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Study on Ampere-Turns of superconducting dipole and quadrupole magnets based on sector coils

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ABSTRACT

General expressions of Ampere-Turns for superconducting dipole and quadrupole magnets based on sector coils are proposed. According to the magnetic field generated by simplified coil layouts using the line current theory, the required excitation current to achieve the desired field strength in the aperture is calculated. The contribution of magnetic field by an iron yoke is taken into account by using the image current method. The validity of derived equations is confirmed by applications to main superconducting magnets which have been built in several high energy accelerators. The proposed analytical expressions provide a simple relationship among the bore field, main dimensions of the magnet, and the total excitation current. These expressions are complementary to the existing method in the electromagnetic design, and are shown to be quite similar to those of conventional magnets. Finally, the comparison of Ampere-Turns between superconducting magnets and conventional magnets is presented.
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1. Introduction

Superconducting magnets are widely used in high energy particle accelerators [1–3]. Compared with conventional magnets, superconducting magnets can provide higher field above the iron saturation limit, allowing shorter machine circumference with lower operational cost. Dipole and quadrupole magnets are two kinds of superconducting magnets most commonly used, whose main functions are to bend and focus the particle beams, respectively.

Most of the dipole and quadrupole magnets have been built based on the so-called cos $n\theta$ layout, where the shape of the coil is an annulus, and the conductors are arranged in sectors around the magnet aperture [4–6]. Other coil layouts, such as block coil or racetrack coil, are intrinsically less efficient in the use of superconducting material.

The prime purpose of the electromagnetic design is to obtain a multipolar field with the required field quality and a sufficient safety factor. For superconducting magnets, the field quality is dominated by the current distribution in the coil, so they are known as coil-dominated magnets. Analytical and numerical field computation methods can be used to calculate the magnetic field from a given current distribution. Usually, computer codes are used for 2D and 3D field analysis in the electromagnetic design. However, the design and optimization process of superconducting magnet are time consuming due to the rather complicated geometry of the magnet, the requirement of an extremely uniform field, and the difficulty in solving an inverse problem. Before entering into an extensive and detailed 2D and 3D magnetic field study, a basic and conceptual design is necessary. It will allow one to derive the most important characteristics and parameters of the magnet with relatively good accuracy, and help one to find a reasonable starting point for the numerical design and optimization.

For simple dipole and quadrupole sector coils, there are already some analytical formulas to calculate the field strength in the bore according to coil parameters and current density [2–3,7–8]. L. Rossi and E. Todesco have derived approximate formulas that provide the reachable field as a function of the magnet aperture, the coil cross-sectional area and the superconducting cable parameters in superconducting dipole and quadrupole magnets [4–5,9]. F. Borgnolutti et al. have proposed analytical formulas to evaluate the magnetic energy stored in superconducting quadrupoles made of sector coils [10]. These formulas are expressed in terms of engineering current density, and involve an intermediate variable “equivalent coil width” in which the area of a standard coil is the same as that of the analyzed coil.

Excitation current is a basic and important parameter, not only for magnet operation but also in the short sample test of superconductor. Given the current, the current density can be calculated according to the conductor parameters.

Ampere-Turns can be calculated as total excitation current in the coil to achieve the desired field strength in the magnet aperture. They have been widely used in conventional magnets to estimate the coil size, magnet cross-section and the design parameters without the need to carry out detailed magnetic

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designs [11–13]. However, a general expression of Ampere-Turns for superconducting magnets is not available in the literature.

The main purpose of this paper is to find general equations of excitation Ampere-Turns for superconducting dipole and quadrupole magnets based on sector coils. Firstly, the Ampere-Turns of iron-free dipole and quadrupole coils are developed. Then the effect of iron yoke is included using the image current method. The analytical formulas of fields generated by line currents are used to derive the expressions of Ampere-Turns, which is different from the approach of using magnetic circuit and Ampere′s law in conventional magnets [11–13]. The general expressions are applied to realistic superconducting magnets, and the comparison with Ampere-Turns of conventional magnets is presented.

2. Ampere-Turns of iron-free coil

Similar to conventional magnet, Ampere-Turns of superconducting magnet can be defined as $NI = N \bullet I$, where N is the conductor turns of each pole, and I is the excitation current.

Usually, the length of superconducting magnet is much larger than the transverse dimension. A 2D field analysis is sufficient for the study of Ampere-Turns, since the 3D fringe field has a negligible effect on the achieved field level in the magnet bore.

2.1. Current shell with ideal cos $n\theta$ current distribution

The complex magnetic field can be expressed as a multipolar expansion [1–3]

$$B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1} \tag{1}$$

where B_x and B_y are the x and y components of magnetic field at position $z = x+iy$, R_{ref} is the reference radius, B_n and A_n are the normal and skew multipole fields, respectively. Using the European field index notation, the multipole field with $n=1$ indicates a dipole field.

As well known, the multipole field in the aperture generated by a line current I at position $z_0 = x_0 + iy_0 = r_0 e^{i\theta_0}$ reads [2,5,7]

$$B_n = -\frac{\mu_0 I}{2\pi}\frac{R_{ref}^{n-1}}{r_0^n} \cos n\theta_0 \tag{2}$$

$$A_n = \frac{\mu_0 I}{2\pi}\frac{R_{ref}^{n-1}}{r_0^n} \sin n\theta_0 \tag{3}$$

where μ_0 is the permeability of free space.

The ideal way to create a pure multipole field is to have a superconducting coil where the current density is proportional to the cosine of azimuth. Consider a shell with a current density that varies with the azimuthal angle $J = J_E \cos n\theta$, where J_E denotes the maximum engineering current density in the coil. When $n=1$, the shell becomes a pure dipole coil, as shown in Fig. 1.

Using the integration of fields generated by line currents, a simple relation of dipole field in the magnet aperture exists

$$B_1 = \int_{r_1}^{r_2}\int_0^{2\pi} \frac{\mu_0 J_E \cos^2\theta}{2\pi r} r dr d\theta = \frac{\mu_0 J_E}{2}(r_2 - r_1) \tag{4}$$

where r_1 and r_2 are the inner radius and outer radius, respectively. Because of the perfect four-fold symmetry of the coil, all skew field harmonics equal zero.

The number of Ampere-Turns for each pole is

$$(NI)_{Dipole} = \int_{r_1}^{r_2}\int_0^{\pi/2} J_E \cos\theta r\, dr\, d\theta = \frac{J_E(r_2^2 - r_1^2)}{2} \tag{5}$$

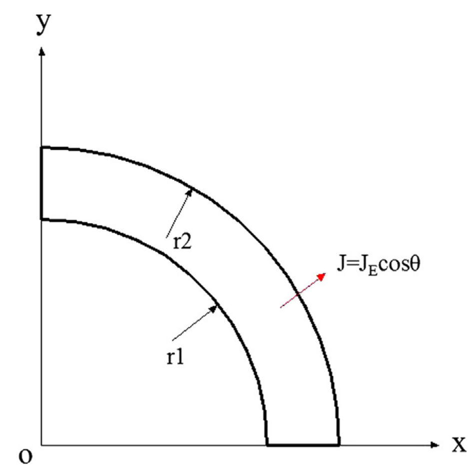

Fig. 1. Dipole coil with cos θ current distribution (one quarter coil).

Comparing the above two equations yields

$$(NI)_{Dipole} = \frac{B_1(r_1 + r_2)}{\mu_0} = 2\frac{B_1 \overline{R}}{\mu_0} \tag{6}$$

where $\overline{R}$ is the average radius of the dipole coil $\overline{R} = (r_1 + r_2)/2$.

When $n=2$, the shell becomes a quadrupole coil. The quadrupole field in the aperture is expressed as

$$B_2 = \int_{r_1}^{r_2}\int_0^{2\pi} \frac{\mu_0 J_E R_{ref} \cos^2 2\theta}{2\pi r^2} r\, dr\, d\theta = \frac{\mu_0 J_E R_{ref}}{2} \ln\frac{r_2}{r_1} \tag{7}$$

The Ampere-Turns for each pole are

$$(NI)_{Quadrupole} = \int_{r_1}^{r_2}\int_0^{\pi/4} J_E \cos 2\theta r\, dr\, d\theta = \frac{J_E(r_2^2 - r_1^2)}{4} \tag{8}$$

Since $B_2 = GR_{ref}$, Eq. (8) becomes

$$(NI)_{Quadrupole} = -\frac{G(r_2^2 - r_1^2)}{2\mu_0 \ln(r_1/r_2)} \tag{9}$$

Using power series expansion of the function $\ln(r_1/r_2)$, Eq. (9) can be simplified.

Let $t = r_1/r_2$; then $0 < t < 1$.

$$\ln t = \ln(1+(t-1)) \approx (t-1) - \frac{(t-1)^2}{2} + \frac{(t-1)^3}{3} - \frac{(t-1)^4}{4} \tag{10}$$

Using the above equation, it is easy to prove that

$$\ln t \approx -2\frac{1-t}{1+t} \tag{11}$$

A parameter γ is defined as the ratios of the left hand side and right hand side terms in Eq. (11) to show the relative error of approximation.

$$\gamma = \ln t \Big/ \left(-2\frac{1-t}{1+t}\right) \tag{12}$$

It is shown in Fig. 2 that the discrepancy of γ from 1 is within a few percents when $1/3 < t < 1$, corresponding to most practical coil layouts. It will be further discussed in Section 5.

Combining Eqs. (9) and (11), we have

$$(NI)_{Quadrupole} \approx \frac{G\overline{R}^2}{\mu_0} = 2\frac{G\overline{R}^2}{2\mu_0} \tag{13}$$

where $\overline{R}$ is the average radius of quadrupole coil.

For conventional magnets, in which the field quality is dominated by the shape of iron pole, the Ampere-Turns for dipole and quadrupole magnets are expressed as follows [11–13]:

$$(NI)_{Dipole,Iron} = \frac{Bh}{\mu_0} \tag{14}$$

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