A comparative study of pi and eems on emu for hybrid fuelcell power systems

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Received: 30 January 2025 Revised: 02 February 2025 Accepted: 02 March 2025

Abstract— This study investigates the Energy Management Unit (EMU) for a hybrid power system integrating PEMFC, batteries, supercapacitors, and Photovoltaic (PV) as renewable energy sources. The EMU is designed to support power supply, reduce the load on the PEMFC, and enhance operational efficiency and reliability. It intelligently manages power distribution by adjusting the use of energy sources based on system conditions, such as battery state of charge (SOC), load changes, or PV energy availability. Two types of management algorithms used in the EMU were tested: Proportional Integral (PI) and External Energy Management Strategy (EEMS). The comparison results show that EEMS outperforms PI in terms of stability and efficiency, with an average efficiency of 88.85% for EEMS compared to 88.77% for PI. Furthermore, the EEMS method demonstrates superior performance by maintaining minimal fluctuations ranging from 0.02 to 0.03, even under dynamic load conditions, while the PI method shows greater fluctuations, varying between 0.05 and 0.08.

Keywords— EEMS, Energy Management, Fuel Cell, Hybrid Power System, PI

1. Introduction

The growing global demand for clean energy has driven the advancement of technologies such as Proton Exchange Membrane Fuel Cells (PEMFC), which offer high efficiency, low emissions, and rapid power response. These attributes make PEMFC a highly promising solution, especially in the transportation and stationary power generation sectors [1]. PEMFC operates based on an electrochemical reaction, using hydrogen and oxygen as fuel, producing electricity, heat, and water as byproducts [2–5]. Despite generating high current at low output voltage, this characteristic makes PEMFC well-suited for hybrid power systems that require precise energy management [6].

This study focuses on evaluating the performance of the Energy Management Unit (EMU) that governs energy flow in a hybrid power system combining PEMFC, batteries, supercapacitors, and Photovoltaic (PV) systems. The integration of PV allows the direct harnessing of renewable energy from sunlight, reducing the load on PEMFC and boosting overall system efficiency. As a result, PV not only lowers hydrogen consumption but also extends PEMFC's operational lifespan while enhancing system performance in managing power fluctuations over time [1].

In hybrid power systems, the EMU is responsible for efficiently distributing energy from various sources and ensuring system stability. This distribution is dynamically prioritized based on fluctuating system conditions. The control strategies used in the EMU allow the system to adapt to varying power demands, maintaining optimal operational efficiency and system stability. Energy prioritization is determined by the operational status of each component, enabling a responsive adjustment to changes in power demand [1]. This paper compares two energy management algorithms for the EMU: Classical Proportional Integral (PI) and External Energy Management Strategy (EEMS). Consequently, this research not only contributes to enhancing the efficiency of hybrid power systems but also ensures optimal energy management, supporting the transition to a more sustainable and environmentally friendly energy future.

2. Related Works

A hybrid power system is a combination of multiple energy sources designed to work together to optimally meet power demands. The integration of various energy sources, such as photovoltaic (PV), fuel cells, batteries, and supercapacitors, aims to enhance the efficiency, reliability, and sustainability of energy supply, particularly in applications that require stable and flexible power. This combination allows for adaptive energy management, where each resource contributes according to the system's needs. The schematic of a PV-fuel cell hybrid system is shown in Figure 1.

The fuel cell serves as the primary energy source, generating electricity through an electrochemical reaction. The output voltage of the fuel cell is regulated by a DC-DC boost converter to ensure stability and meet the system's requirements. The solar panel (PV) functions as a renewable energy source, generating power from sunlight. The energy produced by the PV can either be directly used for the load or directed to a DC-AC converter to be converted into alternating current, depending on the system's needs.

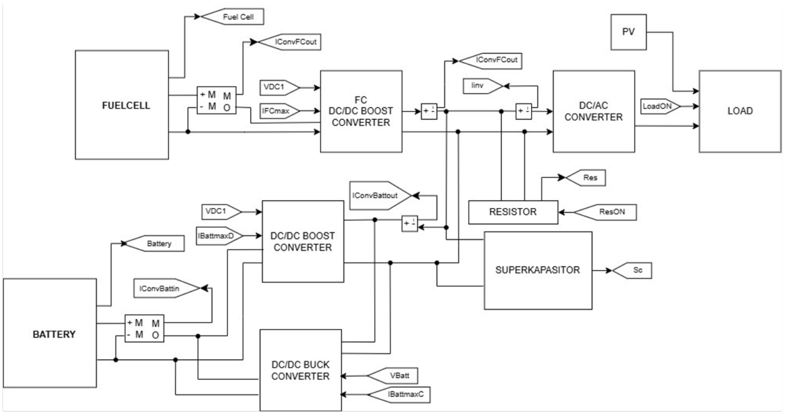

Figure 1. The Schematic Of A PV-Fuel Cell Hybrid System

In this system, the battery plays a crucial role as an energy storage backup. When the power generated by the PV and fuel cell is insufficient, the battery automatically provides additional energy to ensure the load requirements are met. When system conditions allow, such as during excess power generation from the fuel cell or PV, the battery is recharged via a DC-DC buck converter. On the other hand, when energy is needed, the battery can discharge through a DC-DC boost converter.

The supercapacitor is responsible for handling sudden or transient power demands, especially during load spikes. Due to its ability to deliver large currents in short bursts, the supercapacitor helps maintain system stability. The output voltage of the supercapacitor is regulated through a DC-DC boost converter to ensure compatibility with other system components.

The entire hybrid power system is managed by a control unit that monitors the condition of each component and automatically adjusts energy distribution based on real-time circumstances. For instance, when sunlight is abundant, the PV system takes priority as the primary energy source. When PV power is insufficient, the fuel cell activates to support the load. Under specific conditions, such as during power demand spikes or shortages from primary sources, the battery and supercapacitor work in harmony to maintain a stable energy supply. This setup ensures seamless transitions between energy sources without disrupting the load. Each component operates according to its role, contributing optimally based on the system's needs at any given time.

A. Proton Exchange Membrane Fuel Cell

A Fuel Cell is an electrochemical device that directly converts the chemical energy of a fuel into electrical energy. The electrochemical reaction in a Proton Exchange Membrane Fuel Cell (PEMFC) involves the transfer of charges from one electrode to another, accompanied by the movement of electrons. The chemical reaction occurring in the fuel cell is represented by the following equation.

$$\begin{array}{ll} \text{Anode} : & \\ \text{Cathode} : & \\ \text{General} : & \end{array} \begin{cases} H_2(g) \rightarrow 2H^+(aq) + 2e^- \\ 2H^+(aq) + \frac{1}{2}O_2(g) + 2e^- \rightarrow H_2O(l) \\ H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l) \end{cases} \quad (1)$$

In the transfer process, ions and electrons follow separate paths. The H+ ions move from the anode to the cathode through the electrolyte/membrane, while the electrons (e-) flow through a conductor that carries the electrical current. The fuel cell model adopted in this study follows the approach proposed by (Puranik, Keyhani, & Khorrami, 2010). The voltage generated by the electrochemical reaction is expressed using the Nernst equation as follows.

$$E_n = E_0 + \frac{RT}{2F}\ln\left(\frac{PH^2\sqrt{Po^2}}{P_{ref}}\right) \quad (2)$$

Where,

E_0	:	Standar Potential (1.229 V pada 25°C)
R	:	The Universal Gas Constant (8.314 J/mol· K)
T	:	Temperature in Kelvin
F	:	Faraday Constant (96,485 C/mol)
P_{H_2}	:	Partial Hydrogen Pressure (atm)
P_{O_2}	:	Partial Oxygen Pressure (atm)
P_{ref}	:	Operating Temperature (1 atm)

Activation losses arise from the resistance to electrochemical reactions at the anode and cathode and can be modeled using the Tafel equation.

$$V_{activation} = \frac{RT}{\propto F}\ln\left(\frac{i}{i_0}\right) \quad (3)$$

Where,

i	:	The Operating Current of The Cell (A)
i_0	:	Exchange Current Density
$\propto$	:	Transfer Coefficient

Concentration losses occur due to the decrease in reactant concentration at the electrode and can be expressed as.

$$V_{concentration} = -\frac{RT}{2F}\ln\left(1 - \frac{i}{i_{lim}}\right) \quad (4)$$

Where,

i_{lim}	:	Limit current refers to the maximum current that can be generated before a depletion of reactant concentration occurs.

The electrical efficiency of a PEMFC can be expressed as the ratio between the actual electrical output power and the theoretical maximum power.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{cell} \cdot I}{\Delta G \cdot \dot{n}} \quad (5)$$

Where,

ΔG	:	The change in Gibbs energy (J/mol) of the reaction
$\dot{n}$	:	Molar Hydrogen Consumption Rate

B. Modelling of the Energy Management Unit

The Energy Management Unit (EMU) model is designed to simulate the adaptive distribution of energy within a hybrid system that integrates multiple energy sources. This management is achieved by adjusting operational strategies based on the dynamic conditions of the system. In specific scenarios, such as during high power demand, the EMU can combine contributions from all available energy sources to maintain power stability. Conversely, when the load is low or solar intensity is high, the system can prioritize renewable energy sources like PV to reduce dependence on the PEMFC, thereby improving efficiency and extending the lifespan of the components. With intelligent control, the EMU ensures that each energy source is utilized optimally, based on the current needs and operational conditions.

The EMU is equipped with power converters, such as DC-DC converters, responsible for adjusting the voltage from various energy sources (PEMFC, PV, battery, and supercapacitor) to meet the load requirements. The EMU controller is tasked with managing the power distribution between the PEMFC, PV, battery, and supercapacitor through these power converters. The total voltage supplied by the EMU to the load is a combination of the various sources, namely PEMFC, PV, battery, and supercapacitor. The voltage modeling can be expressed as follows.

$$V_{total} = V_{PEMFC} + V_{PV} + V_{batt} + V_{SC} \quad (6)$$

Where,

V_{total} : The total voltage supplied to the load

$V_{PEMFC,PV,batt,SC}$: The voltage generated by each energy source

With the integration of PV into the system, the EMU not only harnesses renewable energy to support the load but also alleviates the strain on the PEMFC and energy storage, thereby enhancing the efficiency and sustainability of the system.

C. Modelling of DC-DC Buck/Boost Converter

The DC-DC Buck Boost Converter is a power converter capable of either stepping up (boosting) or stepping down (buck) the output voltage based on the system's requirements. In a hybrid system based on Proton Exchange Membrane Fuel Cells (PEMFC), this converter plays a crucial role in regulating the power distribution from various energy sources, such as the fuel cell, battery, supercapacitor, and Photovoltaic (PV) systems. The converter adjusts the input voltage to a stable output by controlling the duty cycle of semiconductor switches, such as MOSFETs.

In buck mode, the converter lowers the output voltage to match the load requirements, while in boost mode, the output voltage is increased. The output voltage (Vout) is calculated based on the input voltage (Vin) and the duty cycle (D) as follows.

Boost Mode

$$V_{out} = \frac{V_{in}}{1 - D} \quad (7)$$

Buck Mode

$$V_{out} = D \cdot V_{in} \quad (8)$$

The duty cycle (D) represents the ratio of the time the switch is on to the total duration of one cycle.

$$D = \frac{T_{on}}{T_{on} + T_{off}} \quad (9)$$

Where,

T_{on} : Turn On Time

T_{off} : Turn Off Time

The converter operates based on the principle of energy storage and release by the inductor, controlled in real-time by the controller within the EMU. This controller dynamically adjusts the converter's operating mode, either boosting or bucking the output voltage, based on changes in system conditions, such as sudden increases in power demand or excess power from a specific source. The converter intelligently selects the appropriate energy source, such as PV when solar intensity is high to maximize solar energy utilization, or the battery for immediate power needs. With the integration of PV, the converter helps reduce the workload on the fuel cell and extends the battery lifespan. The stability of the DC bus voltage is maintained even amidst power fluctuations from various sources, enabling the converter to support the overall system efficiency by ensuring that each energy source is used optimally according to the current needs and operational priorities.

3. METHOD

In an Energy Management Unit (EMU), effective control over power distribution from various energy sources is crucial to ensuring energy efficiency, system stability, and the longevity of components. This research examines and analyzes three control strategies applied in the EMU modeling: Proportional-Integral (PI) control and the External Energy Management Strategy (EEMS). Each of these control strategies is described in detail as follows.

A. Proportional-Integral (PI) Control

Proportional-Integral (PI) Control is one of the most fundamental and widely used control strategies due to its simplicity. PI control combines two essential components. Proporsional (P) aims to reduce the error in proportion to the detected error. Integral (I) corrects the cumulative error over time to ensure system stability.

Proporsional Integral (PI) Control Equation

$$V_{control}(t) = K_p \cdot e(t) + K_i \cdot \int e(t)\, dt \tag{10}$$

Where,

$V_{control}$	:	Control Voltage
$e(t)$	:	Error (the difference between the desired output and the actual output)
K_p *dan* K_i	:	Proportional and integral constants tuned to maintain system stability

B. External Energy Management Strategy (EEMS)

The External Energy Management Strategy (EEMS) is an adaptive control strategy designed to enhance energy efficiency in Proton Exchange Membrane Fuel Cell (PEMFC) based hybrid systems by incorporating external energy sources such as Photovoltaics (PV), batteries, and supercapacitors based on realtime operational conditions. The core concept of EEMS is to reduce hydrogen consumption by maximizing the use of energy from batteries and supercapacitors within predefined limits, and by utilizing PV energy to alleviate the load on the PEMFC. A key advantage of EEMS lies in its simplicity, requiring only the cost functions of the battery and supercapacitor without the need for empirical battery energy calculations. As illustrated in Figure 2, EEMS inputs include the battery state of charge (SOC), DC bus voltage (Vdc), and PV power. The EEMS algorithm produces two primary outputs: the battery power reference and the supercapacitor voltage (ΔV). The battery power is compared with the load power demand to determine the fuel cell power reference (Pfc*) and the fuel cell current (Ifc*). Meanwhile, the supercapacitor voltage and the reference DC bus voltage (Vdc_ref) are compared with the actual DC bus voltage to decide whether the supercapacitor needs to be charged or discharged. With the integration of PV as one of the external energy sources, EEMS ensures maximum utilization of solar energy, supports the system's power needs, and maintains DC bus voltage stability despite power fluctuations. This approach not only reduces dependence on the PEMFC but also improves the overall operational efficiency of the hybrid system and extends the lifespan of components such as batteries, supercapacitors, and the fuel cell.

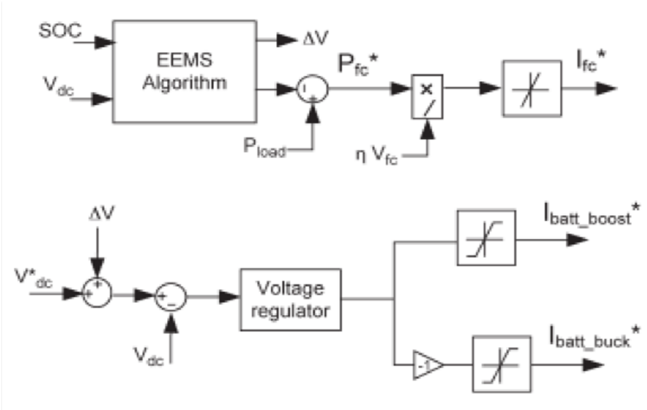

Figure 2. EEMS Strategy Framework

The Proton Exchange Membrane Fuel Cell (PEMFC) was selected for this study due to its capability to deliver stable and efficient power, with current and voltage levels suitable for hybrid power systems. The specifications of the PEMFC used (refer to Table 1) include a nominal power output of 10,287.5 W and a peak power of 12,544 W, reflecting its capacity under normal and peak operational conditions. The open-circuit voltage is 52.5 V, while the nominal voltage under standard load conditions is 41.15 V. This fuel cell operates at a nominal current of 250 A, with a peak current capability of up to 320 A. These attributes make the PEMFC an ideal choice for systems requiring a reliable and efficient power source, especially in applications that demand rapid response and high power stability. These parameters ensure optimal performance in supporting the hybrid power system framework proposed in this study.

Table 1. PEMFC Spesifications

Parameter	Unit (Symbols)	Value
Nominal Power	$P_{nom}\ (W)$	10287,5
Maximum Power	$P_{max}\ (W)$	12544
Operating Temperature	$T\ (K)$	318,15
Open Circuit Voltage	$E_{oc}\ (V)$	52,5
Voltage at 1 A	$V_1\ (V)$	52,46
Nominal Voltage	$V_{nom}\ (V)$	41,15
Voltage at Maximum Operating Point	$V_{max}\ (V)$	39,2
Nominal Current	$I_{nom}\ (A)$	250
Maximum Current	$I_{max}\ (A)$	320
Number of Electron Movements	z	2
Universal Gas Constant	$R(J/mol\ K)$	83,145
Faraday Constant	$F(A\ s/mol)$	96485
Boltzman Constant	$k\ (J/K)$	$1{,}38\times\ 10^{-23}$
Planck's Constant	$h\ (J\ s)$	$6{,}626 \times 10^{-34}$

Parameter	Unit (Symbols)	Value
Absolute Fuel Supply Pressure	P_{fuel} (nom) (atm)	1,16
Absolute Air Supply Pressure	P_{air} (nom) (atm)	1
Nominal Air Flow rate	V_{air} (nom) (atm)	732
Nominal Fuel Flow rate	$V_{fuel\,(nom)}$ (lpm)	114,9
Nominal Fuel Composition	$x_{nom}(\%)$	99,95
Nominal Air Composition	y_{nom} $(\%)$	21
Nominal Water Vapor Composition	w_{nom} $(\%)$	1
Voltage Constant at Nominal Operation Condition	K_c	11,491

Lithium-ion batteries were selected for this study due to their high energy storage efficiency and ability to provide stable power within the hybrid power system. The battery specifications (see Table 2) include a nominal voltage of 48 V, which is the standard voltage under normal operating conditions. The battery's maximum capacity of 40,000 mAh provides substantial energy storage to support the system. The cut-off voltage of 36 V indicates the minimum operational voltage, while the fully charged voltage is noted at 55.87 V. Designed to deliver a nominal discharge current of 17.39 A, the battery's low internal resistance of 0.012 Ω ensures high energy efficiency and minimal power loss during charging and discharging. These features make lithium-ion batteries a robust and efficient backup power source for the PEMFC-based hybrid system.

The supercapacitor used in this study is specified (see Table 3) to enhance the hybrid power system by providing additional power during sudden load surges. It has a capacitance of 15.6 F, indicating its capability to store and release large amounts of energy rapidly. The series resistance of 150 mΩ ensures efficient energy transfer with minimal power loss. The rated voltage is 291.6 V, achieved by arranging 108 capacitors in series and one capacitor in parallel, ensuring optimal voltage stability. The initial voltage of 270 V signifies the voltage at the start of operation. Designed to operate at an ambient temperature of around 25°C, the supercapacitor maintains stable performance under standard operating conditions. These specifications highlight the supercapacitor's critical role in stabilizing the system by providing supplementary power when needed without compromising overall performance.

The photovoltaic (PV) panels simulated in this study are based on the Trina Solar TSM-250PA05 model, chosen for their efficient and stable power generation capabilities. Each panel has a maximum power output of 250 W, adequately supporting the hybrid power system's energy supply. Comprising 60 cells per module, these PV panels offer high energy conversion efficiency. The open circuit voltage is recorded at 37.6 V, with a maximum operating voltage of 31 V, allowing the PV panels to function effectively within a suitable voltage range for renewable energy applications. The current at maximum power point is 8.06 A, contributing to consistent power generation. The shunt resistance of 301.8 Ω and series resistance of 0.25 Ω indicate high panel efficiency with minimal power loss. Selected for their reliable performance, high power efficiency, and adaptability to varying lighting conditions, the Trina Solar TSM-250PA05 panels are an excellent choice for supporting the PEMFC-based hybrid power system.

Table 2. Battery Spesifications

Parameter	Description
Baterry Type	Lithium-Ion
Nominal Voltage	48 V
Maximum Capacity	40000 mAh
Cut-Off Voltage	36 V
Fully Charge Voltage	55.87 V
Nominal Discharge Current	17.39 A
Internal Resistance	0.012 Ω

Table 3. Supercapasitor Spesifications

Parameter	Description
Rated Capacitance	15.6 F
Series Resistance	150×10^{-3}
Rated Voltage	291.6 V
Number of Series Capacitors	108
Number of Parallel Capacitors	1
Initial Voltage	270 V
Operating Temperature	25 ˚C

Table 4. Photovoltaic (PV) Spesifications

Parameter	Description
PV Brand	Trina Solar TSM-250PA05
Maximum Power	250 W
Cells Per Module	60
Open Circuit Voltage	37.6 V
Short-Circuit Current	8.55 A
Voltage At Maximum	31 V
Current At Maximum	8.06 A
Shunt Resistance	301.8 Ω
Series resistance	0.25 Ω

4. RESULT AND DISCUSSION

This study evaluates the performance of the Energy Management Unit (EMU) in a PV-Fuel Cell hybrid power system that integrates a Proton Exchange Membrane Fuel Cell (PEMFC), battery, supercapacitor, and photovoltaic (PV) panels. Two control methods, Proportional Integral (PI) and External Energy Management Strategy (EEMS), are compared through simulations in Matlab/Simulink under varying load conditions of 50, 40, 15, 10, 25, 40, 5, and 10 Ω.

Figure 3 illustrates the load power (Pload) sharply increasing from 4000 W to 6000 W around the 100th second. The photovoltaic power (Ppv) remains stable at approximately 3000 W, while the fuel cell power (Pfc) rises from 2000 W to 5000 W, albeit with a slightly delayed response to the load changes. The battery power (Pbatt) fluctuates between -2000 W and 2000 W to balance the system, while the supercapacitor power (Psc) quickly responds with power fluctuations ranging from -3000 W to 3000 W.

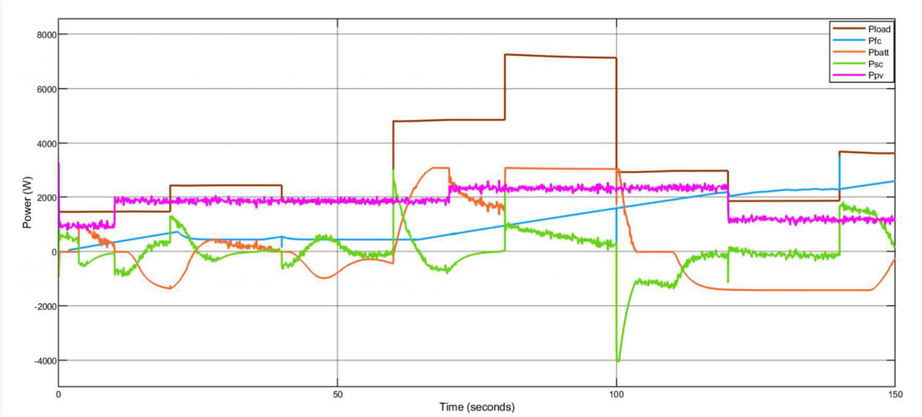

Figure 3. Power Distribution Using the PI Control System

The PI control system demonstrates its ability to maintain power stability despite the delayed response of the fuel cell. The overall system effectively balances power contributions from various sources, with the rapid response of the supercapacitor playing a crucial role in handling sudden load changes. This test serves as a foundational evaluation before comparing it with other control strategies, such as the External Energy Management Strategy (EEMS).

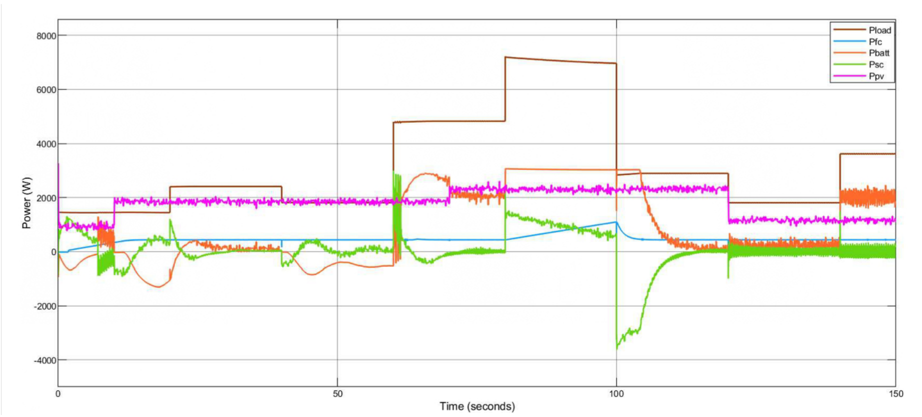

Figure 4. Power Distribution Using the EEMS

The test results using the External Energy Management Strategy (EEMS) in Figure 6 demonstrate a sharp increase in load (Pload) from 4000 W to 6000 W around the 100th second. The photovoltaic panels (Ppv) remain stable at approximately 3000 W, consistently contributing power throughout the test. The fuel cell (Pfc) responds more swiftly compared to PI control, with power output increasing from 2000 W to 5000 W as the load rises. The battery (Pbatt) fluctuates between -2000 W and 2000 W to balance the power, while the supercapacitor (Psc) responds rapidly, showing power fluctuations between -3000 W and 3000 W.

The quick response of the fuel cell and supercapacitor reflects EEMS's ability to effectively adjust power output to sudden load changes. Overall, EEMS exhibits more responsive and efficient performance compared to PI control, stabilizing the system more swiftly and making it a more optimal choice for maintaining power stability and energy efficiency, particularly under varying load conditions.

The efficiency graph for the Proportional Integral (PI) method in Figure 5 shows a fluctuating pattern, stable under constant load but less responsive to significant changes. Efficiency is calculated using the formula $\mu = \frac{P_{input}}{P_{output}}$. Under stable conditions, with an input power of 4000 W and output of 3600 W, efficiency is recorded at 0.9 or 90%. At peak efficiency, output power increases to 5600 W, resulting in an efficiency of 1.4 or 140%. Conversely, when efficiency drops, output power decreases to 2400 W, yielding an efficiency of 0.6 or 60%. The average efficiency across these conditions is 0.97 or 97%. These results indicate that the PI method can maintain relatively high efficiency, despite significant fluctuations during sudden load changes.

The efficiency graph for the External Energy Management Strategy (EEMS) in Figure 6 displays a more stable pattern with a few significant peaks at certain times. The formula for calculating efficiency is $\mu = \frac{P_{input}}{P_{output}}$. In stable conditions, with an input power of 4000 W and output of 3600 W, efficiency is recorded at 0.9 or 90%. During a minor surge, output power rises to 4800 W, resulting in an efficiency of 1.2 or 120%. After the surge, efficiency stabilizes again with an output power of 3800 W, providing an efficiency of 0.95 or 95%. This demonstrates that EEMS can better manage efficiency surges, keeping fluctuations within more controlled limits.

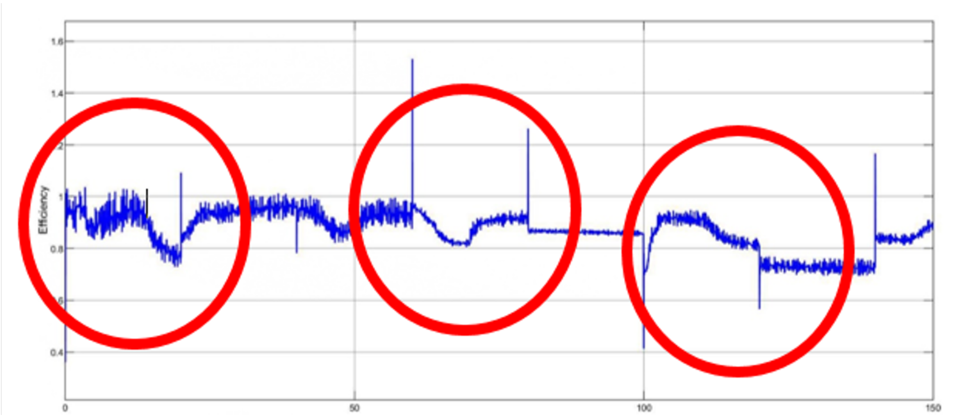

Figure 5. Efficiency of the Energy Management Unit (EMU) Utilizing PI Control Strategy

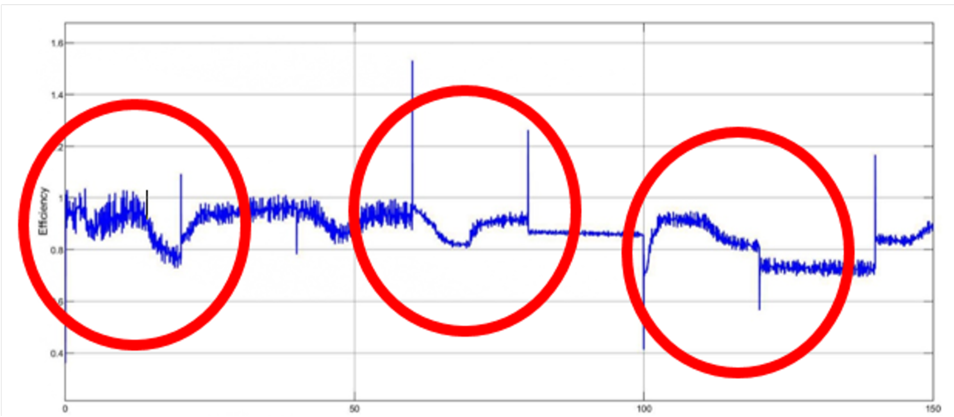

Figure 6. Efficiency of the Energy Management Unit (EMU) Utilizing EEMS

5. CONCLUSION

Based on the analysis conducted, the following conclusions can be drawn:

1. The EEMS method, with an average efficiency ranging from 0.85 to 0.92, outperforms the PI method, which achieves an average efficiency between 0.80 and 0.87.
2. EEMS effectively maintains minimal fluctuations, between 0.02 and 0.03, even with dynamic load changes. In contrast, the PI method exhibits more pronounced fluctuations, varying from 0.05 to 0.08.

CREDIT

Conceptualization, Methodology, Writing - original draft preparation, and Supervision: Cindy Reviko Ekatiara, Katherin Indriawati; Formal analysis and investigation: Cindy Reviko Ekatiara; Writing - review and editing: Cindy Reviko Ekatiara.

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