Physica C 500 (2014) 25–32

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Design optimization of superconducting magnetic energy storage coil

Uttam Bhunia *, Subimal Saha, Alok Chakrabarti

Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700 064, India

ARTICLE INFO

Article history:
Received 14 August 2013
Received in revised form 8 November 2013
Accepted 20 February 2014
Available online 28 February 2014

Keywords:
SMES
Transient load
Rutherford-type cable
Optimization

ABSTRACT

An optimization formulation has been developed for a superconducting magnetic energy storage (SMES) solenoid-type coil with niobium titanium (Nb–Ti) based Rutherford-type cable that minimizes the cryogenic refrigeration load into the cryostat. Minimization of refrigeration load reduces the operating cost and opens up the possibility to adopt helium re-condensing system using cryo-cooler especially for small-scale SMES system. Dynamic refrigeration load during charging or discharging operational mode of the coil dominates over steady state load. The paper outlines design optimization with practical design constraints like actual critical characteristics of the superconducting cable, maximum allowable hoop stress on winding, etc., with the objective to minimize refrigeration load into the SMES cryostat. Effect of design parameters on refrigeration load is also investigated.

1. Introduction

The power quality is one of the most important issues in power distribution systems. Special electrical equipment, critical industry process including those that employ embedded processors or microcontrollers, etc. have stringent requirement of quality power and are sensitive to any voltage sag or short interruptions in supply. Superconducting magnetic energy storage (SMES) system has the ability to mitigate short time voltage fluctuation and sag effectively. The SMES system will drastically reduce the downtime of the facility due to unexpected power fluctuation, sag, etc. Optimization of conductor requirement for superconducting solenoid-type coil has been studied for past few decades [1–4]. The published works were mostly dealing with the relationship between geometrical parameters of coil and magnetic field to reduce the conductor volume. Borchi [5] developed a multi-objective technique using fuzzy logic (FL) along with finite element method to optimize the volume of micro-superconducting energy storage system for toroidal type and axi-symmetric configuration. Higashikawa Kohei et al. [6] used genetic algorithm (GA) along with finite element (FE) to optimize high temperature superconducting (HTS) coil geometry for SMES to minimize ac loss. Korpela et al. [7] and several other groups used sequential quadratic programming (SQP) together with FEM to minimize conductor volume of HTS based SMES coil. The primary attention about HTS SMES system has been focused on conduction-cooled operation at about 20 K. Due to its inferior ac characteristics and high material cost (approximately two orders more for first generation bismuth based Bi2223 tape than niobium titanium (Nb–Ti) at present times), one better and tempting option is thus to utilize common work horse Nb–Ti as a conductor. Moreover, after the commercial availability of 4 K cryo-cooler in recent years, it has been found that Nb–Ti based low temperature superconductor (LTS) along with helium re-condensing technology are still far better choice for small scale SMES development as far as operational reliability and capital investment is concerned. In general, the SMES system is operated in DC energy storage charging, freewheeling and discharging mode. But, if energy is charged or discharged, a time varying magnetic field causes dynamic loss especially the ac loss in the stabilizer, superconducting cable, all metallic parts, etc. In this study, we have considered the solenoid-type SMES coil since it has the advantage of high energy storage density and simplest configuration. The primary aim of this study is to design and develop small scale SMES system with lower operating cost so that cryo-cooler based helium re-condensing system become feasible for practical application. Unlike previous published papers, this work gives an analytical formulation of the optimization problem in terms of coil parameters and aims to minimize cryogenic refrigeration load including both dynamic and static heat load into the cryostat using differential evolution (DE) algorithm, which in turn reduces the operating cost of the system. The corresponding optimal design of 5 MJ class SMES coil using Rutherford-type cable is discussed as a case study. Effect of allowable hoop stress and maximum allowable voltage across the coil to the refrigeration load and coil parameters has also been investigated.

* Corresponding author. Tel.: +91 33 2321 3092; fax: +91 33 2334 6871.
E-mail address: ubhunia@vecc.gov.in (U. Bhunia).

http://dx.doi.org/10.1016/j.physc.2014.02.019
0921-4534/

2. Mathematical description

2.1. Stored energy and its dependence

We consider solenoid-type coil with basic parameters as shown in Fig. 1. The geometry of a solenoid is defined by its inside radius (a), shape factor $\alpha = b/a$ and $\beta = l/a$, where $2l$ is solenoid length and b the outside radius. The center magnetic field B_0 and peak magnetic field B_m on winding for a thick solenoid coil of finite length may be written as:

$$B_0(\alpha,\beta,a) = \mu_0 aJ(B_m)K_0(\alpha,\beta) \tag{1}$$

$$B_m(\alpha,\beta,a) = \mu_0 aJ(B_m)K_m(\alpha,\beta) \tag{2}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability in free space, $J(B_m)$ is the operating current density of the coil. For a thick solenoid coil, peak or maximum field (B_m) exists at the innermost layer at coil mid-plane ($z = 0$). Here $K_m(\alpha, \beta)$ is expressed in a Legendre polynomial series expansion [8] as:

$$K_m(\alpha,\beta) = K_0(\alpha,\beta) - \frac{1}{2}K_2(\alpha,\beta) + \frac{3}{8}K_4(\alpha,\beta) - \frac{5}{16}K_6(\alpha,\beta) + \cdots \tag{3}$$

The polynomial terms K_0, K_2, K_4, and K_6 are dimensionless form factors expressed as:

$$K_0(\alpha,\beta) = \beta \ln \frac{\alpha + (\alpha^2+\beta^2)^{1/2}}{1+(1+\beta^2)^{1/2}} \tag{4a}$$

$$K_2(\alpha,\beta) = \frac{1}{2\beta}(c_1^{3/2} - c_3^{3/2}) \tag{4b}$$

$$K_4(\alpha,\beta) = \frac{1}{24\beta^3}\left[c_1^{3/2}(2+3c_2+15c_2^2) - c_3^{3/2}(2+3c_4+15c_4^2)\right] \tag{4c}$$

$$K_6(\alpha,\beta) = \frac{1}{240\beta^5}\left[c_1^{3/2}(8+12c_2+15c_2^2-70c_2^3+315c_2^4) - c_3^{3/2}(8+12c_4+15c_4^2-70c_4^3+315c_4^4)\right] \tag{4d}$$

where

$$\left.\begin{array}{ll} c_1 = \frac{1}{1+\beta^2}; & c_2 = \frac{\beta^2}{1+\beta^2}; \\ c_3 = \frac{\alpha^2}{\alpha^2+\beta^2}; & c_4 = \frac{\beta^2}{\alpha^2+\beta^2}; \end{array}\right\} \tag{5}$$

The inductance (L) of the air core thick solenoid coil of finite length is given by:

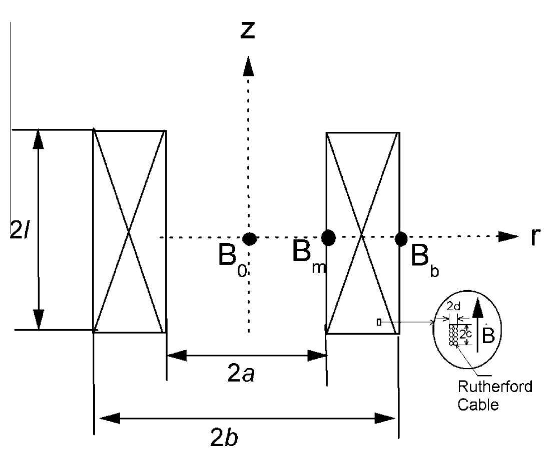

Fig. 1. Schematic of solenoid coil parameters.

$$L(\alpha,\beta,a) = aN(\alpha,\beta,\alpha)^2\theta(\alpha,\beta) \tag{6}$$

where $N(\alpha, \beta, a)$ is the total number of turns of the solenoid. Knowing the conductor dimension, N may be determined in terms of coil parameters. The geometry dependent factor $\theta(\alpha, \beta)$ is given by [9]:

$$\theta(\alpha,\beta) = \frac{\mu_0\pi}{8\beta}\frac{(\alpha+1)^2}{1+0.9\frac{\alpha+1}{4\beta}+0.64\frac{\alpha-1}{\alpha+1}+0.84\frac{\alpha-1}{2\beta}} \tag{7}$$

The energy stored in a solenoid-type SMES coil is expressed as:

$$E_S(\alpha,\beta,a) = \frac{1}{2}LI^2 = \frac{2\,a^3\,B_m(\alpha,\beta,a)^2\beta^2(\alpha-1)^2\theta(\alpha,\beta)}{K_0(\alpha,\beta)^2 x(\alpha,\beta,a)^2} \tag{8}$$

Peak field to center magnetic field ratio is defined as:

$$x(\alpha,\beta,a) = \frac{B_m(\alpha,\beta,a)}{B_0(\alpha,\beta,a)} \tag{9}$$

The winding volume is written as:

$$V(\alpha,\beta,a) = 2\pi a^3\beta(\alpha^2-1) \tag{10}$$

2.2. Operating current density

The coil is immersed in a pool of liquid helium at 4.2 K. The operating current of superconducting coil depends upon the critical characteristics of the superconducting cable, which is a strong function of peak magnetic field (B_m) inside winding and operating temperature. Considering the space or filling factor (λ) of the coil, the safety margin factor (ζ) over critical characteristics of the superconducting cable (i.e. J_C vs B) , operating current density (J) of coil is determined in terms of coil peak field (B_m) as follows:

$$J(B_m) = J_C(B_m)\lambda\,(1-\zeta) \tag{11}$$

Safety margin factor ζ needs to be considered carefully depending on critical current degradation, minimum quench energy (MQE) of the cable, cooling and winding details, operating temperature margin, etc. However, for the present study we assume the operating current safety margin as 30%. The safety margin factor ensures that the coil will not quench in normal operation. The winding packing fraction (λ) depends on winding details such as insulation thickness, and inter-turn spacers. Over the available type of conductor, Rutherford-type cable has been chosen for the present study since it offers relatively low ac loss and liquid helium bath cooling suitable for small-scale transportable SMES unit is feasible to adopt. For the present study, we assume the winding space factor (λ) as 0.85. However, depending on the winding scheme, insulation, etc. space factor needs to be determined appropriately. In order to relate the coil parameters with operating current density (J), J is fitted with peak magnetic field B_m in the following form as:

$$J(\alpha,\beta,a) = \frac{p}{q+\frac{B_m}{J(B_m)}} \tag{12}$$

Here, p and q are the parameters fitted from J vs B_m/J plot. Substituting from Eq. (2), operating current density can be expressed as:

$$J(B_m) = J(\alpha,\beta,a) = \frac{p}{q+\mu_0 aK_m(\alpha,\beta)} \tag{13}$$

For example, Nb–Ti alloy based Rutherford-type cable as specified in Table 1 has measured critical characteristics as shown in Fig. 2(a) and operating current density J at 4.2 K varies with B_m/J as shown in Fig. 2(b). The fitted parameters are found as, $p = 7.6322$ T and $q = 1.42619 \times 10^{-8}$ Tm^2/A for this particular cable.