**Shape optimization of field windings in a high temperature superconducting synchronous generator with finite element method**

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Based on magnetic field analysis by finite element method, the optimal design of high temperature superconducting (HTS) field windings in a demonstrative HTS generator model is presented. The studies are focused on pursuing the minimal volume of HTS magnet, as well as the minimum vertical component ($B_{\perp}$) of magnetic flux density passing through the surface of HTS tapes. Two types of HTS rotors are analyzed. It is proved that the $B_{\perp}$ can be decreased effectively by adopting flux diverters for the configuration with iron core and by adjusting cross-sectional shape of HTS magnet for the configuration without iron core respectively.

## INTRODUCTION

High temperature superconducting (HTS) technologies enable generators and motors more compact and lighter than their conventional counterparts. Substituting HTS conductors for conventional conductors will eliminate energy losses caused by resistance, and the efficiency of HTS generators will increase 0.5%-1.0% approximately [1]. However, the vertical field $B_{\perp}$ has a strong impact on the critical current $I_c$ of HTS tapes. How to reduce $B_{\perp}$ becomes an important task. In this paper, two types of HTS rotors are analyzed, which are the HTS rotors with or without iron cores.

There are two steps in optimization procedures. In the first step, the magnetic flux distribution excited by the initial HTS conductors in which two rotors are analyzed accurately on the basis of Biot-Savart's law and two-dimensional finite element method, and then the maximum $B_{\perp}$ in the initial magnets are obtained. In the second step, structures and configurations of the HTS magnets are adjusted by changing design variables. The optimized models are compared with previous ones till a qualified scheme is found out.

## OPTIMAL DESIGN OF THE HTS MAGNET

For HTS generator, there are two types of rotors with HTS field windings, one is traditional magnetic iron core rotor and the other is nonmagnetic rotor.

### Initial HTS magnets

The cross section of the initial HTS magnets consisting of six rectangle shape single-layer pancake coils is shown in Figure 1 and Figure 2, and the magnet is wound on the iron core rotor or on the nonmagnetic module (nonmagnetic rotor) respectively. Each pancake coil has 50 turns. The cross section of HTS tapes is assumed as 4.5*0.5 mm, in which a DC current of 54 A runs through.

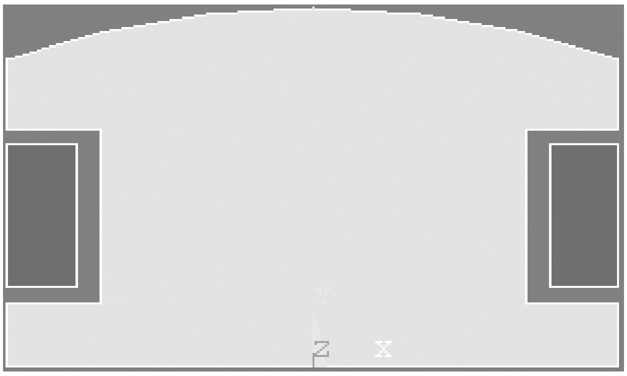


Figure 1 Initial HTS magnet wound on traditional rotor

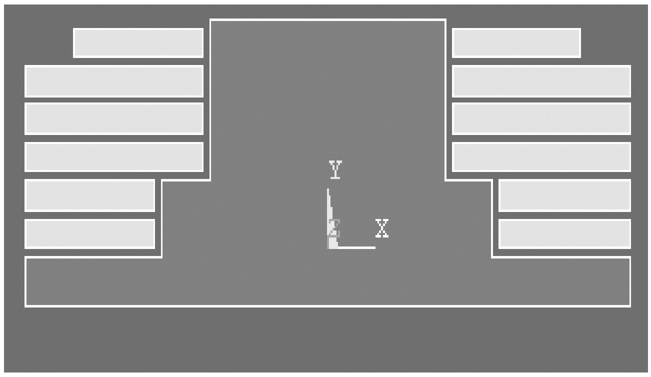


Figure 2 Initial HTS magnet wound on nonmagnetic rotor

With above two configurations, the maximum $B_{\perp}$ of about 0.52 T and 0.42 T can be achieved respectively in the iron core rotor type HTS magnets and nonmagnetic rotor type ones. The magnetic field distribution of initial HTS magnet wound on traditional rotor and nonmagnetic rotor is shown in Figure 3 and Figure 4, and the value of $B_{\perp}$ according to the location of points on the HTS magnet edge is shown in Figure 5 and Figure 6.

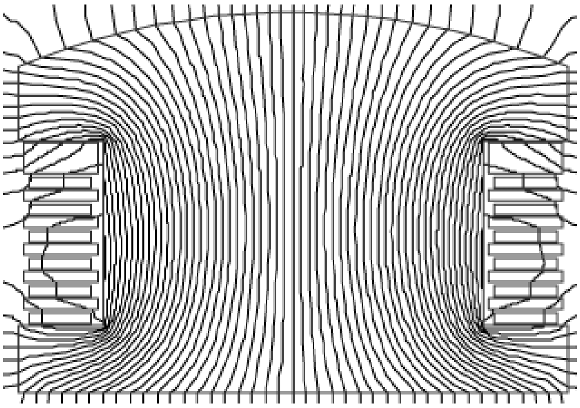

Figure 3 Magnetic field of traditional rotor

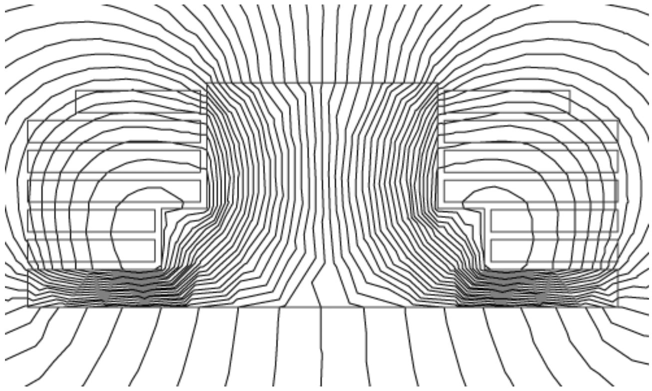

Figure 4 Magnetic field of nonmagnetic rotor

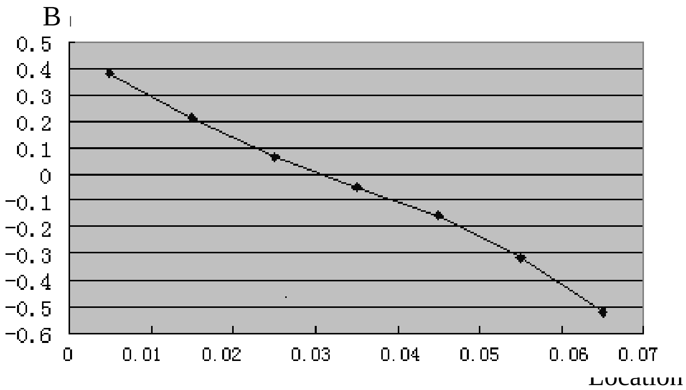


Figure 5 $B_{\perp}$ through HTS magnet of traditional rotor

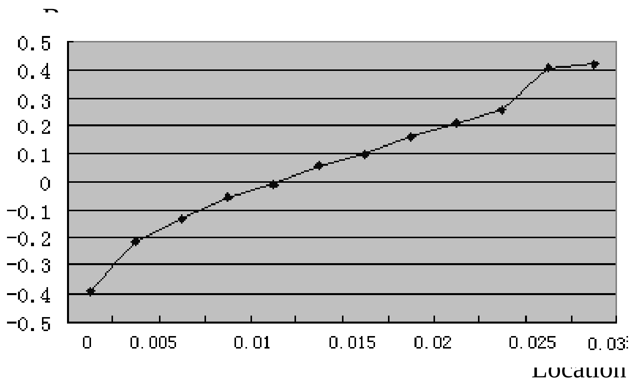


Figure 6 $B_{\perp}$ through HTS magnet of nonmagnetic rotor

From Figure 3 and Figure 4, it can be concluded that a lot of flux lines go through the HTS magnets, and that proves the value of $B_{\perp}$ is too great and has effects on the operation stability of initial HTS magnets. From Figure 5 and Figure 6, the value of maximum $B_{\perp}$ can be obtained.

<u>Optimized HTS magnets</u>

Based on initial design, flux diverters are employed for iron core rotor configuration, which are made of laminated steel sheets. Ring-shaped flux diverters are inserted between the HTS coils to reduce $B_{\perp}$ of the magnetic field in the coils. For this configuration, the maximum value of $B_{\perp}$ in the coils, with the same exciting current of DC 54 A, is reduced to 0.02 T. The shape of optimized HTS magnet wound on iron core rotor and its magnetic field distribution are shown in Figure 7 and Figure 8 respectively, and Figure 9 shows the value of B$_\perp$ according to the location of the spots on optimized HTS magnet.

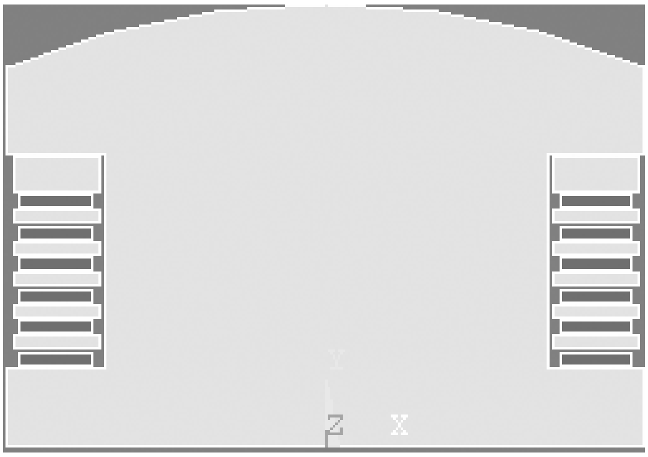


Figure 7 Optimized magnet wound on iron core rotor

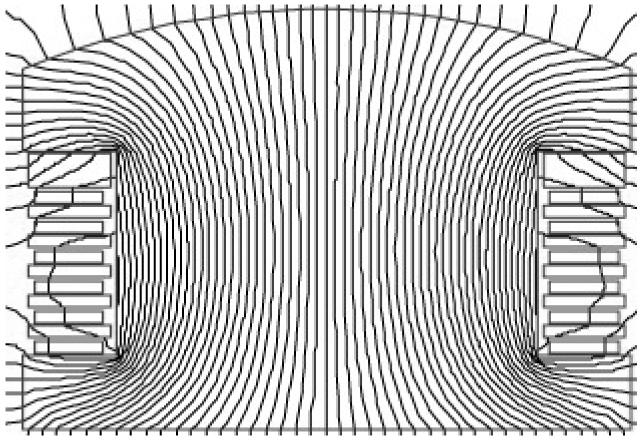

Figure 8 Magnetic field of optimized magnet of iron core rotor

For nonmagnetic core rotor, a step-shaped magnet is introduced and the shape of the initial magnet is optimized by finite element analysis software ANSOFT. The objective function is the HTS magnet volume, and the constraint is the value of the outer width of each coil, therefore we can get the step-shaped model of the optimized magnet. The objective function and constraints are shown as formulas (1), (2) and (3), in which $V$ is volume of magnets, $r_i$ is bend radius at winding end of each pancake, $l$ is axial length of the rotor, and $w_i$ and $h$ are width and height of each pancake. After optimization, the volume of optimized step-shaped magnet is 93% of the initial magnet wound on nonmagnetic rotor. The maximum value of B$_\perp$ in the coils is 0.53 T. For further study, two iron plates, which are used to reduce the value of B$_\perp$, are installed on above optimized HTS magnets, and the value of B$_\perp$ is reduced to 0.3 T. However, magnetic saturation of iron plates must be considered by selecting proper materials and suitable shape and dimensions.

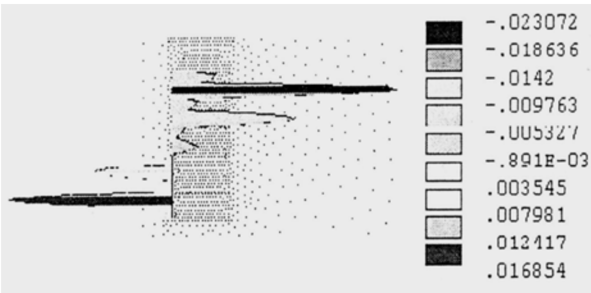


Figure 9 B$_\perp$ of optimized magnet in iron core rotor

Figure 10 illustrates the step shape of optimized HTS magnet, and Figure 11 and Figure 12 are magnetic field distribution of step shape magnet and the value variation of B$_\perp$.

$$V = \min F(x) \tag{1}$$

$$F(x) = 2\sum_{i=1}^{n} (\pi r_i + 2l) w_i h \tag{2}$$

$$0 \le w_i \le 16.5mm \tag{3}$$

And the optimized step-shaped magnet with iron plates is shown in Figure 13, Figure 14 and Figure 15 illustrate its magnetic field distribution and the value of B$_\perp$ according to location of the spot on HTS magnet edge.

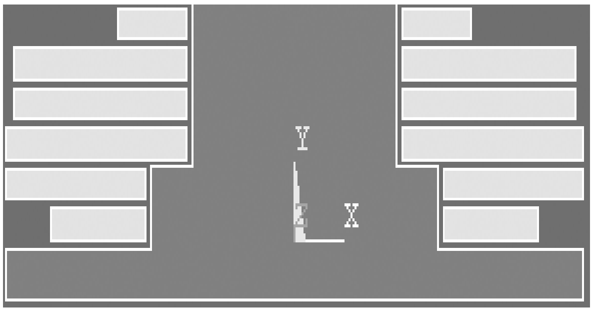


Figure 10 Step shape magnet

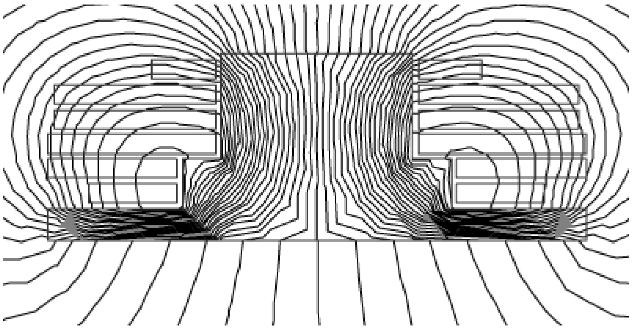

Figure 11 Magnetic field of step shape magnet

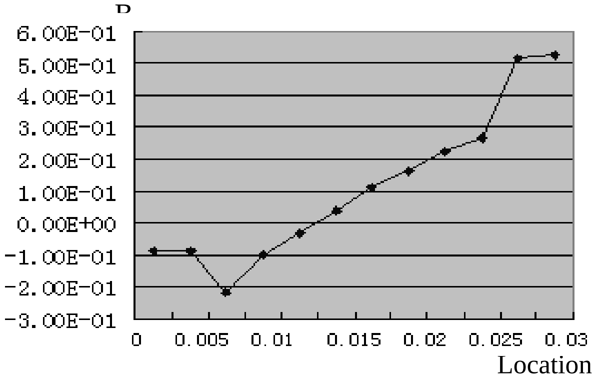


Figure 12 The variation of $B_{\perp}$ of step shape magnet

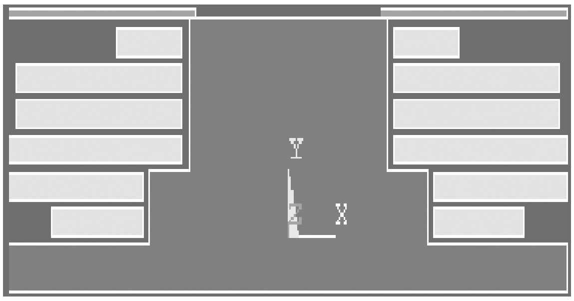


Figure 13 Step shape magnet with iron plates

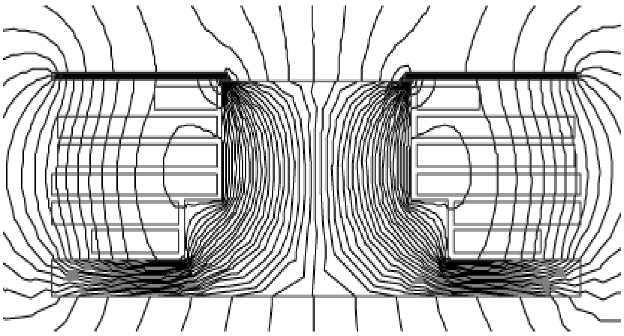

Figure 14 Magnetic field of step shape magnet with iron plates

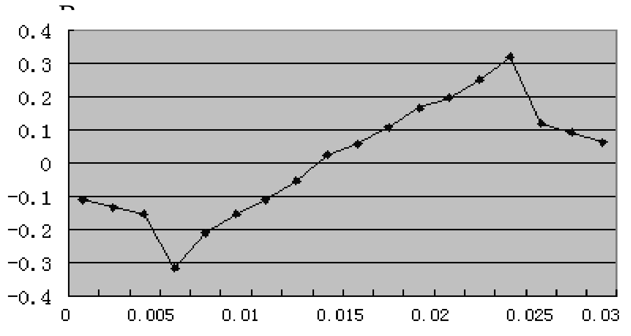


Figure 15 Variation of $B_{\perp}$ of magnet with iron plates

## CONCLUSIONS

The optimal shapes of HTS magnet with iron core and without iron core are studied, and the value of $B_{\perp}$ in each kind of HTS magnet is achieved. It can be conclude that the iron core type HTS magnet with diverters and the nonmagnetic core type HTS magnet with step-shaped HTS magnet and iron plates are two effective ways to reduce $B_{\perp}$.

## REFERENCES

1. Al-Mosawi, M.K., Beduz, C., Goddard, K. etc, Design of a 100kVA high temperature superconducting demonstration synchronous generator, Physica C (2002) 372-376 1539-1542
2. Young-Sik, Jo., Young-Kil, K., Myung-Hwan, S. etc, High temperature superconducting synchronous motor, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY (2002) 12 833-836