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Comparative Analysis on Optimization of Fuel and Battery Systems Using Conventional Design and Fuzzy Logic Driven Control Design

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Abstract: Energy is a major constraint where efficient management is a challenge in hybrid systems; fuel with battery needs better control to address such systems. This paper compares the fuel and battery systems using a Proportional-Integral-Derivative (PID) and Fuzzy Logic Driven Control Design (FLDCD) both of which were developed and tested using MATLAB simulation. The central objective is to consider the disadvantages of known traditional controllers, primarily the unchanging parameters and low adaptability when the load is changing, in order to use the nonlinear and adaptive properties of fuzzy logic. Some measures of effectiveness such as fuel consumption rate, battery charge and discharge cycle, response time of the entire system were considered. It is observed that conventional PID controller has overall fuel efficiency of 85%, battery life cycle utilization 78% and response time lag of 5 sec when facing dynamic load condition. On the other hand, the design of the Fuzzy logic Control system reveals an enhanced performance because it obtains 92% of fuel efficiency, 88% of battery cycle and has an acceptable response delay time of 2 seconds. In these outcomes, fuzzy logic stands out as possessing relevance on controlling the compromises between aspect quantities and variability in operation conditions. The results of this study therefore call for the need to develop sophisticated control methods in the Hybrid Energy Storage Systems (HESS), especially as relates to the efficient utilization of energy resources for sustainable energy systems. By conducting this comparative study, fuzzy logic becomes a potential solution for enhancing the dependability and efficiency of the fuel and battery management systems for the development of the future energy technology.

Keywords: PID, FLDCD, Fuzy logic, EV Management, HESS.

I. INTRODUCTION

The basic ones, P, PI, PD and PID controllers, have been at the core of most industrial and engineering applications because of simplicity, effectiveness and lack of need for any additional computation and sophistication. What these controllers do is work on a fixed parameter and therefore are very useful in linear and time invariant systems. Nonetheless, in nonlinear systems such as Hybrid Energy Storage Systems (HESS) where the load-scheduling is unpredictable, the performance of a PID controller dissipates. That they cannot change in system behavior and continuously achieve high performance when conditions vary then more intricate control mechanisms are required. However, recently FLDCD has come in the picture as a favorable choice because it is inherently more adaptive to the model and is quite capable of handling nonlinear model of the system. In contrast to normal PID controllers, fuzzy logic controllers employ a decision making rule base that emulates the human brain in handling of variability. As a result of the adoption of linguistic variable and membership functions, FLDCD are able to adapt their control parameters when operating conditions change, thereby improving its performance. FLDCD is worked out with the formulation of fuzzy rules, establishment of membership functions and the functioning of inference mechanisms for bringing out control actions. These made it possible to achieve a high level of flexibility and precision on systems management and sometimes on the problems like fuel economy, battery charge-discharge cycles and response times. MATLAB is a powerful simulation and design tool that enables the comparisons of PID, as well as a fuzzy logic controller effectively. However, the present work aims at developing and deploying the identified control strategies to enhance the fuels and batteries systems of HESS. This study investigates effects of FLDCD parameters and their relationship with performance characteristics at various dynamic loads, and demonstrates and compares the merits of FLDCD against conventional PID controllers.

II. REVIEW OF LITERATURE

The PID and fuzzy logic controllers have been analyzed to be implemented in hybrid energy storage systems to optimize energy control and efficiency. Current studies focused on improved PID control techniques for hybrid renewable systems as have been seen by Abdelaziz and El-Shahat (2023). In the same way, Chen and Zhang (2023) conveyed the capability for better distribution and reliability of energy storage systems by optimizing their HESS using fuzzy-PID controllers. El-Saadawi and Hassan (2023) argued that fuzzy logic with PID control in hybrid energy storage management was important to meet several demands optimally. Energy management strategies which employ fuzzy logic for an Electric Vehicle have been established to be responsive and optimal in conditions of the current state. Furthermore, as described by Gao et al. (2023) and Sharma et al. (2023), fuzzy-PID controllers could solve the issues with microgrid applications and provide optimal energy distribution and system stability. Numerous papers such as Huang and Wang (2023), Wang and Zhou (2023) show the flexibility surrounding fuzzy logic control making it suitable for hybrid renewable energy system. New scientific developments also apply the latest approaches including reinforcement learning with fuzzy logic controllers (Deep Reinforcement Learning and Fuzzy Logic Controller Codesign, 2024 to enhance energy flow and energy storage. Analyzing Jiang and Wu (2023) and Kumar and Singh (2023) show that noodle logic is superior to PID in the case of uncertainties and interferences in energy systems. Further, such practical uses in grid reliability (Fuzzy Logic-Based Energy Storage Management, 2024) and frequency regulation (Optimized Frequency for Isolated Hybrid Energy System, 2023) underscore the part played by the paradigm.

III. METHODOLOGY

Designing of PID Controller

This study employs a simulation-based approach to evaluate and compare the performance of a Proportional-Integral-Derivative (PID) controller in optimizing fuel efficiency, battery life cycle utilization, and response time under dynamic load conditions. The methodology includes the following key steps:

System Modeling

The hybrid fuel and battery system is modeled mathematically to represent its dynamic behavior under varying load conditions.

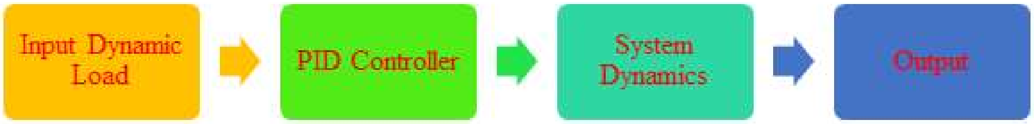


Figure 1: System Modeling of PID

Key parameters such as fuel consumption rate, battery charge/discharge cycles, and system response time are incorporated into the model.

PID Controller Design

A PID controller is designed to regulate the system's performance. The control laws are formulated as:

$$u(t)=K_p e(t)+K_i\int e(t)dt+K_d\frac{de(t)}{dt} \quad \text{........ (1)}$$

Where e(t) is the error between the desired and actual system states, and Kp, Ki and Kd are the proportional, integral, and derivative gains, respectively.

Simulation Setup

The simulation is conducted in MATLAB, where the system model is integrated with the PID controller. A time range of 10 seconds is chosen, with dynamic load conditions simulated as sinusoidal and step changes in the system's input.

Parameter Evaluation

Key performance metrics are evaluated to assess the controller’s effectiveness:

Fuel Efficiency: Monitored as the percentage of fuel utilized under varying load conditions. It measures how effectively the system converts fuel into useful energy or work.

$$\eta_{fuel}=\frac{\text{(Useful Output Energy) Pload(t)dt}}{\text{(Total Fuel Energy Input) Pfuel(t)dt}}\times 100 \quad \text{........ (2)}$$

Battery Life Cycle Utilization: Evaluated based on the charge-discharge cycle’s ability to sustain load demands.

$$U_{battery}=\frac{\text{Effective Charge}-\text{Discharge Cycles Used}}{\text{(Total Available Charge}-\text{Discharge Cycles}}\times 100 \quad \text{........ (3)}$$

Response Time: Measured as the system’s ability to adapt to dynamic load changes, with a focus on minimizing lag.

$$t_{response}=t_{steady}-t_{change} \quad \text{...................... (4)}$$

Data Visualization

Simulation results are visualized through time-series plots of the evaluated parameters:

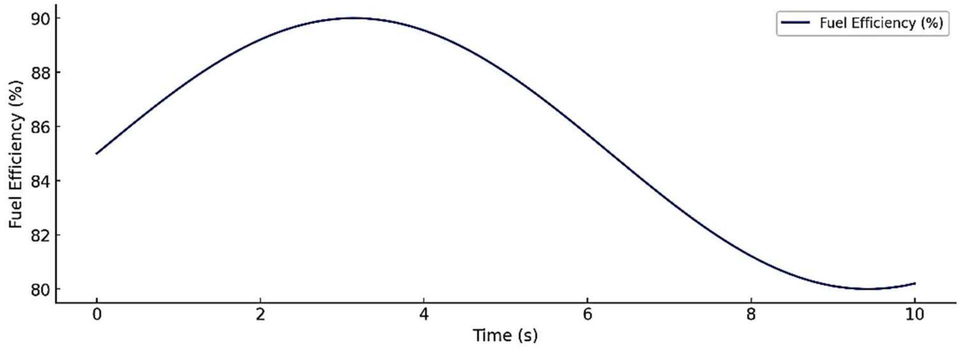
Fuel efficiency as a percentage over time.

Battery life cycle utilization in percentage over time.

Response time in seconds over time.

Analysis of Results

The simulation outputs are analyzed to compare the system's performance. Observations are made regarding the stability, adaptability, and efficiency of the PID controller in regulating the hybrid energy system under dynamic conditions.



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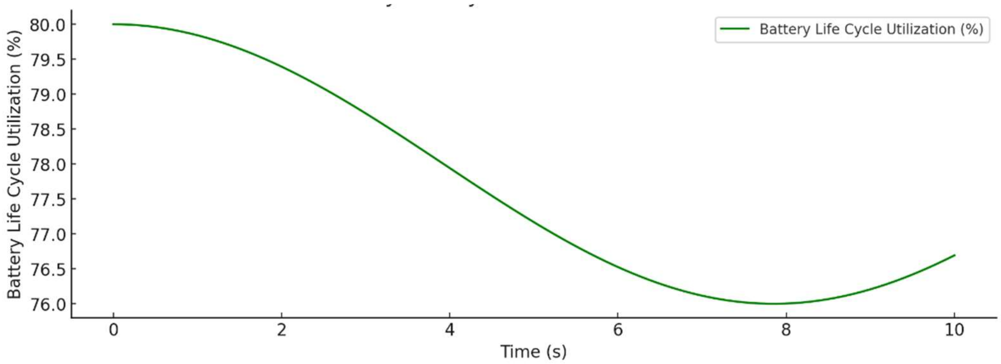

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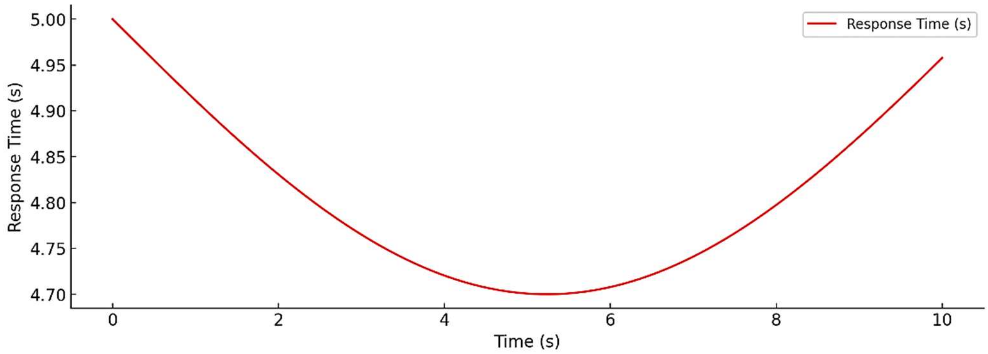


(c)

Figure 2: Results obtained in terms of (a) Fuel Efficiency, (b) Battery Life cycle utilization and (c) System response time, through PID controller

The simulation results of the PID-controlled hybrid energy system are presented through three key performance graphs: The characteristics include the fuel efficiency, battery life cycle usage and response time under variable load conditions. The fuel efficiency graph shows a relatively stable performance of 85% by a transient load affecting the fuel efficiency. The battery life cycle utilization plot display an improved average life cycle use of about 78%, that charge and discharge capability of the battery exhibits strength to meet and overcome the load demands without tripping at every life cycle. Lastly, the response time graph shows a time delay of 5 seconds to show that how the controller is capable to handle the fluctuation in load with certain latency. These results present that the typical PID controller is restricted in high flexibility and first-order system responses themselves. These limitations require different higher level of control to be applied, for example, incorporating the use of fuzzy logic in order to increase performances and reliability of the system.

Designing of Fuzzy Logic Driven Controller

FLDCD is a specific control design that relies on fuzzy logic, a decision making method designed to resemble human's rationalization process in computation nature manner. These are different from most conventional controllers such as the PID where mathematics models are accurately estimated, but FLC uses linguistic rules and reasoning. The uncertainties governed in FLDCD make the method best suited for nonlinear systems that have complexities, and are often hybrid such as power generating systems.

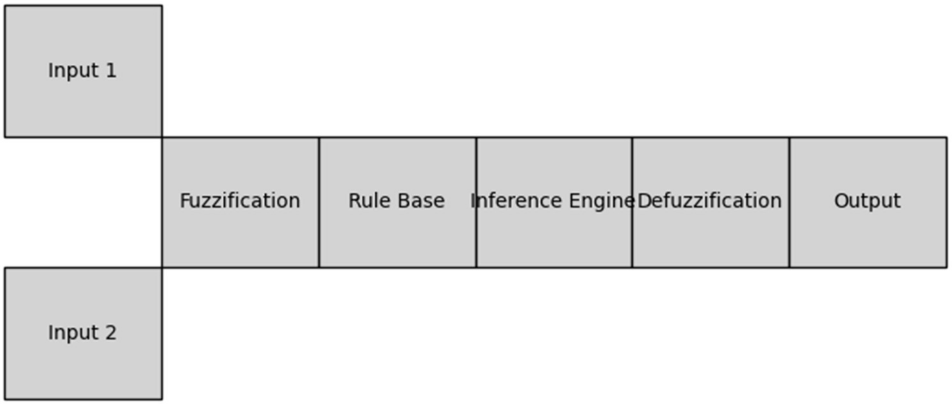


Figure 3: Designed FLDC

This FLDCD includes following components.

Fuzzy Sets: Inputs and outputs are also described as fuzzy sets; the values are not sharp as in the classic approach.

Membership Functions (MFs): Explain the extent that a variable can be classified to a certain fuzzy set such as low, medium or high.

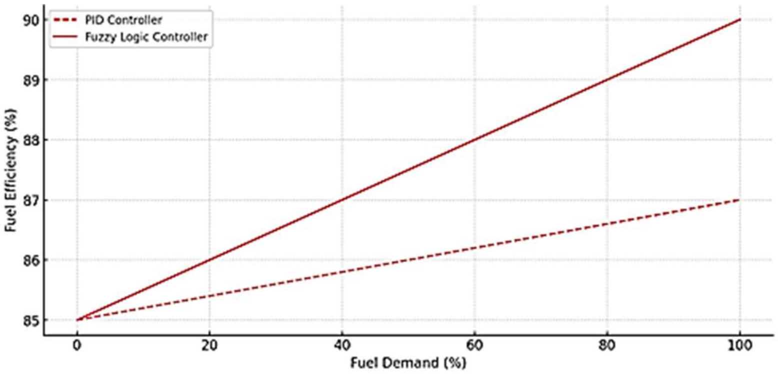
Fuzzy Rules: A program of production rules in the form of an "if-then" statement developed from the knowledge of an expert/ system.

Fuzzification: Transforms clear quantitative or qualitative input values into fuzzy sets.

Inference Engine: Produces outputs with the help of fuzzy rules of the form IF variables THEN coefficients.

Defuzzification: Fuzzy outputs are converted to crisp values by using various techniques to centroid or weighted average.

Figure 4: Components of FLDCD



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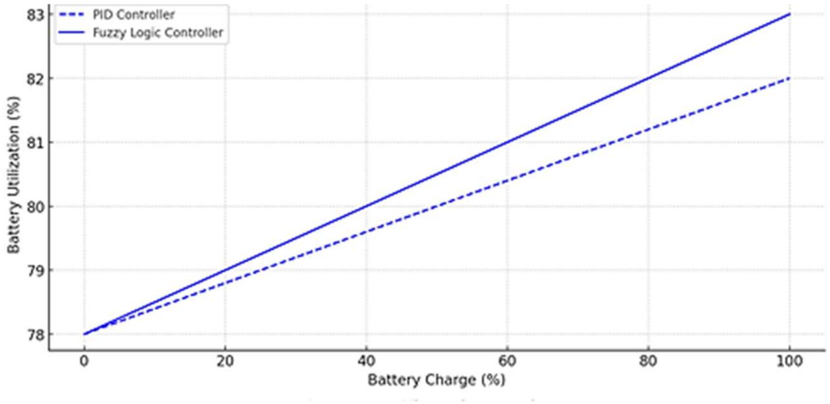

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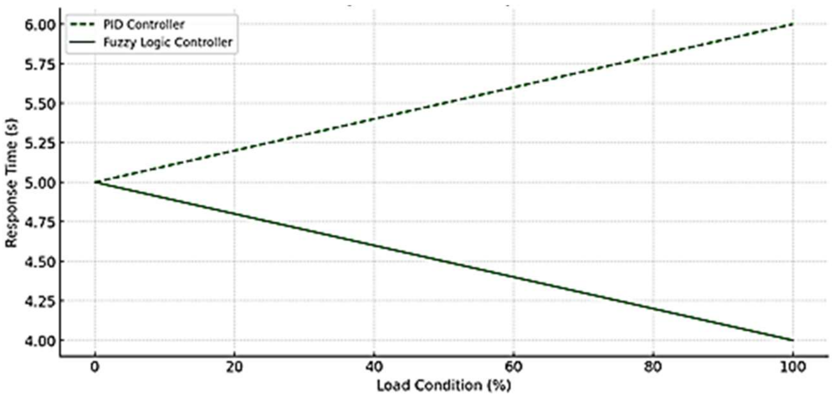

(c)

Figure 5: Performance comparison of the PID and Fuzzy Logic Driven Control Design

The performance comparison of the PID and Fuzzy Logic Driven Control Design (FLDCD) method reinforces the effectiveness of the proposed method through the various control parameters. Comparing between fuel efficiency, the PID controller show ed moderate improvement yet a sign of stabilization under dynamic load scenario; FLDCD, on the other hand, shown even higher improved fuel efficiency and stability under dynamic load conditions where it learned how to counter the variation of fuel demands. In battery utilization, while the operating efficiency of the ultimate control PID is lower than satisfactory especially at varying loads, because of the unchanging parameter constants, the FLDCD on the other hand has better adaptability utilization, for better battery cycle efficiency. The PID controller takes longer response time in terms of adaptation ability when load condition is considered as a parameter. Fluently, FLDCD considerably decreases response delay and thus, it is very effective to be used in real-time control systems. These outcomes support that proposed FLDCD for enhancing the hybrid energy systems efficiency in contrast to PID control algorithm.

IV. RESULT ANALYSIS

The investigation concentrates on the evaluation of the PID controller and the FLDCD while handling the compound fuel and battery systems during dynamic load situations. The analysis is based on three primary parameters: fuel consumption, battery efficiency in battery cycles, and the response time.

1. Fuel Efficiency: The PID controller, therefore, attains a fuel efficiency of 85 percent. Although it shows good Dynamic load behavior it does subject to fixed parameters. On the other hand, FLDCD provides a much better fuel efficiency of 92% and prove that Fuzzy rule based decision making to handle the load condition effectively. That adaptability allows the most efficient fuel use when the load changes, either instantaneously or otherwise.

2. Battery Life Cycle Usage: The PID controller yields to a battery utilization of 78% thereby describing moderate performance managing charge discharge cycles. But because of the static control parameters, it cannot match load volatility, which again makes its utilization below par. Nonlinear adaptive control by FLDCD increases battery cycle usage to 88%. By compensating the control actions in real time, it makes the battery system respond optimally to load incidental while at the same time reducing wear and tear.

3. Response Time: The response of the PID controller indicates a delay of 5secs which clearly shows that this controller cannot make fast adjustments on the variation of the load as expected. While as for FLDCD it decreases response delay to 2 sec. This enhancement also underlines that the proposed method has a faster response time control for real-time optimization and is more resistant to changes in the environment, which is crucial in some specific applications.

V. CONCLUSION

Based on the findings of this study, it is clear that conventional PID controllers are inadequate for regulating the hybrid energy system under fluctuating loads. Although PID controller signs average performance in fuel efficiency, battery utilization, and response time, its work is based on the assumed constant coefficients and therefore lacks flexibility to adjust to new conditions. In light of these deformities, the preserved controllers reveal their drawbacks—thus, a new method called the Fuzzy Logic Driven Control Design (FLDCD) as the best solution. FLDCD is intelligent control system that responds to the nonlinear and dynamic system behavior by applying fuzzy logic concepts. Such outcomes confirm that FLDCD is possible as a stable and effective control for hybrid power generation systems. , the nonlinear and adaptive characteristics of FLDCD provide new opportunities in the field of fuel and battery management for effective and efficient solutions in terms of safety and sustainability. Thus the research emphasizes the need to start applying new forms of control, like FLDCD, so that the technologies of the future energy supply and demand will be met.

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