Evaluation of the intrinsic fault tolerance of an EMA landing gear based on a five-phase SM-PMSM

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Abstract

Nowadays, aircraft electrification is being intensively investigated by the industry and academia in order to meet the actual environmental goals regarding pollutant emissions. In this context, the More Electric Aircraft (MEA) initiative is leading to the progressive substitution of hydraulic systems by power electronics based electromechanical actuators (EMA). Although three-phase electrical machines are the industry standard, the introduction of multiphase systems provides a number of benefits, such as an increased fault tolerance. Taking this into account, this paper analyses, the intrinsic fault tolerant performance of an EMA landing gear (for extension/retraction operation) based on a five-phase surface mounted permanent magnet synchronous machine (SM-PMSM) in terms of torque regulation under a variety of open circuit fault conditions. A detailed simulation model has been implemented in order to carry out the analysis. The obtained results demonstrate that the usage of the conventional field oriented control (FOC) can be enough to operate the system in a pseudo-optimal fashion for this particular landing gear application.

Introduction

Nowadays, the need of efficient and eco-friendly transport systems has encouraged the development of new transportation technologies. Regarding air transport, the MEA (More Electric Aircraft) initiative has become the model to follow [1]. This initiative pursues the development of more efficient aircrafts with minimal environmental impact, while ensuring the reliability, availability and security requirements proper of the aeronautic sector [2], [3]. In order to achieve these goals, the MEA initiative proposes the progressive introduction of electric systems in airplanes, i.e., mainly replacing hydraulic actuators by electromechanical actuators (EMA).

Apart from the power electronics and the mechanical components, the electrical motor can be considered as a key element of an EMA. There are several available motor technologies. Among them permanent magnet synchronous motors (PMSM) can be highlighted, as they provide high efficiencies and energy densities [2]. In general, the most extended phase-configuration of PMSMs in transport and industry is the three-phase one. However, a number of advantages of motor with more than three phases (Multiphase motors) that can be very convenient for the aviation standards have been reported in the recent scientific literature. Such advantages can be summarized as [4]:

- Reduced harmonic distortion in the stator currents, leading to a low ripple in the electromagnetic torque production, allowing a smoother machine operation.
- Reduction of the harmonic content in the DC bus current. This decreases the operation temperature of the DC capacitor, improving its efficiency and extending its lifespan.
- Reduction of the per-phase current and power ratings. This can significantly improve the overall efficiency of the system, also allowing a simpler cooling system and extending the lifespan of semiconductor devices.
- Increase of the reliability and the availability of the system, because of the intrinsic fault tolerance of multiphase motors. Furthermore, the additional degrees of freedom allow the design of specific control algorithms that can improve the operation of the multiphase machine after the occurrence of a fault.

In this context, mechanical (jamming of the motor or ball screw) or electrical (open or short circuit faults on power electronics and machine windings) faults can occur in the electrical machine, jeopardizing system operation. Among many types of faults that can occur, open-circuit faults are the most common [5]. When an open circuit fault occurs in a multiphase machine, a number of remedial strategies can be implemented. For example, in [6] an optimization methodology that allows optimizing the current references during post-fault operation is presented. However, multiphase machines pose an intrinsic fault tolerance capability. Depending on the severity of the fault, it could be possible to drive the system under a single or multiple faults following a degraded operation. As the no inclusion of additional control and fault detection strategies simplifies the implementation of the control system, this paper presents a simulation model with fault emulation capabilities, and studies the impact of open circuit faults in a given real landing gear system, which includes a star connected five-phase surface mounted (SM) PMSM. The performance of the torque regulation under faulty conditions will be quantified, and thermal unbalances in the system will be analyzed.

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Model of a star connected five-phase SM-PMSM

A convenient approach to simulate multiphase motors is to use decoupled models with multiple space vector planes [7]-[9]. These models allow simulate the operation of the machine when there are no faults. In addition, they provide a representation that simplifies the tuning of PI controllers for the regulation of the phase current and electromagnetic torque. However, without modifications, such decoupled models are not suitable for the simulation of faulty operation conditions as, for each kind of fault; it is required to substitute the model by a particular model that considers a given fault [10], [11].

Therefore, this work proposes the usage of a multiphase PMSM model in its natural coupled current and voltage variables, which simplifies the particularization of the model for a great variety of fault conditions. Following this approach, the equation that relates the voltages and currents in a permanent magnet motor is given by:

$$\mathbf{V} = \mathbf{RI} + \frac{d\mathbf{L}}{dt}\mathbf{I} + \mathbf{L}\frac{d\mathbf{I}}{dt} + \frac{d\mathbf{\Psi}_{PM}}{dt}, \quad (1)$$

where **V** and **I** are *5*-dimensional vectors representing the voltages and currents of each phase. **R** and **L** are *5x5* matrices with the values of resistances and inductances of the motor:

$$\mathbf{R} = \begin{bmatrix} R_s & 0 & 0 & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 & 0 \\ 0 & 0 & 0 & R_s & 0 & 0 \\ 0 & 0 & 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & 0 & 0 & R_s \end{bmatrix}, \quad (2)$$

$$\mathbf{L}(\boldsymbol{\theta}_e) = \begin{bmatrix} L_{11}(\theta_e) & L_{12}(\theta_e) & \cdots & L_{15}(\theta_e) \\ L_{21}(\theta_e) & L_{22}(\theta_e) & \cdots & L_{25}(\theta_e) \\ L_{31}(\theta_e) & L_{32}(\theta_e) & \cdots & L_{35}(\theta_e) \\ L_{41}(\theta_e) & L_{42}(\theta_e) & \cdots & L_{42}(\theta_e) \\ L_{51}(\theta_e) & L_{51}(\theta_e) & \cdots & L_{51}(\theta_e) \end{bmatrix}. \quad (3)$$

From (3), it can be seen how the inductances of the matrix can depend on the position of the rotor depending on the construction of the PMSM. When implementing a SM-PMSM, such inductances are constant.

On the other hand, $\mathbf{\Psi}_{PM}$ represents the per phase flux linkage produced by the rotor permanent magnets, as shown in (4). The sub-index i represents each element of the flux linkage vector. The sub-index k represents the harmonics order. In this work only the fundamental and third order harmonics are considered.

$$\Psi_{PMi}(\theta_e) = \psi_0 + \sum_{k=1}^{\infty} \psi_k \cos\left[k(\theta_e - \delta_{1i})\right]. \quad (4)$$

On the other hand, the electromagnetic torque produced by the motor is given by the following expression:

$$T_{em} = \left(\frac{d\mathbf{L}}{dt}\mathbf{I}\cdot\mathbf{I} + \frac{d\mathbf{\Psi}_{PM}}{dt}\cdot\mathbf{I} \right) / \omega_m, \quad (5)$$

where, ω_m is the mechanical speed of the rotor. Finally, (6) describes the mechanical part of the machine.

$$T_{em} - T_l = J\frac{d\omega_m}{dt} + B\omega_m, \quad (6)$$

where, T_l is the load torque, J is the equivalent inertia of the rotating masses and B is the viscous friction. The relationship between the electrical machine rotation and EMA linear motion is given by the ball screw model.

In such equations, the variables are highly coupled belonging to different domains. Therefore, a convenient way to implement this model is to use the language and graphical interface provided in the Matlab/Simulink toolbox Simscape (Fig. 1). In this model, each phase has been modeled by a constant resistor R_s, a variable inductance $L_k(\theta_e)$ and a voltage-controlled source $V_{ck}(\mu)$. These voltage-controlled sources include coupling effects of currents and back-EMF.

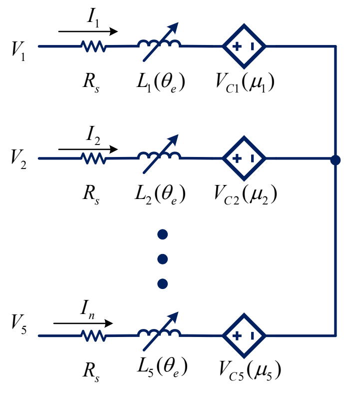

Fig. 1 Schematic of the multiphase motor model.

Vector control of the 5-phase PMSM EMA

Fig. 2 depicts the general diagram of the cascaded control strategy that controls the extension and retraction of the landing gear, including the following blocks:

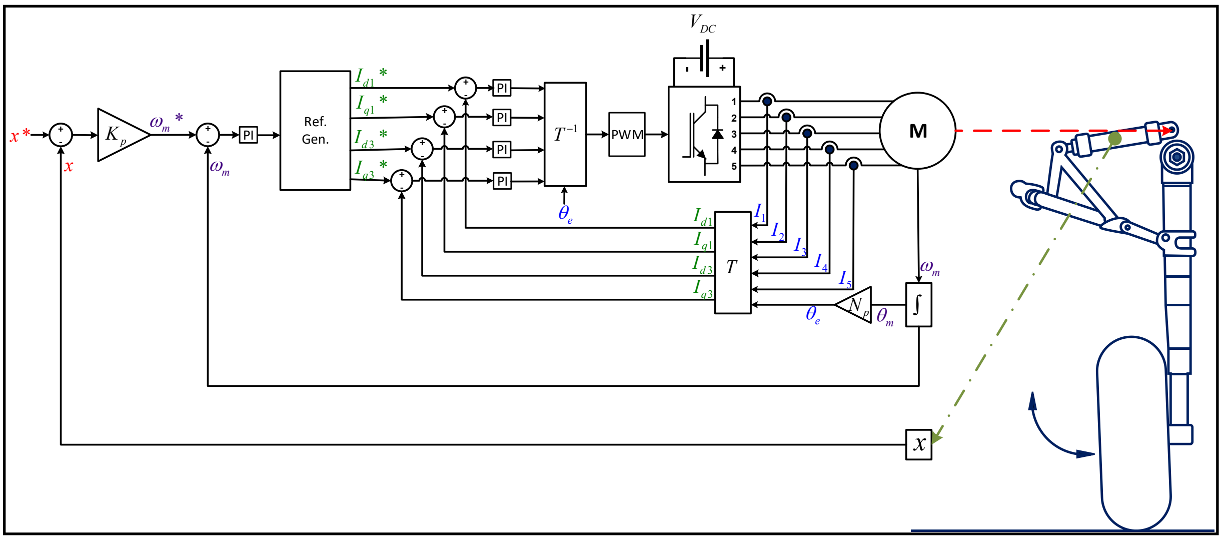

Fig. 2. General diagram of the landing gear EMA control system.

- The outer position loop (with a single gain), responsible for the control of the landing gear linear position $\boldsymbol{x}$.
- The speed loop, which receives the speed reference form the position loop and, using a discrete PI, determines the required electromagnetic torque in each operation instant.
- The inner torque loop, which is based on the well-known field oriented control (FOC) approach, is adapted to the multiphase scenario, using PI regulators to control the four degrees of freedom of the five-phase SM-PMSM. A decoupling transformation $\mathbf{T}$ is used to independently control the fundamental (I_{d1}, I_{q1}) and third harmonic (I_{d3}, I_{q3}) currents.

It is important to point out that, for the sake of simplicity, the required saturation blocks and anti-windup loops have not been included in the control diagram. On the other hand, the simulated multiphase SM-PMSM was designed to include a third harmonic in the flux linkage Ψ_{PM}. Therefore, the third harmonics currents are able to produce electromagnetic torque, increasing the torque density of the machine.

Simulation results during healthy and faulty operation

In order to evaluate the feasibility of relying solely on the intrinsic fault tolerance of the machine under a number of faulty conditions, several simulations have been carried out, considering normal operation, single open switch fault and two open switch faults (non-adjacent and adjacent). Table I collects the most relevant parameters of the simulated EMA landing gear system. Fig. 3 shows the counter load torque. In the following, simulation results during an extension of the landing gear are presented.

Table I. Most relevant parameters of the multiphase SM-PMSM and EMA landing gear.

Parameter	Symbol	Value
Stator inductance	L_s	9.6 mH
Stator resistance	R_s	2.5 Ohm
First harmonic PM flux	ψ_1	0.1314 Wb
Third harmonic PM flux	ψ_3	0.0262 Wb
Rated power	P_N	1.51 kW
Rated torque	T_N	12.1 Nm
Rated speed	ω_N	1200 RPM
Pole pair number	N_p	9

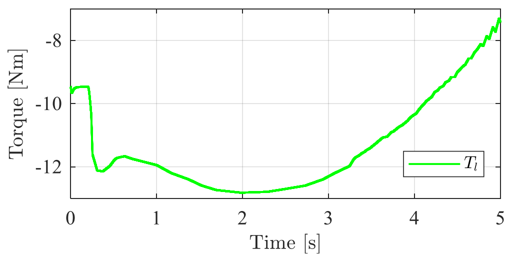

Fig. 3 Counter load during landing gear extension operation.

The power system operates without faults until second 1.5, where a single open circuit fault is provoked in the windings of phase 1. Figs. 4 and 5 show the torque regulation of both the fundamental and third harmonic components. The torque regulation is smooth until the fault occurs. During the fault, a significant high frequency torque ripple is produced, as no remedial control algorithm is applied. Although this perturbation produces a significant ripple in the machine mechanical speed (Fig. 6), the position controller is able to track the linear position reference in a satisfactory fashion (Fig. 7), leading to a correct landing gear extension.

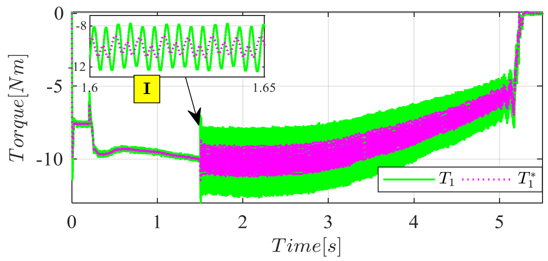

Fig. 4 Torque regulation results of the first harmonic component.

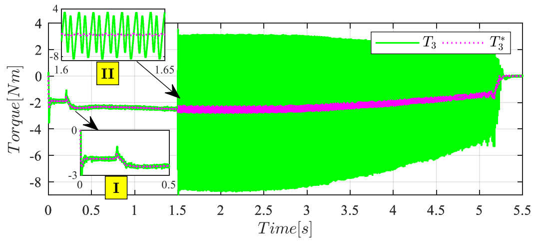

Fig. 5 Torque regulation results of the third harmonic component.

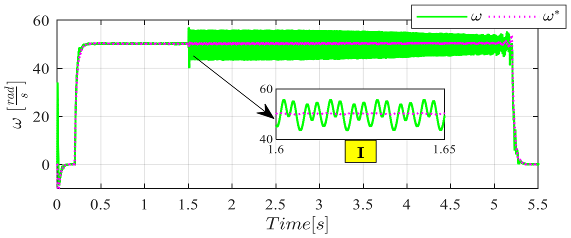

Fig. 6 Speed regulation results during healthy and faulty operation.

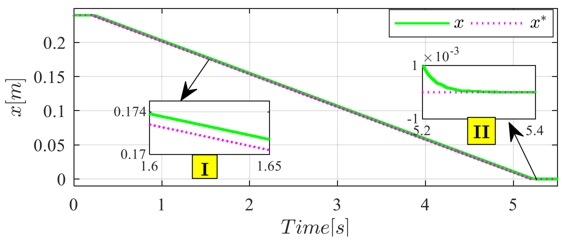

Fig. 7 Linear position control of the landing gear EMA during healthy and faulty operation.

Finally, table II compares the performance of the EMA actuator for a variety of fault conditions. The actuator operates pseudo-optimally under a variety of faults. If the power system is overdimensioned, it can withstand the high current and thermal conditions derived from the unbalanced operation.

Conclusions

In this work, the operation of a five-phase landing gear EMA under normal operation and fault conditions has been tested. As the landing gear operates during a brief period of time, the intrinsic fault tolerance of the system can be enough to guarantee a sufficient pseudo-optimal operation during some fault conditions.

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Table II. Comparison of performance for various operation conditions.

	Speed ripple [rad/s]	Fundamental torque ripple [Nm]	Max phase current [A]
No fault	0.46	0.34	3.51
1 phase OC	12.14	4.57	7.48
2 non-adjacent OC	22.63	12.62	13.75
2 adjacent OC	29.84	19.53	12.06

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