The Calculation of an Air Gap Between Pancake Windings in a Superconducting Magnet by Using the Response Surface Method

Myunghun Kang · Myunghwan Ku · Youngmin Kim · Heejoon Lee · Gueesoo Cha

Received: 6 September 2010 / Accepted: 7 September 2010 / Published online: 30 September 2010
© Springer Science+Business Media, LLC 2010

Abstract The effects of a gap at a high temperature superconducting magnet which has an insert magnet and an outsert magnet are examined. Both magnets consist of pancake windings. The optimum gap of an insert magnet and an outsert magnet are calculated by using the response surface method. The insert magnet consists of 8 YBCO pancake windings. The number of turns of a pancake winding and the inner diameter of the insert magnet are 60 turns and 40 mm, respectively. The outsert magnet consists of 12 BSCCO-2223 pancake windings. The number of turns of a pancake winding and the inner diameter of the outsert magnet are 100 turns and 115 mm, respectively.

The calculation results show the optimum gap of the insert magnet and the outsert magnet are 0 and 10.3 mm, respectively. When there is a gap of 10.3 mm in the outsert magnet the central magnetic field increased by 11.4% from 604.2 to 542.6 mT. RSM is proved to be an effective mean for finding optimum gaps in a shorter time comparing with other non-deterministic optimization technique.

Keywords Response surface method · Air gap · Superconducting magnet

1 Introduction

There have been researches done over a long time in order to enhance the uniformity at the center of a magnet for the development of new materials or the exploration of existing material structures [1].

The development of high temperature superconducting (HTS) wires allowed the production of long wires which provide a high current density under a very high magnetic field. Therefore, the studies of high field magnets manufactured with HTS wires have gotten a great deal of attention [2]. Unlike the low temperature superconducting (LTS) wire, the HTS wire has a strong anisotropy because it is produced in the form of a flat tape. In the case of the superconducting magnet made with pancake windings, when the distance from the center of the magnet to the pancake winding is increased, the magnitude of the magnetic field applied to the HTS wire decreases and the critical current of the magnet increases. Therefore, when there is an air gap between the pancake windings, the central magnetic field of the HTS magnet made by highly anisotropic HTS wire can be increased [3].

To find an air gap between the pancake windings that maximizes the central magnetic field of an HTS magnet, the effects of the air gap between the pancake windings on the central magnetic field were calculated [3, 4]. That calculation needed a lot of time because the calculation was carried out at various air gaps. As the number of calculation points increases, the error generally decreases and the result approaches the true value. To avoid large computations and to provide reasonable accuracy in the calculation, constructing a proper response function with minimum calculation points can be seen to be a better choice [5].

In this paper, the optimum air gaps between the pancake windings of an HTS magnet consisting of an insert and an outsert magnet were calculated. The response surface method (RSM), one of the designs of the experiments (DOE), was adopted for the calculation of the optimum gaps.
for the insert and the outsert magnet in order to maximize the central magnetic field of the HTS magnet. The RSM selects appropriate sampling points in the design region to find the proper response surface. Nine points were selected to construct the response surface in this paper.

The $(1+1)$ evolution strategy was used for the estimation of the critical current of the HTS magnet at each sampling point, which is one of the non-deterministic optimization techniques. The results of the calculation by using a 9-point RSM were compared with those of a 21-point fitting.

2 The Calculation Method and the Analysis Model

The critical current of an HTS wire varies by the magnitude and the angle of the applied magnetic field because of the anisotropy. Of special note, when a perpendicular magnetic field is applied to the wider surface of the HTS wire, the critical current decreases rapidly. In the case of the HTS magnet made with pancake windings, the current of the HTS magnet is determined by the magnetic field applied to the outermost pancake windings where the largest perpendicular magnetic field is applied.

In a LTS magnet with little anisotropy, the central magnetic field decreases when the distance from the pancake winding to the center of the magnet becomes longer. But when the distance from the pancake winding to the center of the magnet becomes longer in an HTS magnet, the central magnetic field can be increased because the reduced perpendicular magnetic field applied to the outermost pancake windings increases the critical current significantly.

To determine the gaps that maximize the central magnetic field of the HTS magnet consisting of an insert magnet and an outsert magnet, the calculation model was chosen as shown in Fig. 1. The insert magnet was composed of 8 YBCO pancake windings and the outsert magnet was composed of 12 BSCCO-2223 pancake windings. In consideration of the YBCO wire’s minimum bending diameter, the inner diameter of the insert magnet was determined to be 40 mm. The number of turns for each pancake winding was 60. The outsert magnet had 100 turns per pancake winding. The inner diameter of the outsert magnet was determined to be 115 mm in consideration of the outer diameter of the insert magnet and the current lead.

The characteristics of the YBCO wire and the BSCCO-2223 wire used in the calculation are shown in Table 1. The critical currents of the YBCO wire and the BSCCO-2223 wire were 70 and 125 A, respectively, at 77 K, 1 µV/cm. The critical current of the magnet was calculated by using the $E-J$ relation with the $I_c-B$ and the $n$-value characteristics, according to the magnitude and the angle of the applied magnetic field. The magnitude and the angle of the magnetic field applied to one turn of the HTS wire were needed for the calculation of the voltage generated from the pancake winding. In order to calculate the applied magnetic field of one turn of the HTS wire more accurately, the cross-section of the HTS wire was divided into $M$ elements. The applied magnetic field of one turn of the HTS wire was calculated as the average magnetic field of the $M$ elements as shown in (1) and (2) [4].

$$B_{\perp,n} = \left( \frac{\sum_{i=1}^{M} |B_{\perp,ni}|}{M} \right) / M, \quad B_{//,n} = \left( \frac{\sum_{i=1}^{M} |B_{//,ni}|}{M} \right) / M$$

(1)

$$B_n = \sqrt{B_{\perp,n}^2 + B_{//,n}^2}, \quad \theta_n = \tan^{-1} \left( \frac{B_{\perp,n}}{B_{//,n}} \right)$$

(2)

where $B_{\perp,ni}$ and $B_{//,ni}$ are the perpendicular and the horizontal magnetic fields applied to the $i$th element of the $n$th turn, and $B_n$ and $\theta_n$ are the magnitude and the angle of the magnetic field applied to the $n$th turn, respectively.

The response surface method utilizes the relation between the response value and the design variables. With the response value, a regression analysis is carried out to estimate the response surface. In the response surface analysis, a statistical model appropriate for the response surface is assumed. As an example, if the response surface is believed to be curved, the response surface equation can be expressed

Table 1  The specifications of the YBCO wire and the BSCCO-2223 wire

<table>
<thead>
<tr>
<th>Type of wire</th>
<th>YBCO</th>
<th>BSCCO-2223 reinforced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>4.55 mm</td>
<td>4.4 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.310 mm</td>
<td>0.285 mm</td>
</tr>
<tr>
<td>Critical current</td>
<td>70 A, 77 K, 0 T</td>
<td>125 A, 77 K, 0 T</td>
</tr>
<tr>
<td>Min. bend diameter</td>
<td>25 mm</td>
<td>38 mm</td>
</tr>
</tbody>
</table>