

Magneto-thermally Coupled Field Simulations of Homogenized Foil Windings

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Foil windings have, due to their special layered structure, different properties than wire windings, with advantages for high frequency applications. Both electromagnetic and thermal analyses are relevant for foil windings. Both physical phenomena are coupled through Joule losses and temperature dependent material properties. For an efficient simulation of foil windings, homogenization techniques are used to avoid resolving the single turns. This paper comprises a weakly coupled magneto-thermal simulation that uses a homogenization method in the electromagnetic and thermal part. The method is validated with a commercial solver.

Index Terms—Foil windings, homogenization, multi-physics, finite element method

I. INTRODUCTION

BESIDES traditional wire or litz wire windings, foil windings are used in various application areas, for example in inductors [1] or in transformers [2] used in DC-DC converters [3]. Compared to wire windings, foil windings have better mechanical properties [1] and better thermal properties [4, 5] because the foil acts as a highly thermally conductive connection from the interior to the surface and thus allows efficient cooling.

In the design of applications, not only the electromagnetic behavior but also the thermal behavior of the foil winding is important [6]. Because of the layered structure of a foil winding with its very thin turns, a classic simulation approach leads to unmanageably large models and long simulation times [7]. The homogenization approach for electromagnetic models of [7] avoids the resolution of every single turn of the foil winding. In this paper, this is combined with a thermal homogenized model in a weak coupling scheme. The formulation is presented in Sec. II, and a validation is done in Sec. III.

II. FORMULATION

A schematic representation of a foil winding is shown in Fig. 1. It has the width w , height h and consists of N turns. The foil consists of a conducting material and an insulation material. The subscripts ‘c’ and ‘i’ are used to indicate the respective affiliation. The width of each turn is $b = b_c + b_i$ (see Fig. 1b). The fill factor $\lambda = \frac{b_c}{b}$ describes the proportion of the conductor thickness to the total foil thickness. A local coordinate system $(\alpha, \beta, \gamma) \in L_\alpha \times L_\beta \times L_\gamma$ is defined on the foil winding domain Ω_{fw} . Its unit vectors $\vec{e}_\alpha$, $\vec{e}_\beta$ and $\vec{e}_\gamma$ are shown on a cross section (purple) in Fig. 1a. They are perpendicular to the turns, in winding direction and towards the tips of the foil winding, respectively.

Throughout the paper, it is assumed that the foil is significantly thinner than the skin depth $\delta = \sqrt{2/(\omega\mu_c\sigma_c)}$, with the angular frequency $\omega = 2\pi f$, the frequency f , and the permeability μ_c and conductivity σ_c of the conducting material. Furthermore, it is assumed that the height of the foil winding is much larger than the width of one turn, i.e., $h \gg b$.

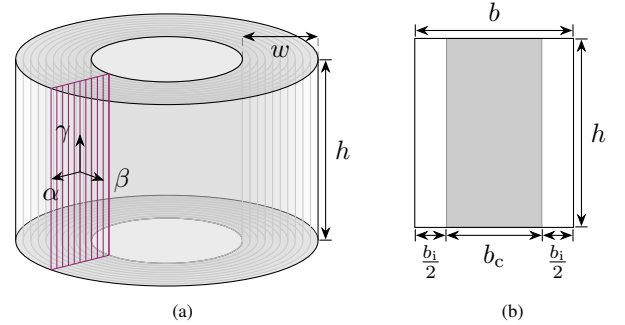


Fig. 1: Schematic representation of a foil winding. (a) shows the foil winding domain Ω_{fw} with the local coordinate system (α, β, γ) on a cross section (purple). (b) shows the cross section of one turn, with the conducting material in gray and the insulation material in white. (Both figures are adapted from [8]).

The coupled formulation consists of two parts. The magnetic part is described by the homogenized foil winding model [8]

$$\text{curl} \left(\nu \text{curl} \vec{A} \right) + \sigma \partial_t \vec{A} - \sigma \Phi \vec{\zeta} = 0 \quad \text{in } \Omega, \quad (1a)$$

$$\int_{\Sigma(\alpha)} \sigma \left(-\partial_t \vec{A} + \Phi \vec{\zeta} \right) \cdot \vec{\zeta} dS = \frac{I}{b} \quad \alpha \text{ in } L_\alpha, \quad (1b)$$

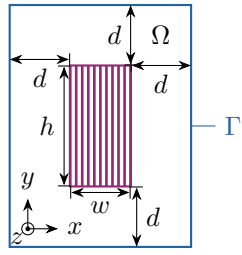
with the magnetic vector potential (MVP) $\vec{A}$, the *voltage function* Φ , the *distribution function* $\vec{\zeta}$ [9], the reluctivity ν , the electric conductivity σ , the current flowing through the foil winding I , and a cut $\Sigma(\alpha)$ at α through the foil winding. The thermal part is described with the transient heat conduction equation

$$-\text{div} (\kappa \text{grad} T) + c_v \partial_t T = q_v, \quad (2)$$

with the temperature T , the thermal conductivity κ , the volumetric heat capacity c_v and the volumetric heat source q_v .

All the material parameters are homogenized by mixing rules [10] in the foil winding domain and are described by tensors, which are diagonal with respect to the local coordinate system. The mixing is determined by λ , except for the volumetric heat capacity, where the relative volumetric ratio is used [11].

The magnetic and the thermal sub-problem are coupled as follows: The heat source for the thermal model are the Joule



Parameter	Value
w	10 mm
h	20 mm
ℓ_z	50 mm
d	10 mm
N	30
λ	80 %

Fig. 2: Cross section of the validation model with the dimensions in the table. The foil winding (purple) is centered within a box filled with air. On the boundary Γ (blue), an electric BC and an isothermal BC is applied to the magnetic and thermal problem, respectively. (Adapted from [8]).

Tab. I: Material properties used for the validation model.

Material	σ	μ	κ	c_v
Conductor	60 MS/m	μ_0	385 W/(m K)	3.45 MJ/(m ³ K)
Insulator	0 S/m	μ_0	90 mW/(m K)	1.03 MJ/(m ³ K)
Air	0 S/m	μ_0	26 mW/(m K)	1 kJ/(m ³ K)

losses $q_v = (-\partial_t \vec{A} + \Phi \vec{\zeta}) \cdot (-\sigma \partial_t \vec{A} + \sigma \Phi \vec{\zeta})$ from the magnetic model, and the electric conductivity depends on the temperature as $\sigma(T) = \sigma_{\text{ref}} / (1 + \alpha_{\text{ref}}(T - T_{\text{ref}}))$, with the temperature coefficient $\alpha_{\text{ref}} = 3.93 \cdot 10^{-3} \text{ K}^{-1}$ and the material's electric conductivity $\sigma_{\text{ref}} = 60 \text{ MS/m}$ at the reference temperature T_{ref} [11, 12]. A weak coupling between magnetic and thermal sub-problem is realized, where the magnetic sub-problem is solved in time or frequency domain and the thermal sub-problem is solved in time domain.

The coupled problem is discretized in space with the Ritz-Galerkin method. The temperature T and the MVP $\vec{A}$ are discretized with lowest order finite element (FE) nodal and edge shape functions, respectively. The voltage function Φ is discretized with basis functions that vary only in α -direction [13].

III. VALIDATION

The coupled simulations are carried out with the Python-based FE solver *Pyrit* [14]. The obtained results are compared to reference results computed with COMSOL Multiphysics®. The considered model is shown in Fig. 2, and the material parameters are collected in Tab. I. Homogeneous electric and isothermal boundary conditions (BCs) are used on the whole boundary. For the magnetic simulation, the foil winding is connected to a current source via a field-circuit coupling scheme and simulated in frequency domain at $f = 50 \text{ Hz}$. The thermal simulation is carried out in time domain using a constant time step of $\Delta t_{\text{th}} = 2 \text{ min}$ over a period of 10 h. The voltage function is discretized with seven basis functions.

Figure 3 shows the relative error of the thermal internal energy $U = \int_{\Omega} c_v T d\Omega$ between the resolved (U_r) and homogenized (U_h) results at the end of the simulation over the number of mesh elements N_e . The results show a convergence order between $\mathcal{O}(N_e^{-0.5})$ and $\mathcal{O}(N_e^{-1})$.

IV. FUNDING

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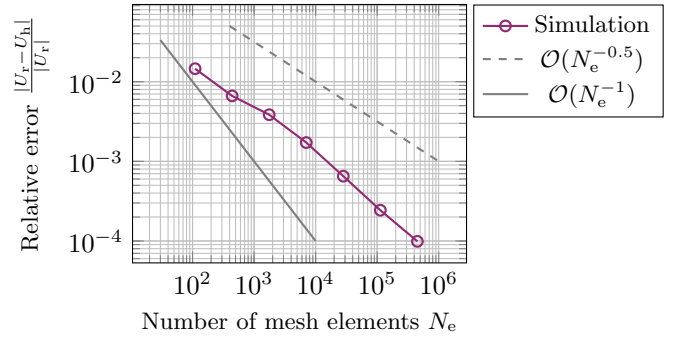


Fig. 3: Relative error between the resolved thermal internal energy U_r and the homogenized thermal internal energy U_h at the final time instance over the number of mesh elements N_e .

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