STATE OF THE ART OF CONTROL STRATEGIES FOR ELECTRIFIED AIRCRAFT POWER TRAINS

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Abstract

Current power plant designs for electrified aircraft require the interaction of several complex subsystems to accomplish its function. Examples of such subsystems are thermal management systems, one or several fuel cell systems, power electronics such as DC-AC inverters and DC-DC converters, battery management systems, electric motors and fans or propellers. This paper explores the current developments in control algorithms for each isolated system.

Keywords

electric aircraft; control theory; fuel cell; thermal management

1. INTRODUCTION

Many different configurations have been proposed for aeronautical all-electric power trains. However, some components and subsystems are mostly the same across different power train topologies, each one representing an individual control task. The strong coupling between some of these systems requires not only a detailed design of the local controller for each subsystem, but also an all-encompassing supervisory unit to coordinate the operation of the different subsystems.

Different control strategies have been presented in the literature for each component of the power train, ranging from PID controllers to complex algorithms like model predictive or fault-tolerant control. Given the strong weight and efficiency constraints present in aircraft applications, a convenient implementation of control strategies can help increase the feasibility of the system.

The most recent advancements of control techniques for each subsystem in the power train are presented, their application context will be explained and their characteristics will be compared.

2. BASE ARCHITECTURE

The study to be carried on will consider a nacelle-integrated, propeller power train in tractor configuration, with a power rating in the range between 200 kW and 2 MW. Control strategies for the following subsystems are the scope of the literature review:

- Thermal management system
- Electric motor and inverter
- Fuel cell
- Propeller pitch control

For the complete power plant to perform as expected, a simultaneous control of these subsystems is required. The possible energy management strategies to define setpoints for each individual subsystem could be implemented in a manner similar to the way gas turbine engine controllers are designed, that is, a fully integrated control unit which controls and monitors all aspects of the propulsion unit. Such an arrangement for a nacelle-integrated aeronautical electric powertrain is shown in Figure 1.

3. CONTROL STRATEGIES

The local control strategies for each subsystem will be broadly classified, based on their fundamental structure, into one of the following categories:

- PID control and its variants
- Adaptive control
- Model predictive control
- Robust control
- Fuzzy control

Although advances in the development of more sophisticated controllers have been made, PID control techniques are still ubiquitous in industrial applications due to their adaptability, low computing power required, and simple implementation. Based on the error signal between the setpoint and the measured values, the actuators of the plant are controlled through proportional, integral, and differential regulation. However, their performance can be limited outside a vicinity of the setpoint by the need of a linear operation.

Adaptive control techniques like Model Reference Adaptive Control (MRAC) can help reduce the impact of plant model mismatch and guarantee stable control even in the presence of parametric uncertainties. Adaptive control techniques can estimate unknown model parameters on-line and adapt to plant changes.

Model Predictive Control (MPC) has received more attention in many areas of research, especially in power converter applications. The essence of MPC lies in the iterative use of an analytical model of the plant for the prediction of the trajectories of the system. This leads

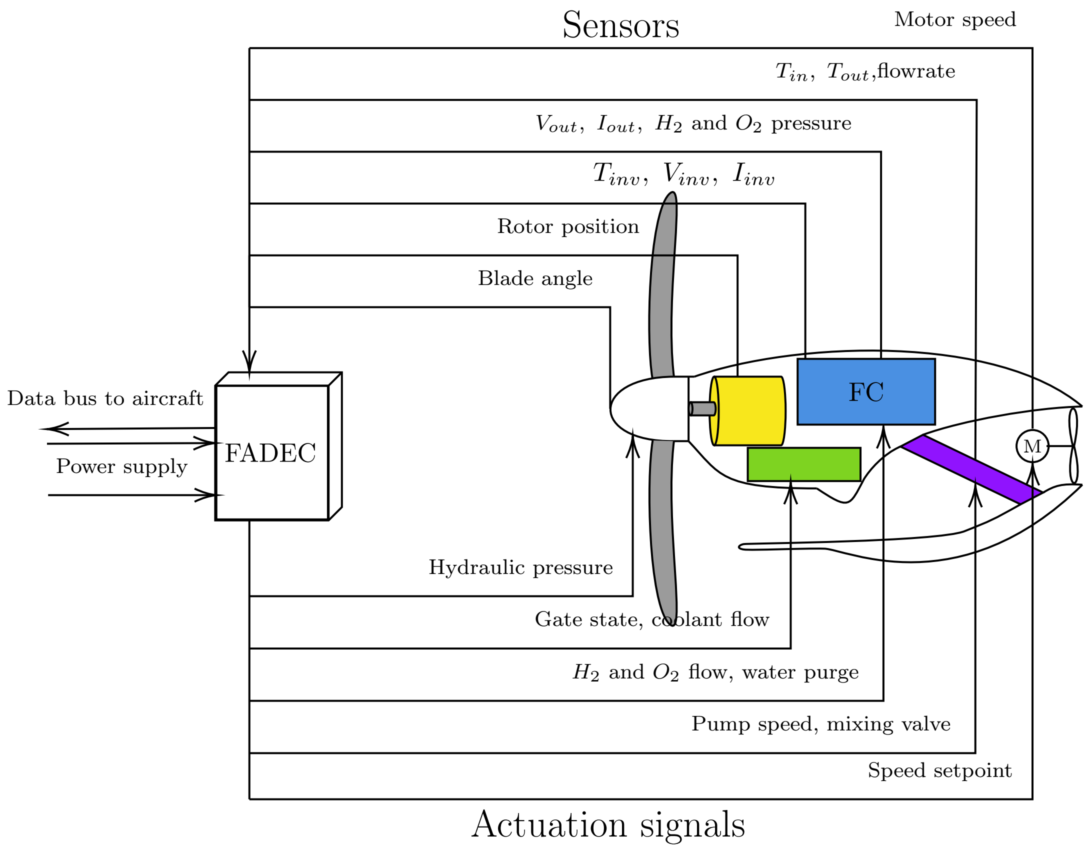


FIG 1. A schematic diagram of a control unit for a nacelle-integrated aeronautical electric powertrain.

to an optimization problem whose solution yields the control input sequence. The inherent capability of MPC to take actuator constraints directly into account constitutes a substantial advantage over other control methods.

In a similar way than adaptive methods, robust control methods are able to guarantee the stability of a system even with uncertainties. In this work, two instances of robust control are shown: one in combination with MPC, called Robust MPC (RMPC), and another one embedded in an adaptive approach, namely Nonlinear Dynamic Inversion (NDI).

Fuzzy controllers are a type of nonlinear controllers which use a series of pre-defined rules (so-called fuzzy rules) to encode information about the system to be controlled. Inputs are fuzzified and inference is done based on the fuzzy rules. Then the output is defuzzified and used to control the system. Fuzzy models can help approximate arbitrary nonlinear systems and model them with relatively low computational power.

3.1. Fuel Cell

Hydrogen fuel cells (FC) proposed for the use in aviation are often of the Proton Exchange Membrane (PEM) type due to their high power density, or of the solid oxide (SOFC) type for their high efficiency and their extended lifetime. [1]. A typical arrangement of a fuel cell is presented in Figure 2

Model Predictive Control approaches are mentioned first. Barzegari [2] presents the modelling of a PEM cascaded dead-end fuel cell and the implementation of a model-predictive controller that uses a SISO model of the FC. The stack current is considered as the input and its voltage as the output. Since dead-end fuel cells do not allow the expelling of the generated water through an exhaust, it has to be regularly drained using purge valves. The MPC algorithm commands the opening and closing times of the water purge valves, which by draining the accumulated water regulate the output voltage.

As mentioned before, a characteristic of MPC is its capability to take into account constraints on the control inputs. In this case, the current of the stack is limited by its maximum value and a predefined maximum rate of change. The authors declare a maximum voltage tracking error of less than 10%. Chatrattanawet et al. [3] present a robust MPC implementation for a PEM FC. Since MPC is model-based, differences between the model predictions and the real behaviour of the system impact the performance of the plant negatively and can even lead to instability or turn the internal optimisation problem unfeasible. A robust version of MPC, derived using a linear time varying (LTV) system which differs from the ideal linear time invariant (LTI) system, is presented. Stability is guaranteed using Lyapunov functions. The controlled variables are the cell temperature and the partial pressure of hydrogen, regulated by manipulating the inlet flow rates of air and hydrogen. A

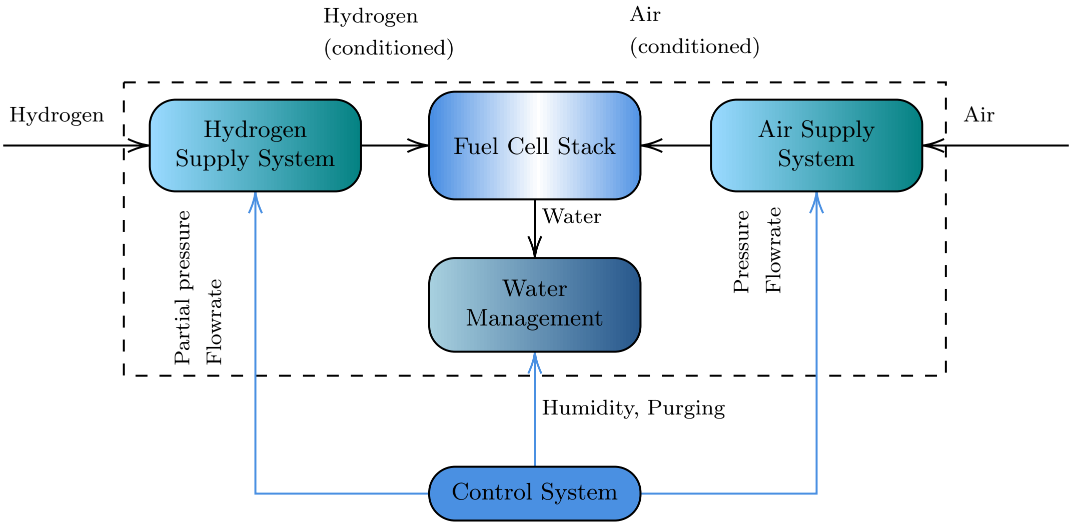


FIG 2. Example of a generic fuel cell system, excluding the thermal management system. The usual control actuations are also represented.

controllability analysis shows that the partial pressure of hydrogen is directly controlled by the inlet flow rate of hydrogen, and the cell temperature is controlled by the inlet flow rate of air.

Real Time Optimisation (RTO), another form of optimal control, can also be used to operate a plant optimally by continuously searching for inputs that minimise a cost function. In the so-called two-step method, the parameters of a model of the plant are first estimated based on measurements and then new inputs to the plant are calculated by solving an optimisation problem. De Avila Ferreira et al. [4] present an RTO scheme for a solid oxide fuel cell (SOFC) with the objective of maximising the efficiency of the system. The approach in this work results relatively insensitive to the accuracy of the model. Its parameters are estimated in real time by using Constraint Adaptation, a method in which the constraints of the optimisation problem are modified to match the plant model to the measurements.

As previously stated, fuzzy models can help approximate arbitrary nonlinear systems using linear fuzzy functions and are therefore an effective way of modelling such systems at a low computational cost. This is an important requirement for MPC algorithms. Yang et al. [5] present an insight into the control of the air delivery system of a PEM FC, proposing a fuzzy MPC controller to keep the oxygen excess ratio within the ideal range and suppress fluctuations caused by load changes.

In their work, the FC system architecture for the air side consists of a motor-driven compressor, a cooler, and a humidifier before the air enters the FC. Since the model results in high order nonlinear equations, a fuzzy predictive controller is derived with fuzzy rules calculated offline. The controller manipulates the voltage input to the air compressor to regulate the oxygen excess ratio. The setpoint is defined as the oxygen excess ratio that maximises power for a given value of the stack current. The objective function to be minimised is composed of the error between the actual oxygen excess ratio value and the reference, and a term to penalise control input changes. This method is copmared gainst feed forward control and PID + feed forward. The results shos that the proposed method brings in a significant reduction in the mean absolute error in comparison, but not a substantially lower root-mean-square error.

In comparison with the algorithms presented above, a comprehensive control scheme for a solid oxide fuel cell (SOFC) using exclusively PI controllers is presented by Dotzauer [6]. This method has the advantage of requiring a relatively low amount of computing power, being a very simple design, and potentially facilitating the integration of the system in a real application.

However, PI and PID controllers are by definition linear controllers. Their application on nonlinear systems can therefore be unsatisfactory, requiring in the best of cases to be designed to be under-damped and then requiring extensive testing to adequately tune the controller. Applications for fractional calculus have been investigated in the last decades, one of them being the Fractional PID controller. Fractional PID controllers achieve better performance in higher order, highly nonlinear systems [7]. Sharma and Babu [8] propose a cascaded control strategy with the main objective of controlling the stack voltage and the secondary objective of maintaining the oxygen excess ratio. In their work, the performance of traditional PI and PID controllers for the secondary and primary objectives respectively is compared with fractional PI and fractional PID in the same way, where the fractional controllers show better performance than their traditional counterparts. The fractional controller is also compared to an already available sliding mode controller, showing better performance.

A summary of the literature reviewed in this section is presented in Table 1.

3.2. Inverter

The combination of inverter and electric motor plays the crucial role of converting the electric energy into mo-

Ref.	Year	Approach	Plant model	Objective	Actuation	Merit figure
[2]	2017	MPC	Dead-end PEM	Voltage tracking	Purge valve	$\Delta V < 10\%$
[3]	2017	Robust MPC	PEM	H_2 partial pressure tracking	$H_2 + O_2$ inlet flow rates	Quick settling time <20 s
[4]	2019	RTO	SOFC	Efficiency maximisation	Current, fuel and air flowrates	$\Delta\eta = 7\%$
[5]	2019	Fuzzy MPC	PEM	O_2 excess ratio tracking	Air flowrate	MAE = 0,7%[1]
[6]	2025	PI	SOFC + Burner	Power regulation	Air and fuel pressure	Quantitative evaluation
[8]	2020	Fractional PID	PEM	Voltage tracking	Air flowrate	IAE + TV[2]

TAB 1. Comparison of the different fuel cell control approaches.
[1] Mean Absolute Error.
[2] Integral Absolute Error + Total Variations. For values see tables in original work.

tion. Two-level inverters for applications such as urban air mobility and general aviation have been developed by several companies. Multilevel inverters are still uncommon in electric propulsion of aircraft. However, they constitute a very promising technology for cases with increased voltage and power levels, showing improving trends mainly in terms of efficiency, power density, and reliability. [9]

A standard control scheme for an electric motor is shown in Figure 3. An external control loop for a mechanical variable, be it speed or torque, defines the set point for an internal current control loop. The main differences between control strategies lie in the structure of the inner control loop. The most common scheme used in electric drive applications is the Field Oriented Control (FOC), in which the stator current is expressed into two components. One of these, the quadrature component, affects the torque directly, with the direct component being responsible for other effects. Gliese et al. [10] present a FOC current control for a superconducting synchronous motor. This type of machine is a promising choice for achieving weight reductions. When cooled under their critical temperature, superconducting materials can offer essentially zero resistance, allowing higher currents with a smaller mass or volume footprint. The controller presented in this work consists of two PI controllers, one for each current component, which calculate the reference voltages for each phase. These voltages are in turn used to modulate the PWM signals that control the inverter switches. The PI gains for the controllers are calculated analytically, but no performance metrics are presented in the results of the paper.

When considering modern control implementations for motors and inverters, MPC algorithms cannot be overlooked. Compared to other control techniques, where a compromise between low harmonic distortion (for given switching losses) and controller bandwidth has to be made, MPC achieves both low distortion and high bandwidth. This is exemplified in Figure 4, where several control techniques are schematically represented in the trade-off space between bandwidth and distortion. Since the large bandwidth translates into response times of a few milliseconds [14], the very short time that the MPC algorithm has available to calculate the optimal trajectory implies a high computational burden. This constrains the practical implementation of MPC for electric motor inverters. Current efforts are therefore mainly centred in improving the optimisation part of the algorithm to reduce the computational cost. It is important to note that, since the switches in an inverter can only be in either and open or closed, the optimisation problem to calculate the optimal trajectories for the states of the switches is an integer optimisation problem.

The Sphere Decoding Algorithm (SDA) for integer optimisation evolved to be the most prominent method for direct MPC of inverters. It consists on finding first an unconstrained optimal trajectory for the control input and later constructing a hypersphere centered on this solution with a given radius. The actual integer solutions are then searched for inside of this sphere with a branch-and-bound method, reducing the radius of the sphere each time. To further reduce the computational burden associated with it, Struve et al. [11] propose a modified version of the SDA taking advantage of a domain change using Laguerre Polynomials to reduce the dimensionality of the optimisation problem.

Andersson and Thiringer [12] also published an assessment of an improved MPC scheme with SDA that reduces the computational burden for electric drive applications. They propose an improved computation of the unconstrained solution, necessary as the first step of the optimisation, and a streamlined SDA that avoids nested for-loops. The authors report an improvement in the inverter efficiency and declare a reduction in the execution time of the algorithm of 40% for a prediction horizon of four steps.

Deng et al. [13] report on multi-port inverter architectures for use in electric aircraft and their control. They propose a quadruple active bridge (QAB) converter model for sourcing power from a combination of a fuel cell, a super capacitor and a battery. Although details about the optimisation strategy adopted in the MPC are not disclosed, the authors compare the response of the converter with a PI controller during a load transient and a load dump. The MPC shows better

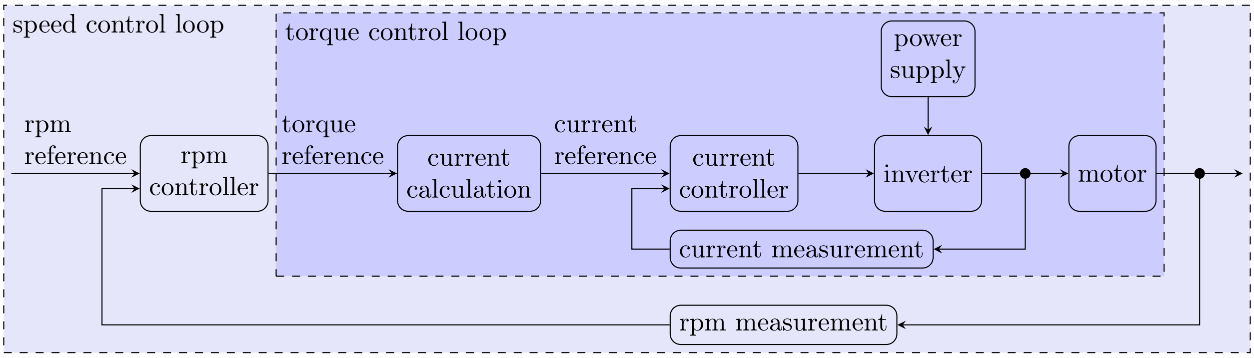


FIG 3. An example standard motor control loop

Reference	Year	Approach	Motor type	Inverter topology	Merit figure
[10]	2024	FOC	Superconducting homopolar	Two levels	Δ T = 1°C Δ RMS E[3]= 10,4% [4]
[11]	2024	MPC	Induction	Three levels	N/A
[12]	2020	MPC	IPMSM	Two levels	TAT reduced by 40%
[13]	2024	MPC	PEM	Three levels	Δ V = 3.5V[5] Δ I = 0.4A Δ RT[6]= 1.5ms

TAB 2. Comparison of the different inverter control approaches.
[3] RMS Error.
[4] Compared to closed-loop MPC.
[5] Compared with PI control.
[6] Response Time.

performance in all categories: response time, voltage fluctuation, and current fluctuation.
For a summarised version of the reviewed literature in this section, see Table 2.

3.3. Propeller control

Depending on the power class of the power train, the propeller may also require a control input. This is done through a variable pitch mechanism, in which an actuator actively regulates the pitch of the blades to absorb the full shaft power while keeping the speed constant. A hydraulic cylinder integrated in the propeller hub is used as the actuator. In legacy hydromechanical systems, the oil pressure in the cylinder is controlled by a flyweight governor spinning at a speed proportional to that of the propeller. The motion of the flyweights actuate a hydraulic valve, pumping or draining oil from the cylinder and thus moving the blades around the pitch axis. A typical representation of this system is shown in Figure 5.
Modern turboprop engines incorporate digital propeller pitch control, based on an electronic speed sensor and an electro-hydraulic servo valve that actuates the blades. Electronic control of blade pitch allows finer speed control and an increased flexibility for the implementation of custom control laws. All-electric propeller control systems are usually only found in low-power applications, in which the complexity of an electro-hydraulic system is not justified. Electrified aircraft power trains are not the exception and are expected to feature electro-hydraulic blade pitch control or all-electric pitch control, depending on their power class.
Legacy hydro-mechanical propeller pitch controllers based on flyweight governors can be modelled as pure P-controllers [15]. Since the time constant and the damping of the hydraulic system is relatively high, using a pure P controller has proven to be sufficient in this application.
Although almost no innovative control techniques for propeller pitch control are present in recent literature, several proposals focus on the coupling between propeller pitch control and flight control. Without mentioning a specific control technique, one application of electronic active propeller pitch control can be found in [16]. Here, an electric-motor-driven fan is configured to intentionally windmill during descent, generating power and therefore increasing the drag. This makes a steeper descent possible, reducing acoustic disturbances on the ground.
An interesting application of adaptive control in this context is presented by Henderson [17] , who implements an extremum seeking controller to continuously adjust the propeller pitch angle aiming to achieve minimum power consumption whilst tracking a thrust setpoint. This control technique allows the controller to automatically adapt not only to changing operational conditions of the plant, but also to modifications of the plant itself, such as a change of the propeller. However, an inherent

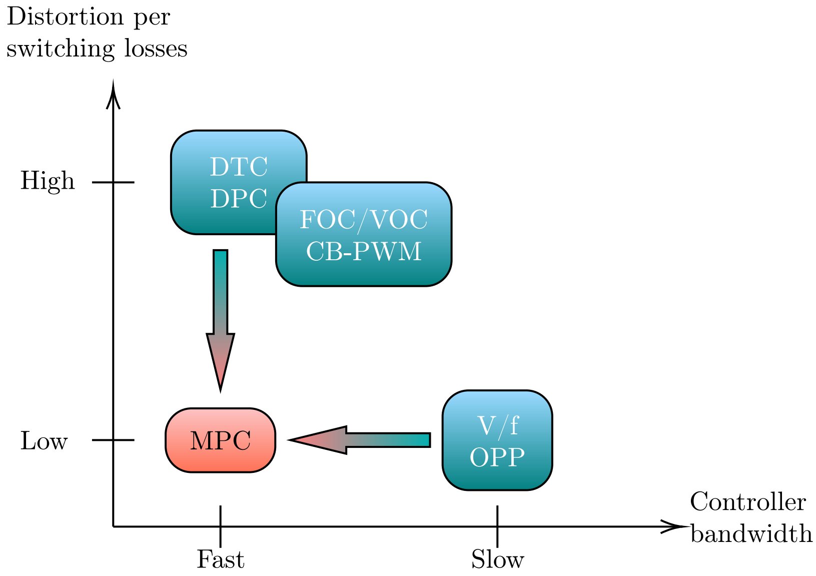


FIG 4. Schematic representation of different inverter control techniques in the trade-off space comprised of controller bandwidth vs distortion. This includes hysteresis-based control schemes such as direct torque control (DTC) and direct power control (DPC), field-oriented control (FOC) and carrier-based pulse width modulation (CB-PWM) and volts per frequency (V/f) with optimized pulse patterns (OPP). Adapted from Geyer [14].

disadvantage of this adaptive control technique is that the inputs to the plant have to be continuously disturbed for the algorithm to search for the extremum of the cost function. This leads to oscillations in the output, which never reaches a constant steady state.
In variable pitch propellers, a coupling between shaft speed and propeller pitch is inherently present. Depending on the mechanism used, the coupling can potentially be asymmetrical, where a change in pitch has a significant effect on the speed control, but a change in speed has a small impact on pitch control. Wu [18] applies Active Disturbance Rejection Control (ADRC), a type of feedback decoupling, to compensate the speed-pitch coupling, reducing the speed fluctuations upon pitch changes. Feedback decoupling can be implemented when characteristics of the plant and operating conditions are known. ADRC does not present such a limitation, at the cost of requiring the tuning of parameters.

3.4. TMS

The Thermal Management System (TMS) constitutes the most significant challenge for electrified aircraft power trains. The temperature of a fuel cell must be kept within precise margins to operate in optimal conditions, since it influences the internal water balance and electrochemical reaction activity [19]. Since fuel cells achieve efficiencies between 50 - 60%, a significant amount of energy is converted to heat, which needs to be rejected to the environment. In combustion engines, a large portion of this heat is evacuated through the exhaust gases. Fuel cells have to resort to forced air or liquid loop cooling solutions, the latter of which is preferred in proposed aviation applications. A direct effect of this can be observed in Figure 6, where the polarization curve of a fuel cell can be observed for different temperatures. The cell voltage for a given current rises with temperature, since the temperature directly affects the rate of the reaction. Too high of a temperature leads however to a decrease of the water content of the cell and an increase in internal resistance, which also reduces the performance of the fuel cell [20].

Typical liquid cooling systems for fuel cells are represented in Figure 7 in two variants: single-loop and double circulation, i.e., with minor and main loop. Examples of both of these topologies are examined in this section.
Robust MPC algorithms, already presented in Subsection 3.1, are capable of identifying optimal trajectories for the controlled variables. This makes it already suitable for high-accuracy temperature regulation. However, the implementation of terminal constrains on the outputs to achieve better tracking can complicate the finding of a feasible solution to the optimisation problem [22]. Instead, the output trajectory can be constrained so that the tracking error lies inside of an analytically defined, potentially time-varying region (the “funnel”), so that the cost penalising the tracking error becomes infinite at the boundary of the funnel. This modification of MPC is called Funnel MPC (FMPC). By avoiding terminal constraints, difficulties finding a feasible solution are substantially reduced.
Cao et al. [19] present a control strategy for a liquid loop TMS based on a Tube-Robust MPC (Tube-RMPC), a particular version of FMPC where the boundaries do not vary with time, such that the funnel becomes a tube-shaped region in which the state of the system evolves. This technique offers increased robustness against modelling inaccuracies and reduced computational burden. The cooling loop used for the study features a thermo-

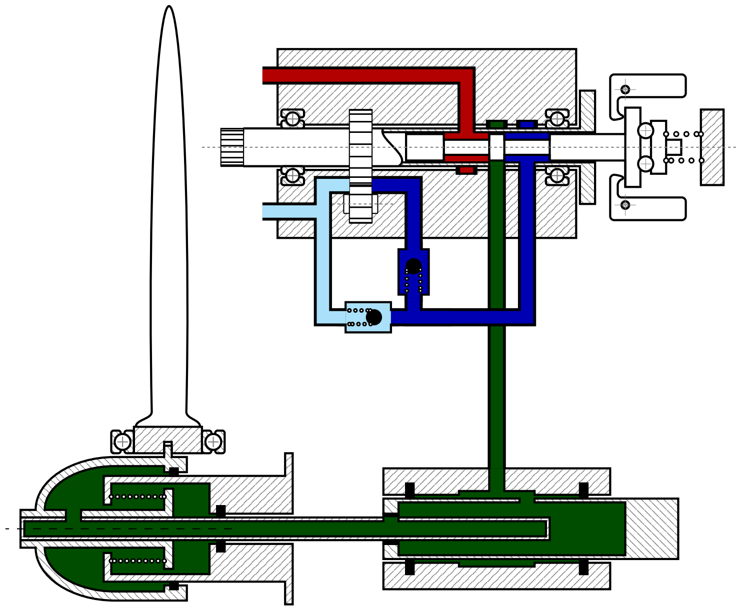


FIG 5. Schematic representation of a legacy hydromechanical propeller pitch control system. Extracted from [15].

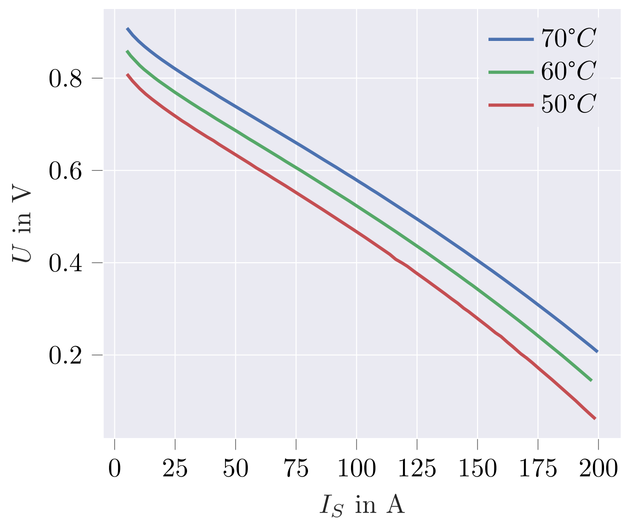


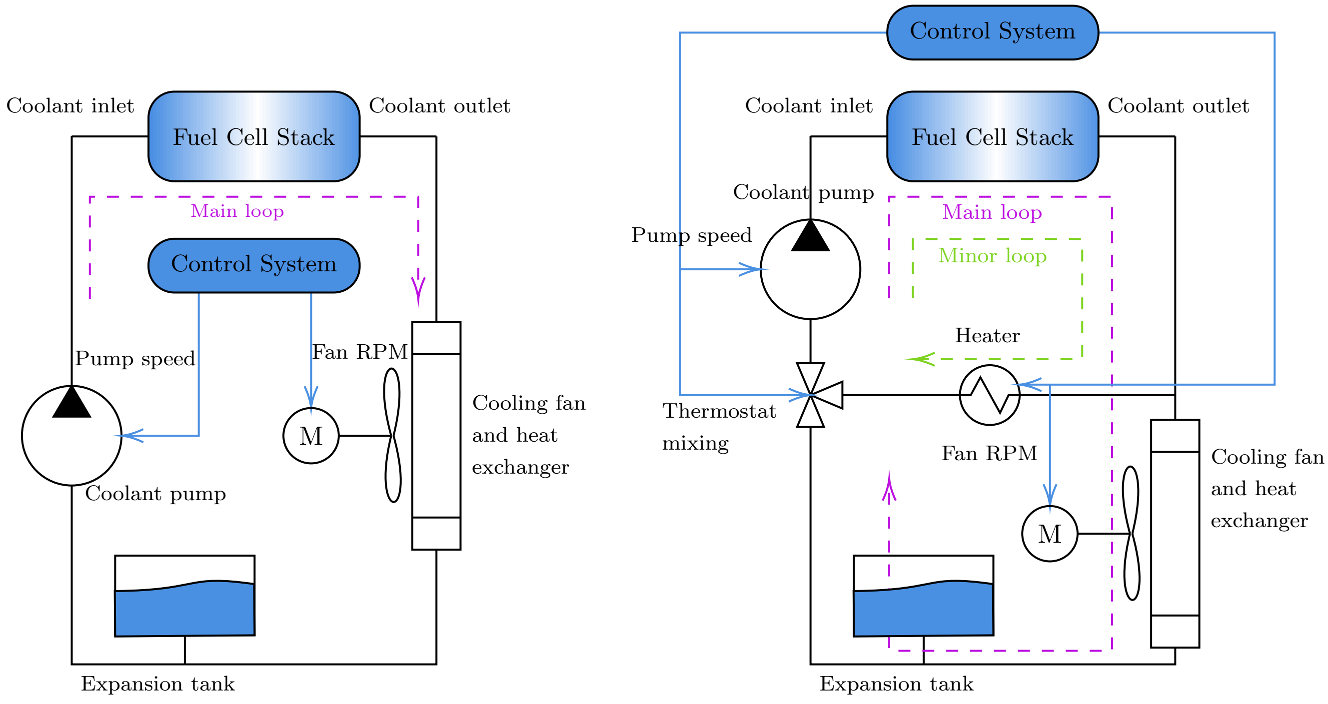
FIG 6. Polarization curves of a fuel cell at different temperatures, based on reference [21]

stat, a cooling liquid heater, a cooling fan for the heat exchanger and a water pump, all being controlled by the Tube-RMPC. This control scheme has shown improved speed and robustness in the dynamic response.

Another possibility to achieve robust error tracking in nonlinear systems is with Sliding Mode Controllers (SMC). This control technique relies on the definition of a Sliding Function, along which the states of the system are forced by the controller to lay on and "slide" along, changing in this way the apparent dynamics of the system. This control method exhibits good robustness against disturbances, since the controller always "forces" the states of the system to lay on the sliding surface.

Fang et al. [23] present an SMC-based approach for controlling the temperature of a PEM FC. By setting the sliding variable equal to the instantaneous value of the error plus its integral in time, the controller forces the states to values that reduce the error to zero. A low pass filter is added to suppress the chattering that occurs when crossing through the sliding surface. The suggested plant consists of a dual-loop cooling circuit, one minor loop and a main loop, equipped with assisting and main pumps respectively. The main pump circuit features a liquid cooler and the assisting pump circuit features a liquid heater, so that the main pump moves relatively cool liquid and the assisting pump moves hot liquid. The liquids circulating through each of these loops are mixed before entering the fuel cell. Temperature regulation is achieved using a single input by controlling the speed relationship between both pumps as to maintain a constant total flowrate in the system. The SMC is chosen because the system cannot be stabilised by regular PI controllers, mainly due to the large time delay between the loop mixing position and the temperature sensor.

Chen et al. [24] present a temperature and humidity control scheme for a PEM fuel cell based on a MIMO fuzzy controller. The controlled plant is a single liquid coolant



(a) Single loop (b) Minor + Main loop

FIG 7. The two topologies examined in this paper for liquid cooling of fuel cells.

loop featuring a variable speed pump and a water chiller, and a controllable humidifier. Given the strong coupling between temperature and humidity in a fuel cell, the authors define fuzzy rules for the simultaneous control of the coolant pump speed and the humidifier setpoint based on four inputs: the errors in temperature and humidity and their derivatives. With this approach, the authors declare an overshoot in temperature of less than 1%, compared to a value of 2% for a comparable PID controller. An average efficiency increase of 2,17% with respect to PID control is also shown.
Another fuzzy approach is presented by Liu et al. [21]. Here the temperature of a PEM fuel cell is regulated through the speed of the coolant pump in a two-loop system similar to the one presented in reference [19]. Based on the error between the measured temperature and the setpoint, a set of fuzzy rules modify the gains of a PID controller in real time.
An adaptive control approach for the cooling of a PEM fuel cell is presented by Huang et al. [25]. They propose a liquid coolant loop composed of a reservoir and a variable speed pump. The controller is designed with the assumption that the fuel cell is already warmed up. The molar flow of coolant is the controlled variable, with the objective of maintaining a given operating temperature. The model used is non-affine with respect to the control input, so it cannot be explicitly written in terms of the coolant flow. Dynamic inversion is therefore used to robustly control the coolant flowrate. Two unknown parameters in the dynamic inversion are set with a set of parameter adaption laws based on the standard discontinuous projection algorithm, so that the value of the coolant flowrate results robust with respect to modelling inaccuracies. The proposed control strategy is compared with a PI controller. The adaptive controller shows reduced temperature overshooting and a significantly reduced convergence time.
Tümer et al. [26] also present an MPC-based humidity and temperature control for a liquid-cooled PEM fuel cell. In this case, a single cooling loop is driven by a variable speed pump. This simpler architecture has only one manipulated variable, the coolant flowrate, while the controlled variable is the temperature in the stack. The interaction between the humidity of the membrane of the cell and the stack temperature is taken into consideration by developing both humidity and temperature controllers working in tandem. They are able to reject disturbances and track the setpoint changes. The effects of temperature on humidity are strongly coupled: temperature affects humidity strongly, but humidity has a mild effect on temperature. The joint humidity and temperature controllers show good tracking and disturbance rejection capability.
A summary of the literature reviewed in this section is presented in Table 3.

4. SUMMARY

This work presented a review of the latest relevant literature on control strategies for a modern, nacelle-integrated electric power train for aircraft. The different control algorithms for each subsystem are classified according to their fundamental structure and their use cases described.In this way, this work offers a clear and broad overview on the state of the art on control

Ref.	Year	Approach	Plant model	Topology	Actuation	Merit figure
[19]	2024	Tube-RMPC	PEM	Minor + main loop, one pump	Thermostat Heater Pump speed HEX fan speed	ΔT = 1° C Δ RMS E[7]= 10,4% [8]
[26]	2024	MPC	PEM	Single loop	Pump speed	Overshoot = 0.6%
[23]	2017	SMC	PEM	Minor + main loop, two pumps	Main + assisting pump speed	$\Delta T \pm 1°$ C
[24]	2021	Fuzzy	PEM	Single loop	Pump speed	Overshoot < 1% $\Delta\eta = 2,17\%$ [9]
[25]	2017	Adaptive	PEM	Single loop	Pump speed	Δ CT[10]= 300 s Δ Overshoot = 0,4 K

TAB 3. Comparison of the different TMS control approaches.
[7] RMS Error.
[8] Compared to closed-loop MPC.
[9] Compared to PID control.
[10] Convergence Time.

strategies for aeronautical power plants based on fuel cells.

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