Induced Voltage and Alternating Current Loss in Superconducting Magnet System for SSTF

Q.L. Wang, S. Baang, C. S. Yoon, S.B. Kim, H.K. Park, M.K. Kim, Y.J. Kim, S. I. Lee, K. Kim

***Abstract*—The induced voltage in the Samsung Superconducting Test Facility (SSTF) is analyzed according to the calculation of self-inductance and mutual inductance. The voltage induced by blip and compensating coils in the main coils is about 6.4 V. In order to charge the main coils, the power supply must provide the minimum voltage of 1.1 kV. The compensating coils have an influence on the field distribution. The compensating coils result in the decreasing center field about 2.67%. AC losses that include the coupling, hysteresis and eddy losses are calculated in the main, blip and compensating coils. It leads to the temperature rise of about 8 K in main coils.**

***Index Terms*—CICC, Test facility, Induced voltage, AC losses.**

I. Introduction

Samsung Superconducting Test Facility (SSTF) is being constructed at SAIT(Samsung Advanced Institute of Technology). The main purpose of the facility is testing the superconducting magnets and CICC (Cable-In-Conduit Conductor) for the KSTAR device. All three kinds of cables -one for toroidal field (TF) coils and two (Nb_3Sn and NbTi) for poloidal field (PF) coils - will be tested in the form of short sample, model coils as well as full-scale coils. SSTF will also be used to test cable-to-cable joints and insulators for LHe connection [1].

The blip coils system is employed to provide fast electromagnetic disturbances to short CICC samples for the test of CICC. The system consisting of blip coils and main coils, where blip coils are located in the bore of the main coils, behaves like a transformer. Due to the rapid change of the magnetic flux, a high voltage will be induced in the power supply of the main coils. On the other hand, the change of the magnetic flux will also introduce the large AC losses, which may cause the magnet to quench. Thus, it is required that the ramping of the blip coils system should induce nearly zero voltage in the main coils. Therefore, the blip coils system should consist of blip coils and compensating coils [2]. The compensating coils need to be charged or discharged simultaneously with the blip coils, but the direction of the axial magnetic field is opposite to the direction of field generated by blip coils. In the article, the induced voltage, AC losses and temperature rise are analyzed by the calculation of field and quasi-three-dimensional thermal hydraulic analysis according to the present design parameters.

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Qiuliang Wang, Sungkeun Baang, Sangbo Kim, Hyunki Park, Myungkyu Kim, Yongjin Kim, Sangil Lee, and Keeman Kim are with the Samsung Advanced Institute of Technology 103-5Moonji-dong, Yusong-gu, Taejon-305-380, Korea (telephone: 82-42-865-4401, e-mail: qlwang @venus.sait.samsung.co.kr).

C.S.Yoon is with the Hannam University, Taejon 306-791 Korea (telephone: 82-42-629-8283, e-mail: csyoon@mail.hannam.ac.kr)

II. Compensating Method of Induced Voltage

There are two designs to compensate the induced voltage in the main coils. One is the compensating coils are located between the main coils and blip coils so that the mutual inductance between the blip coils system and the main coils is close to zero. The other design coaxially locates the compensating coils to the blip coils, with its radius the same. In our work, the second method is employed [3].

III. Calculation on Induced Voltage in SSTF

We assume two superconducting solenoids with turns of N_1 and N_2, currents of I_1 and I_2 respectively, are coaxially arranged. The real winding of the solenoid coil is a rectangular cross-section. The regular structure of the first coil is replaced by the current rings of $N_{a1} \times N_{b1}$ with infinite thin fictitious filament, which N_{a1} is the number of layers and N_{b1} is the number of turns. On the basis of the structure, the winding structure forming the coils with uniform distribution current density can be assumed. Because the magnetic flux is coupled by all fictitious turns of the coil replacing the winding of the real coil, the mutual inductance of two solenoid coils with the same axis with the number of N_1 and N_2 turns can be calculated as follows

$$M = \sum_{i=1}^{Na2} \sum_{j=1}^{N_{b2}} 2\pi r_{ij} \frac{N_2}{N_{a2}N_{b2}} \sum_{m=1}^{N_{a1}} \sum_{n=1}^{N_{b1}} \frac{N_1}{N_{a1}N_{b1}} \frac{\mu}{\kappa\pi} \sqrt{\frac{a_{mn}}{r_{ij}}} \left[\left(1 - \frac{1}{2}\kappa^2\right) K(\kappa) - E(\kappa) \right] \quad (1)$$

where $K(\kappa)$ and $E(\kappa)$ are the complete elliptic integration of first and second kind with argument $\kappa^2 = 4a_{mn}r_{ij} / \left[\left(a_{mn}^2 + r_{ij}^2\right)^2 + \left(z_{ij} - b_{mn}\right)^2 \right]$. a_{mn} and b_{mn} are the filament coordinate of radius and axis and r_{ij} is the radius coordinate. Finally, the self inductance of superconducting solenoid is defined as an overall magnetic flux generated by the current of I =1 A and coupled by all turns of the winding.

The basic parameters and structure of SSTF are listed in Table I and the configuration is shown in Fig. 1. For the operating current at the maximum of 22.38 kA, the maximum field of 10.477 T in the system is located at r=0.175 m and z =0.38 m. The maximum magnetic field in the main coils is 9.71 T. The transfer function of the main coils is 3.57×10^{-4} T/A. The blip and compensating coils are located inside of the main coils. They operate with the same current but in the opposite direction. The transfer function of blip coils and

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compensating coils is 1.42×10^{-4} T/A. The self-inductances of each coil are calculated and listed in Table II. The total mutual inductance and self-inductance of main coils are calculated as a superposition of self-inductance and mutual inductance of all individual section. For the main coils, the total self-inductance is $L = L_1 + L_2 + 2M_{12} = 132(\text{mH})$.

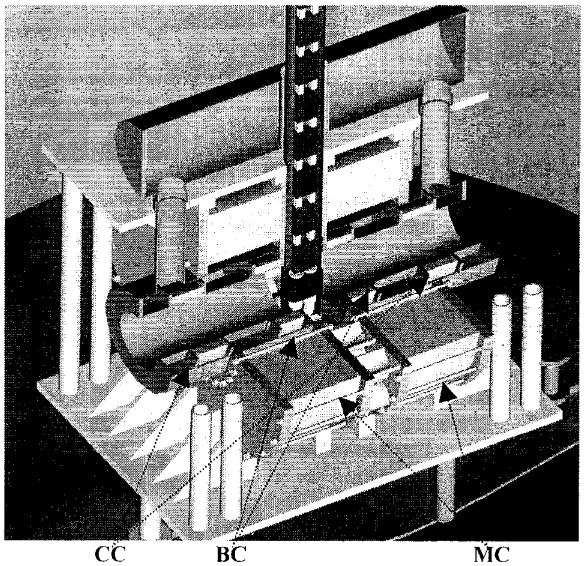

Fig. 1 Configuration of Samsung Superconducting Test Facility (1, 2-Main coils-MC, 5,6 -compensating coils-CC.3,4-blip coils-BC).

TABLE I
PARAMETERS OF BLIPS, COMPENSATING COILS AND SUPERCONDUCTING MAIN COILS SYSTEM

Parameter	Unit	BC	CC	MC
Inner diameter	mm	352	352	740
Outer diameter	mm	448	448	1457
Height	mm	132	165	382.4
Number of turns		72	90	240
Number of turns		12	15	25
Operating current	kA	+7.0	−7.0	22.38

TABLE II
INDUCTANCE MATRIX OF SSTF (Unit : mH)

	No.1	No.2	No.3	No.4	No.5	No.6
1	52.614	13.32196	2.33383	0.9728	2.72702	0.5567
2		52.6139	0.97283	2.3338	0.55668	2.7270
3			2.24079	0.1716	0.36574	0.0542
4				2.2408	0.05420	0.3657
5					3.19096	0.0253
6						3.1910

The requirement to charge or discharge the main coils up to *dB/dt* = 3 T/s ramp rate results in an expensive and high voltage/current power supply. The maximum operating current of 22.38 kA for the main coils must be provided by the power supply. The maximum induced voltage for the self-inductance is determined as $V_{max} = -LdI/dt = -1.1067$kV. The blip coils, which are located in the bore of the main coils, are strongly coupled to the main coils. In the design, the changing rate of magnetic field in the blip coils is 20 T/s and the coils must generate magnetic field of 1 Tesla at the center of system. Therefore, the current ramp rate is 140 kA/s. If the compensating coils are absent, the blip coils induce a voltage on the current leads of the main coils of $V_{ps} = -M_{BKG-BC}\frac{dI_{BC}}{dt} = -0.927$ kV. The total induced voltage on the power supply is about 2.033 kV. If compensating coils are used, the induced voltage of blip coils and compensating coils is calculated by the total mutual inductance coefficient on the basis of Fig. 1. The total induced voltage between the main coils and compensated blip coils is $V_{ps} = -MdI/dt = -6.4316\ V$. According to this calculation, the induced voltage can be remarkably decreased in the main coils from 927 V to 6.43 V when the coupling is compensated.

IV. Influence of Compensating Coils on Field of SSTF

The decrease of the mutual inductance between the blip, compensating coils and main coils causes a decrease of the magnetic field in the working space of the SSTF magnet system. Fig. 2 shows the magnetic field distribution along the axial direction of magnet system with and without the compensation coils. The magnetic field is decreased to 2.67% when the compensating coils are used.

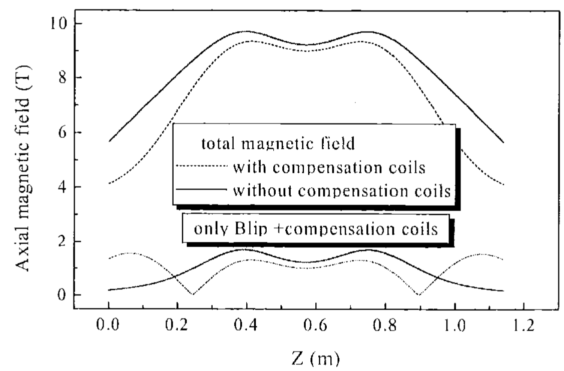

Fig. 2 Magnetic field distribution with compensation coils and without compensation coils in the axis of SSTF.

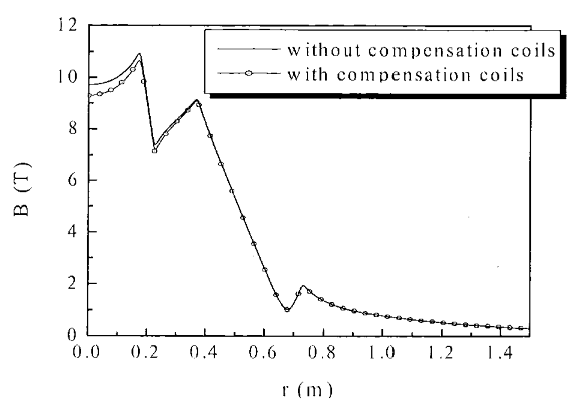

Fig. 3 Magnetic field distribution of SSTF background magnet system along the R-direction for z = 0.38 m, with and without compensation coils.

Fig. 3 shows the magnetic field distribution along the radial direction of the main coils with and without the compensating coils. They decrease the stray field in the main coils and outer space. The spatial magnetic field ($\boldsymbol{B}$) distribution for the overall SSTF is shown in Fig. 4.

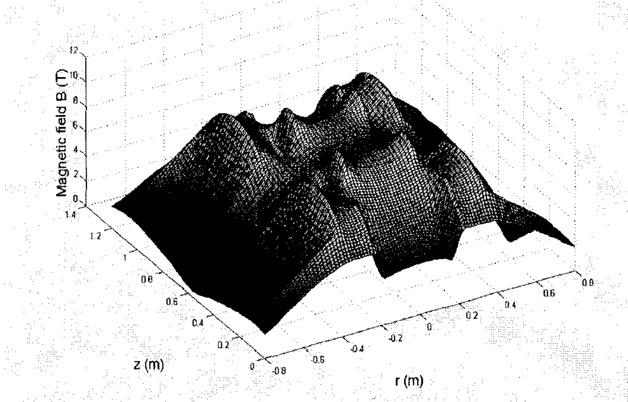

Fig. 4 Overall magnetic field ($\boldsymbol{B}$) distribution for SSTF with operating current 22.38 kA in the background magnets.

V. AC LOSSES AND TEMPERATURE RISE IN SSTF

The high current multi-strands superconducting conductors used in SSTF are subjected to a high pulsed field. The twisted superconducting strands are not insulated, but they are surrounded by the high resistance chrome layer. The high field and current ramping rate can induce large energy losses. The AC losses in hard composite superconductors, which usually consist of many cabled sub-cables, strands and filaments, can be divided into several constituents: hysteresis losses, coupling losses, and eddy losses in the pure strands. All these AC losses contribute to the total energy deposition in the magnet. Also, the AC losses strongly depend on the space distribution of field.

1) Hysteresis losses in superconducting filaments. When a pulse field which is over the penetration field $B_p = \frac{\mu_0 j_c}{\pi} d_{eff}$, where j_C and d_{eff} are the critical current density and effect filament diameter, penetrates from the outside of a round superconducting filament, it reaches to the center of filament. If the external field sweep is larger than B_p and the transport current in the superconducting strands is I_{tr}, the hysteresis loss is equal to

$$Q_{hys} = \frac{2}{3\pi} J_c d_{eff} \left(1 + \frac{I_{tr}^2}{I_c^2} \right) \frac{dB}{dt} A_{non\_cu} \text{ (W/m)} \qquad (4)$$

where I_C is the critical current of the superconducting strands, $A_{non\text{-}cu}$ is the non copper cross-sectional area. In superconducting strands for the SSTF the penetration field is in the range of 10 to 200 mT. It is much lower than the operating field of 8 T. While the field direction is changed, the field may be much lower than its penetration field, and a reasonable estimate of hysteresis loss is

$$Q_{hys} = \frac{B^2}{6\mu_0 B_p} \frac{dB}{dt} \left(1 - \frac{B}{4B_p} \right) A_{non\_Cu} \quad \text{(W/m)} \qquad (5)$$

2) Coupling losses in superconducting strands. Coupling losses is due to eddy currents circulating between superconducting filaments which generates Joule heating in composite strands. Coupling losses in the superconducting strands depends on the filament twist L_p and transverse resistivity of superconducting strands. Based on the coupling time constant of single superconducting strands, the coupling losses in the superconducting strands are:

$$Q_{cp} = \frac{n\tau_{cp}}{\mu_0} \left(\frac{dB}{dt} \right) A_{st} \quad \text{(W/m)} \qquad (6)$$

where n is equal to 2. A_{st} is the cross-sectional area of superconducting strands. The current induced by the pulsed field among superconducting strands also leads to the coupling losses in the multi-stage cable. The coupling time constant depends on the twist pitch of the cable and the transverse resistivity. The total coupling time constant $n\,\tau_{cp}$ of N stage cable is estimated as $(\tau_{cp})_{total} = \sum_{i=1}^{N} (\tau_{cp})_i$, each of them is associated with the contribution of each stage of cabling to the total AC losses [4]. i=1 means the superconducting strands itself.

3) Eddy losses in the pure copper strands. In the multi-stage cable, the pure copper strands are contained. The eddy losses are calculated as follows

$$Q_{eddy} = \frac{R_{st}^2}{4\eta_{cu}} \left(\frac{dB}{dt} \right)^2 A_{pure-Cu} \quad \text{(W/m)} \qquad (7)$$

where R_{st} is the radius of pure strands radius, $A_{pure\text{-}cu}$ is the pure copper area.

4) Eddy losses in the conduit. The eddy current losses in the conduit due to the transverse field is

$$Q_{eddy} = \frac{1}{12\rho_{ss}} \left(w_o^3 h_o - w_i^3 h_i \right) \left(\frac{\partial B}{\partial t} \right)^2 \quad \text{(W/m)} \qquad (8)$$

where w_o, h_o denote the outer dimension of conduit. w_i, h_i are inner dimension of the conduit. ρ_{ss} is the resistivity of stainless steel conduit.

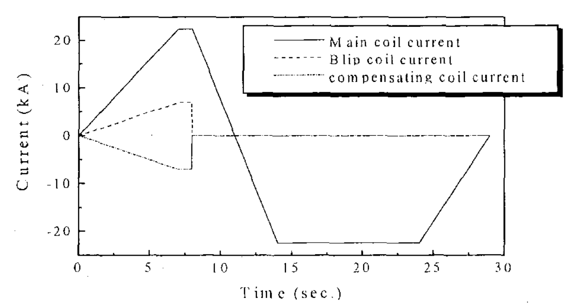

Fig. 5 Operating current versus time in SSTF system.

To simulate a possible test sequence on superconducting magnets (PF and TF) and a full-scale CICC sample, the current of the coils versus time is shown in Fig.5 [1]. The AC losses for the main, blip and compensating coils that include all total losses are illustrated in Fig. 6. From Fig. 6 (a), the coupling loss in the main coils is much higher than hysteresis loss, but for the blips and compensating coils, the hysteresis loss is larger than the coupling loss (as shown in Fig.6 (b)).

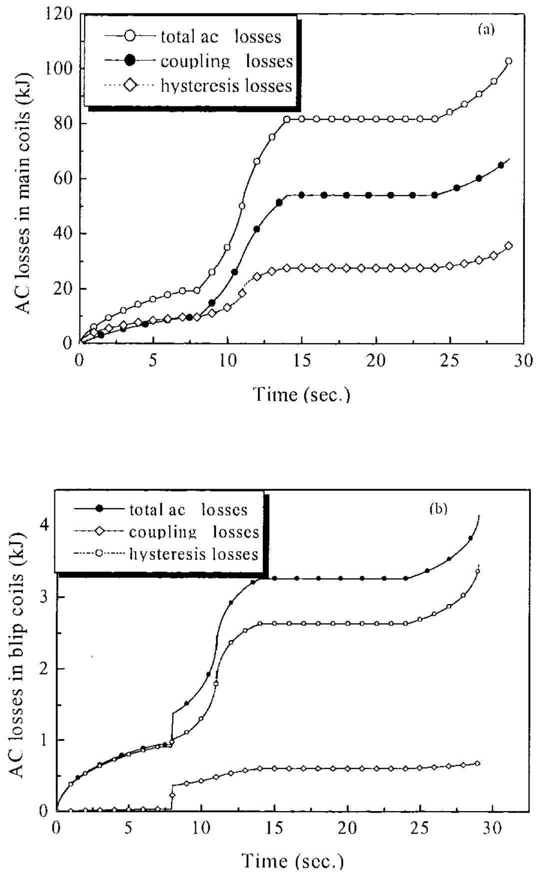

Fig. 6 AC losses in SSTF of the operating current shown in Fig.5.

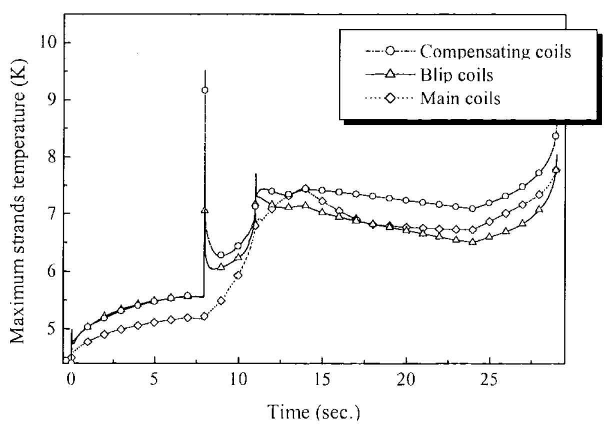

Fig. 7 Temperature rise in SSTF for inlet and outlet pressures of 0.6 and 0.3 MPa and inlet temperature of 4.5 K for main coils and 4.4 K for the blip and compensating coils.

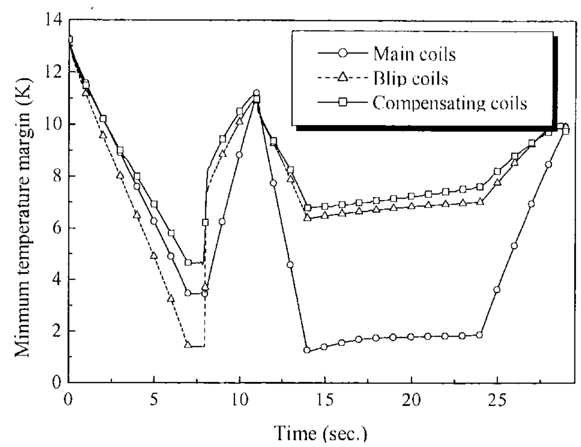

Fig. 8 Temperature margin in SSTF for operating condition for the system as Fig.7.

This is because that the cable of main coils has a long coupling time constant $n\tau$= 60 ms at field of 0 T. By contrast, the twist pitch length of the cable used in the blip and compensating coils is 0.375 times that of the cable used in the main coils, i.e. the time constant of cable is equal to $(0.375)^2$ $n\tau$. In addition, the effective filament diameter of the cable used in the blip and compensating coils is increased to 2.69 times that of the cable used in the main coils.

The temperature rise due to the AC losses is simulated by a-quasi-three-dimensional model to solve the mass, momentum and energy equations [4]. The maximum temperatures for the each magnet versus time are illustrated in Fig. 7. A sharp temperature rise due to the fast discharging of blip coils occurs in the blip and compensating coils. The temperature margin for the SSTF is shown in Fig. 8.

VI. Conclusions

The induced voltage of SSTF superconducting background magnet system is analyzed. The compensation coils can remarkably decrease the mutual coupling between the blip coils and superconducting background magnet. The coupling losses are the main energy deposition in SSTF system. Due to the fast discharging SSTF, there exists a noticeable peak temperature rise in the strands of blip and compensating coils.

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