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Article

Hybrid energy storage system integrating lithium-ion batteries and supercapacitors for enhanced electric vehicle performance

Ashiq Hussain[1,*], **Muhammad Fasih Aamir**[1,2,*]

[1] Graduate School of Science and Technology, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8577, Japan

[2] International Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science (NIMS), 1-1 Namiki, Tsukuba 305-0044, Japan

*** Corresponding author:** Ashiq Hussain, s2420914@u.tsukuba.ac.jp; Muhammad Fasih Aamir, aamir.fasih.ke@u.tsukuba.ac.jp

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Abstract: The increasing adoption of electric vehicles (EVs) has highlighted persistent challenges related to battery efficiency, limited lifespan and performance fluctuations during highly dynamic driving conditions. To address such issues, this study proposes a novel Hybrid Energy Storage System (HESS) that strategically combines lithium-ion batteries and supercapacitors to take advantage of the high energy density of batteries and the rapid charge-discharge characteristics of supercapacitors. The hybrid configuration is governed by an Arduino-based control unit equipped with an intelligent power management algorithm, which tracks real-time acceleration profiles and dynamically allocates power to the appropriate energy source. During steady-state operation, the batteries supply the required power, while peak loads during sudden acceleration or regenerative braking are effectively handled by the supercapacitors. Extensive simulations and laboratory experiments demonstrate that this strategy significantly reduces battery stress, mitigates thermal effects, and increases overall cycle life. Additionally, a dedicated mobile application enables real-time monitoring of key operating parameters, including SOC, vehicle speed and overall system status, thereby improving user interaction and enabling proactive maintenance decisions. Overall, the proposed HESS substantially improves energy efficiency and operational stability, representing a practical and scalable solution for achieving long-term sustainability and high performance in next-generation electric vehicle technologies.

Keywords: hybrid energy storage system (HESS); electric vehicles (EVs); supercapacitors; energy management system (ESS); battery management; Arduino control

1. Introduction

1.1. Background

The rising number of internal combustion engine (ICE) vehicles, which depend heavily on non-renewable fossil fuels, has led to serious energy shortages and environmental degradation, including increased greenhouse gas emissions [1–3]. In response, many countries are accelerating the transition toward electric vehicles (EVs) as a cleaner and more sustainable alternative to reduce oil dependency and curb urban air pollution [4,5]. The first electric vehicle (EV) was developed in 1834 [6]. Throughout the 19th century, numerous companies, particularly in America, Britain, and France, endeavored to advance EV technologies [7]. However, these early vehicles relied on a single battery source, which proved insufficient for practical use [8–11]. Additionally, technological limitations in battery design combined with the rapid progress of internal combustion engine (ICE) vehicles contributed to the decline of EV popularity by the 1930s [12–14]. In 1898, German engineer Dr. Ferdinand Porsche developed the first hybrid electric vehicle (HEV), known as the Lohner Electric Chaise [15]. HEV technology was designed to address the limitations of both ICE vehicles and pure EVs by combining an internal combustion engine with a battery-powered electric motor [16–18]. This hybrid configuration offers several advantages, including reduced emissions, improved reliability, enhanced fuel efficiency, and extended driving range compared to either ICE vehicles or EVs alone [19, 20]. Additionally, HEVs can recover kinetic energy during braking, similar to EVs, improving overall energy efficiency [20, 21]. However, the HEV powertrain is inherently more complex due to the integration of multiple components and sophisticated control systems [22–24].

The use of electric vehicles (EVs) gained early momentum through the efforts of the California Air Resources Board (CARB), which issued strong regulatory signals aimed at reducing vehicular emissions [25–27]. This initiative drew global attention, as EVs were seen as a promising solution to environmental pollution [28–30]. Consequently, countries around the world began accelerating their shift toward electric mobility in an effort to build cleaner and more sustainable transportation systems. Several factors influence the efficiency and performance of electric vehicles, with the energy storage system (ESS) being one of the most critical components [31]. The ESS plays a central role in determining the overall functionality and range of an EV. Among the various energy storage options, batteries remain the most widely used devices across all EV platforms [32]. While different battery chemistries have been explored, lithium-ion (Li-ion) batteries have emerged as the most promising due to their high energy density, lightweight design, and widespread use in portable electronic devices such as smartphones and laptops [33].

Despite their advantages, the broader adoption of EVs is still hindered by limitations such as the relatively low energy density and limited lifespan of Li-ion batteries [34]. Several factors such as overheating, internal redox reactions, and overcharging, can accelerate battery degradation. Although significant advancements have been made to mitigate these issues, battery performance still poses a barrier to the large-scale deployment of electric vehicles [35]. One of the primary factors that reduces the battery lifecycle in electric vehicles (EVs) is the sudden discharge of energy during peak power demands, such as rapid acceleration [36]. This scenario frequently occurs in EVs due to varying influences like driving habits and road conditions, which cause abrupt fluctuations in power consumption [37, 38]. While batteries perform optimally under steady, smooth power demand at constant speeds, such ideal conditions are rarely encountered in real-world driving. Therefore, to extend the lifespan of the energy storage system, an effective battery management system (BMS) is essential to regulate and ensure a smooth and consistent flow of power from the battery to the vehicle. One of the prominent solutions is to utilize the supercapacitor along with the battery to absorb the fluctuation in energy consumption by the battery during unprecedented events. Several studies investigated the impact of the integration of a supercapacitor along with a battery on electric vehicle performance and durability. Research by Pedram et al. [39] demonstrated that hybrid systems significantly reduce battery current ripple under dynamic load conditions, leading to improved battery efficiency and thermal behavior. Similarly, Garcia et al. [40] highlighted that hybrid configurations enhance powertrain reliability by decoupling high-power transients from the main battery. Other works have focused on the optimization of power flow between storage devices, showing that proper coordination between batteries and supercapacitors can substantially extend battery cycle life and improve regenerative energy utilization [41,42].

More recent studies have explored advanced control frameworks for HESS in EVs. For example, fuzzy-logic-based and model predictive control approaches have been proposed to achieve smoother power sharing and improved energy efficiency [43, 44]. Optimization-based strategies using dynamic programming and real-time energy management have also been reported to enhance system-level performance under standardized driving cycles [45]. In addition, several authors have examined the role of supercapacitors in absorbing regenerative braking energy more effectively than batteries, thereby reducing energy losses and mechanical braking demand [46]. These studies collectively confirm that HESS offers clear technical advantages over single-source battery systems.

Despite these advancements, experimental validation remains limited in many reported works. A significant portion of the literature relies heavily on numerical simulations using predefined driving cycles, with minimal focus on hardware implementation or real-world operating conditions [41–44]. Moreover, while some studies have introduced sophisticated energy management algorithms, their practical deployment is often constrained by computational complexity, sensor dependency, and the need for accurate system modeling [47–50]. Recent research has also begun to emphasize the importance of real-time monitoring and connectivity; however, IoT-based integration in HESS is still at an early stage and is rarely coupled directly with control decisions [51–55].

Overall, although existing studies clearly demonstrate the benefits of hybrid battery–supercapacitor systems, several shortcomings remain when viewed from a practical implementation perspective. Most studies do not provide a simple and intuitive criterion for activating supercapacitor support during real driving conditions, often relying instead on complex SOC- or model-based thresholds. Charging strategies for supercapacitors are frequently limited to regenerative braking, reducing their availability during frequent acceleration events. Furthermore, many proposed HESS architectures depend on multiple DC–DC converters, increasing system cost and complexity and limiting applicability in low-cost EV platforms. Experimental prototype validation and user-level monitoring are also insufficiently addressed. In contrast, the present work directly tackles these limitations by introducing a throttle-variation-based activation mechanism, a low-complexity switching architecture, and integrated IoT-based real-time monitoring, thereby offering a practical and scalable solution aligned with real-world electric vehicle operation.

1.2. Purpose of this research

As discussed in the above section, most existing studies on HESS for electric vehicles primarily focus on improving energy efficiency, power smoothing, and battery performance through advanced control strategies and converter-based architectures. While these studies demonstrate the technical benefits of combining batteries and supercapacitors, many of them rely on complex energy management algorithms, such as optimization-based or predictive control methods, which limit their practical applicability in real-time and low-cost electric vehicle platforms. In addition, several studies assume that supercapacitors are charged exclusively through regenerative braking, which restricts their effectiveness under frequent acceleration or urban driving conditions.

Furthermore, existing research often lacks clear and practical criteria for determining when the supercapacitor should actively support the battery during vehicle operation. Although peak power mitigation is widely acknowledged, few studies explicitly define the activation threshold or duration of supercapacitor operation in a manner that is simple, intuitive, and implementable using low-complexity hardware. Most reported works emphasize simulation-based validation under standardized driving cycles, with limited focus on prototype-level implementation or real-world operation. Moreover, real-time monitoring and remote visualization of battery and supercapacitor health parameters are rarely integrated directly into the energy management framework, despite their importance for diagnostics, reliability, and user awareness.

To address these gaps, this study proposes an IoT-based hybrid battery–supercapacitor energy storage system for electric vehicles that emphasizes simplicity, practicality, and real-time applicability. The proposed system introduces a throttle-variation-based energy management strategy to explicitly identify peak power demand conditions and dynamically allocate power between the battery and supercapacitor. By reducing control complexity and integrating real-time monitoring, the proposed approach aims to enhance battery lifetime and improve overall system performance. The main contributions of this research are summarized as follows:

a. Development of a low-complexity hybrid battery–supercapacitor energy storage architecture for electric vehicles, in which the supercapacitor is employed as an auxiliary power source to mitigate peak power demands and reduce battery stress during rapid acceleration events.

b. Design and implementation of a throttle-difference-based energy management strategy that provides a clear, intuitive, and real-time criterion for activating supercapacitor support, eliminating the need for computationally intensive control algorithms.

c. Integration of an IoT-based monitoring framework that enables real-time observation and remote visualization of key vehicle and energy storage parameters, including state of charge and vehicle speed, thereby enhancing system transparency and operational reliability.

d. Validation of the proposed hybrid energy storage system through both simulation and prototype-level hardware implementation, demonstrating its practical feasibility and effectiveness in improving battery lifetime and operational efficiency under dynamic driving conditions.

2. Methodology

This work presents the detailed methodology adopted for the design, implementation, and validation of the proposed IoT-based hybrid energy storage system for electric vehicles using a battery and supercapacitor. The methodology focuses on system architecture, operating principles, energy management strategy, control and switching logic, IoT-based monitoring, and simulation setup. The proposed approach aims to protect the battery from sudden peak power demands by intelligently coordinating power flow between the battery and the supercapacitor under different driving conditions.

2.1. System architecture

The suggested system architecture is a hybrid energy storage system in which a lithium-ion battery is the primary energy source and a supercapacitor bank serves as an auxiliary energy storage device to handle peak power needs, as shown in **Figure 1**. An Arduino microcontroller serves as the system's central control unit. The controller continuously monitors throttle input to determine the vehicle's operating mode. The controller uses relay-based switching to switch the energy source between the battery and the supercapacitor in response to throttle changes. This architecture enables the battery to run under more stable current circumstances, while the supercapacitor meets short-duration high-power demands during abrupt acceleration.

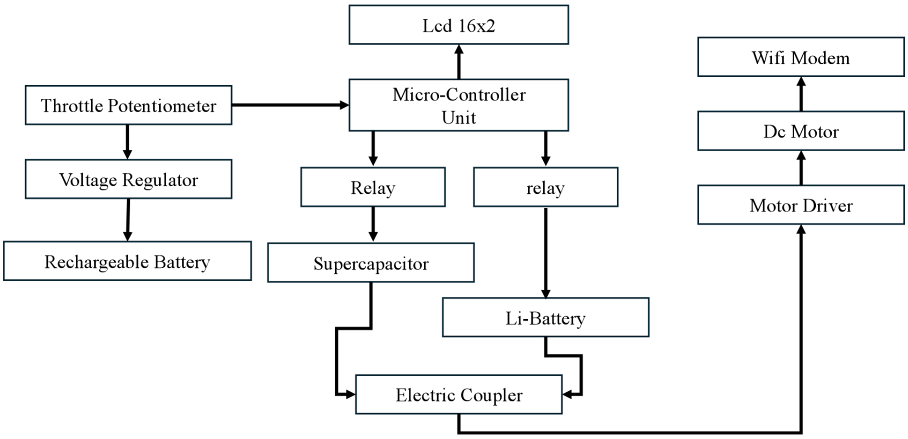


Figure 1. Schematic of System Architecture-hybrid energy storage system.

During normal driving conditions, the lithium-ion battery provides the electric car with sustained energy. The battery's high energy density makes it suited for long-term operation; yet, it is vulnerable to large current transients. In the proposed architecture, the battery provides power mostly during steady-state operation, avoiding exposure to sudden peak loads that could exacerbate aging and thermal stress.

To address quick power fluctuations, a supercapacitor bank has been included as an additional energy storage device. Supercapacitors have a high-power density and a quick charge-discharge rate, making them excellent for supplying energy during unexpected acceleration events. When peak power demand is recognized, the supercapacitor temporarily replaces the battery as the motor's primary power source, protecting it from high current discharge and increasing its operational life.

The Arduino microcontroller serves as the system's central processor. It accepts input from the throttle potentiometer and other sensors, processes the control algorithm, and generates relay switching signals. The Arduino implements the energy management logic in real time, ensuring a smooth transition between battery and supercapacitor modes. Its low cost, simplicity, and ease of programming make it ideal for prototyping and low-cost electric vehicle applications.

The throttle potentiometer represents the electric vehicle's accelerator input. It generates an analog signal based on the driver's acceleration requirement. The controller continuously monitors the throttle position and calculates the variation between time periods. This variation is the essential indicator for detecting unexpected acceleration and activating supercapacitor support. The relay modules function as electrically regulated switches, connecting the battery or the supercapacitor to the motor drive circuit. The relays open or close in response to Arduino control signals, allowing the right energy source to be selected. Relay-based switching is preferred because of its simplicity, dependability, and adaptability for low-complexity system designs. The DC motor reflects the electric car prototype's traction load. It turns electrical energy into mechanical motion, and its power consumption changes with throttle input. Peak power requirements result from sudden increases in motor speed or torque demand, which are met by the hybrid energy storage system. The motor driver connects the energy storage system and the DC motor. It provides controlled power to the motor, protects the controller from excessive currents, and allows for smooth motor performance under variable load situations.

A voltage regulator provides a constant and regulated voltage to the Arduino, sensors, Wi-Fi module, and display modules. This component protects low-power devices from voltage fluctuations and maintains system stability. The system features a 16 × 2 LCD display for user engagement and monitoring. It allows for the local, real-time viewing of system data such as voltage, current, motor speed, and active energy source. This display simplifies debugging, testing, and on-site monitoring. The Wi-Fi module allows for remote system monitoring using IoT technology. It sends crucial operational data to a mobile app or online interface, such as battery and supercapacitor status, motor speed, and charge level. This feature improves system openness, enables remote diagnostics, and allows for future extensions like data logging and predictive maintenance.

Overall, the suggested system architecture allows for coordinated interaction between energy storage devices, control units, power electronics, and monitoring components. By dynamically dividing power between the battery and supercapacitor depending on throttle variation, the architecture significantly decreases battery stress during peak demand events while maintaining efficient and dependable electric vehicle performance.

2.2. Operating principle of the hybrid energy storage system

The operating principle of the proposed hybrid energy storage system is based on classifying vehicle operation into two distinct modes, namely normal demand mode and peak demand mode, according to the variation in throttle input, named as throttle difference. The throttle difference is defined as the change in vehicle acceleration between two consecutive time steps. It represents the variation in throttle input demanded by the driver or control system. A low throttle difference indicates smooth driving with gradual power demand, whereas a high throttle difference corresponds to sudden acceleration or deceleration. These rapid changes generate transient power spikes that stress the battery. During normal driving conditions, when the throttle position changes gradually and the power demand remains relatively low, the lithium-ion battery supplies energy to the DC motor. This mode ensures efficient utilization of the battery for sustained energy delivery and avoids unnecessary stress on the battery during steady-state operation.

In the developed prototype, the throttle input is implemented using a potentiometer connected to the Arduino microcontroller. The potentiometer provides an analog signal proportional to the driver’s acceleration demand. The microcontroller continuously reads this signal and compares the current throttle value with the previous value to determine the throttle variation. When the throttle variation remains below a predefined threshold, the system remains in battery mode. In this state, the battery relay remains closed while the supercapacitor relay remains open, allowing the battery to supply power to the motor through the motor driver.

During sudden acceleration or rapid changes in throttle position, the power demand of the DC motor increases sharply. Supplying this transient power directly from the battery can result in high current draw, increased internal losses, and thermal stress, which accelerate battery degradation. To prevent this, the proposed system activates the supercapacitor during peak demand conditions. In the prototype, when the throttle variation exceeds the predefined threshold, the Arduino generates control signals that disconnect the battery relay and simultaneously connect the supercapacitor relay. As a result, the supercapacitor becomes the primary energy source for the motor during this short-duration high-power event.

Due to its high-power density and fast charge–discharge characteristics, the supercapacitor is capable of supplying the required transient current almost instantaneously. During this period, the battery is effectively isolated from the peak load, thereby reducing high-current stress and protecting it from accelerated aging. The motor continues to operate smoothly because the switching process is fast and does not interrupt the power supply to the motor. Once the acceleration stabilizes and the throttle variation falls below the threshold value, the system automatically switches back to battery mode. The Arduino deactivates the supercapacitor relay and reconnects the battery relay, allowing the battery to resume supplying energy for normal vehicle operation. This continuous monitoring and rapid switching process ensures that the supercapacitor is used only when necessary, while the battery is reserved for energy-intensive but low-power-fluctuation operation.

In the prototype, the current operating mode—battery or supercapacitor—is displayed on the 16 × 2 LCD and transmitted to the remote monitoring interface via the Wi-Fi module. This allows real-time observation of system behavior and verification of correct switching during different driving conditions. Through this operating principle, the proposed hybrid energy storage system effectively smooths battery current, enhances battery lifetime, and improves overall system performance under dynamic driving conditions.

2.3. Energy management strategy

The energy management strategy of the proposed system is based on throttle variation rather than complex state-of-charge or model-based control methods. The throttle input is measured using a potentiometer connected to the Arduino. The controller continuously compares the current throttle value with the previous value to compute the throttle difference.

A predefined threshold is used to distinguish between normal and peak demand conditions. When the throttle difference remains below the threshold, the system operates in battery mode. When the throttle difference exceeds the threshold, indicating sudden acceleration, the controller activates the supercapacitor. This rule-based strategy is simple, computationally efficient, and suitable for real-time implementation in low-cost electric vehicle platforms. By prioritizing the supercapacitor during high-power demand events, the strategy reduces battery current peaks and minimizes battery degradation. At the same time, the battery remains responsible for supplying energy during steady-state operation, ensuring optimal utilization of both energy storage devices.

2.4. Control algorithm and switching logic

The control algorithm is implemented using Arduino programming and operates in a continuous loop. The algorithm begins by reading sensor data, including throttle position, voltage, current, and motor speed. The throttle value is mapped and compared with a predefined threshold to determine the operating mode. If the throttle value exceeds the set threshold, the Arduino sends a control signal to deactivate the battery relay and activate the supercapacitor relay. In this mode, the supercapacitor supplies power to the motor. If the throttle value remains below the threshold, the battery relay remains active, and the supercapacitor is disconnected. The switching logic is designed to be fast and reliable, ensuring smooth transitions between battery and supercapacitor modes without interrupting motor operation. The controller periodically checks the throttle condition and updates the relay states accordingly. This logic ensures continuous protection of the battery from sudden high current demands.

2.5. IoT-based monitoring framework

An IoT-based monitoring framework is included in the proposed hybrid energy storage system, allowing for real-time observation and remote supervision of vehicle and storage parameters. A Wi-Fi module connected to the Arduino microcontroller establishes a wireless connection between the hardware system and a remote monitoring platform. The microprocessor continuously collects data from voltage, current, and speed sensing devices, as well as the functioning state of the energy storage system, and communicates it via the Wi-Fi module at regular intervals. Key metrics such as battery voltage, supercapacitor voltage, motor current, motor speed, and the active working mode (battery or supercapacitor) are sent to a mobile app or web dashboard. This enables users to check the energy storage system's real-time status without requiring physical access to the vehicle. The device also gives instant visual feedback on switching events, allowing for verification of proper supercapacitor activation during peak power demand.

The IoT framework improves system transparency and dependability by allowing remote diagnostics and fault detection. Any problematic behavior, such as sudden voltage decreases or frequent switching events, can be detected in real time, allowing for prompt corrective action. Furthermore, continuous data logging enables performance analysis and long-term evaluation of battery and supercapacitor utilization trends. This architecture also lays the groundwork for future improvements, such as predictive maintenance, cloud-based data analytics, and adaptive energy management methods based on past driving behavior.

3. Simulation setup

3.1. Simulation environment and system modeling

The simulation of the proposed IoT-based hybrid energy storage system was carried out using Proteus 8 Professional software prior to hardware implementation. Proteus was selected because of its strong capability to simulate microcontroller-based systems and mixed analog–digital circuits, making it suitable for validating Arduino-controlled power electronics applications. The complete system schematic was designed in the Proteus environment to closely resemble the actual hardware prototype. All major system components were modeled, including the Arduino microcontroller, lithium-ion battery, supercapacitor bank, relay modules, DC motor, motor driver, voltage regulator, throttle potentiometer, and display units. Each component was connected according to the proposed system architecture to ensure accurate representation of power flow and control behavior. Virtual instruments such as the LCD and virtual terminal were used to observe voltage, current, motor speed, and operating mode during simulation. This modeling approach ensured that the simulation environment closely matched real-world system behavior.

3.2. Control logic and workflow

The control logic of the hybrid energy storage system was implemented by uploading the Arduino program into the simulated microcontroller within Proteus (**Figure 2**). The Arduino code continuously reads the throttle input provided through a virtual potentiometer and processes it according to the predefined energy management strategy. The throttle value is monitored in real time and compared with a preset threshold to identify normal and peak power demand conditions. Based on the throttle input, the Arduino controls the relay switching logic to select the appropriate energy source. When the throttle variation remains below the threshold, the battery relay is activated, allowing the battery to supply power to the motor. When the throttle variation exceeds the threshold, indicating sudden acceleration, the controller deactivates the battery relay and activates the supercapacitor relay. This switching process follows the simulation flow illustrated in the flowchart and ensures a smooth transition between battery and supercapacitor modes without interrupting motor operation. The switching behavior, relay response, and motor operation were carefully observed during simulation to verify the correctness of the control logic. The results confirmed that the control algorithm performs as intended and accurately follows the proposed energy management strategy.

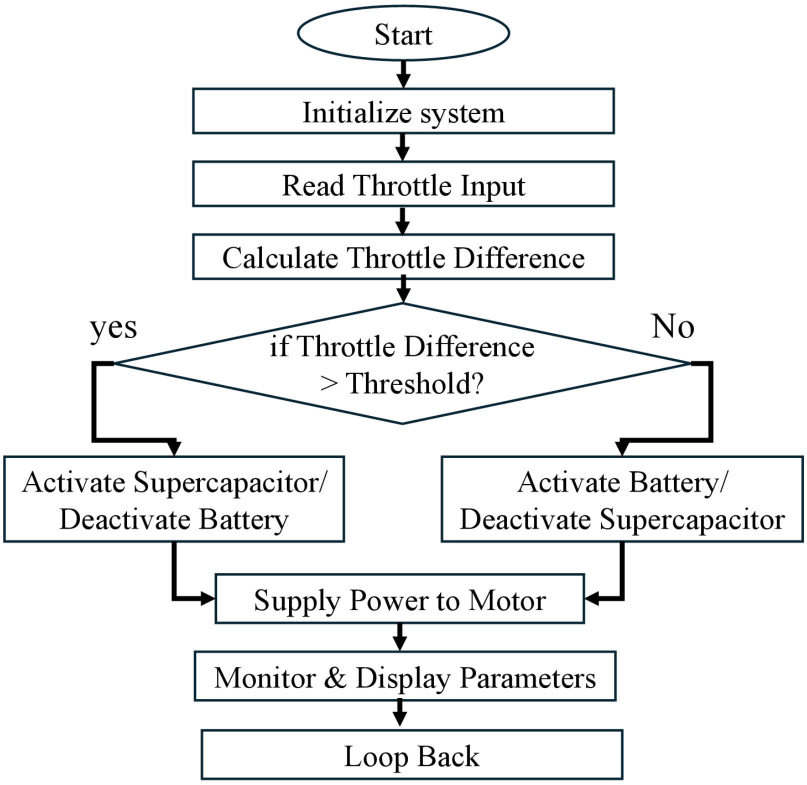


Figure 2. Workflow diagram of a hybrid energy storage system.

4. Results

This work presents the results obtained from the simulation and implementation of the IoT-based hybrid energy storage system using a battery and a supercapacitor for electric vehicle applications. The purpose of this work is to evaluate the performance of the proposed system under different operating conditions and to verify the effectiveness of the control strategy. In addition, the effectiveness of the proposed hybrid configuration in improving energy utilization and extending battery operating duration was also analyzed. The results include simulation-based analysis, comparison between battery-only and battery-supercapacitor operation, and evaluation of energy usage over time. Special emphasis is given to the improvement in battery duration achieved by integrating a supercapacitor, as illustrated in the comparative energy usage results.

4.1. Simulation results

When a control signal is sent by the microcontroller, the DC motor is activated via a motor driver circuit. The motor driver, composed of various electronic components, ensures smooth voltage delivery to the DC motor while minimizing fluctuations and protecting the motor from abrupt voltage changes. A Wi-Fi modem is integrated into the system to enable real-time monitoring of vehicle parameters over the internet. These monitored features include the SOC of the battery and the vehicle's speed, which are tracked at different time intervals. The supercapacitor bank is designed to be charged via a solar panel mounted on the roof of the vehicle. **Figure 3** illustrates the circuit diagram in Proteus software. However, in our prototype setup, the supercapacitor is charged using an external battery source. The lithium-ion battery, on the other hand, is charged by converting AC voltage to DC using a full-bridge rectifier followed by a filter circuit to ensure stable charging. The throttle difference ranges from 1 to 100 units and serves as the key variable on which our prototype operates. It represents the variation in throttle position between two consecutive operational states of the vehicle. This difference determines whether the system draws energy from the battery or the supercapacitor.

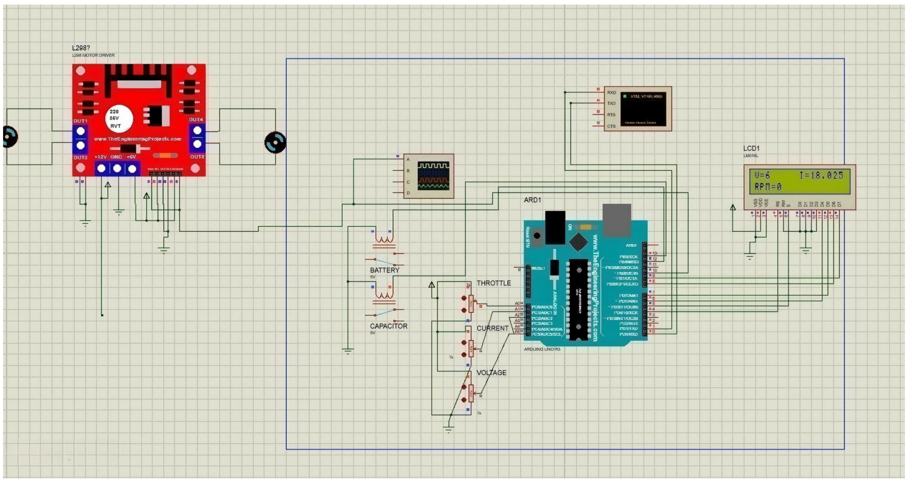


Figure 3. Circuit Diagram of Supercapacitor setup in Proteus.

In our setup, a threshold value of 50 units is predefined, serving as the boundary between the operating states of the battery and the supercapacitor. An algorithm, implemented through Arduino programming, monitors the throttle difference in real time. If the throttle difference between two-time instances is less than or equal to 50 units, the system draws power from the battery as shown in **Figure 4**.

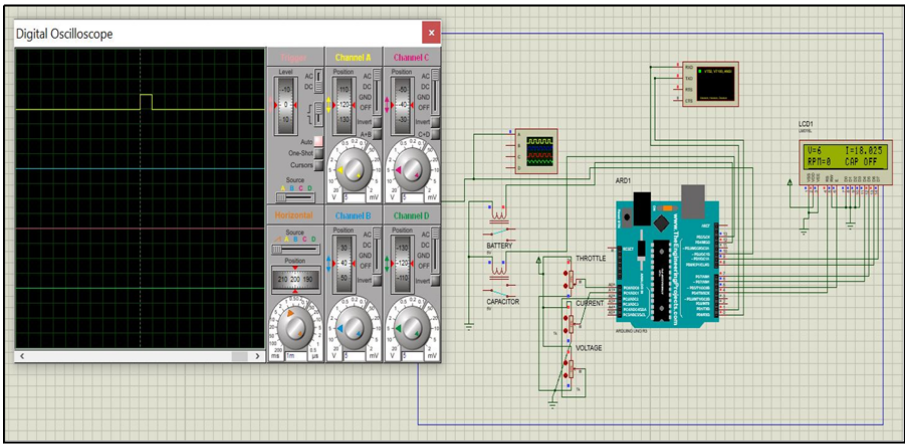
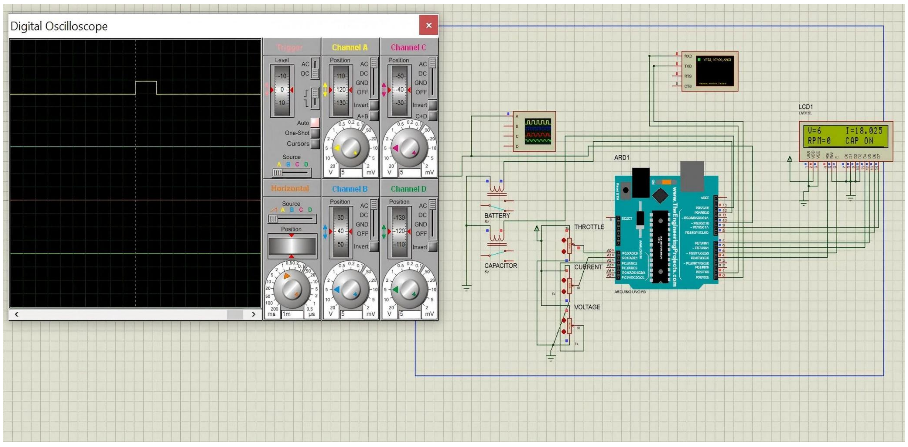


Figure 4. Simulation performance under a throttle difference of less than 50 units.

The throttle variation required to compute this difference is generated using a throttle potentiometer, which simulates acceleration and deceleration states in the prototype. The potentiometer shown in **Figure 1** is used to measure the throttle difference. When this throttle difference remains below the preset threshold value, the microcontroller continuously sends a signal to the relay connected to the battery, keeping the battery circuit closed and supplying power to the system. This state persists until the microcontroller sends a signal to open the battery relay.

Whenever the throttle difference exceeds the set threshold, the system requires more energy. If this high energy demand is supplied solely by the battery within a short time, it can cause rapid battery drain, reducing the battery's overall lifecycle. To prevent this, the microcontroller sends a signal to open the battery relay and simultaneously closes the relay connected to the supercapacitor, as shown in **Figure 5**. The supercapacitor then acts as the primary energy source, quickly discharging to provide the extra charge needed by the system. This switching process continues with the microcontroller monitoring the throttle difference every 3 s. When the throttle difference drops below the threshold again, the system switches back to the battery as the power source. By offloading these short bursts of high energy demand to the supercapacitor, the battery is protected from rapid drain, thereby extending its lifetime. Additionally, the SOC of both the battery and the supercapacitor is continuously monitored and displayed via a mobile app connected through a Wi-Fi modem. This allows real-time tracking of the charge levels at any given time.



V=6 I=18.025
RPM=0 CAP ON

Figure 5. Simulation performance under a throttle difference greater than 50 units.

Before building the physical prototype, the expected results were first verified using Proteus Design Suite software. After confirming the simulation results, the prototype hardware was developed, as shown in **Figure 6**. The system's performance was evaluated in two conditions: a) With only the battery; b) Supercapacitor along with the battery. **Figure 7** presents a detailed comparison between the conventional battery-only energy storage system and the proposed battery–supercapacitor hybrid system under identical operating conditions. The results clearly demonstrate the advantages of hybridization in terms of voltage stability, energy consumption behavior, and operational duration.

Figure 7a illustrates the schematic voltage response of a lithium-ion battery and the hybrid battery-supercapacitor system when subjected to step load conditions. In the battery-only case, the voltage response is relatively slow and settles at a lower level due to the limited power handling capability of the battery and its internal resistance. On the other hand, the hybrid system shows a much faster voltage rise and achieves a higher and more stable voltage profile. This improved response is mainly due to the supercapacitor, which can rapidly supply or absorb power during sudden load changes. As a result, voltage fluctuations are minimized, leading to smoother and more reliable system operation.

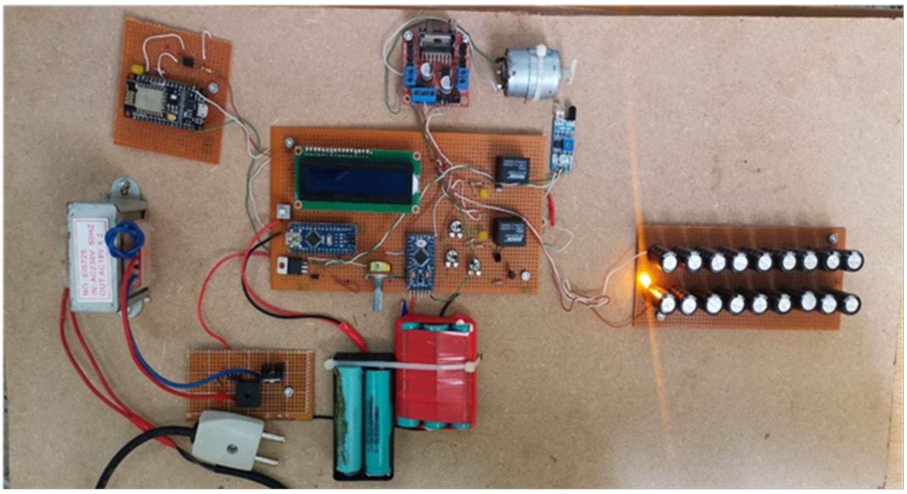


Figure 6. Hardware implementation of a prototype of a hybrid battery-supercapacitor system.

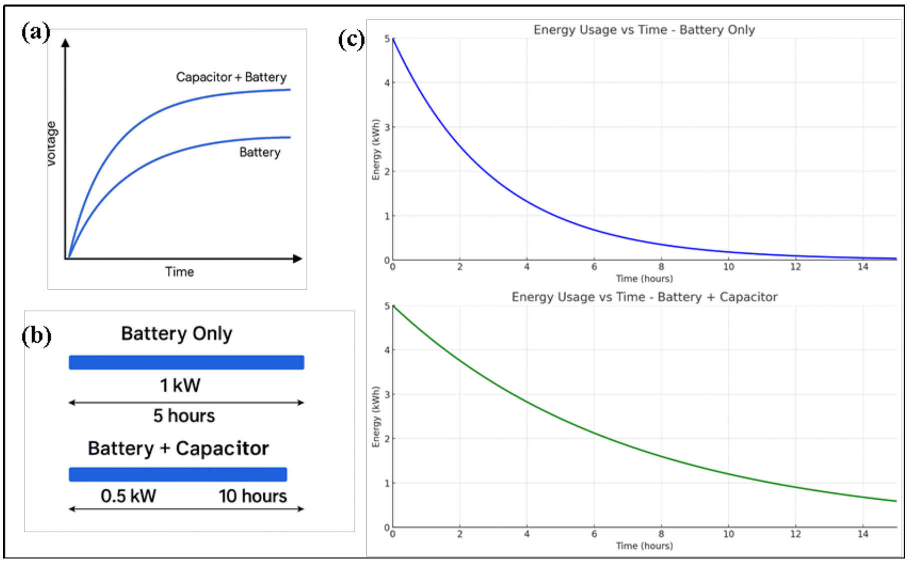


Figure 7. **(a)** Schematic voltage response of a lithium-ion battery and the proposed battery–supercapacitor hybrid system under step load conditions; **(b)** Comparison of energy consumption profiles for a battery-only system and the hybrid configuration under equivalent load conditions, showing reduced peak energy demand and slower decay in the hybrid system; **(c)** Operational time comparison between battery only and hybrid storage systems for a constant power requirement; **(d)** Power supply duration comparison between battery-only and hybrid system.

Figure 7b compares the energy consumption profiles of the battery-only system and the hybrid configuration under equivalent load conditions. It can be observed that the battery-only system experiences a rapid decline in stored energy, indicating higher peak energy demand and faster battery depletion. In contrast, the hybrid system exhibits a slighter and more gradual decrease in energy. This behavior confirms that the supercapacitor effectively supports transient and peak power demands, thereby reducing the energy drawn from the battery. Consequently, the battery operates under less stressful conditions, which is beneficial for extending its lifetime. By offloading peak energy demands to the supercapacitor, battery degradation is estimated to decrease by 20–30% compared to traditional single-source systems. **Figure 7c** presents a direct comparison of the operational time for both configurations under a constant power requirement. When operating solely with the battery, the system supplies approximately 1 kW of power for nearly 5 hours before the stored energy is exhausted. However, in the hybrid configuration, the battery supplies a reduced average power of about 0.5 kW, while the supercapacitor assists during high-power demands. This load sharing allows the system to operate for approximately 10 h, effectively doubling the operational duration compared to the battery-only case. This result clearly highlights the significant improvement in battery usage efficiency achieved through hybridization. **Figure 7d** further illustrates the power supply duration comparison between the two systems. The battery-only configuration delivers a higher power level for a shorter time, followed by a sudden drop once the battery energy is depleted. In contrast, the hybrid system maintains a lower but more stable power output over a longer duration. This sustained power delivery demonstrates that the supercapacitor successfully reduces high current stress on the battery and enables a more controlled and gradual discharge process.

The results presented in **Figure 8** further analyze the performance of the proposed battery–superacapacitor hybrid system by comparing its energy output and power supply duration with a conventional battery-only configuration. These results provide deeper insight into how hybridization affects energy utilization and operational sustainability. **Figure 8a** shows the variation of cumulative energy output with time for both the battery-only system and the hybrid battery–supercapacitor system. In the battery-only case, the energy output increases rapidly during the initial hours due to the higher power draw from the battery. However, this rapid energy delivery leads to faster depletion of the battery. In contrast, the hybrid system exhibits a more gradual increase in energy output over time. Although the rate of energy output is lower, the hybrid configuration maintains energy delivery for a longer duration. This behavior indicates that the supercapacitor assists in meeting short-term power demands, allowing the battery to discharge at a slower and more controlled rate. **Figure 8b** presents a direct comparison of power supply duration between the two configurations. The battery-only system supplies a constant power of approximately 1 kW, but this power delivery is sustained only for about 5 h, after which the battery energy is exhausted, and the output abruptly drops to zero. On the other hand, the hybrid battery–supercapacitor system supplies a reduced but stable power of approximately 0.5 kW for nearly 10 h. This extended power supply duration clearly demonstrates the effectiveness of load sharing between the battery and the supercapacitor.

The results highlight that, while the battery-only system delivers higher power for a short time, the hybrid system prioritizes energy efficiency and longevity by spreading the energy output over a longer period. This trade-off is particularly desirable in electric vehicle applications, where sustained operation and reduced battery stress are more critical than short-term high-power output.

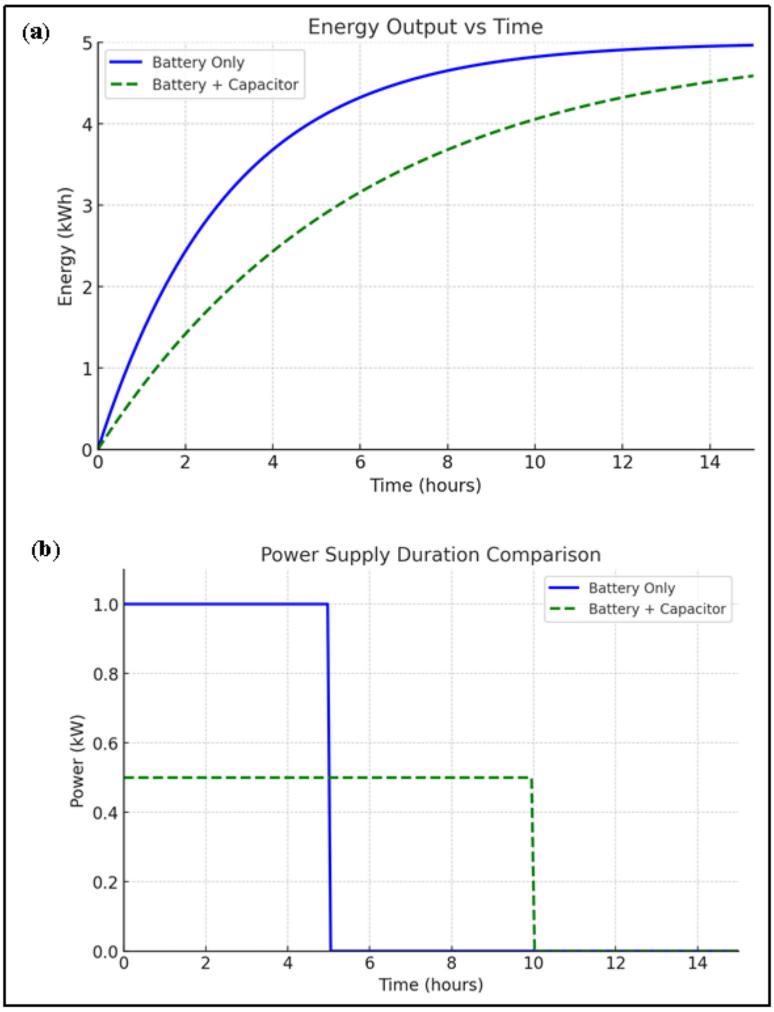


Figure 8. **(a)** Energy output as a function of time for a battery-only system and the proposed battery–supercapacitor hybrid, showing that the hybrid configuration delivers a smoother and more gradual energy profile over extended operation; **(b)** Power supply duration comparison for both configurations, highlighting that the hybrid system maintains continuous power for a longer period by reducing instantaneous load on the battery.

4.2. IoT hybrid energy storage system

The results presented in this work clearly demonstrate the effectiveness of the proposed IoT-based hybrid energy storage system that integrates a lithium-ion battery with a supercapacitor for electric vehicle applications. By analyzing voltage behavior, energy consumption, power delivery, and operational duration, the comparative evaluation between the battery-only system and the hybrid configuration provides strong evidence of the benefits achieved through energy storage hybridization. One of the most important observations from the results is the improvement in voltage stability under dynamic load conditions. The voltage response analysis shows that the battery-only system exhibits a slower response and lower steady-state voltage due to its limited power handling capability and internal resistance. In contrast, the hybrid battery–supercapacitor system responds more rapidly and maintains a higher and smoother voltage profile. This improvement is primarily attributed to the supercapacitor's ability to deliver high power almost instantaneously. Stable voltage behavior is critical for electric vehicle operation, as it directly influences motor performance, control reliability, and overall system efficiency.

Energy consumption analysis further highlights the advantages of the hybrid system. The battery-only configuration experiences rapid energy depletion when subjected to equivalent load conditions, indicating higher peak energy demand and increased battery stress. When the supercapacitor is introduced, the energy decay becomes noticeably slower. This demonstrates that the supercapacitor successfully absorbs transient and peak power requirements, allowing the battery to operate in a more favorable and less stressful regime. As a result, the battery is protected from sudden high current draws, which are known to accelerate aging and thermal degradation. A key outcome of this study is the significant improvement in operational time achieved through hybridization. The results show that, for a constant power demand, the battery-only system supplies approximately 1 kW of power for about 5 h. In contrast, the hybrid system delivers a reduced average power of around 0.5 kW for nearly 10 h. This effectively doubles the operating duration of the system. Such an improvement is particularly valuable for electric vehicles, where extended driving range and efficient energy utilization are major performance indicators.

The energy output analysis further supports these findings. While the battery-only system delivers energy at a faster rate initially, it does so at the cost of rapid energy depletion. The hybrid system, on the other hand, provides a more gradual and sustained energy output over time. This controlled energy delivery reflects better load sharing between the battery and the supercapacitor, resulting in improved system endurance and reliability. Although the instantaneous energy output of the hybrid system is lower, its ability to maintain power delivery over an extended period makes it more suitable for real-world driving conditions. Power supply duration comparison also reveals a clear distinction between the two configurations. The battery-only system delivers higher power for a short duration, followed by an abrupt cutoff once the battery energy is exhausted. In contrast, the hybrid system maintains a steady and consistent power output for a longer period. This smoother power profile reduces mechanical and electrical stress on the drivetrain and power electronics, contributing to improved system durability.

Overall, the results confirm that integrating a supercapacitor with a lithium-ion battery significantly enhances energy management performance. The hybrid energy storage system improves voltage stability, reduces peak energy demand, extends battery operating time, and enhances overall system reliability. Additionally, the IoT-based monitoring framework enables real-time observation of key parameters, making the system more transparent and suitable for future optimization and intelligent energy management strategies.

5. Conclusions

The study developed an IoT-based energy management framework to enable real-time monitoring, control, and optimization of energy systems. The proposed system integrates sensors, microcontrollers, and wireless communication modules to continuously collect operational data such as voltage, current, power flow, state of charge, and load conditions. This data is transmitted to a remote interface, allowing users to observe system behavior and make informed decisions in real time. The IoT framework supports coordinated operation of energy storage devices, loads, and power electronics, enabling efficient energy utilization and improved system reliability. By leveraging real-time data acquisition and communication, the proposed system enhances operational transparency, enables remote diagnostics, and supports intelligent energy management strategies. The major findings of the study are summarized as follows.

a. The IoT-based monitoring system successfully enables real-time visualization of key electrical and operational parameters, improving system awareness and facilitating timely detection of abnormal operating conditions.
b. Real-time data transmission and remote accessibility allow effective supervision and control of the energy system, reducing manual intervention and enhancing overall operational efficiency.
c. The integration of IoT technology improves coordination between energy sources, storage devices, and loads, leading to more stable system operation and optimized energy flow.
d. The proposed system demonstrates potential for reducing energy losses and improving system performance through data-driven monitoring and control, while also providing a scalable platform for future extensions such as predictive maintenance and intelligent energy optimization.

Despite its contributions, this study has several limitations that should be acknowledged. The proposed IoT-based energy system was implemented under controlled conditions and does not fully account for communication delays, data loss, cybersecurity concerns, or hardware reliability issues that may arise in real-world deployments. In addition, the system does not incorporate advanced data analytics or machine-learning-based decision-making, which could further enhance performance. Therefore, future work should focus on integrating intelligent data analytics, addressing cybersecurity and communication reliability, and validating the proposed framework through long-term real-world implementation to improve its robustness and practical applicability.

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