Integrated Study and Optimization of HTS SMES Based on Circuit and Magnetic Field Analysis

Xiao Y. Chen[1], Jian X. Jin[1], Ying Xin[2], You G. Guo[3], and Jian G. Zhu[3]
[1]Center of Applied Superconductivity and Electrical Engineering, University of Electronic Science and Technology of China
[2]Innopower Superconductor Cable Co., Ltd, China
[3]Faculty of Engineering and Information Technology, University of Technology Sydney, Australia
E-mail jxjin@uestc.edu.cn, chenxy@uestc.edu.cn, yingxin@innopower.com, joe@eng.uts.eud.au, youguang@eng.uts.edu.au

Abstract — This work proposes an integrated superconducting magnetic energy storage (SMES) simulation and optimization model based on the circuit and magnetic field analysis, which covers three main coupling factors, i.e., electromagnetic force, AC loss and critical current in a high temperature superconducting (HTS) coil. A SMES case study using COMSOL is carried out, and the simulation results are obtained from the proposed model.

I. INTRODUCTION

Currently the worldwide theoretical and experimental studies of superconducting magnetic energy storage (SMES) ~~devices~~ mainly focus on the interactive influences between the SMES and power grids, especially in distributed generation (DG) systems and Micro Grids (MG), which lead to several attractive functions, e.g., power compensation, frequency regulation, harmonic suppression, etc. The essence of the above functions rely on the controlled charge, storage and discharge processes in a SMES device. The coil current variation will influence the surrounding magnetic field, and then result in the change of electromagnetic force, AC loss and critical current.

Research works considering the above three factors have been carried out for simulation and optimization designs of ~~in~~ superconducting coils [1-3], however there is no integrated theoretical model which covers all three coupling factors together with dynamic circuit analysis. This work [4] proposes to develop an integrated SMES model based on the circuit and magnetic field analysis and to provide a method to link superconductivity technology to power electronics in a SMES device.

II. THE INFLUENCE OF CIRCUIT AND MAGNETIC FIELD ON J_C

The basic SMES circuit shown in Fig. 1 mainly includes charging voltage source U, HTS coils L, load R, diodes D_1, D_2, power switches K_1, K_2, and superconducting persistent current switch (SPCS) K_3. It has three fundamental operation states: charge, storage and discharge state.

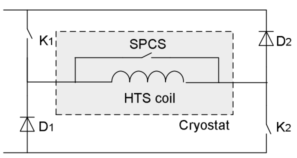

Fig. 1. The circuit model of a SMES device

The critical current density J_c of the HTS coil in a SMES device is mainly determined by the surrounding magnetic field B, operating temperature T, electromagnetic force F_e. The time-varying magnetic field caused by the operation current of the HTS coil will directly or indirectly influence J_c, as shown in Fig. 2: i) the amplitude and orientation of the surrounding magnetic field change J_c directly because of the anisotropy of HTS tapes; ii) the F_e distributions change J_c indirectly and even destroy HTS coil structure; iii) the HTS coil AC loss Q_{ac} may influence the operation temperature in several subregions and then change J_c indirectly.

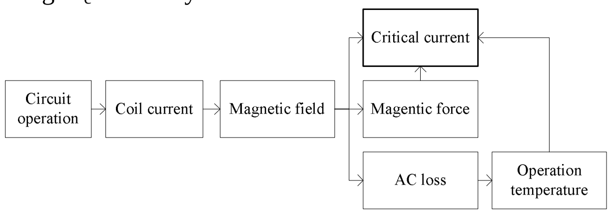

Fig. 2. The influence of time-varying magnetic field on J_c

III. CIRCUIT AND MAGNETIC ANALYSIS OF A SMES DEVICE

In the energy-charge state, the current of the HTS coil $I(t)$ can be expressed by

$$I(t) = \frac{U}{L}t + I_0 \tag{1}$$

In the energy-storage state, the HTS coil and SPCS form a close circuit in the cryostat, the current of the HTS coil can be seem to remain undamped. In the energy-discharge state, the current of the HTS coil $I(t)$ drops with a time-varying discharge power $P_1(t)$ and can be expressed by

$$I(t) = \sqrt{I_0^2 - \frac{2}{L}\int_0^t P_1(t)dt} \tag{2}$$

Assume that $P_1(t) = P_1 = I_1^2 R$, then the HTS coil is discharged with a constant power P_1 in time period t_s, which is defined as the constant-power discharge time when $I(t{=}t_s) = I_1$, and discharged with a decreased power in the residual discharge process. The current of the HTS coil $I(t)$ in the whole discharge process can be expressed by [4]

$$I(t) = \begin{cases} \sqrt{I_0^2 - \frac{2}{L}P_1 t}, & t \le t_s \\ I_0 \exp(-\frac{Rt}{L}), & t > t_s \end{cases} \tag{3}$$

The radial component of magnetic flux density $B_r(t)$ and the axial component $B_z(t)$ at a random location $P(r,z)$ around the HTS solenoid coils can be expressed by

$$\begin{bmatrix} B_r(t) \\ B_z(t) \end{bmatrix} = \frac{\mu_0 I(t)}{2\pi r\sqrt{(a+r)^2+z^2}} \times \begin{bmatrix} \frac{a^2+r^2+z^2}{(a-r)^2+z^2}Ez - Kz \\ \frac{a^2-r^2-z^2}{(a-r)^2+z^2}E + K \end{bmatrix} \tag{4}$$

IV. CALCULATIONS OF DIFFERENT COUPLING FACTORS

A. The Calculation of J_c in the HTS Coils

The J_c of the HTS coils as functions of voltage across the HTS coils, E, operation temperature, T, surrounding magnetic flux density, B, and its direction, θ, can be expressed by [5]

$$J_c = J_{cm}(T, B_r(B,\phi)) + (\frac{m+1}{\rho_{FF}} E J_0 (T, B_r(B,\phi))^m)^{m+1} \quad (5)$$

for $B_r \le B_g$

$$J_c = |J_{cm}(T, B_r(B,\phi))| + (\frac{m+1}{\rho_{FF}} E J_0 (T, B(B,\phi))^m + |J_{cm}(T, B_r(B,\phi))|^{m+1})^{m+1}, \text{for } B_r > B_g \quad (6)$$

B. The Calculation of F_e in the HTS Coils

When the operating current circulates in the HTS coils, HTS coils experience electromagnetic force which causes instability and deformation of the HTS tapes. Therefore, it is important to consider the mechanical forces on HTS coils caused by electromagnetic force. The radial stress σ_r and hoop stress σ_h in HTS coils can be calculated by [6]

$$r\frac{\partial \sigma_r}{\partial r} + \sigma_r - \sigma_h + rJ(r)B(r) = 0 \quad (7)$$

C. The Calculation of Q_{ac} in the HTS Coils

Although SMES is not a AC devices, time-varying current and magnetic field during the charge and discharge periods will generate AC losses and cause the degradation of J_c, even result in thermal instability in the HTS coils. The magnetization losses can be calculated by [7]

$$Q_{ac} = \frac{2B_m^2}{\mu_0}\frac{\pi\omega}{2\beta d}(\frac{2}{\beta}\ln(\cosh\beta) - \tanh\beta) \quad (8)$$

V. A SMES CASE STUDY

The Center of Applied Superconductivity and Electrical Engineering (CASEE) with the collaboration of Innopower Superconductor Cable Co., Ltd, has developed a 0.2 H Bi-2223 coil in 2009, as shown in Fig. 3. The main parameters are as follows: inner diameter - 136 mm; outer diameter - 161.2 mm; height - 483 mm; No. of turns - 3×748; critical current - 60 A (77K, self-field).

Fig. 3. The 0.2H HTS coil developed by Innopower and CASEE

The designed operation current of the 0.2 H Bi-2223 coil is 200 A. Assume that the charging power U = 2 V, the initial charging time t = 20 s according to (1). When the operation current reaches 200 A and keeps a time period of 10 s. After that, The Bi-2223 coil is discharged with $P_1 = U_1 I_1$ = 10V × 20A = 200 W. The current of the Bi-2223 coil will drop according to (3). The change of the current in the charge, storage and discharge process is shown in Fig. 4.

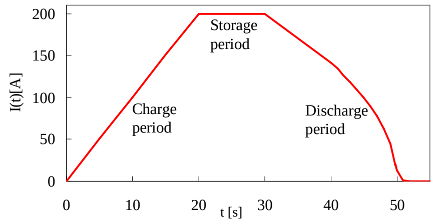

Fig. 4. The change of $I(t)$ in the charge, storage and discharge process

The magnetic field distribution of the 0.2H / 200A Bi-2223 coil based on COMSOL software is shown in Fig. 5. The radial magnetic flux density B_r along the surface of the Bi-2223 coil is shown in Fig. 6. The maximum B_r value at 200 A is 1.72 T, as shown in Fig. 7. A two-stage G-M cryocooler is applied to cool the Bi-2223 coil and the designed operation temperature should be 20 K.

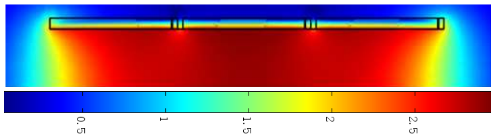

Fig. 5. The magnetic field distribution of the 0.2H/200A coil

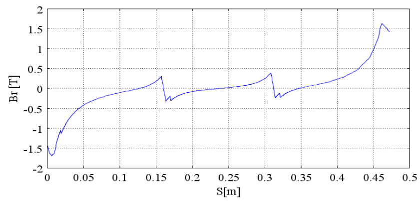

Fig. 6. B_r along the surface of the 0.2H/200A coil

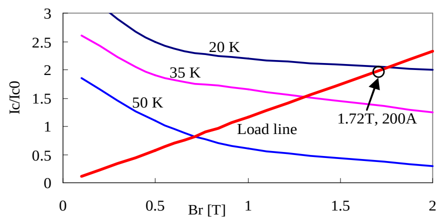

Fig. 7. The load line of the HTS coils and I_c/I_{c0} vs. B_r

VI. REFERENCES

[1] S. Stavrev, *et al.*, "Comparison of Numerical Methods for Modeling of Superconductors," *IEEE Trans. on Mag.*, vol. 38, no. 2, pp. 849-852, March 2002.

[2] K. Higashikawa, *et al.*, "Coupled analysis method for high-field magnet coil using coated conductor based on *J-E* characteristics as a function of temperature, magnetic field vector and mechanical strain," *IEEE Trans. on Appl. Supercond.*, vol. 19, no. 3, pp. 1621-1625, June 2009.

[3] I. O. Golosnoy, and J. K. Sykulski, "Efficient numerical modeling of field diffusion in high-temperature superconducting wires," *IEEE Trans. on Mag.*, vol. 46, no. 8, pp. 3173-3176, Augest 2002.

[4] J. X. Jin, *et al.*, "Theoretical modeling and simulation of magnetic energy storage system," *Proceedings of 29th Chinese Control Conference*, pp. 4894-4898, July 29-31, 2010.

[5] K. Higashikawa, *et al.*, "Anisotropic distributions of current density and electric field in Bi-2223/Ag coil with consideration of multifilamentary structure," *Physica C*, vol. 419, pp. 129-140, 2005.

[6] M. J. Park, *et al.*, "Stress analysis of HTS magnet for a 600 kJ SMES," *IEEE Trans. on Appl. Supercond.*, vol. 17, no. 2, pp. 1994-1997, June 2007.

[7] E. H. Brandt, and M. Indenbom, "Type-II super-conductor strip with current in a perpendicular magnetic field," *Physical Review B*, vol. 48, pp. 12893-12906, November 1993.