Title	Overturning Force Simulation on Normal-State Transition of Toroidal HTS-SMES Taking Into Account an Electromagnetic and Thermal Condition
Author(s)	Noguchi, So; Itoh, Ryusei; Oga, Yuki; Igarashi, Hajime
Citation	IEEE Transactions on Applied Superconductivity, 24(3), 5700304 https://doi.org/10.1109/TASC.2013.2286008
Issue Date	2014-06
Doc URL	http://hdl.handle.net/2115/56585
Rights	© 2014 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.
Type	article (author version)
File Information	TAS24-3 Overturning Force.pdf

[Instructions for use](#)

Overturning Force Simulation on Normal-State Transition of Toroidal HTS-SMES Taking into Account an Electromagnetic and Thermal Condition

So Noguchi, *Member, IEEE*, Ryusei Itoh, *Student Member, IEEE*, Yuki Oga, Hajime Igarashi, *Member, IEEE*

Abstract—Recently, many investigations about toroidal high-temperature superconducting magnetic energy storage systems have been reported. Some papers reported that there was a possibility that the chain of normal-state transitions occurred on the toroidal HTS-SMES magnet by normal-state-transition simulation. Hence, it should also be investigated that the behavior of unbalanced electromagnetic force during the sequential normal-state transition of the superconducting coil elements. In this paper, we have developed a simulation code to investigate the behavior of the overturning electromagnetic force on the toroidal HTS-SMES system during the normal-state transition. The magnetic field and the circuit analysis were coupled and solved in the previously developed simulation code. Additionally, in order to investigate the normal-state transition more accurately, we also take the thermal analysis into account. Carrying out the newly developed numerical simulation, we investigate the time transition of the transport current, the overturning force, and the magnetic field applied to the superconducting coil elements for a few toroidal HTS-SMESs.

Index Terms—Electromagnetic force, HTS-SMES, thermal analysis, superconducting magnet.

I. INTRODUCTION

ENERGY PROBLEM is one of the most important problems over all the world. Renewable energy, such as wind generator and photovoltaics, has been developed and introduced to power lines. However the renewable energy is faced on an energy storage with a large capacity. The one of the solution is a superconducting magnetic energy storage (SMES).

Recently, various kinds of high-temperature SMES (HTS-SMES) systems have been investigated [1]–[5]. The advantages of HTS-SMES systems are a quick response and a large capacity, whereas it is necessary to solve the problems about cooling condition [3], stability [4], stress [5], and so on. An ideal configuration of the HTS-SMES is a toroid composed by many superconducting coils [1], [2]. The merits of the toroidal structure are a low flux leakage and a low magnetic field perpendicular to the HTS tape surface which lessens a critical current of the HTS tape. The normal-state-transition simulation reveals the possibility that the chain of

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

Number of coils	12	16
Radius of toroid [m]	1.143	1.221
Inner radius of coil [m]	0.465	0.634
Thickness of coil [m]	0.162	0.155
Length of coil [m]	0.113	0.062
Operating current I [kA]	1.79	2.07
Winding volume [m ³]	0.754	0.683

TABLE II
SELF- AND MUTUAL-INDUCTANCE OF SUPERCONDUCTING COIL ELEMENT

Number of coils		12	16
Self-inductance [mH]	L	2447.7	1056.8
	$M_{0,1}$	410.2	279.7
	$M_{0,2}$	118.5	114.0
	$M_{0,3}$	47.2	55.1
	$M_{0,4}$	24.1	30.2
	$M_{0,5}$	15.7	18.7
	$M_{0,6}$	13.5	13.0
	$M_{0,7}$	-	10.3
Mutual-inductance [mH]	$M_{0,8}$	-	9.5

normal-state transitions occur on the toroidal HTS magnet [6]. Hence, the behavior of an overturning force during the chain of normal-state transitions should also be investigated in detail.

The HTS-SMES is rotationally symmetrical and the transport current is identical on every superconducting coil (SC) element, subsequently the overall electromagnetic force applying to the HTS-SMES is balanced in the stable operation. However, when one of the SC elements transitions to the normal state, the transport current of the normal-state-transitioned SC element is immediately reduced by a shunt resistor connecting in parallel to avoid it burnout [6], [7]. The SC element has a high mutual inductance so that the current is induced in the other SC elements. Consequently, the magnetic field applying to the SC elements is changed due to the different current intensity of every SC elements, and then the electromagnetic force becomes unbalanced. There is a possibility that a critical accident follows.

We have previously investigated the overturning force in the chain of normal-state transitions by a simulation based on

Manuscript received July 16, 2013.

The authors are with the Graduate School of Information Science and Technology, Hokkaido University, Kita 14 Nishi 9, Kita-ku, Sapporo 060-0814, Japan (phone: +81-11-706-7671; fax: +81-11-706-7670; e-mail: noguchi@ssi.ist.hokudai.ac.jp).

Fig. 1. The electrical circuit of the m -toroidal HTS-SMES system with the shunt resistance.

a magnetic field analysis and an electrical circuit analysis [8]. The thermal behavior was not considered in [8]. However, it becomes obvious that the thermal behavior affects the behavior of the overturning force during the chain of normal-state transitions [9]. Therefore, we coupled the thermal analysis with the previously developed electromagnetic and circuit simulation. In this paper, in order to investigate the time transient of the overturning electromagnetic force during the chain of normal-state transitions more accuracy, we develop the algorithm to consider the thermal behavior of the SC elements.

II. TOROIDAL HTS-SMES SIMULATION MODEL

In the simulation, the HTS-SMES magnets, whose configuration was optimized by the optimal design method in [2], were used for investigation of the overturning forces. The critical current of the YBCO tape is dependent on the direction and intensity of the magnetic flux density. Moreover, it is also dependent on the temperature. Therefore, it is calculated based on percolation model [10] taking into account the magnetic flux density and the temperature. The conditions of the designed toroidal HTS-SMES are the storage energy of 72 MJ, 12- and 16-toroidal SC elements, and the safety margin of 10%. Table I and II show the specifications of the designed toroidal HTS-SMES magnet. Please refer to [9] in order to know more detail.

III. SIMULATION METHOD

In order to investigate the time transition of the overturning electromagnetic force, it is necessary to figure out the phenomenon precisely. Hence, we have newly developed the simulation code coupled the electrical circuit and magnetic field analysis with the thermal analysis.

A. Electrical Circuit and Magnetic Field Analysis

Fig. 1 shows the electrical circuit of the toroidal HTS-SMES system, where the SC elements are connected in series and the shunt resistors are in parallel with them. A normal-state-transition simulation is carried out by solving the following equations:

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

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

Fig. 2. Time transition of the coil current I_k (solid line) and the critical current I_{ck} (dashed line) of 12-toroidal HTS-SMES magnet with the safety margin 10% ($I_c/I=0.9I_c$). The critical current I_{ck} changes according to the magnetic field applying to the HTS tape and the temperature of the HTS tape.

Fig. 3. Time transition of the overturning force F_k of 12-toroidal HTS-SMES magnet during the chain of normal-state transitions.

where m , M , R_s , $R_n(\mathbf{B}, T)$, I_k , and I are the number of the SC elements, the mutual-inductance ($M_{k,l} = L$ when $l = k$, where L is the self-inductance), the shunt resistance, the HTS wire resistance that is dependent on the magnetic flux density $\mathbf{B}$ and the temperature T , the current of k th SC element, and the total operating current of HTS-SMES, respectively. The shunt resistor R_s is 3.0Ω in the circuit simulation. When the current I_k of the k th SC element increases, the resistance $R_{nk}(\mathbf{B}, T)$ gradually increases based on the E - J characteristics. Here, the relationship between the resistance R_n and the resistivity ρ is the following equation:

$$R_n(\mathbf{B}, T) = \sum_{e=1}^u \frac{\rho_e(\mathbf{B}, T) l_e}{S_e} \quad (3)$$

where u is the number of the finite elements in the thermal finite element analysis mentioned below, l_e and S_e are the length and area of e th finite element, respectively. $\rho_e(\mathbf{B}, T)$ is calculated by taking into account the magnetic flux density $\mathbf{B}$ and the temperature T of the SC element based on the percolation model that is obtained by experiment [10].

When the transport current in the SC elements varies, the magnetic field applied to the YBCO tape also varies and then the critical current I_c varies according to the B - J - θ characteristics of YBCO tape. Therefore, the magnetic flux density $\mathbf{B}$ applied to the YBCO tape is calculated by the Biot-

Fig. 4. Time transition of the magnetic field applied to the superconducting coil elements of 12-toroidal HTS-SMES when the overturning force on (a) the 1st, (b) 3rd, (c) 4th, and (d) 5th superconducting coil elements reaches to its peak, respectively.

Savart law.

B. Thermal Analysis

When the transport current becomes relatively large at a local point, the resistivity appears according to the percolation model, and then a Joule heat is generated at the point. The resistivity of the SC element is dependent on not only the magnetic flux density but also the temperature. Hence, it is necessary to consider the diffusion of the heat for the accurate analysis. The thermal analysis is carried out by solving the following thermal diffusion equation:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(\lambda_{rr} r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left(\lambda_{\phi\phi} \frac{\partial T}{\partial \phi} \right) + \frac{\partial}{\partial z} \left(\lambda_{zz} \frac{\partial T}{\partial z} \right) + Q_j + Q_c + Q_i = C \frac{\partial T}{\partial t} \quad (4)$$

where Q_j , Q_c , Q_i , λ , and C are the quantity of the Joule heat, the cooling heat, the initial heat, the thermal conductivity, and the heat capacity, respectively. The Joule heat Q_j is calculated based on the current density and the electrical resistivity ($Q_j = j^2 \rho$). The SC elements are assumed to be cooled by conduction-cooling of the cooling heat Q_c on the outer periphery of the coils. The thermal diffusion is simulated with the finite element method.

IV. SIMULATION RESULTS AND DISCUSSION

A. Simulation results

In the simulation, the initial temperature of all the SC elements is 20 K. An initial heat density of $Q_i = 10^{11} \text{ W/m}^3$ is applied to a certain point of the 0th SC element from $t = 0$ to

0.2 ms. Figs. 2 and 3 show the time transition of the SC currents I_k , the critical currents I_{ck} , and the overturning forces F_k of the 12-toroidal HTS-SMES magnet as the result of the simulation with the thermal analysis. Here, the positive direction of the overturning force is defined as counterclockwise.

When one of the SC elements is transitioned into the normal state, the SC current in the normal-state-transitioned SC element is immediately reduced by the shunt register connecting in parallel to avoid the normal-state-transitioned HTS coil from burning. When the current of a SC element is attenuated, the current of the neighbor SC elements is induced. In Fig. 2, the 0th SC element begins transitioning into the normal state at approximately 2 ms, and the current of the neighboring 1th SC element increases. The chain of the normal-state transitions occurs as shown in Fig. 2. With the advance of the chain of the normal-state transitions, the magnetic field becomes unbalanced so that the large overturning force appears as shown Fig. 3.

Fig. 4 shows the time transition of the magnetic field applied to the SC elements. Fig. 4 (a) shows the magnetic field distribution when the overturning force on 1st SC element reaches to its peak, and the maximum applied magnetic field is 9.173 T. During the chain of the normal-state transitions, the magnetic field intensity slightly increases, finally the maximum magnetic field becomes 9.301 T. The large magnetic field is applied to the SC element and the large overturning force is also applied to the SC elements.

Fig. 5 shows the overturning forces of the 16-toroidal HTS-SMES. The chain of the normal-state transitions of 16-toroidal HTS-SMES finishes in shorter time than that of the 12-

Fig. 5. Time transition of the overturning force F_k of 16-toroidal HTS-SMES magnet during the chain of normal-state transitions.

Fig. 6. Time transition of the overturning force F_k of 16-toroidal HTS-SMES magnet during the chain of normal-state transitions after the 0th superconducting coil element completely transitions into the normal state at $t=0$ without thermal analysis.

toroidal one. It is the reason why the self- and mutual-inductances of the 16-toroidal HTS-SMES are smaller than those of the 12-toroidal one.

B. Comparison between with and without Thermal Analysis

Fig. 6 shows the overturning forces of the 16-toroidal HTS-SMES without thermal analysis [11]. Comparing the simulation results of Figs. 5 and 6, the behavior of the overturning forces clearly differs. In the simulation coupled with the thermal analysis as shown in Fig. 5, the normal-state transition of all the SC elements finishes in approximately 0.028 s whereas 0.5 s without thermal analysis as shown in Fig. 6. The normal-state transitions of Fig. 5 sequentially occur more quickly than those without considering the thermal behavior. In addition, the overturning force with the thermal analysis is approximately 4.8 times greater than that without thermal analysis. For these results, it is proved that it is necessary to evaluate the overturning force with the thermal diffusion behavior in the simulation.

V. CONCLUSION

We have investigated the unbalanced overturning force of the toroidal HTS-SMES during the chain of the normal-state transitions using the developed simulation code taking into account the electromagnetic and electric circuit behavior as well as the thermal behavior. In the stable operation, the

electromagnetic force applied to the SC elements keeps balance because of the toroid structure. However, when one of SC elements transitions to the normal state, the large overturning force appears on the SC elements.

In additions, the overturning force with consideration of the thermal behavior analysis is approximately 4.8 times greater than that without the thermal behavior consideration. The chain of the normal-state transitions with consideration of the thermal behavior finished approximately 17.9 times faster than that without the thermal behavior. In order to investigate the behavior of the overturning force that occurs during the chain of normal-transitions in detail, the thermal analysis has to be performed with the magnetic and electrical circuit analysis.

REFERENCES

- [1] K. Higashikawa, T. Nakamura, K. Shinkimachi, N. Hirano, S. Nagaya, T. Kiss, and M. Inoue, "Conceptual design of HTS coil for SMES using YBCO coated conductor," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 1990-1993, Jun. 2007.
- [2] S. Noguchi, A. Ishiyama, S. Akita, H. Kasahara, Y. Tatsuta, and S. Kouso, "An optimal configuration design method for HTS-SMES coils," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 1927-1930, Jun. 2005.
- [3] Y. Hong, H. Yeom, S. Park, S. Kim, and Y. Choi, "Temperature distribution of cryogenic conduction cooling system for a HTS SMES," *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 745-749, 2008.
- [4] A. Kim, S. Kim, K. Kim, J. Kim, S. Kim, M. Park, I. Yu, S. Lee, M. Sohn, H. Kim, J. Bae, and K. Seong, "Performance analysis of a toroid-type HTS SMES adopted for frequency stabilization," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1367-1370, 2011.
- [5] K. Kim, S. Lee, S. Kim, M. Park, I. Yu, J. Lee, S. Lee, K. Choi, K. Seong, and H. Yeom, "Stress analysis for toroid-type HTS SMES coil and bobbin structure considering large parallel magnetic field," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 2275-2278, 2011.
- [6] A. Ishiyama and H. Asai, "A stability criterion for cryocooler-cooled HTS coils," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 1832-1835, 2001.
- [7] H. Kojima, N. Hayawaka, S. Noguchi, F. Endo, N. Hirano, S. Nagaya, and H. Okubo, "Thermal runaway characteristics of Bi2223 coil for conduction-cooled SMES," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 1959-1962, Jun. 2007.
- [8] Y. Oga, S. Noguchi, and H. Igarashi, "Simulation of chain of quenches on toroidal HTS-SMES taking account of B - J - θ characteristics," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4701604, Jun. 2012.
- [9] Y. Oga, S. Noguchi, and H. Igarashi, "Normal transition simulation on toroidal HTS-SMES considering electromagnetic and thermal characteristics," *IEEE Trans. Supercond.*, vol. 23, no. 3, p. 4700505, Jun. 2013.
- [10] K. Yamafuji and T. Kiss, "A new interpolation of the glass-liquid transition of pinned fluxoids in high- T_c superconductors," *Physica C*, vol. 258, nos. 3&4, pp. 197-212, Feb. 1996.
- [11] Y. Oga, S. Noguchi, and H. Igarashi, "Overturning force simulation on chain of quenches of toroidal HTS-SMES," *IEEE Trans. Supercond.*, vol. 22, no. 3, p. 4701904, Jun. 2012.