Overturning Force Simulation on Chain of Quenches of Toroidal HTS-SMES

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***Abstract*—In recent years, many toroidal HTS-SMES consisting of some superconducting element coils have been investigated and designed. In stable operation, the electromagnetic force applying to the superconducting element coils maintains balance because of the toroid structure and the same transport current of each superconducting element coil. However, if one of the superconducting element coils transitioned into a resistive state, the balance of the electromagnetic force would be broken down, and then the huge electromagnetic force would work onto the superconducting element coils. The huge electromagnetic force may overturn the superconducting element coils, and consequently a large accident occurs. However, the behavior of the overturning electromagnetic force after the transition of some superconducting element coils into the resistive state has been not yet well investigated. For the design of the HTS-SMES magnet, it is, therefore, necessary to investigate the overturning electromagnetic force on the design stage. We have developed a simulation code to investigate the behavior of the overturning electromagnetic force on the toroidal HTS-SMES system after the transition of one superconducting element coil into the resistive state. The magnetic field and the circuit analysis are coupled and solved in the developed simulation code.**

***Index Terms*—Electromagnetic force, HTS-SMES, magnetic field simulation, superconducting magnet.**

I. Introduction

IN recent years, many high-temperature superconducting magnetic energy storage (HTS-SMES) systems have been investigated and designed in many countries [1]–[3]. Their structure is usually a toroid consisting of some superconducting element coils owing to storing excessively high energy. The toroidal structure has the advantages of a small flux leakage and a small magnetic field perpendicular to the HTS tape surface. So far some optimal design methods for the toroidal HTS-SMES magnet have been proposed to reduce the winding volume [4]. Moreover, recently, it was confirmed that there was a possibility that the chain of quenches occurs on the toroidal HTS-SMES magnet by the quench simulation [6]. Therefore, the behavior of unbalanced electromagnetic force during the chain of the quenches should be also investigated.

In stable operation, the electromagnetic force applying to the superconducting element coils maintains balance because of the toroid structure and the same transport current of each superconducting element coil. However, if one of the superconducting element coils transitions into the resistive state, the transport current in the resistive superconducting element coil has to be immediately reduced by the shunt resistor connecting in parallel to prevent the resistive HTS conductor from burning. As the result, the current of the other superconducting element coils is induced on account of the high mutual inductance. Consequently, the distribution of the magnetic field is changed due to the different current of each superconducting element coil. The changing high magnetic field and the large current result in a huge electromagnetic force exceeding a several MN onto the superconducting element coils. The huge electromagnetic force may overturn the superconducting element coils and then a large accident occurs. Moreover, when a few superconducting element coils successively transition into the resistive state in a short time, the superconducting element coils would strongly vibrate owing to the alteration of the electromagnetic force direction. As the result, the superconducting tapes might be seriously damaged.

When the HTS-SMES magnet consisting of some superconducting element coils is designed, it is very important to take account of the mechanical strength properties for the electromagnetic force to overturn the superconducting element coils from the viewpoint of safety. It is, therefore, necessary to investigate the overturning electromagnetic force on the design stage. We have developed a simulation code to investigate the behavior of the overturning electromagnetic force on the toroidal HTS-SMES system after the transition of one superconducting element coil into the resistive state. In the simulation, the magnetic field and the circuit analysis are coupled and solved.

II. Simulation HTS-SMES Model

The toroidal HTS-SMES magnets, which were used for investigating the chain of quenches, were optimizedly designed by the optimal design method in [3]. The coils are wound with YBCO tape, whose critical current is computed based on the percolation model [5]. The safety margin of the designed magnet is set to be 10% of the operating current. The numbers of the superconducting element coils are 8, 16, and 24, and the storage energy is 72 MJ. Table I shows the specifications of the designed HTS-SMES magnets. Fig. 1 shows the schematic view of the 8-troidal SMES magnet with the design variables, and Fig. 2 shows the external view of the 8-, 16- and 24-toroidal SMES magnet.

In this paper, it is assumed that one superconducting element

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TABLE I SPECIFICATIONS OF HTS-SMES MAGNET WOUND WITH YBCO TAPE

Number of coils	8	16	24
Radius of toroid (m)	1.139	1.221	1.307
Inner radius of coil (m)	0.619	0.634	0.456
Thickness of coil (m)	0.178	0.155	0.132
Length of coil (m)	0.113	0.062	0.072
Operating current (kA)	1.76	2.07	2.04
Winding volume (m^3)	0.714	0.683	0.748

TABLE II RESISTANCE, SELF AND MUTUAL INDUCTANCE OF SUPERCONDUCTING ELEMENT COIL.

Number of coils	8	16	24
Resistance of normal coil (Ω)	22.0	10.5	7.7
Self inductance L (mH)	4158.7	1056.8	697.3
Mutual inductance $M_{0,1}$ (mH)	567.4	279.7	194.5
$M_{0,2}$ (mH)	160.2	114.0	77.1
$M_{0,3}$ (mH)	70.7	55.1	36.3
$M_{0,4}$ (mH)	52.4	30.2	19.3
$M_{0,5}$ (mH)		18.7	11.3
$M_{0,6}$ (mH)		13.0	7.2
$M_{0,7}$ (mH)		10.3	4.9
$M_{0,8}$ (mH)		9.5	3.5
$M_{0,9}$ (mH)			2.7
$M_{0,10}$ (mH)			2.3
$M_{0,11}$ (mH)			2.0
$M_{0,12}$ (mH)			1.9

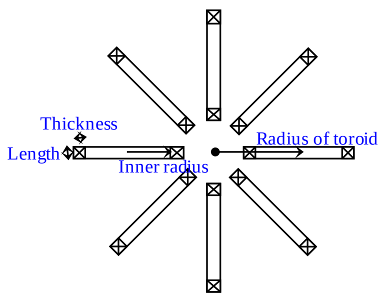

Fig. 1. The schematic view of 8-troidal HTS-SMES magnet with design variables, where are the inner radius, the length, the thickness, and the radius of toroid.

coil is quenched immediately after the transport current reaches to the critical current. That is, if the transport currents of some element coils reach to the critical current 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, L_k, $M_{l,k}$ are the shunt resistor, the self inductance of the kth superconducting element coil, and the mutual inductance between the lth and kth superconducting element coils, respectively. R_{nk} is the resistance of the kth superconducting element coil in a normal state, and it is supposed that it appears immediately after the kth superconducting element coil is quenched. It is also assumed that the temperature of kth superconducting element coil drastically rises due to a thermal runaway, which is a peculiar phenomenon of HTS tape. When the kth superconducting element coil is in superconducting state, R_{nk} = 0. In this paper, the resistance of the superconducting element coil in the normal state is calculated from the silver and the copper resistance. The self and the

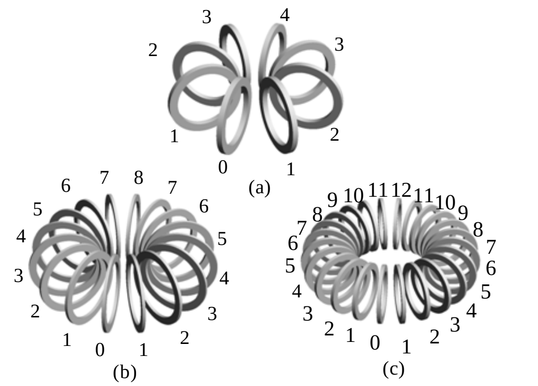

Fig. 2. The external view of the m-toroidal SMES coils with numbering the superconducting element coils. (a) 8-troidal magnet, (b) 16-toroidal magnet, and (c) 24-toroidal magnet.

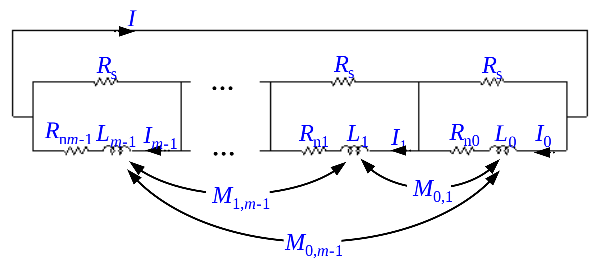

Fig. 3. The electrical circuit of the m-toroidal HTS-SMES system with the shunt resistors.

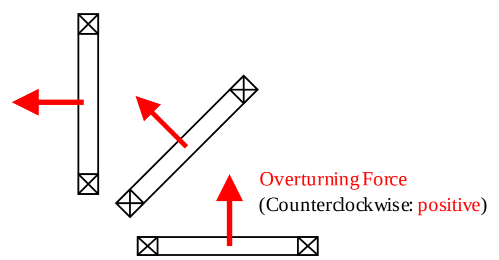

Fig. 4. The definition of the positive orientation of the overturning force on the numerical analysis.

mutual inductance are computed by a numerical analysis. Table II shows the resistance of the element coil in the normal state, the self and the mutual inductance.

III. SIMULATION METHOD

A. Electrical Circuit Analysis

The quench simulation is performed solving the following equations of the electrical circuit [6]:

$$L\frac{\mathrm{d}I_k}{\mathrm{d}t}+\sum_{l=0}^{k-1}M_{k,l}\frac{\mathrm{d}I_l}{\mathrm{d}t}+\left(R_s+R_{nk}\right)I_k=R_sI, \tag{1}$$

$$\sum_{l=0}^{m-1}R_sI_l=mR_sI, \tag{2}$$

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, by any reason. Before t = 0, the operating current

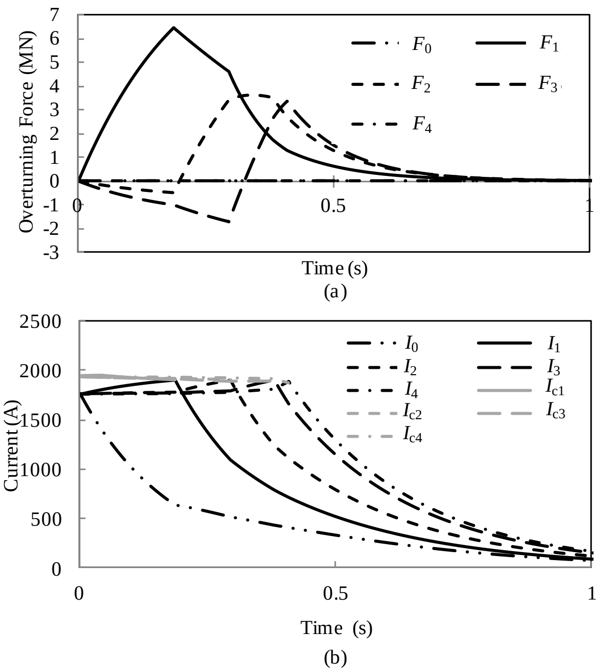

Fig. 5. The time transitions of (a) the overturning force F_k, (b) the coil current I_k and critical current I_{ck} of 8-toroidal HTS-SMES magnet during the chain of quenches after the 0th superconducting element coil transitions into the normal state at t = 0.

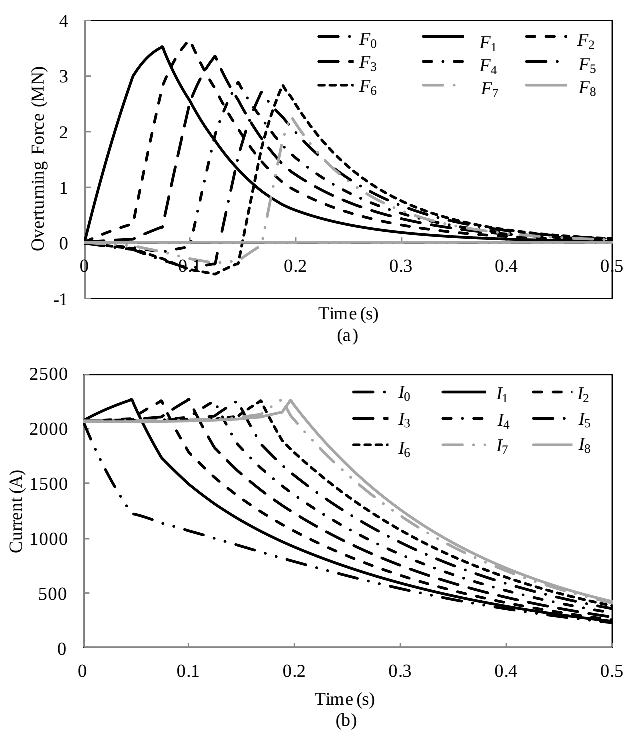

Fig. 6. The time transitions of (a) the overturning force F_k, (b) the coil current I_k and critical current I_{ck} of 16-toroidal HTS-SMES magnet during the chain of quenches after the 0th superconducting element coil transitions into the normal state at t = 0.

shown in Table I flows in every superconducting element coil. When the current I_k of the kth superconducting element coil increases to the critical current, the kth superconducting element coil transitions into the normal state, and then the normal resistance R_{nk} appears.

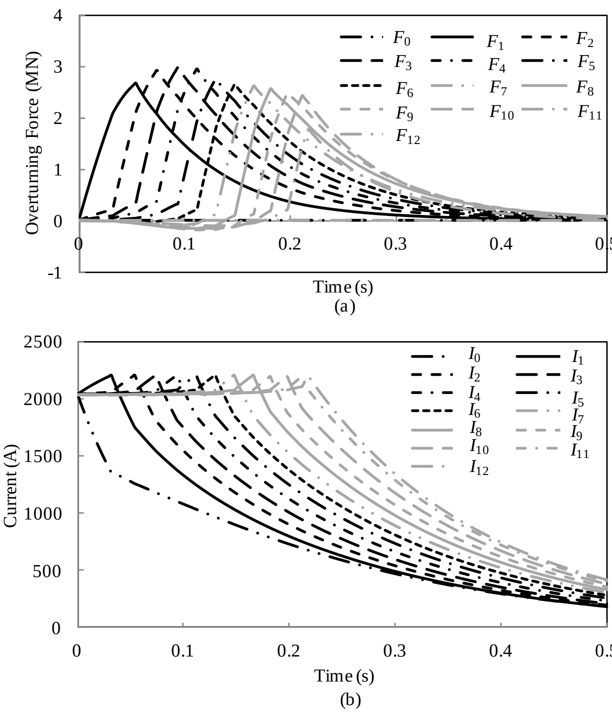

Fig. 7. The time transitions of (a) the overturning force F_k, (b) the coil current I_c and critical current I_{ck} of 24-toroidal HTS-SMES magnet during the chain of quenches after the 0th superconducting element coil transitions into the normal state at t = 0.

B. Magnetic Field Analysis

When the transport current in the superconducting element coils changes, the magnetic field applied to the YBCO tape also changes and then the critical current I_c changes according to the B–J–θ characteristics of YBCO tape [5]. Moreover, the distribution of the magnetic field is changed due to the different current of each superconducting element coil. The changed high magnetic field and the large current result in a huge electromagnetic force on the superconducting element coils. Therefore, it is necessary to compute the magnetic Field. The magnetic field is computed from a numerical analysis, based on the Biot-Savart law.

IV. Simulation Result & Discussion

We have investigated the behavior of the overturning forces on the toroidal HTS-SMES magnet with the shunt resistor R_s = 0.10 Ω during the chain of the quenches. Here, Fig. 4 indicates that the positive orientation of the overturning force is defined to be counterclockwise.

Fig. 5 shows the time transitions of the coil current, the critical current and the overturning force of the 8-toroidal HTS-SMES magnet. Figs. 6 and 7 also show the time transitions of the coil current and the overturning force of the 16- and 24-toroidal HTS-SMES magnet, respectively. Fig. 8 shows the distribution of the magnetic field when the overturning force of the 1st superconducting element coil reaches to its peak. Fig. 9 shows the distributions of the magnetic field on 24-toroidal HTS-SMES magnet when the overturning force of the 3rd, 5th, 7th, and 9th superconducting

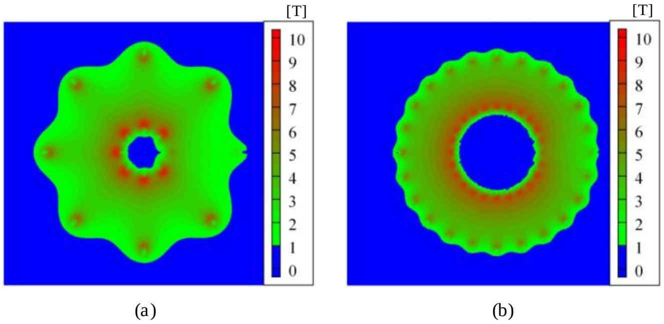

Fig. 8. The distribution of the magnetic field when the overturning force on the 1st superconducting element coil reaches to its peak. (a) 8-toroidal and (b) 24-toroidal HTS-SMES magnet.

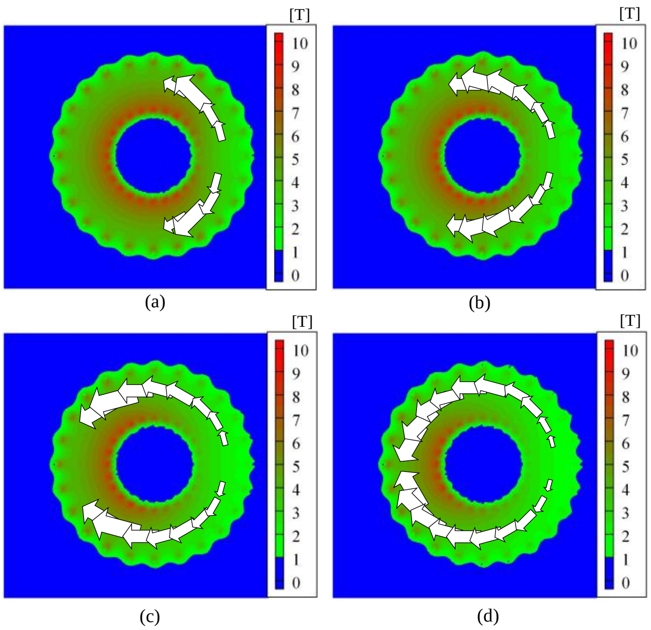

Fig. 9. The distribution of the magnetic field when the overturning force on (a) the 3rd, (b) 5th, (c) 7th, and (d) 9th superconducting element coil of 24-toroidal HTS-SMES magnet reaches to its peak, respectively. The arrows denote the overturning force on superconducting element coils.

element coil reaches to its peak, respectively.

When one of superconducting element coils reached to quench, the transport current in the quenched superconducting element coil is immediately reduced by the shunt resistor connecting in parallel to prevent the quenched HTS conductor from burning. As the result, the current of the other superconducting element coils is induced on account of the high mutual inductance. Consequently, the distribution of the magnetic field is changed due to the different current of each superconducting element coil as shown in Figs. 8 and 9. The changing high magnetic field and the large current result in a huge electromagnetic force exceeding a several MN on the superconducting element coils. As shown in Figs. 5, 6, and 7 the maximum of overturning force in the case of 8-, 16-, and 24-toroidal HTS-SMES magnet are 6.5, 3.7, and 3.0 MN, respectively. As shown in Fig. 8, when the number of the superconducting elements coils is small, the distribution of the magnetic field easily becomes largely imbalance after one superconducting element coil is quenched, and then the radial component of the magnetic field applying on the superconducting element coil also increases easily. For that reason, the maximum of overturning force is large when the number of the superconducting element coils is small.

When the superconducting element coils are successively quenched in a short time, the superconducting element coils would vibrate owing to the alteration of the electromagnetic force direction, as shown in Figs. 5, 6, and 7. As the result, the superconducting tapes or the superconducting element coils might be seriously damaged.

It becomes obvious that the strength of the overturning force is influenced by the number of the superconducting element coils. To weaken the electromagnetic force such as overturning force, the large number of the superconducting element should be adopted.

V. Conclusion

In the electromagnetic simulation, the behavior of the overturning forces on the toroidal HTS-SMES magnet after the transition of one superconducting element coil into the resistive state was investigated.

In the stable operation, the electromagnetic force applying to the superconducting element coils maintains its balance because of the toroid structure and the same transport current of each superconducting element coil. However, if one of superconducting element coils reached to quench, the huge overturning force appears on the superconducting element coils. Moreover, when the superconducting element coils are successively quenched in a short time, the superconducting element coils would strongly vibrate owing to the alteration of the electromagnetic force direction. As the result, the superconducting tapes or the superconducting element coil might be seriously damaged. For the design of the toroidal HTS-SMES magnet, it is necessary to investigate the overturning electromagnetic force on the design stage.

When the HTS-SMES consisting of some element coils with balancing the electromagnetic force is designed, it is very important to take account of the mechanical strength properties for electromagnetic force overturning the superconducting element coils from the viewpoint of safety.

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