EXPERIENCES IN DEVELOPING THE HIGH CURRENT DENSITY WAX-FILLED SUPERCONDUCTING SADDLE MAGNETS

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EXPERIENCES IN DEVELOPING THE HIGH CURRENT DENSITY
WAX-FILLED SUPERCONDUCTING SADDLE MAGNETS

Yan Luguang*, Yu Yunjia, Ye Zuxian, Jing Bohong, Li Huidong, Wang Silian,
Yi Changlian, Chen Haoshu and Ma Hongda

Institute of Electrical Engineering, Academia Sinica, Beijing, China

Abstract - The design, construction technology and test results of three model saddle magnets are described. The main research and development experiences are summarized.

Several years ago we initiated a program to build a 5MJ, 35cm bore, 4T adiabatically stable saddle magnet for our experimental MHD generator. To solve the problems associated with such middle size high current density magnet, a series of three model saddle magnets SSM-1, SSM-2 and SSM-3 has been designed, constructed and tested in sequence. Finally, the SSM-3 magnet achieved "short-sample" performance. The present paper describes these model magnets and their test results, summarizes the main research and development experiences. These model magnets used multifilamentary twisted rectangular NbTi conductor with Cu/s.c=2 and 40µm polyimide tape insulation. Different winding shape, construction technology, support structure design and filling materials were investigated on them. Main parameters of these model magnets are listed in Tab. 1. Fig. 1 presents their pictures.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Main parameters of model saddle magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>SSM-1 &quot;Whole&quot;</td>
</tr>
<tr>
<td>Conductor</td>
<td>Cross section (mm²)</td>
</tr>
<tr>
<td>Weight kg</td>
<td>47.8</td>
</tr>
<tr>
<td>Winding</td>
<td>Cross section</td>
</tr>
<tr>
<td>Shape</td>
<td>Constant perimeter</td>
</tr>
<tr>
<td>I.D. mm</td>
<td>148</td>
</tr>
<tr>
<td>O.D. mm</td>
<td>310</td>
</tr>
<tr>
<td>Length mm</td>
<td>565</td>
</tr>
<tr>
<td>No. of layers</td>
<td>41</td>
</tr>
<tr>
<td>No. of turns</td>
<td>1711</td>
</tr>
<tr>
<td>Magnet</td>
<td>L H</td>
</tr>
<tr>
<td>Bo/I G/A</td>
<td>54.8</td>
</tr>
<tr>
<td>Bm/I G/A</td>
<td>63.9</td>
</tr>
<tr>
<td>&quot;Short-sample&quot; &quot;Boco T</td>
<td>1.03</td>
</tr>
<tr>
<td>Bmco T</td>
<td>5.64</td>
</tr>
<tr>
<td>Wmco kJ</td>
<td>6.58</td>
</tr>
<tr>
<td>performance</td>
<td>288</td>
</tr>
</tbody>
</table>

*presently on leave at Kernforschungszentrum Karlsruhe, F.R.G.
The SSM-1 magnet is a 1/3 model of the magnet for experimental MHD generator. It has four large layers designed as constant perimeter winding to approximate the intersecting ellipse cross section, each large layer consists of seven small layers. The winding is wound directly on the 12.5mm thick stainless steel bore tube, during winding after each small radial layer (7 turns) the gaps are filled with melted paraffin-wax by brushes. After every large layer a banding is made with 25mm wide, 0.5mm thick silk tape, after applying epoxy with brushes the banding is cured at room temperature. The magnet radial electromagnetic force is supported by 12 pairs aluminium alloy I-beam ring girders, each pair is clamped together by 16xM10 stainless steel bolts. Axial force is supported by aluminium alloy end flanges and 8 brass bars.

The magnet was tested three times in a Ø 600 mm vertical dewar. The first (No. 1) test was conducted with magnet wax-filled by brushes during winding. Before the second (No. 2) test the magnet was vacuum impregnated with wax. The third (No. 3) test was conducted after repeated vacuum impregnation of wax. Test has been done both for the "whole" winding (all four large layers in serie) and the "inner" winding (the inner two large layers). Fig. 2 presents the test results.

From the test results it was observed:

1. After about 20 training steps the highest achieved performance of wax-filled by brushes magnet is 47% of the "short-sample" performance. Vacuum impregnation reduced training and increased the performance to 60%, repeated impregnation further increased it to 68%. Degradation and training are still serious.

2. Unlike the solenoids, the quench current during training does not increase monotonously, there were several undulations, their amplitude reached 60A.

3. From the recorded bridge signal it
was observed that before quench there appeared repeatedly a lot of 1-3 mV amplitude and 1-2 sec. long small pulses.

(4) Comparison between the "whole" winding and "inner" winding test results shows that for both cases the products of highest quench current and peak field \((I_{\text{q}}B_{\text{m}})_{\text{max}}\) are approximately identical. That means the magnet performance is limited to the same electromagnetic force level.

During dissection of the magnet after tests it was observed that the bandings on the inner two layers were broken in many places, the thickness of wax layer between the straight part of winding and bore tube reached 5-6 mm.

2 - SSM-2 MAGNET

Based on the test results of SSM-1 magnet, it was decided to reduce the thickness of wax layer and to improve the banding between layers. Using the bore tube, the coil forms and conductors of the two inner large layers of the SSM-1 magnet, the SSM-2 magnet has been constructed. It has the same parameters and winding technology as the "inner" winding of SSM-1. The main differences are:

(1) an additional banding with Ø 0.8 mm stainless steel wire is made on the silk banding of the first large layer.

(2) wax-filling with brushes during winding is avoided.

(3) simpler support structure consisting of 12 pairs of 20 mm thick stainless steel clamps and 24xM20 stainless steel bolts is used (Fig. 1b).

The magnet was tested six times. The first four tests were with vacuum wax-impregnated magnet, the effect of repeated impregnation and warming to LN\(_2\) temperature was investigated. The fifth test was with magnet vacuum impregnated with alcohol after removing wax. The last test was with unfilled magnet after removing alcohol. Fig. 3 presents the test results. It can be seen from the test results that:

(1) There is no improvement in magnet performance in comparison with SSM-1 magnet.

(2) As SSM-1, the first reimpregnation improved the magnet performance, but the second reimpregnation did not give further improvement.

(3) In comparison with wax filling, the impregnation with alcohol also does not improve the magnet performance, although in this case the small pulses in bridge signal disappeared.

(4) When magnet was unfilled, the magnet performance decreased strongly. The highest performance dropped from 67% to 37% of the "short-sample" performance. The SSM-2 test results show clearly that to get good magnet performance it is necessary to change the magnet design and construction technology.

![Fig. 3 SSM-2 test results](image-url)
3 - SSM - 3 MAGNET

After SSM-2 magnet test it was decided to make a new design and to improve the winding technology seriously. The SSM-3 magnet has been designed and constructed. In comparison with two previous models, the main changes are:

(1) Instead of previous constant perimeter multilayer winding the double-pancake winding is used.
(2) The winding cross section is modified from intersecting ellipse to 45° segment.
(3) The bore diameter and conductor cross section are larger.
(4) The weftless epoxy-fiberglass tape is used for interlayer bandings. After curing the bandings are machined to given dimension.
(5) Many efforts have been paid to improve the winding technology. The SSM-3 magnet used the same support structure of SSM-1. The design and construction technology of SSM-3 are detailly described in /1/.

Fig. 4 presents the test results of the SSM-3 magnet. The first test was with unfilled magnet, the second was conducted after vacuum impregnation of wax. During second test the bolts of support structure were damaged at 1.525kA magnet current. The third test was with the magnet with redesigned support structure. The improvement of the support structure is described in /2/.

From the test results it can be seen clearly that the magnet performance has been improved significantly. Even the unfilled magnet reached 77% of "short-sample" performance, the magnet with improved support structure achieved "short-sample" performance (97%).

Fig. 4 SSM-3 test results

4 - MAIN EXPERIENCES AND CONCLUSION

The main experiences gained from these three model magnets are:
- For MHD magnet, where the requirement of magnetic field homogeneity is low, the double-pancake segment winding is better in the aspects of force transmission and winding compactness.
- Much attention should be paid to improve the winding technology, to develop suitable winding instruments.
- The weftless epoxy-fiberglass tape banding has been proved quite good. The machining of bandings after curing is necessary for winding the succeeding pancake.
- Filling seems to be unavoidable. Wax filling has several advantages, such as simpler technology, cheaper, magnet can be rewind and conductor can be reused.
- Correct design of support structure is also important. Ring girders with pin-plate clamping are a good solution.

The SSM-3 magnet demonstrated the feasibility of construction high performance, close-packed, wax-filled middle-size saddle magnets.

REFERENCES