

Fig. 4. The transitions of the coil current, the total current and the storage energy when one of 8 element coils transitions into the normal state at $t = 0$ and $R_s = 0.10 \, \Omega$.

Fig. 5. The transitions of the coil current, the total current and the storage energy when one of 8 element coils transitions into the normal state at $t = 0$ and $R_s = 0.50 \, \Omega$.

Fig. 6. The transitions of the coil current, the total current and the storage energy when one of 16 element coils transitions into the normal state at $t = 0$ and $R_s = 0.75 \, \Omega$.

Fig. 7. The transitions of the coil current, the total current and the storage energy when

one of 16 element coils transitions into the normal state at $t = 0$ and $R_s = 1.00 \Omega$.

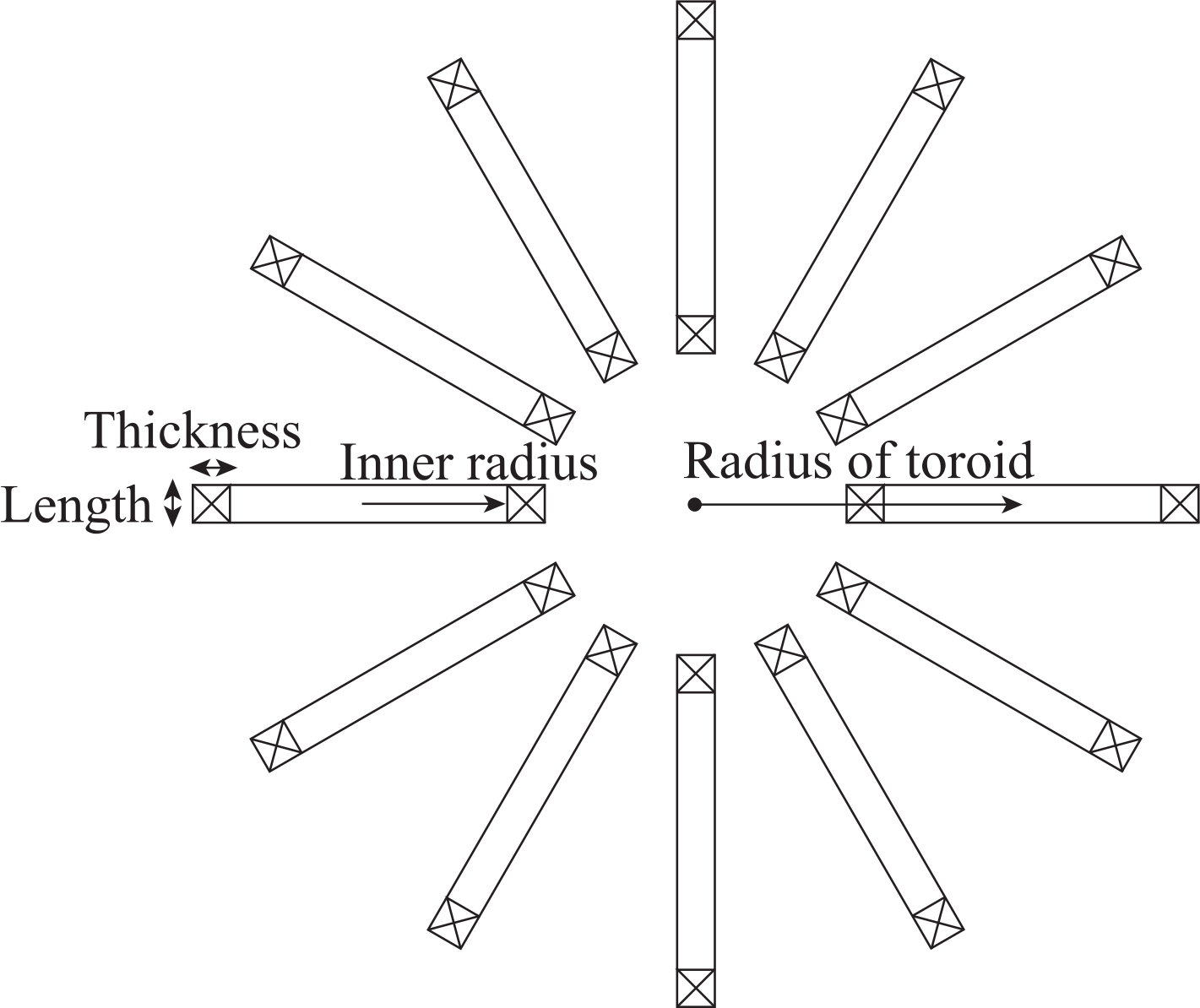
Fig. 8. The transitions of the coil current, the total current and the storage energy when one of 24 element coils transitions into the normal state at $t = 0$ and $R_s = 0.05 \Omega$.

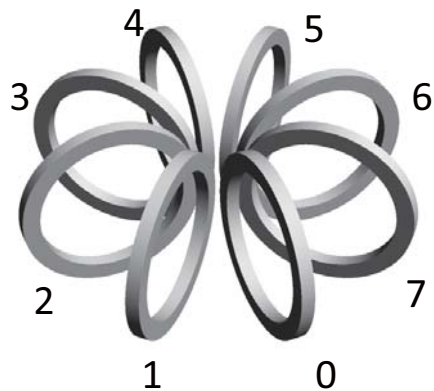
Fig. 9. The transitions of the coil current, the total current and the storage energy when one of 24 element coils transitions into the normal state at $t = 0$ and $R_s = 0.65 \Omega$.

Number of coils	8	12	16	18	24
Radius of toroid (m)	1.355	1.18	1.133	1.293	1.344
Inner radius of coil (m)	0.884	0.617	0.539	0.693	0.66
Thickness of coil (m)	0.209	0.319	0.297	0.154	0.132
Length of coil (m)	0.16	0.08	0.07	0.11	0.1
Operating current (kA)	6.23	7.15	7.54	7.58	8.04
Critical current (kA)	7.12	8.17	8.62	8.66	9.19
Total ampere turns	30.3	39.8	45.6	42	46.3
Storage energy (MJ)	72	72	72	72	72
Maximum magnetic field parallel to tape (T)	7.45	8.19	8.64	7.69	7.37
Maximum magnetic field perpendicular to	3.27	2.57	2.3	2.27	1.97
Winding volume (m ³)	1.662	1.494	1.437	1.475	1.445

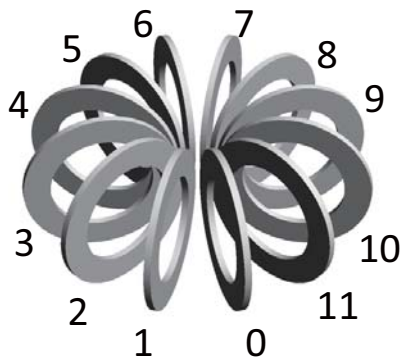
Number of coils	8	12	16	18	24
Resistance of normal coil R_n	6.26	3.84	2.77	2.53	1.86
Self inductance L (mH)	293.153	117.596	67.94	60.406	35.438
Mutual inductance $M_{0,1}$ (mH)	53.242	31.951	22.475	19.252	12.846
$M_{0,2}$ (mH)	17.706	12.529	9.736	8.466	6.121
$M_{0,3}$ (mH)	8.543	5.994	4.898	4.32	3.315
$M_{0,4}$ (mH)	6.522	3.421	2.768	2.448	1.949
$M_{0,5}$ (mH)		2.377	1.743	1.521	1.225
$M_{0,6}$ (mH)		2.09	1.229	1.034	0.818
$M_{0,7}$ (mH)			0.984	0.774	0.577
$M_{0,8}$ (mH)			0.912	0.645	0.43
$M_{0,9}$ (mH)				0.606	0.339
$M_{0,10}$ (mH)					0.285
$M_{0,11}$ (mH)					0.256
$M_{0,12}$ (mH)					0.246

Shunt (Ω)	resistor	Number of coils				
		8	12	16	18	24
0.10		x	x	x	x	x
0.50		o	x	x	x	x
0.65		o	x	x	x	o
0.70		o	x	x	o	o
0.75		o	o	x	o	o
1.00		o	o	o	o	o
1.50		o	o	o	o	o

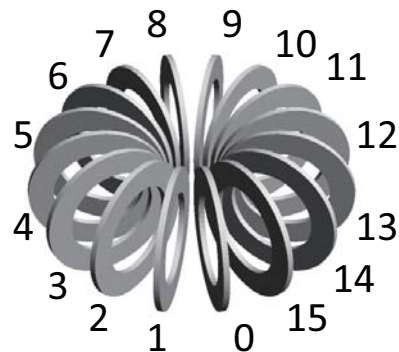




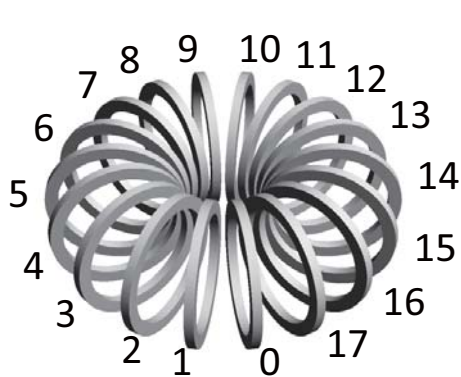
(a) 8-toridal magnet



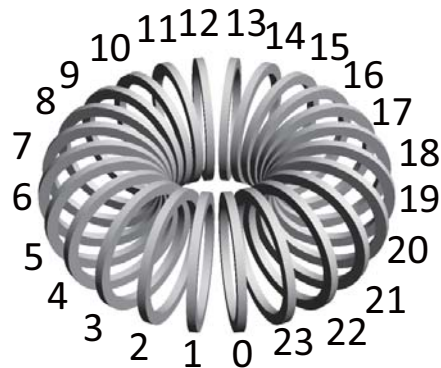
(b) 12-toridal magnet



(c) 16-toridal magnet



(d) 18-toridal magnet



(e) 24-toridal magnet

