Quasi-3D Machine Model for Thermal Simulations with Spray Cooling

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The axial heat flow in an electric machine with spray-cooled end windings is modelled by a quasi-3D finite-element approach. The approach allows to accurately resolve the cross-sectional winding geometry while efficiently accounting for the temperature gradients in axial direction.

***Index Terms*—Cooling, electric machines, finite element analysis, quasi-3D method, spray cooling.**

I. Introduction

Spray cooling of end windings offers a promising technology for an effective cooling of high-power-density electric machines [1]–[3]. The pronounced spatially dependencies and the expected high temperature gradients hamper the application of standard thermal network models [4]. A sufficient spatial resolution in 3D machine models is cumbersome. This work proposes to tackle this problem by a quasi-3D thermal finite-element (FE) method.

II. Thermal Quasi-3D Finite-Element Model

A quarter part of a single machine winding is considered (Fig. 1a). The cross-sectional plane is denoted by $\mathcal{S}$. The length within the yoke is ℓ_z, whereas the winding length of the overhang is ℓ_{end}. The temperature $\vartheta(\vec{r})$ in the winding is described by the stationary heat equation

$$-\nabla \cdot (\lambda \nabla \vartheta) = p \,, \tag{1}$$

with $\lambda(\vec{r}, \vartheta)$ the thermal conductivity and $p(\vec{r})$ is the Joule heat source density. The symmetry planes in the machine's center and the overhang's center, and the almost perfectly thermally insulating interface between winding and yoke are combined into the boundary part Γ_{adia} and equipped with an adiabatic boundary condition. The cooling effect of a spray exerted on the end-winding parts is modeled by a convection boundary condition imposed on the boundary part Γ_{spray}:

$$\lambda \frac{\partial \vartheta}{\partial n} = h \left(\vartheta - \vartheta_{\text{ref}} \right) \qquad \text{on}\, \Gamma_{\text{spray}} \,, \tag{2}$$

with $\partial/\partial n$ the outward normal derivative, h the convection coefficient determined experimentally [1], and ϑ_{ref} a reference temperature.

A local Frenet-Serret coordinate system (s, u, v) with s along the winding direction and (u, v) in the cross-sectional plane $\mathcal{S}$ is defined (Fig. 1b). The mapping between (u, v, s) and (x, y, z) preserves the scale in $\mathcal{S}$. The material distribution does not depend on s but varies considerably with u and v.

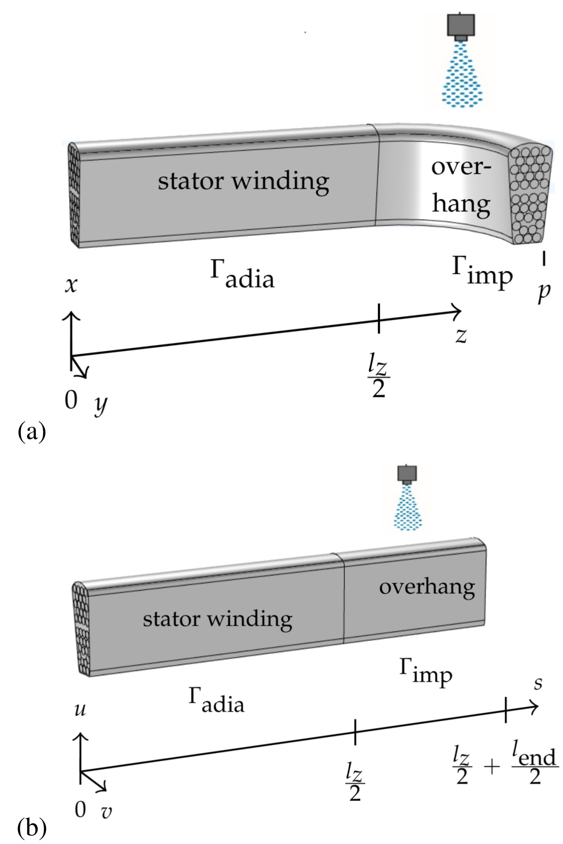

Fig. 1: Stator winding: part within the stator yoke and end-winding part; spray cooling of the overhang: (a) original geometry and (b) adapted geometry.

The temperature is discretized by

$$\vartheta(\vec{r}) = \sum_{j=1}^{N_\perp} \sum_{q=1}^{N_\parallel} u_{jq} N_j^\perp(u, v) N_q^\parallel(s) \,, \tag{3}$$

where u_{jq} are the degrees of freedom (DoFs), $N_j^\perp(u, v)$ are $N_\perp$ 2D hat functions defined on a triangularization of $\mathcal{S}$ and $N_q^\parallel(s)$ are $N_\parallel$ polynomial functions defined on a set of 1D elements along the s-axis. The same tensor-product FEs are used for weighting (1), which leads to the discrete system of equations

$$K^{\text{q3d}}u + C^{\text{q3d}}u = f^{\text{q3d}} + C^{\text{q3d}}u_{\text{ref}}\,, \tag{4}$$

where u_{ref} contains ϑ_{ref} on the nodes of Γ_{spray},

$$K^{\text{q3d}} = M^{\perp} \otimes K^{\parallel} + K^{\perp} \otimes M^{\parallel}\,; \tag{5a}$$

$$C^{\text{q3d}} = C^{\perp} \otimes C^{\parallel}\,; \tag{5b}$$

$$f^{\text{q3d}} = f^{\perp} \otimes f^{\parallel}\,, \tag{5c}$$

in which $\otimes$ denotes the Kronecker product, and where

$$K^{\perp}_{ij} = \int_{\mathcal{S}} \lambda \nabla N^{\perp}_j \cdot \nabla N^{\perp}_i \,\mathrm{d}S\,; \tag{6a}$$

$$K^{\parallel}_{pq} = \int_0^{\ell_s/2} \frac{\mathrm{d}N^{\parallel}_q}{\mathrm{d}s}\frac{\mathrm{d}N^{\parallel}_p}{\mathrm{d}s}\,\mathrm{d}s\,; \tag{6b}$$

$$M^{\perp}_{ij} = \int_{\mathcal{S}} \lambda N^{\perp}_j N^{\perp}_i \,\mathrm{d}S\,; \tag{6c}$$

$$M^{\parallel}_{pq} = \int_0^{\ell_s/2} N^{\parallel}_q N^{\parallel}_p \,\mathrm{d}s\,; \tag{6d}$$

$$C^{\perp}_{ij} = \int_{\partial\mathcal{S}} h N^{\perp}_j N^{\perp}_i \,\mathrm{d}s\,; \tag{6e}$$

$$C^{\parallel}_{pq} = \int_{\ell_z/2}^{\ell_s/2} N^{\parallel}_q N^{\parallel}_p \,\mathrm{d}s\,; \tag{6f}$$

$$f^{\perp}_i = \int_{\mathcal{S}} p N^{\perp}_i \,\mathrm{d}S\,; \tag{6g}$$

$$f^{\parallel}_p = \int_0^{\ell_s/2} N^{\parallel}_p \,\mathrm{d}s\,, \tag{6h}$$

with $\ell_s = \ell_z + \ell_{\text{end}}$. The method is implemented in the FE solver Pyrit [6]. The formulation has similarities with the quasi-3D method proposed in [7] but employs standard FEs in the longitudinal direction.

III. Example

A 3.7 kW, 1430 rpm squirrel-cage induction machine [8] is used as an example. Its thermal behavior with an air-cooled jacket has been reported in [9], [10]. To illustrate the beneficial effect of spray-cooling applied to the end-winding parts, a fictitious operation condition with a 10 times larger power density is considered. The spray-cooling effect is modeled by the convection boundary condition at the overhang surface Γ_{spray} [5]. The model neglects the curvature of the coil.

Spray cooling extracts a considerable amount of heat from the winding overhang (dashed lines in Fig. 2). The good thermal conductivity of the wires is capable of extracting the heat from the center machine parts (solid lines in Fig. 2). The observed high temperature difference between the individual wires confirms the necessity to finely mesh the winding cross section.

IV. Conclusion

A quasi-3D FE model succeeds in providing reliable simulation results for the large temperature gradients in spray-cooled electric-machine windings.

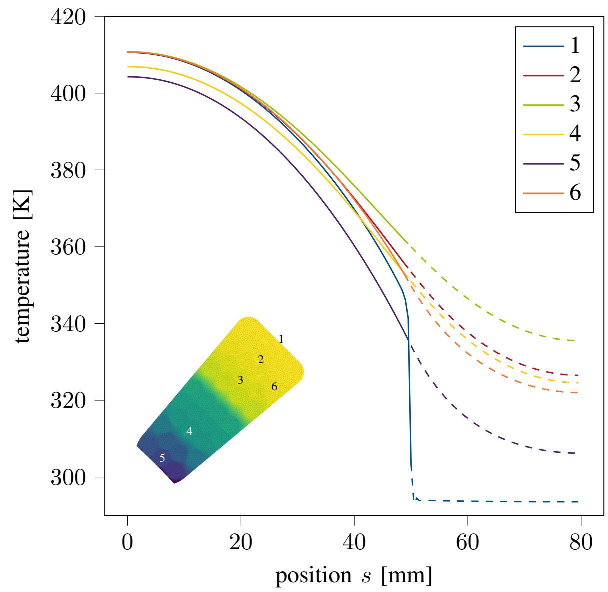

Fig. 2: Temperature along the winding for a 10 times higher power density.

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