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Analytical Modeling of an Inductor in a Magnetic Circuit for Pulsed Field Magnetization of HTS Bulks

Mohamed Elbaa, Kévin Berger, Bruno Douine, El Hadj Ailam, Salah Eddine Bentriddi

Abstract— The development of bulk magnets based on REBCO type superconductors that can generate up to 17 T requires the implementation of a magnetization system, sometimes pulsed. Therefore, at least one coil around the High Temperature Superconducting (HTS) bulk is required. There are numerous formulas to calculate electromagnetic quantities of an axisymmetric coil in the air. In this paper, we proposed an analytical approach in order to assess the magnetic vector potential and to compute the inductance of a coil having a rectangular cross-section and concentric with a magnetic circuit including an air-gap. On a proposed geometry, analytical results are compared with those obtained by using Finite Element Analysis (FEA) achieved with COMSOL Multiphysics software. The obtained analytical expressions give accurate results with an error less than 1% when 50 harmonic terms are used in the Fourier series expansion.

Index Terms— Electromagnets, Inductance, Modeling, Pulse measurements, Solenoids.

I. INTRODUCTION

IN electrical engineering as in physics, superconductors are widely used to obtain very strong magnetic fields. Superconducting bulk magnets made with (RE)BCO type superconductors are being considered to undergo pulsed magnetization and to reach very high magnetic flux density up to 17 T [1]. It is very important to estimate and evaluate the magnetic field components that strongly depends on the geometry of the used inductor, in the final aim to optimize the experimental configuration. In the design stage of the inductor needed for magnetizing the High Temperature Superconducting (HTS) bulks, modeling and simulation are highly recommended to perform necessary calculations of the different electromagnetic characteristics of the studied system, as the inductance of the coil. Sophisticated commercial software give very accurate results by considering the nonlinearity of materials involved in the studied problem. However, this method is computer consuming and poorly flexible to adjust with the problem design.

Analytical models have been proposed since a long time for computing the magnetic field distribution of ironless circular coils [2]–[10] and more recently for a axisymmetric coil with an iron core of finite length [11]. Although these methods give

accurate results, they are not suitable to study circular coils placed in a magnetic circuit containing a large air-gap.

In the present work, we propose to use analytical methods to achieve that task by the resolution of Laplace's and Poisson's equations. Such methods lead to meaningful solutions with very helpful physical insights at the design stage. They are useful tools during the optimization of the design since continuous derivatives are obtained from the analytical solution. It allows us to calculate the magnetic vector potential A in a non-closed magnetic circuit with an air-gap concentric with the coil. The air-gap can later be the location of an HTS bulk to be magnetized. The obtained analytical expression of the magnetic vector potential could later be used to calculate induced currents in HTS bulks based on the well-known "Brandt's method" developed in 1998 for disks and cylinders in an axial magnetic field [12], [13].

An axisymmetric problem has to be considered here, allowing some simplifications and considerations to obtain field components over the different regions of interest. Four regions have to be considered, three free space regions (air) and one region with the coil conductor. Both Dirichlet and Neumann conditions are considered on the problem boundaries. In each region, the analytical solution is obtained as combination of Bessel and Struve functions, where coefficients are determined by the use of interface conditions between successive regions. Then, the distribution of magnetic vector potential and magnetic flux density are calculated with help of MATLAB matrix inversion tool to determine the desired coefficients. Besides, a finite elements model is achieved with COMSOL Multiphysics software for the same definition of the problem. Analytical and FEA results are also compared and discussed in what follows.

II. PROBLEM FORMULATION AND ASSUMPTIONS

The geometry of the studied problem is shown in Fig. 1. The regions I , II and IV correspond to a free space filled with air, the region II corresponds to a circular coil of N turns with rectangular cross section with inner radius R_2 , outer radius R_3 and length $L = (Z_4 - Z_1)$. We consider a uniform current density J passing through the coil cross section in the θ -direction. The coil is centered on the air-gap of length $e = (Z_3 - Z_2)$ of the non-closed ferromagnetic circuit, located in the lower part as shown in Fig. 1. The whole system is limited in the axial direction by $z = 0$ and $z = Z_5$, where the outer boundaries of the magnetic circuit must be chosen sufficiently far away from the

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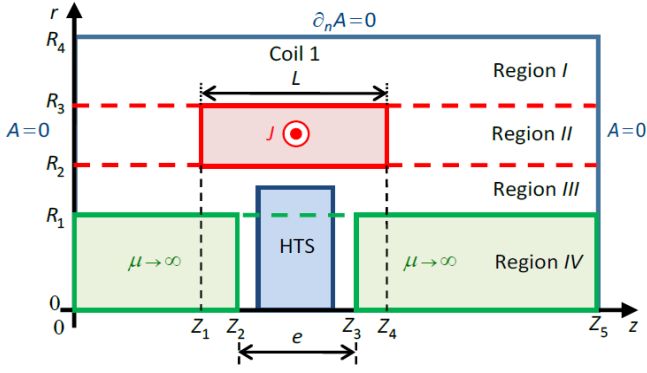


Fig. 1. Geometry of the studied problem. L is the length of the coil while e is the length of the air-gap of the magnetic circuit. Boundary with $\partial_n A = 0$ represents a boundary with to a ferromagnetic material, while boundaries with $A = 0$ correspond to a magnetic isolation.

calculation zone. The homogeneous Dirichlet boundary conditions are considered in regions *I*, *II* and *III*. However, homogeneous Neumann boundary conditions are used in regions *IV*.

Another approximation is employed in the modeling of this problem by assuming infinite permeability of the ferromagnetic circuit $\mu \rightarrow \infty$. This implies that the magnetic field is not calculated inside the ferromagnetic circuit. The interface conditions are then used to obtain the tangential component of magnetic field to be null.

The problem being axisymmetric, cylindrical coordinates are the most appropriated to the formulation of the magnetic vector potential, where only the θ -component exists and it depends only on the r and z coordinates.

The expressions of magnetic vector potential are obtained with resolving a Poisson's equation in the coil region and a Laplace's equation in the other regions, as follows:

$$\nabla^2 A_i = \begin{cases} -\mu_0 J & \text{for } i = II \\ 0 & \text{for } i = \{I, III, \text{ and } IV\} \end{cases} \quad (1)$$

By using the separation of variables method [11], [14], we consider the general solution of (1) in Regions *I* to *IV*.

Considering homogenous Dirichlet boundary conditions at $z = 0$ and $z = Z_5$ in Regions *I*, *II* and *III* and homogenous Neumann boundary conditions at $z = Z_2$ and $z = Z_3$ in Region *IV* we have:

$$\begin{cases} A_i(r, z = 0) = 0 \text{ and } A_i(r, z = Z_5) = 0 & \text{for } i = \{I, II, III\} \\ \partial_z A_{IV}|_{z=Z_2} = 0 \text{ and } \partial_z A_{IV}|_{z=Z_3} = 0 & \text{for } i = IV \end{cases} \quad (2)$$

Moreover, the tangential component of the magnetic field is null at $r = R_4$

$$\partial_r (rA_i)|_{r=R_4} = 0 \quad (3)$$

and the vector potential tends to zero when $r = 0$

$$A_{IV}(r = 0, z) = 0 \quad (4)$$

III. ANALYTICAL EXPRESSION OF THE MAGNETIC VECTOR POTENTIAL

Considering the boundary conditions (2), (3) and (4), the general solution of (1) can be expressed as:

$$A_I(r, z) = \sum_{n=1}^{\infty} b_n^I \left(\frac{K_0(\alpha_n R_4)}{I_0(\alpha_n R_4)} I_1(\alpha_n r) + K_1(\alpha_n r) \right) \sin(\alpha_n z) \quad (5)$$

$$A_{II}(r, z) = \sum_{n=1}^{\infty} \left(a_n^{II} I_1(\alpha_n r) + b_n^{II} K_1(\alpha_n r) \right) \sin(\alpha_n z) - C_n L_1(\alpha_n r) \quad (6)$$

$$A_{III}(r, z) = \sum_{n=1}^{\infty} \left(a_n^{III} I_1(\alpha_n r) + b_n^{III} K_1(\alpha_n r) \right) \sin(\alpha_n z) \quad (7)$$

$$A_{IV}(r, z) = A_0 r + \sum_{k=1}^{\infty} a_k^{IV} I_1(\beta_k r) \cos(\beta_k (z - Z_2)) \quad (8)$$

where n and k are positive integers, $\alpha_n = n\pi / Z_5$ and $\beta_k = k\pi / (Z_5 - Z_2)$ are the eigenvalues of the problem, I_1 and K_1 are respectively the modified Bessel functions of the first and second kind of order 1, and L_1 is the modified Struve function of order 1.

$$C_n = \frac{\mu_0 \pi J_n}{2\alpha_n^2}, \text{ and } J_n = \frac{2J}{n\pi} (\cos(\alpha_n Z_1) - \cos(\alpha_n Z_4)) \quad (9)$$

A_0 is an integration constant due to the Neumann boundary conditions in Region *IV*. It can be determined by applying the condition of continuity of the magnetic vector potential at the interface between Region *III* and Region *IV*.

$$A_{IV}(r = R_1, z) = A_{III}(r = R_1, z), \text{ for } z \in [Z_2, Z_3] \quad (10)$$

By integration in respect to the z variable of (10) over the interval $[Z_2, Z_3]$, we obtain:

$$A_0 = (R_1 (Z_3 - Z_2))^{-1} \sum_{n=1}^{\infty} m_n (a_n^{III} I_1(\alpha_n R_1) + b_n^{III} K_1(\alpha_n R_1)) \quad (11)$$

$$\text{with } m_n = \alpha_n^{-1} (\cos(\alpha_n Z_2) - \cos(\alpha_n Z_3))$$

$a_n^I, b_n^I, a_n^{II}, b_n^{II}, a_n^{III}, b_n^{III}$ and a_n^{IV} are the integration constants. The relations between those integration constants are determined by applying the interface conditions between the different regions.

IV. ANALYTICAL EXPRESSION OF THE MAGNETIC VECTOR POTENTIAL

The interface conditions must satisfy the continuity of the radial component of the flux density and the continuity of the axial component of the magnetic field. The radial and axial flux density can be deduced from the magnetic vector potential by:

$$B_r = -\partial_z A \text{ and } B_z = \frac{1}{r} \partial_r (rA) \quad (12)$$

The interface conditions between Region *I* and *II* at $r = R_3$ and region *II* and *III* at $r = R_2$ lead to:

$$\begin{cases} A_I(r = R_3, z) = A_{II}(r = R_3, z) \\ \partial_r (rA_I)|_{r=R_3} = \partial_r (rA_{II})|_{r=R_3} \end{cases} \quad (13)$$

$$\begin{cases} A_{II}(r = R_2, z) = A_{III}(r = R_2, z) \\ \partial_r (rA_{II})|_{r=R_2} = \partial_r (rA_{III})|_{r=R_2} \end{cases} \quad (14)$$

At the interface between Region *III* and *IV*, a specific conditions concerning the axial component of the magnetic field at $r = R_2$, piecewise defined, are applied around this interface because of the presence of the air-gap in the ferromagnetic circuit:

$$\partial_r (rA_{III})|_{r=R_1} = \begin{cases} 0, & z \in [0, Z_2] \\ \partial_r (rA_{IV})|_{r=R_1}, & z \in [Z_2, Z_3] \\ 0, & z \in [Z_3, Z_5] \end{cases} \quad (15)$$

The continuity of the radial component of the flux density yields to:

$$A_{IV}(r = R_1, z) = A_{III}(r = R_1, z), z \in [Z_2, Z_3] \quad (16)$$

The coefficients of the regions *I* to *IV* are related to (12), (13), (14), (15), (16), and using the Fourier series method, and rewriting equations in matrix and vectors format:

$$\begin{bmatrix} \eta_{11} & \eta_{12} & \eta_{13} & 0 & 0 & 0 \\ \eta_{21} & \eta_{22} & \eta_{23} & 0 & 0 & 0 \\ 0 & \eta_{32} & \eta_{33} & \eta_{34} & \eta_{35} & 0 \\ 0 & \eta_{42} & \eta_{43} & \eta_{44} & \eta_{45} & 0 \\ 0 & 0 & 0 & \eta_{54} & \eta_{55} & \eta_{56} \\ 0 & 0 & 0 & \eta_{64} & \eta_{65} & \eta_{66} \end{bmatrix} \begin{bmatrix} b_n^I \\ a_n^II \\ b_n^II \\ a_n^III \\ b_n^III \\ a_n^IV \end{bmatrix} = \begin{bmatrix} -C_n L_1(\alpha_n R_3) \\ -C_n L_0(\alpha_n R_3) \\ -C_n L_1(\alpha_n R_2) \\ -C_n L_0(\alpha_n R_2) \\ 0 \\ 0 \end{bmatrix} \quad (17)$$

$$\eta_{11} = \frac{K_0(\alpha_n R_4)}{I_0(\alpha_n R_4)} I_1(\alpha_n R_3) + K_1(\alpha_n R_3), \eta_{12} = -I_1(\alpha_n R_3),$$

$$\eta_{13} = -K_1(\alpha_n R_3), \eta_{21} = \frac{K_0(\alpha_n R_4)}{I_0(\alpha_n R_4)} I_0(\alpha_n R_3) - K_0(\alpha_n R_3),$$

$$\eta_{22} = -I_0(\alpha_n R_3), \eta_{23} = K_0(\alpha_n R_3), \eta_{32} = -I_1(\alpha_n R_2),$$

$$\eta_{33} = -K_1(\alpha_n R_2), \eta_{34} = I_1(\alpha_n R_2), \eta_{35} = K_1(\alpha_n R_2),$$

$$\eta_{42} = -I_0(\alpha_n R_2), \eta_{43} = K_0(\alpha_n R_2), \eta_{44} = I_0(\alpha_n R_2),$$

$$\eta_{45} = -K_0(\alpha_n R_2), \eta_{54} = I_1(\alpha_n R_1) h_{n,k} - I_0(\alpha_n R_1) f_{n,k},$$

$$\eta_{55} = K_1(\alpha_n R_1) h_{n,k} + K_0(\alpha_n R_1) f_{n,k}, \eta_{56} = I_0(\beta_n R_1) g_{n,k},$$

$$\eta_{64} = I_1(\alpha_n R_1) g_{n,k}, \eta_{65} = K_1(\alpha_n R_1) g_{n,k}, \eta_{66} = -I_1(\beta_n R_1)$$

with

$$f_{n,k} = \begin{cases} (-1)^{n+1} \frac{n^2}{n^2 - k^2} \sin(k\pi), & n \neq k \\ n\pi / 2, & n = k \end{cases} \quad (19)$$

$$h_{n,k} = 2m_n m_k (R_1 (Z_3 - Z_2))^{-1} \quad (20)$$

$$g_{n,k} = \begin{cases} \frac{2\alpha_n \beta_k}{(\alpha_n^2 - \beta_k^2)} \left(\cos(\alpha_n Z_2) + (-1)^{k+1} \cos(\alpha_n Z_3) \right), & \alpha_n \neq \beta_k \\ \frac{k\pi}{2} \sin(\beta_k Z_2) + \frac{1}{4} \left(\cos(\beta_k Z_2) + (-1)^{k+1} \cos(\beta_k Z_3) \right), & \alpha_n = \beta_k \end{cases} \quad (21)$$

Thus, we have to solve a system of six linear equations with six unknowns. By rewriting above equations in matrix and vectors format, a numerical solution can be found by using mathematical software, e.g. matrix inversion using MATLAB

tool. It should be noted here that a numerical matrix inversion is required for the calculation of the unknown coefficients which could be used even in symbolic form.

V. INDUCTANCE EXPRESSION

The inductance of the coil is related to the total stored magnetic energy:

$$W = \frac{1}{2} LI^2 = \frac{1}{2} \int_0^{2\pi} \int_{Z_1}^{Z_4} \int_{R_2}^{R_3} J A_{II}(r, z) r dr dz d\theta \quad (22)$$

Assuming that the current density is uniformly distributed over the whole cross section of the coil:

$$I = JS / N \text{ with } S = (R_3 - R_2)(Z_4 - Z_1) \quad (23)$$

where, N and I are respectively the number of turns in the coil and the electrical current in the wire. The magnetic vector potential is the one defined in the Region *II* of the problem.

Substituting (6) and (23) into (22) and integrating in respect to the r , θ and z variables, the obtained analytical expression of the inductance is given by:

$$L = 2\pi \frac{N^2}{JS^2} \sum_{n=1}^{\infty} \left\{ \frac{\pi}{2\alpha_n^2} \left(\begin{array}{l} a_n^II (R_3 U(R_3) - R_2 U(R_2)) \\ + b_n^II (R_3 V(R_3) - R_2 V(R_2)) \\ - \mu_0 J_n \frac{\alpha_n}{6\pi} (R_3^4 W(R_3) - R_2^4 W(R_2)) \\ (\cos(\alpha_n Z_1) - \cos(\alpha_n Z_4)) \end{array} \right) \right\} \quad (24)$$

where $\mathbf{U}(r)$, $U(r)$, $V(r)$ and $W(r)$ were defined in reference [11].

VI. ANALYTICAL RESULTS AND COMPARISON WITH FINITE ELEMENT SIMULATIONS

Table I contains the values of the geometric parameters used in our problem. The outer boundaries in the axial direction are chosen such that their values do not affect the obtained results. The analytical solutions in all the regions have been computed with a finite number of harmonic terms equal

TABLE I
GEOMETRIC PARAMETERS

Symbol	Quantity	Value
R_1	Lower edge of the domain in the radial direction	0.030 m
R_2	Inner radius of the coil	0.080 m
R_3	Outer radius of the coil	0.120 m
R_4	Upper edge of the domain in the radial direction	0.150 m
Z_1	Inner boundary of the coil	0.200 m
Z_2	Inner boundary of the air-gap	0.225 m
Z_3	Outer boundary of the air-gap	0.275 m
Z_4	Outer boundary of the coil	0.300 m
Z_5	Outer boundary of the domain in the axial direction	0.500 m
L	Axial length of the coil	0.100 m
e	Axial length of the air-gap	0.050 m
N	Number of turns of the coil	1000
J	Current density in the coil	5 A/mm ²
N_{\max}	Number of harmonic terms in Regions <i>I</i> to <i>IV</i>	50

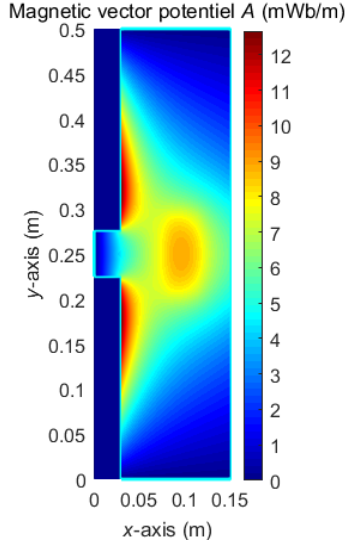


Fig. 2. Distribution of the magnetic vector potential around the air-gap.

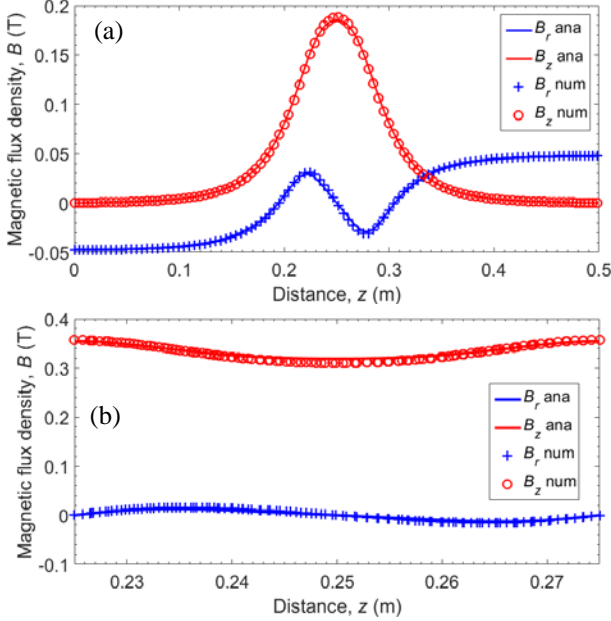


Fig.

3. Radial and axial components of the magnetic flux density B_r and B_z along the z -axis, (a) in the Region III at $r = (R_1 + R_2)/2$ and (b) in the air-gap at $r = R_1/2$.

to 50.

In order to validate our analytical results, we have to compare them with those obtained by using Finite Element Method (FEM) led on COMSOL Multiphysics software. The mesh size and the requested precision are chosen so that the quantities derived from the FEM calculation serve as a reference. Obviously, the same geometric parameters as those defined in Table I are used. Homogeneous Dirichlet and Neumann boundaries conditions are also considered in FEM simulations as with the analytical model.

Fig. 2 shows the distribution of magnetic vector potential of the defined problem when the air-gap is centered with the coil. The radial and the axial components of the magnetic flux density along the z -axis in Region III at $r = (R_1 + R_2)/2$ are plotted and compared with the numerical results in Fig. 3(a). Fig. 3(b) also shows B_r and B_z along the z -axis but in the air-gap, at $r = R_1/2$.

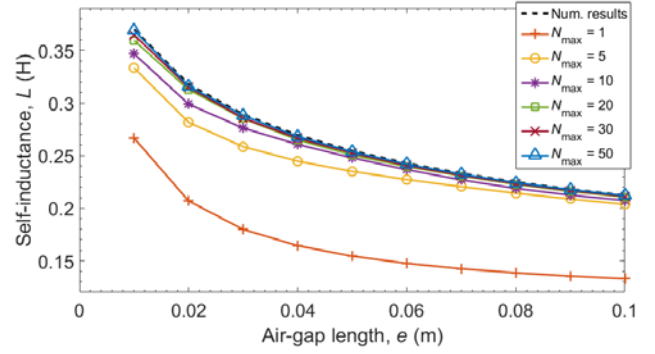


Fig. 4. Self-inductance of the coil using (24) with an air-gap length varying from 0.01 m to 0.05 m. Comparison between the numerical values obtained with COMSOL and analytical results for different number of harmonic terms from 1 to 50.

From Fig. 3 we can clearly observe that the results obtained by the analytical method are very closer to those obtained by the FEM software. A small discrepancy between the analytical and numerical results still exists. The maximal discrepancy is lower than 3% for the B_z component and around 10% for B_r . These discrepancies can be explained by the limitations of the analytic development, in particular the numerical errors linked to the matrix inversion which generates errors during the evaluation of the coefficients. Indeed, the use of modified Bessel functions leads to badly conditioned matrix.

Finally, Fig. 4 shows the self-inductance of the coil using (24) with an air-gap length varying from 0.01 m to 0.05 m. A comparison is made between the numerical values obtained with COMSOL and analytical results for different number of harmonic terms from 1 to 50. Obviously, the inductance decreases with the increase of the air-gap length. The higher the number of harmonic terms, the closer is the solution to the reference value obtained numerically. The maximal error is of 39.37%, 11.47%, 6.35%, 2.92%, 1.52% and 0.75% for a number of harmonic terms of 1, 5, 10, 20, 30, 40, and 50 respectively. We can conclude that the proposed formula is correct and efficient.

VII. CONCLUSION

In this paper, we have developed analytical formulas complementary to those proposed in [11] to calculate the inductance of a coil in an open magnetic circuit. We have shown that analytical methods provide very good match with numerical ones. An analytical expression to compute the inductance of a coil having a rectangular cross-section and concentric with an iron core including an air-gap is given. This value might be useful during studies concerning the magnetization by PFM of HTS bulks. The proposed analytical expressions of the magnetic vector potential could later be used to calculate induced currents in HTS bulks based on the well-known ‘‘Brandt’s method’’ developed in 1998 for disks and cylinders in an axial magnetic field.

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