Materials Research Proceedings 37 (2023) 89-93 https://doi.org/10.21741/9781644902813-20

Experiments and simulations for the development of a dual-stator PMSM for lightweight fixed-wing UAV propulsion

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Keywords: UAV, Full-Electric Propulsion, Axial-Flux PMSM, Simulation, Testing

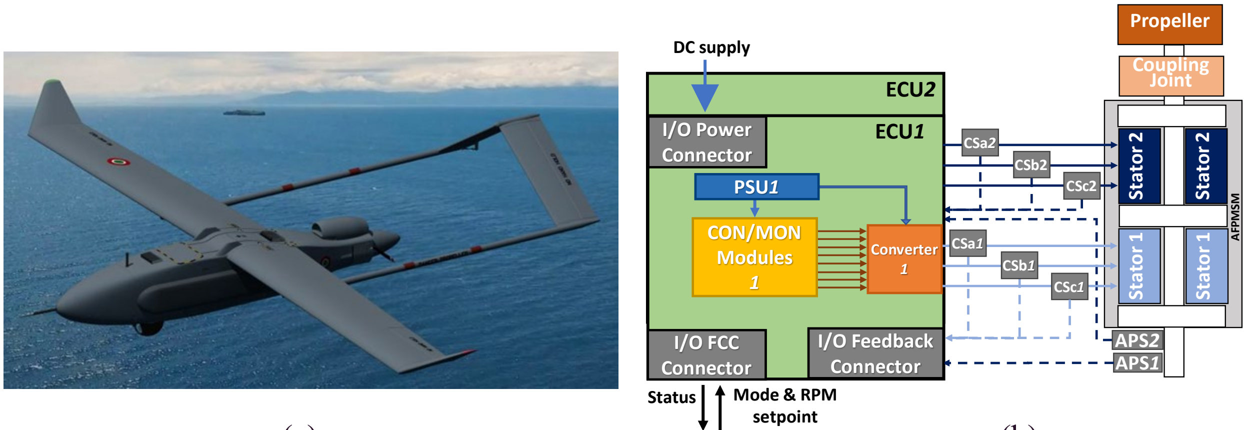
Abstract. The work summarizes the experimental and simulation studies carried out on the full-electric propulsion system of a lightweight fixed-wing UAV developed in the research program TERSA. The electric motor, specifically designed for the project, is a double-stator axial-flux PMSM with single output shaft, directly connected to a twin-blade fixed-pitch propeller. The system dynamics is firstly addressed by nonlinear simulation, modelling the motor and related sensors, the propeller and the digital controllers, to design the closed-loop control architecture. Successively, an experimental campaign is defined to identify/substantiate the main motor parameters (resistance and inductance of phases, torque and speed constants, back-electromotive force waveforms) and to validate the closed-loop control design.

Introduction

In the air transport sector, Full-Electric Propulsion Systems (FEPSs) are expected to obtain large investments in forthcoming years, aiming to replace/support the operation of conventional internal combustion engines, especially in small-size power applications [1]. Even if immature nowadays in terms of reliability and energy density (e.g., gasoline energy density is about 100 times higher than lithium-ion battery packs [2], typically ranging about 300 kJ/kg), the design of the next-generation long-endurance UAVs is moving toward the use of FEPSs, pulled by the wider objectives of aerospace electrification. In this context, the Italian Government and the Tuscany Regional Government funded the research program TERSA[1] [3], led by Sky Eye Systems (Italy) in collaboration with University of Pisa and other Italian industries. The TERSA project aims to develop a Unmanned Aerial System (UAS) based on a lightweight fixed-wing UAV (Fig. 1), having the following main characteristics:

- Main performance data: MTOW from 35 to 50 kg; Endurance >6 h; Range >3 km;
- Take-off/landing systems: pneumatic launcher and parachute/airbags;
- Propulsion system: FEPS with a twin-blade fixed-pitch propeller;
- Payloads: SAR (Synthetic Aperture Radar) and SAAS (Sense-And-Avoid System).

[1] Tecnologie Elettriche e Radar per Sistemi aeromobili a pilotaggio remoto Autonomi, Fund ID F/130088/01-05/X38



(a) (b)

Figure 1. (a) TERSA UAV layout; (b) FEPS architecture.

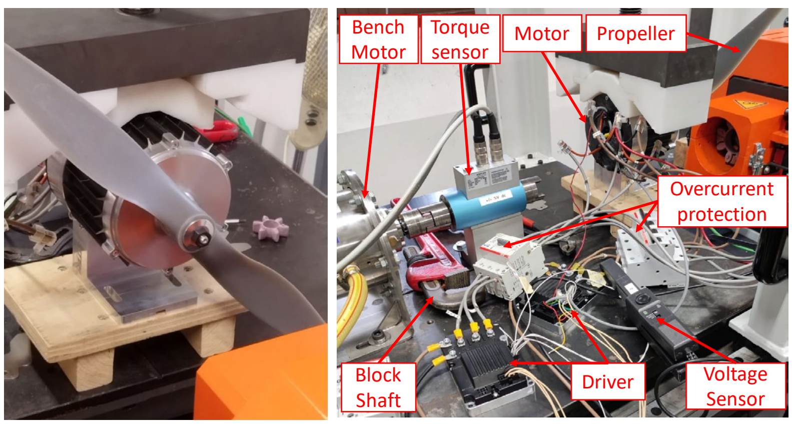
The FEPS of TERSA UAV is based on Axial-Flux PMSM (AFPMSM) technology [4], which, though characterized by lower technology readiness level, is preferable to conventional radial flux PMSMs in terms of weight (core material is reduced), torque-to-weight ratio (magnets are thinner), efficiency (losses are minimized), and versatility (air gaps are easily adjustable) [5], [6]. Another key aspect for application in UAV flying into unsegregated airspaces is clearly reliability and safety. Due to the weight limitations, hardware redundancy in FEPSs is often a drawback, and reliability is enhanced via motor phase redundancy [7], or unconventional converters [8]. Although the use of unconventional converters leads to a more compact solutions, it requires an ad-hoc design of motor and power electronics [8],[9], so PMSMs with multiple three-phase arrangements using conventional converters driven by standard techniques are in some extent convenient [10]. Starting from these considerations, the reference FEPS has been equipped with a dual-stator AFPMSM that can operate in both active/active or active/stand-by configurations, providing the system with fault tolerant potentialities [11] This paper summarizes the activities carried out for the modelling, the simulation, the control design and the experimental characterization of the TERSA UAV FEPS. The work is articulated in two parts: the first one dedicated to the system description and to the nonlinear modelling, and the second to testing and simulations for model validation.

System description

The TERSA UAV FEPS, Fig. 1(b), is composed of a AFPMSM mechanically connected to a twin-blade APC22×10E fixed-pitch propeller and electrically connected to two Electronic Control Units (ECUs). Each ECU includes a three leg converter, a Power Supply Unit (PSU) and a I/O connector interface. The ECUs receive commands from the Flight Control Computer (FCC) and feedbacks from Current Sensors (CSa, CSb, CSc) and an Angular Position Sensor (APS). The closed-loop control applies two nested loops, on the propeller speed and motor currents (via Field-Oriented Control, FOC) respectively. The cascade regulators implement proportional/integral actions on tracking error signals, plus anti windup function with back-calculation to compensate for commands saturation.

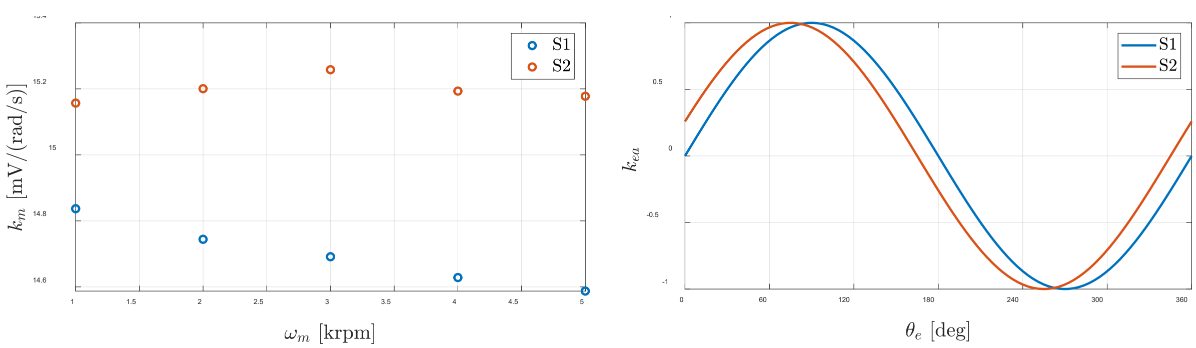
Experiments and simulations

Two test campaigns with different experimental setup have been carried out to identify/substantiate the main parameters of the propulsion system model and to validate the closed-loop regulators. In the first campaign, since the motor model identification requires three parameters (the motor speed constant k_m, the resistance R and the inductance L of the phases) and three BEMF waveforms as functions of the electrical angle ($k_{ex}(\theta_e) = e_x / k_m \dot{\theta}_e$, where e_x is the BEMF of the phase x $(= a, b, c)$ and θ_e is the electrical angle), two tests have been designed. The first one is done with blocked rotor to identify R and L, and the second one with the rotor dragged by the bench motor to identify k_m and k_{ex}. In the second campaign, a first test has been done by blocking the rotor while commanding the motor current with step inputs of different amplitudes, and a second test (Fig. 2) has been performed by connecting the propeller and by commanding the angular speed with tracking signals of different amplitudes. Figure 3 reports the motor speed constant and the BEMF waveforms for both stators. Figure 3(a) highlights that the dependency of the speed constant on the angular speed is more relevant in the stator 1 (S1), even if the maximum variation is about 1%. In addition, Fig. 3(b) shows an electrical angle phase misalignment (about 15 deg) in the BEMF waveforms. Figure 4 summarizes the simulation results. Figure 4(a) points out the validation of the current controller, accomplished by requesting step commands of quadrature current (40 A and 60 A, respectively) while the output shaft is blocked. The model exhibits a slight delay (1 ms) when the command signal is applied, but the prediction error rapidly diminishes (within 5ms). The validation of the speed controller is finally reported in Fig. 4(b), and it is performed by requesting two ramped-step speed commands, with 2 and 4 krpm amplitudes, both characterised by a 1 krpm/s slope. In both cases, the test ends by removing the electrical power and letting the motor passively decelerate (thus permitting a more direct identification/substantiation of system inertias). Apart from a low frequency (about 8 Hz) harmonic disturbance due to imperfect rig grounding, the model behaves satisfactorily during both controlled and uncontrolled phases.



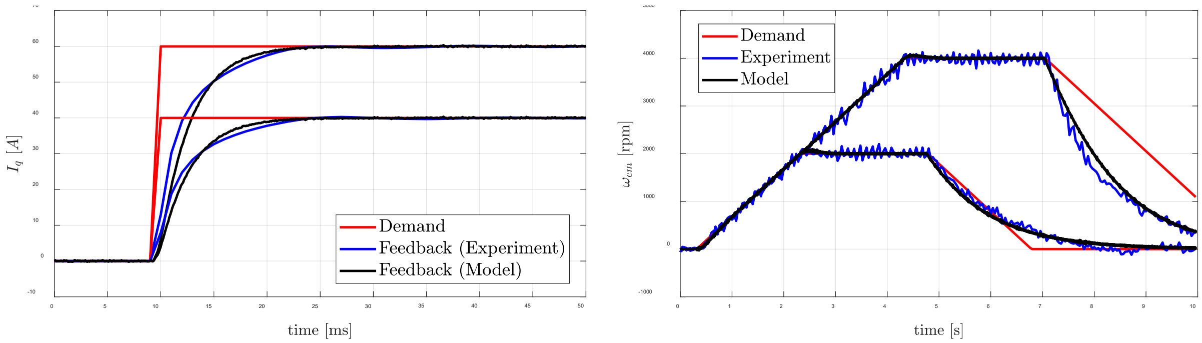
(a) (b)

Figure 2. Experimental setup for speed tracking tests: (a) connected propeller (b) rig layout.



(b)

Figure 3. BEMF of motor modules: (a) speed constant; (b) BEMF wrt electrical angle.



(a) (b)

Figure 4. Closed-loop control validation: (a) current (b) angular speed.

Summary

The main parameters of the nonlinear model of the TERSA UAV propulsion system are identified/substantiated through experiments and the closed-loop control performances are validated. Due to manufacturing imperfections, the BEMF of the stator modules are misaligned wrt the motor angle and they have different torque constants. The asymmetry, though partially compensated by the control actions, can cause a reduction of the propulsion system efficiency and high-frequency torque ripples that, affecting bearings and seals, can potentially lead to premature failure. The FEPS model can be used to develop advanced model-based monitoring techniques, for the enhancement of the system diagnostics and prognostics.

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