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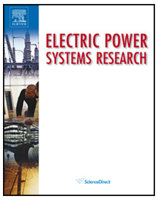

A switched-reluctance motor for aerospace application: Design, analysis and results

M. Tursini, M. Villani, G. Fabri, L. Di Leonardo*

Department of Industrial and Information Engineering and Economy, University of L'Aquila, I-67100 L'Aquila, Italy

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ABSTRACT

This paper presents a five-phase switched reluctance motor designed to satisfy the requirements of flap actuators in medium size aircrafts, a real example of the more electric aircraft trend. In normal conditions the machine operates with two phases conducting simultaneously but it is designed to satisfy the load specifications also with one or two phases open as consequence of fault remedial strategies. A finite-element study, aiming to predict both the healthy and faulty-mode performance, is presented. The mean torque vs. current capability and the torque ripple are investigated and optimum commutation angles are evaluated in static conditions. Experimental tests on the motor prototype are included, which confirm its capability to satisfy the planned degraded modes of operation and validate the design.

1. Introduction

Switched-reluctance (SR) machines have a simple mechanical structure without windings and permanent magnets on the rotor: both the stator and rotor have salient poles, hence they are referred to as doubly salient machines [1,2].

Though its origin dates back to the nineteenth century, the SR machine was ignored for a long time due to its poor performance. The developments in power electronics and converters achieved in the last decades and the use of accurate design procedures have brought to reconsider and propose this type of machine for all those applications in which robustness is a must. Several examples can be found in literature, both in variable speed drives [3–7], and in power generation [8,9].

In particular, SR motors have been considered as the engine of electromechanical actuators (EMAs) devised to replace the well established hydraulic and pneumatic actuators in more electric aircrafts (MEAs). Such an interest is related to the matter that SR motors enable direct exploitation of fault-tolerance criteria [10–12].

In fact, electrical drives for aircraft application must assure reliability levels much greater than those required in industry, and this involves specific design strategies [13].

One feasible approach aiming at including fault-tolerance in electrical drives is the one which allows to foresee redundancy and independence of the phases in their structure. The design concept is based on a modular approach whereby each phase (module) is as much as possible insulated from the others as regard to electrical, magnetic and thermal issues. As to the motor structure, such principles have the natural implementation through the use of concentrated stator windings [14].

The SR motor represents an effective candidate for aircraft applications because of its inherent modularity and fault-tolerance. In fact, its structure is strictly based on concentrated windings and the lack of permanent magnets (PM) makes the machine behavior independent from temperature and safe as regards some important failure conditions.

Compared to PM machines, the SR motor is much more robust, easy to build, and cheaper and it has the advantage that no dragging torque is produced in the case of phase short-circuits [15]; nevertheless, some key figures such as power-to-weight and power-to-size ratios, and efficiency, which are relevant for aircraft actuators, could be lower in principle without accurate design, and they need to be carefully evaluated for the given application [16].

In the recent past, the authors proposed multi-phase PM machines with modular structure for aircraft applications, including an actuator designed for the deployment of the wing's flaps [17].

The block scheme of the flap-actuator concerned is shown in Fig. 1. It is based on a rotating electric motor with a ball-screw device integrated into the rotor body, which turns the rotational

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* Corresponding author at: R13 technology srl., I-67100 L'Aquila, Italy.
E-mail addresses: marco.tursini@ing.univaq.it (M. Tursini), marco.villani@univaq.it (M. Villani), giuseppe.fabri@univaq.it (G. Fabri), dileonardolino@gmail.com (L. Di Leonardo).

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Nomenclature

B	air-gap flux density at the aligned position
L	active motor length
D	bore diameter
Δ	specific electric loading
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 in rpm
I	peak phase current
V	peak phase voltage
A, . . ., E	phases of the motor

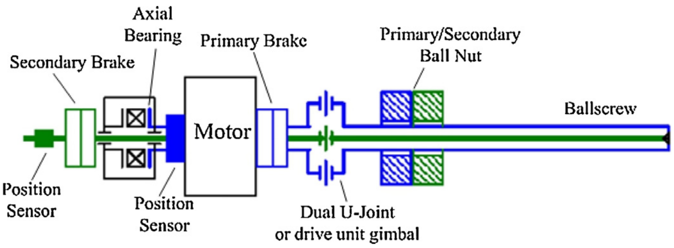

Fig. 1. Block scheme of the flap-actuator.

Table 1
Specifications of an electrical motor for flap actuator.

DC voltage supply (max)	V	250
Rated torque in the healthy mode operation	Nm	12.0 @ 600 rpm
Weight	kg	<4.0
Stack length	mm	60
Outer stator diameter	mm	110
Cooling system		Natural air
Torque with one phase open	Nm	12.0 @ 600 rpm
Torque with two phases open	Nm	12.0 @ 400 rpm

motion in a linear movement. The developed prototype refers to a medium size aircraft (120–180 passengers). The specifications of an electrical motor matching to such ratings are shown in Table 1, in which the stack length and outer stator diameter have been fixed for the encumbrance limits and the maximum speed depends on the transmission ratio of the ball-screw device and the linear speed requested by the flap panel.

In this paper a five-phase fault-tolerant SR machine developed for the same flap actuator is concerned, and design details, prototyping issues and performance are presented. The work completes the study illustrated in [18] and will enable, in the near future, a comparative evaluation between PM and SR machines in order to identify the better solution for such specific application.

The paper is organized as follows: preliminary design issues and sizing equations of the SR motor are resumed in Section 2; torque production principles and related feeding strategy are presented in Section 3; the design refinement by means of finite element analysis is discussed Section 4; performance analysis and optimization of the feeding strategy are shown in Section 5; the multi-phase fault tolerant control scheme is presented in Section 6; finally, experimental verification of the SR motor-drive prototype is reported in Section 7.

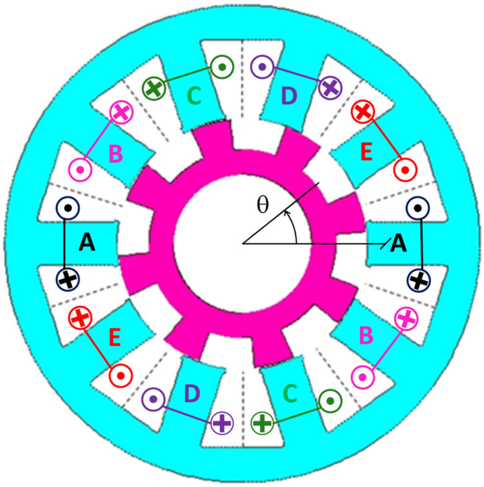

Fig. 2. Cross-section and winding distribution of the five-phase 10/8 SR motor.

2. Switched-reluctance motor design

The SR motor is a type of reluctance motor, doubly salient with phase coils mounted around diametrically opposite stator poles. There are no windings or permanent magnets on the rotor, which is basically a piece of steel (and laminations) shaped to form salient poles. The stator has concentrated coils on $N_s = 2mq$ stator poles where m is the number of phases and q is the number of the stator poles pairs per phase, while the rotor has N_r poles.

The cross section of the SR motor presented in this paper is shown in Fig. 2. According to the multiphase constraint of the flap actuator application it has $m = 5$ phases, whereby a solution with $N_s = 10$ stator poles and $N_r = 8$ rotor poles has been chosen: the concentrated windings on the diametrically opposite poles are connected in series.

The torque comes from the tendency of the rotor poles to align with the excited stator poles; it follows that to achieve smooth torque generation the phase feeding must be switched according to the rotor position.

The structure here considered foresees two adjacent phases conducting simultaneously according to the winding signs depicted in the cross-section scheme: such feeding strategy and the related commutation logic will be discussed in the next Section 3.

The preliminary performance analysis of the SR motor requires defining the dimensions for stator and rotor shapes, stator windings, pole numbers, and pole arcs.

An approximate sizing of the SR motor is obtainable by using the output power Eq. (1), which relates bore diameter and length, speed, and magnetic and electric loadings as follows [2]:

$$P_o = \left(\frac{\pi^2}{120}\right) a\gamma\eta D^2 LB\Delta n_s \tag{1}$$

where the parameters a and γ can be computed as:

$$a = \left(1 - \frac{1}{k_1 k_2}\right) \tag{2}$$

$$\gamma = \frac{\alpha_c N_{ph} N_r}{360} \tag{3}$$

where:

- k_1 is the ratio between the aligned saturated inductance per phase and the aligned unsaturated inductance per phase;
- k_2 is the ratio between the aligned unsaturated inductance per phase and the unaligned inductance per phase;