Electromagnetic Design of HTS D-shaped Coils for a Toroidal-type Superconducting Magnet

H. Liu*, X. Deng, L. Ren, Y. Xu, J. He, Y. Tang

State Key Lab. of Advanced Electromagnetic Engineering and Technology (R&D Center of Applied Superconductivity, Huazhong University of Science and Technology), 1037 Luoyu Road, Wuhan, 430074, P. R. China

Abstract

High current and magnetic field are essential for achieving MCF (magnetic confinement fusion). Superconducting materials and technology have unique advantages to achieve high magnetic field and large-current transmission. With the commercialization of 2G HTS tapes, they are paid wide attention to in Tokamak magnet application. In order to investigate the feasibility of applying HTS into Tokamak magnets, a toroidal-type magnet has been designed using YBCO tapes by means of FEM analysis combining with Matlab. The effects of the coil number and coil arrangements on the critical current, the maximum parallel magnetic field, the inductance and the storage capacity of the magnet are analyzed. Based on that, key technological points of the electromagnetic design are discussed.

1. Introduction

In recent years, with the improvement of the performance of HTS conductors, they have been applied in various superconducting magnets [1]. Compared to LTS conductors, HTS conductors show higher operating temperatures and larger critical currents with a moderate decrease under high magnetic fields. In fact, higher operating temperatures help reduce the cooling costs, which improves the economy, while larger critical currents could diminish the magnet size and save space. These advantages make it easier for HTS conductors to meet applications.

* Corresponding author. Tel.: +86-27-8754-4755; fax: +86-27-8754-0937.
E-mail address: hustceeliuhao@gmail.com
of large currents and high magnetic fields. Therefore, it may be promising to apply HTS into Tokamak magnets. In almost every current Tokamak, the D-shaped structure is adopted in the design of TF magnets, because it won’t produce any bending moment induced by electromagnetic force and also makes it convenient to design the supporting structure and reduce the size of the support [2].

In this paper, a toroidal-type superconducting magnet has been designed by methods of FEM analysis combining with Matlab and the D-shaped coil is chosen as the unit coil for further study of ITER magnet. Analysis is carried out in detail on the critical current, the maximum parallel magnetic field, the inductance and the storage capacity of the magnet. In addition, a D-shaped model coil is now under intensive manufacture for validation experiments.

2. Design of the toroidal-type magnet

2.1. Design and parameters of the toroidal-type magnet

The operating temperature of the toroidal-type magnet is 20 K. Every coil of the magnet is D-shaped double pancakes and wound with one tape. All coils are arranged at identical intervals. The design goals are to maximize the storage capacity of the magnet and get a high parallel magnetic field in accord with the requirements of ITER TF magnets. In the design, Amperium™8501 YBCO tape produced by AMSC is used and the total length of the tapes is fixed and equal to 2 km. The specifications of the YBCO tapes are shown in Table I. The dimensions of the D-shaped coil, the number N of coils and the inner radius Rin of the magnet are considered as design variables. Assume that N and Rin are integers that vary from 6 to 16 and 75 mm to 300 mm respectively.

Table 1. Specifications of Amperium™8501: Copper Laminated HTS wire.

<table>
<thead>
<tr>
<th>Wire Property</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Measured size (Including the insulating layer)</td>
<td>0.35 mm × 4.8 mm</td>
</tr>
<tr>
<td>Min. Ic (77 K, self field, 1 μV/cm)</td>
<td>90 A</td>
</tr>
<tr>
<td>Min. double bend diameter (Greater than 95% Ic retention)</td>
<td>30 mm</td>
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The optimal design is obtained where N is 12 and Rin is 75 mm. Both the storage capacity E and the maximum parallel magnetic field Bmax of the magnet reach the biggest values, that is, 10.86 kJ and 1.037 T. The critical current Ic is 359 A and the inductance L equals 0.344 H. The storage capacity E is calculated by the expression \( E=0.5LIop^2 \), where Iop is the operating current and is set to be 70% Ic to ensure the safety and stability of the magnet.

Fig. 1. (a) Dimensions of the D-shaped coil (b) Structure of the designed magnet; (c) Structure of the D-shaped coil

Fig.1.(a) shows the dimensions of the D-shaped coil. Fig.1.(b) and (c) shows the structures of the designed magnet and D-shaped coils. The magnet is cooled by GM cryocooler. The coils are cooled by the cooling plates made of pure copper that are connected to a GM cryocooler. The inner supportings are made of brass. Every cooling plate and inner supporting is cut with several kerfs to reduce the eddy current loss. The outer supportings and fastening boards are made of 316LN stainless steel. The epoxy boards are used for insulation between the coils and the cooling plates.
2.2. The D-shaped coil and the \( I_c \) calculation

The D-shaped curve was first proposed by J. File in order to solve the problem of the mechanical support against huge electromagnetic force in the Tokamak nuclear fusion reactor [3]. The curve is expressed by equation (1).

\[
y = \pm \int_{r_i}^{r_o} \left( 2 \ln x \sqrt{\ln^2 \left( \frac{r_o}{r_i} \right) - 4 \ln^2 x} \right) dx + C, \quad x \in [r_i, r_o] \tag{1}
\]

Where C is a constant that determines the up-and-down position of the D-shaped curve along y axis, while \( r_i \) and \( r_o \) are the inner radius and outer radius, respectively. In this design, the D-shaped curve is simplified as a combination of 5 arc segments and 1 linear segment that are vertical symmetrical, as shown in Fig.1. (a). Considering that the actual size of the designed magnet is small, the resulting error of the simplification is negligible.

The critical current of the YBCO tape is determined by the magnetic field applied perpendicular to the tape surface. The critical current of the magnet is obtained by the intersection of the \( I_c-B_z \) curve of the tape at 20 K and the load line of the magnet, as shown in Fig. 2.

![Graph of Ic vs Bz and load line](image)

Fig. 2. \( I_c-B_z \) characteristics curve and load line of the magnet at 20 K ;

2.3. Method and process of the electromagnetic design

FEM (finite element method) analysis combining with Matlab is used in the design and Fig. 3 presents the whole procedure. The Matlab program controls and calls the FEM program for electromagnetic calculation and gets the calculation results for post-processing. It is worth mentioning that the model construction is aided by 3D CAD software and the FEM analysis is only conducted on \( 1/N \) model for the high symmetry of the magnet.

3. Electromagnetic analysis of the toroidal-type magnet

Fig. 4 shows the magnetic field distribution of the toroidal-type magnet when excited by the current of 200A.

![Magnetic field distribution](image)

Fig. 4. (a) Distribution of \( B_x \) component; (b) Distribution of \( B_y \) component; (c) \( B - \)Distance curve
It can be observed that the linear segment of the magnet bears the largest parallel component of magnetic field, while the upper and lower arc segments near to the linear segment bear a larger perpendicular component of magnetic field which means \( I_c \) will be determined by them. In addition, the parallel component of magnetic field along \( x \) axis is unevenly distributed and the leakage magnetic field declines to zero quickly when the distance from the origin exceeds the outer radius. This means a toroidal-type magnet would produce little leakage magnetic field.

Fig. 5 shows the relation curves between the coil number \( N \), the coil arrangements and the critical current \( I_c \), the maximum parallel magnetic field \( B_{\text{max}} \), the inductance \( L \) and the storage capacity \( E \) of the magnet in (a), (b), (c), and (d), respectively. The coil arrangements can be represented by the varied inner radius \( R_{\text{in}} \).

From Fig. 5, it could be recognized that when \( N \) is fixed and \( R_{\text{in}} \) is varied, both \( B_{\text{max}} \) and \( L \) have an obvious and regular change, while \( I_c \) and \( E \) are irregularly changed. When \( R_{\text{in}} \) varies from 75 mm to 300 mm, the overall trend of \( B_{\text{max}} \) and \( L \) is getting reduced with a maximum variation of -46% and -37.9%, respectively. It implies that as the inner radius gets larger, the maximum parallel magnetic field becomes smaller and the coupling of coils turns weaker. Since \( E \) is determined by both \( L \) and \( I_{\text{op}} \) (70% \( I_c \)), the phenomenon of the irregular change of \( E \) can be well demonstrated. In addition, when \( R_{\text{in}} \) is a fixed parameter and \( N \) is a variable, the changing trends of the four inspection objects are not obvious. However, in general, \( L \) and \( E \) are both getting the smallest values when \( N \) turns to the biggest value. It reveals that whether maximizing the inductance or the storage capacity is considered as the designing goal, the bigger \( N \) won’t always be an optimal choice, less likely the biggest \( N \).

4. Conclusion

The electromagnetic design of a toroidal-type magnet has been accomplished. The magnet consists of 12 D-shaped coils. The operating current is 251 A at 20 K. The electromagnetic analysis shows that the critical current of the magnet is determined by the upper and lower arc segments near to the linear segment of the D-shaped coils. The leakage magnetic field of the toroidal-type magnet is weak and can be ignored. Besides, values of the maximum parallel magnetic field and the inductance of the magnet are greatly dependent on the radius of the magnet while the storage capacity and the critical current are not so. When the radius of the magnet is fixed, the inductance and the storage capacity of the magnet have no direct relationship with the number of coils.

Mechanical stress analysis of the magnet shall be introduced in another paper. Research and development of HTS large-current conductors will be paid great attention to and included in the future work.

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References