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BATTERY-SUPERCAPACITOR HYBRID ENERGY STORAGE SYSTEM FOR ELECTRIC VEHICLE POWER MANAGEMENT

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Abstract

Rapid motor acceleration imposes short-duration high-current demand on an electric-vehicle battery, causing terminal-voltage sag and avoidable electrochemical stress. This paper presents a bench-scale, microcontroller-based hybrid energy storage system that couples a 12 V battery with a 12 V supercapacitor module through independently controlled relays. An ATmega328P controller acquires battery current, capacitor current, source voltages, and temperature using two ACS712-30A sensors, resistive voltage dividers, and a DS18B20 sensor. Battery-only and hybrid startup tests were performed from the same reported initial voltages of 11.27 V and

11.18 V. The controller summary recorded a reduction in peak battery current from 18.73 A to 1.33 A, corresponding to 92.90% peak-current shaving. In hybrid mode the supercapacitor supplied a 7.56 A peak, while the minimum battery voltage remained at

11.27 V instead of falling to 10.09 V. The measured voltage sag therefore decreased from 1.18 V to 0.00 V. Short-duration periodic telemetry also shows sustained current sharing without a meaningful temperature rise. The results demonstrate effective transient offloading while identifying the need for repeated trials and synchronized high-rate logging before vehicle-scale deployment.

Index Terms—Hybrid energy storage system, electric vehicle, supercapacitor, peak-current shaving, voltage sag, ATmega328P, power management.

1 INTRODUCTION

Electric-vehicle propulsion requires an energy source that can supply both sustained energy and rapid power bursts. Batteries provide the energy density needed for useful range, but abrupt acceleration and motor starting can draw currents far above the steady operating level. Battery internal impedance converts these peaks into terminal-voltage drop and resistive heating. Repeated high-rate events can therefore increase stress even when average current remains modest.

A battery-supercapacitor hybrid energy storage system combines complementary devices: the battery supplies the longer-duration energy component, while the supercapacitor responds to short, high-power demands. Reviews of battery-supercapacitor systems identify reduced battery stress, improved transient response, and DC-link stabilization as principal benefits, while also emphasizing that topology and control determine how effectively power is shared [1]–[3].

The objective of this work is to implement a low-cost experimental power-management prototype and quantify its effect under two controlled operating modes. The contribution is an instrumented comparison of battery-only and relay-coupled hybrid operation using reported startup peaks, source-voltage sag, periodic current sharing, and temperature. The paper also separates event-level peak registers from the lower-rate telemetry shown in the supplied serial log, preventing the two acquisition views from being interpreted as the same sample stream.

2 RELATED WORK AND DESIGN REQUIREMENTS

Prior work classifies hybrid energy storage systems as passive, semi-active, or fully active. Active converter-based architectures provide the greatest power-flow authority, whereas passive and relay-switched arrangements are simpler and useful for proof-of-concept testing [1], [2]. Experimental EV studies similarly use the supercapacitor to supply the rapid component of acceleration demand so that battery current remains closer to its average value [4].

The present prototype targets three measurable requirements: reduce the battery startup-current peak, prevent a measurable fall in battery terminal voltage during the recorded event, and maintain stable short-term temperature. It is a laboratory demonstrator, not a production traction-power unit. Relay contact ratings, pre-charge, protection coordination, electromagnetic compatibility, isolation, and automotive functional safety remain outside the scope of this test.

3 SYSTEM ARCHITECTURE AND HARDWARE IMPLEMENTATION

3.1 Power Path and Switching

The energy path contains a 12 V chemical battery, a nominal 12 V supercapacitor module, a DC motor load, and two independently driven active-LOW relays connected to microcontroller pins D7 and D8. In battery-only mode the capacitor path is isolated. In hybrid mode the sources are coupled so the low-impedance capacitor path can respond to transient demand while the battery continues to support the bus.

3.2 Measurement and Control

- **Current measurement:** Two ACS712-30A Hall-effect sensors measure battery current at A0 and capacitor current at A1. The 30 A variant has a typical sensitivity of 66 mV/A at 25 °C [5].
- **Voltage measurement:** Resistive dividers scale capacitor and battery terminal voltages to analog inputs A2 and A3, respec-tively.
- **Temperature measurement:** A DS18B20 digital sensor connected to D2 monitors the prototype temperature during each short run.
- **Controller and telemetry:** An ATmega328P performs sensor acquisition, relay sequencing, peak tracking, and UART/LCD reporting. Its integrated analog-to-digital converter produces a 10-bit result [6].

At startup, the firmware auto-calibrates the sensor offsets before enabling a test sequence. During each run it reports periodic measurements of time, mode, battery current, capacitor current, motor current, battery voltage, capacitor voltage, and temperature. Separate final registers report the maximum currents and minimum battery voltage observed by the controller.

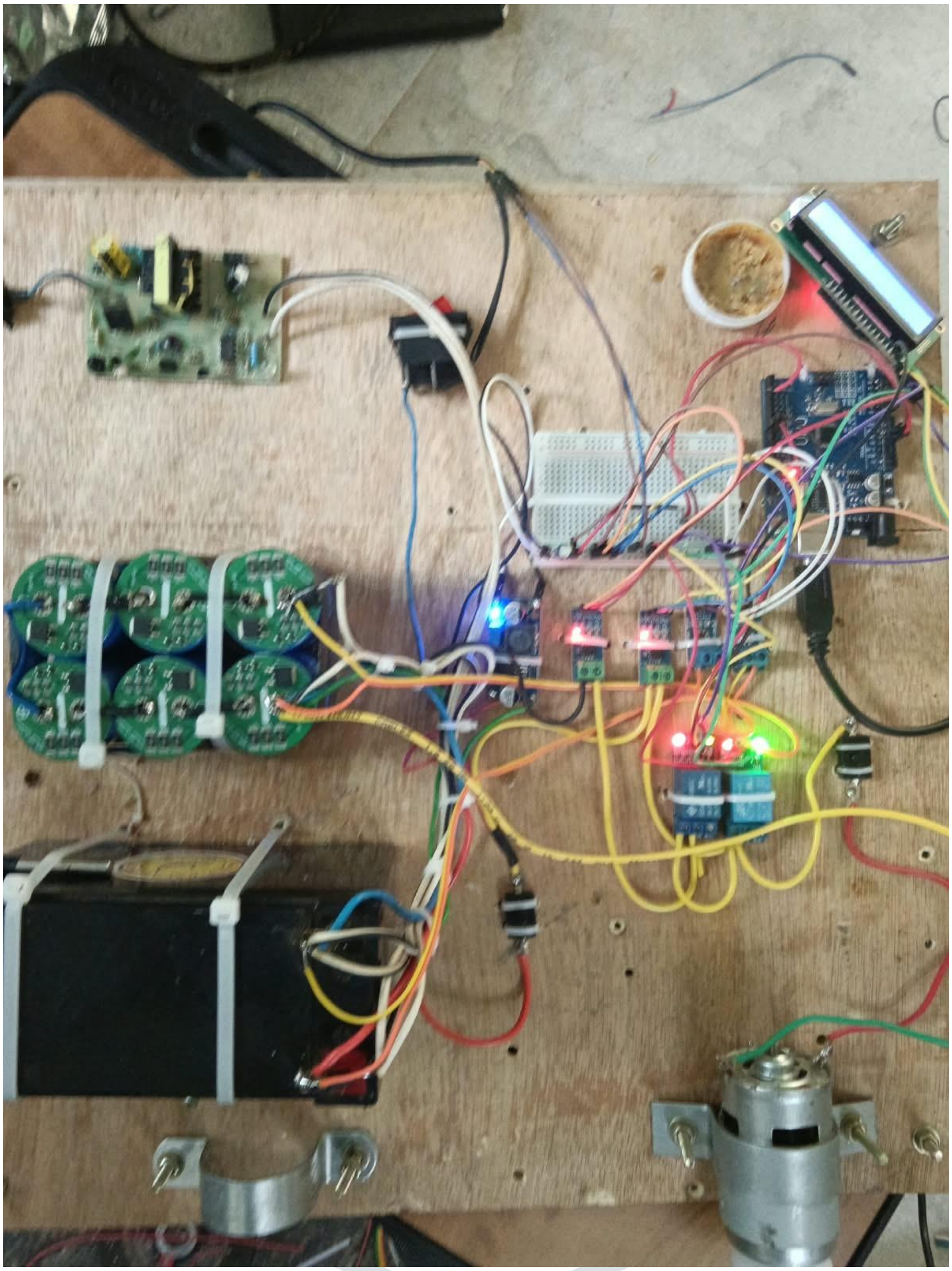

Figure 1: Hardware prototype of the battery-supercapacitor HESS test bench

4 MATHEMATICAL FORMULATION AND CONTROL LOGIC

4.1 Battery Terminal Voltage

For a short load event, the battery terminal voltage can be represented by the open-circuit voltage minus the current-dependent internal drop:

$$\square_{\square} = \square_0 - \square_{bat}\square_{int} \quad (1)$$

The recorded voltage sag is defined from the initial and minimum battery voltages:

$$\Delta\square = \square_{init} - \square_{min} \quad (2)$$

4.2 Current Sharing and Peak Shaving

Neglecting measurement error and small auxiliary currents, motor current is the sum of the source contributions:

$$\square_{mot} = \square_{bat} + \square_{cap}$$

(3)

Peak-current shaving is evaluated against the battery-only peak:

$$\square_{ps} = \frac{\square_{bat,battery} - \square_{bat,hybrid}}{}$$

5 EXPERIMENTAL PROCEDURE

After automatic sensor calibration, the battery-only test was run for 5.0 s and the hybrid test for 4.1 s. Both final summaries report initial source voltages of 11.27 V for the battery and 11.18 V for the capacitor. The supplied periodic log contains 35 battery-only records and 28 hybrid records at approximately 0.1–0.2 s spacing. The controller summary additionally retains event peaks and a minimum voltage that may occur between the displayed periodic records.

Performance is compared using peak source currents, motor peak current, minimum battery voltage, sag, periodic mean currents, and final temperature. Because the supplied data describe one short run per operating mode, the analysis is descriptive; no confidence interval or statistical significance is claimed.

(4)

6 RESULTS AND DISCUSSION

Table 1: Experimental performance comparison

Parameter	Battery only	Hybrid HESS	Interpretation
Initial battery voltage	11.27 V	11.27 V	Matched reported baseline
Initial capacitor voltage	11.18 V	11.18 V	Matched reported baseline
Peak motor current	18.73 A	8.89 A	52.54% lower recorded peak
Peak battery current	18.73 A	1.33 A	92.90% peak shaving
Peak capacitor current	0.00 A	7.56 A	85.04% of hybrid motor peak
Minimum battery voltage	10.09 V	11.27 V	Higher transient voltage floor
Battery voltage sag	1.18 V	0.00 V	100% elimination in this run
Mean periodic battery current	0.388 A	0.121 A	Lower sustained battery loading
Mean periodic capacitor current	0.000 A	0.224 A	64.9% of hybrid mean motor current
Mean periodic motor current	0.388 A	0.344 A	Distinct short operating traces
Final temperature	34.9 °C	35.0 °C	No meaningful short-run rise

6.1 Peak Current Offloading

Equation (4) gives a peak-current-shaving value of 92.90%. At the reported hybrid event peak, the supercapacitor supplied 7.56 A, or 85.04% of the 8.89 A motor peak, while the battery supplied 1.33 A. The result is consistent with the intended division of labor: the capacitor handles the rapid component and the battery carries a smaller share. The motor peak itself was 52.54% lower than in the battery-only summary, indicating that the switching and source dynamics also changed the observed startup profile; this difference should be examined with synchronized speed and torque measurements in future tests.

In battery-only mode the mean periodic battery current was 0.388 A and equals the logged motor current. In hybrid mode the mean battery current fell to 0.121 A while the capacitor supplied 0.224 A on average. The capacitor therefore contributed approximately 64.9% of the mean logged motor current during the displayed hybrid window.

6.2 Voltage Sag and Thermal Response

The battery-only final summary recorded a minimum of 10.09 V from an initial 11.27 V, corresponding to 1.18 V sag. The hybrid summary retained 11.27 V as the minimum, so the recorded sag was 0.00 V. This is a complete elimination for the supplied run, although the periodic plots settle above the initial first sample and do not reproduce the higher-rate minimum detector. The result should therefore be interpreted as a controller-reported event metric rather than a value reconstructed from the visible trace.

Final temperature changed from 34.9 °C in battery-only mode to 35.0 °C in hybrid mode. A 0.1 °C difference over a few seconds is insufficient to establish a thermal benefit, but it does indicate that no abnormal heating was visible during the test.

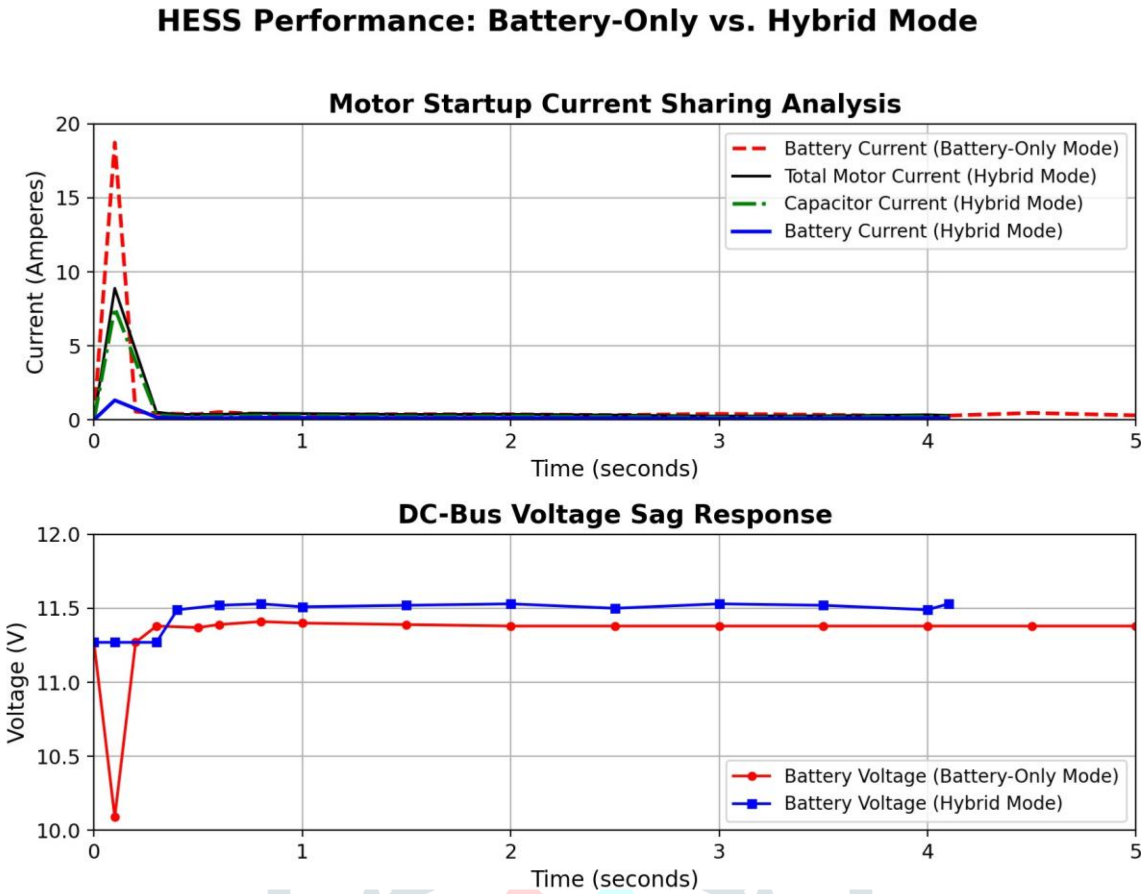

Figure 2: Combined HESS performance waveforms: motor startup current sharing analysis (top) and DC-bus voltage sag response (bottom) comparing battery-only vs. hybrid mode.

Figure 2 combines the current-sharing and voltage-sag traces into a single comparative view. The startup current spike and the corresponding battery-voltage dip in battery-only mode are visibly larger than the equivalent hybrid-mode traces, illustrating together the peak-shaving and sag-elimination effects reported numerically in Table 1.

6.3 Limitations and Engineering Implications

The measurements support the immediate claim of transient battery-current reduction and bus-voltage stabilization in this prototype. They do not directly demonstrate longer battery life, because degradation was not measured. Any lifecycle benefit remains an engineering expectation derived from lower current stress rather than an outcome of the short experiment.

Future validation should repeat both modes under controlled mechanical torque, synchronize high-rate raw samples with the peak detector, report sensor calibration uncertainty, measure relay timing and contact drop, and record battery and capacitor state of charge. A vehicle-scale design should replace or supplement relay-only sharing with a properly sized bidirectional converter, pre-charge path, fusing, isolation monitoring, and fault-state logic.

7 CONCLUSION

A microcontroller-based battery-supercapacitor power-management prototype was implemented and evaluated in battery-only and hybrid modes. For the supplied run, hybrid operation reduced the reported battery peak from 18.73 A to 1.33 A, achieving 92.90% peak-current shaving. The supercapacitor supplied a 7.56 A event peak, and the reported battery-voltage sag decreased from 1.18 V to 0.00 V. Periodic telemetry independently showed sustained current sharing, with the capacitor supplying about two-thirds of the mean logged motor current while the battery contribution remained smaller. The final temperature stayed near 35 °C. These results establish proof-of-concept transient offloading and voltage stabilization; repeated, synchronized, and uncertainty-bounded tests are required before claims about lifecycle extension or production EV performance can be made.

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