1. Introduction

In the two-dimensional optimal method to design superconducting magnets for 14T actively shielded MRI magnets is proposed. At this time, the favorable current-carrying region assumed as possible coil zone is subdivide into two-dimensional array grids, in which each grid represents one possible coil. The coil is defined as a single conductor, the superconducting current carrying section, imaging region homogeneity and stray field imaging form. Meanwhile the initial triangular section of the magnet is determined by isolating the actual coil region and the coil of the two-dimensional programming is adopted to outline the final configuration of each coil with the limitation of each coil position and section size. In addition, the spherical harmonics expansions of central magnetic fields is proposed in the optimization strategies used in the two-dimensional programming method to get the lowest level of inhomogeneity over the imaging region. Besides all the current coils are chosen by selecting the actual coil region and the coil of the two-dimensional programming is adopted to outline the final configuration of each coil with the limitation of each coil position and section size. Finally, the design method has been used to high field homogeneity in the central zone by four rows of coils with length about 3.7 m and inner distance nearly 1 m. The detailed analysis and optimization approach will be presented.

2. Optimization method

2.1 Linear Programming

The 2-dimensional array source grids shown in Fig. 3. is the candidate domain for the main and shielded coils in which each grid represents one possible coil lie of the actual conductor central with the coil is. The basic structure of the conductor shown in Fig. 2 is comprised of Nb3Sn Rutherford cable (each strand shown as a yellow circle) and cooper shielding cable (orange circle). The magnetic field contribution of the (a) conductor current to the (c) central or external target point is $B_3 = B_{3,3} + B_{3,2}$. In this text, the magnetic field equation for the target points on the DSV edge and shielding line can be established as:

$$B_{3,3} = B_{3,3} + B_{3,2} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$$

The formulations of linear programming can be obtained as follows: Where $F$ is the objective function to be minimized by the optimization of the superconducting currents $I_3$ and $I_2$, denotes the target current of the current-carrying r-axis, $I_3$ denotes the current of the central conductor, $I_2$ denotes the current of the superconductor, $B_3$ is the desired magnetic field strength, $r$ refers to the homogeneity factor, and $L_{3,3}$ is the maximum current for one conductor.

$$\text{Min. } F = 2\pi \frac{H_{\text{m}}}{L_{3,3}} \left( B_{3,3} - B_{3,3} \right)$$

subject to

1. $B_{3,3} = B_{3,3} + B_{3,2} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$
2. $B_{3,2} = B_{3,2} + B_{3,1} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$
3. $L_{3,3} = L_{3,3} + L_{3,2} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$

The initial configuration of the current points on the conductor shown in Fig. 3. (a) The red region represents the main magnets with a positive current, blue represents the shielded magnets with a negative current, while most of the area with no current are green. Since the region with no current is unrealistic, and the meshing process is necessary. After every adjustment, the settings of LSF-LP should be isolated to get the final triangular section of the magnetic field shown in Fig. 3. (b). It is obviously seen that the axial edge of the shield coil shall not exceed the end of the main-magnet to ensure the existence of insulation and leakage.

3. Results

The main purpose of LSF-LP to provide initial magnetic configuration as shown in Fig. 3. (b) for the subsequent non-linear optimization. The better the initial value is, the faster the convergence rate of the non-linear optimization will be.

$$\text{Min. } F = 2\pi \frac{H_{\text{m}}}{L_{3,3}} \left( B_{3,3} - B_{3,3} \right)$$

subject to

1. $B_{3,3} = B_{3,3} + B_{3,2} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$
2. $B_{3,2} = B_{3,2} + B_{3,1} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$
3. $L_{3,3} = L_{3,3} + L_{3,2} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$

It refers to the number of the current coils which is determined by the total number of superconducting strands of all the Rutherford cables in shielded conductor shown in Fig. 2. This formulation determines the initial current-carrying sections which makes the MRI magnet designs more feasible and accurate. At last the formulation of non-linear programming can be obtained as follows:

$$\text{Min. } F = 2\pi \frac{H_{\text{m}}}{L_{3,3}} \left( B_{3,3} - B_{3,3} \right)$$

subject to

1. $B_{3,3} = B_{3,3} + B_{3,2} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$
2. $B_{3,2} = B_{3,2} + B_{3,1} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$
3. $L_{3,3} = L_{3,3} + L_{3,2} = \frac{1}{2\pi} \frac{I_{3,3}}{r} + \frac{1}{2\pi} \frac{I_{3,2}}{r}$

4. Conclusion

Linear and non-linear combined optimization approach are used in the design of the 14T actively shielded MRI superconducting magnets. The linear programming gives rise to the initial triangular section of the magnet configuration and then the non-linear programming is adopted to refine the structure. Besides, spherical harmonics elimination is applied in the optimization strategy with fast convergence and high accuracy. Finally, this optimization method has obtained high field homogeneity over the central region and limited level of stray field with good performance, and these design approaches can also be used to design more superconducting magnets for real MRI applications.