

Article

Enhancing Efficiency in Hybrid Marine Vessels through a Multi-Layer Optimization Energy Management System

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Abstract: Configuring green power transmissions for heavy-industry marines is treated as a crucial request in an era of global energy and pollution crises. Following up on this hotspot trend, this paper examines the effectiveness of a modified optimization-based energy management strategy (OpEMS) for a dual proton exchange membrane fuel cells (dPEMFCs)-battery-ultra-capacitors (UCs)-driven hybrid electric vessels (HEVs). At first, the summed power of the dual PEMFCs is defined by using the equivalent consumption minimum strategy (ECMS). Accordingly, a map search engine (MSE) is proposed to appropriately split power for each FC stack and maximize its total efficiency. The remaining power is then distributed to each battery and UC using an adaptive co-state, timely determined based on the state of charge (SOC) of each device. Due to the strict constraint of the energy storage devices' (ESDs) SOC, one fine-corrected layer is suggested to enhance the SOC regulations. With the comparative simulations with a specific rule-based EMS and other approaches for splitting power to each PEMFC unit, the effectiveness of the proposed topology is eventually verified with the highest efficiency, approximately about 0.505, and well-regulated ESDs' SOC are obtained.

Keywords: energy management strategy; optimization; equivalent consumption minimum strategy (ECMS); hybrid electric vessels; multi-stack PEMFC



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1. Introduction

Recently, the marine industry and vessel traffic services have facilitated economic growth, global trading markets, ecosystem stabilization, and so on. They have been recognized internationally as an aid to the safety of life at sea [1] and fueled an efficient movement for the cross-border trade of merchandise on an unprecedented scale. However, the transportation sectors, in general, and vessel services in particular, are facing the challenges of a full-blown global energy crisis and environmental pollution from the heavy use of fossil fuel and oil scarcity [2]. Although an energy storage device was integrated for hybrid vessels [3,4], the mentioned prototypes still employed traditional diesel engines. As a result, identifying an alternative power source for the industry's shift away from fossil fuels is crucial sustainable development.

Proton exchange membrane fuel cells (PEMFCs) have been acknowledged as a preferable alternative to traditional fuels and realistically put into small-scaled and large-scaled installations [5], due to their properties of high efficiency, high power density, low operating temperature, low noise, and zero emission. In terms of the shipping sector, the PEMFCs are viewed as the most promising clean resource and as friendly to the marine ecosystem [6], and their use sees increasing growth [7] on ships that currently make coastal voyages. Nevertheless, the complex operations of naval vessels against the severe fluctuations of propulsion load and environmental impacts pull the standalone PEMFC lifetime down due

to its slow dynamic response. Additionally, the required quick start-up time and regenerating excessive power also represent challenges for the standalone PEMFCs, requiring significant effort.

To overcome these inherent demerits, the hybridization of the PEMFCs with one or more energy storage devices (ESDs) has been switching into an upward trend for the research community in terms of designing feasible hybrid configurations and developing effective energy management strategies (EMSs) for practical realization. Various EMSs with enhancements have been proposed such as [8,9], fuzzy logic-based state machine EMS [10,11], equivalent consumption minimum strategy (ECMS) [11–13], model predictive control [14], and a learning-based algorithm with the balance-of-plant [15] for the hybrid electric ships and vessels powered by an integrated PEMFC battery power source. Extended to a hybrid topology of PEMFC, battery, and ultra-capacitors (UCs), Peng et al. [16] constructed a particle swarm optimization (PSO)-based EMS with a wavelet transform technique to obtain an optimal power reference for each device. Other achievements can be referred to in the literature [17–19]. Moreover, it has been established that a single-stack PEMFC hardly satisfies the heavy marine load request regarding the recently gained technology. It is estimated that the required propulsion power for vessels usually varies from 18 MW to around 30 MW and may be up to higher than 80 MW [20], which exceeds the workability of the latest PEMFCs [21]. Consequently, the single-stack PEMFC has been turned into multi-stack PEMFC for further compatible realization and developments. Yet, appropriately splitting power for each PEMFC stack and retaining high efficiency has been an increasingly active focus in the related fields.

The research on designing EMSs for multi-stack PEMFC hybrid power sources has been ongoing for several hybrid electric transportations. Generally, there are three methodologies for power-sharing on a multi-stack PEMFC: equal distribution (EqD), daisy chain, and instantaneous optimization-based method [22]. The first approach offers simple calculation with equally distributed power for each stack; however, the overall efficiency was recorded as low. The daisy chain method manipulates all stacks in sequential operations. The overall efficiency was improved only at low-power operation compared to the former. At the high-power range, the former outperformed the daisy chain [23]. Based on the demerits of each method, adaptive control was proposed. In [24], the authors developed an adaptive state machine to allocate power for multi-stack PEMFC. In [25], the authors introduced a degree of performance degradation with virtual resistance to assist the power-sharing process. Other techniques of using a fuzzy logic-based state machine and hierarchical EMS approaches for a multi-stack PEMFC battery–UCs power system, realized on hybrid tramways, can be referred to [26,27]. Although the overall efficiency was improved, the mentioned studies could not achieve the optimal power reference and maximize the overall efficiency.

On the contrary, the optimization-based category is able to achieve the optimal solution for power coordination, enhance efficiency, and prolong the durability and lifetime of all PEMFC stacks [28]. This approach can be classified into offline control, well known as global optimization, and real-time control, known as local optimization. As the existing demerits of offline control are burdensome computation, being time-consuming, and it being impossible to instantly change updates in real time [29], real-time control is preferable with various accomplishments recorded. In [30], the authors first built the efficiency map and established an online control to define the optimal power reference for each stack through equivalent dual-power for hybrid locomotives powered by multi-stack PEMFC interconnected with supercapacitors. Subsequently, on the basis of the map-search engine (MSE), an Extremum-seeking-based EMS was exploited to optimize the PEMFC power by seeking out the highest efficiency for each PEMFC primary source [31]. Similarly, in [32], Do et al. developed an ES-based EMS with an enhanced map-search method to split power for dual PEMFCs at which each PEMFC stack could operate in their highest efficiency regions. The effectiveness of these contributions was realized on hybrid electric locomotives and tramways. In the field of marine vessels, the authors in [33] initiated an optimization-based

multi-layer EMS for passenger ships driven by a hybridization of multi-stack PEMFC and battery. Unfortunately, the proposed method followed the daisy chain method, which returns low total efficiency and causes the possibility of increased stack degradation. As observed, the emergence of dual PEMFCs into the optimization-based EMS, with the effective use of the power distribution, has not garnered much attention from scholars and has been limited to hybrid vessels.

Comprehensively motivated by the existing research gaps, this paper aims at conducting a multi-layer optimization-based EMS (MOEMS) for vessels driven by dual-PEMFC (dPEMFC) battery–UCs hybrid power sources. In this manner, the dPEMFC functions as a primary source while the battery and UCs are supplements and all devices are interconnected, in parallel, to a DC bus via DC/DC converters. The MOEMS is established based on the hybrid off–online algorithm to exert the highest efficiency and prolong the dPEMFC lifetime. For this purpose, an ECMS framework is first utilized as an online control in the upper layer to optimize the equivalent power of the dual stacks. Subsequently, an MSE, obtained through offline data acquisition, is integrated into the mediate layer to appropriately share power for each primary unit. An adaptive co-state is introduced to distribute the remaining load to supplements, whose dynamics are derived based on the instant battery and UCs' state of charge (SOC). The determined reference power is then designated to a lower layer for the pulse-width modulation (PWM). The effectiveness of the proposed control scheme is validated via numerical simulations on a specific vessel model with another rule-based benchmark.

The remainder of this paper is organized as follows: Section 2 describes the modeling of the system, including DC/DC converters dynamics. Then, Section 3 dedicates the proposed EMS for appropriate power allocation. The feasibility of the proposed method is certified by comparative simulation in Section 4. Finally, Section 5 summarizes key points and suggestions for further development.

2. System Configuration and Modeling

2.1. Overview of the Hybrid Vessel Power System

The proposed hybrid vessel power system integrates multiple energy sources to meet the varied power demands of maritime operations while prioritizing efficiency and environmental sustainability. The configuration of the dual FC/BAT/UC vessel is depicted in Figure 1, with the Alsterwasser passenger vessel, the world's first hydrogen fuel cell passenger vessel involved in the examined objective, whose dynamics and characteristics are detailed in [34], for the proposed EMS implementation. The core of this system are two PEMFC stacks, which serve as the primary power source while a battery pack and a UC bank are complemented to provide auxiliary power and energy storage capabilities.

The dual PEMFC configuration allows for greater power output and operational flexibility compared to single-stack systems. Each PEMFC stack is connected to the DC bus through a unidirectional DC/DC converter, which steps up the fuel cell output voltage to match the bus voltage. This arrangement enables efficient power delivery from the fuel cells to the vessel's electrical systems.

The battery pack and UC bank are both integrated into the system via bidirectional DC/DC converters. This configuration allows these components to either supply power to the DC bus or absorb excess energy for storage, depending on the vessel's instantaneous power requirements and the state of the overall system. The DC bus serves as the central power distribution point, connecting to an inverter that converts the DC power to AC for use by the vessel's electric propulsion motor and other onboard systems. This architecture provides a flexible platform for implementing sophisticated energy management strategies to optimize power flow and system efficiency.

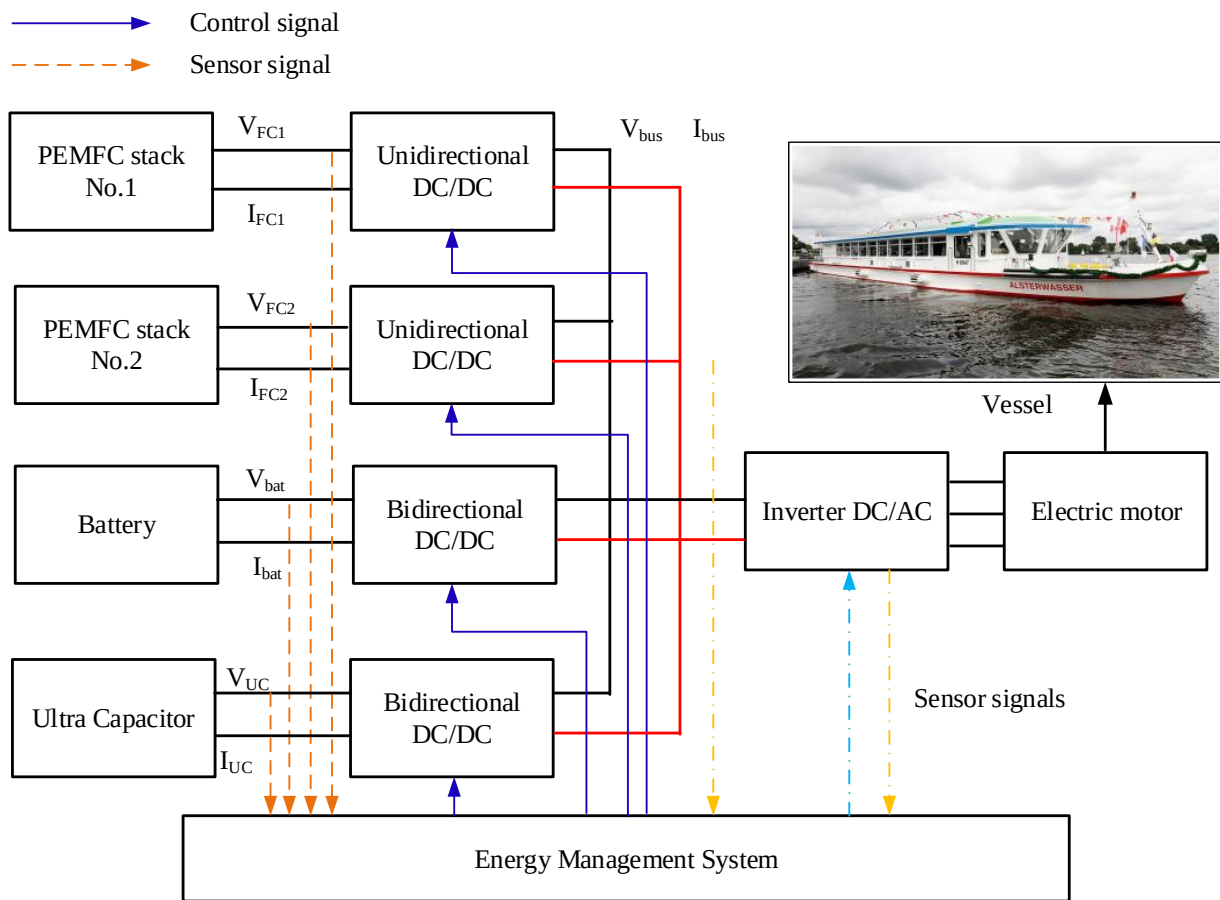


Figure 1. Configuration of dual PEMFC/battery/UCs hybrid vessels.

An energy management strategy is then designed and validated based on this model to meet the power needs of the hybrid vessel, as shown in Figure 2.

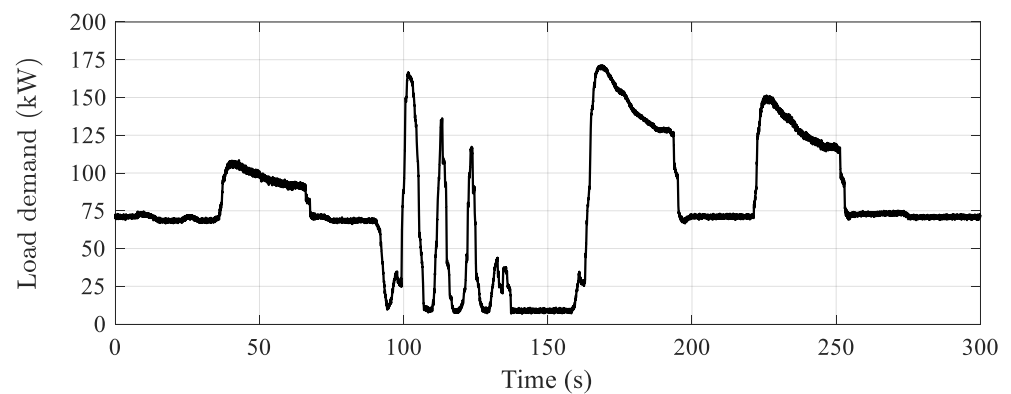


Figure 2. Part of the power requirement of hybrid electric vessels.

2.2. Component Modeling

To effectively analyze and optimize the hybrid vessel power system, it is crucial to have accurate mathematical representations of each component. This section outlines the models used for the key elements of the system: fuel cells, batteries, UCs, and DC/DC converters.

2.2.1. Fuel Cell Model

The fuel cell model captures the complex electrochemical processes occurring within the PEMFC. A simplified electrical equivalent circuit represents the fuel cell, as illustrated

in Figure 3. The output voltage of the fuel cell is determined by several factors and can be inheritably expressed based upon [35–38] as

$$V_{cell} = E_{Nernst} - V_{act} - V_{ohm} - V_{conc} \quad (1)$$

In this equation, E_{Nernst} represents the thermodynamic potential, while V_{act} , V_{ohm} , and V_{conc} account for activation, ohmic, and concentration voltage losses, respectively.

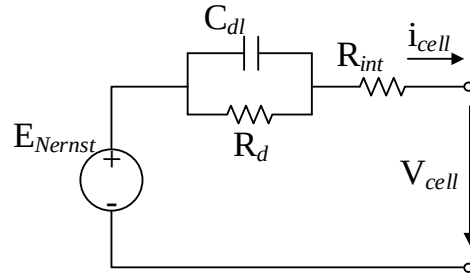


Figure 3. A simplified model of the FC.

Each of these terms is further defined by equations that incorporate factors such as temperature, pressure, and current density. The model also includes dynamics related to the double-layer capacitance effect and reactant flow rates.

The Nernst equation provides the reversible thermodynamic potential:

$$E_{Nernst} = 1.229 - 8.5 \times 10^{-4}(T_{FC} - 298.15) + \frac{RT_{FC}}{2F} \ln \left[p'_{H_2} (p'_{O_2})^{0.5} \right] \quad (2)$$

where p'_{H_2} and p'_{O_2} are partial pressures of hydrogen and oxygen, T_{FC} is the cell temperature, R is the universal gas constant, and F is the Faraday constant.

Ohmic voltage loss is estimated by

$$V_{ohm} = iR_{ohm} \quad (3)$$

where i is the cell current and R_{ohm} is the internal resistance of the electrolyte membrane.

Activation voltage loss is characterized as

$$V_{act} = \zeta_1 + \zeta_2 T_{FC} + \zeta_3 T_{FC} \ln(c'_{O_2}) + \zeta_4 T_{FC} \ln(i) \quad (4)$$

where c'_{O_2} is oxygen concentration at the cathode/membrane interface, and $\zeta_1, \zeta_2, \zeta_3, \zeta_4$ are parametric coefficients.

Concentration voltage loss is approximated by

$$V_{conc} = \frac{RT_{FC}}{nF} \ln \left(\frac{(i/A)_L}{(i/A)_L - (i/A)} \right) \quad (5)$$

The voltage drop, V_{drop} , due to the double capacitor layers' effect, is calculated as [37,38]

$$C \frac{dV_{drop}}{dt} = i - \frac{V_{drop}}{R_a} \quad (6)$$

where R_a is the sum of activation and concentration resistances.

$$R_a = \frac{V_{act} + V_{conc}}{i} \quad (7)$$

Then, the voltage output of a single cell can be calculated by

$$V_{cell} = E_{Nernst} - V_{drop} - V_{ohm} \quad (8)$$

The total voltage output for a stack of N cells is given by

$$V_{stack} = NV_{cell} \quad (9)$$

The dynamics of reactant flow within the fuel cell are crucial for accurate modeling. For the anode, one has

$$V_a \frac{dp'_{H_2}}{dt} = (\dot{m}_{H_2,in} - \dot{m}_{H_2,out} - \frac{Ni}{2F})RT_{FC} \quad (10)$$

where V_a is the anode volume, $\dot{m}_{H_2,in}$ and $\dot{m}_{H_2,out}$ are hydrogen inlet and outlet flow rates through the PEMFC stack, and $F = 96,485$ (C mol⁻¹) is the Faraday constant.

The hydrogen outlet flow rate is given by

$$\dot{m}_{H_2,out} = k_a (p'_{H_2} - p_{amb}) \quad (11)$$

where k_a is a flow constant for the anode and P_{amb} is the ambient pressure.

Similarly, for the cathode:

$$V_c \frac{dp'_{O_2}}{dt} = (\dot{m}_{O_2,in} - \dot{m}_{O_2,out} - \frac{Ni}{4F})RT_{FC} \quad (12)$$

where V_c is the cathode volume, while $\dot{m}_{O_2,in}$ and $\dot{m}_{O_2,out}$ are oxygen inlet and outlet flow rates through the FC stack.

$$\dot{m}_{O_2,out} = k_c (p'_{O_2} - p_{amb}) \quad (13)$$

The total power input to the system is proportional to the hydrogen consumed:

$$P_{tot} = \dot{m}_{H_2,used} \Delta H = \frac{Ni}{2F} \Delta H \quad (14)$$

where ΔH is the enthalpy of combustion for hydrogen.

For the dual fuel cell system, the individual and total power output are

$$P_{FC,i} = V_{stack,i} i_i \quad (15)$$

$$P_{dFC} = P_{FC,1} + P_{FC,2} \quad (16)$$

where P_{FC1} and P_{FC2} are the output power of PEMFC-1 and PEMFC-2.

The average efficiency of the dPEMFC system is calculated as (only when at least one PEMFC runs)

$$\eta_{FC_total} = \frac{\frac{P_{FC,1}}{\eta_{FC1}} + \frac{P_{FC,2}}{\eta_{FC2}}}{\frac{P_{FC,1}}{\eta_{FC1}} + \frac{P_{FC,2}}{\eta_{FC2}}} \quad (17)$$

where η_{FC1} and η_{FC2} are the efficiencies of PEMFC-1 and PEMFC-2, respectively (obtained from calculating the ratio between the output net power and total power that includes power for auxiliaries such as pump, fan, compressor, and so on, i.e., $\eta_{FCi} = \frac{P_{FC,i}}{P_{tot,i}}$).

The hydrogen consumption rate can be derived from the power output and efficiency of each fuel cell [39]:

$$\dot{m}_{H_2_total} = \frac{P_{FC,1}}{\eta_{FC1} LHV} + \frac{P_{FC,2}}{\eta_{FC2} LHV} \quad (18)$$

where LHV is the lower heating value of hydrogen.

The efficiency map of each PEMFC system is displayed in Figure 4.

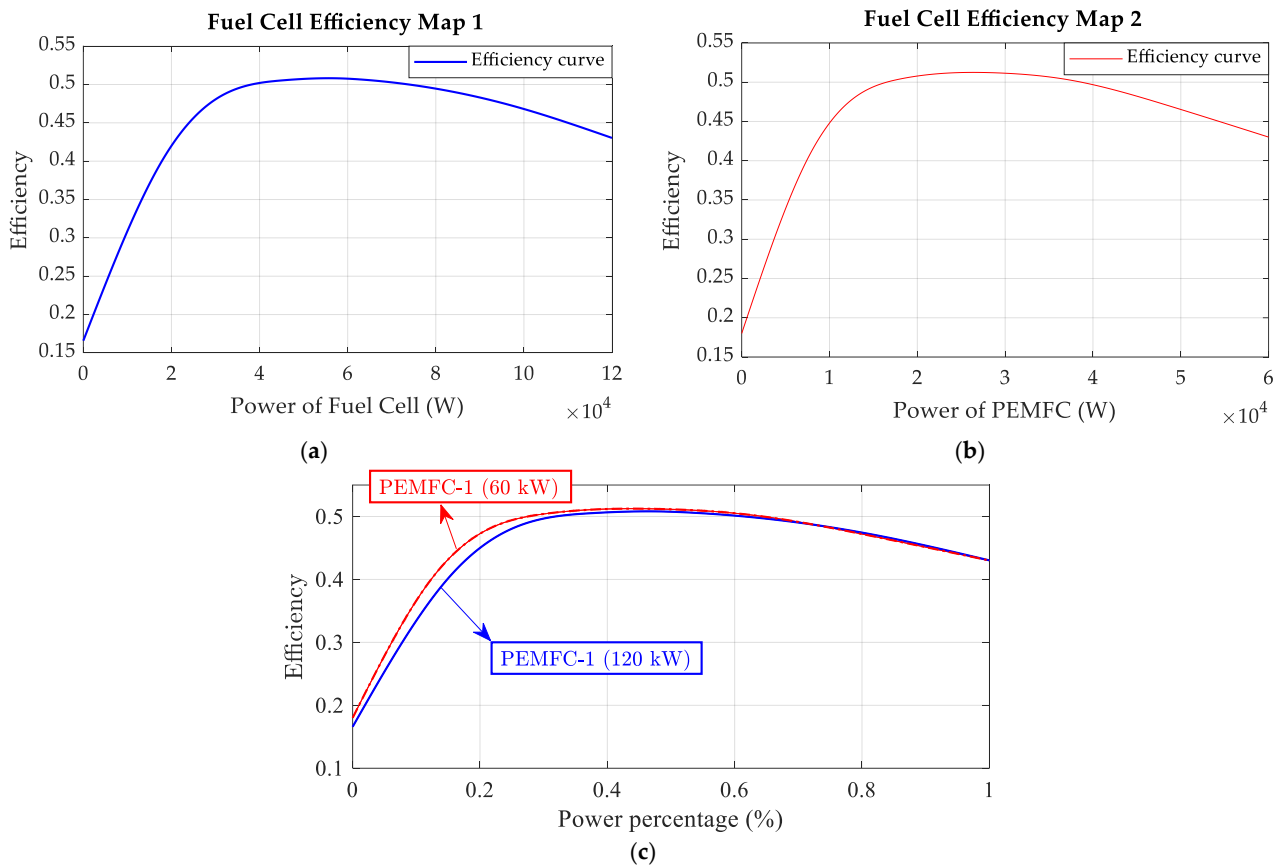


Figure 4. Efficiency maps of FC systems: (a) PEMFC-1 (120 kW), (b) PEMFC-2 (60 kW), (c) comparison of their efficiency maps.

2.2.2. Battery Model

In hybrid power systems, the battery serves as a critical energy buffer, complementing the fuel cell during periods of high power demand or when rapid load changes occur. To effectively design an energy management system (EMS), it is essential to develop an accurate battery model that captures key parameters and operational states. This model provides the foundation for implementing efficient control strategies.

The battery can be represented as a controlled voltage source, with its behavior described by several key equations [40]:

$$E = E_0 - K \frac{Q_{\max}}{Q} + Ae^{B(Q-Q_{\max})} \quad (19)$$

where Q and $Q_{\max}$ represent, in turn, instant and maximum battery capacity, E_0 is the free-load open-circuit voltage, A is a constant, B is a constant of battery exponential capacity, and K signifies the polarized factor.

The battery voltage (V_{bat}) is then obtained as a function of its open-circuit voltage, internal resistance, and current flow:

$$V_{bat} = E - Ri \quad (20)$$

with R (Ω) being the battery internal resistor and i (Amp) is the instant current flow.

To relate the battery voltage to its state of charge (SOC_{bat}), we can rewrite the equation as [41]

$$E = E_0 - K \frac{1}{SOC_{bat}} + Ae^{BQ_{\max}(SOC_{bat}-1)} \quad (21)$$

The energy released from the battery during discharge can be calculated using:

$$E_{release} = E_0 - K \frac{1}{SOC_{bat}} \times it - Ri + Ae^{BQ_{max}(SOC_{bat}-1)} - K \frac{1}{SOC_{bat}} \times i^* \quad (22)$$

where i^* denotes the low-frequency filtered current, and t is the time parameter.

The battery's output power is determined by

$$P_{bat} = V_{bat}i \quad (23)$$

Then, the state of charge SOC_{bat} is a crucial parameter that indicates the battery's remaining capacity. It can be derived from the charging current and the battery's maximum charge:

$$SOC_{bat} = \frac{Q_{max} - it}{Q_{max}} \quad (24)$$

To account for battery degradation over time, a capacity loss model is employed:

$$Q_{loss}(\sigma, Ah) = \sigma(I_c, \theta, SOC_{bat})Ah^z \quad (25)$$

where Ah is the accumulated charge throughput, z is the power law exponent representing Ah throughput dependence, σ is a nonlinear function of severity factors, I_c is the charging current, θ is the test temperature, and σ can be expressed as

$$\sigma = (A_{bat}SOC_{bat} + B_{bat}) \exp\left(\frac{-E_a + \eta I_c}{R_g(273.15 + \theta)}\right) \quad (26)$$

where A_{bat} , B_{bat} , and η are constants determined through curve fitting, $\eta = -63.54$, $A_{bat} = -74.99$, $B_{bat} = 12895.92$, R_g is the universal gas constant and equals 8.314 J/mol/K, and E_a is the activation energy that equals 31,700 J/mol [42].

The accumulated charge throughput (Ah), which represents the battery capacity loss, is calculated as

$$Ah = \int_0^t \sigma |I_c(t)| dt \quad (27)$$

Finally, the State of Health (SOH) of the battery can be determined using

$$SOH(t) = \frac{Q_{nom} - Q_{loss}(t)}{Q_{nom}} \quad (28)$$

where Q_{nom} is the nominal capacity of the battery.

2.2.3. Ultra-Capacitor Model

Ultra-capacitors (UCs) are incorporated into the system as secondary power units due to their exceptional characteristics, including high power density, rapid charge and discharge capabilities, and impressive power release. The integration of UCs alleviates the burden on fuel cells and batteries during high peak power demands, thereby enhancing overall system performance, extending component lifespans, and potentially reducing system size and costs [43]. The UC model employed in this study is based on an equivalent circuit approach [44]. Each UC unit cell consists of two parallel RC branches, as illustrated in Figure 5 [45,46]. This configuration effectively captures the device's electrical behavior under various operating conditions.

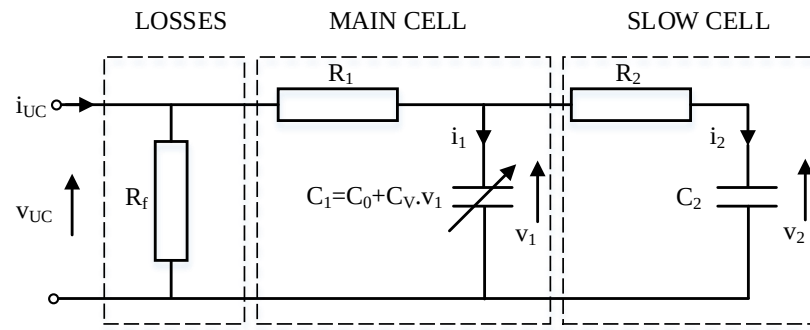


Figure 5. A simplified model of one UC.

The immediate branch, represented by R_1C_1 , accounts for the rapid response during short-duration charge or discharge events. The delayed branch, denoted by R_2C_2 , models the charge redistribution phenomenon that occurs after the initial charge/discharge process. A leakage resistor R_f is included to represent self-discharge behavior, although its impact is often negligible due to the typically low leakage current in high-capacity UCs.

The energy stored in a UCs bank at voltage U_{uc} is given by

$$E_{uc} = \frac{1}{2} C_{eq} U_{uc}^2 = \frac{1}{2} \frac{N_{p_uc}}{N_{s_uc}} C_{uc} U_{uc}^2 \quad (29)$$

where C_{eq} is an equivalent capacity of the UCs, N_{p_uc} and N_{s_uc} represent the parallel branches and the serial connection of the UCs, respectively, and C_{uc} is the capacitance of a single UC unit.

The voltage across the UC bank can be determined by considering the characteristics of a single UC pack:

$$U_{uc} = N_{s_uc} \left(v_1 + R_1 \frac{I_{uc}}{N_{p_uc}} \right) \quad (30)$$

where U_{uc} and I_{uc} are the voltage and current of the UC bank, while v_{uc} and i_{uc} represent the voltage and current of an individual UC unit.

The voltage across the secondary capacitor C_2 is described by a non-linear function of its capacitance and resistance R_2 :

$$v_2 = \frac{1}{C_2} \int \frac{1}{R_2} (v_1 - v_2) dt \quad (31)$$

The rate of change in the instantaneous charge of C_2 is proportional to the current i_2 :

$$\frac{d}{dt} Q_2 = i_2(t) \quad (32)$$

The current through the main capacitor C_1 can be expressed as a function of its charge Q_1 :

$$i_1 = \frac{dQ_1}{dt} = C_1 \frac{dv_1}{dt} = (C_0 + C_v v_1) \frac{dv_1}{dt} \quad (33)$$

where the charge Q_1 is calculated using the equivalent capacitance C_1 and the voltage across it:

$$Q_1 = C_0 v_1 + \frac{1}{2} C_v v_1^2 \quad (34)$$

From this, we can derive the voltage v_1 across C_1 :

$$v_1 = \frac{-C_0 + \sqrt{C_0^2 + 2C_v Q_1}}{C_v} \quad (35)$$

A critical parameter for UC operation is its state of charge (SOC_{UC}), which is defined as the ratio of its current capacity to its maximum capacity:

$$SOC_{UC} = \frac{1}{Q_{UCmax}} \int_{t_0}^t I_{UC}(\tau) d\tau \quad (36)$$

where I_{UC} is the charging current and Q_{UCmax} is the maximum capacity of the UC.

This SOC_{UC} value serves as a crucial indicator for evaluating the state of the UC bank and plays a significant role in energy management strategies.

2.2.4. DC/DC Converter Model

In the hybrid power system under consideration, DC/DC converters play a crucial role in managing power flow between various components. Specifically, two DC/DC boost converters are employed to interface the PEM fuel cell system with the high-voltage DC bus, facilitating the necessary voltage step-up. Additionally, a bidirectional DC/DC converter is positioned between the battery and the DC bus, enabling both power distribution and regenerative energy capture [37,40]. When modeling these converters for energy management purposes, it is important to consider the different time scales at which various system components operate. The power management layer typically functions at a lower frequency compared to the local control loops of individual converters. This separation of time scales allows us to make certain simplifying assumptions in our model. Given that the switching frequency and modulation rate of modern DC/DC converters are significantly higher than the time constants of other system components (such as the inductor), we can employ an averaged model approach. This method effectively captures the converter's behavior from the perspective of the energy management system without the need to model high-frequency switching dynamics. Furthermore, assuming well-designed inner control loops, we can expect the converter to respond rapidly to reference changes. This allows us to further simplify our model by reducing the fast dynamics of the DC/DC converter to an equivalent static model.

The resulting simplified model for the DC/DC converters can be expressed using the following set of equations [47]:

$$V_I = V_h + L \frac{di_L}{dt} + i_L R_L \quad (37)$$

$$V_O = \frac{V_h}{\kappa} \quad (38)$$

$$\eta^\beta = \frac{i_O}{\kappa i_L}, \quad \begin{cases} \beta = 1, & \text{for boost converter} \\ & \text{or for bidirectional converter with } i_O V_O \geq 0 \\ \beta = -1, & \text{for bidirectional converter with } i_O V_O < 0 \end{cases} \quad (39)$$

where V_I and V_O represent the input and output voltages of the converter, respectively. L and R_L are the inductance and resistor of the inductor, κ denotes the conversion ratio of the converter, i_L and i_O are the input (inductor) current and output current, respectively, and η represents the converter's efficiency.

This model, while simplified, captures the essential behavior of the DC/DC converters from an energy management perspective. It accounts for the voltage conversion ratio, current transformation, and power transfer efficiency, which are the key parameters of interest for system-level energy management strategies. By using this static equivalent model, we can effectively represent the DC/DC converters in the overall system simulation without the computational burden of modeling high-frequency switching dynamics. This approach strikes a balance between model fidelity and computational efficiency, making it well-suited for energy management system design and optimization.

It is worth noting that, while this model is adequate for many energy management studies, more detailed models may be necessary for analyzing specific phenomena such as

transient responses, or for designing the converters' internal control loops. However, for the purposes of system-level energy management, this simplified model provides a solid foundation for strategy development and evaluation.

3. Enhanced Equivalence Consumption Minimum Strategy

In this section, the multi-layer EMS for vessels driven by the hybrid dPEMFC battery–UCs is dedicatedly discussed. The comprehensive control architecture is illustrated in Figure 6.

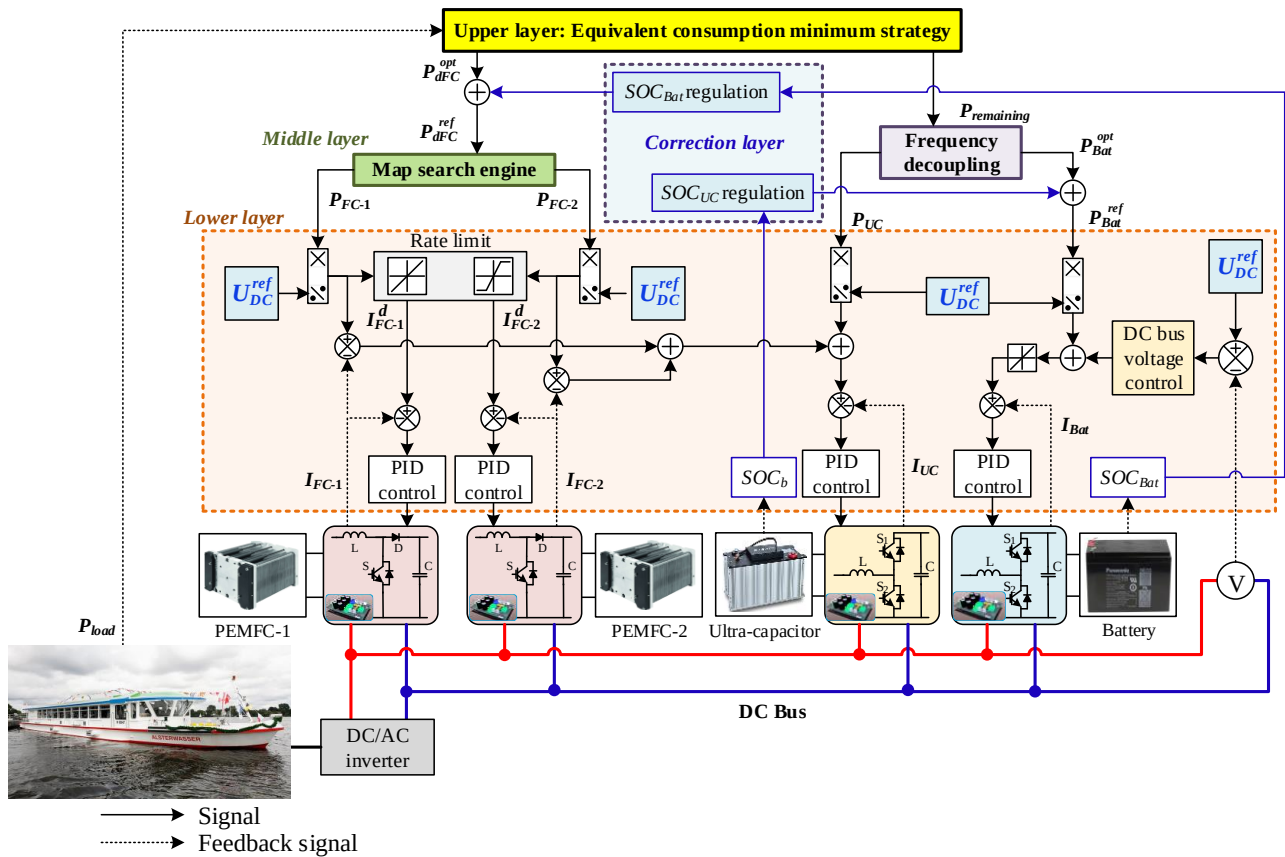


Figure 6. Comprehensive multi-layer EMS for vessels.

3.1. Upper Layer: ECMS-Based EMS for Optimal Power Observation

3.1.1. Optimal Power for Dual PEMFCs

In this manner, the ECMS is employed for seeking out the optimal working point of the dPEMFC (optimal power) while concerning the supplements SOC_s. This methodology has been broadly applied and verified on various systems. In this manner, the total consumption is first calculated by converting the electric consumption of the battery and UCs into equivalent hydrogen consumption. Thus, the objective function can be defined as

$$\min(m_{H_2} + K_{Bat}\gamma_{Bat}P_{Bat}), \quad (40)$$

subject to

$$\begin{cases} p_{FC,1}^{\min} \leq P_{FC,1} \leq p_{FC,1}^{\max} \\ p_{FC,2}^{\min} \leq P_{FC,2} \leq p_{FC,2}^{\max} \\ SOC_{Bat}^{\min} \leq SOC_{Bat} \leq SOC_{Bat}^{\max} \end{cases}, \quad (41)$$

where m_{Bat} denotes the battery equivalent consumption, γ_{Bat} is the battery state-dependent coefficient, and K_{Bat} represents the penalty coefficient of battery. Regarding [48], the

penalty coefficients K_{Bat} should be constrained between the initial $SOC_{Bat}(t_0)$ and current $SOC_{Bat}(t)$. The coefficient γ_{Bat} is performed as

$$\gamma_{Bat} = 1 - \sigma \frac{2SOC_{Bat} - (SOC_{Bat}^{\max} + SOC_{Bat}^{\min})}{(SOC_{Bat}^{\max} + SOC_{Bat}^{\min})}, \quad (42)$$

where σ , conventionally designed by 0.6 [29], denotes an adjustable balance coefficient.

The battery's equivalent consumption can be defined as [48]

$$m_{Bat} = \beta_{Bat} P_{Bat} \frac{\bar{m}_{dFC}}{\bar{P}_{dFC}} \text{ (kg)}, \quad (43)$$

where $\bar{m}_{dFC}$ (kg) is the average hydrogen consumption, $\bar{P}_{dFC}$ (kW) is the average power of the dPEMFC, and β_{Bat} is the battery equivalent conversion coefficient, which is expressed by [29]

$$\beta_{Bat} = \begin{cases} \frac{1}{\bar{\eta}_{chg}\bar{\eta}_{dischg}} P_{Bat} \geq 0 \\ \eta_{chg}\bar{\eta}_{dischg} P_{Bat} < 0 \end{cases}, \quad (44)$$

with η_{chg} and $\bar{\eta}_{chg}$ being, in turn, the charged and its average coefficients; η_{chg} and $\bar{\eta}_{chg}$ being, in turn, the discharged and its average coefficients of the battery, whose dynamics are specified by [29]

$$\eta_{chg/dischg} = \begin{cases} 0.5 \left(1 + \sqrt{1 - \frac{4R_{chg}P_{aux}}{V_{OC}^2}} \right) & P_{aux} \geq 0 \\ 2 / \left(1 + \sqrt{1 - \frac{4R_{dischg}P_{aux}}{V_{OC}^2}} \right) & P_{aux} < 0 \end{cases}, \quad (45)$$

where R_{chg} and R_{dischg} are, in turn, internal charged and discharged resistors (Ω), V_{OC} is an open circuit voltage (V), and P_{aux} is the auxiliary power (kW).

The optimal solution for the battery can be computed by the following [49]:

$$P_{Bat}^{opt} = \begin{cases} U_{DC,min} \frac{(E_{Bat} - U_{DC,min})}{R_{dischg}}, K_1 \leq \alpha\chi_{min} \\ E_{Bat}^2 \frac{(1 - K_1/\alpha)}{4R_{dischg}}, \alpha\chi_{min} \leq K_1 \leq \alpha \\ 0, \alpha \leq K_1 \leq \frac{\alpha}{\bar{\eta}_{chg}\bar{\eta}_{dischg}} \\ E_{Bat}^2 \frac{\{1 - (K_1\bar{\eta}_{chg}\bar{\eta}_{dischg}/\alpha)^2\}}{4R_{dischg}}, \frac{\alpha}{\bar{\eta}_{chg}\bar{\eta}_{dischg}} \leq K_1 \leq \frac{\alpha\chi_{max}}{\bar{\eta}_{chg}\bar{\eta}_{dischg}} \\ -U_{DC,max} \frac{(U_{DC,max} - E_{Bat})}{R_{chg}}, K_1 \geq \frac{\alpha\chi_{max}}{\bar{\eta}_{chg}\bar{\eta}_{dischg}} \end{cases}, \quad (46)$$

where K_1 is determined based on the battery charged and discharged status as follows:

- Discharged ($P_{Bat} \geq 0$):

$$\begin{cases} K_1 = \gamma_{Bat} \bar{m}_{H_2} \frac{1}{\bar{\eta}_{chg} \bar{P}_{dFC}} \\ \chi_{min} = \sqrt{1 + \frac{4U_{DC,min}}{E_{Bat}^2} (U_{DC,min} - E_{Bat})} \end{cases}, \quad (47)$$

- Charged ($P_{Bat} < 0$):

$$\begin{cases} K_1 = \gamma_{Bat} \bar{m}_{H_2} \frac{\bar{\eta}_{dischg}}{P_{dFC}} \\ \chi_{min} = \sqrt{1 + \frac{4U_{DC,max}}{E_{Bat}^2} (U_{DC,max} - E_{Bat})} \end{cases} \quad (48)$$

Subsequently, the dPEMFC optimal power can be obtained by

$$P_{dFC}^{opt} = \max \left\{ \min \left(P_{load} + P_{aux} - P_{Bat}^{opt}, P_{dFC}^{max} \right), P_{dFC}^{min} \right\}, \quad (49)$$

It is worth noting that, following the optimal control above, the battery power is optimized in such a way that the dPEMFC operates in the highest-efficiency region and the battery SOC, SOC_{Bat} , is strictly constrained within the pre-set interval, constrained by $SOC_{Bat}^{min} \leq SOC_{Bat} \leq SOC_{Bat}^{max}$. As a result, the optimal solution P_{Bat}^{opt} varies with positive and negative values to stabilize the SOC_{Bat} and P_{dFC}^{opt} .

3.1.2. Reference Power for Battery and UCs

Despite the optimal power for dPEMFC and battery defined regarding the above calculations, the battery may not fulfill the abrupt or sudden load change as its slow dynamic. Hence, to tackle this problem, the computed P_{Bat}^{opt} is considered the pre-optimal power, or the remaining load, $P_{remaining}$, in other words. Hence, a frequency decoupling mechanism is applied to decouple high frequency and low frequency. Thereby, the filtered remaining load is handled by the battery while the high-frequency load is tackled by the UCs. The frequency decoupling mechanism is initiated as shown in Figure 7:

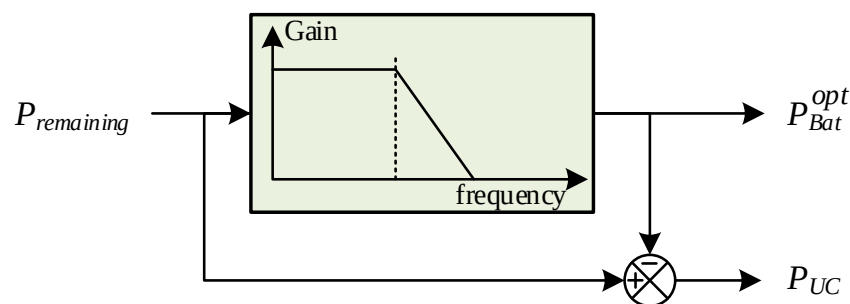


Figure 7. Frequency decoupling mechanism.

The UCs aim at not only addressing the high-frequency load but also compensating for the deviation between the computed optimal power references and their rated limits for safety operation. These errors are summed into the input reference of the UC and tackled in the lower layer.

3.2. Correction Reference Power for SOC Regulation

Despite the optimal power for each source defined, the SOC of the ESDs may not be strictly constrained within the desired intervals. Hence, instead of directly designating these optimal parameters to the middle and lower layers, the optimal reference power of the dPEMFC and battery are fine-corrected to regulate the SOC in such a way that the final SOC at the end of a driving cycle should be equal to the initial ones, as displayed in the “Corrected layer” in Figure 1.

The structures of the fine-corrected power are illustrated in Figure 8. In this manner, the fine-corrected power of the optimal dPEMFC and battery power, namely P_{dFC}^{ref} and P_{Bat}^{ref} , are computed as follows:

$$P_{dFC}^{ref} = P_{dFC}^{opt} + \gamma_1^b \Delta_1(t) + \gamma_2^b \int_0^t \Delta_1(\tau) d(\tau) + \gamma_3^b \frac{d\Delta_1(t)}{dt}, \quad (50)$$

$$P_{Bat}^{ref} = P_{Bat}^{opt} + \gamma_1^{uc} \Delta_2(t) + \gamma_2^{uc} \int_0^t \Delta_2(\tau) d(\tau) + \gamma_3^{uc} \frac{d\Delta_2(t)}{dt} \quad (51)$$

where $\Delta_1(t) \triangleq SOC_{Bat}^{ref} - SOC_{Bat}(t)$ with SOC_{Bat}^{ref} and $SOC_{Bat}(t)$ being the reference and currently time-varying battery's SOC; γ_1^b , γ_2^b , and γ_3^b are positive constants for the battery's SOC regulation. $\Delta_2(t) \triangleq SOC_{UC}^{ref} - SOC_{UC}(t)$ with SOC_{UC}^{ref} and $SOC_{UC}(t)$ being the reference and currently time-varying battery's UC; γ_1^{uc} , γ_2^{uc} , and γ_3^{uc} are positive constants for the battery's SOC regulation.

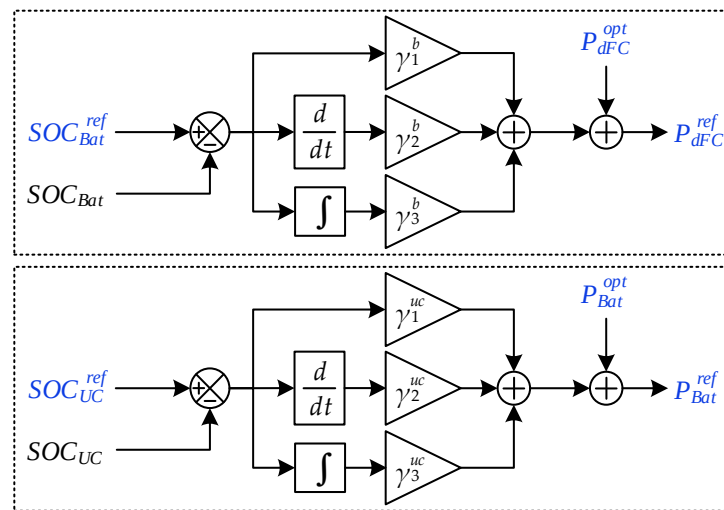


Figure 8. Correction of the power reference for each source.

3.3. Middle Layer: Map Search Engine

To meet the calculated power requirements for the dual fuel cell system, it is essential to implement an efficient energy allocation strategy. The MSM is used to enhance the performance of the dual PEMFC system and reduce hydrogen consumption. As presented in Equation (16), there are numerous power distribution combinations between the two fuel cells that still meet the required power of the dual FC system. Enhancing the efficiency of each FC not only improves the overall efficiency of the dual FC system but also reduces energy consumption (as shown in Equations (17) and (18)). In this study, the output power of the dual FC system ranges from 0 to 150 kW, divided between two FCs of different capacities: 60 kW and 110 kW. For each power requirement, the MSM seeks the optimal distribution between FC 1 and FC 2, ensuring that the combined output meets the required power while achieving maximum efficiency.

Consequently, power allocation curves for PEMFC-1 and PEMFC-2 are established based on the power demand, and the average efficiency of the dual FC system is determined (Figures 9 and 10).

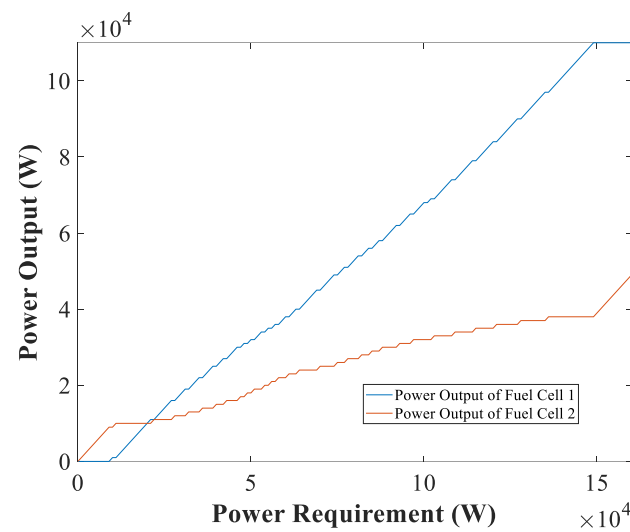


Figure 9. Power output distribution for each PEMFC illustration using the MSM method.

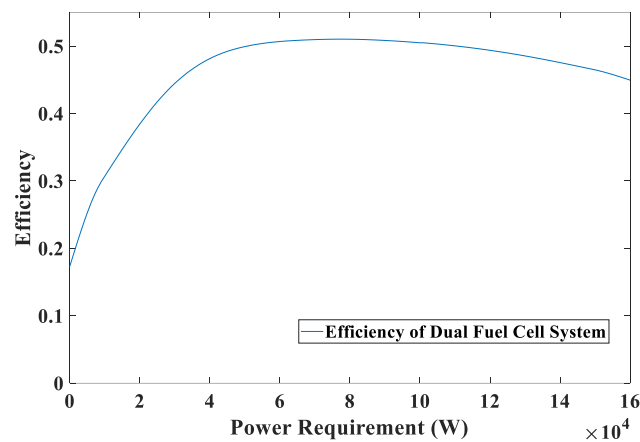


Figure 10. The average efficiency of the dual FC system.

3.4. Lower Layer: Pulse-Width Modulation

In this layer, the input duty cycles to DC/DC converters are generated through pulse-width modulation (PWM) generation to regulate the output power of each source to meet the determined reference one. Moreover, the voltage of the DC bus should be regulated to guarantee the control performance. In accordance with each device's characteristics, the battery is designated to maintain the DC bus voltage. In this scenario, the proportional–integral–derivative (PID) controls are employed due to their simplicity and robustness.

3.4.1. Duty Cycle for the Individual PEMFC

$D_{FC,i}$ is defined as the duty cycle input to the boost DC/DC converter of the i -th PEMFC. Thus, $D_{FC,i}$ is specified as

$$D_{FC,i} = f_{a-PWM}(Out_{FC,i}), \quad (52)$$

Herein, $Out_{FC,i}$ is the output of the PID control for the PEMFC current regulation as

$$PWM_{FC,i} = K_{FC,i}^P \left(I_{FC,i}^d - I_{FC,i} \right) + K_{FC,i}^I \int_0^t \left(I_{FC,i}^d(\tau) - I_{FC,i}(\tau) \right) d\tau + K_{FC,i}^D \frac{d \left(I_{FC,i}^d - I_{FC,i} \right)}{dt}, \quad (53)$$

where $K_{FC,i}^P$, $K_{FC,i}^I$, and $K_{FC,i}^D$ are positive constants; $I_{FC,i}$ is the measured current of the i -th PEMFC; and $I_{FC,i}^d$ is the desired current, which is obtained by

$$I_{FC,i}^d = \text{rate-limit}\left(I_{FC,i}^{ref}\right), \quad (54)$$

with $I_{FC,i}^{ref}$ being directly obtained from the individual i -th PEMFC reference power (fine-corrected optimal power) and reference DC bus voltage U_{DC}^{ref} .

Moreover, due to the use of the rate limit operator, there exists a deviation between the optimal current $I_{FC,i}^{opt}$ and desired current $I_{FC,i}^d$ as $\varepsilon_{FC,i} = I_{FC,i}^{opt} - I_{FC,i}^d$, which will be then addressed by the UC later. The control structure for the $D_{FC,i}$ is illustrated in Figure 11.

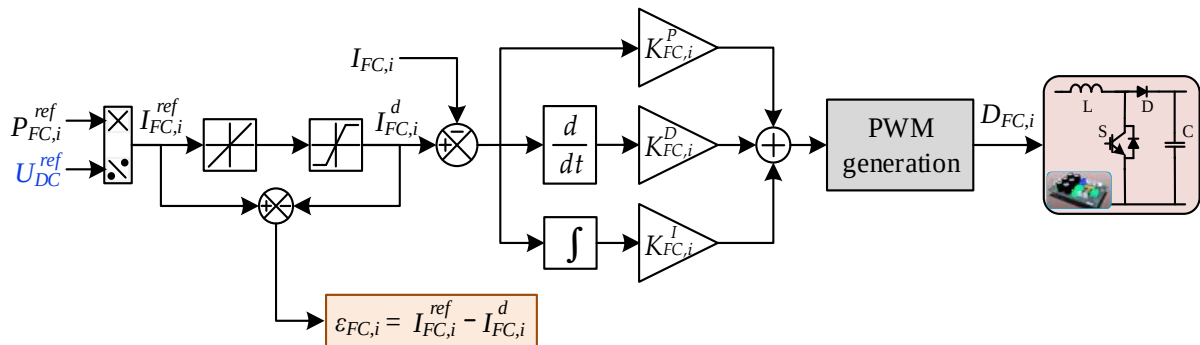


Figure 11. PWM generation for individual PEMFC.

3.4.2. PWM for the Battery and DC Bus Voltage Regulation

Define D_{Bat} is the duty cycle input to the bi-directional DC/DC converter of the battery. Thus, D_{Bat} is specified through an analog-PWM operator as

$$D_{Bat} = f_{a-PWM}(Out_{Bat}), \quad (55)$$

Out_{Bat} is the output of the PID control for the battery current regulation as

$$Out_{Bat} = K_{Bat}^P (I_{Bat}^d - I_{Bat}) + K_{Bat}^I \int_0^t (I_{Bat}^d(\tau) - I_{Bat}(\tau)) d\tau + K_{Bat}^D \frac{d(I_{Bat}^d - I_{Bat})}{dt}, \quad (56)$$

where K_{Bat}^P , K_{Bat}^I , and K_{Bat}^D are positive constants; I_{Bat} is the measured current of the battery; and I_{Bat}^d is the desired current, which is obtained by

$$I_{Bat}^d = \text{rate-limit}\left(I_{Bat}^{ref}\right), \quad (57)$$

with I_{Bat}^{ref} being attained from the sum of the battery's optimal power and output of the DC bus voltage regulation I_{DC}^{out} , obtained by

$$I_{DC}^{out} = K_{Udc}^P (U_{DC}^{ref} - U_{DC}) + K_{Udc}^I \int_0^t (U_{DC}^{ref}(\tau) - U_{DC}(\tau)) d\tau + K_{Udc}^D \frac{d(U_{DC}^{ref} - U_{DC})}{dt}, \quad (58)$$

with U_{DC} being the measured DC bus voltage, K_{Udc}^P , K_{Udc}^I , and K_{Udc}^D are the proportional, integral, and derivative gains, respectively.

Moreover, due to the use of the rate limit operator, there exists a deviation between the optimal current $I_{FC,i}^{ref}$ and desired current $I_{FC,i}^d$ as $\varepsilon_{Bat} = I_{Bat}^{ref} - I_{Bat}^d$, which will be then addressed by the UCs later. The control structure for the D_{Bat} is configured in Figure 12.

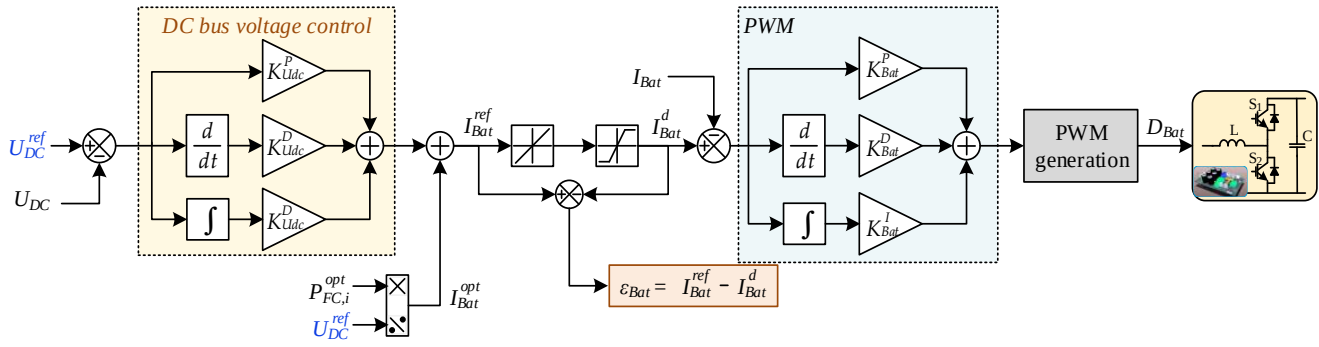


Figure 12. Control architecture for DC bus voltage regulation and PWM generation for the battery.

3.4.3. PWM for the UCs

Similarly, D_{UC} is the duty cycle input to the bi-directional DC/DC converter of the UCs, which is specified through an analog PWM operator, as illustrated in Figure 13. Thus, one has

$$D_{UC} = f_{a-PWM}(Out_{UC}). \quad (59)$$

Out_{UC} is the output of the PID control for the UC current regulation, expressed by

$$Out_{UC} = K_{UC}^P (I_{UC}^d - I_{UC}) + K_{UC}^I \int_0^t (I_{UC}^d(\tau) - I_{UC}(\tau)) d\tau + K_{UC}^D \frac{d(I_{UC}^d - I_{UC})}{dt}, \quad (60)$$

where K_{UC}^P , K_{UC}^I , and K_{UC}^D are the proportional, integral, and derivative gains, respectively; I_{UC} is the measured current of the UC; and I_{UC}^d is the desired current, which is obtained by

$$I_{UC}^d = \frac{P_{UC}}{U_{DC}^{ref}} + \sum_{i=1}^2 \epsilon_{FC,i} + \epsilon_{Bat}, \quad (61)$$

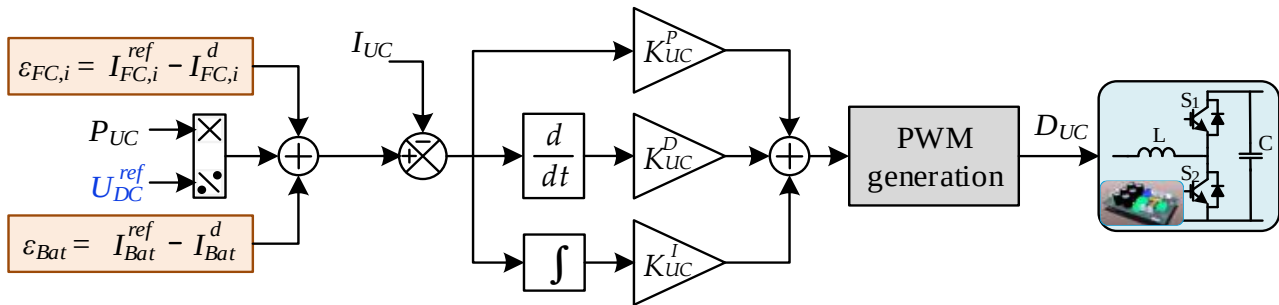


Figure 13. Control architecture of PWM generation for UCs.

4. Comparative Simulations and Discussions

Regarding the examined topology in Figure 1, in this simulation setup, two different characteristics of PEMFCs are employed: one with the maximum power of 120 kW (PEMFC-1) and another one with the maximum power of 60 kW (PEMFC-2). The reason is to demonstrate the MSE effectiveness compared to other conventional methods of EqD and daisy chain in splitting power. If two PEMFC stacks have the same specifications, then the MSE and EqD approaches have the same performance since the power for each stack is simply half that of the dPEMFC power. Therefore, two different PEMFCs should be considered for validating the MSE superiority in appropriately allocating power for each PEMFC power source.

The parameters of the hybrid power source are selected as shown in Tables 1–3 with the sampling time of $t_s = 0.01$ s, subject to the load profile shown in Figure 8.

Table 1. The 120 kW PEMFC system parameters [36,37].

Parameters		Symbol	Value	Unit
Cells number	PEMFC-1		30	
	PEMFC-2		18	
Rated power	PEMFC-1		110	kW
	PEMFC-2		60	kW
Membrane thickness			178	μm
Area		S	232	cm^2
Coefficients		ξ_1	−0.948	−
		ξ_2	$0.00286 + 2 \times 10^{-4} \ln(S) + 4.3 \times 10^{-5}$	−
			$\ln(c_{H2})$	
		ξ_3	7.6×10^{-5}	−
		ξ_4	-1.93×10^{-4}	−
Membrane resistivity parameter			12.5	−
Fuel cell capacitance		C_{dl}	0.035×232	F
Cathode	Pressure	P_{O2}	3	atm
	Flow constant	k_a	0.065	mol/s/atm
	Volume	V_a	0.01	m^3
Anode	Pressure	P_{H2}	3	atm
	Flow constant	k_c	0.065	mol/s/atm
	Volume	V_c	0.005	m^3
Hydrogen enthalpy of combustion			285.5×10^3	kJ/mol
Thermal resistance			0.115	C/W
Total energy (for 6 h)			302.522	kW

Table 2. Battery's parameters [36,37].

Parameters	Value	Unit
Capacity	6.5	Ah
Rated voltage	1.2	V
Constant voltage	1.2848	V
Internal resistance	0.0046	Ω
Number of batteries	360	−
Exponential zone amplitude	0.144	V
Exponential zone time constant inverse	2.3077	$(\text{Ah})^{-1}$
Polarization resistance constant	0.01875	Ω

Table 3. Bank of UCs' parameters [36,37].

Parameters	Value	Unit
Number of UC	80	
Rated voltage	2.7	V
Absolute maximum voltage	2.85	V
Absolute maximum current	1900	A
Rated capacitance	3000	F
Capacitance in the main cell	2100	F
	623	F
Capacitance in the slow cell	172	F
Resistance in the main cell	0.036×10^{-3}	Ω
Resistance in the slow cell	1.92	Ω

Moreover, to further evaluate the effectiveness of the proposed topology in effectively sharing power with each source, we consider the following algorithms in the comparative simulation:

- A1: Rule-based EMS for sharing power to each unit and MSM for splitting power to each PEMFC stack.

- A2: Optimization-based EMS with the daisy chain method for distributing commanded power for each PEMFC stack. In this setup, the PEMFC-1 (110-kW) first supplies power to the load until it reaches its maximum value; then, the PEMFC-2 (60-kW) enters the system.
- A3: Same as A2, but the PEMFC-2 (60-kW) supplies power to the load first until it reaches its maximum value; then, the PEMFC-1 (110-kW) enters the system.
- A4: Optimization-based EMS with equal distribution for sharing power to each PEMFC stack. In this setup, the reference power for each PEMFC stack is half that of the optimal power, i.e., $P_{FC,i}^{ref} = 0.5P_{dFC}^{opt}$.
- A5: Optimization-based EMS with MSM for sharing power to each PEMFC stack without fine-corrected optimal power. In this manner, the reference power of the dual PEMFC and battery are the same as their optimal power.
- A6 (proposed): Optimization-based EMS with MSM for sharing power to each PEMFC stack with fine-corrected optimal power.

Generally, all examined control strategies could fulfill the load demand, as shown in Figure 14. Herein, it should be noted that the optimal power of the dPEMFC and battery and the calculated power of the UCs under A2, A3, A4, and A5 are similar to each other since they are obtained regarding the optimization-based EMS. Only the power-sharing under A1 and A6 is different due to the different algorithms. Thus, to facilitate the observation, only four power efforts were plotted: demand load and power performance under A1, A2, and A6.

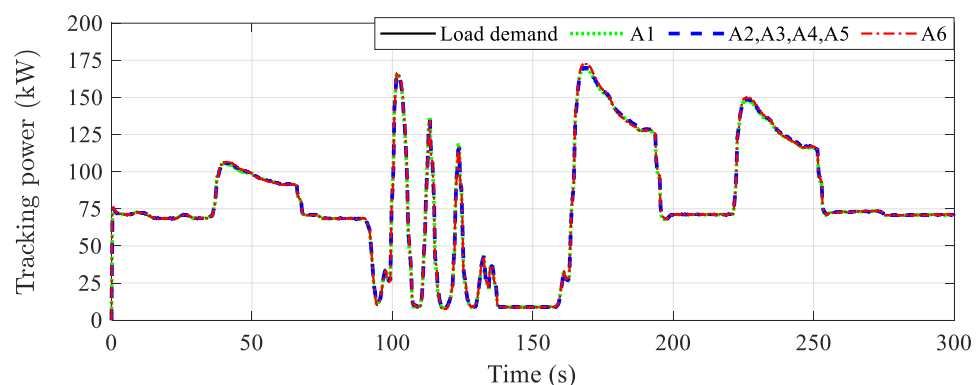


Figure 14. Power tracking qualification under different algorithms.

Figure 15 shows the total power efforts of the dPEMFC (top) and individual PEMFC power (bottom). Figure 16 displays the total efficiency of the dPEMFC system (top) and each primary supply's efficiency (bottom). Subsequently, the reference battery and UCs power were obtained concerning the frequency decoupling technique, as performed in Figure 17. As mentioned above, since the optimal power of the dPEMFC and battery and the calculated power of the UCs under A2, A3, A4, and A5 are the same as each other, only three power efforts of A1, A2, and A6 were plotted in the top sub-Figures 15 and 17.

As seen in Figure 15, as the heuristically designed rules, the power reference of the dPEMFC varied depending on the load demand, as shown. Although the rules were designed such that both PEMFC stacks were constrained to operate within the highest efficiency regions, they could not be manipulated at the optimal working point. Accordingly, the highest total efficiency could not be exhibited, as displayed in Figure 16, in which the efficiency of each PEMFC varied following their power behaviors. The average efficiency was about 0.488 for the dPEMFC, and 0.4833 and 0.498 when distributed for each PEMFC-1 and PEMFC-2, respectively. Moreover, by not operating at the optimal point, the battery and UCs were charged and discharged arbitrarily, which accordingly resulted in an overcharge, as shown in Figure 17.

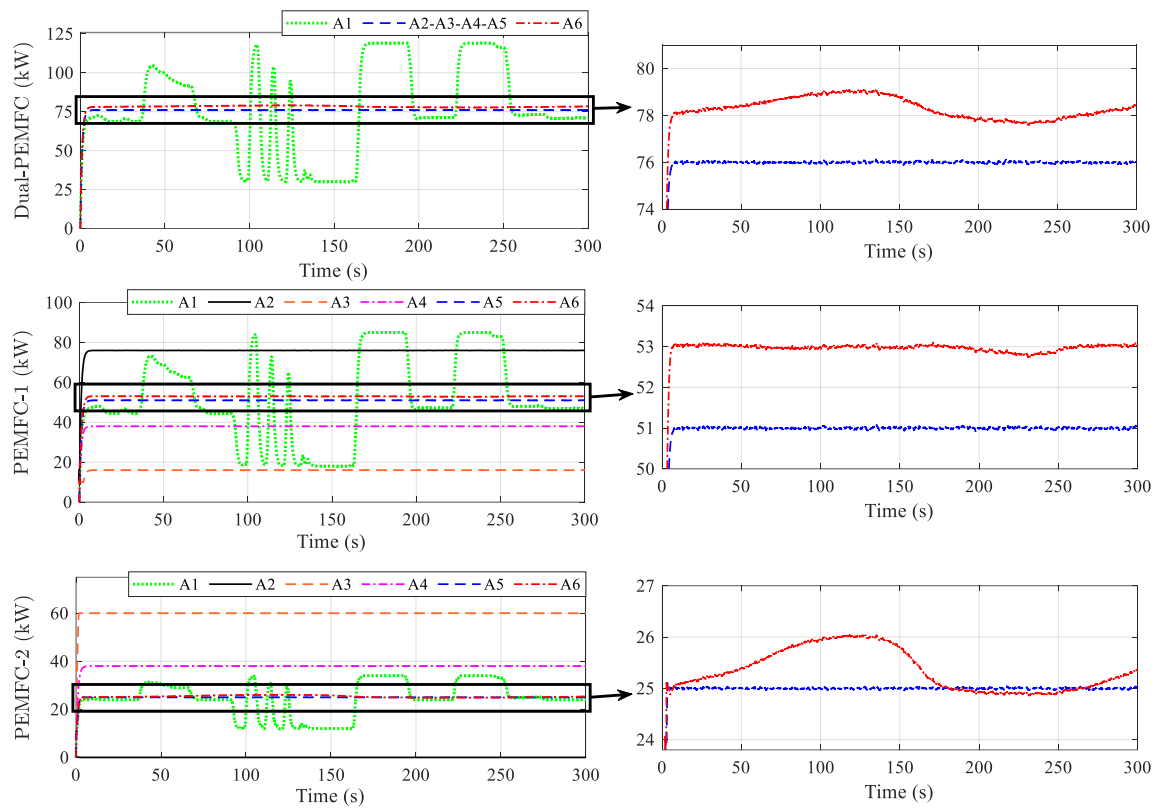


Figure 15. The power performance of the dPEMFC and individual PEMFC systems under different algorithms.

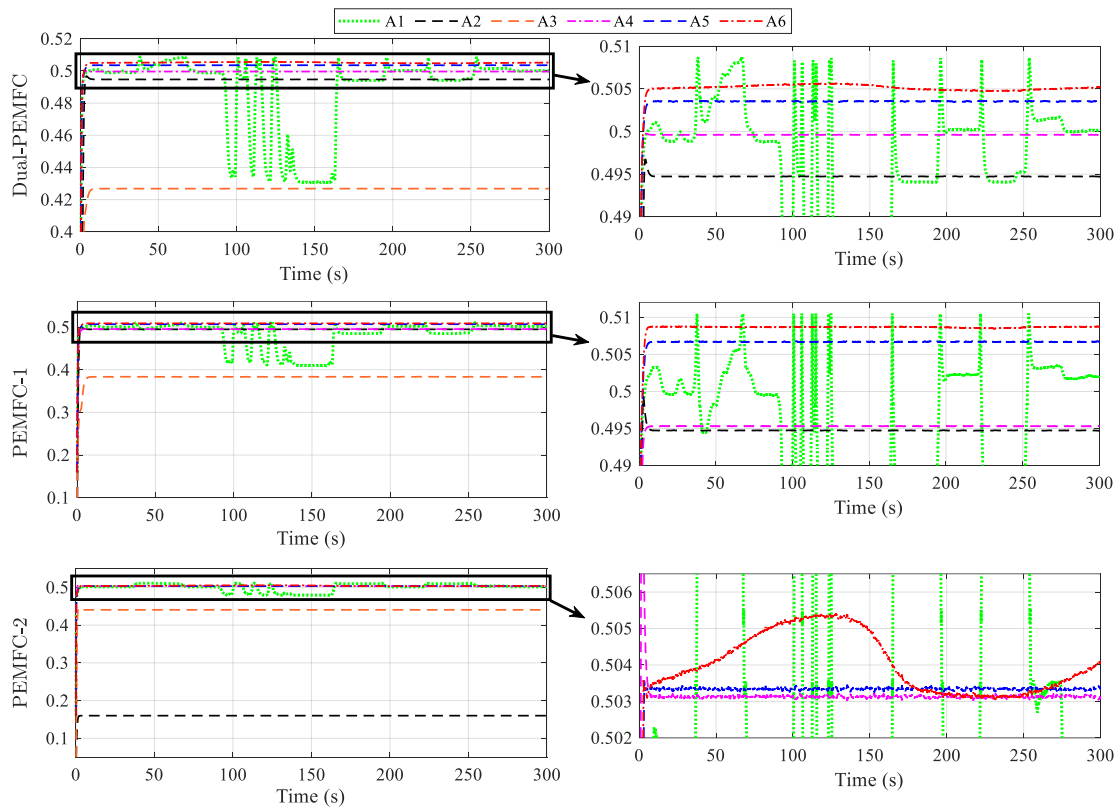


Figure 16. Efficiency of PEMFCs under different algorithms: (Top) overall efficiency of dPEMFC, (Middle) efficiency of PEMFC-1, (Bottom) efficiency of PEMFC-2.

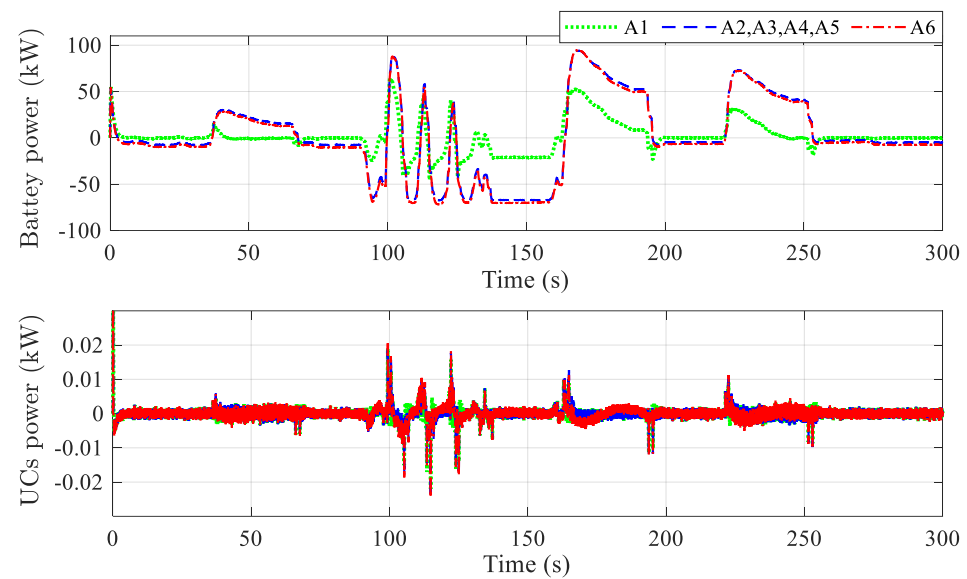


Figure 17. Reference power of the battery and UCs under different algorithms.

On the contrary, other algorithms (A2 to A6) could manipulate the dPEMFC system such that the adjacently highest efficiency was exhibited, as disclosed in Figure 15 thanks to the use of the optimization to seek out the optimal working point. Despite achieving the optimized reference power, in theory, the actual behaviors among them are different.

Despite being obtained through the optimization-based technique, the daisy chain approaches, A2 and A3, exhibited the worst performance. Since the dPEMFC optimized power was around 78 kW, if prioritizing using the 110 kW PEMFC (A2), it could sufficiently support the dPEMFC required to load and thus the 60 kW PEMFC was maintained with the minimum power to run the auxiliary systems (pump, fan, temperature system, and so on); thus, returning the lowest efficiency of about 0.16 and the overall efficiency was about 0.4945 as a result. Likewise, under A3, the 60 kW ran first to supply power to the system. In our design, its acceptable maximum power supply of 50 kW was selected for safety. Therefore, the 110 kW was entered to handle the remaining 28 kW. Consequently, the efficiency was just about 0.3835 for the 110 kW PEMFC and 0.4405 for the 60 kW PEMFC because those operating points are out of the high-efficiency regions with the overall efficiency being only 0.4268. Meanwhile, A4 could improve the overall efficiency a little (0.4996). With the halved power required of 39 kW for each PEMFC, as depicted in Figure 10, the 60 kW PEMFC unit operated in the high-efficiency region at which the efficiency of 0.5032 was exhibited. Meanwhile, the 110 kW operated in the low-efficiency region at which the efficiency of this source was approximately 0.495.

A5 and A6, owing to using the MSE, returned the best performance in which both PEMFC systems could operate in their highest efficiency regions compared to A2, A3, and A4. With the MSE, the optimized power was appropriately allocated to each device based on its characteristic and efficiency map by which the reference power for the PEMFC-1 was determined at about 50 kW and for the PEMFC-2 at around 28 kW.

However, the superiority of the proposed methodology, A6, is governed by not only the overall efficiency of the dPEMFC and hydrogen consumption but also the SOC regulation of the ESDs, as shown in Figures 17 and 18. As observed, the proposed methodology could well constrain the SOC of the battery and UCs compared to other optimization-based methods (A2 to A5). These accomplishments came from the fine-corrected power development to force strictly regulate the SOC by adjusting the reference power of the dPEMFC and battery. The deviation of the SOC_{UC} from its reference SOC_{UC}^{ref} was corrected by manipulating the battery reference power; however, this may also cause the deviation of the SOC_{Bat} from its reference SOC_{Bat}^{ref} to increase. Therefore, the battery reference power was corrected by regulating the dPEMFC power as expressed in (50) and (51). The SOC of

the ESDs were critically controlled such that the final SOC_s were the same as the initial ones at the end of the driving cycle (about 0.7692 for the battery's SOC and 0.6 for the UCs). As a result, with well-regulated ESD behaviors, only the proposed method A6 could satisfy the load demand regarding the real driving cycle [34]. In brief, the superiority of the proposed control algorithm compared to others is summarized in Table 4.

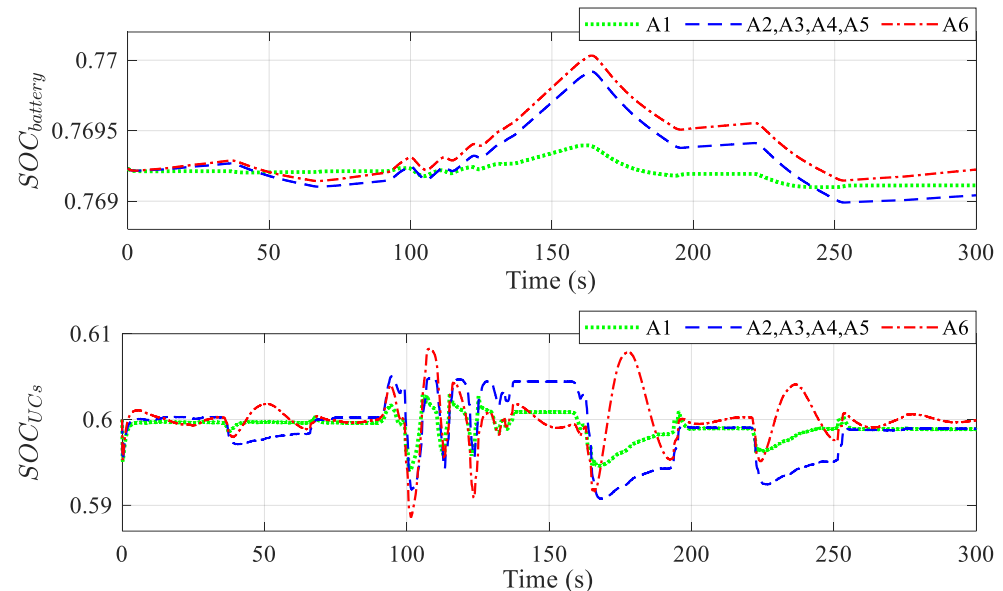


Figure 18. SOC_s of the battery and UCs under different algorithms.

Table 4. Control performance summary.

EMSs	Average Power (kW)			Average Efficiency		
	dPEMFC	PEMFC-1	PEMFC-2	dPEMFC	PEMFC-1	PEMFC-2
A1	76.36	51.72	24.63	0.488	0.4833	0.5004
A2	76	76	Off	0.4947	0.4947	0.16
A3	76	16	60	0.4269	0.3835	0.4404
A4	76	38	38	0.4996	0.4953	0.5031
A5	76	51	25	0.5035	0.5067	0.5033
A6	78.6	52.93	25.5	0.5056	0.0587	0.05045

5. Conclusions

This paper proposed a novel topology of using the hybrid power sources of dual PEMFCs interconnected with battery and UCs to supply the HEV powertrain. Of the setup, the optimization-based hierarchical EMS was established to appropriately allocate optimal power for the dual PEMFC systems and battery such that each PEMFC unit could operate in the high-efficiency region. By using two PEMFC sources, the MSE was then initiated to split the optimal power for each unit properly. Moreover, as the risk of balancing the ESDs' behaviors, a fine-corrected layer was introduced to strictly regulate the SOC_s of the battery and UCs varying around desirable values. In this design, the UCs' SOC was controlled by the battery power whereas the dPEMFC power manipulated the battery's SOC. As a result, not only the optimal power was exhibited and allocated to each supply but the ESDs' SOC_s were also well constrained as demonstrated through comparative simulations. Moreover, with the optimal power obtained, the PEMFC systems operated in the highest efficiency regions, which consumed the lowest fuel; thus, prolonging the lifetime of all devices. However, some related problems, such as system degradation, remaining useful life, ESDs behavior constraints, state-of-health, and so on, have not yet been taken into

consideration. Therefore, these existing regards motivate us to keep going for further developments of control strategies to enhance the overall system performance.

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