Multi-objective Evolutionary Optimization of a Surface Mounted PM Actuator for Aerospace Applications

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***Abstract*—Overall optimization of electromechanical aerospace actuators requires a multi-objective analysis in order to account for both performance and efficiency, while considering technical costs, due to the conflicting nature of the respective criteria. This paper introduces a particular multi-objective, population-based optimization methodology, utilizing the differential evolution algorithm combined with manufacturing-cost and motor-clean-interface related constraints. The methodology presents stable convergence characteristics and has been applied to further extend previous work regarding the optimization of a Fractional Slot Concentrated Winding (FSCW) Surface Mounted Permanent Magnet (SMPM) motor. The resultant motor design has been validated through a prototype and experimental results illustrated its suitability for aerospace actuation applications.**

***Index Terms*—Design optimization, differential evolution, equivalent magnetic circuit, finite element method, permanent magnet motors, aerospace engineering.**

I. INTRODUCTION

This paper introduces an evolutionary multi-objective optimization algorithm, facilitating the comparative approach on both the stator and rotor geometry optimization of a SMPM motor involving FSCW configuration [1]. A Differential Evolution based optimization algorithm, employing three optimization criteria, regarding motor performance, motor efficiency and motor clean interface, is implemented [2]. Three additional optimization constraints are used, rendering the preservation of three cost terms under the specified values. The cost terms are application-specific and account for fill factor, stator tooth-slot shape and tooth-tip flux leakage effect, respectively, thus enabling efficiency, performance and manufacturing cost consideration. The optimization algorithm offered stable convergence characteristics. The overall performance improvement of the optimized design has been validated through measurements on a prototype.

II. METHODOLOGY

A. Preliminary Actuator Design

In a first step, an estimation of the actuator structure is achieved by considering classical machine design analytical techniques, according to specifications and space limitations. The initial design is based on the analysis performed in [1]. Table I summarizes basic properties of the SMPM actuator.

TABLE I
MACHINE PROTOTYPE DESIGN CHARACTERISTICS

Slot Number/ Pole number	18/ 20
Motor active length	100 *mm*
Stator outer radius	50 *mm*
Gap width	0.5 *mm*
Rotor inner/outer radius	29 mm/ 35.75 *mm*

B. Proposed Optimization Algorithm

The proposed optimization methodology implements a three objective Differential Evolution based optimization routine, utilizing the concept of Pareto non-domination to produce an optimum solutions front [3], [5]. The latter feeds an automated SMPM design script, generating a 2D FEM model corresponding to each optimization run, thus allowing for precise computation of the objective function values. The block diagram of the procedure is illustrated in Fig. 1. Stator tooth width W_{t2}, stator tooth length L_{tooth}, stator tooth tip height h_{tp}, stator slot opening W_{so} and magnet angle θ_{mag} have been selected as the five optimization variables, since they play a key-role in terms of both performance and efficiency. The three objective functions F_1, F_2, F_3 correspond to maximization of torque capability, minimization of total iron and copper losses and minimization of back-EMF harmonic content and torque ripple, respectively. This objective profile accounts for performance, efficiency and motor clean interface.

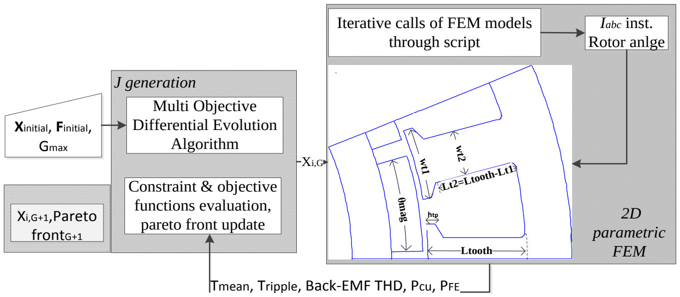


Fig. 1. Overall optimization procedure block diagram.

C. Introduction of Cost Functions as Constraints

Three particular cost terms C_1, C_2, C_3 have been introduced in the form of constraints in the optimization routine. The first two account for technical-manufacturing complexity of the actuator design [1]. Figure 2 illustrates the variation of the first and second technical cost terms. The third cost term relates the tooth tip shape and the magnet angle with the resulting leakage flux, in a rather innovative manner. An equivalent magnetic circuit approach was adopted to determine a convenient straightforward interpretation [4]. Figure 3 illustrates the third cost variation, the magnetic circuit for one stator slot and the respective leakage flux lines.

The introduction of the three abovementioned terms enables successive estimation of technical cost thus accounting for the effect of stator tooth and magnet shape optimization on manufacturing complexity.

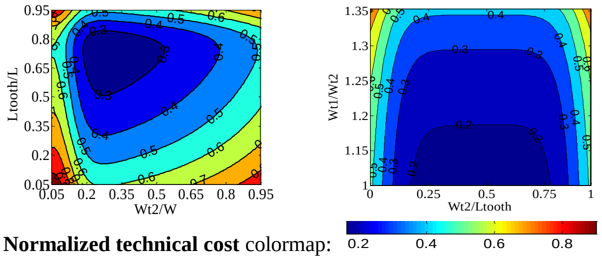
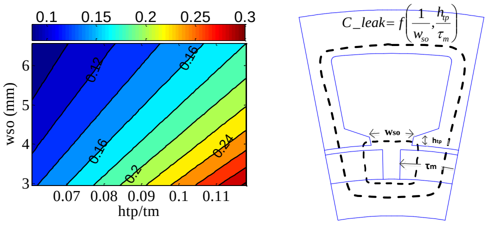


Fig. 2. Technical cost terms variation. (a) C1 term. Fill factor effect. (b) C2 term. Stator tooth-slot shape effect.

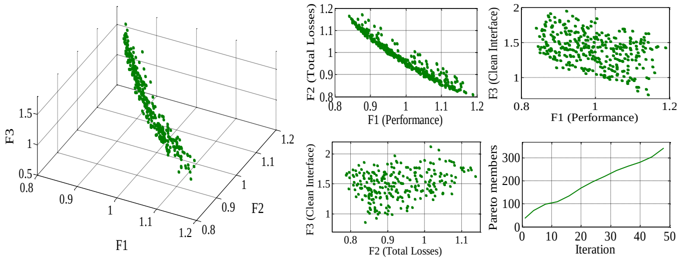


(a) (b)

Fig. 3. (a) Technical cost term C3 variation. Flux leakage. (b) Magnetic circuit for one stator slot and respective leakage flux lines.

III. SIMULATION RESULTS

The resulting Pareto front in the 3D objective function space is illustrated in Fig. 4(a). Figure 4(b) depicts the three projections of the Pareto front on the respective objective function surfaces, as well as the evolution of the number of the front members-optimal solutions throughout the optimization process. The conflicting nature of the objective functions is evident [3], [5]. The design parameters values for the existing actuator, as well as those for two new optimal designs, each emphasizing on a different criterion, are tabulated in Table I.



(a) (b)

Fig. 4. (a) Final 3D Pareto front after 48 generations. (b) 2D projections of the Pareto front and Pareto front members number evolution.

TABLE II
OPTIMAL DESIGN PARAMETER VALUES

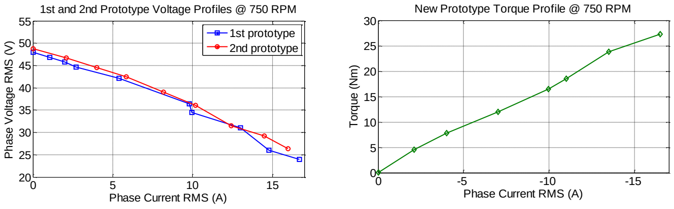
Var	*Init. Design*	*Cand. Design 1*	*Cand. Design 2*
W_{t1} (mm)	6.83	5.83	5.70
L_{tooth} (mm)	9.26	8.73	8.92
θ_{magnet} (deg)	15.3	13.84	16.2
h_{tp} (mm)	0.96	0.79	0.54
W_{t2} (mm)	4.2	4.32	4.37
[F1 F2 F3]	[1 1 1]	[1.1 0.91 0.98]	[1.003 0.967 1.05]

IV. EXPERIMENTAL VALIDATION

From the two aforementioned optimum designs the first was selected, based on the application demands for increased efficiency. The optimized actuator topology has been validated by measurements on a prototype. The motor parts and the measurement setup are shown in Fig. 5. The corresponding measured voltage profiles at a 750 RPM operating speed for the new and the old prototype are compared in figure 6(a). The respective torque profile for the new prototype is illustrated in Fig. 6(b).

(a) (b) (c) (d)

Fig. 5. SMPM actuator manufactured prototype. (a) motor with housing (b) SMPM rotor (c) stator and fractional pitch winding (d) motor measurement and testing setup.



(a) (b)

Fig. 6. (a) Voltage profile for the new and the old motor prototype. (b) Torque profile for the new manufactured prototype.

V. CONCLUSION

A novel population-based optimization methodology enabling a comparative approach on the optimization of a FSCW PMSM motor for aerospace actuation applications has been introduced. Manufacturing cost analysis and an equivalent magnetic circuit approach were utilized in the process. The resulting actuator architecture achieves suitable performance-efficiency characteristics as verified both through simulation and experimental testing.

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