Calculation of Temperature Variation Effects on AC losses in HTS coils

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We calculated the effect of the ambient temperature variations on the AC losses in high temperature superconducting (HTS) coils. In case of a short sample of an HTS tape, the magnetization loss at the lower temperature could be higher than the one at the higher temperature when it transports the same current. It happens above certain magnetic field. We calculated the AC losses of solenoidal coils with the various dimensions. They were categorized by the aspect ratios. The rated operating current that was set about 70 % of the critical current. We also calculated the temperature variations effect for the real HTS machine with the data from the solenoidal models. Three types of superconducting magnetic energy storages were adopted for the calculation of the effect.

***Index Terms*—AC loss, High temperature superconducting (HTS) coil, Superconducting magnetic energy storage (SMES), Temperature dependency.**

I. Introduction

HIGH TEMPERATURE SUPERCONDUCTING (HTS) MACHINES have wider range of operating temperature than the conventional low temperature superconducting (LTS) ones do. The HTS power cable and HTS transformer are normally operating between 65 K and 77 K. In case of superconducting magnetic energy storage (SMES), the cryogen-free HTS magnets can be used. They are normally operating below 20 K, or in liquid He for the tests. [1], [2].

Though lowering the operating temperature needs more cooling power, we can get higher performances. The increased critical current, I_c, by the low temperature provides more margin for the load factor and so makes the system more stable. We might expect less AC losses due to the increased I_c.

In some ways it is true below certain magnetic field, but the AC losses at the lower temperature could be even larger beyond a certain magnetic field than the losses at the higher temperature. Fig. 1 shows the magnetization losses by the magnetic flux densities of an HTS tape at 4.2 K and 77 K. The loss at 4.2 K becomes larger beyond 181.5 mT of external AC magnetic field in this case.

We calculated the AC losses of HTS solenoids with various aspect ratios at 65 K and 77 K. Most solenoids except very thin ones have larger AC losses at 65 K when the conducting AC currents are same as the rated current of 77 K at both temperatures. It is a well-known phenomenon.

For the real applications, several types of superconducting magnetic energy storages (SMES) were adopted for the analysis. Two of them were composed of solenoids and had the capacities of 600 kJ and 5 MJ, respectively [3], [4]. The other one had toroidal structure and its capacity was 2.5 MJ [5].

Their temperature dependency of AC losses was calculated in this paper. The losses were calculated at the operating temperatures of 4.2 K, 14 K, and 20 K. Two kinds of magnetic field variations during the operations were supposed for the loss calculations. The results show that there is no reason to expect that lowering the operating temperature of SMES improves the performance of the system, especially for the AC loss and cooling power.

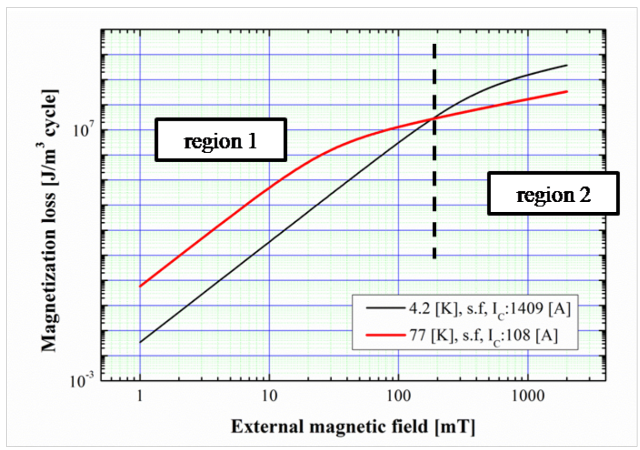

Fig. 1. Calculated magnetization losses of an HTS tape by magnetic flux densities of at 4.2 K and 77 K.

II. Calculation of AC losses in HTS solenoid coils

A. Magnetization loss with critical state model

The magnetization loss density due to the perpendicular magnetic field to the HTS tape is expressed as (1), where F is space factor of HTS tape, f is frequency, B_c is critical penetration field, B is the field of full penetration, $\beta\perp$ is the ratio of B_c to B, w is one half of the width of the tape, and t means one half of the thickness of the superconducting layer [6].

$$P_\perp = F\frac{4\pi w^2}{\mu_0 4wt}B_c B\left[\frac{2}{\beta_\perp}\ln(\cosh(\beta_\perp)) - \tanh(\beta_\perp)\right]\left[J/m^3 \cdot cycle\right] \quad (1)$$

B. Losses of HTS Solenoid coils

The characteristics of the AC loss of an HTS coil for AC operation are more complicated than those of the single tape. The magnetic fields in the coil vary point by point.

We calculated the magnetization losses of HTS solenoids by their aspect ratios at 65 K and 77 K. The magnetic field distributions were calculated by finite element method (FEM). The loss in an element was calculated by using Eq. (1) and the total loss was the sum of the losses in each element. Total 6,300 models were analyzed by FEM.

Fig. 2 shows the perspective results of this iterative analysis. Each calculated magnetization losses at 65 K were normalized to the ones at 77 K. So the number above 1 means that the loss at 65 K is bigger than the one at 77 K.

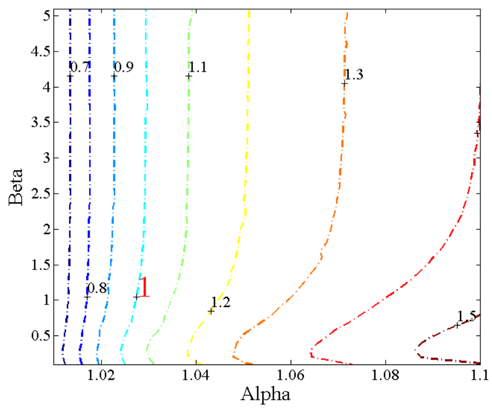

Fig. 2. The normalized loss (loss@65 K to loss@77 K) according to (α, β) for inner radius is 50 [mm].

III. Case studies of SMES

We have analyzed three HTS SMESs that are designed by us [3]-[5]. The specifications of three SMESs are listed in Table I. Fig. 3 shows the bird's view of toroidal type. AC losses in SMES are generated during charging and discharging periods. So we analyzed AC losses for two cases. The first scenario for the operation is that SMES is fully discharging its energy from 100 % to zero. The other one is assumed to use only 50 % of the stored energy.

The magnetization losses at 4.2 K, 14 K, and 20 K were the scenario 1 was 1.2 times larger than the one at 20 K. The losses for the scenario 2 decreased with the temperature variation. But in case of 5 MJ SMES, the losses for both scenarios increased with the decrease of the temperature. In case of 2.5 MJ SMES that was the toroidal system, the losses for both scenarios decreased with the temperature because the perpendicular magnetic fields were small.

IV. Conclusion

The Operating temperature variations of HTS electrical power machines are wider than those of LTS machines or HTS DC machines. Normally we set the operating temperature decided for the current at the temperature. But the temperature variation is inevitable for the HTS machines such as power cables or transformers during the AC operation. In case of SMES, charging and discharging cause the AC losses and so the temperature variation.

Normally, we expect better performances by lowering operating temperature. But the AC losses at lower temperature becomes larger above certain magnetic field. We analyzed the temperature dependency of AC losses of HTS solenoids. Iterative calculations of the magnetization losses of 6,300 HTS solenoids show that the losses at 65 K are bigger than the ones at 77 K when the coils operate with the rated operating currents.

For the application for the real system, three HTS SMESs were adopted for the analysis of the temperature dependency of the losses. They were two solenoidal SMESs and one toroidal SMES. The losses at 4.2 K, 14 K, and 20 K were calculated and compared with each other. In case of solenoidal SMES, the losses increase with the decrease of the temperature because of the strong perpendicular magnetic fields.

TABLE I
Specifications of Three SMESs

Specification	600 kJ	2.5 MJ	5 MJ
Storage Energy [MJ]	0.618	2.53	5
Operating current [A]	282	960	500
No. of coils [EA]	22(DPC)	56(SPC)	19(SPC)
Max. perpendicular B [T]	1.25	3.29	6.57
Max. parallel B [T]	8.57	4.45	8.76
HTS tape width [mm]	4	12	10
Total length [km]	10.8	12.1	18.6

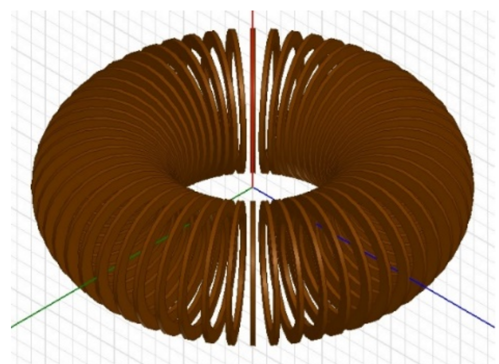

Fig. 3. Bird's eye view of SMES of 2.5 MJ toroidal type.

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