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Energy Management In Hybrid Energy Storage System For Evs Using PI And PID Controller

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Abstract: This paper proposes an adaptive energy management strategy for hybrid energy storage systems (HESS) in electric vehicles (EVs) using PI and PID controllers. Existing speed-based energy management strategies have limitations. The proposed method optimizes power allocation between batteries and ultracapacitors using PID control, filtered demand power, and PSO algorithm for parameter optimization. Simulation results demonstrate improved performance, economy, and prolonged battery life.

***Key words* - Electric Vehicles (EVs), Hybrid Energy Storage System (HESS), Energy Management, PI Controller, PID Controller, Power Optimization**

I. INTRODUCTION

Worldwide transport can significantly reduce gas emissions and energy consumption by adopting electric vehicles, which are more fuel-efficient than their internal combustion engine counterparts .The transportation sector is undergoing a significant transformation with the advent of electrical vehicle driven by growing concerns about climate change, air pollution and energy sustainability .Evs offer a promising solution but their widespread adoption is hinder by limited battery technology, range anxiety, and charging infrastructure.to address these challenges ,hybrid energy storage system(HESS) have emerged as a viable solution, combining different energy storage technologies such as battery supercapacitor, fuel cell. However, the efficient management of energy flow between these components is crucial to optimize Ev performance, range and lifespan.

For effective energy management in HESS, industrial control systems often rely on PID and PI controllers, which provide a straightforward and efficient control strategy. A PID controller is a widely used control system that ensures precise and stable operation by adjusting the control variable based on the error value. It combines three essential components: proportional, integral, and derivative terms, which work together to minimize the error efficiently. On the other hand, a PI controller offers a simpler alternative by excluding the derivative term. While it reduces complexity and is suitable for applications where noise amplification is a concern, it may not achieve the same level of precision as a PID controller.

Electric vehicles (EVs) have gained attention as a sustainable solution to reduce environmental impact and address the growing energy crisis. These vehicles produce zero tailpipe emissions and rely on renewable energy sources for charging, making them an eco-friendly alternative to traditional combustion engine vehicles. Despite their potential, EV adoption faces critical barriers. Limited driving range due to current battery technologies, shorter battery lifespans caused by frequent charge cycles, and the need for improved energy efficiency in powertrains and charging systems are among the significant challenges that must be addressed for EVs to achieve widespread success. Hybrid Energy Storage Systems (HESS) combining batteries and ultracapacitors offer improved performance, but require sophisticated energy management strategies. Traditional speed-based energy management methods have limitations, failing to optimize power allocation between energy storage components. [1]

Recent advancements in control theory and power electronics enable the development of adaptive energy management strategies. Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers have demonstrated effectiveness in optimizing power allocation and improving system efficiency.

This paper proposes an adaptive energy management strategy for HESS in EVs using PI and PID controllers. The proposed method optimizes power allocation between batteries and ultracapacitors, enhancing overall system performance, economy, and battery lifespan. Simulation results demonstrate the effectiveness of the proposed strategy.

II. DESCRIPTION OF THE ENERGY SYSTEM

The hybrid energy storage system (HESS) comprising a battery and an ultracapacitor can be implemented in three primary configurations: passive, semi-active, and fully active. Each structure presents unique characteristics and trade-offs in terms of complexity, controllability, and cost.

- **Passive Structure:** In the passive configuration, the battery and ultracapacitor are connected in parallel without the use of additional converters. This design is straightforward and cost-effective but lacks the capability to regulate the current flow between the components. Consequently, it relies on the inherent electrical properties of the battery and ultracapacitor, which may lead to suboptimal current distribution and reduced system efficiency.
- **Fully Active Structure:** The fully active configuration involves connecting both the battery and the ultracapacitor to separate DC/DC converters. This allows for precise control of the current flowing through each component, optimizing the performance of the system. However, this structure significantly increases the complexity and cost of the system, making it less practical for cost-sensitive applications.
- **Semi-Active Structure:** The semi-active configuration offers a compromise between performance and cost-efficiency. In this setup, the ultracapacitor is integrated with a DC/DC converter, while the battery is directly linked in parallel with the load. This arrangement allows for optimized energy storage and delivery, leveraging the strengths of both components. The ultracapacitor, with its rapid charge/discharge capabilities, assists in handling quick power demands, while the battery, providing higher energy density, supports sustained power output. The use of a DC/DC converter ensures efficient energy management between the ultracapacitor and the battery, contributing to overall system effectiveness without significantly increasing the cost. This design offers several advantages:

    i. Simplified control compared to the fully active structure.
    ii. Enhanced system stability, as the bus voltage remains more consistent.
    iii. Reduced cost compared to the fully active configuration.

III. BLOCK DIAGRAM AND DESCRIPTION

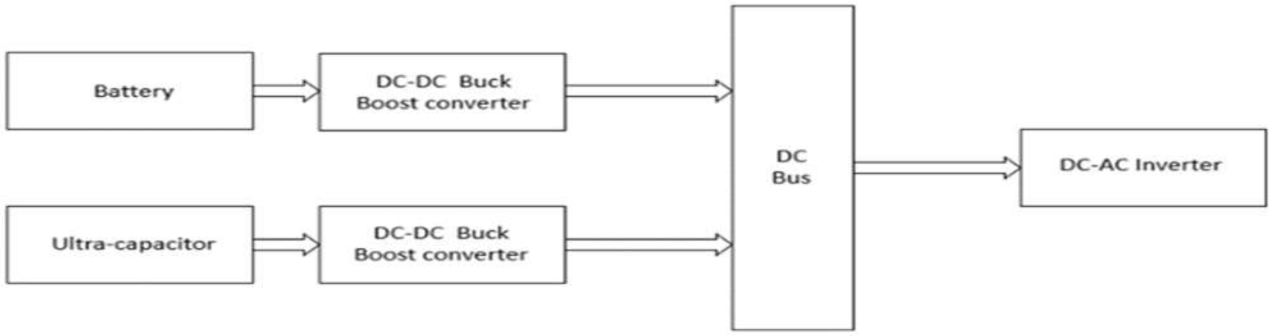

Fig. 1 Block diagram of HESS model

The components you described represent a typical energy management system for electric or hybrid vehicles, and they work together to optimize the vehicle's performance. Here's a brief explanation of each part in context:

- Battery: The battery is a primary energy source for an electric vehicle (EV), known for its high energy density. It stores and provides energy for long-duration tasks such as cruising or maintaining a constant speed. Due to its nature, it is less efficient at handling rapid power surges or quick changes in load, like when the vehicle accelerates suddenly. However, it can provide consistent power for extended periods, making it essential for sustained travel.

- Ultra-Capacitor (UC): The ultra-capacitor complements the battery by offering high power density. Unlike the battery, which is slower to respond to power demands, the ultra-capacitor can charge and discharge quickly, making it ideal for short bursts of energy. This makes it particularly useful for instantaneous power demands such as acceleration and regenerative braking. The ultra-capacitor reduces stress on the battery by handling these rapid load changes, thus enhancing the vehicle's overall performance and efficiency.

- DC-DC Buck/Boost Converters: These converters are critical in ensuring that the voltage from both the battery and ultra-capacitor matches the vehicle's system requirements. The DC-DC Buck Converter steps down the voltage when needed, while the DC-DC Boost Converter increases it. These converters help maintain the right voltage levels for the energy storage devices and manage the power flow to the DC Bus. They are key in regulating the power distribution between the battery and ultra-capacitor, ensuring that both can be used efficiently without causing over-voltage or under-voltage conditions.

- DC Bus: The DC Bus is the central power distribution system. It combines the power output from the battery and ultra-capacitor, ensuring that the energy is stable and continuous for use by other components. It maintains a consistent voltage and acts as a power hub, directing energy where it's needed in the system. This helps avoid power fluctuations that could affect system stability and performance.

- DC-AC Inverter: The DC-AC Inverter is essential for converting the DC power from the DC Bus into AC power. The electric motor in most vehicles operates on alternating current (AC), so the inverter is required to convert the stored DC energy into the appropriate form. It ensures the motor receives the correct voltage and frequency for smooth and efficient operation, optimizing vehicle performance, particularly for functions like acceleration and smooth transitions between different driving conditions.

Flow-Chart

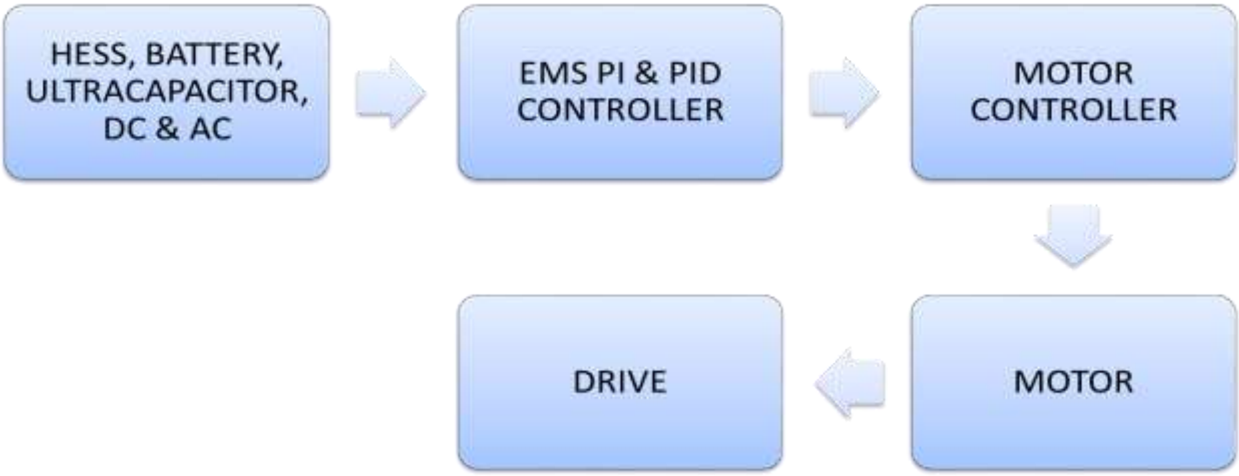

Fig 2. Flow chart of energy management system

- The block diagram illustrates the Energy Management System (EMS) designed for a Hybrid Energy Storage System (HESS) in Electric Vehicles (EVs). It highlights the integration of multiple components to ensure efficient and reliable energy utilization.
- At the core, the HESS comprises a combination of energy storage devices such as batteries and ultracapacitors, along with both DC and AC power sources. These components supply the primary energy needed for vehicle operation. The energy management process begins here, where the system optimizes power flow based on demand.
- The EMS leverages Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers to maintain balance and manage energy distribution effectively. These controllers ensure stability by regulating power output and minimizing inefficiencies.
- The regulated energy is then transmitted to the Motor Controller, which converts the managed electrical energy into actionable instructions for driving the motor. This conversion process ensures that the motor receives the precise energy required for efficient propulsion.
- Finally, the energy reaches the Drive System and Motor, where it is transformed into mechanical energy to propel the EV. This systematic flow from the energy source to the motor ensures seamless energy conversion and maximum performance efficiency.

IV. STRUCTURES AND MODELS

Battery Model:

Batteries are highly complex, non-linear electrochemical devices used for energy storage. Their internal processes involve intricate interactions and reactions that are challenging to describe using precise mathematical equations. Modelling these processes often requires extensive data collection and computational effort, especially when relying on experimental data for accuracy.

To simplify this complexity, an equivalent circuit model is commonly used to represent the external characteristics of a battery. This approach avoids delving into the detailed electrochemical reactions inside the battery and instead focuses on electrical parameters like open-circuit voltage (OCV), direct current (DC) internal resistance, and polarization resistance. These parameters are expressed through a simplified circuit representation, offering a practical way to characterize the battery's behaviour.

The internal resistance of a battery is categorized into two types:

a. Ohmic Internal Resistance: This includes resistance arising from various sources such as the electrode material, electrolyte, separator, and contact points within the battery.
b. Polarization Internal Resistance: This is the resistance induced by polarization during electrochemical reactions.

For this study, the primary focus is to validate the control strategy and optimization algorithm. Minor discrepancies in individual data sets are deemed negligible, and the influence of polarization resistance is excluded for simplicity. Instead, the Rint equivalent circuit model is adopted.

This model consists of: An ideal voltage source (U): Represents the battery's open-circuit voltage, an equivalent series resistance (R): Accounts for the battery's internal resistance.
The mathematical representation of this model provides a simplified framework for analysing the battery's performance, focusing on key aspects while neglecting the complexities associated with polarization effects. This approach is depicted in Figure 2, which illustrates the essential components of the Rint model. However, this method requires a significant amount of data and computational effort to fully leverage the experimental data generated. Unlike more detailed electrochemical models, the equivalent circuit model avoids an in-depth analysis of the electrochemical reactions within the battery. Instead, it characterizes the battery's external behaviour by focusing on parameters such as open circuit voltage, DC internal resistance, and polarization resistance, all represented through a simple circuit structure. This is why the equivalent circuit model is preferred for this analysis.

In this context, the battery's internal resistance is categorized into two types: ohmic internal resistance and polarization internal resistance. Ohmic internal resistance encompasses the resistances of the electrode material, electrolyte, diaphragm, and the contact points between various components. Polarization internal resistance, on the other hand, refers to the resistance arising from polarization effects during the electrochemical reactions. [2]

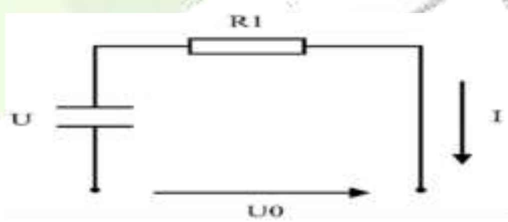

Fig.3 Battery Model

Ultracapacitor model

The ultracapacitor is distinguished by its high power density, which allows it to deliver and absorb energy quickly. However, its energy density is much lower compared to storage batteries. This inherent limitation, along with the correlation between its voltage and state of charge, prevents the ultracapacitor from being used as the sole power source for electric vehicles (EVs). Instead, it is primarily employed as an auxiliary power source to complement the primary energy storage system by providing rapid bursts of energy when needed.

To model the dynamic behavior of ultracapacitors, equivalent circuit models are often used. These models employ resistors and capacitors to represent the working characteristics of supercapacitors in a way that is both physically meaningful and practically applicable. The accuracy of the equivalent circuit model is highly dependent on the proper identification of its parameters, as these directly influence its ability to replicate the actual performance of the ultracapacitor. For this reason, it is crucial to select an appropriate model that effectively captures its dynamic characteristics. [3]

In this study, the classical equivalent circuit model is chosen for its simplicity and effectiveness in describing ultracapacitor behaviour. This model comprises three key components: a large series resistance (R_1), which accounts for internal resistance; a parallel resistance (R_2), which represents leakage currents and self-discharge; and an ideal capacitor (C), which models the primary energy storage capability. Together, these components provide a robust framework for analysing ultracapacitor performance.

The parameters of the model are determined by measuring the voltage response of the ultracapacitor during the charging process. This data-driven approach ensures that the model accurately reflects the ultracapacitor's real-world behaviour. By utilizing this classical equivalent circuit model, the study aims to develop and optimize control strategies that enhance the integration and functionality of ultracapacitors in hybrid energy systems.

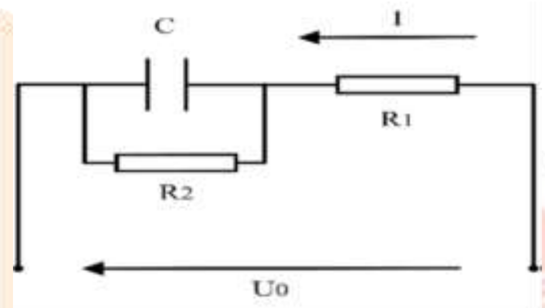

Fig. 4 Ultracapacitor

V. CONTROL STRATEGY AND OPTIMIZATION OF HESS PREPARE YOUR PAPER BEFORE STYLING

PID controller

When designing a PID controller for a specific system, please follow the steps outlined below to achieve the desired response.

i. Obtain the open-loop response and identify areas for improvement.
ii. Introduce a proportional control element to enhance the rise time.
iii. Implement a derivative control to mitigate overshoot.

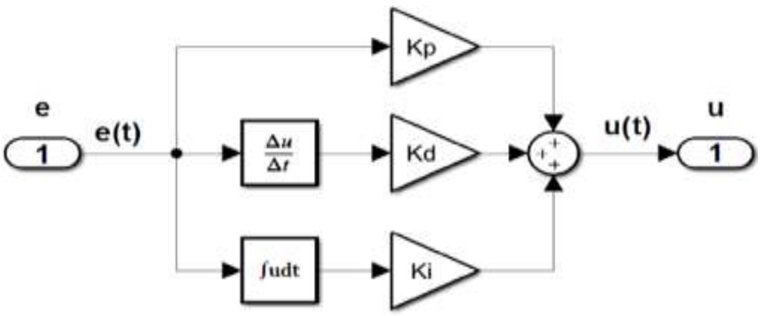

Fig.5 PID controller

The PID controller in the time-domain is described by the relation:

$$u = K_{pe} + K_1 \int edt + K_D \frac{de}{dt} = K_p(e + \frac{1}{T_1} \int edt + T_D \frac{de}{dt} \quad (1)$$

Lastly, please keep in mind that you do not need to implement all three controllers (proportional, derivative, and integral) into a single system, if not necessary. For example, if a PI controller meets the given requirements (like the above example), then you don't need to implement a derivative controller on the system. Keep the controller as simple as possible.
Increasing the proportional gain (K_p) causes the control signal to increase proportionally for a given error, which accelerates the system's response but may lead to more overshoot. This adjustment can also reduce, but not completely eliminate, the steady-state error.

When a derivative term (K_d) is added to the controller, it enables the system to "anticipate" errors. Unlike a proportional-only controller, which responds solely to the magnitude of the error, a derivative controller adjusts the signal based on how the error is changing over time. This anticipatory action helps reduce overshoot by introducing damping into the system, although it does not affect steady-state error.

The introduction of an integral term (K_i) works to minimize steady-state error by continuously integrating any ongoing error. Over time, the integrator increases the control signal, helping to eliminate the error. However, a downside to using an integral term is that it can make the system slower or more oscillatory, particularly when the error reverses direction and the integrator needs time to adjust.

In summary, the effects of adjusting K_p, K_i, and K_d on the closed-loop system are as outlined. These general principles apply in most cases, though the precise impact will depend on the specific system. To fully understand the effects of tuning these parameters, further analysis or practical testing may be necessary. [4]

PI controller

PI controller or Proportional controller is a combination of Proportional controller action and Integral controller action which is designed to regulate a process variable based on its set point and manipulated variable. Also, it can be identified as a combination of proportional and integral controllers.

$$u = K_{pe} + K_1 \int edt \quad (2)$$

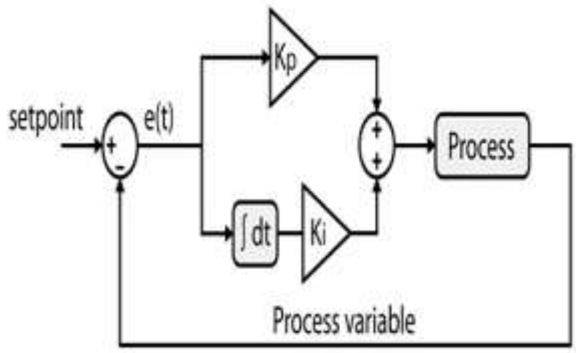

Fig. 6 PI controller

VI. OPTIMIZATION OF ENERGY MANAGEMENT STRATEGY

The design and application of a PID controller are fundamentally driven by three parameters: proportional, integral, and derivative. Each of these parameters plays a critical role in shaping the controller's performance. The proportional function links the controller's output to the input in a linear relationship, which helps reduce the error, accelerate response times, and decrease regulation time. However, increasing the proportional gain excessively can worsen the system's dynamic behaviour and may even destabilize the closed-loop system.[5] The integral function, on the other hand, is effective in eliminating steady-state errors, ensuring that the system reaches the desired set point. However, this comes at the cost of reduced stability, potentially leading to overshooting and slower system response. The derivative function aims to improve the system's dynamic characteristics by responding to the rate of change in the error. This helps speed up the system's response and reduce overshoot. While it enhances dynamic performance, the derivative function is highly sensitive to noise, which can decrease the system's ability to suppress

As a result, selecting the optimal values for these PID parameters is essential to balance both the dynamic and static performance of the system. The key challenge is to adjust the proportional, integral, and derivative gains in a way that optimizes overall control performance, ensuring the system is both fast-responding and stable. In this context, the optimization of the PID controller parameters is crucial for achieving effective control. This study uses an algorithm to calculate and fine-tune these PID parameters, aiming to improve the power distribution in a Hybrid Energy Storage System (HESS) so that it aligns more closely with the ideal state. The goal is to optimize the system's performance, achieving efficient and stable power management. In the algorithm's optimization process, two primary factors—the battery's operating current and the overall power consumption of the HESS—are considered as multi-objective parameters. These factors are used to guide the optimization, with the aim of enhancing both energy efficiency and system stability simultaneously.

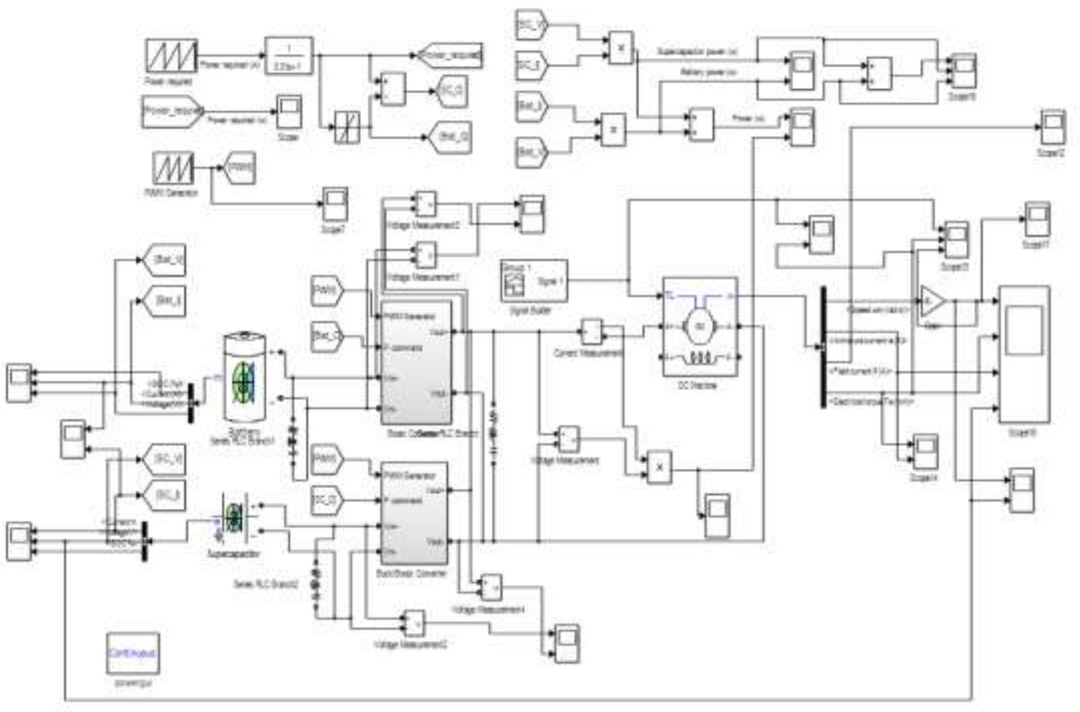

Fig. 7 Simulation Diagram

VII. DYNAMIC PROGRAMMING

Dynamic programming (DP), rooted in the Bellman principle, is an algorithm for solving complex problems through breaking them down into simpler sub problems. In the context of optimizing power output within a power system, the problem can be seen as a multi-stage decision-making issue where each stage corresponds to a discrete time period. At each of these time intervals, the algorithm aims to distribute energy optimally, leading to the best control outcome over time. This makes the DP algorithm well-suited for power system control, as it focuses on step-by-step optimization. [6]

However, DP has its limitations. It requires prior knowledge of system conditions and assumes that the driver's power demand matches the anticipated demand. This means that the DP algorithm typically calculates optimal solutions in an offline manner, which are theoretical in nature, rather than adapting dynamically in real-time. The algorithm selects the best control action for each stage based on predefined conditions, which are divided into several segments (or stages), progressively solving smaller optimization problems. This decomposition of the problem into smaller steps ultimately helps achieve the overall optimal solution.[7]

VIII. RESULTS

To evaluate the effectiveness and rationality of the proposed PID control strategy and the Particle Swarm Optimization (PSO) algorithm, a simulation analysis is conducted using an Electric Vehicle (EV) model within MATLAB and Advisor. These parameters are crucial for setting up the EV model in the simulation environment.[8]

Modeled as a constant power load, which simplifies the simulation by assuming that the energy demand does not fluctuate during operation, regardless of the vehicle's speed or driving conditions. This load assumption aligns with many EV scenarios where energy consumption is relatively constant under normal driving conditions.

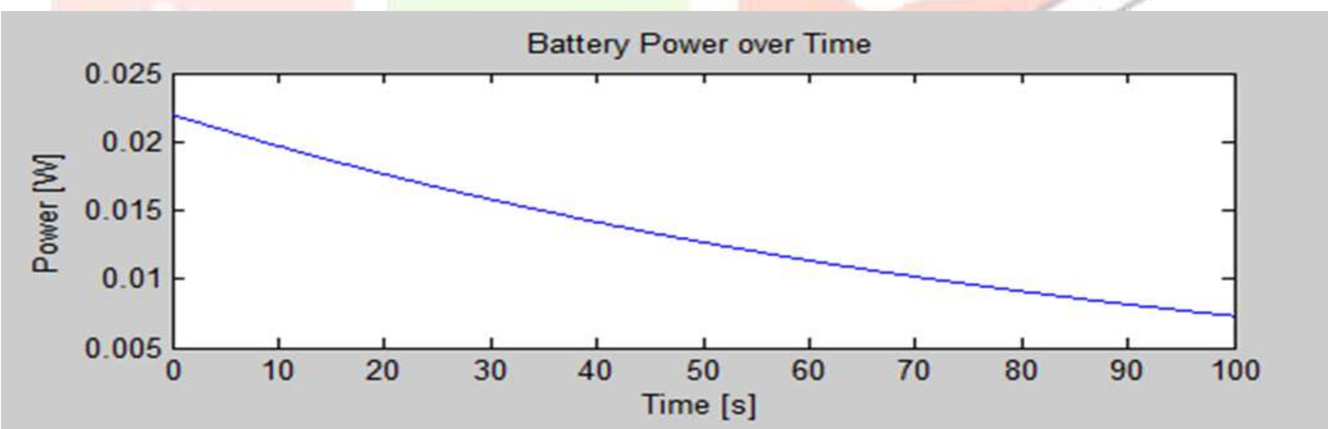

Fig 8. Battery power profile,

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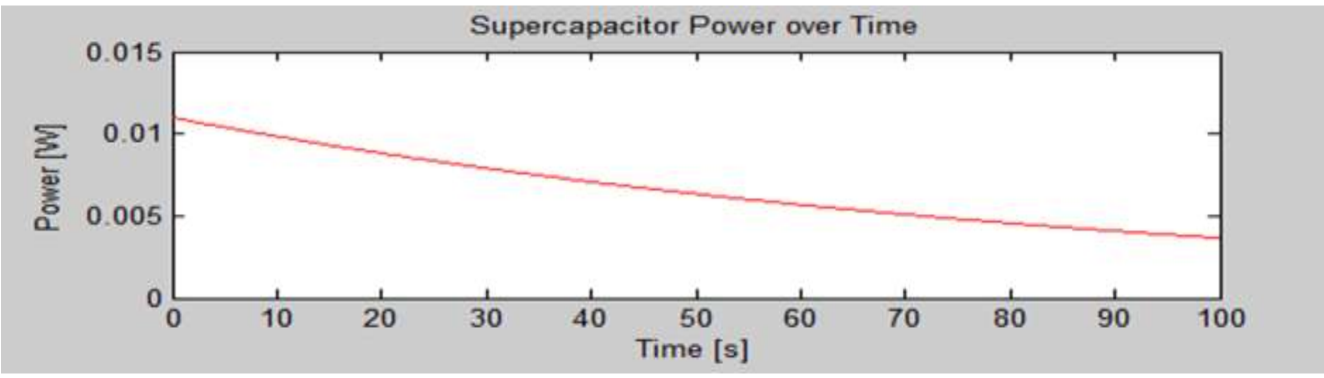

Fig 9. Supercapacitor capacitor power profile

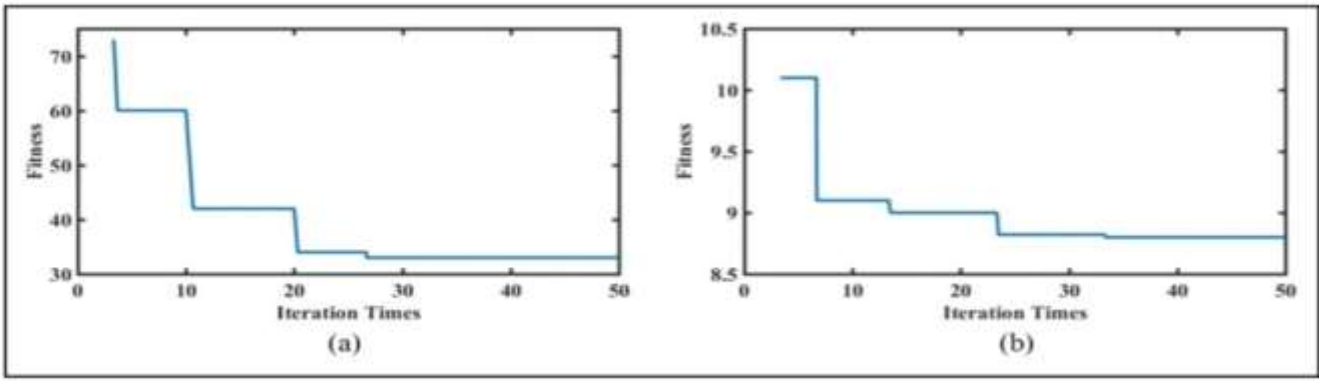

Fig 10. (a) Filter Iteration using PI, (b) Filter Iteration using PID

Emissions, making any emissions-related post-processing unnecessary for this analysis. Therefore, the output related to vehicle emissions is set to zero.[9]

The working conditions in the simulation are derived from an experimental approach that is commonly used to assess vehicle performance under various real-world driving

Scenarios. These conditions aim to simulate typical urban and suburban driving environments, which are representative of
The day-to-day use of electric vehicles. Specifically, these conditions include:

Acceleration: This condition tests how the vehicle responds when increasing speed.
Climbing: It simulates the energy consumption required when the vehicle is driving uphill, accounting for the additional power needed to overcome gravity.[10]
Deceleration: This represents the vehicle's energy recovery, typically through regenerative braking, as it slows down.
Uniform Speed: This tests the vehicle's behaviour when driving at a constant speed, a typical scenario in highway driving.[11]

Each of these conditions is integrated into the simulation to replicate real-world driving behavior, enabling a comprehensive evaluation of how the PID control strategy

And PSO optimization perform in various typical driving situations. These conditions are carefully designed to reflect urban or suburban environments, offering a well-rounded set of parameters for assessing the vehicle's energy management and performance under practical scenarios.[12]

IX. CONCLUSION

- This paper presents a novel energy management framework for Hybrid Energy Storage Systems (HESS), utilizing a PID (Proportional-Integral-Derivative) control strategy. The primary parameter used to regulate the output power of the battery and ultracapacitor is the power difference between these two components. The goal is to optimize the energy transfer between the storage elements by effectively managing this power difference.

- To improve the performance of the PID controller, an optimization approach is applied to tune its parameters. The optimization method is designed to enhance the controller's efficiency and ensure the system operates at its best. By refining the PID parameters, the system can dynamically adjust to varying load conditions, improving energy utilization and reducing losses.

- To assess the effectiveness of the optimized control strategy, a Dynamic Programming (DP) algorithm is incorporated. The DP algorithm calculates the theoretical minimum energy usage for the system, serving as a benchmark to compare the control system's performance. This comparison helps evaluate how closely the PID-controlled system achieves ideal energy efficiency.

- The paper discusses the robustness and stability of the proposed control system, illustrating its ability to enhance the battery's lifespan and decrease the overall energy consumption of the hybrid energy storage system. The findings show that the system remains stable under varying operating conditions while efficiently managing the energy flow between the battery and ultracapacitor, thereby improving the long-term performance of the system.

- However, the study has certain limitations. It does not take into account the impact of temperature variations and polarization effects on the battery state, which can influence the accuracy of the system's performance. Additionally, the energy system is modeled using a generalized approach, which may reduce the precision of the simulation results.

- Future research will focus on refining the optimization process by incorporating more detailed models that account for factors such as temperature and polarization effects. This will lead to more accurate simulations, improving the system's overall performance, extending its operational life, and enhancing the economic benefits for applications such as electric vehicles.

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