Design Optimization of Switched Reluctance Motor for Aerospace Application

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***Abstract* - The switched reluctance motor, due to the high MTBF, mates properly the aerospace reliability requirements. In normal operation the electric machine operates in healthy mode but it is designed to satisfy the load specifications also with one or two faulty phases. This paper presents a design optimization for a five-phase switched reluctance motor developed to satisfy the requirements of flap actuators in medium size aircrafts. The design issues are described at the beginning in order to introduce the problem, than the optimization procedure is described. A new Controlled Random Search (CRS) algorithm is used for minimizing the optimization function. The detailed finite-element analysis validates the better performance of the optimized solution. Experimental tests on the motor prototype are included.**

***Index Terms* - Aerospace, actuator, electric aircraft, electric motor, design optimization, fault-tolerant, finite element analysis, multi-phase, switched-reluctance.**

I. Nomenclature

B	air-gap flux density at the aligned position;
L	active motor length;
N_{ph}	number of phases;
N'_{ph}	number of phases conducting simultaneously;
N_s	number of stator poles;
N_r	number of rotor poles;
N_t	number of turns per phase;
η	motor efficiency;
n_s	rotor speed;
I	peak phase current;
V	peak phase voltage;
$A,...,E$	phases of the motor.

II. Introduction

In addition to performance, in the aerospace application, the main design issue is the reliability of the project. In safety critical application, parameters such as Mean Time Between Failure (MTBF) or failure rate and design approaches like the fault tree analysis are widely used.

In order to calculate the reliability of the design and to identify the best solution, evaluating simple devices with few parts is easier to manage and increases the idea of robustness. Based on this approach, electric motors with fewer components are preferred. The switched reluctance motor (SR), with no windings or permanent magnets on the rotor, has higher MTBF and lower failure rate with respect to other types of motor; however, the torque of SR motors is weaker than the other ones, then a better optimization and refinement of the design is necessary to improve the performance. The paper shows the procedure and the optimization algorithm used for the design of a flap actuator.

III. Switched Reluctance Motor

The switched reluctance motor (SR) is a type of motor doubly salient with phase coils mounted around diametrically opposite stator poles [1], [2]. There are no windings or permanent magnets on the rotor. The rotor is basically a piece of (laminated) steel and its shape forms salient poles. The stator has concentrated coils. The SR motor is generally a highly saturated electromagnetic structure with inductances strongly non-linear current-dependent. The cross section of the SR motor presented in this paper is shown in Figure 1.

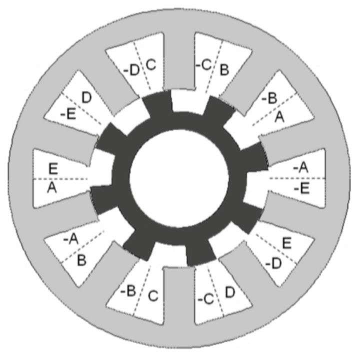

Figure 1 Cross-section and winding distribution of the five-phase 10/8 SR motor.

A particular advantage of the SR topology is that its lack of rotor excitation means that no currents will be excited in

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a faulted winding that is held in short circuit, assuming low coupling between power lanes, and hence no drag torques will be created. The lack of drag torques in SR motor delivers a further advantage in terms of thermal rating.

The specifications of the SR for the flap actuator are shown in Table I: the stack length and outer stator diameter have been fixed for the encumbrance limits. According to a fault tolerant constraint, it has 5 phases, whereby a solution with 10 stator pole and 8 rotor poles has been chosen: the concentrated windings on the diametrically opposite poles are connected in series. This solution foresees two-phases conducting simultaneously. The torque comes from the tendency of the rotor poles to align with the excited stator poles; to achieve smooth torque generation the phase feeding must be switched according to the rotor position. The preliminary performance analysis of the SR motor requires to define the dimensions for stator and rotor shapes, stator windings, pole numbers, and pole arcs. An approximate sizing of the SR motor is obtainable using the power output equation [1], [3].

TABLE I
SPECIFICATIONS OF THE SR MOTOR FOR FLAP ACTUATOR

DC voltage supply (max)	V	250
Rated torque in healthy operation	Nm	12.0 @ 600 rpm
Torque with one-phase open	Nm	12.0 @ 600 rpm
Weight	kg	<4.0
Stack length	mm	60
Outer stator diameter	mm	110
Cooling system		natural air

TABLE II
SR MOTOR: PRELIMINARY DESIGN

N.of stator poles		10
N.of rotor poles		8
N.of phases		5
Stack length	mm	60
Outer stator diameter	mm	110
Inner stator diameter	mm	64
Turns per phase		180
Wire size	mm^2	0.70
Air-gap	mm	0.35
Lamination material		800-50
Phase resistance (75°C)	Ω	1.13
Average torque @ 600 rpm	Nm	12.5
Phase current	A	30
k_T	Nm/A	0.42

The resulting machine dimensions is the starting point for the design procedure, final design is achieved through an iterative process of steady-state performance calculations. By using this sizing procedure, a preliminary design has been found whose main dimensions are shown in Table II. The stator and rotor lamination is a traditional 800-50 electrical steel, 0.50 mm thickness. Moreover, a conventional temperature of 75°C has been imposed for the stator winding.

IV. FINITE ELEMENT ANALYSIS AND DESIGN OPTIMIZATION

The preliminary design of the 10/8 SRM has been gradually refined by an optimization algorithm that has been combined with the 2D Finite Element model.

A versatile FE model has been developed with variable motor dimensions in order to allow the design optimization. For this reason, a “parametric” model of the machine has been prepared. It uses a limited number of independent parameters which define the geometry of the motor itself. The mesh has been accurately refined in the air-gap and in the regions where the flux density was expected to be high.

The Finite Element analysis is used to evaluate the motor performance and the design requirements namely to compute the objective function value and constraints of the minimization problem. It represents mathematically the optimal design problem and considers the parameters of the motor as independent variables. The optimization procedure uses the information obtained by the FE program to iteratively update the set of motor parameters and try to identify an “optimal” motor by making a trade-off between the different parameters of the machine.

The set of design variables used in the optimization procedure are listed in Table III, with their limits: Figure 2 shows in details the geometric dimensions.

The stator pole tapering has significant impact on shaping the electromagnetic torque and self-inductances, whereas the rotor pole tapering is of no consequence. It affects the slot fill factor and the winding insertion. For these reasons, in the proposed design, the stator and rotor poles do not present any taper.

TABLE III
DESIGN VARIABLES

Variables		lower	upper
x1. Stator tooth width	mm	9	13
x2. Stator yoke thickness	mm	6	9
x3. Inner stator diameter	mm	60	80
x4. Stator tooth arc ratio		0.80	0.95
x5. Stator pole shoe height	mm	1.0	1.5
x6. Rotor tooth arc ratio		0.60	0.95
x7. Rotor tooth height	mm	4	10
x8. Rotor tooth width	mm	2	5
x9. Rotor yoke thickness	mm	8	16
x10. Rotor to stator pole arc ratio		0.80	0.95
x11. Turns per phase		100	200
x12. Wire size	mmq	0.30	0.80

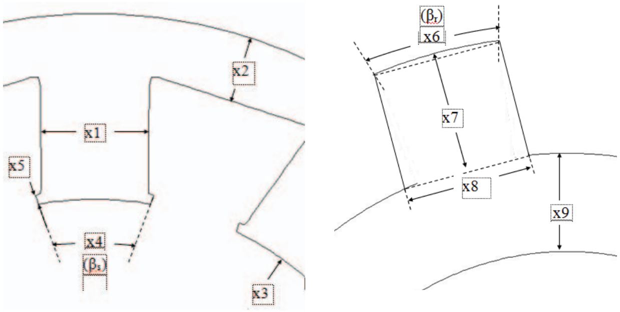

Figure 2 Design variables of the Switched Reluctance motor: Stator (left) and rotor (right) details.

The aim of the optimization was to maximize the torque constant in the healthy mode operation and satisfy the following constraints:

- slot fill factor ≤ 0.45;
- flux density in the stator teeth ≤ 1.8 T;
- flux density in the stator yoke ≤ 1.7 T;
- average torque in healthy mode operation > 12 Nm.

The optimal design of the SR motor has been formulated as a mixed-integer nonlinear programming problem, namely as a minimization problem with the following structure

$$\begin{aligned} &\min \ f(x) \\ &s.t. \quad g(x) \leq 0 \\ &\quad l \leq \mathrm{x} \leq \mathrm{u} \\ &\quad \mathrm{x_i} \in \mathrm{Z}, \ \mathrm{i} \in \mathrm{I_z} \end{aligned}$$

where Z is the set of the integer numbers, $x \in R^n$, f: $R^n \rightarrow R$, g: $R^n \rightarrow R^m$, l, u $\in R^n$, $\mathrm{l_i}, \mathrm{u_i} \in \mathrm{Z}$, $\mathrm{i} \in \mathrm{I_z}$.

It well known [4] that the previous problem is equivalent to the following one

$$\begin{aligned} &\min \ P(x) = f(x) + \frac{1}{\varepsilon} \max\{0, g_1(x), \ldots, g_m(x)\}. \\ &s.t. \quad l \leq \mathrm{x} \leq \mathrm{u} \\ &\quad \mathrm{x_i} \in \mathrm{Z}, \ \mathrm{i} \in \mathrm{I_z} \end{aligned}$$

for sufficiently small value of the penalty parameter ($\varepsilon = 10^{-1}$ in our implementation).

Then, the previous mixed integer box constrained problem has been solved by using the new Controlled Random Search (CRS) algorithm proposed in [5].

The class of Controlled Random Search (CRS) includes algorithms that derive from the method proposed in [6] and that are designed to tackle hard nonlinear optimization problems that have different local minimum points besides the global ones and that cannot modelled by objective functions and constraint functions with an available mathematical analytic representations (therefore the first-order derivatives of such functions cannot be explicitly calculated or approximated).

The CRS algorithms have been proven to be useful tools in solving many minimization problems deriving from real world applications [7], [8], [9] and [10]. Furthermore algorithms belonging to this class have shown an efficient behavior when compared with other global optimization methods (see for example [11]).

The basic idea of a CRS-type method is that of randomly generating an initial set of sample feasible points and iteratively updating this sample by substituting the worst point, in terms of objective function value, with a better one obtained by an approximate local search. Such a local search implies that the set of sample points becomes cluster more and more round the sub-regions which are more likely to contain a global minimizer. In this way, a CRS-type algorithm follows an approach which is a compromise between a pure random search strategy and a deterministic local search.

The main distinguishing feature of the CRS algorithm proposed in [5] is the possibility of directly handling the discrete variables without a significant computational effort.

We refer to [5] for the description of the algorithm and a detailed discussion of the rationale behind its approach.

V. Results

The results are presented in Table IV: it includes some of the key machine dimensions and the torque-to-current performance at 600 rpm in the healthy mode and faulty mode operations.

TABLE IV
SR MOTOR: OPTIMIZED DESIGN

Stack length	mm	60
Outer stator diameter	mm	110
Inner stator diameter	mm	70
Shaft diameter	mm	40
Rotor to stator pole arc ratio (β_r/β_s)		0.92
Stator pole arc to pole pitch ratio		0.54
Rotor pole arc to pole pitch ratio		0.40
Turns per phase		164
Wire size	mm^2	0.50
Slot fill factor		0.45
Phase resistance (75°C)	Ω	1.17
Healthy mode operation:		
Average torque @ 600 rpm	Nm	14.0
Phase current	A	25
k_T	Nm/A	0.56
Faulty mode: one-phase open:		
Average torque @ 600 rpm	Nm	13.3
Phase current	A	30
Faulty mode: two-phase open:		
Average torque @ 600 rpm	Nm	13.0
Phase current	A	45

In the healthy operation, the torque-to-current ratio is higher with respect to the preliminary design. The ripple is about 30% without faults: as a low ripple is not a stringent requirement for the flap actuator, such a value can be considered acceptable. Moreover, this ripple will be absorbed by the inertia of the system and it is not expected to affect the operation of the actuator.

In case of one or two-phase open, the torque behavior changes respect to the healthy mode operation and the average torque decreases. In such condition, a new set of currents for the healthy phases has been imposed, in order to satisfy the degraded operating modes.

Figure 3 points out a strong torque ripple, but in this severe condition the SR motor is able to run and guarantee the regular operation of the flap actuator without affecting the stability of the aircraft. It is evident that the motor cannot run for a long time under such high current value, and this represents only a temporary operating condition.

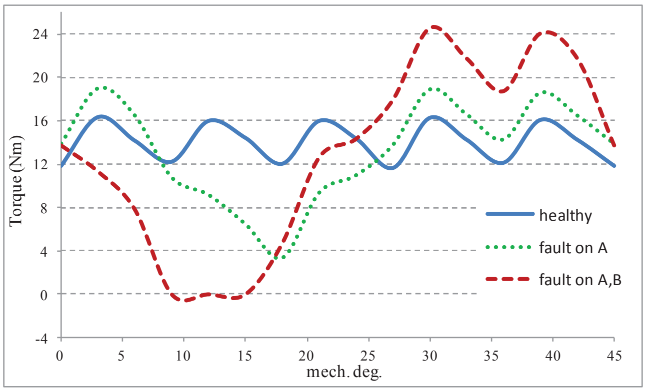

Figure 3 Optimized design: torque vs. rotor position in the healthy and faulty mode operation (FE analysis).

Staring from the optimized design a prototype has been manufactured and tested: Figure 4 shows a picture of the rotor used in the 10/8 SR motor.

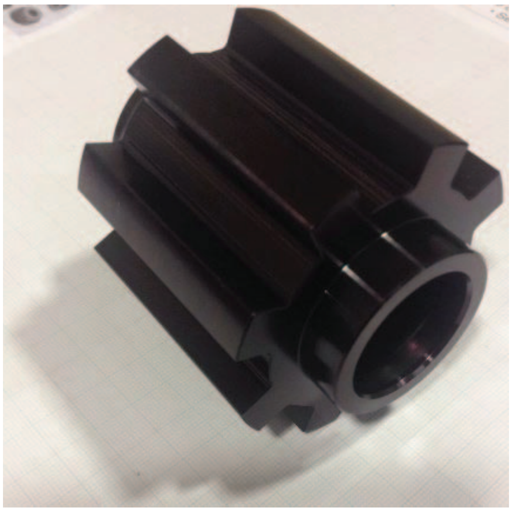

Figure 4 Prototype of the SR rotor assembled in the EMA.

Preliminary experimental results are shown in the following figures.

Figures 5 and 6 refer to the healthy mode operation of the machine at constant load-torque and speed values:

- Figure 5 shows the current waveforms of two adjacent phases along with the electrical position and the commutation sector. It should be noted that an advance angle of 4.5 degrees is adopted in the computation of the commutation sectors to take into account the effective shape of the motor inductance.
- Figure 6 reports the motor speed and currents in the same torque-speed conditions of 300 rpm, 8 Nm. One can see how the torque ripple of the motor affects the speed due to the low inertia of the motor.

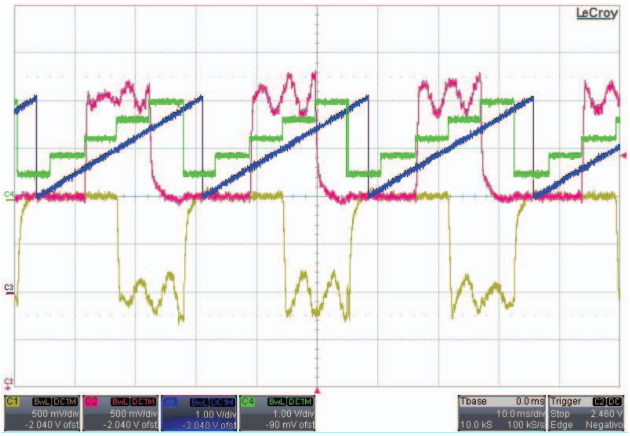

Figure 5 Healthy mode operation @ 300 rpm, 8 Nm:
Phase–A and Phase–B measured currents (yellow, red), commutation sector (green), electrical position (blue); current is scaled to 15A/div.

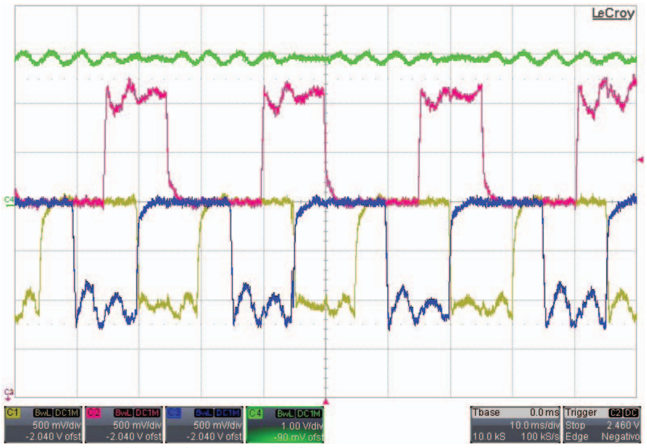

Figure 6 Healthy mode operation @ 300 rpm, 8 Nm:
Phase–A, Phase–B, and Phase-C measured currents (yellow, red, blue); motor speed (green); current is scaled to 15A/div.

The experimental results confirm the goodness of the proposed design and the suitable fault tolerant architecture. Moreover, the test results demonstrate that the specifications, in terms of torque speed and current consumption, are fully satisfied.

VI. Conclusions

In this paper we have highlighted the optimization approach which follow the design step for the optimum solution of a switched reluctance motor.

Starting from the application requirements, the dimensional constraints and performances were considered. Then the preliminary design was found and it was optimized by means of an advanced CRS algorithm coupled with a FE model.

Prototype characterization has performed confirming all the results and trends obtained in the design and optimization steps.

VII. Acknowledgment

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IX. Biographies

Luca Castellini was born in Perugia, Italy, in 1976. He graduated in aerospace electronic engineering from the University of Perugia, Perugia, Italy, in 2002.

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Stefano Lucidi received the M.S. degree in electronic engineering from the University of Rome "La Sapienza", Italy, in 1980.

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His research interests are mainly focused on the study, definition and application of nonlinear optimization methods and algorithms. This research activity has produced 70 papers published in international journals and 17 papers published in international books.

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