Defining Control Loops for a Fuel Cell Powered Aeronautic Propulsion System

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Abstract The main function of the Full-Authority Digital Engine Controller in turbofan engines is to ensure that the thrust required by the aircraft is provided while avoiding exceedances on engine parameters. Limits on maximum and minimum values of shaft speeds, temperatures, and pressures are defined to protect the engine from damage and to ensure its correct operation. The maximum available thrust becomes a function of environmental variables like altitude, ambient pressure and temperature, and of some operational parameters such as airspeed and auxiliary power demands (air conditioning, anti-ice, etc). This work explores the definition of similar control loops for an electric power train. It is assumed that the main source of energy is a hydrogen fuel cell and that it is supported by a battery to shave power demand peaks at certain phases of flight. A top-down methodology is used, in which the different operational scenarios (both steady-state and transient) are considered and the management problem for each one is discussed.

Introduction

The main function of the propulsion system of an aircraft is to provide thrust. Since this variable cannot be normally measured directly, Full-Authority Digital Engine Control (FADEC) systems are designed to regulate a variable that can be correlated with thrust. In turbofan engines, the Engine Pressure Ratio (EPR) or the fan rotational speed (equivalent to the speed of the low pressure shaft, NLP) are commonly used to this end, with the fuel mass flow rate being used as manipulated variable. Other engine actuators such as the compressor stator vanes and bleed valves, are usually scheduled in open-loop to maintain the operational margins of the engine.

The EPR or NLP demand is set by the FADEC based on the Power Lever Angle (PLA), which is the main interface between pilot and the engine control system, and depending on the difference between demand and current value, a fuel flow command is issued. This command, however, may be limited by a set of protection rules which, due to safety and operability restrictions, regulate excessive transients and other engine limits which could lead to compressor stalls and surges or other failures in the engine. Upper limits are commonly

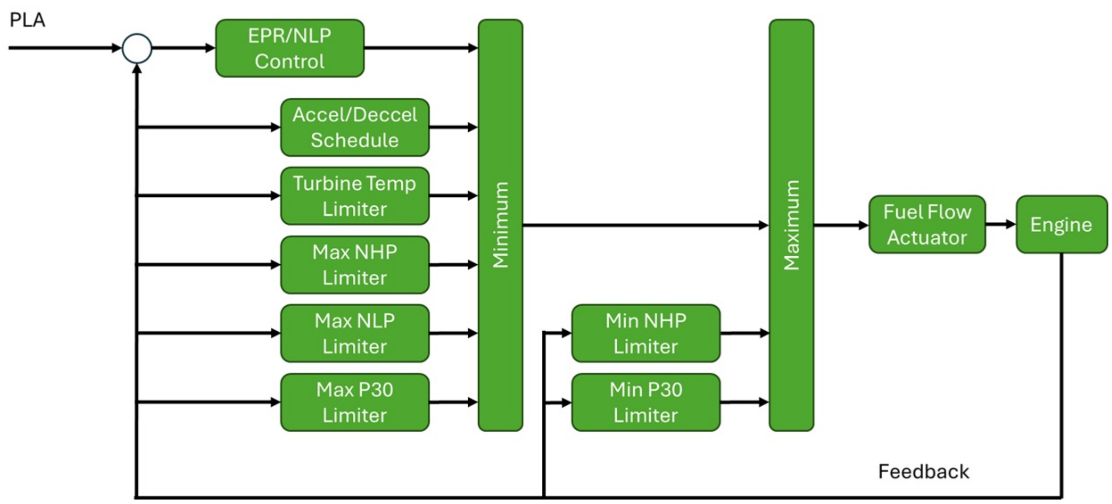

Figure 1: *Standard Control Laws for a Turbofan Engine*

in place for shaft speeds (NHP, NLP), for the compressor discharge pressure (P30), for turbine temperature, and for the acceleration and deceleration during transient maneuvers. Minimum limiters on P30 and NHP are used to ensure that the engine does not flame out, and usually correspond to certain pre-determined idle schedules. The selection process follows a min/max approach, and is schematically shown in Fig. 1, which has been adapted from [1].

In an (Hybrid)-Electric Aircraft Propulsion ((H)-EAP) system, the propeller rotational speed and its pitch angle, if it is variable, are the parameters to be regulated to set the thrust. Controlling these two parameters based on pilot's input is a relatively straightforward task, considering that an electric motor is a very simple machine for which a high level of understanding has been already achieved. However, depending on the specific architecture of a H-EAP system, the control task can be way more complex than in a turbofan engine, since a larger number of subsystems need to be controlled. Furthermore, a generic architecture for such a controller is not possible, given the fact that there are many different ways of arranging an (H)-EAP: pure electric with batteries, turbo-electric with or without batteries, parallel-hybrid, series-hybrid, etc. The control challenges posed by H-EAP systems are the main topic in [2]. The authors of that work, however, focus mainly on hybrid electric systems, in which a turbomachine still provides a certain amount of the power required.

The present work considers the particularities of controlling a very specific architecture: a pure EAP in which the energy comes from a hydrogen fuel cell and a battery is used for power shaving. The problem of energy and power management for such a propulsion system has already been treated in the literature. An implementation point of view is considered for example in [3], where a module to essentially control the flow of energy between fuel cell, motor and battery is described. A methodology for energy management based on heuristic rules is shown in [4], whereas [5] treats the problem using dynamic programming.

The following section of the paper describes the EAP system that is addressed in this work. After that, the control loops that are considered necessary for normal operation of this plant are described. The paper is closed with a conclusion section in which the main points of the work a re-stated and brief discussion of the future work to be developed is performed.

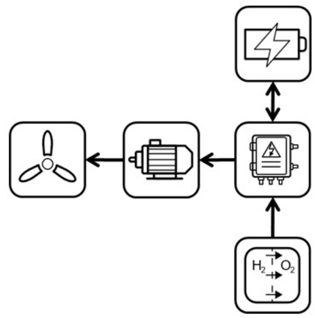

Figure 2: *Generic Structure of a Battery/Fuel Cell Electric Power Train*

The System under Consideration

This paper considers an EAP composed by an electric machine actuating a propeller. The energy for the motor is provided by an electrical power distribution system, whose main task is to manage the flow of energy between the machine and the main two sources of power: a battery and a hydrogen fuel cell. It is assumed that only the battery can have a bi-directional flow of energy, i.e., it can be charged or discharged during the operation, acting either as a sink or source of energy. The fuel cell only provides energy, and the electrical machine is limited to operate as a motor, so no energy recovery from windmilling is considered.

A generic diagram of the architecture of such a system is shown in Fig. 2, from which the multivariable nature of the control problem becomes evident. While the PLA command defining the demanded thrust directly translates into a set point for the speed/torque of the electric motor, it is not immediately clear how the power required for this should flow from the two sources. The definition of the appropriate set points for the other main components, namely the battery management, the fuel cell, and the power distribution systems, is not a straightforward task and requires a careful design.

The different components of the system are sized during the EAP design process to achieve a certain performance during most critical static operating points. For example, the fuel cell could be sized to achieve its highest efficiency at the standard power level needed by the aircraft during cruise, whereas the battery would have enough storage capacity to provide the extra energy needed to maintain take-off power for the required time [6]. While very important for the tuning of the control loops, this sizing is not that crucial for the architectural definition presented in the next section.

Control Loops for the EAP System

A max/min approach, similar to that of used in turbofan engines and shown in Fig. 1, is also proposed for the EAP. The proposed control logic is presented in Fig. 3. The way the limiters act and interact is however different, due to the increased complexity of the system and its individual subsystems.

Steady State Loops. An example schedule for power split between the battery and the fuel cell depending on the demanded propulsive power can be seen in Fig. 4, which has been adapted from [2]. In this case, the fuel cell is sized such that it can provide alone up to 67% of the maximum rated power. This point would probably be the Maximum Continuous power (MCT) rating of the EAP. To reach the full power, the Battery is needed, but this level of thrust could only be maintained for as long as the battery still has sufficient charge.

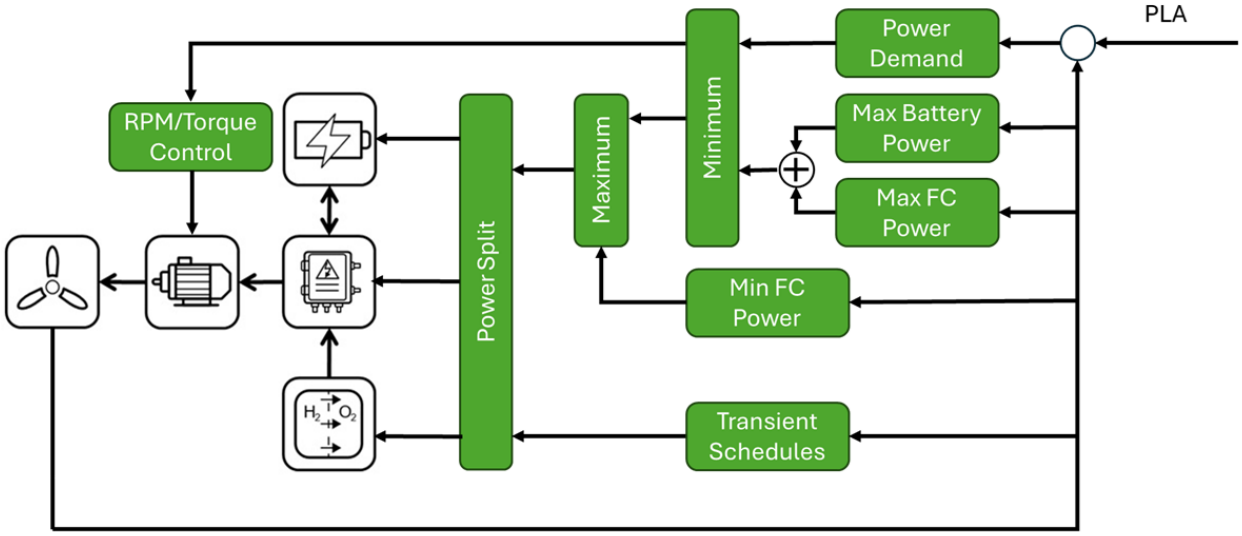

Figure 3: *Proposed Set of Control Laws for an Electric Aircraft Propulsion System*

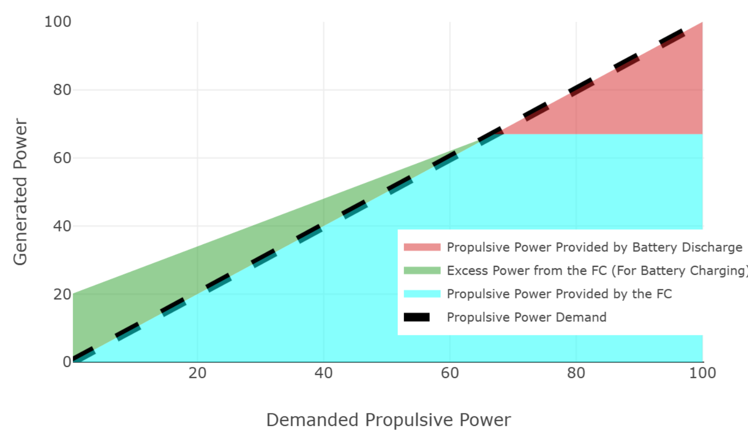

Figure 4: *Example of a Schedule for Power Split According to Demanded Propulsive Power*

This would be the case during take-off or a go-around maneuver. For power demands below MCT, the fuel cell has extra power capacity, which can be use to charge the battery in phases of flight that not require extreme power.

The power that can be delivered by the fuel cell or the battery at a given instant, however, is not constant. It will be limited by factors such as the Outside Air Temperature (OAT), which affects the effectiveness of the thermal management systems of the power sources. The states of charge (SoC) and health (SoH) of the battery will also act as limiters for the power available. The thermal challenges are usually addressed by the control system of turbofan engines by means of de-rating the maximum available thrust. When the OAT is below the value for which the turbine would reach its thermal limit, the maximum thrust is available. For OAT values beyond this, the maximum available thrust is reduced proportionally. In the case of an EAP, these limitations are more dynamic, since they depend on more factors and affect several different components.

Transient Loops. One of the advantages of electric motors over turbomachines are their faster dynamics. An electric machine can change its speed almost instantaneously. These fast dynamics, however, cannot be followed up by a fuel cell, whose electrochemical processes have a large inertia and very long time constants. To have time to adjust the power delivered by the fuel cell, the transients have to be absorbed by the battery. The transient control loops will ensure that the battery provides the extra power needed during acceleration maneuvers, and absorbs the surplus power during deceleration.

Idle Limiter. Contrary to internal combustion engines, electric motors do not need to remain on when not needed, wasting energy while idling. Fuel Cells, however, need to provide at least a minimum amount of power required by its auxiliary systems and the aircraft. This minimum fuel cell power requirement plays a role similar to the idle limiters in turbofan controls. Any excess in power can be used to charge the battery when the conditions allow it.

Closing Remarks and Future Work

This work discussed some of the control challenges presented by an Electric Aircraft Propulsion system powered by a combination of fuel cell and battery. An architectural design of such a system is proposed, discussing which control laws are considered necessary for the correct operation of the system. The factors which would limit the available thrust are mentioned and their effect in the design of the control loops are also considered.

The next steps are the detailed design of such control loops for an exemplary system. This includes the definition of numerical values for parameters such as the different required power levels and the minimum and maximum limiters, but also numerical targets regarding required acceleration times, contingency ratings, and other needs imposed, for example, by certification requirements. The specific control algorithms to be used for the definition of the loops, and the hardware and software architectures needed to implement the logic in an actual system, are also topics of extreme interest, which will be addressed in future works.

It must be stated again, that the generalization of such a control architecture is an almost impossible task, since each electrified topology would require specific considerations. A *one-size-fits-all* solution cannot be achieved.

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