Geometry optimization of PMSMs comparing full and fractional pitch winding configurations for aerospace actuation applications

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Abstract — This paper introduces a particular optimization methodology presenting improved convergence characteristics when applied to optimize the geometry of both Fractional Slot Concentrated Winding (FSCW) and Full Pitch Concentrated Winding (FPCW) permanent magnet motor configurations. The proposed algorithm has been adapted to optimally combine technical and physical advantages of the FSCWs and FPCWs into an optimally shaped stator-winding configuration. The resultant motor design has been experimentally validated and provided suitable characteristics for aerospace actuation applications.

I. INTRODUCTION

Fractional Slot Concentrated Winding (FSCW) Permanent Magnet Synchronous Machines (PMSMs) have been gaining popularity over the last few years. This is mainly due to the advantages of low cogging torque, short end turns, high slot fill factor, fault tolerance and flux-weakening capabilities favoring FSCWs to Full Pitch Concentrated Windings (FPCWs) in specific applications [1]. However, fractional pitch configuration affects the performance of the actuator similarly to the case of a reduced number of turns in the winding, leading to back-EMF voltage amplitude and power-factor reduction in regard to the case of FPCWs [2]. Such a performance related effect can be critical in aerospace applications that require actuation systems to comply with maximum efficiency and high power density specifications. As FSCW technical characteristics call for less copper, while FPCW physical characteristics call for maximum EMF per inductor, the optimum actuator topology can be a function of the application specifications and has to be determined analytically [3],[4].

This paper introduces a particular optimization algorithm, developed in order to facilitate the comparative approach on the geometry optimization of PMSMs involving FPCW and FSCW configurations. More specifically, a Rosenbrock based optimization algorithm has been applied to optimize such topologies and offered stable convergence characteristics in all cases considered. The resultant optimized design has been introduced in an experimental prototype, and overall performance improvement has been validated.

II. ACTUATOR MODELING

A first estimation of the actuator structure is achieved by considering classical machine design techniques. Table I summarizes basic properties of the surface mounted PMSM.

TABLE I

MACHINE PROTOTYPE DESIGN CHARACTERISTICS (DIMENSIONS IN MM)

General	Number of phases	3
	Number of poles	20
	Motor active length	100
	Magnet inner radius	32.75
	Rotor outer radius	35.75
	Magnet angle	19.125 deg
Gap	Gap width	0.50
	Stator outer radius	50

After determining the basic machine structure, 2D FEM has been introduced for the accurate evaluation of the objective function during optimization runs. An FPCW topology and two FSCW topologies involving non-overlapping both alternative teeth wound as well as all teeth wound configurations have been modeled.

A. *FPCW topology*

The FPCW topology produces the largest possible EMF for a given number of inductors in the winding. One pole of the 20-pole machine has been modeled, as shown in Fig. 1, by using appropriate anti-periodic lateral boundary conditions (3334 nodes).

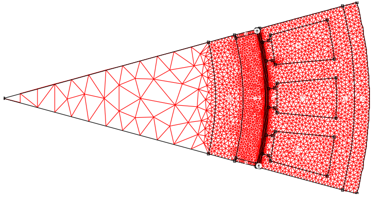
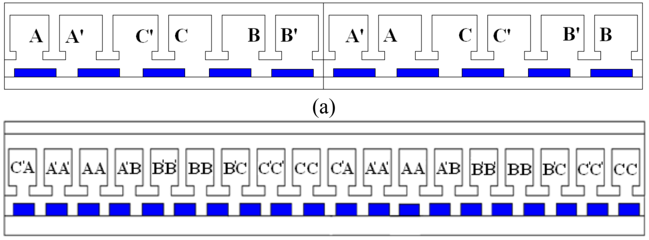


Fig.1. 2D FEM of one pole of the FPCW PMSM

B. *FSCW, non-overlapping topology*

This actuator configuration, can be combined with two types of stator winding, developed as described in Fig. 2.



(a)

(b)

Fig.2. FSCW stator winding configurations: (a) non-overlapping, alternate teeth wound (b) non-overlapping, all teeth wound

Figs. 3a and 3b show the FEM models of the alternative teeth wound (FSCW1) and all teeth wound (FSCW2) configurations (34353 and 26588 nodes respectively). The number of stator slots in each case has been determined analytically, in order to enable optimal electromagnetic coupling of the stator and 20-pole rotor MMF vectors.

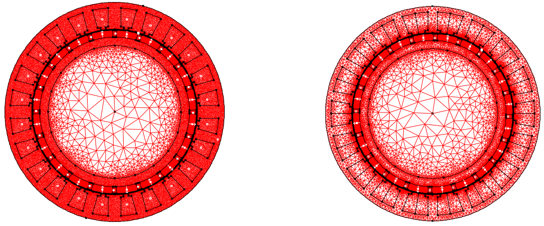

(a) (b)

Fig.3. 2D FEM of the FSCW PMSM:
(a) non-overlapping, alternate teeth wound
(b) non-overlapping, all teeth wound.

III. PROPOSED OPTIMIZATION ALGORITHM

The proposed optimization methodology implements a zero order, Rosenbrock based optimization routine, developed to ensure convergence at least to a local optimum, independently of the initial actuator configuration. The latter feeds an automated PMSM design script, generating the FEM model corresponding to each optimization run, thus allowing for precise computation of the objective function value.

Stator tooth width and stator slot opening have been selected as the main optimization variables since they play a key-role in sense of performance and efficiency. An objective function formula, specially developed to combine torque, back-EMF and copper losses profiles in conjunction with a particular cost term accounting for different levels of technical-manufacturing complexity of each actuator design has been also introduced. The latter enables successive estimation of technical cost thus accounting for the effects of stator tooth shape optimization on manufacturing complexity.

IV. RESULTS AND DISCUSSION

Table II summarizes the main output parameter values of the geometrically optimized actuator topologies.

TABLE II
OPTIMALLY SHAPED ACTUATOR OUTPUT PARAMETER VALUES

Topology	T_{mean} (Nm)	T_{ripple} (Nm)	EMF (%)		$I_{in\ rms}$ (A)	$P_{cop.}$ (W)	$T_{mean}/\sqrt{P_{cu}}$
			3rd	5th			
FPCW	31.5	0.70	3.2	4.4	20.0	600	1.28
FSCW1	31.8	1.10	8.8	3.9	18.0	485	1.44
FSCW 2	34.0	0.65	5.6	0.8	16.5	475	1.56

Compared to FPCW and FSCW1 geometrically optimized configurations, FSCW2 topology offers the maximum torque per copper loss square root ratio, combined with minimum ripple and back-EMF harmonic content, thus enabling superior actuator performance and efficiency characteristics.

Furthermore, Fig. 4 illustrates the effect of the tooth width variation around optimum value on the mean torque and torque ripple in the case of the FSCW2 configuration. As can be observed, stator teeth geometrical optimization is a key-step that needs to be undertaken in order to achieve a fair comparison of different winding configurations. Finally, the optimized FSCW2 topology is introduced in a PMSM prototype enabling experimental testing (Fig. 5). Table III illustrates the good agreement of simulation results and experimental measurements on the optimally shaped FSCW2 actuator.

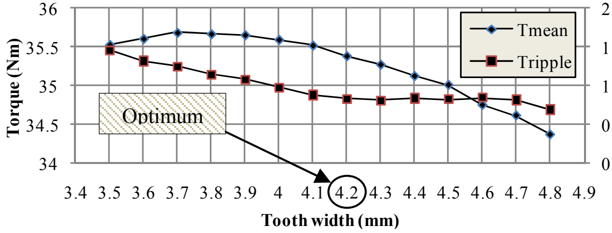


Fig. 4. Mean torque and torque ripple as a function of tooth width

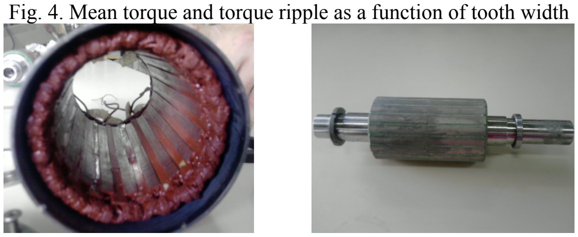

(a) (b)

Fig.5. Prototype (a) stator part (b) rotor part

TABLE III
ELECTROMAGNETIC TORQUE - EMF FFT PROFILES

		Experiment	Simulation
RMS Input current (A)	4	7.5 Nm	8 Nm
	8	15 Nm	16 Nm
EMF harmonic order	3rd	3.35 %	3.13 %
	5th	0.86 %	1.64 %

V. CONCLUSIONS

A particular optimization methodology enabling a comparative approach on the optimization of FPCW and FSCW PMSM configurations has been introduced. The latter has been applied to determine the global optimum between the most favorable candidate fractional and full pitch PMSM configurations for aerospace actuation applications and enabled stable convergence characteristics in all cases considered. The resulting actuator architecture achieves suitable performance-efficiency characteristics for this class of problems as verified both through simulation as well as experimental investigations.

VI. ACKNOWLEDGMENTS

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