

Optimal power management for hybrid electrical vehicle

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ABSTRACT

This paper introduces an innovative optimal energy management strategy tailored for a hybrid electric-powered hydraulic excavator system. The aim is to bolster power performance, extend the lifespan of power sources, and optimize hydrogen usage. In this system, the fuel cell serves as the primary power source, while integrating supercapacitors and batteries offers benefits such as enhancing power performance and storing regenerative energy for future use. To efficiently distribute power among these three sources and maximize the utilization of regenerative energy, we propose an energy management strategy. This strategy combines fuzzy logic control with a rule-based algorithm. Moreover, we optimize the parameters of the fuzzy logic system using a combination of the backtracking search algorithm and sequential dynamic programming. This optimization aims to reduce hydrogen consumption and prolong the lifespan of the power sources. Simulation results demonstrate that our proposed energy management strategy significantly enhances vehicle performance, improves fuel economy of the hybrid electric-powered hydraulic excavator system, and enhances the durability and efficiency of the battery and supercapacitor systems within the fuel cell system.

Keywords: Power Management; Fuel Cell; Construction Vehicle.

1. INTRODUCTION

Excavators, bulldozers, forklifts, and loaders are essential to construction operations, making their energy consumption and emissions a significant concern [1, 2]. Despite the recent introduction of diesel-electric powertrains for construction equipment [3], their dependence on diesel engines raises environmental issues. The successful implementation of fuel cell vehicles (FCVs) has attracted interest in using fuel cells (FCs) for construction machinery. However, standalone FC systems in vehicles and equipment face challenges such as high costs and limited lifespans [4, 5]. Additionally, the fluctuating power demands, influenced by terrain and speed variations, strain FCs due to their slow response dynamics [6]. Moreover, standalone FC systems cannot recover braking energy because of their irreversible nature. Therefore, hybridizing FCs with auxiliary energy storage devices is crucial. In a hybrid configuration, the FC serves as the primary power source, supplemented by auxiliary sources like batteries (BAT) or supercapacitors (SC) [7]. While BATs offer high energy density, SCs excel in rapid charge and discharge rates [8]. Integrating BATs and SCs with FCs enhances performance, reduces system size, improves fuel economy, and extends the FC's lifespan.

This study proposes a regenerative system configuration for construction equipment and introduces a novel energy management strategy to reduce fuel consumption. Unlike previous optimization-based fuzzy Energy Management Systems (EMS), which often focus on single-objective optimization such as fuel economy or efficiency, this work addresses multi-objective optimization. In addition to reducing fuel consumption, it aims to minimize FC fluctuation and

battery state of charge fluctuations, thereby lowering operating costs and extending the lifespan of energy sources. The parameters of the fuzzy EMS are optimized using a novel Backtracking Search Algorithm combined with Sequential Quadratic Programming (BSA-SQP) scheme.

The remainder of this paper is structured as follows: Section 2 presents the system configuration, modeling, and regenerative system design. Section 3 introduces a novel fuzzy EMS based on hybrid BSA-SQP optimization, tailored to the characteristics of each device and the regenerative system configuration. Section 4 presents comparative simulation results of the proposed EMS against other advanced strategies. Finally, section 5 provides concluding remarks and outlines future work.

2. SYSTEM MODELING

Figure 1 illustrates the configuration of the FC hybrid electric construction excavator, comprising three main components: a hybrid power source, a powertrain, and a hydraulic system. The integration of FC, BAT, and SC facilitates energy provision to both the hydraulic system and powertrain. The energy generated by FC, BAT, and SC is directed to the hydraulic system and powertrain via three DC/DC converters, a DC bus, and electric motors. The system employs two types of DC/DC converters: a boost DC/DC converter links the FC to the DC bus, while two bidirectional DC/DC converters connect the BAT and SC to the DC bus, allowing energy to flow in both directions.

The hydrogen consumption in the reaction of the FC is computed as follows [1]

$$dm_{H_2} / dt = \frac{M_{H_2} N_c A_{FC}}{2F} i_{FC} \quad (1)$$

where dm_{H_2}/dt , M_{H_2} are flowrate of hydrogen mass (kg/s) and the molecular weight of hydrogen, and A_{FC} is the active area of one cell, i_{FC} is the current flow of the FC, N_c is the number of the cells in series, F is Faraday's constant.

Figure 2 illustrates the regeneration mode design implemented in the FC hybrid electric construction excavator. Within the boom system, when the boom cylinder descends, gravitational force facilitates the automatic downward movement of the arm without the need for oil supply from the pump. The study focused on a 20-ton hydraulic excavator, analyzing pressures in various components such as the non-rod side chamber and the rod side chamber of the cylinder, as well as the two ports of the swing motor, the pumps, cylinder displacement, and the rotational angle of the swing. This investigation demonstrates that the potential energy generated by the boom cylinder accounts for 51% of the total recoverable energy in the excavator.

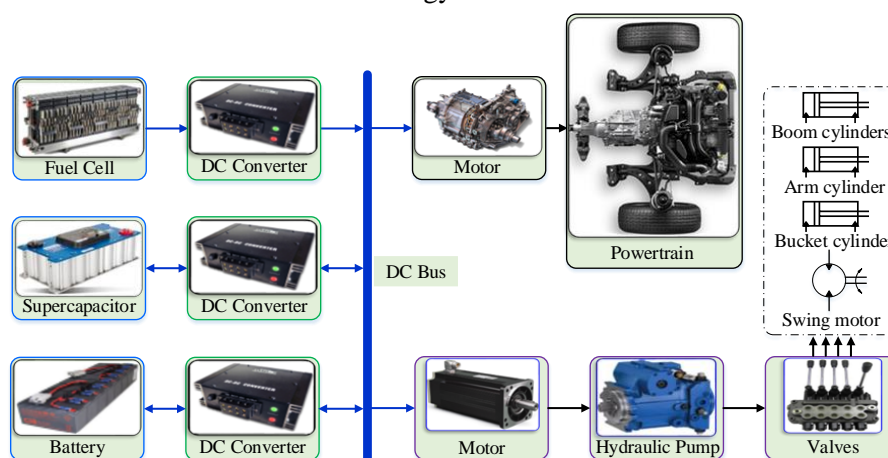


Figure 1. Structure of the hybrid power for construction vehicle.

3. POWER MANAGEMENT METHOD

The main objective of the proposed EMS is to minimize the hydrogen consumption and enhance the efficiency of the fuel cell system, prolong the lifespan of the power sources comprising the fuel cell system, battery, and supercapacitor. Therefore, the equivalent cost function for the multiobjective optimization problem is designed as the following:

$$J = \int_{t_0}^{t_f} [dm_{H_2} / dt + \lambda_1 (SOC_B - SOC_{B_{opt}})^2 + \lambda_2 (SOC_{SC} - SOC_{SC_{opt}})^2] dt \quad (2)$$

where $SOC_{B_{opt}}$ and $SOC_{SC_{opt}}$ are the optimal values of the state of the charges (SOCs) of the battery and supercapacitor, respectively. λ_1, λ_2 are the weighting coefficients.

The EMS for the FC hybrid electric construction excavator, illustrated in figure 3, features three fuzzy control schemes: Fuzzy Loop 1, Fuzzy Loop 2, and Fuzzy Loop 3. Initially, the power demand from the power train is evaluated to devise a power-sharing strategy. The FC, as the primary power source, has its output determined by Fuzzy Loop 1. The remaining power is allocated between the SC and BAT, with their states of charge (SOC) continuously monitored to ensure longevity. The system then checks if it is in regeneration mode: if the boom is raised and power demand exceeds the FC's output, power from the SC and BAT is adjusted as needed. If the boom is lowered, regeneration mode charges the secondary devices. Excess power charges the SC or BAT, with Fuzzy Loop 3 managing the balance. If power demand is lower than the FC output, Fuzzy Loop 2 charges both devices with surplus power. SOC is monitored throughout, with alarms for maximum or minimum thresholds, ensuring optimal operational performance.

The next step is to determine if the system is in regeneration mode. If the voltage signal indicates an upward boom movement and the power demand exceeds the FC's nominal output, the power is distributed between the SC and BAT as needed. For a downward boom movement, regeneration mode uses stored energy to recharge the secondary devices. Two scenarios arise: (1) Excess power charges the SC or BAT, with the remaining device recharged via Fuzzy Loop 3, or (2) if power demand is below the FC output, the surplus charges both secondary devices via Fuzzy Loop 2. The state of charge (SOC) of both devices is monitored, triggering an alarm and stopping charging if it reaches the maximum threshold, or prioritizing charging if it drops to the minimum level. The goal is to keep the SOC within optimal ranges to meet operational demands.

The input variables for the first fuzzy loop are the power demand and a new variable $s = \delta SOC_B + (1-\delta)SOC_{SC}$, where δ is a design parameter. The state of charge (SOC) of the BAT and SC serve as inputs for the second and third fuzzy loops. The strategy uses a knowledge-based fuzzy rule to link these inputs to the output, determining the power distribution percentages for the FC (r_{FC}) and the sharing between the BAT and the SC (r_B).

The fuzzy field scope of the power demand is set as $[-1,1]$ while those of the SOC of the BAT and the SC voltage are set as $[0,1]$. The fuzzy domains of the two outputs are also set as $[0,1]$:

$$in_1 = \frac{P_d}{|P_{d\max}|}, in_2 = SOC_B, in_3 = SOC_{SC} \quad (3)$$

where $P_{d\max}$ denotes the maximum values of the power demand P_d ; $u_{SC\max}$ and $u_{SC\min}$ are the maximum and minimum values of u_{SC} , respectively.

The outputs of the Fuzzy Control Loop 1 and 2 are calculated using centroid defuzzification as the following [9].

$$r_{FC}(t) = \frac{\sum_{j=1}^{n_1} \sum_{i=1}^{n_2} (mf_{in_1}^j(t) mf_s^i(t) z_{FC}^{ij}(t))}{\sum_{j=1}^{n_1} \sum_{i=1}^{n_2} (mf_{in_1}^j(t) mf_s^i(t))} \quad (4)$$

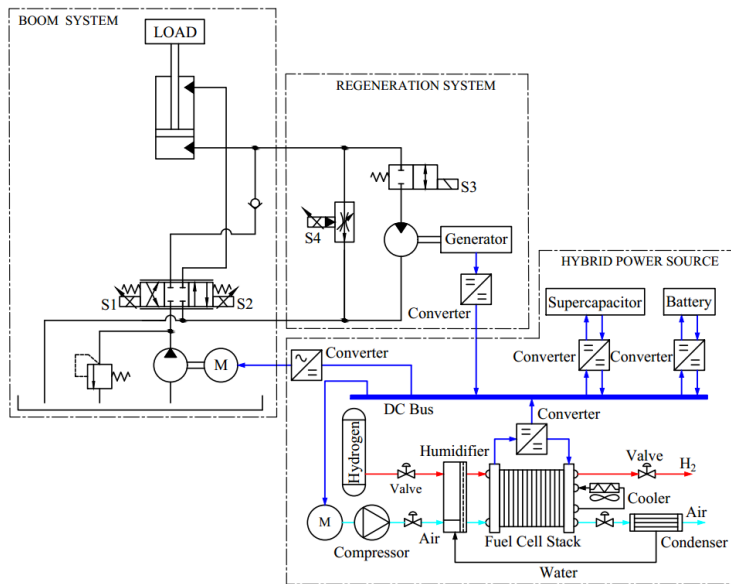


Figure 2. Regeneration system for energy recovery.

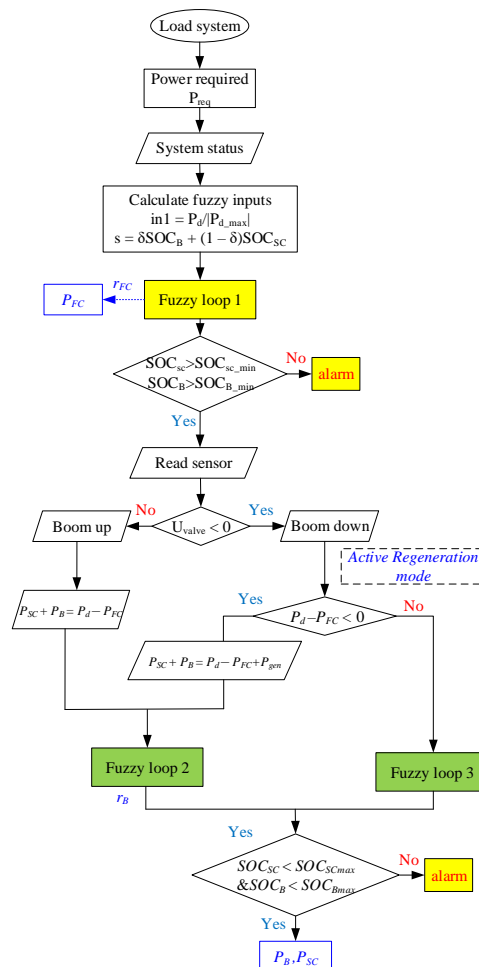


Figure 3. The proposed EMS for the designed FC hybrid electric construction excavator system.

$$r_B(t) = \frac{\sum_{j=1}^{n_3} \sum_{i=1}^{n_4} (mf_{in2}^j(t) mf_{in3}^i(t) z_B^{ij}(t))}{\sum_{j=1}^{n_3} \sum_{i=1}^{n_4} (mf_{in2}^j(t) mf_{in3}^i(t))} \quad (5)$$

where $n_1, n_2, n_3,$ and n_4 are the numbers of active membership functions, $mf_x^i(t)$ ($x=in_1, in_2, in_3, s$) is the degree of the membership function of the inputs, $r_y(t)$ ($y = FC, B$) is the crisp rule output. Thus, the required powers which distribute to the FC, BAT and SC are as the following.

$$\begin{aligned} P_{FC} &= P_d r_{FC}, \quad P_B = P_d (1 - r_{FC}) r_B, \\ P_{SC} &= P_d (1 - r_{FC}) (1 - r_B) \end{aligned} \quad (6)$$

A hybridization of a Backtracking search algorithm and a SQP algorithm is proposed to obtain the optimized parameters of the proposed fuzzy EMS as follows.

Step 1: Initialize the maximal evolution generation of the BSA G_{max1} and the SQP G_{max2} . Generate a target population P of population size M^* and with dimension of the variable vector n^* within lower boundary (LOW) an upper boundary (UP) and historical population $oldP$ using uniform distribution as the following.

$$\begin{aligned} P_{i,j} &\sim U(LOW_j, UP_j) \\ oldP_{i,j} &\sim U(LOW_j, UP_j) \end{aligned} \quad i = 1, 2, \dots, M^*; j = 1, 2, \dots, n^* \quad (7)$$

where $U(LOW_j, UP_j)$ is uniform distribution between the lower and the upper boundary.

Step 2: Calculate the equivalent cost function J for each individual and construct M fuzzy energy management control scheme; P_{opt}, J_{opt} are set as the best position and best objective cost function of the current population.

Step 3: Redesign the historical population $oldP$ at the beginning of each iteration as follows.

$$\text{if } a < b \text{ then } oldP := P \mid a, b \sim U(0,1) \quad (8)$$

Step 4: Execute the mutation operator which is described by:

$$\text{Mutant} = P + F^* \cdot (oldP - P) \quad (9)$$

where F^* is a real number to control the step size amplification of the search direction matrix ($oldP - P$) and decide the search capabilities of BSA.

Step 5: Execute the crossover operator with parameter $mixrate$ that controls the number of elements of candidate solutions that will mutate in a trial and randomly selected individual to mutate in each trial. After $oldP$ is determined, the permuting function is employed as:

$$oldP := \text{permuting}(oldP) \quad (10)$$

Step 6: Execute the selection process and update the value of the population individual P_i . If the fitness value of trail population individual T_i is better than that of original population individual P_i , then P_i will be updated by T_i . If the best position for all new individuals is better than P_{opt} , then P_{opt} and J_{opt} will be updated.

Step 7: If the number of generations reaches the maximum evolution generation G_{max1} or the current J_{opt} is constant in 50 continuous generations, then go to step 8; or else, go to step 2.

Step 8: Implement the SQP: Calculate the Hessian matrix H of the objective cost function.

Step 9: Solve the QP sub-problem and calculate the standard SQP search direction d_{SQP} .

Step 10: Update the new position using the following equation.

$$x_{k+1} = x_k + \alpha d_{SQP} \tag{11}$$

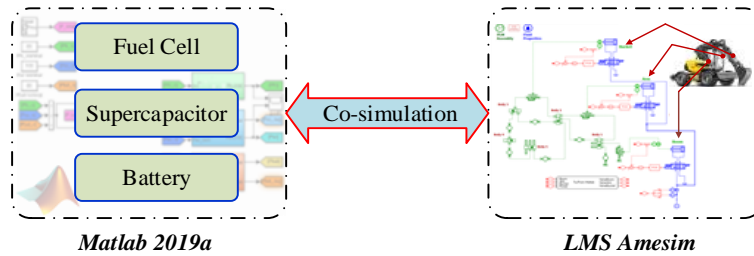


Figure 4. Model of FC hybrid electric excavator using MATLAB and AMESim.

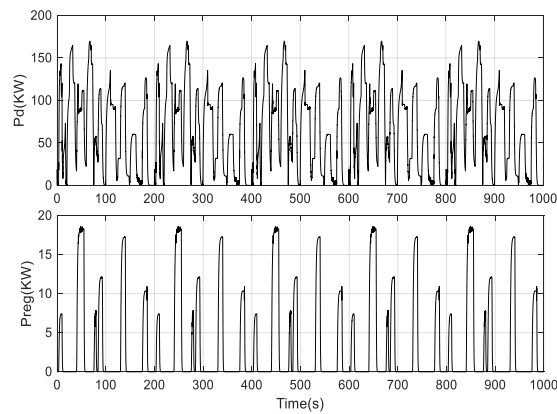


Figure 5. Power demand and regenerative power of the FC hybrid electric construction excavator system.

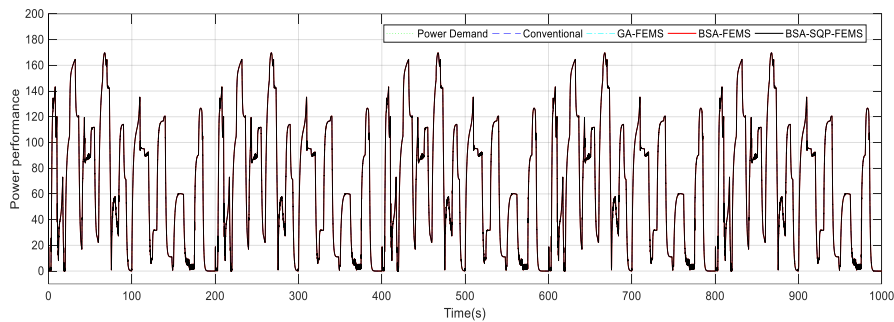


Figure 6. Power performance of the comparative EMSs.

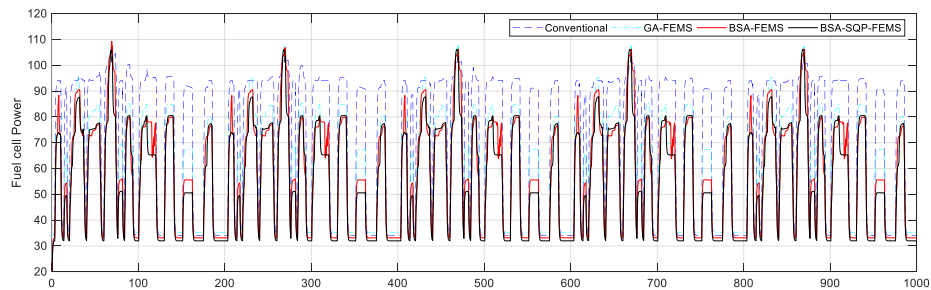


Figure 7. FC powers of the comparative EMSs.

where $\alpha \in [0,1]$, k is the current iteration, and $0 \leq k \leq G_{max2}$. The initial values of the parameters for the training process using the SQP x_0 are obtained from the BSA training process.

Step 11: Calculate the cost function of the new position, then P_{opt} and J_{opt} are updated.

Step 12: If the G_{max2} is reached, go to step 13; or else, go to step 8.

Step 13: Output the current search result.

4. SIMULATION RESULTS

This section presents comparative simulation results aimed at demonstrating the efficacy of the proposed EMS. A model integration using LMS AMESim 15.2 software and MATLAB/Simulink 2019a is established for the FC hybrid electric construction excavator system, depicted in figure 4. The hydraulic excavator system is simulated within the AMESim environment, while the hybrid power source system and power control algorithms are developed in the Simulink environment.

Figure 5 presents the power demand and regenerative power generated during several typical driving cycles, each lasting 1000 seconds. To assess the effectiveness of the control design, four different power controllers are applied to the fuel cell (FC) hybrid electric construction excavator system. These controllers are the proposed BSA-SQP based fuzzy Energy Management System (EMS), a BSA based fuzzy EMS, a GA based fuzzy EMS, and a conventional fuzzy EMS. The parameters for the BSA in the first and second control algorithms are set as follows: $G_{max1}=500$, $M^*=50$, and $F^*=1$. The maximum number of iterations for the SQP algorithm is $G_{max2}=1000$. Parameters for the conventional fuzzy EMS are determined based on expert knowledge.

The comparative performance of four energy management strategies is demonstrated through figures 6-9. To assess the tracking accuracy of total power while excluding regenerative power, a new term, $P_{sum} = P_{FC} + P_B + P_{SC} - P_{reg}$, is introduced. Figure 6 illustrates how the power responses of these strategies adeptly match power demands.

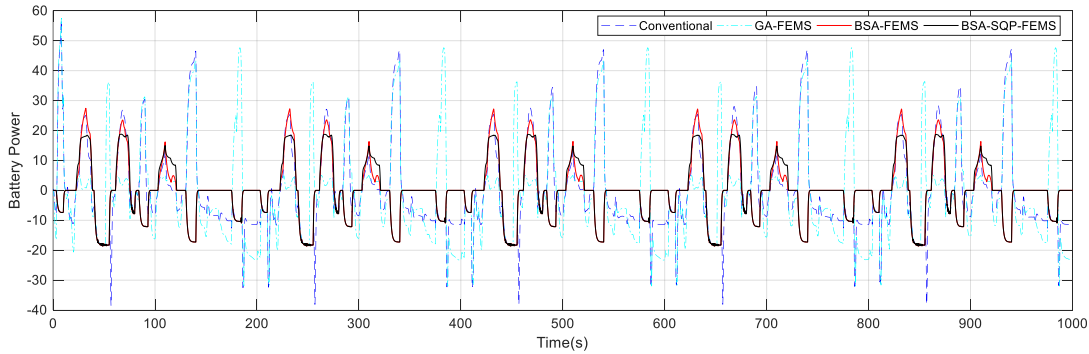


Figure 8. Battery powers of the comparative EMSs.

Specifically focusing on FC power management, figure 7 displays the continuous performance of four control algorithms. Notably, the conventional fuzzy EMS exhibits significant fluctuations in FC power, potentially shortening the system's lifespan. Conversely, the three optimal FEMSs demonstrate superior management, maintaining stable FC power despite varying loads. Among these, the proposed BSA-SQP-based FEMS stands out for its minimal power fluctuations and magnitude, highlighting the algorithm's effectiveness in enhancing fuel economy and system durability.

Examining BAT performance across the four EMSs in figure 8, both the BSA-based FEMS and the proposed BSA-SQP-based FEMS maintain BAT power within a reasonable range, ensuring smooth power responses. Figure 9 illustrates the SC powers of the comparative EMSs, with the SC serving to absorb power with high rates of change. Notably, the proposed algorithm allocates more power to the SC than the others, reducing the demand on the FC and BAT.

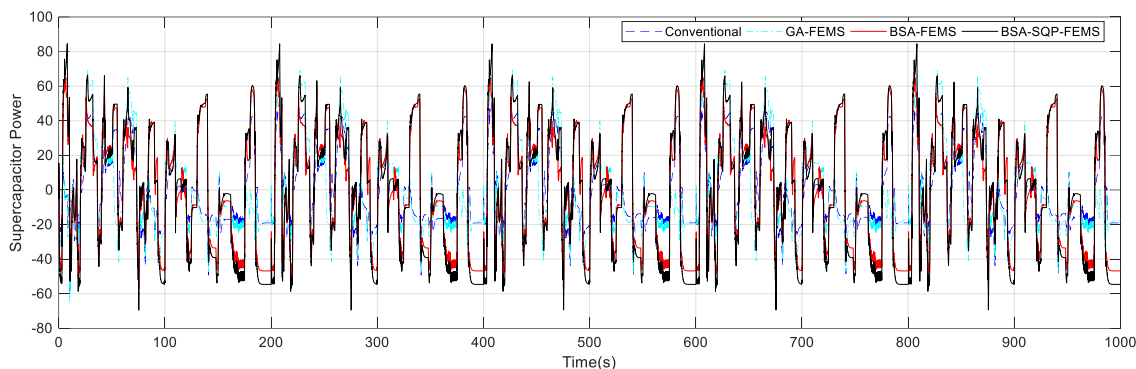


Figure 9. SC powers of the comparative EMSs.

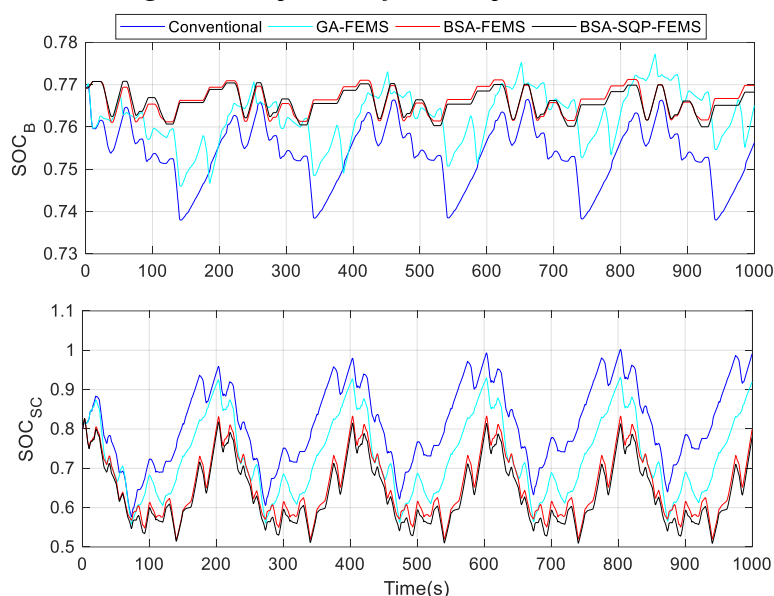


Figure 10. State of charges of BAT and SC of the comparative EMSs.

Further specifics on BAT and SC states of charge (SOCs) are provided in figure 10. The proposed BSA-FEMS and BSA-SQP-FEMS effectively maintain BAT SOC within desired ranges, thereby prolonging BAT lifespan. Additionally, these algorithms maintain lower ranges of SC SOC compared to other methods, as both BAT and SC aim to supply maximum power to minimize hydrogen consumption.

5. CONCLUSIONS

This study introduces a novel energy management algorithm specifically designed for a fuel cell (FC) hybrid electric construction excavator system, which incorporates a regeneration system. The algorithm aims to optimize fuel economy and enhance the durability of the battery (BAT) and FC components. By integrating batteries and supercapacitors (SCs) alongside the FC, the system addresses the limitations of standalone FC systems, such as low power density and slow power response, while enabling the efficient storage and reuse of regenerative energy within the excavator. Considering the complexities of the system, including its separate regeneration circuit, a novel flowchart-based energy management system (EMS) is proposed to effectively allocate power demand and regenerative power among the various power sources. Future work includes testing the proposed algorithm in the actual system and exploring new regeneration system designs.

REFERENCES

- [1]. T. Li, L. Huang, and H. Liu, “Energy management and economic analysis for a fuel cell SC excavator,” *Energy*, **Vol. 172**, pp. 840-851, (2019).
- [2]. B. Dandil, et. al, “Adaptive DC-Voltage control based on Type-2 neuro-fuzzy controller in a hybrid stand-alone power network with hydrogen fuel cell and battery”, *International Journal of Hydrogen Energy*, **Vol. 75**, pp. 303-313, (2024).
- [3]. X. Huang, et al, “Predictive energy management of fuel cell SC hybrid construction equipment,” *Energy*, **Vol. 149**, pp. 718-729, (2018).
- [4]. T. Li, H. Liu, and D. Ding, “Prospects for purely electric construction machinery: Mechanical components, control strategies and typical machines,” *Automation in Construction*, **Vol. 164** (2024).
- [5]. H. Wang, Q. Wang, and B. Hu, “A review of developments in energy storage systems for hybrid excavators,” *Automation in Construction*, **Vol. 80**, pp. 1-10, (2017).
- [6]. L. Xu, J. Li, J. Hua, X. Li, and M. Ouyang, “Optimal vehicle control strategy of a fuel cell/battery hybrid city bus,” *International Journal of Hydrogen Energy*, **Vol. 34**, No. 17, pp. 7323-7333, (2009).
- [7]. T. Azib, O. Bethoux, G. Remy, and C. Marchand, “Saturation Management of a Controlled Fuel-Cell/Ultracapacitor Hybrid Vehicle,” *IEEE Transactions on Vehicular Technology*, **Vol. 60**, No. 9, pp. 4127-4138, (2011).
- [8]. T. X. Dinh et al, “Modeling and Energy Management Strategy in Energetic Macroscopic Representation for a Fuel Cell Hybrid Electric Vehicle,” *Journal of Drive and Control*, **Vol. 16**, No. 2, pp. 80-90, (2019).
- [9]. R. Zhang and J. Tao, “GA-Based Fuzzy Energy Management System for FC/SC-Powered HEV Considering H₂ Consumption and Load Variation,” *IEEE Transactions on Fuzzy Systems*, **Vol. 26**, No. 4, pp. 1833-1843, (2018).

TÓM TẮT

Quản lý năng lượng tối ưu cho hệ thống xe điện lai

Bài báo này giới thiệu một thuật toán quản lý năng lượng tối ưu cải tiến được thiết kế riêng cho hệ thống máy xúc thủy lực chạy bằng điện lai. Mục đích là tăng cường hiệu suất năng lượng, kéo dài tuổi thọ của nguồn điện và tối ưu hóa việc sử dụng hydro. Trong hệ thống này, pin nhiên liệu đóng vai trò là nguồn năng lượng chính, đồng thời tích hợp siêu tụ điện và pin mang lại những lợi ích như nâng cao hiệu suất năng lượng và lưu trữ năng lượng tái tạo để sử dụng trong tương lai. Để phân phối hiệu quả năng lượng giữa ba nguồn này và tối đa hóa việc sử dụng năng lượng tái tạo, chúng tôi đề xuất thuật toán quản lý năng lượng mới. Thuật toán này kết hợp điều khiển logic mờ với thuật toán tối ưu hóa các tham số của hệ thống logic mờ bằng cách sử dụng kết hợp thuật toán tìm kiếm theo chiều lùi và lập trình động tuần tự. Sự tối ưu hóa này nhằm mục đích giảm mức tiêu thụ hydro và kéo dài tuổi thọ của các nguồn điện. Kết quả mô phỏng chứng minh rằng thuật toán quản lý năng lượng được đề xuất của chúng tôi giúp tăng cường đáng kể hiệu suất của xe, cải thiện khả năng tiết kiệm nhiên liệu của hệ thống máy xúc thủy lực chạy bằng điện hybrid, đồng thời nâng cao độ bền và hiệu suất của hệ thống pin và siêu tụ điện trong hệ thống pin nhiên liệu.

Từ khoá: Quản lý năng lượng; Pin nhiều liệu; Xe điện.