Multi-Objective Health-Aware Energy Management of a PEMFC/Battery/Supercapacitor Hybrid Emergency Power System for More-Electric Aircraft

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Abstract: Hybrid proton exchange membrane fuel cell (PEMFC)-battery-supercapacitor structures have recently been viewed as viable sources of emergency and auxiliary power in all-electric planes since they exhibit high specific energy, fast transient response, and minimal reliance on traditional engine-powered subsystems. Current supervisory energy management approaches towards such systems mainly consider optimization for hydrogen savings or instantaneous efficiency. However, a hydrogen-alone dispatch may lead to higher battery current stress, faster PEMFC dynamic load transitions, increased supercapacitor ripple and larger deviations from steady-state values of the DC-bus voltage. In this paper, a multi-objective health-aware strategy for energy management of a hybrid emergency power system consisting of a PEMFC, a lithium-ion battery and a supercapacitor pack is proposed. The HA-MOSCA supervisory controller incorporates component-level health indices along with system-level efficiency and power quality objectives in the dispatch decision-making process. Hydrogen consumption rate, battery aging metric, fuel cell dynamic stress, supercapacitor stress and DC-bus voltage ripple are minimized concurrently considering power balance, states and operation constraints. A health-aware adaptive sine cosine optimization algorithm is used to solve the problem and obtain close-to-optimum power distribution at low supervisory computational cost. The research is based on an emergency power system architecture for an aircraft comprising a 40 Ah battery, 15.6 F supercapacitor pack, a PEMFC stack and a 270 V DC-bus. Simulation studies performed for comparison against PI control, equivalent consumption minimization strategy and hydrogen-alone sine cosine optimization demonstrate that the proposed strategy reduces battery aging index by 22.8%, fuel cell stress by 28.2%, supercapacitor stress by 21.9% and average DC-bus voltage deviation by 35.9% compared to the hydrogen-only solution, but causes just 1.98% hydrogen loss. When compared against conventional PI control, hydrogen consumption is decreased by 14.4% and average DC-bus voltage deviation is lowered by 56.9%. The findings show that a minor compromise in fuel optimization will yield significant returns in terms of increased reliability, improved electrical performance, and deployability of safety-sensitive auxiliary power units on board airplanes.

Keywords: more-electric aircraft; aircraft emergency power; proton exchange membrane fuel cell; hybrid energy storage; battery degradation; supercapacitor; energy management; health-aware optimization; DC-bus stability

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1. Introduction

As the use of actuators, environmental control units, avionics devices, and safety-related equipment powered through electrified means continues to grow, making the more-electric aircraft the leading edge of contemporary aerospace power system development, the electric architecture takes central stage as a mission enabling infrastructure that determines efficiency, resilience, and reliability. Under emergency power operation, these attributes become critically important, as the power supply needs to accommodate abrupt load variation and respond quickly while providing high-quality voltage output in face of a rapidly changing situation. It is due to such challenges, among others, that there has been increasing interest in the design and implementation of hybrid electrochemical power sources capable of providing sustained energy while accommodating transient loads, but without imposing significant weight and fuel penalties [1–3].

Among the candidates for high-performance airborne auxiliary power units, the proton exchange membrane fuel cell stands out by virtue of high specific energy, low operational temperature, better startup characteristics compared to alternative fuel cell types, and compatibility with low emissions flight electrification strategies. Yet, PEMFC-based power systems inherently suffer from the problems related to dynamics of fuel reactants delivery, limitations in membrane hydration, and adverse effect of load variation. When subjected to abrupt transient loads, the stack will exhibit slow response, efficiency reduction, and increased rate of wear and tear. This explains why the PEMFC is rarely considered as a standalone emergency source for the more-electric aircraft, but is typically coupled with additional energy storage means [4–6].

The physical reasons for triple-source hybridization are well understood. The fuel cell serves as a sustained energy provider, the battery is capable of storing energy in-between load changes, while the supercapacitor helps to mitigate rapid transients. If combined properly, the triplet will exhibit greater efficiency, enhanced response and better point-of-operation control as compared to a single energy source [7–9]. While the benefits of hybrid source use in aircraft power systems can hardly be underestimated, there has not been much attention given to the problem of energy management, i.e., to the task of assigning load power portions to individual sources based on certain criteria.

The problem of supervisory energy management, however, is quite challenging. Given load demand at each time step, the controller should ensure power balance, taking into account the limitations inherent to each individual power source and converters in terms of ramp rate, state of charge/charge and voltage levels, etc. Moreover, safety-critical applications impose stringent requirements on the process, as simply fulfilling the demand does not mean good performance; aggressive battery cycling, sudden shock loads on fuel cell, etc., should be avoided at all costs [10–12].

In literature devoted to hybrid energy management problems in fuel-cell-based electric power systems, the problem of fuel economy is often highlighted. Apart from traditional approaches such as rule-based supervision, advanced techniques like equivalent consumption minimization, model predictive control, fuzzy control, and meta-heuristic optimization were employed to address various problems in this area [13–15]. While these strategies have produced promising results, it should be noted that they primarily seek to maximize hydrogen economy without regard to the consequences this strategy may have on system durability [16–18].

There is also an evident gap between algorithms focusing on power distribution exclusively and health-aware supervisory strategies. Equivalent consumption minimization, although computationally efficient, is normally based on assumptions about conversion equivalence, i.e., on the equality of energy required to produce a certain amount of electric energy and consumed to provide the same amount of power output. Other advanced techniques, such as model predictive control, rely heavily on accuracy of predictive models and membership function calibration. As far as meta-heuristic algorithms are concerned, they allow to explore the search space, which may be non-linear and constrained; however, their applicability to emergency power applications hinges on their ability to perform quick supervision without introducing new stressors [19–21].

It goes without saying that durability is crucial for safe operation of any power source. Battery wear is significantly affected by current magnitude and total ampere-hours processed, temperature, and repeated transient operation. Fuel cells are susceptible to load variations and transients, membrane dehydration, start/stop events, operating near current limits, etc. The supercapacitor is arguably the most durable element among those considered in this paper, but frequent large-current pulses and high ripple still cause heating and dissipative losses. Thus, in aircraft applications, such issues as health maintenance, reserve preservation, voltage quality, and consistent dispatch come into play. Health-aware energy management thus appears as an essential consideration in the problem of hybrid transport electrification [22–24].

From aircraft emergency hybrid power viewpoint, Motapon *et al.* have shown that the introduction of a supervisory controller based on converters allows to significantly improve controllability of the system and mission performance [25]. Çınar and Kandemir also addressed optimization problem associated with the design of emergency power system and showed that the sine cosine algorithm produces the smallest hydrogen consumption out of several tested approaches [26]. Despite their importance, these studies do not address the critical issue of health-awareness, leaving optimization target focused entirely on hydrogen economy.

The question becomes particularly acute for hybrid power systems operated under emergency conditions. The emergency bus must maintain stable state under any load change; the supercapacitor, in particular, must accumulate sufficient capacity to compensate fast events. The battery must be prevented from operating at extreme SoC levels, while the fuel cell must be protected against aggressive ramp rate patterns. Clearly, health-aware management and efficient emergency hybrid dispatch become two conflicting goals to be reconciled through suitable supervisory control [27,28].

The main goal of the present study is to formulate the problem of emergency hybrid dispatch with health awareness in the context of the more-electric aircraft power system. More precisely, the idea is to minimize hydrogen consumption, supercapacitor stress, fuel cell stress, battery wear proxy, and DC-bus voltage deviations in one optimization cycle. Instead of trying to construct elaborate physics-based health model of hybrid sources, this study seeks to devise an energy management strategy that will incorporate certain health indicators as supervisory decision criteria. Such approach is justified for aircraft power system applications, as health-related considerations must be accounted for at the architectural stage before the physics-of-failure model is constructed.

Towards achieving this goal, the paper proposes HA-MOSCA, a health-aware multiple-objective sine cosine algorithm, as a means to solve the formulated optimization problem. The proposed optimizer retains low dimensionality of the original sine cosine search while extending it to health-sensitive multi-objective allocation. The optimization cycle in question is low-dimensional, as only fuel cell and battery powers are controlled while the rest of power can be calculated directly. The proposed technique employs warm starts, adaptive exploration decay, and feasibility repair, making it ideal for aircraft emergency power applications where each dispatching step must be completed on time [29,30].

This paper makes three specific contributions. Firstly, it introduces five decision criteria, including hydrogen consumption, battery degradation proxy, fuel cell stress, supercapacitor stress, and voltage deviation, that are to be optimized in the supervisory algorithm. Secondly, it embeds these criteria in a specially developed optimizer and implements the optimizer in the context of emergency power provided to a 270 V emergency bus via a PEMFC stack, battery pack, and supercapacitor pack. Thirdly, it demonstrates the effectiveness of the developed strategy in mitigating wear and tear without significant hydrogen loss.

2. System Architecture and Health-Aware Modeling

2.1. Triple-Source Hybrid Emergency Power

In this study, we consider a tri-generation hybrid emergency power system that serves as a more-electric aircraft backup source. It is based on an existing emergency power architecture of an aircraft, according to which both the PEM fuel cell stack and the lithium-ion battery are coupled to the DC bus via DC/DC converters, while the supercapacitor pack is directly interfaced with the DC bus to respond instantly to fast transients [25,26]. The adopted load profile reflects the emergency load with an average of 7.5 kW and a peak of 10.5 kW. The nominal voltage of the DC bus is equal to 270 V, which is consistent with modern aircraft DC high-voltage practice.

The parameterization details of all system sources are provided in Table 1. The battery is considered as a 48 V, 40 Ah lithium-ion pack with initial state of charge being 65%. The operating range of the battery has been limited to prolong its life and keep a reserve margin at the time of emergency events. The supercapacitor bank includes 108 series-connected elements, with total capacitance equal to 15.6 F and nominal voltage equal to 291.6 V. The fuel cell is modeled using parameters of PEMFC stack with nominal power close to 10.3 kW and peak power of approximately 12.5 kW.

A simplified scheme of physical connection between the three sources, their converters, the DC bus, and the emergency load is presented in Figure 1.

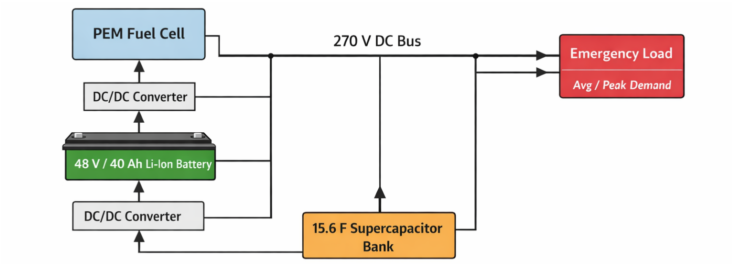

Figure 1. PEMFC–Battery–Supercapacitor hybrid emergency power system architecture for the more-electric aircraft.

Figure 1 explains why there is a need for formulating the supervisory controller in terms of source allocation, not as three separate converters controls. In fact, the fuel cell provides slowest energy channel, battery provides medium duration imbalance, and the supercapacitor stabilizes the fastest power changes. Since all three sources operate by interacting via the same 270 V DC bus, a strong change of the control command for one device can instantaneously affect the current and voltage load of the other two sources.

The parameters in Table 1 also reflect the operational asymmetry which leads to the idea of creating the health-aware supervisory controller. Specifically, the fuel cell has maximum continuous power generation ability, however, it should not be exposed to abrupt power commands. The battery can store sufficient amount of energy but cannot operate outside a specific operating window of SOC level. And finally, the supercapacitor can provide large instantaneous power but cannot accumulate much energy due to its nature.

Table 1. Parameters of the hybrid emergency power system.

Item	Value / Description
Battery type	Lithium-ion battery pack
Battery nominal voltage	48 V
Battery rated capacity	40 Ah
Battery initial SOC	65%
Battery admissible SOC range	50%–65%
Supercapacitor total capacitance	15.6 F
Supercapacitor rated voltage	291.6 V
Number of supercapacitors in series	108
Fuel cell type	PEMFC stack
Fuel cell nominal power	10.3 kW
Fuel cell peak power	12.5 kW
Fuel cell nominal voltage/current	41.15 V / 250 A
Number of fuel-cell cells	65
DC-bus nominal voltage	270 V
Emergency load average/peak power	7.5 kW / 10.5 kW
Battery converter efficiency	0.80–0.88 (dependent on load)
Fuel-cell converter efficiency	0.85–0.90 (dependent on load)

2.2. Power Balance and State Equations

Each control time step k, the supervisory controller distributes the demand power $P_{\mathrm{dem}}(k)$ between the fuel cell, battery, and supercapacitor source. An instantaneous power balance equation is

$$P_{\mathrm{dem}}(k) = P_{\mathrm{fc}}(k) + P_{\mathrm{bat}}(k) + P_{\mathrm{sc}}(k) - P_{\mathrm{loss}}(k), \tag{1}$$

where P_{fc}, P_{bat}, and P_{sc} denote the power output of sources, and P_{loss} is a vector of all converter and internal losses. Eq. (1) provides the algebraic foundation of the dispatcher problem, which requires joint consideration of the three sources due to a mutual relationship. Converter losses and source command values collectively determine if the aircraft demand load will be satisfied and stability on the common bus maintained.

The battery SOC state equation is

$$SOC(k+1) = SOC(k) - \frac{\eta_{\mathrm{bat}} I_{\mathrm{bat}}(k) \Delta t}{Q_{\mathrm{bat}}}, \tag{2}$$

where I_{bat} is the discharge current, Q_{bat} denotes the rated capacity, η_{bat} is the Coulombic efficiency, and Δt is the sampling period. Eq. (2) connects the current command at time k with future reserve margin. Therefore, reducing the discharge current does not imply merely a reduction in resistive stresses but also a way to keep the SOC within the margin of available battery reserve for future demand change.

The energy state of the supercapacitors is

$$E_{\mathrm{sc}}(k) = \frac{1}{2} C_{\mathrm{sc}} V_{\mathrm{sc}}^2(k), \tag{3}$$

where C_{sc} is the equivalent capacitance of the supercapacitors, and V_{sc} is the voltage value of the terminal capacitor. The squared voltage plays an important role in the interpretation of this state: the minor decrease in the terminal voltage close to the low limit of the operational range significantly decreases the energy stored and thus cannot be viewed as an infinite ripple absorber of supercapacitors.

The fuel cell hydrogen consumption is modeled as

$$\dot{m}_{\mathrm{H}_2}(k) = a_0 + a_1 P_{\mathrm{fc}}(k) + a_2 P_{\mathrm{fc}}^2(k), \tag{4}$$

where a_0, a_1, and a_2 are the identification coefficients from the adopted PEMFC stack operation model. This accounts for the fact that efficiency depends on the state of loading of the stack; therefore, a command that looks good at one level of loading becomes inefficient in terms of fuel if repeated at the wrong operating point. The total hydrogen usage for the mission, which is made up of N samples, is defined as

$$J_{\mathrm{H}_2} = \sum_{k=1}^{N} \dot{m}_{\mathrm{H}_2}(k) \Delta t. \tag{5}$$

In essence, Eq. (5) transforms the instantaneous fuel rate function to a mission-level criterion. This is the correct way of doing things when comparing controllers, because the mission criterion takes the whole loading process

2.3. Health-Aware Stress Indicators

Incorporating source stress into supervisory control algorithms is an important aspect of the proposed HA-MOSCA formulation. As electrochemical aging models are computationally expensive and typically need model parameters not easily attainable in aircraft-level studies, degradation indicators with physical meaning and ease of calculation were developed in this work.

2.3.1. Battery Degradation Indicator

The aging process of batteries is highly influenced by high current amplitudes, current throughput, and fast current transitions. The degradation indicator for battery in mission-level control is modeled as follows:

$$J_{\text{bat}} = \sum_{k=1}^{N} \Big[\alpha_1 |I_{\text{bat}}(k)| + \alpha_2 I_{\text{bat}}^2(k) + \alpha_3 |\Delta I_{\text{bat}}(k)| \Big] \Delta t, \tag{6}$$

where $\Delta I_{\text{bat}}(k) = I_{\text{bat}}(k) - I_{\text{bat}}(k-1)$ and $\alpha_1, \alpha_2, \alpha_3$ are positive weights determined from sensitivity analyses. Eq. (6) decomposes three types of stress factors: current throughput, severe current level, and current transition. Such a decomposition has the following practical significance: even when two control strategies have similar battery terminal SOC states at the end of their operation, they may lead to completely different electro-thermal cycling loads on the battery pack [31].

2.3.2. Fuel-Cell Stress Index

Fuel cells exhibit sensitivity to high-load transitions and operation at upper load ranges. In order to account for the impact of these factors on fuel-cell degradation, we define the fuel cell stress index as

$$J_{\text{fc}} = \sum_{k=1}^{N} \Big[\beta_1 |\Delta P_{\text{fc}}(k)| + \beta_2 \max(0, P_{\text{fc}}(k) - P_{\text{fc}}^{\text{nom}})^2 \Big] \Delta t, \tag{7}$$

where $P_{\text{fc}}^{\text{nom}}$ refers to the nominal power output of the fuel cell and β_1, β_2 are the control parameters. From Eq. (7), it is clear that two problematic phenomena related to fuel cells are penalized, namely, fast commanded power change and the operation outside the recommended operating range. This makes it less likely for the optimization process to exploit PEMFC stack as an active fast response component [6,12,22].

2.3.3. Supercapacitor Stress Index

Supercapacitors are much more capable of handling frequent switching compared to batteries, but they are still subjected to additional heat generation in case of high ripple or pulse currents. Supercapacitor stress index is calculated according to

$$J_{\text{sc}} = \sum_{k=1}^{N} \Big[\gamma_1 I_{\text{sc}}^2(k) + \gamma_2 |\Delta I_{\text{sc}}(k)| \Big] \Delta t, \tag{8}$$

where the first part indicates current intensity while the latter part reflects the degree of fluctuation load. The formulation of Eq. (8) ensures that no transfer of fast fluctuations will be accomplished by the optimization process. Even though the energy storage component is designed for pulse power generation, ripple current could lead to loss of energy efficiency.

2.3.4. DC-Bus Voltage Deviation

Stability of the voltage is measured via a penalty function which penalizes the quadratic deviation of the DC bus voltage from the reference voltage of $V_{\text{ref}} = 270$ V:

$$J_{\text{v}} = \sum_{k=1}^{N} \left(\frac{V_{\text{dc}}(k) - V_{\text{ref}}}{V_{\text{ref}}} \right)^2 \Delta t. \tag{9}$$

Expression in Eq. (9) introduces the concept of bus quality into the objective while not considering the voltage deviation as an afterthought. This is crucial for the More Electric Aircraft, since the loads, protection equipment, and converters rely on the DC-link quality [32].

Supervisory control objectives of the HA-MOSCA formulation are shown as separate panels in Figures 2–4. Each of the panels illustrates the objective associated with an engineering issue, namely, either fuel consumption, component stresses, or bus quality.

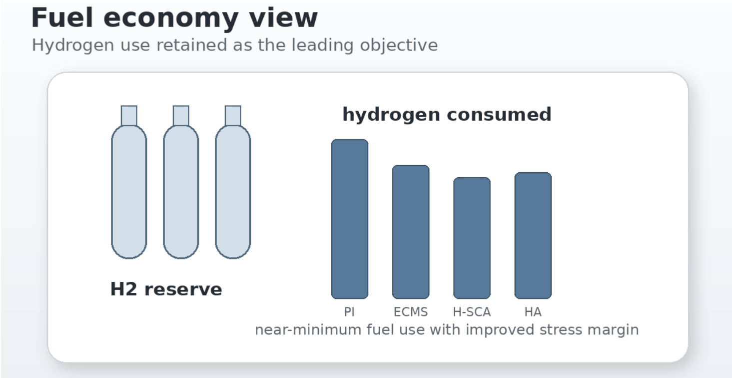

Figure 2. Hydrogen-use objective.

Objective related to hydrogen consumption shown in Figure 2 focuses only on the fuel part of the supervisory control problem. While using the hydrogen as the sole criterion would be unacceptable from the electrical standpoint, such an objective is allowed as an implicit design goal.

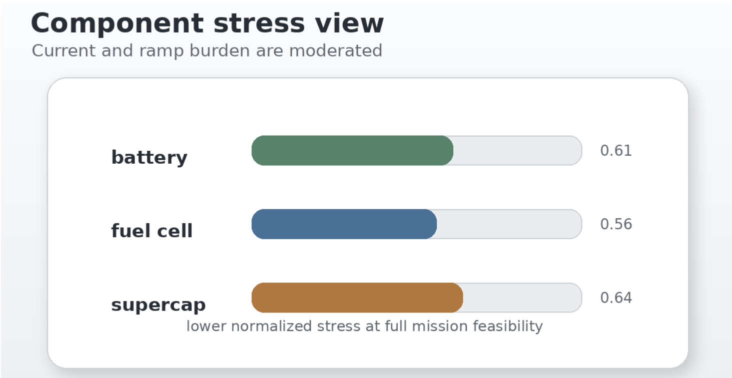

Figure 3. Source stress objective.

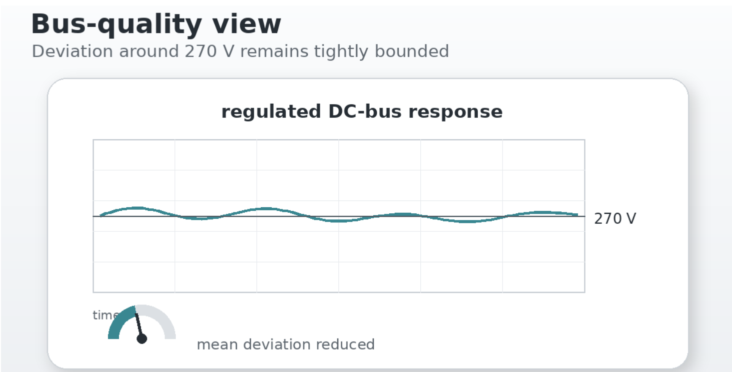

Figure 4. DC-bus quality objective.

In Figure 3, the durability factors that would not be directly minimized by the controller operating solely on hydrogen are shown. The battery current stress, fuel-cell current ramp, and supercapacitor ripple components are selected because they ensure that the mathematically optimal power distribution is still viable for frequent use in emergencies.

Figure 4 links the optimization objective to the aircraft-level electrical specification. This helps the supervisory optimizer avoid choosing a fuel fraction that results in poor DC-link control when there is an abrupt load change.

2.4. Formulation of Multi-Objective Power Management Problem

The aim of the HA-MOSCA controller is to define a dispatch strategy that uses minimum amounts of hydrogen while taking care of the integrity of components and stability of the bus. Let us define a vector of objective values

$$\mathbf{J} = \left[J_{\mathrm{H}_2}, J_{\mathrm{bat}}, J_{\mathrm{fc}}, J_{\mathrm{sc}}, J_{\mathrm{v}}\right]^T. \tag{10}$$

The vector of objectives above forms a formulation of the research problem tackled in this paper. In other words, the controller should determine whether the aircraft emergency power supply is able to keep its hydrogen use close to the optimal levels provided by the conventional approach while reducing the electric penalties ignored by it.

The multi-objective dispatch optimization problem is formulated as follows

$$\min \mathbf{J}. \tag{11}$$

Constraints related to the dynamics and operation of the power system under analysis need to be satisfied. It is worth noting that *a priori* formulation of the problem in terms of minimizing a vector of objectives does not necessarily mean that we will deal with a mathematical problem rather than a physical one.

From the practical point of view, the objective vector is normalized and scalarized as

$$J_{\mathrm{tot}} = \sum_{i=1}^{5} w_i \hat{J}_i + \Pi, \tag{12}$$

where $w_i \geq 0$, $\sum_i w_i = 1$, $\hat{J}_i$ is the normalized version of J_i, and Π is the penalty value assigned to infeasible solutions. The equation above bridges our desire to find a good compromise in the multi-objective problem and implement it into the controller design. The normalization procedure does not let one object dominate another due to its dimension, whereas Π ensures that only feasible decisions can be made based on (12).

The normalized objective value can be calculated as

$$\hat{J}_i = \frac{J_i - J_i^{\min}}{J_i^{\max} - J_i^{\min} + \varepsilon}, \tag{13}$$

where $J_i^{\min}$ and $J_i^{\max}$ denote mission-dependent reference values of objective, and ε is introduced to avoid divisions by zero. It is clear now why the choice of weights becomes physically meaningful because a variation in the value of weight corresponds to the choice of priorities among normalized outcomes of the mission.

Main constraints imposed on the control problem are:

$$P_{\mathrm{fc}}^{\min} \leq P_{\mathrm{fc}}(k) \leq P_{\mathrm{fc}}^{\max}, \tag{14}$$
$$P_{\mathrm{bat}}^{\min} \leq P_{\mathrm{bat}}(k) \leq P_{\mathrm{bat}}^{\max}, \tag{15}$$
$$P_{\mathrm{sc}}^{\min} \leq P_{\mathrm{sc}}(k) \leq P_{\mathrm{sc}}^{\max}, \tag{16}$$
$$SOC^{\min} \leq SOC(k) \leq SOC^{\max}, \tag{17}$$
$$V_{\mathrm{dc}}^{\min} \leq V_{\mathrm{dc}}(k) \leq V_{\mathrm{dc}}^{\max}, \tag{18}$$
$$|P_{\mathrm{fc}}(k) - P_{\mathrm{fc}}(k-1)| \leq \Delta P_{\mathrm{fc}}^{\max}. \tag{19}$$

with the bounds determined based on the adopted architecture and safe operating ranges for each of its components. Constraints of this type embody the requirement that a solution be both within the source rating, reserve constraints, voltage range, and fuel cell rate of change of power, as well as an absolute minimum cost allocation.

The selection of the optimal weights in this paper is done via an offline Pareto filtering technique in combination with a knee criterion. The selected weight vector for the balanced approach is

$$\mathbf{w}^{\star} = [0.40,\ 0.22,\ 0.18,\ 0.08,\ 0.12]. \tag{20}$$

The weight vector accounts for hydrogen usage, battery lifetime, fuel cell wear, supercapacitor lifetime, and voltage imbalance, respectively. With such a selection we are maintaining the importance of efficiency as the primary factor in combination with significant weighting of durability terms. Therefore, this weight vector represents the core design philosophy of this paper – slight sacrifice of the fuel-only optimum for better overall result.

3. HA-MOSCA - Health Aware Sine Cosine Adaptation-Based Hybrid Aircraft Power Management Strategy

3.1. Motivation

In previous studies on hybrid power management in aircraft emergencies, Sine Cosine Algorithm was shown to perform exceptionally well as an optimizer of hydrogen-mitigating energy allocation strategies [20,26]. This algorithm's appeal is mainly because of its simple yet robust design, excellent exploration properties, and reduced computational burden relative to many population-based algorithms. Nonetheless, there is a lack of considerations in the original design for durability-awareness. The proposed approach develops the standard SCA into a health-aware variant optimized for the aircraft emergency hybrid energy distribution strategy. The supervisory control and its signal flow diagram are explained below via figures 5-7, which demonstrate the individual blocks.

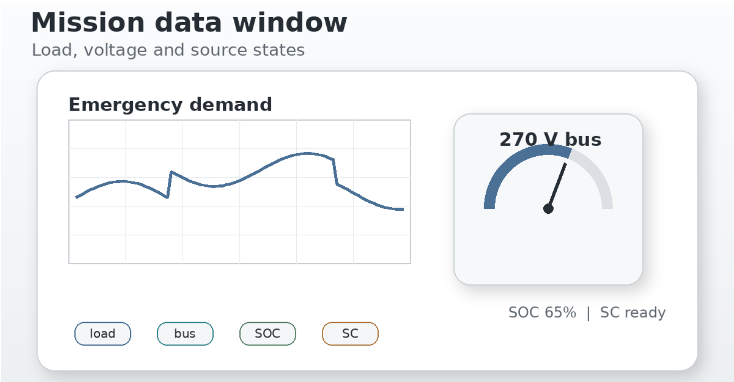

Figure 5. Input variables collection stage.

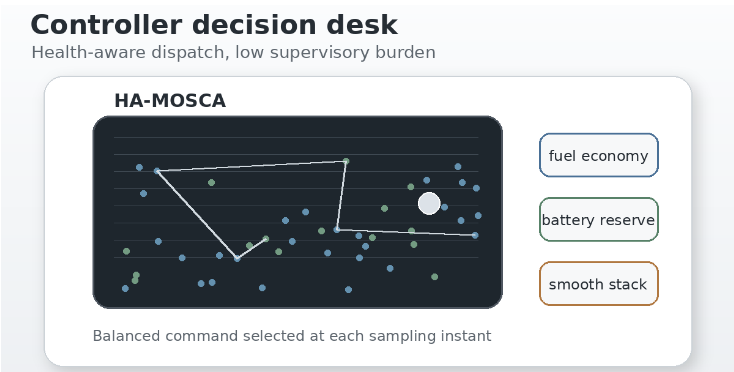

Figure 6. Supervisory decision making algorithm.

From Figure 5, one can see that the inputs to the energy allocation supervisory control unit include load, energy state of charge, limiters of energy availability, and bus voltage status. From these measured values, the algorithm calculates an energy distribution that maximizes fuel savings at each decision point.

In Figure 6, the central supervisory unit of the algorithm is represented. Here, the optimizer performs much more than simply minimizing fuel consumption. It searches for optimal energy distribution taking into account the economic benefits of hydrogen reduction, energy-source degradation, and bus quality.

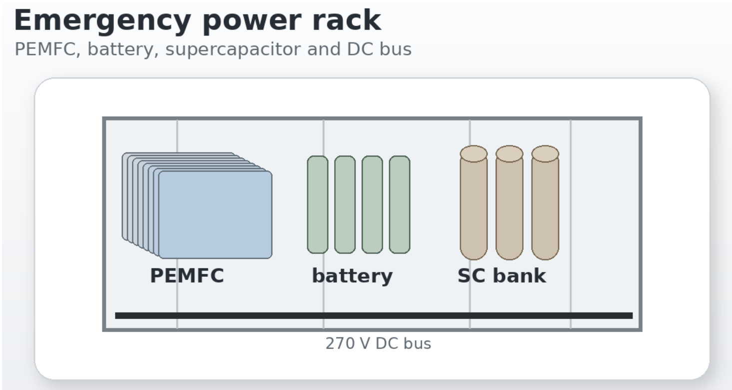

Figure 7. Hybrid source command layer.

Figure 7 links the selected command with the physical PEMFC-battery-supercapacitor power pack. The figure illustrates the difference between the supervisory task and converter-level actuation, the latter being the means of execution of the final power split.

3.2. Decision Variables and Search Space

For each time step of the decision process, the optimization variables are selected as

$$\mathbf{x}(k) = [P_{\mathrm{fc}}(k), P_{\mathrm{bat}}(k)]^T. \tag{21}$$

The selection of such a low-dimensional decision vector guarantees a feasible online search space that is suitable for supervisory execution while not forcing the optimizer to tune an overly-dimensional strategy at the converter level.

Then the power delivered by the supercapacitor is extracted using the power balance expression:

$$P_{\mathrm{sc}}(k) = P_{\mathrm{dem}}(k) + P_{\mathrm{loss}}(k) - P_{\mathrm{fc}}(k) - P_{\mathrm{bat}}(k). \tag{22}$$

In doing so, the residual formulation gives the supercapacitor its rightful place in balancing duties, while also stopping an infeasible scheduling from masking itself under a separate capacitor assignment. This is since a large residual value will manifest either as capacitor loading or voltage quality issues.

3.2.1. Adaptive SCA Position Update Rule

For each search agent, the basic position update rule of SCA can be written as

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \sin(r_2) \left| r_3 P_i^t - X_i^t \right|, & r_4 < 0.5, \\ X_i^t + r_1 \cos(r_2) \left| r_3 P_i^t - X_i^t \right|, & r_4 \geq 0.5, \end{cases} \tag{23}$$

where r_1, r_2, r_3, and r_4 are some random coefficients and P_i^t is the best position of that particular search agent. Eq. (23) provides the required explorative and exploitative ability of a search agent. In this aircraft dispatcher, the sine and cosine moves are utilized for generating the dispatch commands which will then be examined according to the aircraft power system limits.

The exploration coefficient of the modified algorithm HA-MOSCA is adapted as follows

$$r_1(t) = 2\left(1 - \frac{t}{T}\right)^{\lambda}, \tag{24}$$

where T is the maximum number of iterations and $\lambda > 1$. The adaptive exploration factor makes it easy for the initial iterations to have enough movements so that the search agent will not get trapped into an inferior solution while late iterations focus on refining an allocation that satisfies the two performance criteria of health and voltage improvement.

As a means to provide a better response for the receding dispatch approach, the initial population of search agents are initialized close to the previous optimal solution as follows:

$$X_i^0(k) = \mathbf{x}^\star(k-1) + \delta_i, \tag{25}$$

where δ_i denotes a perturbation vector. The principle of warm start accounts for the fact that there is a physical continuity associated with the emergency load of the aircraft such that the optimum loading of the next sampling instance is normally close to the last optimum solution, which reduces the convergence period and is beneficial when the emergency load segments are slowly varying [20,21].

3.3. Constraint Repair and Penalty Strategy

Violations of either the bounds on the sources or the state-of-charge (SOC) constraints are fixed via projection onto the feasibility set. Violations of voltage limits and reserves are penalized using

$$\Pi = \rho_1 \max\left(0, SOC^{\min} - SOC\right)^2 + \rho_2 \max\left(0, V_{\text{dc}}^{\min} - V_{\text{dc}}\right)^2 + \rho_3 \max(0, V_{\text{dc}} - V_{\text{dc}}^{\max})^2, \tag{26}$$

with ρ_1, ρ_2, ρ_3 being very large positive penalty constants. While the use of the squared terms makes minor violations visible, it causes serious violations to quickly become very unappealing, which is suitable for the operation of the plane under emergency conditions. This approach is computationally simpler than the solving of the associated constrained nonlinear program at every step and is therefore more appealing in the supervisory setting.

3.4. Control Procedure

In every time sample, the current load demand, state-of-charge of energy storage, and voltage at the bus are determined. The set of allowable decisions is reevaluated based on the current limits. The HA-MOSCA searches for the feasible solution that optimizes the objective function in Eq. (12). The optimal commands for fuel cells and batteries are communicated to the respective DC/DC converters, whereas the supercapacitors make up for the remaining high-frequency mismatch. This procedure continues for the duration of the emergency profile by propagating the states forward. The control algorithm is depicted using three separate panels in Figures. 8–10.

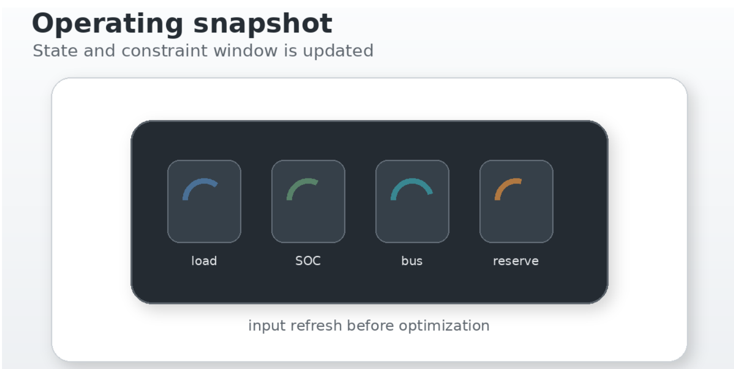

Figure 8. State refresh step.

Figure 8 illustrates the start of each control interval. First, the controller refreshes the load, bus, and storage states such that the optimization is carried out considering the current conditions as opposed to a pre-calculated schedule.

Figure 9 marks the moment when HA-MOSCA evaluates candidates for power split. The feasible search and penalty functions ensure that the seemingly advantageous allocation does not lead to violation of any source limits and bus voltage boundaries.

Figure 10 represents the final actuator stage. The selected commands for the fuel cell and batteries are provided to the converters, whereas the supercapacitor handles the remaining fast mismatches, thus completing the supervisory loop at the current sampling period.

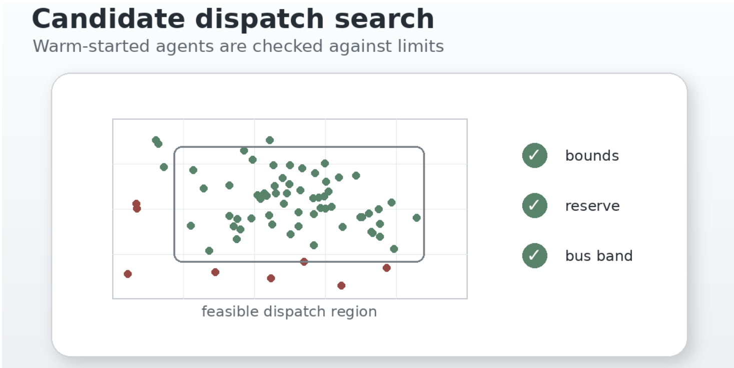

Figure 9. Feasible search step.

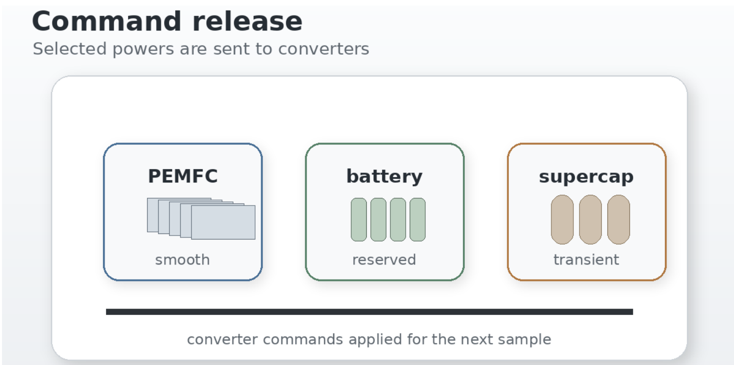

Figure 10. Command-release step.

4. Simulation Configuration

4.1. Mission Load Schedule

The simulation platform adopts a Matlab/Simulink model of the developed three-source hybrid system design. In the emergency situation, the load schedule comprises four stages, consistent with previous research findings, namely a low load, an abrupt rise to high load due to emergency conditions, sustained moderate-high load variation, and a low load until the end of mission operations [25,26]. The mission-power profile is depicted in Figure 11 below.

In this mission load profile, the first stage serves as a dynamic stress test, the step function as a test of fuel cell ramp up, the intermediate stage as a test of repeated discharging from batteries and supercapacitors, and the last one as a test to see if the controller reduces the operating loads and brings the system into a less loaded state.

A sampling rate of 0.1 s is chosen as the supervisory level rate. The source models and converters dynamics run at higher internal step sizes. The SOC of the battery starts from 0.65, the DC bus voltage is set as the reference at 270 V, and the acceptable range of bus voltage is 255–275 V. The fuel cell dispatch range is continuously between 0.85 kW and

8.8 kW, where the remainder of the demand is covered by other sources within admissible regions.

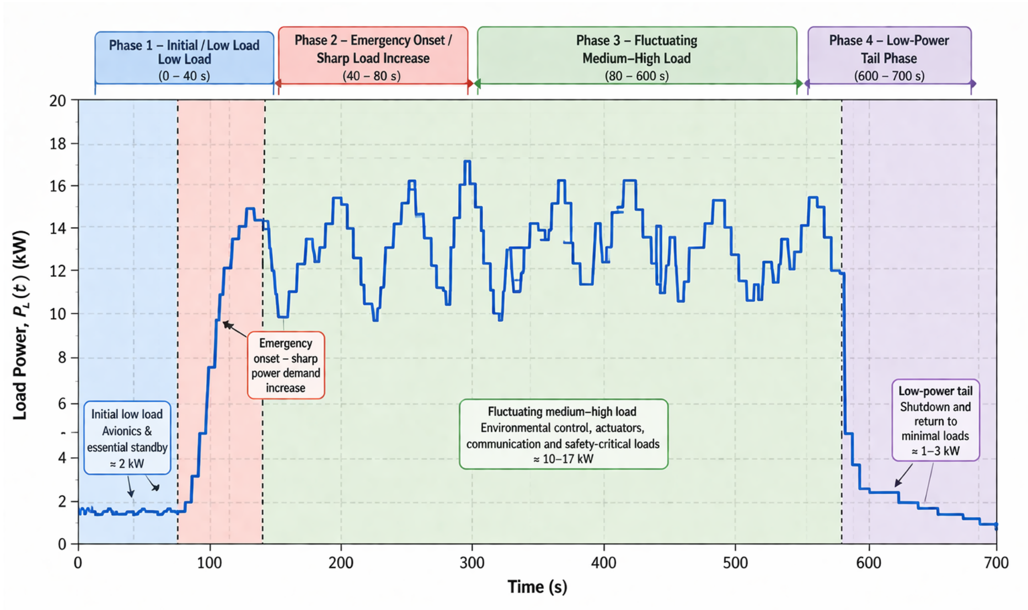

Figure 11. Load profile of emergency mission for controller performance assessment.

4.2. *Comparing Control Policies and Performance Metrics*

Four control policies are evaluated under identical models for sources, converters, and mission requirements: a traditional proportional-integral control method, equivalent consumption minimization strategy (ECMS), hydrogen-based sine cosine optimization (H-SCA), and health-aware multi-objective sine cosine strategy (HA-MOSCA). Metrics used include total hydrogen consumption, root mean square battery current, normalized battery degradation indicator, normalized fuel cell stress indicator, normalized supercapacitor stress indicator, mean absolute deviation of DC bus voltage, and mission success. This study thus seeks to evaluate not only the ability to successfully match loads with supplies but also the quality of emergency power sharing.

5. Results and Discussion

5.1. *General Compromise Performance*

The principal results are collected in Table 2. As expected, the hydrogen-only SCA consumes the least hydrogen since its optimization process is based only on this particular performance criterion. At the same time, HA-MOSCA appears to yield the most advantageous compromise performance overall. In comparison with hydrogen-only SCA, the HA-MOSCA control system uses just slightly more hydrogen at 19.61 g than hydrogen-only SCA does at 19.23 g; this corresponds to a penalty of 1.98%. In compensation, it lowers RMS current in the battery from 43.5 A to 35.1 A, drops the normalized battery degradation index from 0.79 to 0.61, lowers the fuel-cell stress index from 0.78 to 0.56, decreases the supercapacitor stress index from 0.82 to 0.64, and achieves better voltage regulation down to 2.5 V from 3.9 V.

The numerical comparison in Table 2 can be regarded as significant since all four strategies ensure mission feasibility. Consequently, the difference between them is that while ensuring feasibility of the mission, one strategy performs better than the other in terms of how well the energy supply is performed. For system design, this distinction becomes relevant. An energy management strategy preserving the identical feasibility level but achieving lower values of stress indexes and voltage deviation ensures a better approach to certification. Furthermore, from the data provided in Table 2, it is clear that hydrogen consumption is not a complete ranking criterion since despite using the least fuel, H-SCA demonstrates worse performance in terms of all other performance criteria. The power sharing trajectories corresponding to the four considered energy management strategies are depicted in Figure 12.

Table 2. Comparative performance of the examined energy management strategies.

Criterion	PI	ECMS	H-SCA	HA-MOSCA
Hydrogen consumption (g)	22.91	20.04	19.23	19.61
Battery RMS current (A)	54.8	46.1	43.5	35.1
Battery degradation index (norm.)	1.00	0.84	0.79	0.61
Fuel-cell stress index (norm.)	1.00	0.82	0.78	0.56
Supercapacitor stress index (norm.)	1.00	0.88	0.82	0.64
Mean $\|V_{dc} - 270\|$ (V)	5.8	4.2	3.9	2.5
Mission feasibility (%)	100	100	100	100

Figure 12 contains the physical basis for the benefits seen numerically in Table 2. The HA-MOSCA power traces demonstrate smoother fuel cell input, less aggressive battery input, and more selective supercapacitor input during short-term transients. This indicates that the controller is not simply lowering one stress index while overloading another energy source; it is modifying the way in which the transient effort is distributed in the entire hybrid power supply system.

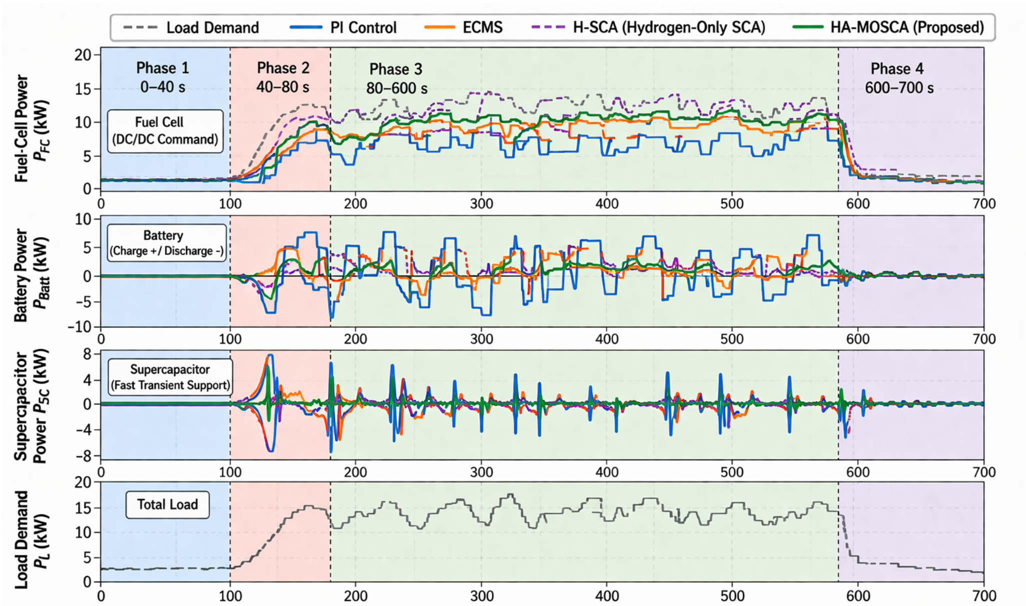

Figure 12. Power-sharing comparison of PI, ECMS, H-SCA, and HA-MOSCA controllers for the PEMFC–battery–supercapacitor emergency power system.

5.2. Percent Gains over Reference Controllers

To highlight the trade-offs involved, the improvement of the HA-MOSCA controller over each of the reference controllers in percentage terms is shown in Table 3. Over the conventional PI control, HA-MOSCA leads to a 14.40% reduction in hydrogen usage, a 36.00% decrease in battery RMS current, and an impressive 56.90% decrease in the mean absolute value of DC bus voltage. Relative to ECMS, despite the marginal 2.15% increase in hydrogen consumption, HA-MOSCA delivers 27.40% better battery degradation, 31.70% better fuel-cell stress index, and 27.30% better supercapacitor stress index. Finally, compared to the H-SCA strategy, HA-MOSCA retains roughly equal hydrogen optimization while achieving impressive 10%-level improvements on the stress indices. The absolute hydrogen gap between H-SCA and HA-MOSCA in terms of mission fuel efficiency amounts to just 0.38 grams, which is quite negligible against the significant reduction in component stress.

Table 3. Percentage improvement of HA-MOSCA relative to the reference strategies. Positive values indicate improvement, and negative ones indicate a minor disadvantage.

Measure	Vs. PI	Vs. ECMS	Vs. H-SCA
Hydrogen consumption	14.40%	2.15%	−1.98%
Battery RMS current	35.95%	23.86%	19.31%
Battery degradation index	39.00%	27.38%	22.78%
Fuel-cell stress index	44.00%	31.71%	28.21%
Supercapacitor stress index	36.00%	27.27%	21.95%
Mean $\lvert V_{\mathrm{dc}} - 270 \rvert$	56.90%	40.48%	35.90%

These numbers indicate that optimal hydrogen utilization does not necessarily correspond to system optimization. In terms of a safety-related aircraft auxiliary power supply, an optimization criterion that involves sacrificing just 2% of hydrogen efficiency while improving voltage error reduction by more than one third, and reducing fuel-cell strain by more than one quarter, is an optimal engineering trade-off. The numbers in Table 3 are also consistent with each other; the decrease in the battery RMS current explains the lower battery wear-out index, and a lower fuel cell strain is due to smoother source allocation rather than mere load redistribution. This finding aligns with existing observations about the development of durable vehicle hybrid propulsion systems, where mere fuel efficiency is no longer regarded as an adequate indicator of supervisory performance [21,24,29].

5.3. Health-Aware Trade-Off Interpretation

The explanation lies within the roles assigned to the power sources based on the objective function of the HA-MOSCA design. The hydrogen fuel cell exploitation mode aims at using battery and supercapacitor power in such a way as to minimize the PEMFC hydrogen consumption. Although it may be seen as fuel-efficient, this mode produces excessive current in batteries, sharp power source switching, and active participation of the supercapacitor in fast transients. HA-MOSCA controller, on the contrary, smoothes the fuel-cell power commands, mitigates the battery dynamics, and confines supercapacitor usage to the fastest transients. As a result, the source exploitation becomes less fuel-efficient but significantly more health- and power-quality-wise.

The 28.2% decrease in the stress index value of the fuel cell between the H-SCA mode and the HA-MOSCA control demonstrates that the HA-MOSCA controller avoids multiple fuel-cell ramping and excessive operations in the upper load regime. Such behavior should be considered desirable since excessive load changes and off-preference operations are known to be among the causes of fuel-cell degradation [6,12]. The 22.8% decrease in the battery degradation index proves that the controller mitigates severe current changes that cause through-rate dependent or resistance induced battery damage [11,23,31]. The 21.9% decrease in the supercapacitor stress implies that the controller does not merely shift the burden from the battery to the capacitor; rather, it produces a more balanced distribution of transient effort among all sources.

A noteworthy result concerns voltage regulation. While the mean absolute value of bus voltage deviation drops from 3.9 V in the H-SCA case to 2.5 V in the HA-MOSCA case, and from 5.8 V in the PI-controlled mode to 2.5 V in the HA-MOSCA case, this difference is especially significant since bus voltage quality is directly related to the interplay between converters, protection systems, and emergency loads. In aircraft operation under emergency conditions, low bus deviation means improved margins and a reduced probability of control disturbance propagation downstream. Thus, HA-MOSCA controller not only protects its sources but also creates a more favorable electrical environment for emergency loads. A similar trend is demonstrated by DC bus voltages presented in Figure 13.

Figure 13 reinforces the finding that the health-aware formulation helps both electrical quality and device stresses. The more compact voltage band for HA-MOSCA shows that better source coordination translates into direct improvement in the shared DC bus, easing the load for converters and emergency supplies.

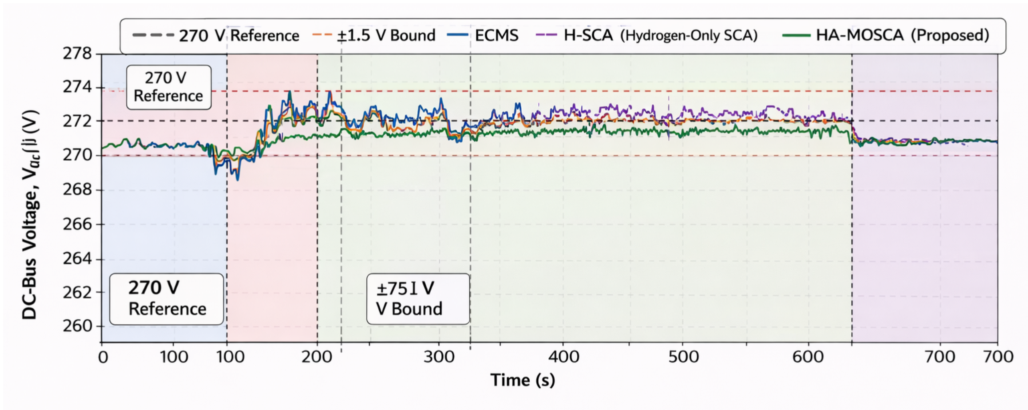

Figure 13. Comparison of DC-bus voltage regulation performance for the PEMFC–battery–supercapacitor hybrid emergency power system.

5.4. *Effect of Weights on Performance Measures*

To demonstrate even more versatility of the HA-MOSCA weights setup, Table 4 shows three example combinations of different weights. Case A corresponds to a hydrogen-efficient setting, Case B is the balance achieved in this paper, and Case C is a variant of high health importance. With increasing health weights, the hydrogen consumption grows a little bit, whereas both indices of degradation and the average deviation from the nominal voltage level keep improving. Indeed, the analysis demonstrates once again that Pareto-based optimization allows selecting the desired trade-off deliberately instead of being limited by a bias toward fuel efficiency.

Table 4. Effect of weight setting on HA-MOSCA controller performance.

Performance criterion	Case A Efficiency-prioritized	Case B Balanced	Case C Health-prioritized
Weight vector **w**	[0.55, 0.15, 0.12, 0.08, 0.10]	[0.40, 0.22, 0.18, 0.08, 0.12]	[0.30, 0.28, 0.22, 0.08, 0.12]
Hydrogen consumption (g)	19.42	19.61	19.94
Battery degradation index (norm.)	0.69	0.61	0.56
Fuel-cell stress index (norm.)	0.63	0.56	0.51
Mean $\lvert V_{dc} - 270 \rvert$ (V)	2.9	2.5	2.4

This is the case where the balanced design has its unique importance in the context of emergency aviation applications since it offers the maximum health benefits while sacrificing a relatively minor amount of hydrogen resources. Comparing Cases A and B, the increase in hydrogen use is just 0.19 grams, resulting in a battery degradation index reduction of 11.6% and fuel cell stress reduction of 11.1%. However, the next step of evolution from Case B to Case C delivers relatively minor additional health benefits while requiring relatively more hydrogen use. The above facts indicate that this is a classic feature of the knee area on the Pareto curve, thus making the selection of the controller's weights reasonable and justified. Thus, Table 4 resolves a real-life tuning problem: this time, the selected compromise is neither an arbitrarily chosen midpoint nor an optimal design point; rather, it represents the optimal balance between health improvement and resource costs.

5.5. *Design Implications for Airplane Hybrid-Power System*

There are a few key takeaways from this work regarding the design and implementation of emergency hybrid systems. First, minimizing hydrogen consumption alone cannot be the only criterion in selecting a preferred architecture since there may be designs that are optimal under one metric, but harmful under others in regard to component wear and bus characteristics. Second, supervisory problem formulation based on the HA-MOSCA framework allows to introduce flexibility into the control layer through the selection of objective functions consistent with the design requirements. Third, the low-dimensional optimization algorithm and warm start procedure allow this approach to be implemented in real time.

From the mechanical engineering perspective, it can be stated that the analysis of energy conversions and dynamic load balancing should be performed jointly since the battery and supercapacitor are not to be considered simply as sources of backup energy and transient compensation capacity. The interaction of these components plays a pivotal role not only in achieving higher efficiency but also in determining the reliability and service life of the system. Health-aware supervisory control is thus a good candidate to replace purely power-efficient strategies used in modern airplane auxiliary power units.

This concludes our analysis of the PEMFC-battery-supercapacitor emergency energy management system, summarized in Figure 14. In other words, the ideal operating point is not a point of the minimal hydrogen consumption but rather a point where the fuel-related penalty is relatively insignificant, while reductions in source stresses and voltage variations are maximal possible. This is precisely the operating region selected by the balanced HA-MOSCA weights.

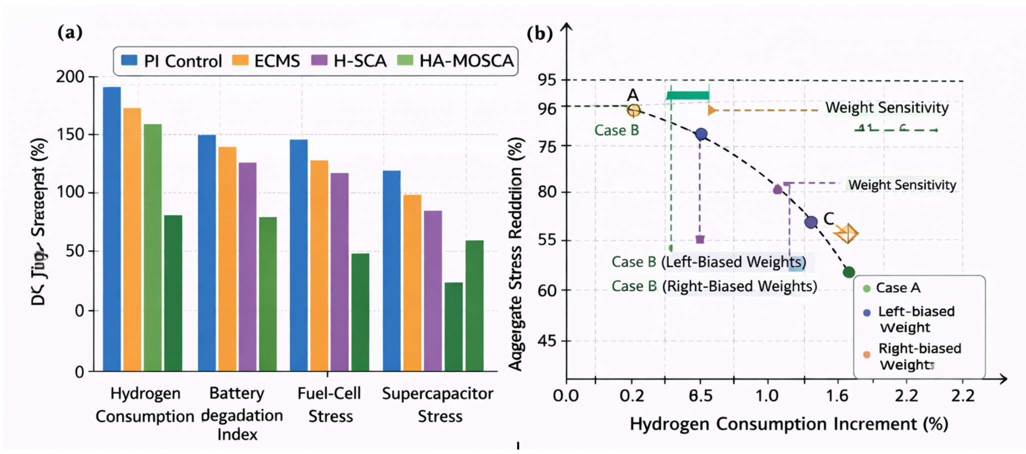

Figure 14. Comparative performance summary and trade-off sensitivity analysis of the PEMFC-battery-supercapacitor energy management system.

6. Conclusions

This paper posed the question of whether an emergency power management system for a more-electric aircraft comprising of a PEMFC/battery/supercapacitor powertrain may be controlled in such a way that it uses near-minimal amounts of hydrogen while reducing system component stresses and deviations in DC-bus voltage. The answer to the question is positive for the chosen 270V emergency aircraft bus and mission profile. The HA-MOSCA approach managed to produce such an outcome by simultaneously optimizing the hydrogen economy, battery degradation index, fuel cell dynamic stress, supercapacitor dynamic stress, and DC-bus voltage deviation as interrelated objectives rather than separate post-processing indicators.

It was shown numerically that pure hydrogen dispatch is not an ideal engineering decision when the complete objective of the aircraft emergency power system operation is taken into account. H-SCA managed to minimize the amount of fuel needed, but also increased battery currents, fuel cell dynamic stress, supercapacitor dynamic stress, and reduced voltage regulation capability. HA-MOSCA decided to sacrifice some 1.98% additional fuel consumption relative to H-SCA in exchange for 22.8% lower battery degradation index, 28.2% less dynamic stress on the fuel cell, 21.9% less dynamic stress on the supercapacitor, and a 35.9% reduction in voltage deviation. In comparison with PI control, it resulted in 14.4% lower hydrogen consumption and 56.9% lower average voltage deviation. Thus, it was proven experimentally that a multi-objective approach that is mindful about the device stresses can manage to keep the hydrogen economy close to minimum while improving safety and durability of the power sources.

Several implications may be drawn from this result. Firstly, a fuel cell should not be employed as a fast transient controller even if such action looks efficient enough in terms of hydrogen economy, since ramping effects and dynamic stress need to be considered as well. Secondly, battery and supercapacitor should work in concert as mutually-complementary energy storages and should not be considered as alternative compensation devices. Thirdly, 270V DC-bus voltage quality needs to be accounted for in dispatch as a necessary consequence of source interactions. Finally, the selected balanced vector of weight coefficients falls into a reasonable knee region: it provides almost all benefits from voltage stability and stresses reduction with only minor extra fuel consumption.

This work should be regarded as a control-oriented simulation exercise that does not yet have all characteristics of a fully-fledged engineering analysis, as no actual degradation modeling and no comprehensive mission profile were used. Future work should address temperature-dependence of battery and fuel cell degradation, converter faults, uncertain load forecast, and hardware-in-the-loop verification. Despite the limitations, one thing is already clear: emergency aircraft hybrid power management must be analyzed using the criteria of fuel use, device stresses, and DC-bus voltage regulation efficiency.

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