Available online at www.sciencedirect.com

ScienceDirect

IFAC Papers Online
CONFERENCE PAPER ARCHIVE

IFAC PapersOnLine 50-2 (2017) 169–174

# Hybrid Aeronautical Propulsion: Control and Energy Management

**Elisabetta Bongermino*, Michele Tomaselli*, Vito G. Monopoli*, Gianluca Rizzello**, Francesco Cupertino*, David Naso***

**Department of Electrical and Information Engineering, Polytechnic University of Bari, Bari, Italy*
*(e-mail: ebongermino@gmail.com, michele_tomaselli@live.it,*
*{vitogiuseppe.monopoli, francesco.cupertino, david.naso}@poliba.it)*
***Department of Systems Engineering and Department of Material Science and Engineering, Saarland University,*
*Saarbrücken, Germany (e-mail: gianluca.rizzello@imsl.uni-saarland.de)*

**Abstract:** In this paper, a control strategy for energy management of a parallel hybrid electric UAV (Unmanned Air Vehicle) powertrain is presented. A Simulink-based model of the system is first presented, consisting of an internal combustion engine, a gearbox (which includes a planetary gear and a continuously variable transmission), an electric motor (which can also work as a generator), an electric drive (Inveter) and a Li-Po battery pack. The proposed control strategy consists of a quasi-real-time iterative algorithm based on Dynamic Programming, which allows to optimize power management and torque-split of the powertrain with final state constraints on state variable. Aim of the study is to investigate new flight capabilities that derive from the use of a hybrid architecture, e.g., silent mode using only electric motor (useful for military and civil purpose), and the capacity of reducing fuel consumption. Simulation studies are performed, based on data of an existing UAV and a real flight mission.

*Keywords:* Hybrid electric aircraft, power management strategy, Dynamic Programming, real-time optimization.

## 1. INTRODUCTION

Over the last years, drones and unmanned aircrafts have been considerably improved mainly because of the increasing interest of governments and aeronautical industries towards the environmental impact as well as the performances of such systems. Such interest is mainly raised by their capability of accessing, monitoring and overseeing hostile environments. Hybrid propulsion can even further boost their development possibilities. In fact, while the internal combustion engine (ICE) can guarantee a long endurance, the electric motor (EM) delivers silent features that represent a very important aspect to reduce the traceability (thermal, chemical and acoustic) of Unmanned Aerial Vehicles (UAV). Additionally, the EM both acts as a power source for the auxiliaries and supports the emergency landings. The aim of this paper is to understand to what extent the powertrain size and weight reduction as well as fuel consumption can be attained by the considered hybrid topology. Moreover, issues related to a Hardware-in-the-Loop based laboratory setup have been addressed. In particular, the Simulink model of the powertrain as well as the Matlab control algorithm used to optimize the torque-split are shown.

Basically, powertrains can be parallel hybrids, series hybrids and series-parallel hybrids (Liu and Peng (2008)). In this paper, a parallel hybrid topology has been addressed. Fig. 1 shows the two distinct paths (i.e. electrical in the left side and mechanical in the right side). By using this configuration, it is possible to flexibly drive the UAV (i.e. electrical, mechanical, or both), to reduce losses, to adopt smaller and more efficient motors and, sot importantly, it enables the EM to work both in motoring and regenerating. The mechanical part of this architecture is made up of the fuel tank and a Wankel rotary ICE. The variable fuel level has been modelled dynamically, while the ICE is described through experimental power maps. The electrical part of the parallel configuration is made up of the battery pack, the inverter and a Permanent Magnet-Assisted Synchronous Reluctance Motor (PMSyR). As regards the battery, it has been modelled in Simscape® of Simulink® while its control system has been implemented through Stateflow®. The inverter is represented through its average model, and a current and torque control is also implemented for the PMSyR. The continuously variable transmission (CVT) and the planetary gear represent the connection point of the electrical and the mechanical part of the parallel architecture and they are both modeled with the Power-Oriented Graph (POG) technique (Zanasi and Grossi (2009)). The output for the gearbox is represented by the power drawn by the propeller.

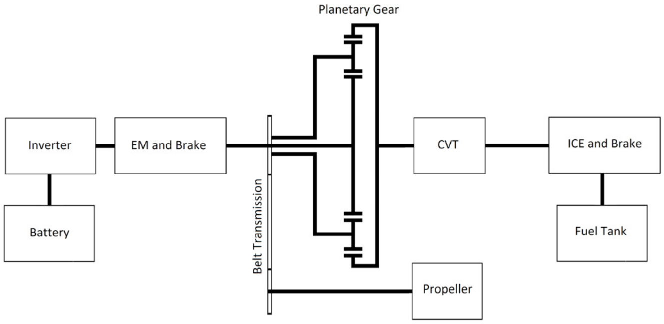

Fig. 1 Powertrain parallel architecture

2405-8963 © 2017, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.12.031

The power splitting between the electrical and mechanical parts can be addressed as a typical optimization problem, keeping in mind the battery state of charge (SOC) as unique constrain. In fact, such parameter deeply influences the battery lifetime (Sciarretta and Guzzella (2007)). Techniques referred to as Dynamic Programming (DP) can be borrowed from the automotive field and can be profitably used to predict the global optimal solution to the torque-split problem. An alternative approach is based on Model Predictive Control (MPC). The main benefit of this technique is the real-time elaboration of the optimal control strategy (Yan et al. (2012)). In the aeronautical field, the existence of a predetermined route makes the DP approach more suitable to solve a global optimization problem. Nevertheless, the main drawback related to the DP approach is the heavy computational burden. To address such an issue, an iterative algorithm to reduce the processing time has been proposed in this paper. In particular, the mission is segmented and the DP is applied at the beginning of each interval thus achieving a reduction of the prediction interval and of the computational burden.

The paper outline is as follows: sections from 2 to 6 describe ICE model, the Electric Drive, the Energy Storage System, the Mechanical Transmission and the Dynamic Programming algorithm respectively. In section 7 results are presented and discussed. Finally, conclusions are drawn in section 8.

## 2. INTERNAL COMBUSTION ENGINE

The Internal Combustion Engine (ICE) is a 63 kW Wankel rotary engine that, thanks to its limited vibration, small size, and a high power-to-weight ratio, is suitable for the aeronautical field. Fig. 2 shows a block-diagram representation of the ICE model.

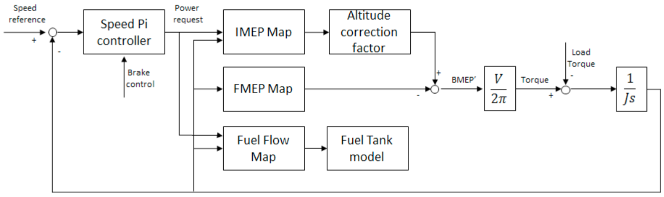

Fig. 2. Internal Combustion Engine model

In this model, the Indicated Mean Effective Pressure (IMEP) map denotes the mean pressure inside the combustion chamber, while the Friction Mean Effective Pressure (FMEP) indicates the losses caused by friction forces. Their difference expresses the Brake Mean Effective Pressure (BMEP).

To take into account the effects of altitude on ICE performances, a corrective factor $\mu$ is introduced

$$\mu = \frac{P_a'}{P_a}\sqrt{\frac{T_a}{T_a'}}, \tag{1}$$

where $P_a$ and $T_a$ are the ambient pressure and temperature at sea level, respectively, while $P_a'$ and $T_a'$ are the pressure and temperature at a reference altitude, respectively.

The BMEP in dependence on altitude is given as

$$BMEP' = \mu \cdot IMEP - FMEP\,. \tag{2}$$

The fuel tank model provides a measure of fuel consumption. A PID controller takes the speed error and generates the reference throttle for the motor as a percentage of needed power [0-100%], in order to obtain the desired speed.

## 3. ELECTRIC DRIVE

The electric drive consist of a 50000 rpm, 50 kW, 10 Nm Permanent Magnet-Assisted Synchronous Reluctance Motor (PMSyR) and a three-phase inverter. A block-diagram representation of the electric drive model is summarized in Fig. 3, and is based to the stator equations expressed along direct and quadrature axes (Krishnan, R. (2001))

$$v_{s,dq} = R_s i_{s,dq} + \frac{d\lambda_{s,dq}}{dt} + j\omega_r \lambda_{s,dq}\,, \tag{3}$$

where $R_s$ is the stator resistance, $v_{s,dq}$, $i_{s,dq}$, $\lambda_{s,dq}$ are the applied voltage at the stator, the stator current, and flux along the dq-axes, respectively, and $\omega_r$ is the electrical angular velocity.

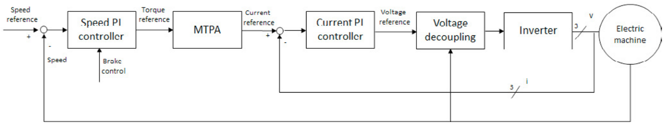

Fig. 3. Electric Drive Model

The inverter model consist of an average model implemented using a s-function block compiled with C-code. The average model includes the nonlinear behavior of real three-phase inverter, i.e. the inverter diodes and transistors dead times.

The d-q magnetic fluxes depend on direct component of the stator current $i_{s,d}$, quadrature component of the stator current $i_{s,q}$, and flow generated by the permanent magnets $\lambda_{PM}$, according to the following equations

$$\lambda_{s,d} = L_d\left(i_{s,d}, i_{s,q}\right) i_{s,d}\,, \tag{4}$$

$$\lambda_{s,q} = L_q\left(i_{s,d}, i_{s,q}\right) i_{s,\mathrm{q}} - \lambda_{PM}\,, \tag{5}$$

where $L_d$ and $L_q$ are the inductances along dq-axes calculated by means of FEM simulations. The expression of the electromagnetic torque is obtained by considering the mechanical component of the EM power

$$C_e = \frac{3}{2} n_p \left[\left(\lambda_{s,d} - \lambda_{s,q}\right) i_{s,d}\right], \tag{6}$$

where $n_p$ is the poles number. Permanent magnets allow an increase in torque and a reduction of the flux on the quadrature axis.

The speed and stator current of the electric drive are regulated using a cascade control. A PI controller produces the torque reference to obtain the desired speed. Equations (4), (5) and (6) show that there is not a univocal relation