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ORIGINAL RESEARCH ARTICLE

Reducing hydrogen consumption in hybrid electric vehicles using Aquila optimization algorithm

A.M. Nassef[1,*], H.E. Ghadbane[2], E.T. Sayed[3], H. Rezk[1]

[1] *Department of Electrical Engineering, College of Engineering in Wadi Alddawasir, Prince Sattam bin Abdulaziz University, Wadi Alddawasir 11991, Saudi Arabia*

[2] *Département d'Electrotechnique et Automatique, Laboratoire de Génie Électrique de Guelma, Université 8 Mai 1945, Guelma 24000, Algeria*

[3] *Chemical Engineering Department, Faculty of Engineering, Minia University, Egypt*

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ABSTRACT

BACKGROUND AND OBJECTIVES: Fuel cell hybrid electric vehicles have earned significant interest owing to their superior performance and ecological advantages. Crafting an energy management approach aimed at boosting the performance of fuel cell electric vehicles by effectively managing power distribution among diverse energy sources represents a vital engineering challenge. This approach considers issues such as hydrogen consumption and efficiency. The objectives of this study were: 1) Developing a state-of-the-art energy management system for fuel cell hybrid electric vehicles to maximize electrical efficiency, reduce fuel consumption, and achieve optimal power distribution. 2) Applying the aquila optimizer to the proposed system to enhance the external energy maximization strategy.
METHODS: Metaheuristic optimization algorithms play a vital role in obtaining the best set of fuel cell electric vehicles' parameters. Among the newest and most efficient algorithms, the Aquila optimization algorithm is highly regarded. It was used in the proposed energy management strategy to optimize the approach of maximizing external energy, resulting in reduced hydrogen use and improved system efficiency. To assess the effectiveness of the proposed energy management strategy, the federal test procedure was utilized to mimic city driving conditions, allowing for a comparative simulation against eight proficient algorithms.
FINDINGS: The simulation findings illustrated that the suggested energy management strategy surpasses other currently available solutions resulting from competitive optimizers by reducing the consumption of fuel, with a considerable decrease of 52.26 percent. Additionally, the recommended energy management strategy technique exhibited a 3.08 percent enhancement in system efficiency.
CONCLUSION: The proposed strategy showed outstanding results over the other methods. Moreover, advancements in the energy management strategy have the capacity to lower dependence on traditional fossil fuels and alleviate the harmful environmental consequences produced by the vehicle's emissions. Consequently, adopting a sustainable transportation framework powered by renewable hydrogen production will substantially lessen detrimental impacts and foster a cleaner and greener environment.

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*Corresponding Author:
Email: *a.nasef@psau.edu.sa*
Phone: +55273 4179
ORCID: 0000-0001-9604-5737

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INTRODUCTION

There is a unanimous agreement that cutting down on gas emissions is crucial for the preservation of our world. To accomplish this goal, everyone should give a hand to the development and transformation to green as well as renewable sources of energy. Examples of green energy sources include biomass, biogas, and fuel cells, whereas solar, wind, and hydro energy fall under the umbrella of renewable energy sources (Ramli *et al.,* 2022; Rashif *et al.,* 2025). The route of using alternatives to fossil fuels will lead to lowering the carbon dioxide (CO_2) emissions in order to decrease global warming by 1.5 degrees Celsius (^oC) as decided in the Conference of Parties (COP-26), which was held in Glasgow, United Kingdom (UK), in 2021 (Nassef *et al.,* 2023). In November 2024, the United Nations conducted the 29th summit of the COP-29 in Azerbaijan as a continuous effort, from its side, to tackle climate change. It is anticipated that during the upcoming COP-30, scheduled to take place in Brazil in November 2025, all prior recommendations will be translated into tangible actions. Some may argue that the emissions from one vehicle are insignificant relative to the output of an industrial factory. Nevertheless, when examining the cumulative emissions from millions of vehicles around the world, it becomes clear that the overall figure is indeed considerable. The electric vehicle is an alternating tool that uses an electric motor (electrical energy) instead of the traditional internal combustion engine (thermal energy) to obtain motion (mechanical energy). Both means give the same results (motion) however, the former is environmentally friendly and the latter is not. Within this framework, the evolution and transition to electric vehicles are progressing and have attracted considerable focus from researchers in numerous fields, particularly in engineering (Santoso *et al.*, 2024). To maximize the power delivered to the electric vehicle, an efficient energy management system (EMS) is needed to optimize the operation of the different power sources. The demand for energy has grown steadily during industrial development. Industrial progress has led to a significant increase in the need for fossil fuels (York and Bell, 2019). Hydrogen can be made as an alternative fuel by the process of either reforming carbon-based fuels or by using power from renewable sources to split water (Payakkamas *et al.*, 2023). The adoption of electric vehicles presents an encouraging approach to lowering carbon emissions in the transportation sector. For efficient reduction of CO_2 emissions, the fuel cell hybrid electric vehicle (FCEV) is an incredibly promising technology. Hydrogen fuel cells (FC) and energy storage systems (ESS) work together in FCEV technology to power the electric motor (Veziroglu and Macario, 2011). Energy savings and fuel economy are both improved by FCEV technology (Arat, 2019). FCEVs present a variety of advantages, such as not relying on fossil fuels, being compact in size, operating quietly, and delivering outstanding performance without generating any polluting emissions (Changizian *et al.*, 2020). Sivakumar (2020) conducted studies on the use of double-chambered salt bridge microbial fuel cells (MFCs) for treating dairy industry wastewater and generating bioelectricity. The optimal parameters identified were 1 molar potassium chloride (MKCl) concentration, 10 percent (%) agarose concentration, and a 0.05 meters (m) salt bridge, achieving up to 89.7% reduction in chemical oxygen demand (COD) and producing power. In a later investigation, Sivakumar (2021) reinforced these conclusions by reporting an 86.3% decrease in COD along with substantial energy output, showcasing the capability of MFCs in removing pollutants and generating power. Hidayat *et al*. (2024) focused on torrefying bamboo pellets for renewable energy in Indonesia, using a fixed counterflow multibaffle reactor. Their findings highlighted bamboo as a promising biomass source for co-firing, offering an effective solution for reducing reliance on fossil fuels and mitigating greenhouse gas emissions. As a result, electric vehicles (EVs) are expected to significantly participate in improving the future smart grids and create a sustainable transportation sector for a safe environment (Nazari-Heris *et al.,* 2022). ESS, encompassing both supercapacitors and batteries, is tasked with handling large power surges that occur during both acceleration and deceleration. On the other hand, the power system of a FCEV is completely electric (Wang *et al.*, 2023). To address the sluggish performance of fuel cells and the limited longevity of batteries, it is imperative to combine them with a high-capacity energy storage technology such as supercapacitors (SCs), which provide quick response times. Hybridization is crucial for overcoming these limitations and improving overall efficiency (Djerioui *et al.*, 2019; Sorlei *et al.*, 2021). By optimizing the operational environment of the fuel cell system,

hybridization significantly enhances its overall performance. In the electric vehicle, it is essential to devise a suitable energy management system responsible for allocating power among the hybrid power sources, taking into account certain constraints that must be satisfied to enhance performance and minimize fuel consumption. Still, the main issue at hand is the effectiveness of the chosen EMS. To attain this objective, numerous EMSs have been documented in the research literature. Generally, EMSs can be categorized into optimization and rule-based systems, as indicated in (Eddine *et al.*, 2022; Zhang *et al.*, 2020). This approach is characterized by a collection of sequential "IF-THEN" rules, which can be divided into two primary subcategories: deterministic and intelligent. The state machine control (SMC) and load following EMS are representative of the deterministic type (Ghadbane *et al.*, 2024a; Ghadbane *et al.*, 2024c). On the other hand, the intelligent strategies are represented by the fuzzy logic-based EMS (Sulaiman *et al.*, 2015). Although this system is simple to design and implement, its performance is constrained by the designer's knowledge and experience (Rahman *et al.*, 2021). Optimization-based approaches utilize tools inherent in the optimization theory to address problems, such as the one at hand. Optimization methods can be classified as either offline (global scale) or online (real-time scale). Offline optimization EMS involves identifying an optimal control solution for a predetermined situation, such as a speed profile. A range of methodologies is present, with disciplined optimum control being one that focuses on direct approaches. However, indirect techniques such as Pontryagin's maximal principle (PMP) (Bauer *et al.*, 2014) and calculus of variations (Peng *et al.*, 2020) are also used. Dynamic programming (DP) (Zhang and Xiong, 2015) and stochastic dynamic programming (Leroy *et al.*, 2014) (SDP) are two computational techniques used in optimization problems. DP is an approach that deconstructs a complicated problem into smaller subproblems, solving each one recursively. Conversely, SDP integrates a layer of uncertainty and randomness into the decision-making process. These techniques have been extensively studied and applied in various fields. These solutions necessitate familiarity with the complete load profiles, leading to the need for extensive data calculations. The development of online approaches is guided by the changes in the objective function value, which bolsters their durability and performance. In this context, the equivalent-consumption-minimization-strategy (ECMS) as outlined by (Lei *et al.*, 2020). The use of real-time strategies is necessarily less than optimum. ECMS is a result of the application of optimum control philosophy. As stated by Serrao *et al.* (2009), the ECMS is developed and showcased using the PMP technique as its foundation. The analogous factor fulfills a function akin to the co-state in the PMP approach. The offline optimization challenge can be optimally resolved through PMP technique. Also, the offline optimization problem can be optimally solved using ECMS with a constant co-state (Zheng *et al.*, 2014). The external energy maximization strategy (EEMS) outlined by Dhifli *et al.* (2020). By optimizing the utilization of both the SC and the battery, the EEMS system strives to enhance power output, hence resulting in an implicit enhancement in the total system efficiency. Moreover, the FC maintains a consistent state with restricted movement, delivering power exclusively to fulfill demand. The battery and SC act as the key sources for managing transient loads. Thus, this will improve the system's efficiency. Numerous studies have confirmed that the integration of metaheuristic algorithms (MAs) with online EMSs can achieve optimal results. Nevertheless, the application of these algorithms in engineering has experienced significant expansion. In the field of engineering applications, these algorithms have been exceedingly popular (Antarasee *et al.*, 2022). An enhanced version of ECMS and EEMS has been introduced by Rezk *et al.* (2021). This version employs two metaheuristic optimizers, the salp swarm algorithm (SSA) and the mine blast algorithm (MBA), to conduct the optimization process. Merging the SSA with the EEMS leads to peak efficiency and enhanced fuel consumption performance. Using a number of meta-heuristic optimization methods, including an artificial bee colony optimization algorithm (ABC) and a whale optimization algorithm (WOA), Zhao *et al.* (2019) performed a comparison analysis. The findings obtained in this study indicate that the optimized EEMS utilizing the Grey Wolf optimizer (GWO) surpasses the ECMS and its optimized variants. In order to enhance fuel efficiency, a genetic fuzzy-based EMS was suggested by Ahmadi *et al.* (2018). Utilizing a genetic algorithm, an optimized EMS was

developed, as detailed by Lü *et al.* (2020). An approach for managing a hybrid storage system that combines batteries and supercapacitors. The battery energy storage (BES) system demonstrated advantages in preserving the battery state of charge (SoC). An optimized EMS was proposed using a salp swarm algorithm, as outlined by Ghadbane *et al.* (2024). Although various optimization algorithms such as Harris hawks optimization (HHO), PSO, and manta ray foraging optimization (MRFO). The application of MRFO methods aims to optimize energy management in hydrogen fuel cell systems, yet these approaches often face drawbacks, including poor convergence performance, a high sensitivity to parameter settings, and limited flexibility in response to different driving conditions (Rezk *et al.*, 2023). Furthermore, many existing methods focus primarily on minimizing hydrogen consumption without simultaneously optimizing system efficiency and overall performance metrics. In response to these deficiencies, the current study proposes an ECMS-based Aquila optimization algorithm system that flexibly adjusts to changing operating conditions. This system achieves considerable reductions in hydrogen consumption, increases system efficiency, and improves overall performance relative to standard optimization techniques. The main goal of this study is to minimize hydrogen usage to improve the performance of the entire power system, capitalizing on the remarkable effectiveness of the Aquila optimizer, while introducing the application of this algorithm to this specific domain for the first time. The actual application of this technology can improve the driving experience of electric vehicles by increasing their range with more efficient fuel usage and higher energy efficiency. To assess the performance and efficiency of the proposed EMS, the resulting fuel consumption and the associated system's efficiency have been compared to the results of other competitive MAs such as equilibrium optimizer (EO) (Faramarzi *et al.*, 2020), GWO (Mirjalili *et al.*, 2014), RIME-based optimization (RIME) (Su *et al.*, 2023), rain optimization algorithm (ROA) (Moazzeni and Khamehchi, 2020), Northern Goshawk optimization (NGO) (Dehghani *et al.*, 2021), Multi-verse optimizer(MVO) (Mirjalili *et al.*, 2016), White Shark optimizer (WSO) (Braik *et al.*, 2022), and Leopard Seal optimization (LSO) (Rabie *et al.*, 2023). This study's main focus is on developing an improved version of the standard ECMS, which is designed to greatly decrease fuel usage while boosting electrical efficiency. This study aims to accomplish the following primary objectives: 1) Develop a state-of-the-art power management system for FCEVs that maximizes electrical efficiency, reduces fuel consumption, and achieves optimal power distribution. 2) The proposed EMS is accompanied with the Aquila optimizer (AO) to ECMS. This study has been carried out in Saudi Arabia in 2025.

MATERIALS AND METHODS

Architecture for FCEVs

The FCEV generates its power from several components, including a lithium-ion battery, energy storage devices built around supercapacitors, and the main source of energy, a proton exchange membrane fuel cell (PEMFC) (Fig. 1). A DC/DC boost converter that can only go in one direction links the fuel cell to the DC connection. The connection of the battery is established through a bidirectional DC/DC boost converter, with the DC bus directly linked to the SC. In contrast, a bidirectional DC/AC converter powers the vehicle's motor in both traction and braking modes, facilitating current flow in both directions between the DC bus to the motor.

Model for vehicle traction

Here's a guide on how to calculate the traction force by examining the physical forces that affect the vehicle's body, as described in Eq. 1 (Eddine *et al.*, 2022a):

$$F_t = F_a + F_r + F_{acc} + F_{gr} \tag{1}$$

The variables F_a, F_r, F_{acc}, and F_{gr} represent the aerodynamic force, rolling resistance force, acceleration force, and resistance force, respectively. The following definitions are assigned to these forces, using Eq. 2 (Eddine *et al.*, 2022a):

$$\begin{cases} F_a = 0.5\,\xi\, C_d\, A_f\, (v \pm v_w)^2 \\ F_r = m_v\, g\, \mu \\ F_{acc} = \pm k_m\, m_v \dfrac{dv}{dt} \\ F_{gr} = \pm m_v\, g \sin\alpha \end{cases} \tag{2}$$

Following is a list of the variables used in the

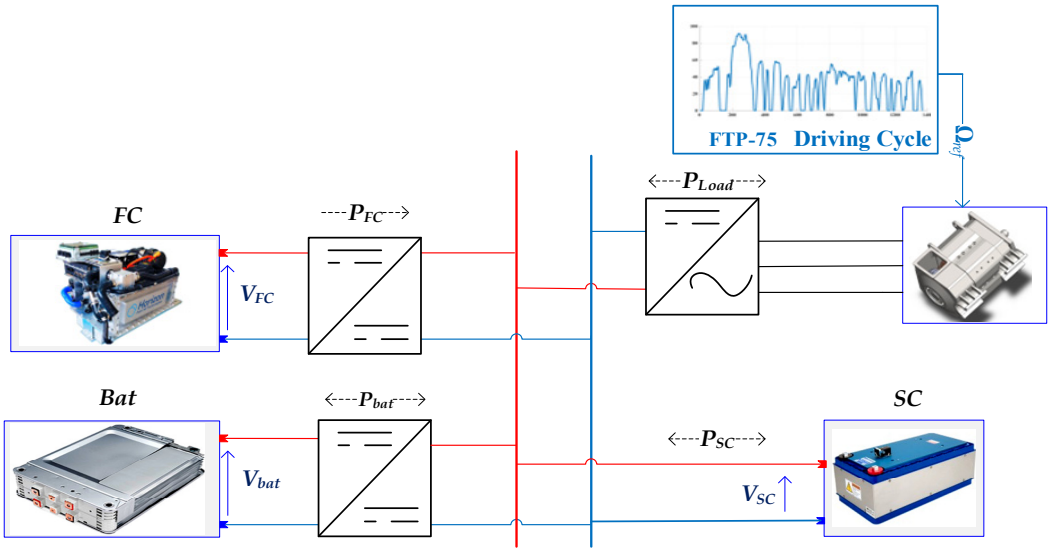

Fig. 1: The structure of the HPS for FHEV

equation: Here, v stands for the vehicle's speed in (m/s), v_w for the wind speed in (m/s), and α for the slope angle in rad. Also, where m_v is the vehicle's mass in kg, and g is the Earth's gravitational acceleration in (m/s^2). ξ denotes the air density in (kg/m^3), and μ stands for the tire's rolling resistance coefficient, which ranges from 0.015 to 0.3. A_f denotes the vehicle's frontal area in (m^2), and C_d varies from 0.2 to 0.4 as the coefficient of aerodynamic drag. k_m signifies the rotational inertia coefficient, which ranges from 1.08 to 1.1.

Hydrogen consumption model for FCs

The FC is an electrochemical device that uses the chemical energy of oxygen and hydrogen to generate electricity. The following relationship exists between the FC output current and hydrogen consumption, using Eq. 3 (Li *et al.*, 2019):

$$C_{H_2}\int_0^t \frac{m_{H_2} n_{cell}}{2F} i_{FC}(t)\,dt \tag{3}$$

The variable C_{H2} represents the rate at which hydrogen is consumed in (g/s). The variable n_{cell} represents the number of cells. m_{H2} represents the molar mass of hydrogen, which is 2.02 (g/mol). i_{FC} represents the output current of the fuel cell in amperes (A). F represents the Faraday constant, which is 96,487 coulombs (C).

Model for estimating the SoC in batteries

Model for estimating the SoC in batteries suggests that the SoC of a battery can be computed using Eq. 4 (Ghadbane *et al.*, 2024d):

$$SOC(t) = SOCi - \frac{1}{Q}\int i_{bat}\,dt \tag{4}$$

Where, SOC_i denotes the initial SoC of the battery.

The suggested approach for energy management

The energy management strategy was created with the key objectives of boosting efficiency, lengthening the operational life of batteries and supercapacitors, and decreasing fuel consumption.

Outlining the Issue

Reducing hydrogen consumption and keeping the battery SoC within allowed values are two goals of the ECMS. The ECMS seeks to optimize the power supply by fully leveraging the capabilities of the bus capacitor and battery, as outlined in Eq. 5 (Ghadbane *et al.*, 2024d):

$$f_{obj} = \min\left(\Delta T.P_{bat} + \frac{C_{bus}.v^2}{2}\right) \tag{5}$$

in which ΔT denotes the sample time, v stands for the charge/discharge voltage, P_{bat} denotes the battery power supplied at ΔT, and C_{bus} is the DC bus supercapacitor capacitance. The energy provided by the battery, contingent upon its system on a chip, imposes limitations on this function through an inequality framework. This can be articulated as shown in Eq. 6 (Ghadbane *et al.*, 2024d):

$$P_{bat} \le \left(SoC - SoC_{\min}\right).V_{bat}.Q_{bat} \tag{6}$$

in which V_{bat} and Q_{bat} denote the nominal voltage and capacity of the battery, respectively, and SoC_{min} denotes the lowest possible level of the battery's SoC.

For the safety of the battery and to enhance power quality, it is important to regulate both the DC bus voltage and the power that is being supplied by the battery. The following is the manner in which these limitations are articulated, using Eq. 7 (Ghadbane *et al.*, 2024d):

$$\begin{aligned} V_{bus}^{\min} - V_{bus} \le v \le V_{bus}^{\max} - V_{bus} \\ P_{bat}^{\min} \le P_{bat} \le P_{bat}^{\max} \end{aligned} \tag{7}$$

In which the minimum and maximum voltages on the DC bus are represented by V_{bus}^{min} and V_{bus}^{max}, respectively.

Aquila optimizer

The AO is a population-based metaheuristic introduced by Abualigah *et al.* (Abualigah *et al.*, 2021). The classical AO follows five key steps:

Step 1: Initialization

During this phase, a variety of recommended random solutions is produced, and the AO parameters are initialized.

Step 2: Expanded Exploration

This stage emulates Aquila's fundamental hunting method, which involves soaring to a great height before executing a vertical plunge. The algorithm searches the space from a high position, represented mathematically by Eq. (8), where $X_1(t+1)$ is the next solution, and $X_{best}(t)$ is the best solution so far, using Eq. 8 (Abualigah *et al.*, 2021):

$$X_1(t+1) = X_{best}(t) \times \left(1 - \frac{t}{T}\right) + \left(X_M(t) - X_{best}(t) \times rand\right) \tag{8}$$

Step 3: Narrowed exploration

In this phase, Aquila engages in a shaped flight, gliding over a short distance while circling its prey. The behavior is mathematically captured in Eq. (9) (Abualigah *et al.*, 2021):

$$\begin{aligned} X_2(t+1) = X_{best}(t) \times Levy(D) + \\ \left(X_R(t) + (y - x) \times rand\right) \end{aligned} \tag{9}$$

Step 4: Expanded exploitation

During this phase, Aquila performs a low-level flight characterized by a gradual increase in the angle of attack, steadily approaching its prey, which can be illustrated by Eq. 10 (Abualigah *et al.*, 2021). Upper Bound (*ub*), Lower Bound (*lb*), and fixed exploitation parameters α and δ are involved.

$$\begin{aligned} X_3(t+1) = \left(X_{best}(t) \times X_M(t)\right) \times \alpha - \\ rand + \left((ub - lb) \times rand + lb\right) \times \delta \end{aligned} \tag{10}$$

Step 5: Narrowed exploitation

The final phase is inspired by Aquila's walk-and-grab attack, known as Narrowed Exploitation, and described in Eq. 11 (Abualigah *et al.*, 2021):

$$\begin{aligned} X_4(t+1) = QF \times X_{best}(t) - \\ \left(G_1 \times X(t) \times rand\right) - \left(G_2 \times Levy(D) + rand \times G_1\right) \end{aligned} \tag{11}$$

The complete AO procedure is outlined in a flowchart as shown in Fig. 2.

RESULTS AND DISCUSSION

Utilizing the MATLAB/Simulink environment, a simulation model has been created to test and validate the performance of each strategy. The components, including sources and converters, are represented by blocks from the SimPowerSystem blocks. The studied EMS was tested on the Driving Cycle FTP-75 to see how well it performed. Motor power and speed profiles for both FTP-75 are shown in Fig. 3.

In the simulations, the battery and supercapacitor were configured using the same set of parameters. There was a voltage of 270 V in the supercapacitor and a battery SoC of 70%. The hydrogen consumption rate in liters per minute is shown in Fig. 4 while Fig. 5 illustrates the H_2 consumption in grams versus

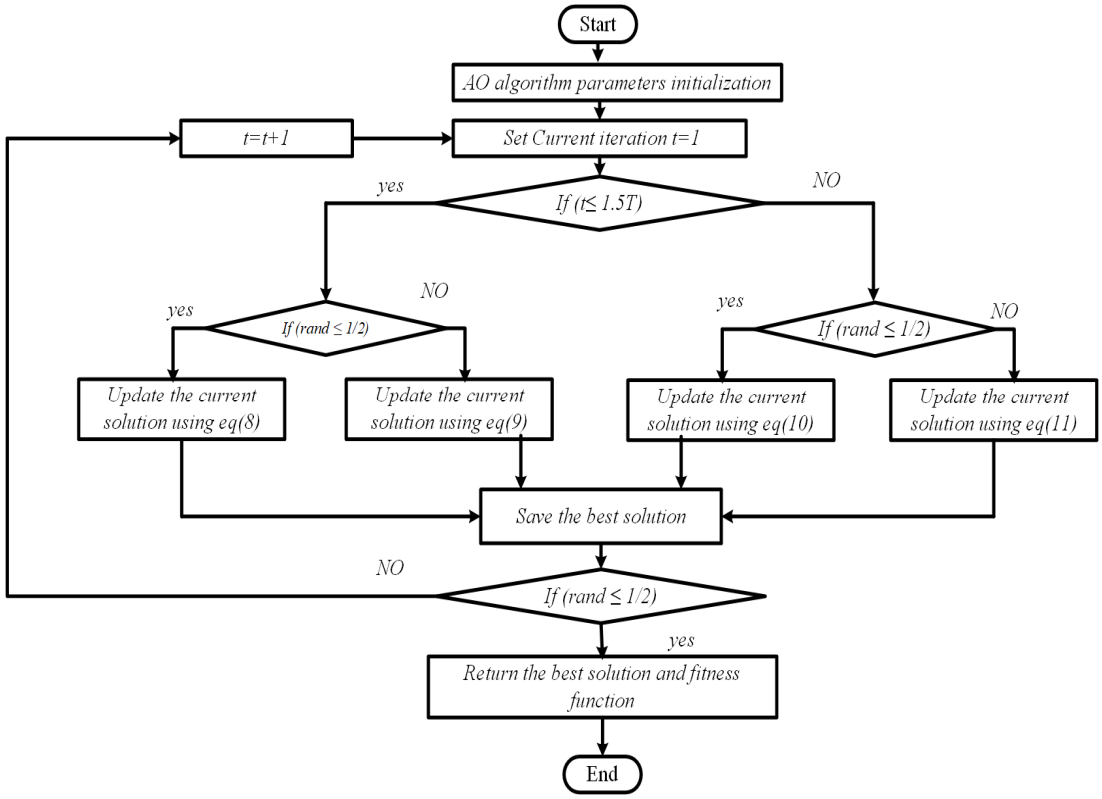

Fig. 2: Aquila optimizer flowchart

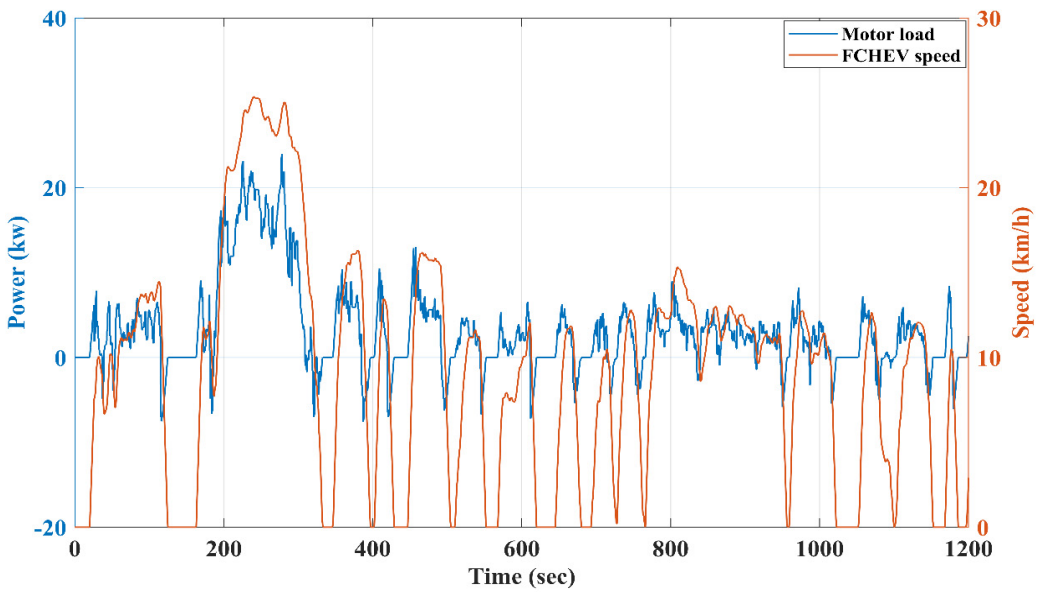

Fig. 3: Power and speed of the FTP-75 driving cycle

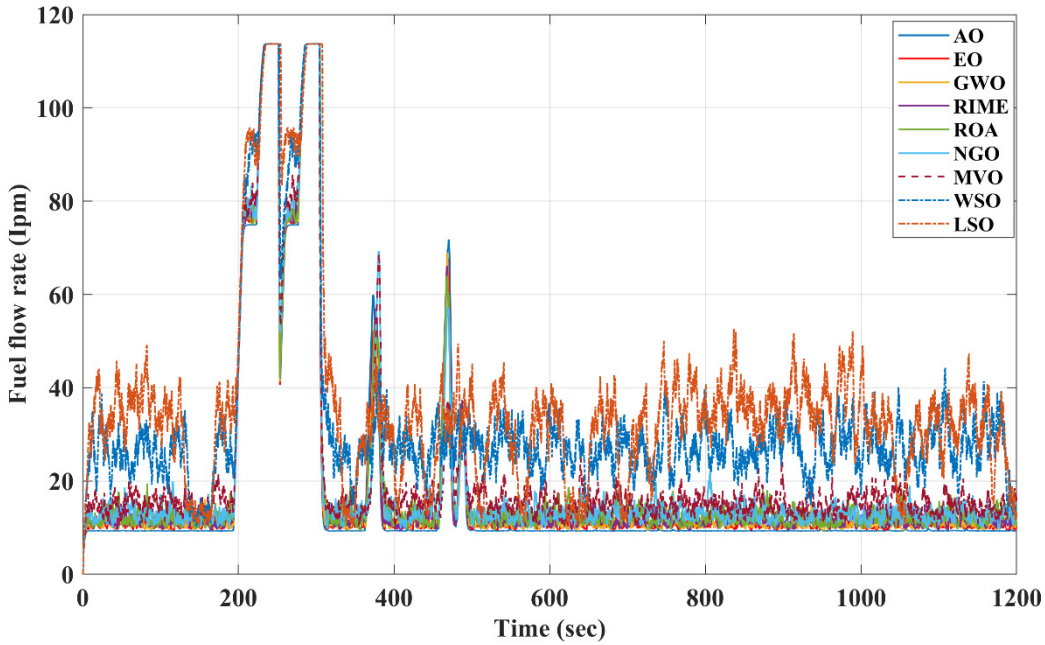

Fig. 4: consumption of hydrogen in (lpm)

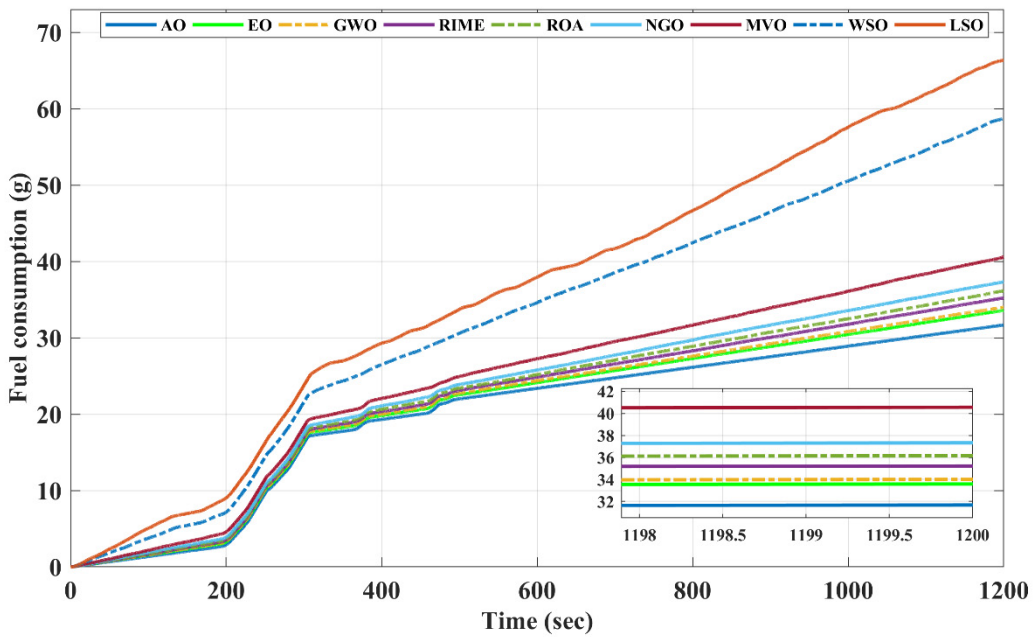

Fig. 5: Consumption of hydrogen (g)

Table 1: Comparative study of several acknowledged EMSs

EMS	Consumed H_2(g)	Efficiency (%)	Final SOC	H_2 Saving (%)	Efficiency 'Increase in h' (%)	Decrease in SoC (%)	Performance Index (%
EO	33.58	56.86	43.96	5.66	0.44	1.79	4.31
GWO	34	56.81	44.32	6.82	0.49	2.15	5.16
RIME	35.22	56.67	45.40	10.05	0.63	3.23	7.45
ROA	36.15	56.69	46.24	12.37	0.61	4.07	8.91
NGO	37.33	56.17	47.23	15.14	1.13	5.06	11.21
MVO	40.56	55.43	50.22	21.89	1.87	8.05	15.71
WSO	58.68	55.41	64.25	46.01	2.89	22.08	26.82
LSO	66.36	54.22	68.93	52.26	3.08	26.76	28.58
AO	31.68	57.3	42.17	0	0	0	0

time in seconds. These statistics reveal that the recommended approach can significantly decrease hydrogen usage and its consumption rate relative to the alternatives being assessed. This recommended strategy may lead to decreased hydrogen utilization and consumption levels relative to alternative methods.

Table 1 presents the comparative results among the several ESMs that were taken into account. The analysis demonstrated that AO based on ECMS is the best solution. The total quantity of hydrogen consumption decreases from 66.36 g (when utilizing the LSO-ECMS) to 31.68 g when the AO based on ECMS is implemented.

To summarize, the utilization of ECMS-based AO revealed considerable advancements relative to alternative control systems, specifically EO, GWO, RIME, ROA, NGO, MVO, WSO, and LSO. Initially, the ECMS-based AO system exhibited noteworthy decreases in hydrogen consumption. The drop was 5.66% compared to EO, 6.82% compared to GWO, 10.05% when measured against RIME, 12.37% compared to ROA, 15.14% in comparison to NGO, 21.89% compared to MVO, 46.01% compared to WSO, and 52.26% compared to LSO. The recommended method utilizing ECMS has proven to lower hydrogen consumption and enhance resource efficiency, highlighted by the substantial reduction in hydrogen usage. Moreover, the application of the ECMS-based AO technique substantially boosts the efficiency of the system. The efficiency enhancement was 0.44% higher than the EO, 0.49% higher than the GWO, 0.63% higher than the RIME, 0.61% higher than the ROA, 1.13% higher than the NGO, 1.87% higher than the MVO, 3.08% higher than the WSO, and 2.89% higher than the LSO. The observed improvements in efficiency indicate that the ECMS-based AO strategy excels in delivering enhanced performance in terms of generating hydrogen-powered systems. Consequently, it yields a more cost-effective and ecologically beneficial system. The ECMS-based AO approach presents certain advantages; however, it is important to evaluate the potential downsides in relation to the battery's SoC. The SoC decreased by 1.79% in comparison to the EO strategy, 2.15% in comparison to the GWO strategy, 3.23% in comparison to the RIME strategy, 4.07% in comparison to the ROA strategy, 5.06% in comparison to the NGO strategy, 8.05% in comparison to the MVO strategy, 22.08% in comparison to the WSO strategy, and 26.76% in comparison to the LSO strategy. Analyzing the decline in SoC is vital, as it can affect not just short-term outcomes but also long-term performance, which is key to maintaining the stability of the hydrogen-based system. The AO technique based on ECMS demonstrated substantial advancement in evaluating the comprehensive performance index. The improvement percentages compared to the EO, GWO, RIME, ROA, NGO, MVO, WSO, and LSO were 4.31%, 5.16 %, 7.45%, 8.91%, 11.21%, 15.71%, 27.08%, and 28.39%, respectively. The study by Rezk *et al.* (2023) employed three optimization techniques: HHO, particle swarm optimization (PSO), and MRFO. Their results during FTP-75 driving cycle

Table 2: Comparative analysis of several regarded EMSs (Rezk *et al.*, 2023)

EMS	Consumed H_2(g)	Efficiency (%)	Final SoC	H_2 Saving (%)	Efficiency Increase in *h'* (%)	Decrease in SoC (%)	Performance Index (%)
HHO	44.78	55.04	58.21	29.25	2.26	16.04	15.470
PSO	59.1	48.7	62.93	46.4	8.6	20.07	34.93
MRFO	63.61	47.17	64.42	50.02	10.13	22.25	37.9

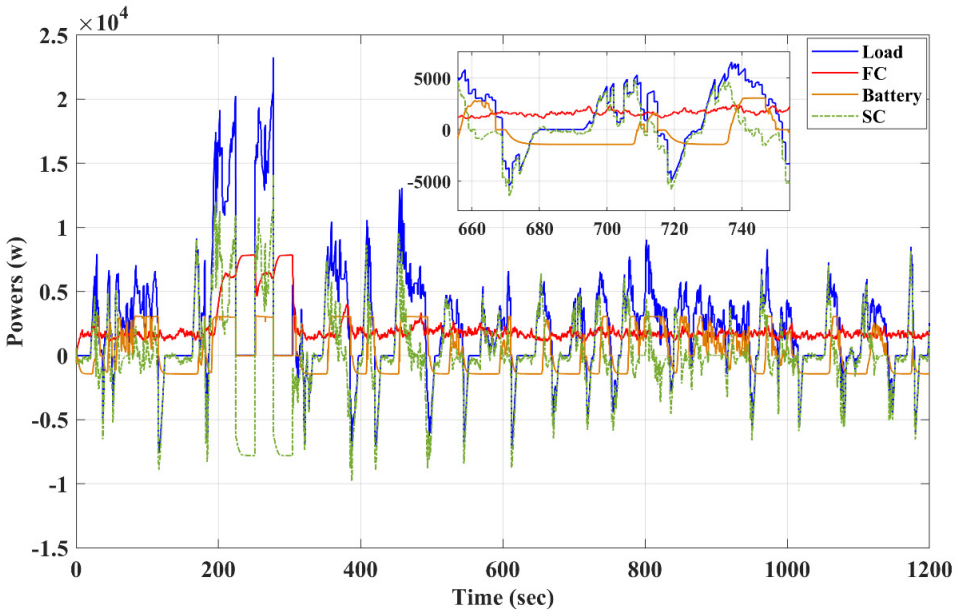

Fig. 6: Load, fuel cell, SC, and battery. power waveforms

confirmed the HHO's superiority. The data presented in Table 2 indicates that the ECMS-based AO system showed remarkable declines in hydrogen usage. The drop was 29.25 % compared to HHO, 46.4 % compared to PSO, and 50.02 % compared to MRFO. Furthermore, the utilization of the ECMS-based AO technique significantly enhances the efficiency of the system. The efficiency enhancement was 2.26% higher than the HHO, 8.6% higher than the PSO, and 10.13% higher than the MRFO. SoC decreased by 16.04% in comparison to the HHO strategy, 20.07% in comparison to the PSO strategy, and 22.25% in comparison to the MRFO strategy. The application of the AO technique with ECMS revealed considerable improvements in the evaluation of the comprehensive performance index. The improvement percentages compared to the HHO, PSO, and MRFO were 15.47%, 34.93%, and 37.9%, respectively.

As it is illustrated in Fig. 6, the FC is responsible for the bulk of the tasks, operating with slower dynamics, whereas the battery's role is to store additional energy for times when the fuel cell's efficiency declines. It may require a significant amount of time for FC to achieve its intended level of productivity. The battery can provide its stored energy when there is a surge in demand or a lack of power, which significantly boosts the system's reliability. Nevertheless, the rapid fluctuations in the load are mitigated by the implementation of a SC. Basically, storing/discharging electrical energy in/from SC usually runs smoothly due to the transient behavior of the capacitor which prevents the voltage on its terminals to change instantaneously.

Fig. 7 illustrates the FC voltage data that

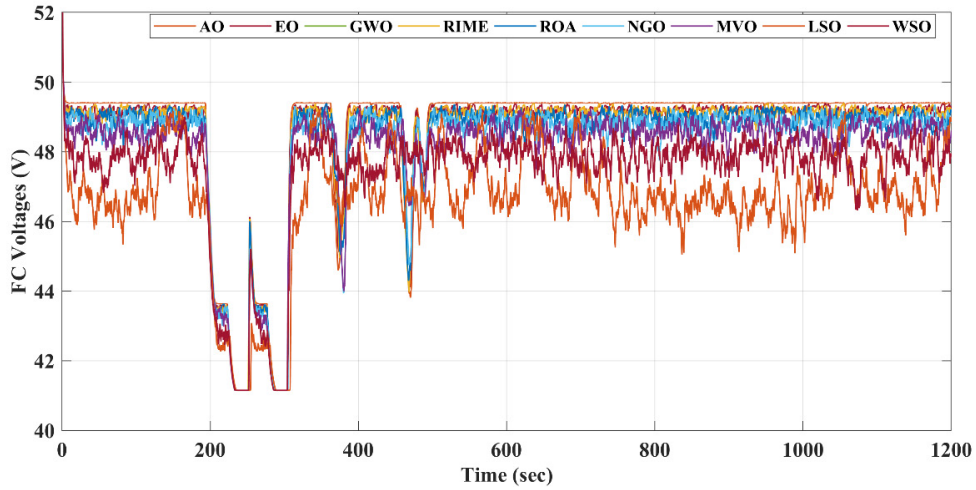

Fig. 7: FC voltage for various EMSs

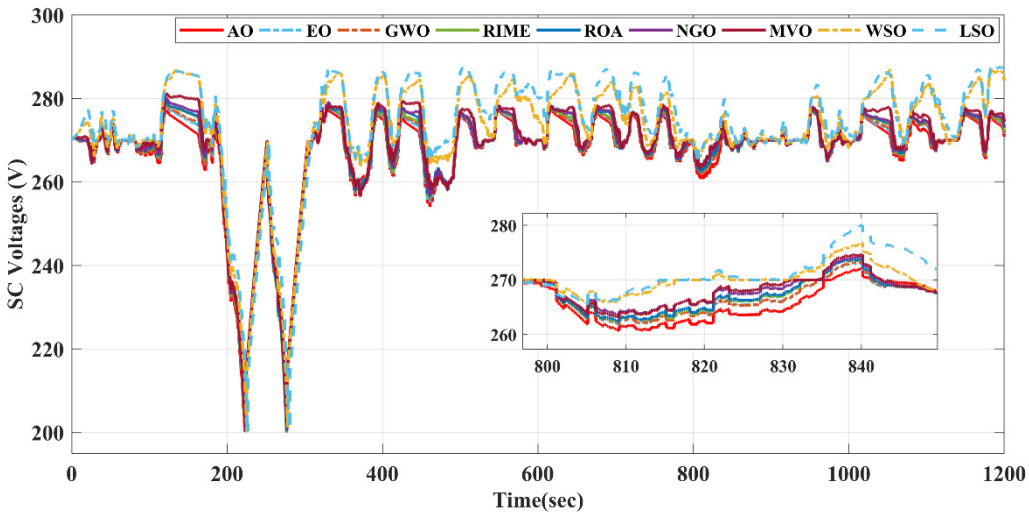

Fig. 8: SC voltage for various EMSs

were acquired from various control schemes. In comparison to alternative methods, the proposed method employs the FC with moderate dynamics. This approach yields a fuel cell characterized by sustained well-being, which subsequently boosts its cost-effectiveness, efficiency, and lifespan.

Fig. 8 shows the voltage of the superconducting circuit (SC). Voltage swings are caused by the changes in power absorption and dissipation occurring in the DC bus. When supply and demand for electricity are balanced, the voltage is 270 V. Nonetheless, the SC voltage swiftly decreases when there are sudden shifts in the load to accommodate the immediate power requirements.

Fig. 9 depicts the voltage of the battery. When following the recommended approach grounded in the AO, the battery voltage shows considerable changes in its levels. This behavior can be understood as a function of the battery system's objective to protect the fuel cell system and limit voltage instability. This results in an increase in the amplitude of voltage variations, as illustrated in the accompanying Fig. 9.

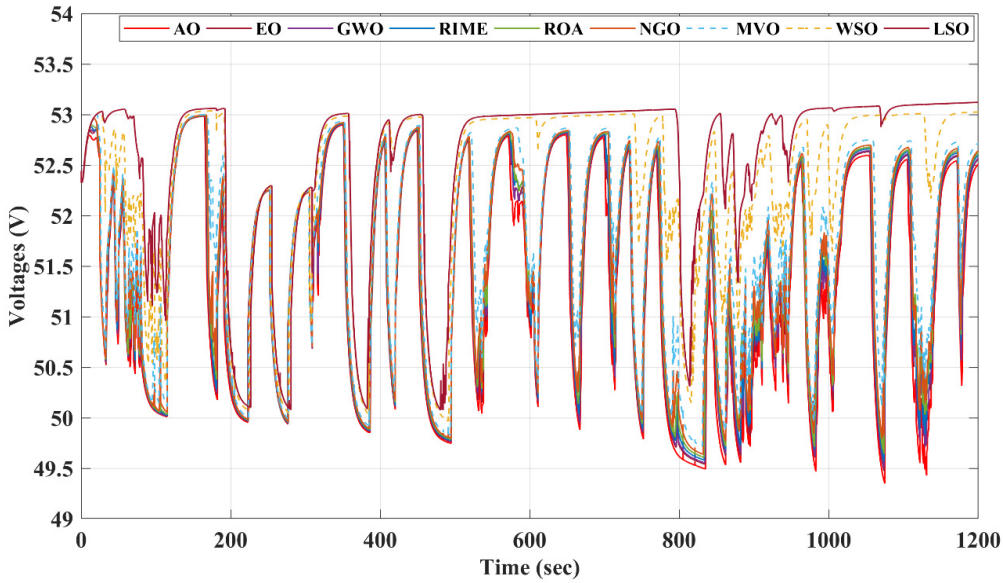

Fig. 9: Battery voltage for various EMS

CONCLUSION

This study introduces an innovative method for achieving an energy-efficient management system, which is implemented in a hybrid fuel cell electric vehicle. The main important contribution of this study is the introduction of an energy management system that utilizes an optimized version of the ECMS with the implementation of the Aquila Optimizer (AO). This novel strategy is designed to boost the fuel economy, performance, and overall effectiveness of HPS employed in fuel-cell electric vehicles. The EMS was evaluated using EO, GWO, RIME, ROA, NGO, MVO, WSO, and LSO. The effectiveness of the electrical systems and fuel economy were examined in a study. The analysis showed that the proposed EMS significantly lowered fuel consumption by 52.26%. Moreover, there was a 3.08% enhancement in overall efficiency. The objective of this study is to lower fuel consumption in order to increase the performance of the entire power system. The researchers intend to delve into the complicated matter of multi-optimization, which is influenced by the nuanced characteristics of the battery's SoC. Moreover, the assessment of the lost power would also be crucial in enhancing the system's efficiency. Besides contributing to fuel savings and efficiency gains, the proposed EMS is key to lowering the environmental footprint. The strategy of minimizing hydrogen consumption indirectly lessens the reliance on hydrogen production, which can result in varying environmental effects depending on the methods employed for production. As FCEVs emerge as a promising alternative to traditional internal combustion engine vehicles, optimizing energy management systems is a key step toward making these vehicles more viable for widespread adoption. Despite these promising advancements, some challenges remain. One of the primary limitations of the proposed approach is its real-time implementation feasibility. The AO algorithm requires substantial computational resources, making real-world applications dependent on advanced, high-speed processors. It is expected that the steady evolution of computing technologies and embedded systems will help address this challenge, facilitating the real-time implementation of the optimization process. Several research directions can be pursued to further enhance the proposed EMS and address existing challenges. Future work will focus on improving the real-time implementation of the AO-based optimization strategy by developing more efficient and computationally adaptive algorithms. Furthermore, an extensive multi-objective optimization framework will be investigated, which will integrate battery

state of charge management with considerations for fuel efficiency and overall system performance. Since SoC depletion was identified as a crucial factor affecting long-term system stability, future studies will investigate advanced control techniques to maintain an optimal charge balance and extend battery lifespan. A significant focus for future studies should be the comprehensive examination of power losses occurring within the system. Understanding and mitigating these losses will be essential in further improving overall system efficiency. Investigating hybrid energy storage solutions. Furthermore, prioritizing real-world experimental validation of the suggested EMS in diverse driving scenarios will be crucial for determining its practical utility and durability. Ultimately, by addressing these challenges and further refining the EMS, current study aims to contribute to the development of more efficient, cost-effective, and environmentally sustainable FCEVs, paving the way for broader adoption of clean energy transportation solutions. For instance, adaptive learning algorithms allow the system to fine-tune the optimization process in real time, improving both convergence speed and computational efficiency while maintaining optimal performance. Upcoming studies will focus on integrating Vehicle-to-Grid and smart grid technologies within the existing EMS framework, analyzing their technical and economic consequences. Enhancing the optimization algorithm to account for real-time grid conditions, energy prices, and dynamic grid needs will further maximize system efficiency and support a more resilient and sustainable energy ecosystem.

RESEARCH GAP

Optimization techniques like Harris Hawks Optimizer and Manta ray foraging optimization have been widely explored for hydrogen consumption, but there is limited research on Aquila optimization algorithm. This study fills the existing gap by showcasing the enhanced effectiveness of the energy management-based AO technique in minimizing hydrogen usage and improving system efficiency when compared to HHO and MRFO. The research findings will offer new insights into optimization strategies for sustainable energy systems.

AUTHOR CONTRIBUTIONS

A.M. Nassef, as the corresponding author, has contributed the research proposal making, built the simulation model, and writing the manuscript, H.E. Ghadbane participated in the preparation of manuscript, performed results analysis, and optimization process using MHs. E.T. Sayed helped in drawing the figures and drafting the manuscript, H. Rezk helped in building the MATLAB Simulink model, drafting the manuscript, results' analysis, and tabulation of the results.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
A	Amperes
ABC	Artificial bee colony optimization algorithm
AC	Alternating current
AO	Aquila optimizer
BES	Battery energy storage
C	Coulombs
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COP	Conference of Parties
DC	Direct current
DP	Dynamic programming
ECMS	Equivalent consumption minimization strategy
EEMS	Enhanced efficient energy management system
EMS	Efficient energy management system
EO	Equilibrium optimizer
ESS	Energy storage system
EVs	Electric vehicles
FC	Fuel cells
FCEV	Fuel cell hybrid electric vehicle
FTP	Federal test procedure
g	Gram
GWO	Grey wolf optimizer
H_2	Hydrogen
HHO	Harris hawks optimization
kg	Kilogram
lb	Lower bound
lpm	Liters per minute
LSO	Leopard seal optimization
m	Meters
m/s	Meters per second
MAs	Metaheuristic algorithms
MBA	Mine blast algorithm
MFCs	Microbial fuel cells
MKCl	Molar potassium chloride
MRFO	Manta ray foraging optimization
MVO	Multi-verse Optimizer
NGO	Northern goshawk optimization
^oC	Degree celsius
PEMFC	Proton exchange membrane fuel cell
PMP	Pontryagin's maximal principle
PSO	Particle swarm optimization
RIME	RIME-based Optimization
ROA	Rain optimization algorithm
SC	Supercapacitor
SDP	Stochastic dynamic programming
SoC	State-of-charge
SSA	Salp swarm algorithm
ub	Upper bound
UK	United Kingdom
V	Volts
WOA	Whale optimization algorithm
WSO	White shark optimizer

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AUTHOR (S) BIOSKETCHES

Nassef, A.M., Ph.D., Associate Professor, Department of Electrical Engineering, College of Engineering in Wadi Alddawasir, Prince Sattam bin Abdulaziz University, Wadi Alddawasir, Saudi Arabia.
- Email: *a.nasef@psau.edu.sa*
- ORCID: 0000-0001-9604-5737
- Web of Science ResearcherID: Q-5076-2019
- Scopus Author ID: 56736102900
- Homepage: https://www.scopus.com/authid/detail.uri?authorId=56736102900

Ghadbane, H.E., Ph.D. Candidate, Département d'Electrotechnique et Automatique, Laboratoire de Génie Électrique de Guelma, Université 8 Mai 1945, Guelma, Algeria.
- Email: *ghadbane.houssameddine@univ-guelma.dz*
- ORCID: 0000-0001-8674-9853
- Web of Science ResearcherID: KDU-6866-2024
- Scopus Author ID: 58863723500
- Homepage: https://www.scopus.com/authid/detail.uri?authorId=58863723500

Sayed, E.T., Ph.D., Professor, Chemical Engineering Department, Faculty of Engineering, Minia University, Egypt.
- Email: e.kasem@mu.edu.eg
- ORCID: 0000-0002-0759-4484
- Web of Science ResearcherID: AEE-4547-2022
- Scopus Author ID: 54985478800
- Homepage: https://scholar.google.com.eg/citations?user=03qdJdsAAAAJ&hl=en

Rezk, H., Ph.D., Associate Professor, Department of Electrical Engineering, College of Engineering in Wadi Alddawasir, Prince Sattam bin Abdulaziz University, Wadi Alddawasir, Saudi Arabia.
- Email: *hr.hussien@psau.edu.sa*
- ORCID: 0000-0001-9254-2744
- Web of Science ResearcherID: M-2100-2019
- Scopus Author ID: 55425573200
- Homepage: https://scholar.google.com.eg/citations?user=R0pThmwAAAAJ&hl=en

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