Development of operation strategy for PV- fuel cell hybrid power system to maximize efficiency and minimize stress

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ABSTRACT

This study explores the development of an energy management strategy (EMS) using a modified external energy management strategy (EEMS) for a hybrid PV-fuel cell power system. The primary aim was to address efficiency challenges and reduce the premature aging of fuel cells, batteries, and supercapacitors (SCs) caused by excessive stress. Incorporating photovoltaic (PV) energy as an additional renewable energy source (RES) has proven to improve the efficiency of the hybrid system. The EEMS-based strategy reduces hydrogen consumption by prioritizing the energy supply from the battery and SC. However, the traditional EEMS approach introduces chattering phenomena that can negatively impact system lifespan. By modifying the EEMS optimization problem, the modified EEMS effectively mitigates chattering, maintaining the battery's state of charge (SOC) and the DC bus voltage within specified ranges, while also reducing stress on the battery and SC. The results demonstrate a significant enhancement in both system performance and efficiency.

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1. INTRODUCTION

Over time, the use of fossil fuels, such as petroleum and coal, in the transportation sector has significantly increased. The rising global crude oil prices, combined with governments' heavy reliance on crude oil imports and petroleum products, are major drivers behind the shift toward renewable energy sources (RES) [1]. The ongoing development and adoption of RES are aimed at reducing dependence on fossil fuels and mitigating carbon emissions, which contribute to climate change [2]. Currently, RES like wind and solar energy have emerged as promising alternatives due to their cost-effectiveness, environmental sustainability, and low emissions [3]. However, wind and solar power are highly dependent on natural resources and weather conditions. To overcome these challenges, modern fuel cell technology is being increasingly recognized as a viable solution.

Fuel cells are electrochemical devices that generate electrical energy through electrochemical reactions. The basic structure of a fuel cell consists of an electrolyte layer sandwiched between an anode and a cathode [4]. Among the different types of fuel cells, proton exchange membrane fuel cells (PEMFCs) are prevalent in the automotive industry due to their ability to operate at low temperatures and support quick start-up processes [5]. However, the transient response of PEMFCs is highly influenced by electrochemical reaction rates, especially at the cathode. As a result, PEMFCs may not be ideal for standalone applications, as they struggle to deliver the power needed for rapid load changes [6].

To improve the performance of PEMFCs in responding to sudden load variations, a power storage system is integrated. In this setup, the PEMFC system typically serves as the primary energy source, while an additional energy storage system (ESS) handles peak power demands. The ESS must be capable of supporting the load for up to two seconds to allow the fuel cell's power to ramp up from 10% to 90%, while also preventing a reduction in the fuel cell's lifespan [7]. As a result, PEMFC hybrid power systems demonstrate significantly enhanced dynamic responses and help extend the operational lifespan of the PEMFC [8].

Batteries function by converting electrochemical energy into electricity and vice versa, while supercapacitors (SCs) store electrical energy in the form of an electric field [9]. Although SCs have a much lower energy density compared to batteries, they offer significantly higher power density [10]. The operation of PEMFCs, batteries, and SCs is managed by an energy management system (EMS), which ensures optimal performance and coordination between the components.

Research on fuel cell hybrid power systems was initially focused on electric vehicles. Studies show that high-power lithium-ion batteries are approximately twice as expensive as fuel cell systems for electric vehicle applications [11]. Additionally, a key challenge in the PEMFC transportation sector is the premature aging of both the fuel cell system and the battery [12]. Therefore, developing effective energy management strategies is crucial to reduce stress on the fuel cell and battery systems, maximize their lifespans, and optimize fuel savings.

A simple power system management strategy was proposed in [13] to regulate the operation of a fuel cell hybrid power system. This strategy addressed the slow dynamics of PEMFCs and the fast dynamics of batteries and SCs. However, it did not consider fuel consumption or the state of charge (SOC) of the battery. Preview study [14], the use of a fuzzy logic controller (FLC) for managing hybrid power sources was proposed. Both simulation and experimental results supported the improvements in performance and system reliability. However, a key limitation of this research is the EMS's vulnerability to cycle changes, as it relies on an offline method. The effectiveness of this system may depend heavily on the accuracy and reliability of the data collected from the sensors.

A comparative study of three energy management strategies for fuel cell hybrid power systems was conducted in [15], where disruption factors impacting the lifespan of each energy source were introduced as criteria for evaluating EMS performance. The study concluded that the selection of each scheme depends on specific criteria. However, strategies such as the external energy management strategy (EEMS) suffer from the issue of chattering phenomena, which causes high-frequency switching between system components, leading to mechanical and electrical stress. This not only reduces the lifespan of components like fuel cells, batteries, and SCs but also results in operational inefficiency. The strategy proposed in this paper addresses this issue by reformulating the optimization problem, ensuring smoother transitions and improved performance of the system components.

Additionally, previous studies have largely concentrated on fuel cell-battery-supercapacitor systems without incorporating other RES like photovoltaic (PV) energy. This paper fills that gap by showcasing the clear benefits of integrating PV energy, including a substantial improvement in efficiency and a reduction in hydrogen consumption. The proposed integration enhances the hybrid system’s sustainability, cost-effectiveness, and alignment with future energy trends that favour renewable sources.

One challenge that arises during the operation of a fuel cell hybrid power system is the inefficient utilization of hydrogen [16], [17]. Given the high cost of hydrogen gas, the energy management system (EMS) must incorporate PEMFC efficiency criteria into its control mechanisms [18]. This becomes particularly important when PEMFC hybrid power systems work in conjunction with other RES to meet dynamic load demands, as highlighted in [19] and [20]. This paper presents an operational strategy for a fuel cell hybrid power system aimed at maximizing both performance and efficiency. The performance of the hybrid energy system, with and without the integration of an additional RES source, specifically photovoltaic (PV), is compared. This comparison serves as a reference for evaluating the need for PV integration with fuel cells and demonstrates how power distribution enables fuel cells to meet load requirements under stable conditions. Moreover, the issue of increased stress due to RES integration in fuel cell hybrid power systems is addressed through optimization techniques. This comprehensive integration represents a holistic approach to hybrid power management, focused on enhancing energy efficiency, system performance, and sustainability. This paper is structured as follows: i) Section 2 describes the research method which includes a system description and the proposed algorithm, namely the modified EEMS; while ii) Section 3 discusses the simulation results of the proposed hybrid power system; and iii) Finally, section 4 provides the conclusion.

2. METHOD

2.1. System description

The fuel cell system is designed to meet the power requirements of the load in combination with other RES, particularly PV systems. Batteries and SC are incorporated to support both sustained and transient peak power demands, where the fuel cell, due to its slow dynamics, cannot meet such load requirements. To prevent overcharging of the batteries and SC, safety resistors are installed in parallel. The structure of the hybrid fuel cell power system is shown in Figure 1. Energy flows are represented by blue lines, while measurement signals and control signals are indicated by red and green colors, respectively.

On the input side, the fuel cell is equipped with a hydrogen regulator featuring a feedforward control structure. The feedforward control signal is generated using the measured fuel cell load current values. The actuator in this control system is a control valve that regulates the hydrogen flow. On the output side, the fuel cell is connected to a DC/DC boost converter. A voltage regulator is required to maintain the converter's output voltage in line with the setpoint by increasing its input voltage, which is derived from the fuel cell output (approximately 41 V under nominal conditions). The setpoint value for the output voltage of the boost converter is determined by the EMS, and is adjusted to achieve the DC bus value of approximately 270 V.

The nominal power of the fuel cell is 10 kW, with a maximum power output of 12.5 kW. The output voltage range of the fuel cell spans from 30 to 60 V. The maximum current of 320 A occurs at a voltage of 39.2 V, while the nominal power is achieved at a current of 250 A and a voltage of 41 V. The boost converter ensures that the fuel cell does not receive a load exceeding 320 A, maintaining an efficiency of 85%. At a 10% load, the efficiency of the boost converter increases to 90%. The voltage regulator of the boost converter has a response time of 0.1 seconds and operates with a load capacitance of 15.6 F.

The batteries used in this system are of the Li-ion type, rated at 48 V and 40 Ah. In this configuration, four batteries are connected in series. The battery management system (BMS) controls the charging and discharging processes through two DC/DC converters: A 4 kW boost converter for discharging and a 1.2 kW buck converter for charging. Both converters are calibrated to ensure their output voltages align with the setpoint values while also limiting input currents to prevent exceeding maximum thresholds. The setpoint voltage and maximum current values are determined by EMS.

The SC consists of six cells connected in series, each with a voltage capacity of 48.6 V, resulting in an overall voltage of 291.6 V and a total capacitance of 15.6 F. The safety resistors are rated at 15 kW. The simulated load is resistive, eliminating the need for converting DC signals to AC.

The fuel cell exhibits a slow dynamic response, requiring the battery and/or SC to supply transient energy demands and peak loads. The EMS is designed to optimize power generation while meeting these energy demands. As a result, an energy distribution management strategy is essential. The energy management strategy employs a PI control approach. This scheme regulates the state of charge (SOC) of the battery using a PI controller that generates the reference power for the battery, as proposed in [21]. The reference power for the fuel cell is then derived from the difference between the load power and the reference battery power. When the SOC of the battery exceeds the reference value, the fuel cell power is reduced, and the battery provides full power. Conversely, when the SOC falls below the reference, the fuel cell supplies nearly all the load requirements. The structure of this control algorithm is illustrated in Figure 2.

The fuel cell power reference P_{fc}^* is then used to determine the fuel cell reference current I_{fc}^* using (1).

$$I_{fc}^* = \frac{P_{fc}^*}{\eta \, V_{fc}} \tag{1}$$

Where η and V_{fc} are the DC/DC converter efficiency (namely 0.85) and the output voltage of the fuel cell, respectively.

The DC bus voltage regulation is performed by the battery converter within the BMS. This regulation technique utilizes the difference between the reference DC bus voltage (V^*_{dc}, in this case, 270 V) and the actual DC bus voltage (V_{dc}) to determine the conditions for the buck and boost converters from the BMS via reference currents ($I_{batt\_boost}^*$ and $I_{batt\_boost}^*$). The voltage regulator algorithm employed is proportional-integral (PI). The reference voltage on the DC bus is compared with the actual voltage to determine the reference current for the charging (buck converter) and discharging (boost converter) processes.

The power response of the hybrid power system using the PI control algorithm (Figure 3) demonstrates that power distribution is well-balanced in this scheme. The fuel cell does not need to generate power that closely matches the load requirements (represented by the brown line); instead, it shares the load with the power supplied by the battery. The SC (represented by the green line) operates during transient conditions and at high load demands. As a result, this scheme clearly requires less hydrogen consumption compared to other schemes, such as the state machine control algorithm proposed in [22]. Having established that the PI control strategy results in lower hydrogen consumption, this scheme is then employed for the hybrid power system integrated with RES.

In this study, the additional RES introduced is solar energy, via photovoltaic (PV) modules. Fourteen PV modules are connected in series. In this context, the EMS readjusts the power distribution for the fuel cell, battery, and SC in response to the fluctuating contributions from the PV energy source, which are influenced by changes in solar intensity and environmental conditions. Variations in solar intensity are simulated as shown in Figure 4, while the temperature is maintained at a constant value of 45 °C.

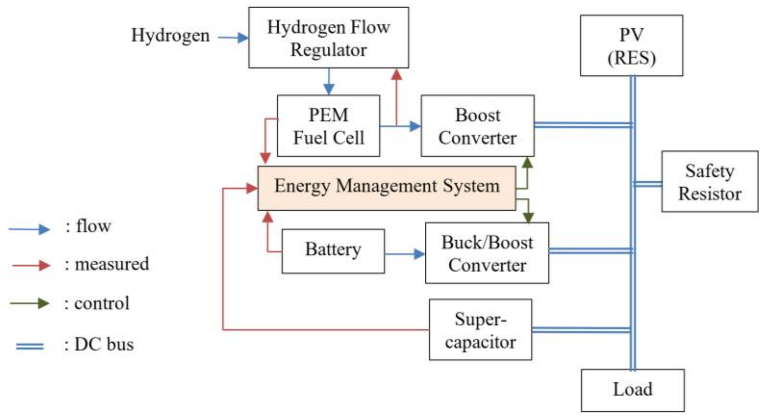


Figure 1. Schematic of the hybrid fuel cell-PV power system

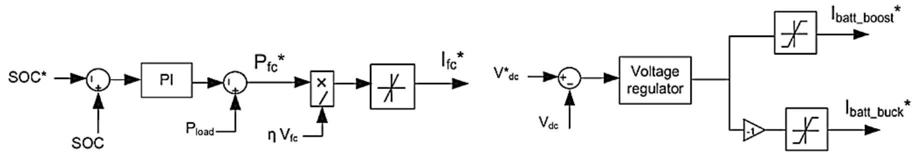


Figure 2. PI control algorithm scheme

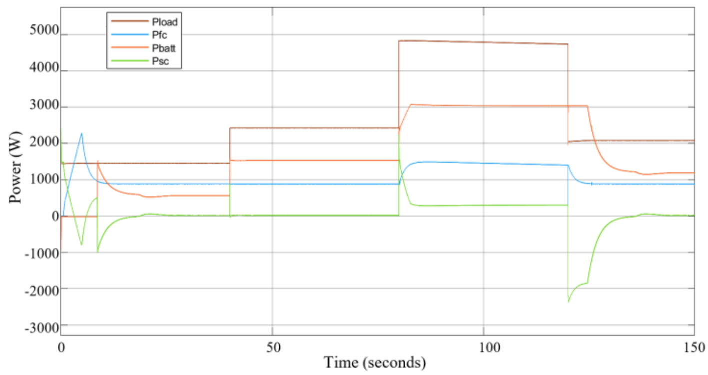


Figure 3. Power response of the hybrid FC simulation with PI control algorithm

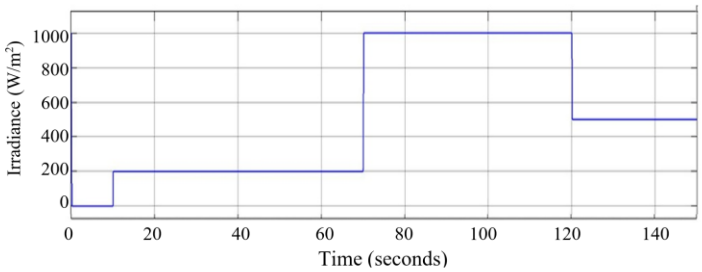


Figure 4. Solar radiation changes

The simulation results of the hybrid fuel cell-photovoltaic (hybrid FC-PV) system using the PI control algorithm are presented in Figure 5. By comparing the simulation results in Figures 3 and 5, it is evident that with the addition of the PV energy source, the usage of battery power (represented by the orange line) is reduced, while the fuel cell power (represented by the blue line) remains relatively unchanged. This is because the PI control algorithm prioritizes the regulation of the battery's SOC rather than optimizing the fuel cell's operation. As a result, the issue of efficiency has not been fully addressed. Therefore, an EMS strategy that incorporates optimization of fuel cell operation is needed to improve overall system performance.

2.2. The EEMS strategy

The fundamental concept of the external energy management strategy (EEMS) is to reduce hydrogen consumption by maximizing supply from the batteries and SCs, while adhering to predefined constraints, as discussed in [23]-[26]. The advantage of EEMS over other optimization methods lies in its relatively simple formulation, as it only requires the cost functions of the batteries and SCs, without the need for empirical energy calculations for the batteries. The schematic of the EEMS is illustrated in Figure 6. The EEMS inputs are the battery state of charge (SOC) and the DC bus voltage V_{DC}. Unlike the PI control strategy, the output of EEMS – besides the reference power from the battery P^*_{batt} – is the SC charge/discharge voltage (ΔV). The battery reference power is then compared with the load power P_{load} to produce the reference power of the fuel cell P^*_{fc} using (2).

$$P_{fc}^* = P_{\text{load}} - P_{\text{batt}}^* \tag{2}$$

Next, the fuel cell power reference is converted into the fuel cell reference current value I_{fc}^* using the same formulas as stated in (1).

In the voltage regulator section, the SC charge/discharge voltage (ΔV) and the voltage reference on the DC bus (V^*_{dc}) will be compared with the actual voltage on the DC bus (V_{dc}) to regulate the battery state (discharge/charge) through the DC/DC converter current (input boost converter/output buck converter). In the EEMS algorithm, the objective function is to maximize the energy supplied by the SC and the battery during a specified time interval ΔT. The value of this time interval is usually used the same as the time sampling value T_s, although it does not rule out other values such as multiples of T_s. In this study, T_s of 0.2 seconds was used. Thus, the optimization problem is defined as in (3)-(7).

$$\max_{\Delta V, P_{batt}} \frac{1}{2} C_r \, \Delta V^2 + P_{batt} \Delta T \tag{3}$$

$$\Delta V \leq V_{dc} - V_{dc\_min} \tag{4}$$

$$P_{batt} \Delta T \leq (SOC - \text{SOC}_{min}) V_{batt} Q \tag{5}$$

$$P_{batt\_min} \leq P_{batt} \leq P_{batt\_max} \tag{6}$$

$$V_{dc\_min} - V_{dc\_nom} \leq \Delta V \leq V_{dc\_max} - V_{dc\_nom} \tag{7}$$

Where Q is the battery capacity (36 V × 40 Ah) and Cr is the rated capacitance of the SC (15.6 F).

In order to consider the additional energy from photovoltaics which have a power of P_{PV}, the EEMS strategy in Figure 6 can be directly used by simply changing the load power P_{load} to the remaining DC power required P_{DCreq}, which as in (8).

$$P_{\text{DCreq}} = \max\left(P_{\text{load}} - P_{\text{PV}}, 0\right) \tag{8}$$

However, this method can result in chattering phenomena, as the EEMS strategy places high stress on the battery and SC systems, as reported in Motapon *et al.* [23]. Additionally, the extra power from the PV system (PPV) may increase the dynamics of the remaining DC power required due to the fluctuating contributions from the PV energy source, which are influenced by variations in solar intensity and environmental conditions. These chattering effects can negatively impact the operational lifespan of each energy source. Therefore, an appropriate energy management system (EMS) should be chosen to minimize stress on the fuel cell, battery, or SC system, ultimately maximizing the lifespan of the hybrid fuel cell power system.

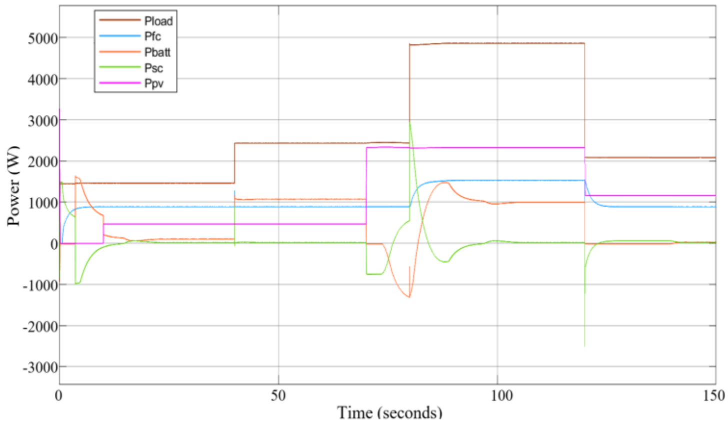


Figure 5. Power response of the hybrid FC-PV simulation with PI control algorithm

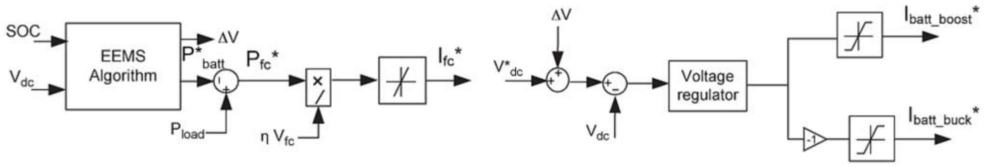


Figure 6. Schematic of the EEMS strategy

2.3. The modified EEMS strategy

This paper proposed the modified EEMS algorithm in order to overcome the shortage of EEMS strategy. Changes were made only to the fuel cell reference power determination scheme, while the voltage regulator scheme remained unchanged. The schematic of the modified EEMS is shown in Figure 7.

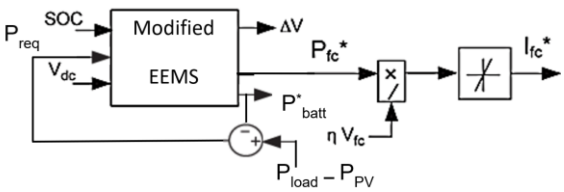


Figure 7. Schematic of the modified EEMS strategy

Unlike the EEMS algorithm, the output of the modified EEMS is directly the reference power from the fuel cell P^*_{fc}, in addition to the SC charge/discharge voltage (ΔV) and the reference power from the battery P^*_{batt}. While an additional input for the modified EEMS (in addition to the battery SOC and DC bus voltage) is the remaining power required P_{req}, as in (9).

$$P_{\text{req}} = \max\left(P_{\text{load}} - P_{\text{PV}} - P^*_{batt}, P_{fc\_min}\right) \quad (9)$$

Where P_{fc_min} is the smallest value of permitted fuel cell power.

In the modified EEMS algorithm, the objective function is to maximize the energy supplied by the SC and battery but minimize the energy supplied by the fuel cell during a specified time interval ΔT = 10 T_s, or mathematically written as (10).

$$\max_{\Delta V, P_{batt}, P_{fc}} \quad \frac{1}{2} C_r\, \Delta V^2 + P_{batt}\Delta T - P_{fc}\Delta T \quad (10)$$

While for the constraints, besides using (4)-(7), the following constraints are also used (11) and (12).

$$P_{fc} \leq P_{\text{req}} \tag{11}$$

$$P_{fc\_min} \leq P_{fc} \leq P_{fc\_max} \tag{12}$$

Where P_{fc_max} is the largest value of permitted fuel cell power. Notice, there are three optimization variables involved in (10) but there are only two outputs of the modified EEMS used, namely ΔV and P^{*}_{fc}. Next, as with EEMS, ΔV is fed to the voltage regulator scheme while P^{*}_{fc} is fed to the fuel cell reference current calculation.

3. RESULTS AND DISCUSSION

3.1. Effect of integrating PV

The simulation results of the hybrid fuel cell–photovoltaic (hybrid FC–PV) system using the EEMS algorithm are presented in Figure 8(a). It is evident that the fuel cell operates continuously at its minimum power, as seen in the graph, where the output power of the DC/DC boost converter is less than 1 kW due to losses with an efficiency of 0.85. The battery power used in this case is higher than that seen with the PI control strategy (Figure 5), particularly during the simulation period from 80 to 120 seconds. Meanwhile, the SC continues to address transient loads.

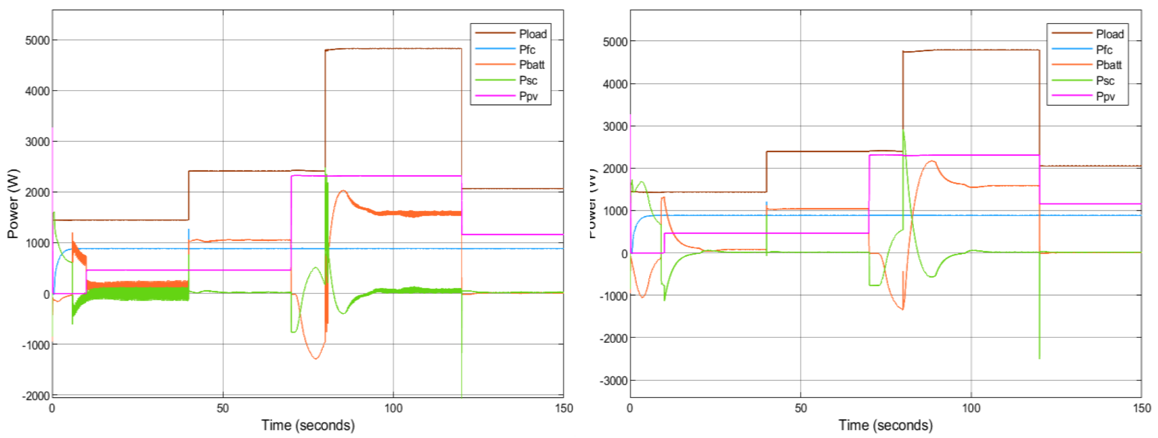
The impact of integrating PV energy sources into the EMS is reflected in the overall increase in system efficiency. Additionally, total hydrogen consumption serves as another key performance indicator. The comparison of performance indices for the two EMS strategies—PI control (without integrating PV) and EEMS (with integrating PV)—is shown in Table 1. The results confirm that integrating RES into the EMS enhances the efficiency of the hybrid fuel cell power system and reduces hydrogen consumption. Specifically, efficiency increased by 5%, while hydrogen consumption decreased by 12%.

Table 1. The performance of two EMS strategies

Strategy	Efficiency (%)	Hydrogen consumption (g)
PI control	87.32	4.365
EEMS	92.24	3.844

3.2. The modified EEMS performance

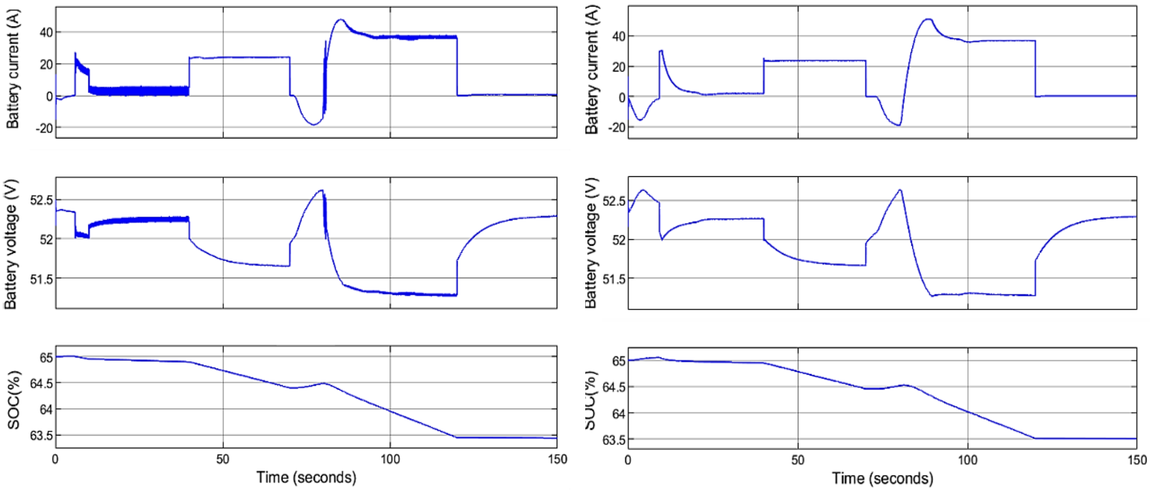
From the simulation results of the EEMS strategy as shown in Figure 8(a), it is clear that the chattering phenomenon appears in both the SC power response and the battery power response. The simulation results of the hybrid FC–PV system with the modified EEMS algorithm, shown in Figure 8(b), indicate that, in addition to the fuel cell operating consistently at its minimum power, the chattering phenomenon has been successfully suppressed.



(a) (b)

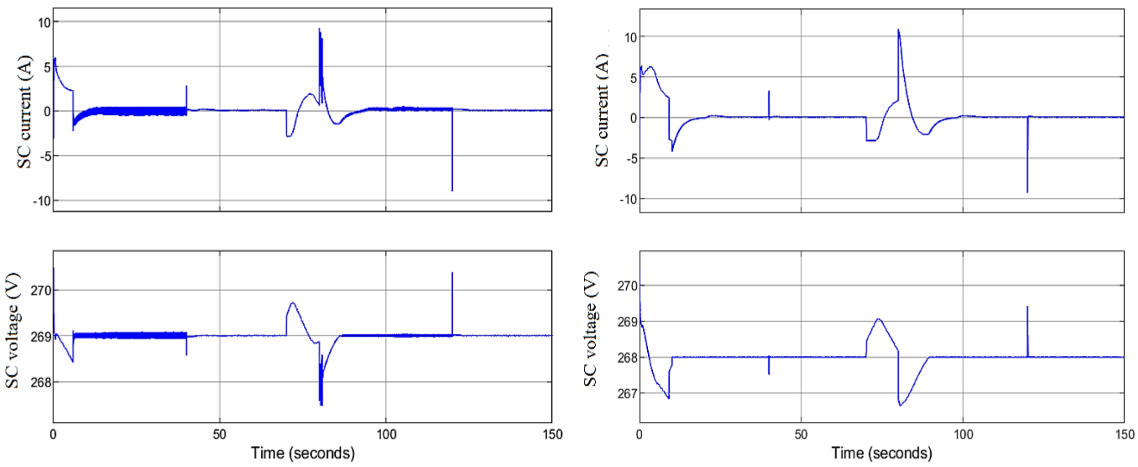
Figure 8. Power response of the PV-fuel cell hybrid power system simulation with (a) EEMS and (b) the modified EEMS

The results also demonstrate the success of the modified EEMS control strategy in maintaining the battery's state of charge (SOC) within the specified range, with smoother current and voltage compared to the results from the original EEMS algorithm, as seen in Figure 9. Similarly, the SC performance shows improvements, as illustrated in Figure 10. The DC bus voltage, which mirrors the output voltage of the SC, is also stabilized, with the modified EEMS algorithm producing a voltage 1 volt lower than the DC bus voltage from the EEMS. These relatively stable SOC and DC bus voltage conditions reflect the effectiveness of the proposed energy management strategy in managing and maintaining both the battery capacity and the DC network. On the fuel cell side, both the EEMS and the modified EEMS produce very similar responses, with both strategies leading to increased system efficiency by keeping the fuel cell operating at a minimum load current of 20 A, as shown in Figure 11.



(a) (b)

Figure 9. Battery condition of the hybrid power system with strategy:
(a) EEMS and (b) the modified EEMS



(a) (b)

Figure 10. The SC condition of the hybrid power system with strategy:
(a) EEMS and (b) the modified EEMS

Unlike the conventional proportional-integral (PI) control strategy, which typically fails to effectively manage fuel consumption and battery state-of-charge (SOC), the EEMS ensures stable SOC levels and DC bus voltage. However, the EEMS strategies often suffer from the chattering phenomenon, which leads to high-frequency switching that imposes unnecessary stress on fuel cells, batteries, and SCs.

This stress accelerates component degradation, ultimately reducing the lifespan of the system. To address these challenges, the study proposes a modification to the optimization problem formulation, effectively mitigating the chattering effect and improving system reliability and longevity.

Another contribution of the paper is the integration of photovoltaic (PV) energy into the hybrid power system. By incorporating PV energy, the research demonstrates a significant improvement in system efficiency and a reduction in hydrogen consumption. Specifically, the PV integration leads to a 5% efficiency gain and a 12% reduction in hydrogen consumption compared to systems that do not incorporate PV energy. This integration not only makes the system more sustainable but also reduces the reliance on hydrogen, contributing to a more environmentally friendly solution. Thus, this study introduces significant innovations in the field of energy management for hybrid power systems.

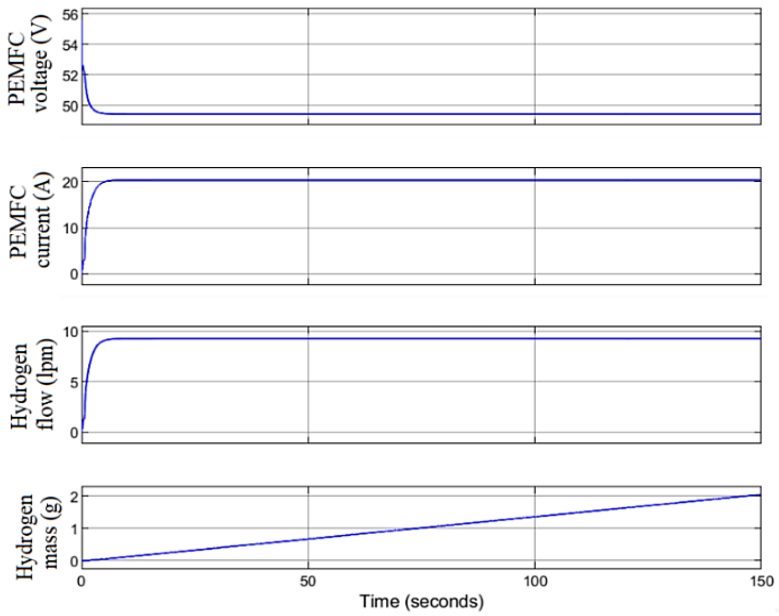


Figure 11. Fuel cell condition of the hybrid power system with the strategy of the modified EEMS

4. CONCLUSION

This study demonstrates that the development of an energy management strategy using the modified EEMS scheme for PV-fuel cell hybrid power systems can effectively address efficiency challenges and mitigate premature aging of fuel cells, batteries, and SCs caused by excessive stress. By integrating photovoltaic (PV) energy as an additional renewable energy source, this operational strategy has shown to significantly enhance the efficiency of the PV-fuel cell hybrid power system. Furthermore, by modifying the optimization problem formulation of the EEMS, this approach has successfully mitigated chattering phenomena, ensuring that the battery's state of charge (SOC) and the DC bus voltage remain within specified ranges while reducing stress on the battery and SC compared to the original EEMS. Future research will explore real-time applications of the proposed strategy, including the integration of multiple renewable energy sources and adaptation to varying operational conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author, [KI], on request.

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