Homogenization and Eddy Current Loss Approximation of Soft Magnetic Composite Material for Electrical Machines

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Keywords: Complex Permeability, Finite Element Analysis, Homogenization, Soft Magnetic Composite Material

Abstract

This paper investigates the soft magnetic composite (SMC) material consisting of irregular grains with induced eddy currents using finite element analysis (FEA). SMC material is made up of iron grains separated by insulation gap. The geometry of the material has been determined using an algorithm based approach and an image based approach. The effective reluctivity has been determined using two homogenization techniques. The first homogenization technique makes use of an energy formulation. The eddy current effects are evaluated taking into consideration the fill factor of the 2-D SMC material. A low frequency approximation is realized for the homogenized material. In the second technique, non-linear properties are determined using the time-stepping technique. A method has been proposed in FEA for directly including an analytical eddy current loss formula for rotating electrical machines with SMC material cores. The eddy current loss and torque have been determined for the radial flux permanent magnet synchronous machine (PMSM) having an SMC stator core and the results are then compared with the laminated stator core machine.

1 Introduction

The rapidly developing soft magnetic composite (SMC) material can be preferred as a substitute for the laminated steel as it imparts three dimensional flux path and eddy current losses are lower at high frequency when compared with the laminated steel [1–3]. The insulation gap in SMC material amplifies the resistivity which intercepts the long-range eddy current conduction between the iron grains making it operational at high frequencies [4]. SMC material has lower permeability than laminated steel which makes it suitable for PMSMs where magnetic reluctance of permanent magnets is a paramount [5]. Due to the heterogeneous nature of SMC materials, it is very costly and demanding to analyse the electrical machines having SMC stator core. Homogenization of SMC decreases the computation time. Various homogenization methods have been put forward in the past for the estimation of apparent resistivity of the SMC material but these methods do not embrace the induced eddy currents [6, 7]. Furthermore, the homogenization approach carried out in [8, 9] with the incorporation of eddy current is relevant only for laminated stack of cores and the bundled conductors. A semi-analytical approach has been opted in [10] for reckoning the uniform permeability of the round wires by modifying the classical Clausius–Mossotti method. An energy method has been proposed for square regular SMC iron grains with regular insulation gap in [11] for the calculation of permeability.

In this work, energy method is used for estimating the electromagnetic properties of the SMC material to integrate it at the electrical machine level. This method makes use of 2-D magnetodynamic FE approach for the computation of homogenized permeability and eddy current loss of the SMC material made up of irregular iron grains overlooking the saturation effect. To analyse the effect of saturation, a time-stepping scheme is opted.

Moreover, in a 2-D time stepping analysis of electrical machines, hysteresis models can be consolidated in a straightforward manner [12]. It is quite uneconomical to distinctly model the eddy current losses as it is inevitable to have a 3-D model. For laminated electrical steel, a novel method for incorporation of core energy dissipation in a time stepped 2-D model has already been proposed in [13].

In this paper, an analytical formula is estimated for directly assimilating the eddy current loss of SMC material in a time stepping technique. A posteriori estimation of eddy current losses in SMC stator core of radial flux surface mounted PMSM is performed. The SMC stator core losses are then compared with the laminated stator core at a very high speed.

1.1 Analytical Geometry of the SMC Material

This paper utilizes 2-D geometries of SMC material which have already been developed using the algorithm and image based approach in [14]. The idea of using these geometries is to make more realistic models for SMCs. The image based approach makes effective use of pixels which are then separated into triangles for the FEA.

For algorithm based approach, three different stages are executed. First stage involved determination and optimization of points for the iron grains. During the second stage, contacts are imposed between the iron grains and finally for the third
stage, the geometry of the SMC material is cropped and scaled for the purpose of the analysis [14].

In this paper, three different 2-D SMC material models with different fill factors are taken into consideration for the purpose of analysis (Table 1). These models are made up of irregular iron grains and insulation gaps. Here, iron grains (conductivity \( \sigma = 11.2 \) MS/m, relative permeability = 4000) are considered as isotropic and the insulation gap is taken as air (\( \sigma = 0 \), relative permeability = 1).

2 Permeability Calculation using Linear and Non-Linear Analysis

2.1 Linear Case

In the 2-D model of the SMC, we are enforcing a net flux density \( B \) along the \( x \)-axis. Taking into account the presence of symmetric fields, the magnetic vector potential (MVP) \( A \) is used to assess the value of flux \( \phi \) over the surface \( S \) of the two dimensional SMC material (domain \( \Omega \)) with imposition of Dirichlet boundary at the top \( t \) and bottom \( b \) of the surface. The \( A \) is considered in \( z \)-direction with the length \( l \) (taken very small 0.1 mm).

\[
\phi = l (A_t(x) - A_b(x)) \quad (1)
\]

The MVP is expressed using nodal basis functions \( W_j(x,y) \) for \( N \) nodes. It can be then denoted as:

\[
A_z(x,y) = \sum_{j=1}^{N} A_j W_j(x,y) \quad (2)
\]

Assuming iron grains (domain \( \Omega_s \)) as the domain of inductor where \( \Omega_s \in \Omega \). For a magnetodynamic system, the induced current density \( J_z \) is related to the electric field \( E \) using the Ohm’s law and Faraday’s law. The \( J_z \) is written in terms of MVP and iron conductivity \( \sigma \) as:

\[
J_z = -\sigma \frac{\partial A_z(x,y)}{\partial t} \quad (3)
\]

Therefore, the \( A-\phi \) formulation can result in following set of differential equations.

\[
S \mathbf{a} + T \frac{\partial \mathbf{a}}{\partial t} = 0 \quad (4)
\]

where, \( \mathbf{a} \) is a vector consisting of nodal values of \( A \), \( S \) is the stiffness matrix determining the geometric and material characteristics of the SMC material, \( T \) matrix consists of elements of the conducting system.

In case of linear system, permeability \( \mu \) of iron grains is constant. The eddy current loss or the active power loss \( P \) (Watts) in \( \Omega \) can be represented as (using (3)).

\[
P = l \int_{\Omega} \frac{J_z^2}{\sigma} d\Omega \quad (5)
\]

Physical \( \mu \) is always real but when modeling eddy currents inside the grain, phase shift is introduced. The \( S \) is the summation of \( P \) and the reactive power loss \( Q \) (var).

\[
S = P + iQ \quad (6)
\]

Then \( Q \) can be written in terms of \( \mu \), angular pulsation \( \omega \) (rad/s) and local value of imposed flux density \( b \).

\[
Q = l \int_{\Omega} \frac{\omega b^2}{\mu} d\Omega \quad (7)
\]

Therefore for the homogenized model, \( \Re(\mu_h) \) and \( \Im(\mu_h) \) are the real and imaginary parts of the homogenised complex permeability. The complex magnetic field \( H \) (A/m) can be then defined as:

\[
H = b_n \left\{ \frac{\Re(\mu_h)}{X} + i \left( \frac{\Im(\mu_h)}{X} \right) \right\} \quad (8)
\]
where \( X = \Re(\mu_h) + \Im(\mu_h) \) and \( b_\text{av} \) is the average value of imposed flux density. Fig. 2 shows the real and imaginary part of the three SMC models with the irregular grains. The imaginary part indicates the phase shift due to the presence of eddy currents inside the iron grains.

### 2.2 Non-Linear Analysis

For the non-linear case, \( 1/\mu = g(b^2) \). The reluctivity is a function of square of magnetic flux density, Newton-Raphson algorithm is being utilised. \( S \) depends on \( A \). The set of algebraic equation is solved for each time step. The \( n^{th} \) order of iteration of \( A \) can be then written as:

\[
A^n = A^{n-1} + dA^{n-1}
\]  

\( (9) \)

The residual non-linear algebraic equation in the non-linear case is given as:

\[
\mathbb{J}(A^n)dA^n = \mathbb{R}(A^n)
\]  

\( (10) \)

Fig. 3: B-H characteristics for the SMC material with highest FF (97.5%) (red) (obtained by non-linear analysis), Laminated silicon steel (M19 - 0.5 mm) (black) at the frequency of 50Hz.

where, \( \mathbb{R}(A^n) \) is the residual vector and \( \mathbb{J}(A^n) \) is the Jacobian matrix. In order to improve the convergence rate and to drive the estimated value closer to the solution, a relaxation factor \( \zeta \) is introduced in the MVP.

The result of non-linear analysis of the 2-D material with the highest fill factor is shown in Fig. 3. The B-H characteristic of the laminated silicon steel (M19-0.5 mm) is also indicated along with the SMC material of 97.5% FF which are further utilised in the electrical machine analysis.

### 3 Computation of Eddy Current Loss Density

A simple formula for calculation of eddy current loss density over \( \Omega \) is given by \[15\].

\[
p_e = \frac{\sigma d^2}{2\alpha} \left( \frac{\partial b}{\partial t} \right)^2
\]  

\( (11) \)

where, \( p_e \) is the eddy current loss per unit volume (W/m\(^3\)), \( d \) is the cross sectional dimension of the material (m) and \( \alpha \) (dimensionless) is the anomaly factor which differs for different materials. It is only applicable for frequency below 2 kHz for skin depth \( \delta \geq d \). At high frequencies, \( \delta \propto 1/\sqrt{f} \) and therefore, \( p_e \propto f^{3/2} \).

For thin laminated material, the eddy current losses per unit volume \( p_l \) is given by \[16\]:

\[
p_l = b^2 \sigma \omega^2 d^2 F(\xi), \quad F(\xi) = \frac{3}{\xi} \sinh \xi - \sin \xi \cosh \xi - \cos \xi
\]  

\( (12) \)

where \( \xi = 2d/\delta \) and \( b \) is the maximum value of flux density. For \( \delta > 2d \), \( F(\xi) = 3/\xi \). Putting this value in (12) gives:

\[
p_l = \frac{b^2 \sigma \omega^2 d^2}{2\xi}
\]  

\( (13) \)

In this paper, (13) has been used to estimate the losses in the 2-D SMC material.
Equating (13) and (11) shows that $p_e \alpha = p_l \xi$. Based on the findings in Fig. 4, an anomaly factor $\alpha$ is defined which is related to the SMC geometry.

**Determination of anomaly factor alpha for 2-D SMC material**

The $\alpha$ is determined for the soft magnetic material using the low frequency approximation. Therefore,

$$p_e \alpha = p$$  \hspace{1cm} (14)

where $p$ (W/m$^3$) is the eddy current loss density obtained as follows:

$$p = \frac{P}{V}$$  \hspace{1cm} (15)

where $V$ (m$^3$) is the volume of the SMC material. Table 2 indicates the variation of obtained anomaly factor with respect to the fill factor of the 2-D SMC material.

### 4 Application Example

Two 8 pole 6 slot concentrated winding surface mounted PM synchronous motors are used as an example for application. The geometries of both machines are identical and is shown in Fig. 5. In the first motor, the stator core is made up of sheets of laminated steel (M19-0.5 mm).

In the second motor, the stator core is made up of SMC material. However, the other parameters remain same for both motors. The air gap width and magnet arc are 0.5 mm and 0.7 respectively.

Table 2 Variation of anomaly factor with different fill factors

| Model No. | Fill Factor (FF) (%) | Anomaly Factor ($\alpha$) |
|-----------|----------------------|--------------------------|
| I         | 85.2                 | 6.3                      |
| II        | 95.4                 | 8.1                      |
| III       | 97.5                 | 9.7                      |

The classical eddy current loss equation and the B-H characteristic obtained in Fig. 3 and Fig. 4 from the linear and non-linear analysis are then further utilised for the calculation of eddy current loss density in the stator core and the electromagnetic torque.

Both motors are being compared at low speed (1500 rpm) and high speed (20,000 rpm) at the q-axis current of 1 A. Fig. 6 and Fig. 7 show that the average torque generation is low for laminated stator core machine when compared with the SMC stator core machine at high speed while the average torque is higher in laminated stator core machine in case of low speed.

### 5 Conclusion

Magnetodynamic FE simulation techniques have been proposed for a 2-D SMC material with inclusion of eddy currents for the calculation of macroscopic permeability. A new technique has been proposed for determination of eddy current loss density for a 2-D SMC material in a time stepping scheme.

For this, a correction factor $\alpha$ has been introduced for different SMC materials having varying fill factors. The value of $\alpha$ increases with increasing fill factor. The macroscopic permeability and factor $\alpha$ are then implemented on a surface-mounted PMSM model. It can be seen that the EC losses are lower in SMC core PMSM when compared with the laminated core PMSM. The validation through experiment is difficult as it only measures the total iron losses in the electrical machine.

### 6 Acknowledgements

This work is supported by European Industrial Doctorate on Next Generation for Sustainable Automotive Electrical Actuation (INTERACT) project which has obtained funding from the European Union Horizon 2020 research and innovation programme. The grant agreement number for this project is 766180.
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