

Particular modeling of coupled EM, thermal and CFD phenomena for advanced dielectric oil spray cooled high speed PM motors

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Permanent magnet (PM) motors are favored in high-speed electric traction applications due to their increased efficiency and robustness based on excitation provided by brushless rotor configurations. In dielectric oil spray cooling, accurately capturing the complex interaction between electromagnetic, thermal, and fluid dynamics requires detailed and computationally demanding coupled simulations. The present work introduces a particular methodology, achieving enough precision while involving modest computational means. The proposed method uses an indirect coupling approach, combining 2D finite element analysis (FEA) for electromagnetic modeling, a 3D distributed lumped parameter thermal network (LPTN) for transient thermal simulation, and CFD-based 3D FEA to evaluate cooling from dielectric oil spray on the winding end zones. To that respect, appropriate time varying local heat transfer coefficients (HTCs) are determined on the hairpin conductor stator non-overlapping end winding parts reflecting the heat transfer due to the oil spray. The accuracy of the proposed methodology has been checked by comparing the results to the ones of a directly coupled 3D FEA model.

Index Terms—Finite element analysis, fluid dynamics, thermal analysis, permanent magnet machines.

I. INTRODUCTION

PERMANENT MAGNET synchronous motors (PMSMs) are widely used in high-speed applications due to their efficiency, compact design, and mechanical robustness. However, high power densities introduce thermal management challenges.

Direct dielectric oil spray cooling is an effective method for heat dissipation [1],[6], leveraging oil flow and vaporization dynamics. However, modeling this process is complex due to time-varying heat transfer coefficients (HTCs), which significantly influence fluid-solid interactions [2].

Traditional HTC estimation relies on empirical models and dimensionless correlations [3],[4] often failing to capture local cooling variations. While offering enhanced accuracy, directly coupled EM-CFD simulations are computationally prohibitive for use in iterative design workflows. Moreover, preventing oil penetration in the air gap is essential to minimize rotational losses, typically addressed using oil deflectors. This work proposes a hybrid methodology depicted on Fig. 1, combining 2D FEA for electromagnetic (EM) losses, CFD for transient HTC estimation, and a 3D distributed lumped parameter thermal network (LPTN). The approach ensures accurate, computationally efficient temperature prediction in oil spray cooled motors, facilitating iterative motor design optimization.

II. METHODOLOGY AND RESULTS

The case of a PMSM with 18 stator slots/16 poles, with M235-35A iron lamination and surface mounted NdFeB permanent magnets on the rotor has been considered. Three phase fractional slot concentrated windings are implemented.

The representation of winding connections is illustrated in Fig. 2(a) showing the motor cross-section. Cooling is ensured

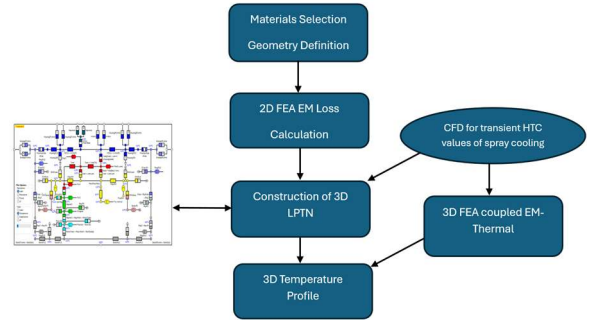


Fig. 1. Flowchart of proposed methodology

by dielectric oil spray through nozzles placed opposite each coil end zone part. The modeling of the cooling effects has been performed on a similar one phase equivalent linear stator part, illustrated in Fig. 2(b). The simulated motor main characteristics are given in table I and selected material properties in table II.

A. Losses determined by EM modeling using 2D FEA

Copper losses in windings, iron losses (eddy, hysteresis) in stator magnetic circuit as well as permanent magnet losses are evaluated via 2D FEA using methods presented in [5].

TABLE I
SIMULATED PMSM MAIN CHARACTERISTICS

Parameter	Value	Unit
Power	20	kW
Torque	25	Nm
Slots/Poles	18/16	
Current Density	30	A/mm ²

TABLE II
MATERIAL PROPERTIES

Material	Thermal Conductivity W/(m·K)	Density kg/m ³	Specific-Heat kJ/(kg·K)	Viscosity cP	Spray Pattern
Copper	360	8920	0.4	-	-
Oil	0.26	1132	2.382	1.9E-5	full cone
Iron	22	7600	0.5	-	-

Material properties defined for thermal analysis of the motor.

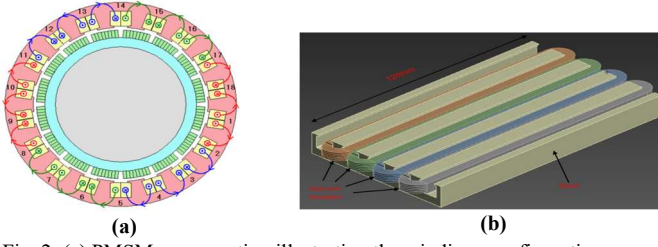


Fig. 2. (a) PMSM cross-section illustrating the windings configuration. (b) One phase linear stator part.

Permanent magnets have been segmented to mitigate harmonic losses and reduce demagnetization risks.

B. HTC's determined by CFD modeling using 3D FEA

The appropriate HTC's implemented along coil end zone parts of the windings in the 3D transient distributed LPTN have been determined by using axisymmetric CFD simulation. Inlet speed was set to 7 m/s and temperature to 40°C, copper defined as stationary wall with no-slip boundary condition and the upper side of the field defined as pressure outlet. A 2D view of the geometry is presented in Fig. 3(a). Volume of Fluid method for multiphase flow and k-ε SST turbulence model were utilized. During the simulation, the surface heat transfer coefficient and wall-adjacent heat transfer coefficient were appropriately monitored Fig. 3(b).

C. Motor temperature computed by 3D distributed LPTN

Motor temperature distribution [T] under nominal operating conditions has been computed by a 3D distributed LPTN (Fig. 4), with appropriately defined thermal resistances [R] and capacitances [C] based on respective materials and heat sources [P]. The Fourier equation (Eq. 1) was solved twice:

$$\frac{d[T]}{dt} = -[C^{-1}][R^{-1}][T] + [C^{-1}][P] \quad (1)$$

once using fixed HTC for spray cooling derived from empirical correlations (~3150 W/m²K), and with transient HTC extracted from CFD simulation. Rotor and stator slot temperature distribution can be seen in Fig. 5. Maximum temperatures tracked in the winding are compared with results from directly coupled 3D FEA in Fig. 6, showing an important temperature underestimation by the static method during the transient phenomenon and better agreement in steady state.

III. CONCLUSION

A hybrid methodology was presented, combining EM analysis via 2D FEA, thermal modeling through a distributed 3D LPTN, and fluid dynamics via CFD. The proposed approach leverages low computational cost of LPTN to incorporate transient HTC refinements from CFD at minimal additional

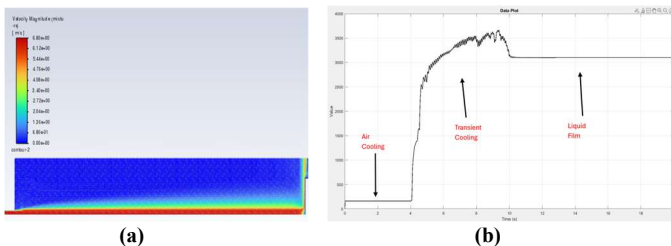


Fig. 3. (a) Axisymmetric view jet (b) Transient HTC via CFD

cost. This enables fast, more accurate simulation of dielectric oil spray-cooled high-speed PMSMs and easy implementation in iterative workflows where full 3D FEA-CFD coupling would be computationally prohibitive. It will be validated by measurements in a linear stator prototype.

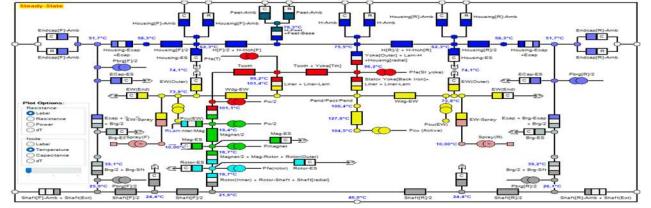


Fig. 4. 3D Transient Distributed LPTN

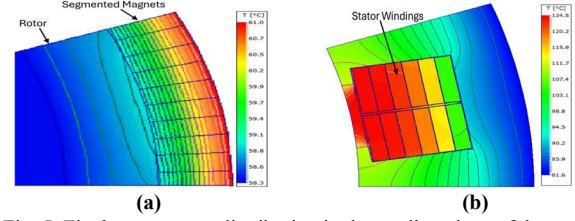


Fig. 5. Final temperature distribution in the median plane of the motor. (a) Rotor surface region comprising the PMs (b) Stator slot region

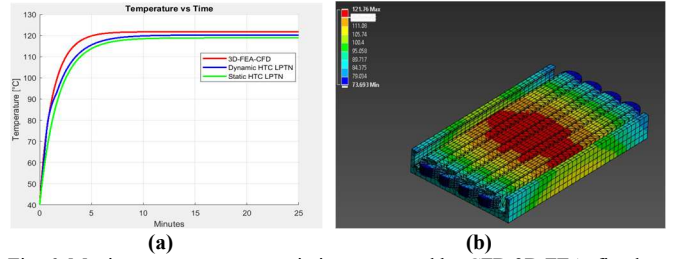


Fig. 6. Maximum temperature variation computed by CFD 3D FEA, fixed value HTC's LPTN, variable value HTC's LPTN.

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