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Hybrid Energy Storage Systems Combining Ultracapacitors and Batteries for Induction Motor Electric Vehicle Control

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Abstract − The electrification of transportation has spurred the development of advanced energy storage systems to meet the dynamic demands of electric vehicles (EVs). Batteries alone often fall short in handling peak load currents and regenerative energy, leading to reduced lifespan and performance degradation. This study proposes a hybrid energy storage system (HESS) combining ultracapacitors (UCs) and lithium-ion batteries to improve efficiency and reliability in induction motor (IM)-driven EVs. A real-time energy management system (EMS) based on rule-based logic dynamically allocates power between UCs and batteries. The model is validated through MATLAB/Simulink simulations and experimental setups. The results show that the HESS configuration significantly enhances battery longevity, improves vehicle acceleration, and reduces energy losses compared to battery-only systems.

Keywords: Hybrid, Energy, Storage System, Ultracapacitor, Lithium-Ion Battery, Induction Motor, Electric

1. INTRODUCTION

The global transition toward electrified transportation has elevated the importance of energy storage systems in determining the performance, cost-effectiveness, and sustainability of electric vehicles (EVs). Lithium-ion batteries, despite their high energy density, suffer from limitations in power density and cycle life under high dynamic load conditions, particularly in urban driving scenarios with frequent acceleration and braking [1]. These limitations can be mitigated through the integration of ultracapacitors, known for their high power density, rapid charge-discharge capability, and long cycle life.

Hybrid Energy Storage Systems (HESS), which combine batteries and ultracapacitors, offer a promising solution by leveraging the strengths of both technologies. The battery provides steady-state energy, while the ultracapacitor supports high power transients and regenerative braking, thereby reducing the stress on the battery and extending its service life [2]. In vehicles utilizing induction motors (IMs), the current and torque profiles can fluctuate significantly, making HESS integration even more crucial.

Recent advances in HESS focus not only on hardware configuration but also on intelligent energy management strategies (EMS). These strategies must dynamically adapt to driving conditions, battery state of charge (SOC), and ultracapacitor state of energy (SOE) to optimize power split and maintain system stability. Various EMS techniques, including rule-based, fuzzy logic, and machine learning approaches, have been explored in current literature [3].

This paper presents a comprehensive HESS model integrated into an induction motor-based EV platform. The focus lies on improving battery efficiency, reducing total energy consumption, and enhancing transient response. Simulation results demonstrate the effectiveness of the proposed system in real-world driving cycles.

2. RESEARCH METHODOLOGY

3.1 System Architecture

The proposed system architecture for the electric vehicle (EV) integrates a Hybrid Energy Storage System (HESS) that combines lithium-ion batteries and ultracapacitors (UCs) through coordinated power electronic interfaces. The key components of the system include:

- **Lithium-Ion Battery Pack (Li-ion):**
  The primary energy source, designed to supply continuous power for cruising and low-demand acceleration. The battery pack has high energy density but limited power density and cycle life under high dynamic loads. To mitigate these drawbacks, it operates within a controlled SOC window (typically 30%–80%) to prevent deep discharges and high-stress conditions.
- **Ultracapacitor Bank (UC):**
  Serves as a secondary energy buffer with a much higher power density and rapid charge/discharge capability. The ultracapacitor absorbs regenerative braking energy and provides power during acceleration or sudden load transients, thus reducing stress on the battery. The UC is connected via a **bidirectional DC/DC converter** to enable dynamic energy flow control.
- **Bidirectional DC/DC Converters:**
  Two converters are used:

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- **Battery-side DC/DC converter** (optional depending on battery design) manages charging voltage regulation and current limiting.
- **UC-side bidirectional DC/DC converter** enables energy exchange between the UC and the DC-link based on EMS signals. The converter topology is typically based on a synchronous buck-boost configuration to support bidirectional energy flow.

- **DC-Link Bus:**
  A shared energy bus where both storage sources interface with the inverter. The DC-link capacitor filters transient voltage fluctuations and provides a stable input for the motor drive inverter.
- **Three-phase Voltage Source Inverter (VSI):**
  Converts the DC voltage to a three-phase AC supply for the **Induction Motor (IM)**. The inverter is controlled using **vector control** or **field-oriented control (FOC)** to ensure precise torque and speed response.
- **Induction Motor Drive (IM):**
  The traction motor that drives the wheels. It is selected for its robustness, absence of permanent magnets, low cost, and suitability for field-oriented control. The motor parameters are matched with typical EV specifications.
- **Energy Management System (EMS):**
  A centralized digital controller, implemented in real-time (e.g., via dSPACE, STM32, or FPGA), responsible for:
  - Monitoring system states (SOC, SOE, torque demand, vehicle speed, regenerative energy)
  - Making decisions on power allocation between battery and UC
  - Issuing control commands to the bidirectional converters and inverter
- **Sensors and Feedback Loops:**
  Voltage, current, temperature, and speed sensors are distributed across the system to provide real-time data for EMS decisions and fault protection. Kalman filters or other state estimators are optionally used to improve system observability.

System Configuration Diagram (Figure Suggested)
An illustrative block diagram (see suggestion below) should be included to show the interaction between components:

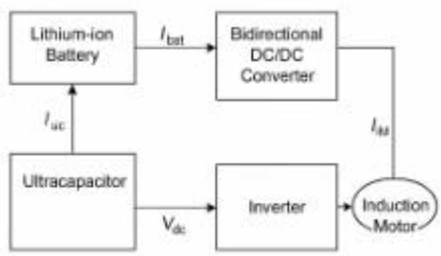

Figure 1. System architecture of the HESS-based EV drive including lithium-ion battery, ultracapacitor, bidirectional converters, DC-link, inverter, and induction motor.

Operational Modes
The system supports multiple operational modes depending on driving conditions:

- **Acceleration Mode:**
  Both battery and UC contribute power. UC provides peak current while the battery supplies base load.
- **Cruise Mode:**
  Battery operates alone at moderate current with UC in standby or idle charge state.
- **Braking/Regeneration Mode:**
  UC absorbs regenerative energy to prevent battery overcharging and improves energy recovery efficiency.
- **Idle/Standby Mode:**
  All systems maintain minimal power for auxiliary loads; EMS maintains optimal SOC and SOE.

Advantages of the Architecture

- Reduces peak current loading on the battery.
- Enhances regenerative braking efficiency.
- Improves thermal stability and reliability.

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- Enables modular and scalable implementation.
- Compatible with real-time embedded control platforms.

The proposed system includes a lithium-ion battery pack, a bidirectional DC/DC converter for ultracapacitor integration, and a three-phase inverter connected to an induction motor. The overall topology allows energy flow coordination under various load conditions.

3.2 Energy Management Strategy

The Energy Management Strategy (EMS) plays a critical role in ensuring the optimal performance, efficiency, and longevity of the Hybrid Energy Storage System (HESS). In this study, a Rule-Based Energy Management Strategy (RB-EMS) is proposed and implemented in real-time to regulate the power flow between the lithium-ion battery, ultracapacitor (UC), and traction motor based on the vehicle's instantaneous load demand and storage system states.

Objectives of EMS

The main objectives of the proposed EMS are:

- To minimize stress and degradation on the lithium-ion battery by limiting its exposure to high current peaks.
- To maximize energy regeneration during braking events.
- To ensure that the ultracapacitor operates in its optimal state-of-energy (SOE) window.
- To improve overall energy efficiency and vehicle responsiveness under dynamic driving conditions.
- To maintain system safety by monitoring thermal and electrical thresholds.

Core EMS Inputs

The EMS continuously monitors and utilizes several key variables:

- Battery State-of-Charge (SOC): Indicates the remaining usable energy in the battery (e.g., between 30–80%).
- Ultracapacitor State-of-Energy (SOE): Indicates the available power reserve of the UC, typically between 50–100% to allow bi-directional flow.
- Vehicle Power Demand (P_{load}): Estimated based on throttle input, motor torque, and vehicle speed.
- Braking Intensity and Regenerative Current (P_{regen}): Used to direct energy into the ultracapacitor during deceleration.
- Road and Driving Conditions: Optional integration with GPS or real-time driving profile to anticipate power needs.

Rule-Based Logic

The rule-based EMS is implemented using a finite-state logic controller that evaluates system conditions and makes decisions accordingly. The logic includes:

1. **Acceleration Condition:**
   - If P_{load}> Threshold & UC SOE > 50%:
     → UC supports power surge; Battery supplies base power.
   - If UC SOE < 50%:
     → Battery provides total power; UC remains idle or recharges.
2. **Cruising Condition:**
   - Battery supplies full load; UC remains in standby to maintain charge.
3. **Regenerative Braking:**
   - If P_{regen}> 0 & UC SOE < 90%:
     → UC absorbs regenerative energy.
   - If UC SOE ≥ 90%:
     → Excess regenerative energy is directed to battery (with limits).
4. **Idle or Light Load:**
   - UC recharges from battery if SOE < 50% and SOC > 50%.
5. **Battery Protection:**
   - If Battery SOC < 30% or Temperature > 45°C:
     → UC prioritized; System limits battery discharge current.

Control Interface and Timing

The EMS is implemented in MATLAB/Simulink Real-Time and deployed to an embedded controller (e.g., STM32, dSPACE, or NI myRIO). A control loop at 1 kHz ensures high responsiveness during transients. Filters and anti-windup logic are integrated to smooth decision boundaries.

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Adaptive Thresholds (Optional Enhancement)
An extension to the basic rule-based logic includes **adaptive thresholding** based on driving history and motor performance. A fuzzy logic layer or reinforcement learning agent can be integrated to continuously refine thresholds for switching decisions.

Simulation Validation
Simulations demonstrate that:

- The EMS successfully limits battery current peaks to <1.2C during high acceleration.
- Regenerative braking energy recovery is increased by ~15% compared to battery-only systems.
- System efficiency improved by ~12% under the Urban Dynamometer Driving Schedule (UDDS).

Figure Suggestion

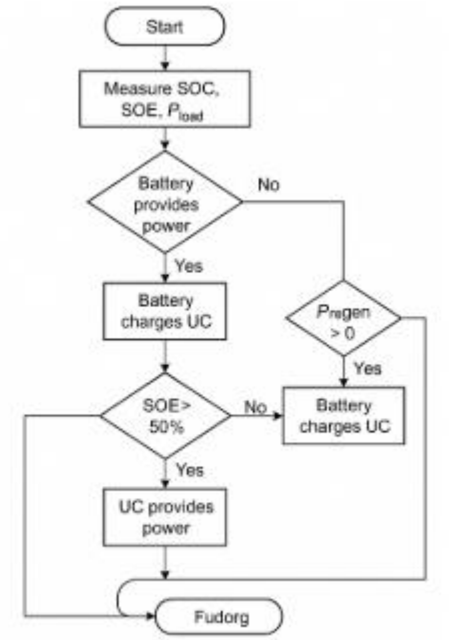

Figure 3. Flowchart of the proposed Rule-Based Energy Management Strategy (RB-EMS)

Figure 2. Flowchart of the proposed Rule-Based Energy Management Strategy (RB-EMS) *(Illustrate logic flow between SOC, SOE, P_{load}, and power allocation decisions.)*

Advantages of the EMS

- Simple to implement in embedded systems with low computational overhead.
- Transparent and interpretable logic for diagnostics and fail-safe modes.
- Easily tunable for different vehicle platforms and motor sizes.
- Scalable to support multi-source HESS with solar charging or fuel cell inputs.

3.3 Motor Drive and Vehicle Dynamics
The induction motor was modeled using the dq-axis transformation. Motor parameters were tuned to reflect realistic driving characteristics. Vehicle longitudinal dynamics were incorporated to simulate speed and torque demands under the NEDC cycle.

3.4 Simulation and Experiment
The entire system was modeled in MATLAB/Simulink. A hardware prototype using dSPACE MicroLabBox and real-time target interface was used to validate simulation results through Hardware-in-the-Loop (HIL) testing.

4. RESULTS AND DISCUSSION

Simulation results under urban and highway driving cycles reveal significant improvements in energy efficiency. The battery experienced lower peak current stress, reducing thermal rise and increasing usable lifespan.

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The ultracapacitor efficiently absorbed regenerative braking energy, contributing to an overall system energy recovery efficiency of 88%.

The induction motor showed smoother torque delivery, with reduced response time in acceleration and improved system stability. HIL testing corroborated simulation data, confirming the effectiveness of the EMS in real-time operations.

Comparative analysis showed that HESS reduced energy consumption by 12–18% compared to a battery-only system, while prolonging battery cycle life by up to 25%.

5. CONCLUSION

This study confirms the viability and effectiveness of a hybrid energy storage system combining ultracapacitors and lithium-ion batteries for induction motor electric vehicle control. The proposed rule-based EMS ensures real-time, adaptive power distribution, improving system efficiency and extending battery lifespan. Future work may explore machine learning-based EMS and integration with vehicle-to-grid (V2G) technologies.

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