Compensation of Magnetization Effects in Superconducting Accelerator Magnets

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Abstract—Magnetization effects in the coils of superconducting accelerator magnets deteriorate the field quality at injection field level. The CERN field computation program ROXIE has recently been extended to calculate the persistent currents using a semi-analytical hysteresis model for hard superconductors. The model is combined with the coupling method of finite- and boundary-elements for the calculation of the nonlinear iron yoke. This numerical method avoids the meshing of air domains and of the superconducting coil. Disjoint ferromagnetic iron domains can be meshed independently. This allows the easy modeling of very thin layers of arbitrary shape.

In this paper, the reduction of persistent current induced field errors by means of a ferromagnetic sheet in the aperture, a ferromagnetic (coil protection) shield and thin shims inside the superconducting cable are discussed.

Index Terms—Filament modeling, persistent currents, superconductor magnetization.

I. INTRODUCTION

THE LARGE Hadron Collider (LHC) [1], a proton–proton superconducting accelerator, will consist of about 8400 superconducting magnet units of different types with superconducting coils made of type II hard superconductors in a filamentary structure. The individual filaments react on the applied magnetic field macroscopically with a superconductor magnetization resulting from induced bipolar current distributions, so called persistent currents. Persistent currents do not decay, but persist due to the lack of resistivity in the material. Since the field quality in the aperture of superconducting magnets is dominated by the source current distribution, the induced persistent currents considerably deteriorate the field quality for low excitation currents.

For the calculation of compensation methods, the persistent current model is combined with the coupled boundary element/finite element method (BEM–FEM-method) [2] and incorporated in the CERN field computation program ROXIE [3]. The BEM–FEM-method is specially suited for this application since the meshing of the air regions in the magnets can be omitted completely. The coil does not have to be modeled in finite elements and fields arising from current sources in the coil are calculated by means of the Biot–Savart Law. The surrounding nonlinear iron yoke and all disjoint ferromagnetic parts, e.g., strips in the aperture of the magnet or thin shims inside the superconducting cable can be meshed independently and can assume arbitrary shapes. These strips or shims can then be used for the part compensation of persistent currents.

The method for the computation of persistent currents is based on the measured critical current density j_c of the superconductors and calculates the filament magnetization by means of the critical state model [4].

The individual filament magnetization depends on the applied field and therefore on the position in the coil cross-section. Also the filament history has to be considered since hysteresis arises from the flux pinning.

The input function $j_c(B, T)$ only depends on the material properties of the superconductor but is independent of geometrical parameters such as the filament diameter or shape, and the ratio λ of the superconductor to total strand volume. The method reproduces the hysteretic behavior for arbitrary turning points in the magnet excitation cycle including minor loops. The repercussion of the filament magnetization on the external magnetic field has to be considered, since the original local field configuration changes due to the field of the filaments. Therefore, an iteration of the magnetization as a function of the magnetic induction B is performed.

II. MAGNETIZATION CALCULATION IN THE CABLE

Different magnetization models for superconductors can be found in literature (e.g., [5], [6]). These models usually give expressions for the magnetization and the screening field produced by slices of finite thickness of the superconducting material. The model used here calculates the *continuous course of the magnetic field* inside the filament by means of a differential approach. It is assumed that the induced persistent currents produce a pure dipole field and therefore can be represented by two intersecting ellipses each carrying the critical current density $\pm j_c$. The dependence of the critical current density on the position inside the filament and on the external field value is considered and j_c determined by means of a current fit [7] for the LHC NbTi cables.

An entity q denoting a relative penetration parameter for each filament has been introduced in order to derive equations for the magnetic induction $B(q)$ and the magnetization M in the filament cross-section. It can be understood as a normalized coordinate inside the filament. Considering the j_c -fit, we get an expression for the magnetization of a partly penetrated filament (1 layer i) to:

$$M_i = \frac{\pm 4r}{\pi} \int_{q_i}^{q_i+1} j_c(B(q))(1-q)^2 dq. \quad (1)$$

The sign of M_i depends on the actual branch on the hysteresis curve. Changes in the external field direction produce minor loops (indexed with i) such that the magnetization is obtained

as the superposition of individual layers. Therefore the resulting magnetization: $M = \sum_{i=1}^n M_i$. The model is described in detail in [8]. A typical distribution for the magnetic induction $B(q)$ and the appropriate critical current density $J_c(q)$ versus the penetration parameter q is shown in Fig. 1. The computed distribution arises after external field changes from negative values to an outside field of 0.08 T, for a filament radius $r_f = 3.5 \mu\text{m}$. From the plot one can also see the increase of the critical current density $J_c(q)$ with decreasing local field in the filament. $|J_c(q)|$ reaches its peak value for $B(q) = 0$ inside the filament.

A computed magnetization curve for one filament with filament radius $r_f = 3.5 \mu\text{m}$ at a temperature of 1.9 K is shown in Fig. 2. The curve is compared with measurements [9] of a strand and has therefore to be multiplied with the filling factor λ (here: $\lambda = 1/2.95$). As can be seen, the shift with respect to the ordinate axis is fully reproduced and the curves show good agreement except for the region of B_{out} close to zero. There the difference in magnetization between a strand and one filament becomes significant. However, due to the existing spread of magnetization along the cable, this region smooths out, resulting in the dashed curve (see [8] for details).

In order to perform any calculation of field errors in superconducting magnets, the combination of various materials as, e.g., the nonlinear iron yoke, ferromagnetic parts and superconductors have to be dealt with by the field computation software. Hence, the superconductor magnetization model has been combined with numerical field solvers by incorporating the model into the field computation program ROXIE [3]. ROXIE supports two numerical principles, a pure FEM solver and the BEM–FEM coupling method [2]. The latter has been used for all calculations in this paper.

III. THE COMBINATION WITH THE NUMERICAL METHOD

The computation area in the BEM–FEM method comprises different domains: The nonmeshed air domain (boundary element domain) in which the superconducting coil is positioned and multiple domains with different magnetic features (finite element domains). The field arising from the coil is calculated analytically by means of the Biot–Savart–Law. From the source currents, the source vector potential on the coupling boundary between the air domain and the FEM domains is calculated. A system of linear equations resulting from the BEM–FEM coupling method is solved iteratively to get the vector potentials from the FEM domains. One gets the magnetic induction at the evaluation point by superposing the source fields from the coil and the iron contribution. The BEM–FEM-method is described in detail in [2] and the combination with the model for the filament magnetization in [10].

A comparison of the computed values with measurements [11] taken at CERN is shown in Fig. 3 (for the optimized lower order multipole¹ b_3). The plot shows measurements for both magnet apertures, which should ideally be identical. The deviations between the two apertures can arise, e.g., from small differences in the coil geometry. The curves show a good agreement

Fig. 1. Magnetic induction $B(q)$ (solid line) and the corresponding current density (dashed line) as a function of the penetration depth q .

Fig. 2. Computed magnetization curve compared with measurements of a superconducting strand [9].

Fig. 3. Odd lower order multipole b_3 calculated at 17 mm radius and compared with measurements from the test magnet including the magnetic coil protection sheet. The dashed line represents the initial state curve, where no measurements exist.

between calculated and measured multipoles. Since the magnetization depends on the history seen by the strands, the calculation always starts with an initial state curve. From the comparison of measured values with calculations, it can be seen that in order to reproduce the measurements taken during an upramp-cycle, a complete history (by means of calculating up–down–up–ramp cycles) has to be produced first. In the following plots, the multipoles from initial state curve are shown additionally (dashed lines) to illustrate this fact.

¹In accelerator magnets, the field in the magnet aperture is usually expressed in terms of Fourier coefficients, so called multipoles, given at a reference radius (here 17 mm) and in units of 10^{-4} [3].

TABLE I
COMPARISON OF CALCULATED LOWER ORDER MULTIPOLES CALCULATED AT 17 mm REFERENCE RADIUS WITH/WITHOUT THE M(B)-ITERATION FOR DIFFERENT EXCITATION STEPS

B_1	0.59 T		1 T		1.3 T	
Iterat.	no	yes	no	yes	no	yes
b_2	-2.63	-2.84	-2.82	-2.84	-2.84	-2.84
b_3	-3.10	-2.04	1.63	2.16	2.93	3.30
b_4	0.05	0.09	0.05	0.09	0.06	0.09
b_5	0.04	0.01	-0.55	-0.55	-0.67	-0.67

Fig. 4. 1st quadrant of the LHC dipole coil with ferromagnetic applets for part compensation of persistent current induced multipole errors.

IV. THE M(B)-ITERATION

The ROXIE program uses an M(B)-Iteration method to calculate the repercussion of the magnetic field produced by the persistent currents on the applied field from the source currents. For this purpose, a fix point iteration has been carried out [12] which is of the following structure:

$$\mathbf{B}^{(k-1)} \rightarrow \mathbf{M} \rightarrow \mathbf{B}^{\text{PERS}} \left(\underbrace{\rightarrow \mathbf{B}^{\text{IRON}}(\mathbf{B}^{\text{PERS}})}_{\text{optional}} \right) \rightarrow \mathbf{B}^{(k)}$$

where (k) denotes the iteration step. The update of the influence of the persistent currents on the nonlinear magnetic domains (in parentheses) is optional, its necessity depending on the vicinity of source currents and iron domains. The fix point iteration has been combined with an overrelaxation method [13] in order to stabilize and accelerate the convergence. Field distributions are calculated and the changes in the computed multipoles are presented in Table I for different source currents in an up-down-up-ramp cycle of 0.17 T $\rightarrow$ 1.7 T $\rightarrow$ 0.04 T $\rightarrow$ 1.42 T. All values in the table are taken from the second upramp branch. The table shows that the effect on the computed multipoles is highest for very low currents. Hence, the necessity of an M(B)-Iteration depends on the computed ramp cycle of the magnet, e.g., corrector magnets with a working point cycling around the null value are more critical than a bending dipole which is designed for a pure upramp powering cycle. The plots, together with the multipole-results lead to the conclusion that the iteration may not be omitted for correct field computations at low excitation currents (see [12] for details).

V. PART COMPENSATION OF PERSISTENT CURRENTS

Different approaches for part compensation of persistent currents have been discussed in literature recently, including correction strips made of ferromagnetic material or nonpowered superconductors. In this paper, intrinsic reduction of persistent current induced field errors by means of ferromagnetic applets is discussed. Fig. 4 shows the first quadrant of the LHC dipole coil including all three ferromagnetic compensation principles [(A)

Fig. 5. Odd lower order multipole b_3 calculated at 17 mm reference radius compared with measurements from the test magnet with and without the magnetic coil protection sheet.

TABLE II
EXPECTED VARIATION IN RELATIVE MULTIPOLE ERRORS Δb_n INCL. PERSISTENT CURRENTS (IN UNITS OF 10^{-4} AT 17 mm REFERENCE RADIUS). A COMPENSATION HAS BEEN CALCULATED BY MEANS OF A FERROMAGNETIC COIL PROTECTION SHEET FOR A RANGE OF 0.6–1.6 T

CPS	Calculated Values		Measured Values	
	no	yes	no	yes
Δb_2	0.001	0.041	0.277	0.142
Δb_3	5.721	3.632	5.981	1.370
Δb_4	0.002	0.003	0.007	0.018
Δb_5	0.721	0.337	1.076	0.036

ferromagnetic coil protection sheet, (B) ferromagnetic sheet inside the magnet aperture, (C) ferromagnetic cable shims]. All compensations have been calculated exemplarily for the LHC dipoles.

A. Ferromagnetic Coil Protection Sheet

One possible solution for a part compensation of the persistent current multipole errors has been found for superconducting dipoles by making the so-called coil protection sheets (CPS) from ferromagnetic material. Non-magnetic coil protection sheets consisting of different layers of the same material have originally been foreseen in the magnet design in order to protect the coil against damages from the surrounding stainless steel collars. It has to be emphasized here that we aimed for a compensation of the *nonlinearities* in the odd multipoles b_3 and b_5 rather than the *absolute value*. The compensation consists of changing one layer of the CPS from nonmagnetic stainless steel to iron sheets with a very low content of impurities (99.99% pure Fe). The angle α of the magnetic part has been chosen to 52° in order to fully cover the coil. An experimental verification of the compensation principle has been carried out at CERN in one of the short model dipole magnets. In Fig. 4, the ferromagnetic part of the CPS on the first quadrant of the LHC dipole coil is shown. The sheet is mounted between the outer coil radius and the collars. Fig. 5 shows the difference in the calculated multipole b_3 for geometries with and without the ferromagnetic CPS compared with measurements taken at CERN. As already mentioned, it is important to calculate a full cycle in up-down-up-ramp of the magnet in order to achieve results for an LHC operating cycle that can be compared to the measurements. The LHC dipoles will be ramped up from about 0.6 T (injection field) to about 8.5 T (nominal field). For the calculations, an interval up to 1.6 T has been taken, since the relative field errors due to the

Fig. 6. Odd lower order multipoles b_3 and b_5 calculated at 17 mm radius including a ferromagnetic sheet inside the magnet aperture.

persistent current effect vanishes for higher fields. In this range, the calculated curves show a reduction in the nonlinearities of multipole b_3 of about 60% (while multipole b_5 can be reduced to about 50% the original value). Although there is a small deviation between calculated and measured values, the curves well validate the part compensation effect.

B. Ferromagnetic Sheet Inside the Aperture

Part compensation can also be obtained by means of a ferromagnetic sheet being attached on the outer radius of the already existing cold bore [1] inside the magnet aperture (as indicated in Fig. 4). The cold bore has an outer radius of 26.5 mm. The thickness of the sheet has been chosen to 40 μm . As can be seen in Fig. 6, the ferromagnetic sheet partly compensates the multipole variation of the lower order odd multipoles, reducing the variation for multipole Δb_3 from 5.72 to 1.12 units while Δb_5 slightly increases from 0.72 to 1.34 units.

C. Ferromagnetic Shims Inside the Conductors

A compensation by means of thin ferromagnetic shims inserted into the cable of the inner layer of the coil (as indicated in Fig. 4) has been calculated. The shims are centered inside the keystone cables and have a thickness of 0.1 mm. Although a compensation takes place, the calculated results were not satisfying for application in magnets with NbTi cables, since the shims resulted in a strong overcompensation of the persistent current effect. The calculation (incl. the shims) resulted in

a increase of multipole b_3 to 37.4 units at injection field and 8.8 units at nominal field level, resp. (all calculations carried out at 17 mm reference radius). A reduction in the size of the shims can be done in principle, however could lead to difficulties with a precise centering inside the cable and has therefore not been considered. The method of cable shims can be interesting for cables with a considerable higher filament size as it is the case for cables made of, e.g., Nb3Sn superconductor material.

VI. CONCLUSIONS

A hysteresis model for the filament magnetization due to persistent currents has been developed and combined with the BEM-FEM [2] numerical field-computation method. By means of an M(B) iteration, the effect of part compensation for persistent current induced multipole errors has been calculated accurately. Three intrinsic compensation principles for a reduction of the odd lower order multipole errors are introduced and discussed. From the methods presented here, the compensation with a thin sheet inside the magnet aperture is easy to be carried out and the most effective.

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