International Journal of Science, Technology and Management (IJSTM) ISSN (online): 2321-774X
Volume 12, Issue 1, 2025

Power Management of Ultracapacitor Battery Hybrid Storage System for BLDC Driven Electric Vehicles Using Advanced Control Techniques

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Abstract - **In recent advancements in hybrid electric vehicle (HEV) technology, the selection and efficient utilization of energy storage systems play a critical role in enhancing performance and energy efficiency. This paper proposes a power-electronically controlled ultracapacitor–battery hybrid energy storage system to drive a BLDC motor for vehicular applications. The system is simulated in MATLAB/Simulink using a standard vehicle drive cycle as input. Speed, torque, and power requirements are calculated based on vehicle dynamics and used to guide the selection of energy storage components. A buck-boost DC-DC converter manages energy flow between the ultracapacitor and the motor during acceleration and deceleration phases. A novel hybrid current control algorithm is introduced for boost mode operation, minimizing DC bus voltage ripple and avoiding chaotic behavior under variable input voltage conditions. Additionally, a PI-based BLDC motor controller is implemented, incorporating a new topology for efficient ultracapacitor recharging during regenerative braking. Simulation results confirm the effectiveness of the proposed system in improving overall energy efficiency and dynamic performance of the vehicle.**

Index Terms - BLDC motor, DC–DC converters, electric vehicles, hybrid energy storage system, super-capacitors, vehicle dynamics.

I. INTRODUCTION

The growing concern over skyrocketing fuel prices and the global environmental impact of emissions has accelerated the demand for cleaner and more energy-efficient vehicle propulsion technologies. Conventional internal combustion (IC) engine vehicles suffer from limited thermodynamic efficiency—typically around 30% to 40%—and are further constrained by real-world factors such as driving speed, road conditions, and fuel quality. In contrast, electric vehicles (EVs) and hybrid electric vehicles (HEVs) offer significant advantages including higher overall efficiency, reduced emissions, smoother control, and the ability to recover kinetic energy through regenerative braking. Unlike conventional braking systems where energy is dissipated as heat, regenerative braking enables energy recovery and reuse, improving overall energy utilization.

Energy storage plays a critical role in the performance and reliability of EVs and HEVs. While batteries are the primary choice due to their high energy density, they have low power density and are adversely affected by rapid current fluctuations and peak power demands that exceed rated capacity, leading to reduced lifespan and performance degradation. Ultracapacitors (UCs), on the other hand, provide high power density and rapid response times but have lower energy storage capacity. As a result, a hybrid energy storage system (HESS) combining batteries and ultracapacitors is gaining popularity for electric drive applications, offering a balance of high energy and high power capability.

Effective integration of battery and UC system's requires a robust power electronic interface. Various converter topologies have been explored in literature. For instance, multi-input DC-DC converters [1] and bi-directional fly back converters [2] have been used to manage power flow between energy sources. Additionally, designs incorporating fuel cells and auxiliary UC-battery systems [3], and actively controlled hybrid converters with PI regulation [4], have demonstrated the feasibility of advanced HESS architectures. BLDC motor-based propulsion systems [5] and UC-based short-cycle energy buffers [6] have further contributed to improved EV performance. A recent implementation using a hybrid current control scheme in a boost converter successfully demonstrated stable operation at high duty ratios and under varying load conditions.

Building on this foundation, the present work proposes a battery UC hybrid storage system combined with a DC-DC converter and inverter-fed BLDC motor drive, with the vehicle serving as the dynamic load. A hybrid current control algorithm is introduced to regulate boost-mode operation of the converter, ensuring a stable DC bus voltage despite variable load and the decaying input voltage characteristic of ultracapacitors during discharge. The BLDC motor is operated in both motoring and regenerative braking modes, with control managed by a PI-based algorithm. The regenerative energy is effectively captured and stored in the ultracapacitor, extending driving range and improving energy utilization. The system builds upon previous work by adapting the constant load regenerative strategy to real-world vehicle operation.

II. System Configuration

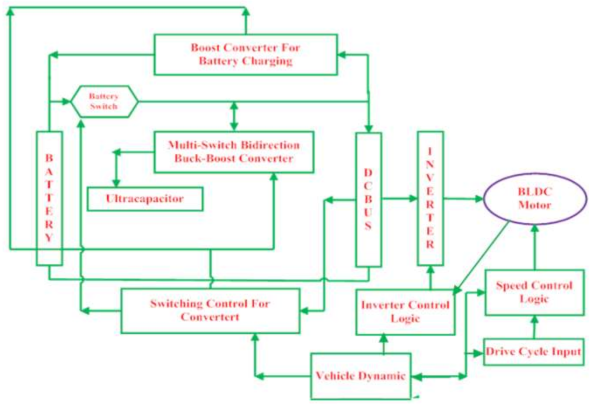

Fig. 1 System Configuration

The block diagram of the proposed system is shown in Fig. 1. The system architecture integrates a hybrid energy storage system (HESS) consisting of a battery and an ultracapacitor, managed by a multi-switch bidirectional buck-boost converter for ultracapacitor charge/discharge operations. Additionally, a boost converter is used to enable battery charging during regenerative braking.

The switching control unit generates appropriate gate signals for the bidirectional converter based on:

- The polarity and magnitude of the load current, and
- The operational mode (acceleration, cruising, or regeneration).

The DC bus is connected to an inverter-fed Brushless DC (BLDC) motor, which serves as the primary propulsion source for the vehicle. A vehicle dynamics block simulates real-world physical conditions such as acceleration, slope, and road resistance. Driver inputs are simulated using a standard drive cycle, providing speed and torque commands. For simulation purposes, it is assumed that both the battery and ultracapacitor are fully charged at the start of the operation.

The system consists of a 156 V, 40 Ah lead–acid battery pack and an ultracapacitor bank composed of three 16 V, 500 F modules connected in series, resulting in an effective ultracapacitor rating of 48 V and 165 F. The electric vehicle used for analysis is a MARUTI 800 model, with a curb weight of approximately 800 kg and a peak power requirement of 27 kW. The propulsion system is driven by a brushless DC (BLDC) motor rated at 156 V, capable of delivering a maximum torque of 100 N·m at 2400 rpm, with a maximum operating speed of 3000 rpm.

A. *Vehicle Modeling*

The vehicle is modeled as a single rigid body with four wheels, where the entire vehicle mass is assumed to be concentrated at a single point [7, 8]. The longitudinal dynamics of the vehicle are governed by the force balance equation, which includes all the major forces acting on the vehicle during motion.

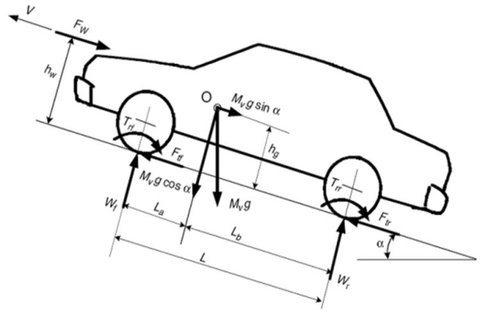

Fig. 1 Forces acting on the vehicle

The total tractive force F_{TR} required to propel the vehicle is given by:

$$F_{TR} = F_a + F_g + F_R + F_{AD} \quad (1)$$

Where:

- F_a = Inertial (acceleration) force
- F_g = Gravitational force due to road gradient
- F_R = Rolling resistance force
- F_{AD} = Aerodynamic drag force

Each component is defined as follows:

Acceleration Force:

$$F_a = M_V \times a \quad (2)$$

Where M_V is the vehicle mass and a is the vehicle acceleration.

Gravitational Force (Road Slope):

$$F_g = M_V \times g \times \sin(\alpha) \quad (3)$$

Where g is the gravitational acceleration and α is the road incline angle.

Aerodynamic Drag Force:

$$F_{AD} = \frac{1}{2} \times \rho \times C_D \times A_F \times V(t)^2 \quad (4)$$

Where:

- ρ = Air density
- C_D = Aerodynamic drag coefficient
- A_F : Frontal area of the vehicle
- $V(t)$ = Instantaneous vehicle speed
- Rolling Resistance Force:

$$F_R = M_V \times g \times C_R \times \cos(\alpha) \quad (5)$$

Where, C_R is the rolling resistance coefficient.

The torque required to propel the vehicle at the wheel is calculated as:

$$T_{VE} = F_{TR} \times R \quad (6)$$

Where, R is the wheel radius.

The corresponding power requirement is:

$$T_{VE} = T_{VE} \times \omega \quad (7)$$

Where, ω is the angular speed of the wheel.

The torque requirement for a given vehicle speed profile is derived from Equation (6). The required motor speed for the BLDC motor is calculated using the vehicle speed, tyre radius, and gear ratio, as shown in Fig. 3 (Motor Speed Estimator).

B. Mathematical Modeling of BLDC Motor, Battery, Ultracapacitor, and Converter

BLDC Motor Model: The BLDC motor is modeled in MATLAB, incorporating mechanical inertia and frictional losses to accurately simulate the motor's dynamic behavior [5]. This allows for precise control and response under varying load conditions.

Battery Model: A detailed battery model is implemented in MATLAB, accounting for temperature effects, internal resistance, voltage fluctuations, and pressure variations during charging and discharging cycles [9]. This model enables realistic estimation of battery performance and lifespan.

Ultracapacitor Model: The ultracapacitor is simulated considering the effects of temperature variations, self-discharge, and charge redistribution. These factors are critical in determining the energy availability and efficiency during high power transients.

DC-DC Converter Model: A bidirectional converter model is developed using SimPower Systems in MATLAB/Simulink [10]. It replicates the behavior of a buck-boost converter used for power flow control between the battery, ultracapacitor, and DC bus under both motoring and regenerative modes.

III. Hybrid Energy Storage System

A hybrid energy storage system (HESS) is proposed in this study to meet the dynamic power demands of an electric vehicle. The system integrates a battery and an ultracapacitor (UC) via a power-electronically controlled DC-DC converter, ensuring both high energy density (battery) and high power density (ultracapacitor). The topology enables effective power management during various driving conditions such as acceleration, cruising, and regenerative braking.

A. DC-DC Converter Topology

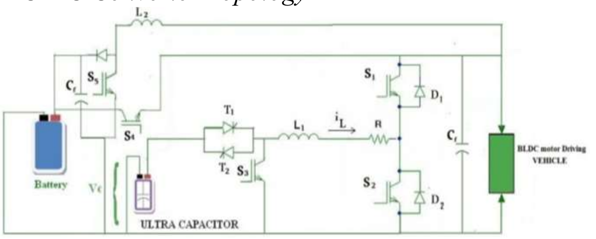

Fig. 5 DC-DC Converter Topology

The proposed DC-DC converter operates in five distinct modes, as illustrated in Fig. 5, enabling flexible energy flow between the ultracapacitor, battery, and load (motor + inverter):

Mode 1 (Discharge Mode - Ultracapacitor to Load):

- Switch S2 is modulated to control power flow from the ultracapacitor to the load.
- Diode D1 provides the current path.
- Switch T1 remains ON during this mode.

Mode 2 (Buck Mode - Regenerative Charging of UC):

- Switch S1 is controlled to charge the ultracapacitor from regenerative braking energy.
- Diode D2 serves as a freewheeling path.
- Switch T2 remains ON.

Mode 3 (Boost Mode - UC Charging from Motor Back-EMF):

- Switch S3 is operated when motor back-EMF < UC voltage, enabling energy transfer to the UC.
- This transition allows further charging even when the vehicle slows down.
- Switch T2 is kept ON during this mode as well.

Mode 4 (Battery - Only Supply Mode):

- Under normal driving conditions, Switch S4 is closed to supply average load power from the battery.

Mode 5 (Battery Charging During Regeneration):

- When State of Charge (SOC) of the battery drops below 50%, Switch S5 is used in boost mode to charge the battery from regenerative energy.

Buck mode is controlled using a fixed-frequency PI-based voltage mode control scheme, ensuring steady voltage regulation during UC charging.

B. Hybrid Current Control Algorithm

To ensure stable and efficient boost-mode operation of the converter, a Hybrid Current Control Algorithm is employed when the ultracapacitor supplies power to the load.

Key Features:

- Operates with variable switching frequency and variable duty cycle, offering rapid response.
- Eliminates the need for a compensator network, unlike traditional PI control.
- Switching period is dynamically adjusted based on measured:
  - Output voltage
  - Output current
  - Circuit parameters
  - Inductor current

Principle of Operation:

- The algorithm is designed to maintain the inductor current ripple and output voltage ripple within specified limits.
- The approximate waveforms of inductor current and output voltage in Continuous Conduction Mode (CCM) are shown in Fig. 6.

During the switch-on interval $0 \leq t \leq dT$:

$$\Delta i_L = \frac{(V_{in})}{L} dt \tag{8}$$

During the switch off interval:

$$\Delta V_a = \frac{\Delta i_L}{C} \times (1-d) \times T \tag{9}$$

Rewriting Equation (9) using Equation (8):

$$\Delta V_o = \frac{V_{in} \times d \times (1-d) \times T}{LC} \quad (10)$$

This shows the relationship between inductor current ripple and output voltage ripple. The average inductor current is computed by equating the converter's input and output power:

$$P_{in} = P_{out} \rightarrow V_{in} \times I_L = V_o \times I_o \quad (11)$$

- Using Equation (11), a reference inductor current is generated based on the desired load current and output voltage.
- A digital control logic developed in MATLAB compares:
    - Actual inductor current vs. reference
    - Actual output voltage vs. reference
- Based on these comparisons, appropriate gate pulses for the boost converter switches are generated in real time.

This control strategy ensures:

- Minimal voltage ripple
- High stability at high duty ratios
- Robust performance under load transitions and varying UC input voltages

IV. System Description

The propulsion command for the vehicle is provided in the form of a standardized drive cycle, as illustrated in Fig. 7. This drive cycle simulates the driver's input and is used to compute the required power and torque for vehicle propulsion through a vehicle dynamics model (Fig. 1). Based on the calculated power demand, a PWM-based PI control algorithm is employed to regulate the operation of the BLDC motor in motoring mode.

The required motor speed is determined from the target vehicle speed, considering the wheel radius and gear ratio, as shown in Fig. 3. The BLDC motor receives power from a hybrid energy storage system (HESS), comprising a battery and an ultracapacitor, via a power inverter. The selection of energy source battery or ultracapacitor is based on the vehicle's power demand in various operating conditions:

- During acceleration, the ultracapacitor supplies the peak power due to its high power density and fast response.
- Under normal driving conditions, the battery provides the average power required for propulsion.
- During regenerative braking, the motor acts as a generator. The inverter switches are controlled to reverse the current flow, allowing energy to be transferred from the motor (load) back to the DC bus.

In regenerative mode, the ultracapacitor initially absorbs the recovered energy through a buck converter, provided the motor's back EMF or the DC bus voltage exceeds the terminal voltage of the ultracapacitor. Once the bus voltage and ultracapacitor voltage reach equilibrium while the vehicle is still in motion the system boosts the DC bus voltage above the ultracapacitor terminal voltage using a boost converter, allowing continued energy transfer and charging.

If the ultracapacitor becomes fully charged and residual kinetic energy still exists, the excess energy is redirected to charge the battery through the boost converter. This energy management strategy ensures efficient utilization of both storage devices while enhancing vehicle range and braking energy recovery.

V. Simulation and Results

The proposed electric vehicle system was simulated using MATLAB/Simulink for test duration of 10 seconds, covering three key operational modes: acceleration, constant speed, and deceleration (regenerative braking).

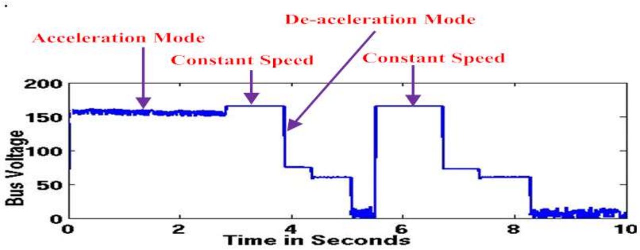

Fig. 7 DC Bus Voltage in Volts

Fig. 7 illustrates the DC bus voltage behavior throughout the simulation. During the acceleration phase, the DC bus voltage is maintained at a constant 156 V, despite the ultracapacitor terminal voltage dropping from 48 V to 47 V, as shown in Fig. 8.

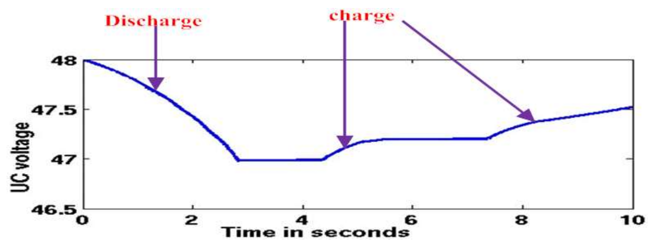

Fig. 8 UC Voltage

The voltage ripple during this phase remains within ±2 V, demonstrating the effectiveness of the hybrid current control algorithm in maintaining bus voltage stability under dynamic load conditions.

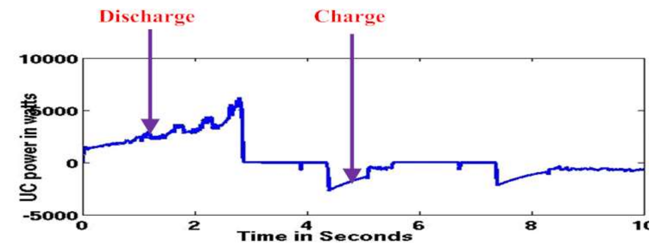

Fig. 9 Ultracapacitor power in watts

During acceleration, the ultracapacitor delivers up to 7 kW of power to support the high torque demand, as depicted in Fig. 9. In the constant speed mode, the vehicle draws power from the battery, with the DC bus voltage corresponding to the battery terminal voltage, as observed in Fig. 8.

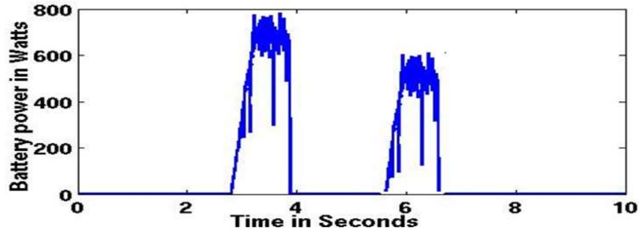

Fig. 10 Battery Power in Watts

Fig. 10 shows that the battery supplies approximately 800 W during this phase. Comparing Fig. 9 and Fig. 10 confirms that the ultracapacitor handles peak power demands, while the battery manages only the average power, enabling a reduction in battery size without compromising performance.

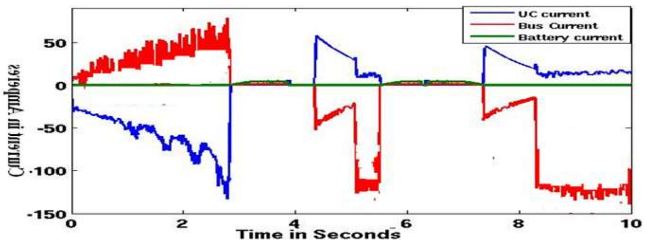

Fig. 11 Battery Current, UC Current & Bus Current

Fig. 11 presents the current contribution of both the battery and ultracapacitor throughout the drive cycle. A negative current from the ultracapacitor indicates its discharge mode during acceleration. The bus current distribution reflects the system's operating mode: positive values indicate motoring, while negative values signify regenerative braking. During regenerative braking, the ultracapacitor captures most of the recovered energy, as seen in Fig. 9. In the initial phase, when the motor's back EMF is higher than the ultracapacitor voltage, energy transfer occurs via the buck converter.

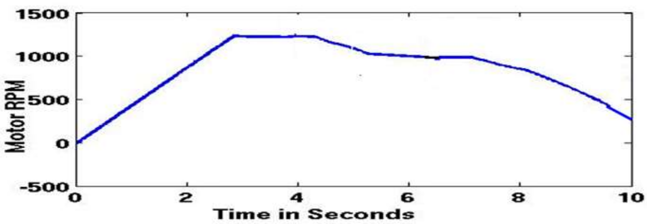

Fig. 12 Motor RPM

During this phase, the bus current is lower than the ultracapacitors charging current, reflecting controlled energy absorption. As the vehicle slows down, the motor speed and back EMF decrease, reducing the available regenerative energy. Once the ultracapacitor voltage equals the DC bus voltage, the boost converter is activated to continue charging the ultracapacitor. This mode requires a significantly higher bus current, as shown in Fig. 11.

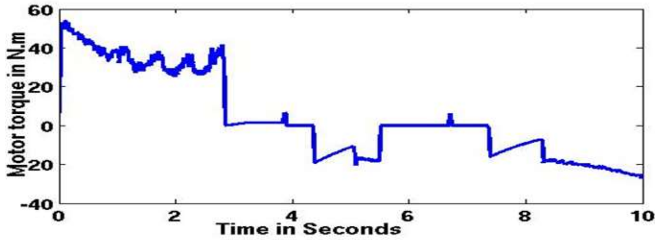

Fig. 12 Motor Torque

Fig. 12 and Fig. 13 display the motor speed and torque profiles across the acceleration, cruising, and deceleration phases. During deceleration, the motor torque becomes negative, and the back EMF decreases, leading to a corresponding drop in DC bus voltage. Nevertheless, the ultracapacitor is successfully recharged from 47 V to 47.5 V, as shown in Fig. 8, indicating effective utilization of regenerative braking even at lower vehicle speeds.

These simulation results confirm that the proposed hybrid storage system, combined with intelligent control strategies, effectively balances energy flow, reduces battery stress, and improves overall energy efficiency of the electric vehicle system.

VI. Conclusion

The proposed system successfully achieves stable operation of the boost converter using a hybrid current control algorithm, maintaining a constant DC bus voltage of 156 V with a ripple of ±2 V, even under dynamically varying load and input voltage conditions. The regenerative charging of the ultracapacitor has been effectively demonstrated; even when the DC bus voltage is lower than the ultracapacitor terminal voltage, by employing the proposed boost converter topology.

The simulation results confirm that the ultracapacitor supplies power during acceleration and absorbs energy during deceleration, significantly reducing the stress on the battery. This operational strategy avoids deep battery discharge during peak loads and frequent high current charging, which are known to degrade battery performance. Consequently, the hybrid energy storage configuration not only improves system efficiency and dynamic response but also contributes to extending the overall battery lifespan, making it a viable and cost effective solution for electric vehicle propulsion systems.

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