Energy management strategy of multi-stack hydrogen fuel cell system considering aging factors

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Abstract. As the demand of low-emission systems grows, hydrogen fuel cells have emerged as a viable and innovative option for sustainable energy applications. This paper explores the implementation of a multi-stack hydrogen Fuel cell system in the context of maritime transportation. The study focuses on addressing two critical challenges: the significant power need of the heavy transport and the aging factor of the stacks. To tackle these issues, an optimized energy management strategy is suggested. This strategy ensures a balanced distribution of the losses across the stacks based on their state of health. In addition to the energy management strategy's aspects mentioned, a comparison is carried out. The studied strategy is evaluated against others based on a current and a cost analysis. This comparison includes a classical option and the strategy that focuses on minimizing hydrogen consumption. This comparison shows the contribution of the studied strategy in improving other performance criteria as well.

1 Introduction

Recently, the global push for sustainable technologies has intensified, particularly in response to the growing impact of climate change. The transportation plays a major role in this transition, as it contributes significantly to global emissions. In fact, transportation is responsible for approximately 29% of the EU's greenhouse gas emissions in 2022 [1]. Calling for significant contributions across different sectors, the European Union has set a challenging goal of climate neutrality by 2050 [2].

Hydrogen Fuel cells (FC) have gained considerable attention as a promising clean energy technology. They produce electricity through hydrogen reactions with minimal pollutant emissions, generating mainly water [3]. Today, the challenge is to implement as a solution to reduce the environmental impact of heavy-duty vehicles (HDVs).

Hydrogen-powered HDVs present challenges, especially due to their high-power. Recent initiatives have developed vessels operating within the megawatt power range, such as cargo ships around 1.2 and fast ferries up to 3 MW [4]. To meet these energy requirements, it is often necessary to adopt a multi-stack system approach (MFC). Research efforts have focused on developing and evaluating various architectures. These evaluations include series and parallel architectures with or without converters [5].

This study focuses on a maritime transport system rated at 1 MW and operating at 1 kV. The setup consists of five fuel cell stacks, each linked to a three-level boost converter. These converters serve a dual purpose: they both enhance the output power of each fuel cell stack and regulate it. All stack-converter units are arranged in parallel, aiming to collectively satisfy the system's highpower requirements.

Beyond the issue of power output, another major concern is the state of health of the stacks. Each stack is subject to differences in the operating conditions and may deteriorate differently over time [6,7]. To address this problem, an EMS (Energy Management Strategy) is implemented to enhance system performance. Over the years, multiple EMS approaches have been proposed, some prioritizing cost minimization [7], others targeting a balance between hydrogen consumption and degradation rates [8].

In this paper, the strategy is designed to ensure a loss balance across the stacks which facilitates thermal management [9].

The EMS under investigation regulates the heat generation and assigns power output to each fuel cell stack according to its state of health status. Essentially, this strategy uses a analytical model that automatically determines the appropriate power contribution of each stack, aiming to achieve an even distribution of losses across all units (stack-converter). This EMS is also compared to other strategies, ie uniform power distribution and minimum fuel consumption.

This paper is organized into three parts. The first part presents an overview of the system's design. The second part concentrates on the EMS's formulation and the simulation results. The third section is dedicated to the comparison between the studied strategy and others, in terms of hydrogen consumption. The paper concludes with a summary of the findings and perspectives.

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2 System description

This paper explores the use of hydrogen-powered fuel cells for heavy duty maritime applications.

Among the various hydrogen fuel cell technologies available, Proton Exchange Membrane Fuel Cells (PEMFCs) are considered mature. They have been identified as a suitable option for this project as described in [10,11].

In practice, fuel cells are generally operated in their ohmic region, to ensure optimal operating conditions.

Based on this consideration, the expression of the fuel cell voltage (v_{FC}) is simplified to a linear form. The equation depends only on E_0 , the open circuit voltage (V), and R_{FC} , the equivalent resistance of the FC (Ω):

$$v_{FC} = E_0 - R_{FC} i \tag{1}$$

This approximation can be done based on the inflexion point method [12], as shown in Fig. 1.



Fig. 1. The polarization curve's approximation.

As a single FC (Fuel Cell) produces a relatively low voltage, this study relies on assembling multiple FCs into stacks. As a result, a higher voltage is obtained. In this paper, the stack is represented by a commercially available model suitable for maritime applications. The considered stack has an open-circuit voltage of 250 V and delivers up to 200 kW of power.

As out earlier, the system is designed for a naval heavyduty transport with a power requirement of 1 MW and an operating voltage near 1 kV. Since one 200 kW stack alone cannot meet these requirements or the needed voltage level, a three-level boost converter is integrated. This converter serves the dual purpose of stepping up the voltage to around 1 kV and managing the power supplied but its connected stack. The management considers variations in stack condition, such as differing rates of degradation based on operational history, which presents an additional challenge discussed later in this work [7].

To satisfy the MW power demand for marine transport, various system topologies were compared [5]. The chosen configuration consists of five units (stack-converter) connected in parallel, as showed in Fig. 2. With five units (n=5), since the total demand is 1 MW

With five units (n=5), since the total demand is 1 MW and each source is providing 200 kW

Assuming ideal switches and modelling the power converters using a continuous and average equivalent approach, the system's equations are given as follows:

$$\frac{dI_{Li}}{dt} = \frac{1}{Li} \left(V_{FCi} \cdot r_{Li} I_{Li} \cdot (a_1 + a_4)_i V_{CI} \cdot (a_1 + a_2)_i V_{C2} \right)$$
(2)

$$\frac{dv_{cl}}{dt} = \frac{1}{Cl} \left(\sum_{i=l}^{n=5} (a_l + a_4)_i I_{L_i} - I_{ch} \right)$$
(3)

$$\frac{dV_{cl}}{dt} = \frac{1}{Cl} \left(\sum_{i=l}^{n=5} (a_l + a_2)_i I_{L_i} - I_{ch} \right)$$
(4)

Let r_{Li} the inductor's resistance (Ω), I_{L_i} the average input current (A), I_{ch} the average load (maritime transport) current (A) and V_{C1} , V_{C1} the average capacitors voltages (V).

The average stack voltages $V_{FCi}\;$ are obtained from equation (1).



Fig. 2. The chosen configuration of the multi-stack system.

By employing a three-level boost converter four modes can be deduced based on the state of its controlled switches $(k_{1,i}, k_{2,i})$ for $i = \{1, ..., n\}$.

Mode 1: $k_{1,i}$ OFF and $k_{2,i}$ OFF, Mode 2: $k_{1,i}$ ON and $k_{2,i}$ OFF, Mode 3: $k_{1,i}$ ON and $k_{2,i}$ ON and Mode 4: $k_{1,i}$ OFF and $k_{2,i}$ ON.



Fig. 3. Example of a sequence.

The average model is then expressed based on the duty cycles (a_1, a_2, a_3, a_4) associated to the average operation of each mode as shown in Fig. 3, with $0 < a_j < 1$ and $\sum_{j=1}^{4} a_j$ (100%). Based on these duty cycles the converter's switches are controlled.

3 Energy management Approach

3.1 The formulation of the energy management approach

Each fuel cell stack may deteriorate differently due to various factors These issues can lead to increased resistance and reduced performance affecting each stack's capabilities [6,13]. To manage this imbalance, an energy management strategy is adopted. It distributes the power based on each stack's state of heath. The aim is to ensure a uniform heat generation, which simplifies the thermal management of the stacks. Following the approach described in [10], the losses in each subsystem are primarily attributed to the internal resistance of the stacks, while other resistive elements are neglected.

The resistance of each stack is modelled to reflect its degradation level.

The first stack is the least degraded and exhibits the lowest resistance. As a stack ages and deteriorates, its resistance tends to rise.

$$R_{FC,i} = (1 + (j-1) tol_R) R_{FC,i}$$
 (5)

With $j = \{1,...,5\}$ and $(j-1) tol_R$ the level of deterioration.

The initial step in formulating the EMS, designed to achieve balanced losses, is to establish the following constraints:

$$P_{loss, i} = \frac{P_{loss, tot}}{n} \tag{6}$$

$$\sum_{i=1}^{h=2} P_i = P_{ch} \tag{7}$$
$$P_i = \alpha_i P_{ch} \tag{8}$$

With n the number of the units, $P_{loss, i}$ the losses occurring each stack, $P_{loss, tot}$ the overall system losses, P_{ch} the power supplied to the load and P_i the power given by each unit.

To allocate the power P_i supplied by each stack a coefficient α_i is introduced. This coefficient indicates the fraction of the total power, assumed equal to P_{ch} , that is contributed by each unit. It translates the effort made by each source according to its state of health. With $\sum_{j=1}^n \alpha_i$, $(0 \leq \alpha_i \leq 1)$.

From Fig. 2, considering the equation (8) and perfect switches, the average equivalent equations are obtained:

$$E_{0,i}-R_{FC,i} I_{L,i} = \frac{(2a_I + a_4 + a_2)_i V_{dc}}{2}$$
(9)
$$\alpha_i I_{ch} = (a_I + a_4)_i I_{L,i} = (a_I + a_2)_i I_{L,i}$$
(10)

With $V_{C1} = V_{C2} = \frac{V_{dc}}{2}$ and V_{dc} the average load voltage. Which means that:

$$(a_{I}+a_{4})_{i} = \frac{2(E_{0,i}-R_{FC,i}I_{L,i})}{V_{dc}}$$
(11)

As a result, the following expression is obtained:

$$\alpha_{i} = \frac{E_{0,i} I_{Li} R_{FC,i} I_{Li}^{2}}{V_{dc} I_{ch}}$$
(12)

Based on this expression, determining each stack's contribution requires calculating the corresponding input currents.

Assuming the simplified expression of the losses and applying the considered constraints, the following equations are obtained:

$$n R_{FC,I} I_{L,I}^{2} = \sum_{i=1}^{n=5} (E_{0,i} I_{L,i}) - V_{dc} I_{ch}$$
(13)

and

$$I_{L,j} = I_{L,I} \sqrt{\frac{R_{FC,I}}{R_{FC,j}}}, \quad with \ j = \{2, ..., n\}$$
(14)

As a result:

$$nR_{FC,I}I_{L,I}^{2} - \left(E_{0,I} + E_{0,2}\sqrt{\frac{R_{FC,I}}{R_{FC,2}}}\right)I_{L,I} + V_{dc}I_{ch} = 0$$
(15)

After calculating one current $(I_{L,1})$, the other current can be easily derived as follows:

$$I_{L,j} = I_{L,I} \sqrt{\frac{R_{FC,I}}{R_{FC,j}}}$$
(16)

Once the calculations are done, the strategy's result (α_i) is implemented in the control system, which then automatically determines the duty cycles. For that, PI controllers are used as in [10]. Consequently, each stack supplies power proportional to its health status. The greater the deterioration, the lower the delivered power.

3.2 Simulation's results

An assessment of the system's behavior is conducted using a naval transport application characterized by a variable power demand reaching up to 1 MW.



Fig. 4. The output power and voltage delivered by the multistack system.

After each variation of the demand a voltage's perturbation is noticed and the voltage is then regulated as expected. These results are encouraging because, despite fluctuations in load demand over time, the output voltage remains within the acceptable tolerance of $\pm 5\%$ around the reference voltage V_{dc}* (1 kV). Once

it is confirmed that the system is well-suited for our case, the outcomes of the energy management strategy are then analysed.



Fig. 5. The results with the given energy management strategy.

From the two figures given above (Fig. 5), it can be seen that the input current through each stack is adjusted according to its capability: stacks with higher internal resistance have lower input currents. As the stack's internal resistance increases, its ability to deliver power to the load decreases. Considering RFC,i < RFC,i+1, it leads to $I_{L,i} \le I_{L,i+1}$, which is confirmed by the results. As a consequence, the EMS (Energy Management Strategy), balancing losses and ensuring that each stack supplies power based on its. Additionally, the α_i (contributions) show little variation with changes in load power. This observation simplifies the study by allowing the uses of average contributions (α_i) . Consequently, fixed percentages can be applied and adjusted if needed, rather than a system that constantly redefines these coefficients.

4 Hydrogen consumption

4.1 Current analysis

In addition to ensuring uniform thermal behaviour, the proposed EMS also contributes to reducing hydrogen consumption. To evaluate this benefit, a comparison is made between three different energy management strategies. The first strategy follows a traditional method, distributing the power equally across all subsystems (fuel cell and its dedicated converter). The second strategy aims to minimize hydrogen consumption by reducing the overall current drawn from fuel cells. The third approach is the strategy proposed in this paper.

To simplify the comparison, the analysis is conducted on a system with two stacks. In this scenario, the second stack is assumed to have twice the internal resistance of the first. Each stack is assigned an open-circuit voltage of 250 V, with a total power demand of 1 MW. The resulting currents in each stack $I_{L,1}$ and $I_{L,2}$ are then calculated analytically for each strategy. The total current, directly linked to hydrogen consumption, serves as the key indicator for comparison.

• The first strategy: Power balance

$$2R_{FC,I}I_{L,I} \stackrel{2}{=} 2E_{0,I}I_{L,I} + V_{dc}I_{ch} = 0$$

$$2R_{FC,2}I_{L,2} \stackrel{2}{=} 2E_{0,2}I_{L,2} + V_{dc}I_{ch} = 0$$
(17)
(17)
(17)
(18)

• The second strategy: $min(I_{L,1} + I_{L,2})$

(

$$R_{FC,I} + R_{FC,I} I_{L,I}^{2} - 2E_{0} I_{L,I} + P_{ch} = 0$$

$$I_{L2} = \frac{R_{FC,I}}{R_{EC,2}} I_{LI}$$
(19)
(19)
(20)

• The third strategy: Loss balance (proposed in this paper)

$$2R_{FC,I}I_{L,I}^{2} - \left(E_{0,I} + E_{0,2}\sqrt{\frac{R_{FC,I}}{R_{FC,2}}}\right)I_{L,I} + V_{dc}I_{ch} = 0$$
(21)
$$I_{L2} = \sqrt{\frac{R_{FC,I}}{R_{FC,2}}}I_{LI}$$
(22)

The obtained results are summarised in Table 2.

Strategy	$\mathrm{I}_{\mathrm{L},1} + \mathrm{I}_{\mathrm{L},2}$
Power balance	6 340.8 A
$\min(\mathbf{I}_{\mathrm{L},1} + \mathbf{I}_{\mathrm{L},2})$	5 071.8 A
Loss balance strategy	5 128 A

Table 1. Current analysis (Hydrogen consumption)

The second approach unsurprisingly achieves the lowest overall current, indicating the most efficient hydrogen consumption. Conversely, the method based on equal power distribution among the stacks performs the worst, with a total current 25% over the optimal value. The loss balancing strategy introduced in this paper offers a notable improvement in hydrogen efficiency, producing results that nearly match the best approach (only 1.1% over the optimal value) (Fig.6).

This method was initially developed to equalize heat generation across fuel cell stacks and simplify thermal regulation, yet it also contributes sustainably to reducing hydrogen consumption. However, this strategy doesn't consider the hydrogen consumption as one of its main parameters to optimize as well as the cost and the durability of the system.



Fig. 6. The current analysis.

4.2 Cost analysis

Building on the previous findings, the next step focuses on evaluating hydrogen consumption in terms of cost and economic impact.

$$\dot{m}_{H2} = \frac{(I.314 \ 10^6) M_{H2} t_{h/d} \ \sum_{i=1}^n I_{L,i}}{2 \ F}$$
(23)

With m_{H2} the rate of hydrogen mass consumption over time (kg/year), M_{H2} the molar mass of hydrogen (kg/mol), F the Faraday's constant (C/mol) and $t_{h/d}$ the number of operating hours of the fuel cell per day (h).

$$C_{H2/year} = C_{\ell/kg} \dot{m_{H2}}$$
⁽²⁴⁾

With $C_{H2/year}$ the cost of the consumed hydrogen by the system per year (ϵ /year), $C_{\epsilon/kg}$ the cost of one kg of hydrogen (ϵ/kg).

To simplify the comparison, the analysis is based on only two stacks and they are assumed to operate continuously ($t_{h/d} = 24h$). Based on [15], $C_{\ell/kg}$ is assumed to be at 5 ℓ/kg . Furthermore, it is considered that the system run under the same conditions as in the previous part.

Table 2.	Cost analysis	s of Hydrogen	consumption
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Strategy	C _{H2/year}
Power balance	363 447 €/year
$\min(\mathbf{I}_{\mathrm{L},1} + \mathbf{I}_{\mathrm{L},2})$	290 749 €/year
Loss balance strategy	293 965 €/year

As expected the differences observed in the cost analysis closely follows those obtained from the current analysis. Still, this cost evaluation adds a valuable perspective, showing how better hydrogen efficiency leads to real financial savings, which is important for industry. The current analysis focuses on energy efficiency, while the cost analysis highlights economic advantages.

Taking the power balance strategy as the baseline with the highest cost, the benefits of the alternative strategies are highlighted. The loss balance strategy saves nearly 69 482 €/year while the best strategy (minimum hydrogen consumption) saves around 72 698 €/year.

Although the loss balancing method was especially developed to balance heat generation among fuel cell stacks, it also helps reduce hydrogen usage without directly optimizing its cost.

For a better result, further studies will be done and the strategy will be compared to other key performances.

5 Conclusion and perspectives

This research investigates the use of hydrogen fuel cells for powering large maritime vessels, tackling two main key concerns: the significant power requirement of the vessel and the varying aging rates of the individual stacks. To achieve the necessary voltage and power, a multi-stack configuration has been implemented. An Energy Management Strategy (EMS) has been designed to equally distribute losses across the stacks. It ensures that each stack contributes power according to its condition while collectively fulfilling the total power requirement.

The primary aim of this EMS is to facilitate thermal management by maintaining a loss balance. Additionally, based on the current and cost analysis done previously, this approach also contributes to enhancing hydrogen consumption. A comparative analysis of this strategy with alternative approaches was presented and other approaches will be integrated in future works.

This study focuses only on hydrogen fuel cells to examine system performance under extreme conditions. Nonetheless, actual applications often rely on a hybrid system where batteries complement fuel cells to boost the overall efficiency [15].

In the current phase, a simplified load profile is used. Future works will incorporate real operational data to evaluate EMS performance under realistic scenarios. Furthermore, experimental validation is planned to validate the theoretical findings.

Hydrogen-powered heavy-duty transport holds a great promise, with many projects currently underway to advance this sustainable technology.

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