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Development of a Hybrid Energy Storage System for a Hand Exoprosthesi

Relator:

Prof. Paolo Motto Ross

Prof. Danilo Demarchi

Letizia Cantore, M.Sc.

Candidate:

Marika Palma

*A mio padre,
Socrate per Platone,
per avermi amata ed insegnato ad
amare in modo smisurato,
il tuo.*

Abstract

The power supply of advanced hand exoprostheses is a critical aspect for ensuring continuous operation, safe energy delivery, and effective management of transient power demands. In this context, Hybrid Energy Storage Systems (HESS) represent a promising solution, as they combine a main energy source with an auxiliary storage element able to support short-duration current peaks generated by the actuation system.

This thesis was carried out within a broader research activity focused on the development of the external power system for a hand exoprosthesis. Starting from a previous prototype developed by the research team, the work contributed to the prototyping and optimization of the hardware platform through the validation of selected power modules, the review and functional verification of the implemented circuit sections, and support to component selection. The main contribution of the thesis concerned the experimental integration of the HESS prototype, the implementation and tuning of the control algorithm, and the validation of the system under representative pulsed-load conditions.

The proposed system combines a lithium-ion battery, used as the main energy source, and a supercapacitor, employed to support the load during high-power transients. The prototype includes the main power management stages, load-sharing circuit, and voltage and current sensing sections. A finite-state machine was implemented on an external microcontroller to manage battery-powered operation, supercapacitor charge and recharge, assist mode, and protection states.

Experimental tests were performed using a resistive pulsed load designed to reproduce the rated and peak power absorption of the exoprosthetic actuation system. A real-time acquisition setup and graphical user interface enabled the monitoring of the main electrical quantities, power flows, efficiency, and supercapacitor contribution. The results confirmed the feasibility of the implemented HESS prototype and the effectiveness of the control strategy, with an average efficiency of approximately 87-90% and 6 V load-bus variations in the order of 10-20 mV under controlled operating conditions.

Future developments may focus on optimizing power components, conversion efficiency, dynamic response, and system integration. Further improvements may also involve load-forecasting control strategies to anticipate transient power demands, as well as the investigation of energy harvesting solutions to extend the autonomy of the system.

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Chapter 1

Energy Management Architectures for Prosthetic Systems

1.1 Introduction

Robotic upper-limb prostheses, within the broader field of wearable robotic systems, are complex electromechanical systems characterized by highly variable power profiles. Their operation relies on the combined activity of electrical actuators, embedded control units, sensing modules and wireless communication interfaces. As a consequence, the energy demand is not constant over time, but alternates between low-power operating phases and short high-power transients associated with motor activation, grasping actions or rapid changes in mechanical load.

In this context, the power supply architecture plays a critical role in determining the overall performance of the device. It directly affects autonomy, voltage stability, dynamic response, efficiency, reliability and long-term lifetime of the energy storage system. In particular, robotic prosthetic hands represent a challenging application, since the actuation of multiple fingers may generate impulsive current demands that are difficult to manage using a conventional battery-only supply.

The increasing integration of biomedical devices with neural interfaces further strengthens the need for reliable and stable power management strategies. In closed-loop prosthetic systems, power interruptions, voltage drops or excessive ripple may affect not only the actuation subsystem, but also sensing, control and communication modules. Therefore, the design of an energy management architecture cannot be considered a secondary aspect, but becomes a key requirement for safe and effective operation.

Among the possible solutions, Hybrid Energy Storage Systems (HESSs), based on the combination of batteries and supercapacitors, represent a promising approach. In these architectures, the battery is mainly responsible for providing the average energy demand, while the supercapacitor is used as a high-power buffer to support fast load transients. This functional separation between the energy domain and the power domain can reduce battery stress, improve bus voltage stability and increase the robustness of the overall system.

This chapter reviews the main energy storage and management strategies relevant to robotic prosthetic applications. First, battery-based and supercapacitor-based systems are discussed, highlighting their advantages and limitations. Then, hybrid battery-supercapacitor architectures are introduced, with particular attention to their suitability for impulsive biomedical loads. Finally, energy harvesting solutions and energy management algorithms are analysed in order to identify the technological gap addressed by this thesis.

1.2 Energy Storage Technologies for Prosthetic Systems

The energy storage subsystem represents one of the most critical elements in modern robotic prostheses and wearable biomedical devices. The increasing complexity of embedded electronics, sensing platforms, wireless communication modules and electromechanical actuators has significantly raised the power requirements of these systems, while maintaining strict constraints in terms of weight, size and portability [1].

Unlike conventional low-power wearable devices, robotic prosthetic systems are characterized by highly dynamic load conditions. During operation, electric actuators may generate short-duration current peaks considerably higher than the average consumption, especially during grasping operations, simultaneous finger activation or rapid motion changes. These transient conditions can produce voltage drops, increased thermal stress and reduced efficiency if the energy storage architecture is not properly designed [2, 3].

For this reason, the choice of the energy storage technology plays a fundamental role in determining the stability, reliability and operational lifetime of the entire prosthetic system. Different energy storage solutions can be adopted depending on the required balance between energy density, power density, transient response capability and cycle life.

The most commonly adopted solutions for biomedical robotic applications can be classified into three main categories:

- battery-based energy storage systems;

- supercapacitor-based energy storage systems;
- hybrid battery-supercapacitor energy storage systems.

Each solution presents specific advantages and limitations. In the following sections, these technologies are analysed with particular attention to their suitability for robotic prosthetic applications characterized by impulsive power demands and rapidly varying load profiles.

1.2.1 Battery-Based Energy Storage Systems

Rechargeable batteries currently represent the most widely adopted energy storage technology for portable biomedical and wearable systems. Among the available technologies, lithium-ion batteries are commonly preferred due to their high energy density, relatively low self-discharge and good compromise between weight and stored energy [1, 2].

In robotic prosthetic applications, batteries are typically responsible for supplying the average power required by embedded electronics, sensors, communication modules and electromechanical actuators. Their high energy density enables extended operational autonomy while maintaining compact dimensions, which is a fundamental requirement for wearable systems.

Despite these advantages, battery-based power systems present several limitations when subjected to highly dynamic load conditions. Prosthetic actuators often generate impulsive current demands characterized by fast transients and high peak currents. Under these conditions, the internal impedance of the battery may produce significant voltage drops and increased thermal dissipation [2, 3].

Furthermore, repeated exposure to high current peaks accelerates electrochemical degradation phenomena, including internal heating, electrode stress and capacity fading. This can progressively reduce the lifetime and reliability of the energy storage system.

Another important limitation concerns the dynamic response speed of batteries. Due to electrochemical constraints, batteries are not optimized for delivering very high power in extremely short time intervals. As a consequence, systems relying exclusively on batteries may experience reduced voltage stability during transient operating conditions.

For these reasons, although battery-only architectures remain attractive due to their simplicity and high energy density, they may not represent the optimal solution for robotic prosthetic systems characterized by highly impulsive power profiles.

1.2.2 Supercapacitor-Based Energy Storage Systems

Supercapacitors, also known as electrochemical double-layer capacitors, represent an alternative energy storage technology characterized by extremely high power density, very fast charge-discharge capability and long cycle lifetime [2, 3]. Unlike batteries, which rely on electrochemical reactions, supercapacitors mainly store energy through electrostatic charge accumulation at the electrode-electrolyte interface.

One of the main advantages of supercapacitors is their capability to deliver or absorb very high currents within extremely short time intervals. This characteristic makes them particularly suitable for applications involving impulsive loads, rapid power fluctuations and repetitive transient conditions, such as robotic prosthetic actuation systems.

Another important advantage is their low equivalent series resistance, which enables reduced voltage drops and lower thermal dissipation during high-current operation. Furthermore, supercapacitors can withstand a high number of charge-discharge cycles with limited degradation, making them suitable for repetitive dynamic applications [2].

Despite these advantages, supercapacitors also present important limitations. Their energy density is significantly lower than that of lithium-ion batteries, meaning that they cannot provide long-term energy supply for continuous system operation. In addition, the voltage across a supercapacitor varies almost linearly with the stored charge, requiring dedicated power conversion stages to ensure stable bus regulation.

As a consequence, systems based exclusively on supercapacitors are generally unsuitable for wearable robotic devices requiring extended operational autonomy. However, their exceptional dynamic response capability makes them attractive as auxiliary power buffers for supporting transient load conditions.

For these reasons, supercapacitors are commonly integrated together with batteries in HESSs, where the battery provides the average energy demand while the supercapacitor compensates fast current peaks and rapid power fluctuations [2, 4].

1.2.3 Hybrid Energy Storage Systems

HESSs combine multiple storage technologies in order to exploit their complementary characteristics. In the case of robotic prosthetic and wearable biomedical systems, the most relevant configuration is the combination of a lithium-ion battery and a supercapacitor module [2, 4].

The basic principle of this architecture is the separation between the energy domain and the power domain. The battery, characterized by high energy density, is mainly used to supply the average power demand of the system and to guarantee operational autonomy. The supercapacitor, characterized by high power density

and fast dynamic response, is used to support short-duration current peaks and rapid load transients [2, 3].

This division of roles is particularly suitable for robotic prosthetic applications, where the load profile is not constant but strongly dependent on the actuation phase. During low-power or steady-state operation, the battery can supply the load and maintain the system active. During transient phases, such as motor start-up, grasping actions or simultaneous activation of multiple actuators, the supercapacitor can provide additional power support, reducing the instantaneous current demand on the battery.

From an electrical point of view, this approach can reduce battery current peaks, limit voltage drops on the DC bus and decrease thermal stress associated with high-current operation. Moreover, by smoothing the battery current profile, HESS architectures may contribute to reducing battery degradation and improving the long-term reliability of the system [2, 4].

Several HESS topologies have been proposed in the literature. In passive configurations, the battery and the supercapacitor are directly connected to the same DC bus. This solution is simple and compact, but the power sharing between the two storage elements is mainly determined by their internal impedances and voltage levels, resulting in limited control capability.

Semi-active configurations introduce a DC-DC converter on one of the two storage branches, usually the supercapacitor branch. This enables a more controlled use of the supercapacitor during transient events while maintaining a moderate level of circuit complexity. Full-active configurations, instead, employ dedicated converters for both the battery and the supercapacitor branches, allowing a more flexible and accurate control of the power flow at the cost of higher complexity, size and control effort [2, 3].

The choice of the most suitable topology depends on several constraints, including required power level, voltage range, converter efficiency, control complexity, system volume and weight. These constraints are especially relevant in wearable biomedical systems, where the available space is limited and additional components must not compromise portability or comfort.

Energy management represents another key aspect of HESS operation. Since the power contribution of each storage element must be coordinated according to the load demand and the state of the system, proper control strategies are required. In the literature, different approaches have been proposed, including rule-based methods, threshold-based strategies, filtering techniques, fuzzy logic and model predictive control [4, 5].

For embedded biomedical applications, deterministic strategies based on thresholds or finite state machines are particularly attractive because of their reduced computational complexity, predictable behavior and easier implementation on

microcontroller-based platforms. These methods allow the system to switch between different operating modes depending on measured quantities such as load current, bus voltage, battery state and supercapacitor voltage [5].

Overall, battery-supercapacitor HESS architectures represent a promising solution for robotic prosthetic systems characterized by impulsive and highly variable power demands. Their main advantage is the possibility of combining the high autonomy of batteries with the fast transient response of supercapacitors. However, their practical implementation requires careful design of the power electronics, sensing architecture and control strategy, in order to achieve stable and efficient power sharing under real operating conditions.

1.3 Energy Harvesting in Wearable Biomedical Systems

Energy harvesting technologies have attracted increasing interest in the field of wearable and biomedical electronics as a possible approach to extend battery lifetime and reduce the dependency on external charging systems. These techniques aim to convert energy available in the surrounding environment or generated by the human body into usable electrical power.

Several energy harvesting approaches have been investigated for wearable biomedical systems, including piezoelectric, triboelectric, thermoelectric and kinetic energy harvesting techniques [6]. In particular, human motion represents one of the most widely explored energy sources for wearable applications due to the continuous availability of mechanical movement during daily activities.

Kinetic energy harvesters can exploit body motion, joint displacement or walking-induced vibrations to generate electrical energy. In the literature, different wearable harvesting mechanisms have been proposed for integration into exoskeletons, prosthetic systems and assistive robotic devices [7]. These systems typically employ electromagnetic, piezoelectric or hybrid transduction mechanisms to convert mechanical energy into electrical power.

Despite the growing research interest in this field, the power levels currently achievable through wearable energy harvesting systems remain relatively limited when compared to the requirements of robotic actuation systems. Prosthetic hands and active exoskeletons may require short-duration power peaks associated with motor activation and dynamic load transitions that are difficult to sustain using harvesting systems alone.

Moreover, the power generated by wearable harvesting devices is strongly dependent on user activity, motion conditions and conversion efficiency, resulting in variable and often unpredictable energy availability. For these reasons, energy harvesting technologies are currently considered more suitable as auxiliary energy

sources for low-power electronics, sensing platforms or battery support functions rather than as primary power supplies for highly dynamic robotic actuation systems.

Nevertheless, energy harvesting remains an important research direction for future wearable biomedical devices, particularly in combination with advanced power management architectures and HESSs capable of optimizing the use of the harvested energy.

1.4 Energy Management Strategies for Hybrid Storage Systems

The performance of a Hybrid Energy Storage System strongly depends not only on the selected storage technologies and converter topology, but also on the adopted energy management strategy. Since batteries and supercapacitors exhibit significantly different electrical characteristics, proper coordination of their power contribution is required in order to achieve stable, efficient and reliable operation.

The main objective of an Energy Management Strategy (EMS) is to regulate the power flow between the storage elements and the load according to the operating conditions of the system. In particular, the EMS determines when the battery or the supercapacitor should supply power, how transient events should be managed and how the storage elements should be protected from unsafe operating conditions [4, 5].

Several control approaches have been proposed in the literature for battery-supercapacitor HESS architectures. Among the most common methods are rule-based control, threshold-based strategies, filter-based approaches, fuzzy logic algorithms and model predictive control techniques [4].

Rule-based and threshold-based methods are widely adopted in embedded systems due to their simplicity, low computational cost and deterministic behavior. In these approaches, the operating state of the system is determined according to measured variables such as load current, bus voltage, state of charge or supercapacitor voltage. Depending on predefined thresholds, the control system can activate different operating modes, enabling or disabling specific power paths and regulating the contribution of the storage elements.

Finite State Machine (FSM)-based approaches are particularly suitable for wearable biomedical systems implemented on microcontroller-based platforms. In these architectures, the system operation is divided into multiple states associated with different operating conditions, such as steady-state supply, transient assistance, recovery or protection modes [5]. Transitions between states are triggered by real-time measurements and predefined control conditions.

The implementation of an effective EMS also requires accurate sensing and monitoring capabilities. Real-time measurements of voltage, current and power are

essential for detecting transient events, evaluating system conditions and ensuring reliable operation under varying load scenarios.

Although advanced control techniques such as fuzzy logic or model predictive control may provide improved optimization capabilities, their implementation complexity and computational requirements can represent a limitation for compact embedded biomedical systems. For this reason, deterministic approaches based on thresholds and state-machine logic remain attractive solutions for real-time wearable applications requiring predictable and low-latency behavior.

Overall, energy management strategies play a fundamental role in determining the efficiency, stability and robustness of HESSs, particularly in biomedical robotic applications characterized by dynamic and rapidly varying power demands.

1.5 Comparative Analysis and Research Gap

The analysis of the literature highlights the increasing importance of advanced power management architectures for wearable biomedical and robotic prosthetic systems. The growing integration of embedded electronics, wireless communication modules and electromechanical actuators has significantly increased the complexity of the power supply requirements, especially in applications characterized by dynamic and impulsive load profiles.

Battery-based power systems remain the most commonly adopted solution due to their high energy density and compactness. However, their limited capability to sustain rapid current transients may result in voltage instability, thermal stress and accelerated degradation under highly dynamic operating conditions [2, 3]. Supercapacitors, on the other hand, provide excellent transient response and high power density, but their limited energy density prevents their use as standalone long-term energy sources.

HESSs represent a promising compromise between these two technologies, combining the high energy density of batteries with the fast dynamic response of supercapacitors. Several studies have demonstrated the potential advantages of HESS architectures in terms of battery stress reduction, improved voltage stability and enhanced transient power support [2, 4, 5].

Nevertheless, the practical implementation of HESS architectures in compact wearable biomedical systems still presents several open challenges. These include the design of efficient and compact power conversion stages, the implementation of reliable real-time sensing architectures and the development of embedded control strategies capable of adapting to rapidly varying load conditions while maintaining low computational complexity.

Moreover, a significant portion of the existing literature focuses on electric vehicles, large-scale energy systems or simulation-based validation, while fewer

studies investigate experimentally validated HESS architectures specifically designed for robotic prosthetic applications operating under realistic dynamic conditions.

In particular, the characterization and management of highly impulsive load profiles generated by robotic prosthetic actuators remain critical aspects for the development of reliable wearable systems. The integration of compact hybrid storage architectures with embedded real-time monitoring and deterministic energy management strategies therefore represents an important research direction for future biomedical robotic platforms.

Based on these considerations, this thesis focuses on the hardware analysis and optimization, functional integration, control development, and experimental validation of a hybrid battery-supercapacitor power management system for robotic prosthetic applications. Particular attention is dedicated to transient power support, embedded sensing, real-time monitoring and finite-state-machine-based power management strategies suitable for compact wearable platforms.

Chapter 2

Hybrid Energy Storage System Architecture

2.1 Introduction

This chapter describes the Hybrid Energy Storage System (HESS) architecture developed within the NerveRepack project for robotic prosthetic applications.

The system was conceived as part of the external power-management platform for wearable biomedical devices, with particular reference to hand exoprostheses characterized by variable and impulsive power profiles. The power-management architecture is required to maintain a stable supply during transient motor activation while satisfying constraints related to compactness, weight, efficiency, safety, and wearable integration.

The HESS combines a lithium-ion battery, used as the main energy source, with a supercapacitor branch intended to support short-duration power transients. The architecture includes dedicated power-conversion stages, charging circuits, load-sharing elements, and distributed voltage and current sensing.

The hardware architecture and PCB layout were developed within the broader NerveRepack research activities and do not represent original contributions of this thesis. The existing prototype was used as the experimental platform for the implementation, optimization, and validation of the Power Management System (PMS).

This chapter first introduces the project context and the main system requirements. The existing HESS architecture and the initial modular prototype are then presented, followed by the component-analysis, circuit-dimensioning, and integration activities that led to the final hardware platform.

2.2 NerveRepack Project Context

The work presented in this thesis was carried out within the European research project NerveRepack, funded under the Horizon Europe framework. The project aims to develop bidirectional neural interfaces and integrated wearable robotic systems for restoring motor functions and sensory feedback in subjects affected by limb loss or neurological impairments.

The overall platform combines implantable neural interfaces, sensing and stimulation electronics, wireless communication, embedded processing, and external mechatronic devices. Within this framework, the electronic platform is responsible for power management, communication, control, and coordination with the implantable subsystem.

The power-management unit is a critical element of the system, since the electromechanical actuators generate variable and impulsive power demands. These transient loads must be supplied while preserving the stability of the regulated bus and ensuring safe operation of the battery, supercapacitor, and connected electronics.

Within Work Package 6, a HESS was developed to coordinate the energy flow between the main battery, the auxiliary supercapacitor branch, and the load. The system was conceived to provide regulated supply voltages, transient power support, and real-time monitoring of the main electrical quantities.

The following sections describe the system requirements and the hardware architecture used as the basis for the control and experimental activities presented in this thesis.

2.3 System Requirements

The development and validation of the HESS were guided by the system-level requirements defined within the NerveRepack project for the external power-management subsystem.

The requirements were derived from the expected electrical demand of the robotic platform, the characteristics of the selected storage elements, and the constraints associated with wearable integration. Particular attention was given to the ability of the system to maintain a stable regulated supply during short-duration load transients, while ensuring safe operation of both the battery and the supercapacitor branch.

The main system-level requirements estimated by the research team are summarized in Table 2.1.

Table 2.1: Main system-level requirements adopted for the HESS prototype.

Requirement	Target
Stable output voltage at the load side	6 V
Maximum supported output current	3 A
Maximum peak power demand	18 W
Minimum operating autonomy	≥ 8 h
Support for transient motor activations	Required
Safe battery charging	Required
Safe supercapacitor charging	Required
Real-time voltage/current monitoring	Required
Compatibility with wearable integration	Required

The 6 V load bus and the 3 A current capability define a maximum target power of 18 W under peak operating conditions. These values were adopted to account for short-duration actuator demands and to provide an adequate design margin during experimental validation.

The autonomy requirement refers to representative operating conditions rather than continuous operation at peak power. It therefore depends on the actuator duty cycle, the consumption of the auxiliary electronics, and the available battery capacity.

The charging and monitoring requirements were included to ensure that the storage elements could be safely managed during operation and experimental testing. Real-time electrical measurements were also necessary for the implementation of the energy-management strategy described in Chapter 3.

2.4 Overall System Architecture

The system is based on two energy-storage branches:

- a lithium-ion battery branch, used as the primary energy source;
- a supercapacitor branch, used to support short-duration power transients.

Figure 2.1 shows the overall architecture of the HESS considered in this work.

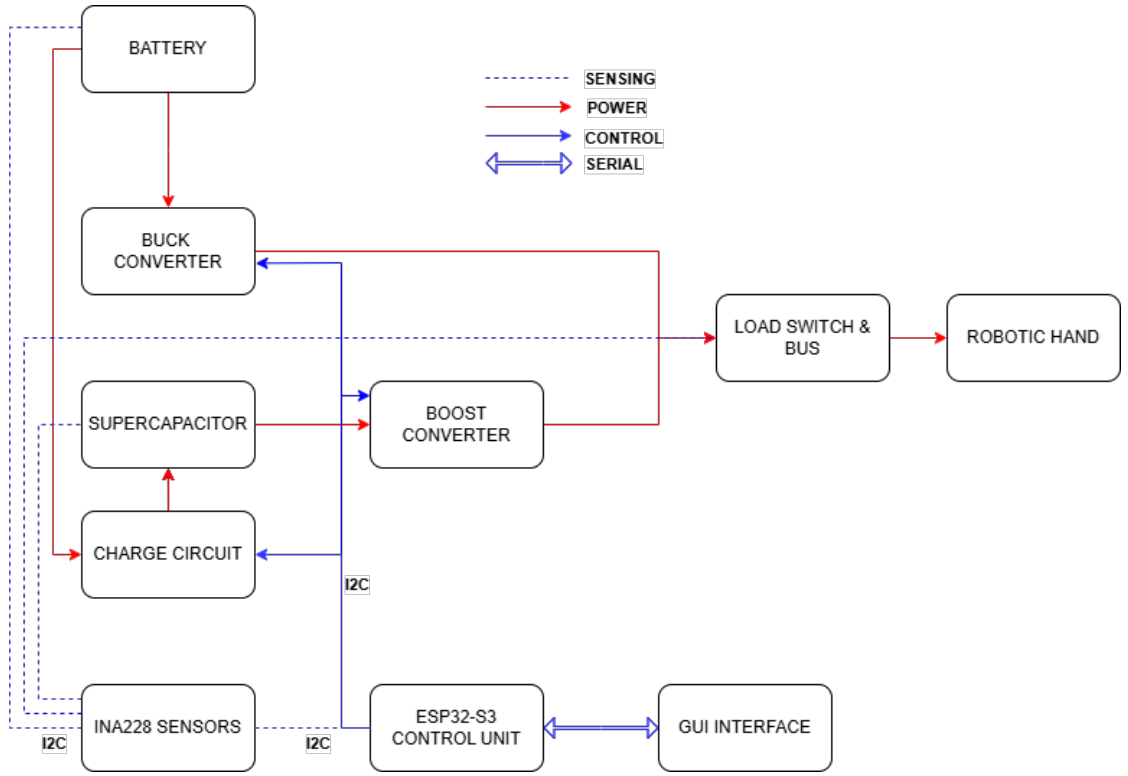


Figure 2.1: Overall architecture of the HESS considered in this work for the NerveRepack robotic exoprosthesis platform.

The system is based on two energy-storage branches:

- a lithium-ion battery branch, used as the primary energy source;
- a supercapacitor branch, used to support short-duration power transients.

The battery supplies the main power path through a dedicated DC–DC converter, operated mainly in step-down mode, which generates the regulated 6 V load bus. The same source also provides the energy required by the auxiliary regulated outputs and by the supercapacitor charging stage.

The supercapacitor is connected to the load bus through a dedicated boost converter. This branch is activated when additional power support is required, allowing part of the transient load demand to be supplied without relying exclusively on the battery.

A controlled charging circuit is used to recharge the supercapacitor from the battery branch. The charging process is managed according to the operating state of the system in order to limit the additional current drawn from the battery and avoid interference with the load supply.

The outputs of the battery and supercapacitor conversion stages are connected to a common load bus through the power-path management circuitry. This stage is responsible for coordinating the contribution of the two branches and preventing undesired reverse current flow.

Voltage and current sensing devices are distributed across the main power paths to monitor:

- battery-side electrical quantities;
- supercapacitor-side electrical quantities;
- load-bus voltage and current;

The acquired measurements are processed by the external control platform, which supervises the operating conditions of the system and manages the transitions between battery operation, supercapacitor assistance, recovery, and protection states.

The architecture therefore combines energy storage, power conversion, sensing, and unit control in order to maintain a regulated load supply under both steady-state and transient conditions.

2.5 Initial HESS Prototype

The hardware activities carried out in this thesis started from a modular prototype and subsequently supported the transition toward the final integrated implementation. This section presents the initial platform, the component-analysis and circuit-dimensioning activities, and the final HESS prototype used in the experimental campaign.

The experimental activities carried out in this thesis started from an initial HESS prototype developed within the NerveRepack research activities. The platform was assembled using separate commercial evaluation boards, custom measuring circuits, external control boards, and a pulsed resistive load used to reproduce representative transient power demands.

The prototype represented the hardware starting point for the subsequent component analysis, subsystem verification, circuit optimization, control development, and experimental validation activities. Figure 2.2 shows the complete initial setup and identifies its main functional blocks.

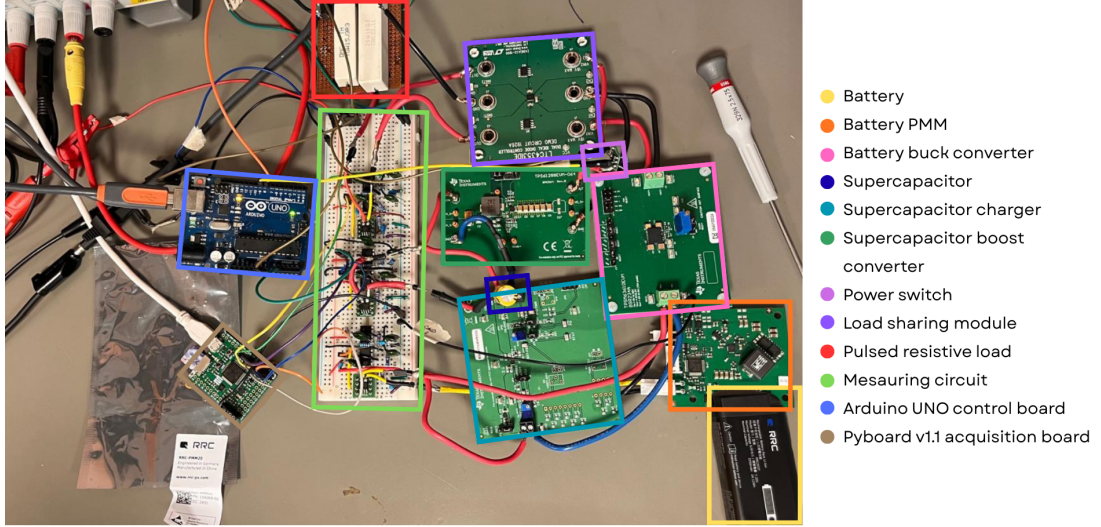


Figure 2.2: Initial modular HESS prototype used as the starting platform for the hardware analysis and optimization activities. The main power, control, acquisition, and load subsystems are highlighted.

The system was organized around two main energy-storage branches. The battery branch included the lithium-ion battery, the battery power-management module, and the buck converter used to generate the regulated load supply. The battery also provided the energy required by the supercapacitor charging path.

The supercapacitor branch included the storage element, the dedicated charging circuit, and the boost converter used to transfer energy to the load bus. This branch was intended to support the load during short-duration power transients.

The outputs of the battery and supercapacitor conversion stages were connected through a power switch and a load-sharing module. These elements were used to control the insertion of the supercapacitor branch and to coordinate the contribution of the two sources while limiting undesired reverse current flow.

A pulsed resistive load was included in the setup to reproduce controlled variations in power demand and to evaluate the transient response of the system under repeatable conditions.

The main electrical quantities were acquired through a dedicated measuring circuit and an external acquisition board. The initial control logic was implemented on an Arduino Uno, while the Pyboard v1.1 was used for data acquisition and communication with the monitoring software.

The modular structure of the setup allowed the behaviour of the individual

subsystems to be evaluated independently. At the same time, the use of separate evaluation boards, wiring connections, and external control and acquisition units introduced limitations in terms of compactness, repeatability, and system integration.

The modular prototype constituted the starting platform for the activities presented in this thesis. Its limitations motivated the component analyses, feedback-network dimensioning, and optimization activities described in the following chapter.

Chapter 3

HESS Hardware Analysis and Optimization

3.1 Introduction

Starting from the initial modular platform described in Chapter 2, a series of hardware-oriented analyses was carried out to support the evolution toward the integrated HESS prototype.

The complete circuit architecture and PCB layout were developed within the broader NerveRepack research activities. The contribution presented in this chapter concerns the analysis and comparison of alternative power-conversion and charging solutions, the evaluation of different supercapacitor configurations, and the dimensioning of the programmable regulation networks used for control.

3.2 Battery-Side Converter Analysis

The battery-side conversion stage is responsible for interfacing the lithium-ion battery with the regulated 6 V load bus. Since the battery voltage varies according to its state of charge, the converter must maintain stable output regulation while supporting the current required by the load under both steady-state and transient operating conditions.

Two candidate devices identified within the NerveRepack research activities were analysed for this function: the TPSM63610E from Texas Instruments and the MP8859 from Monolithic Power Systems. The comparison considered their electrical ratings, current capability, efficiency, integration complexity, thermal behaviour, and compatibility with the intended control architecture.

The TPSM63610E is a synchronous step-down power module integrating the

control circuitry, power MOSFETs, inductor, and compensation components. Its main advantage is the high output-current capability, which provides a wide operating margin with respect to the 3 A maximum current requirement of the system. The device also requires a limited number of external components and provides integrated thermal and overcurrent protection.

In the initial modular prototype, the converter output was configured at approximately 6 V by modifying the feedback network of the evaluation board. In particular, the fixed feedback resistor was replaced and a potentiometer was introduced to allow manual adjustment of the regulated output voltage.

Despite its robust power-delivery capability, the TPSM63610E does not provide a native digital interface for modifying its operating conditions. Any adjustment of the output voltage therefore requires intervention on the external feedback network. This characteristic limits its direct integration with a firmware-based energy-management strategy.

The MP8859 is a digitally programmable synchronous buck-boost converter. Although it can operate in both step-down and step-up conditions, it is used in the battery branch mainly in step-down operation, since the battery voltage is normally higher than the regulated 6 V bus voltage.

The device includes an I2C interface that allows the controller to configure and supervise several operating parameters through firmware. This capability provides greater flexibility during system integration and simplifies the coordination of the battery-side converter with the other controllable stages of the HESS.

The comparison highlighted a trade-off between current capability and digital programmability. The TPSM63610E provides a wider current margin and a simpler high-power implementation, whereas the MP8859 offers direct firmware configurability through its I2C interface.

The MP8859 was adopted in the final integrated prototype because its digital interface simplified the coordination of the battery-side conversion stage with the PMS. However, its lower current margin required careful consideration of the converter operating point, thermal behaviour, and transient loading conditions.

The main characteristics of the two devices are summarized in Table 3.1.

Table 3.1: Comparison of the battery-side converter candidates analysed for the HESS prototype.

Parameter	TPSM63610E	MP8859
Converter topology	Synchronous buck module	Synchronous buck-boost converter
Input-voltage range	3–36 V	2.8–22 V
Output-voltage adjustment	External feedback network	Digitally programmable
Maximum output current	Up to 8 A	Approximately 3 A, depending on the operating conditions
Peak-current capability	Up to 10 A	Dependent on operating and thermal conditions
Digital interface	Not available	I2C
Integrated protection	Thermal and overcurrent protection	Thermal and current-limit protection
Main advantage	High current capability and wide operating margin	Firmware programmability and system-level controllability
Main limitation	No direct digital control	Lower current margin
Prototype application	Initial modular prototype	Final integrated prototype

3.3 Boost Converter Analysis

The supercapacitor-side conversion stage interfaces the low-voltage storage element with the regulated 6 V load bus. During assist operation, the converter must transfer energy from the supercapacitor to the load while maintaining stable output regulation over the usable supercapacitor-voltage range.

The analysis focused on two converter solutions identified within the NerveRepack research activities: the MP8859 from Monolithic Power Systems and the TPS61288 from Texas Instruments. The comparison considered input-voltage range, current capability, efficiency, thermal behaviour, dynamic response, output-voltage controllability, and compatibility with the final hardware architecture.

The main characteristics considered in the analysis are summarized in Table 3.2.

The MP8859 provides a programmable synchronous buck-boost architecture

and a native I2C interface. These characteristics make it attractive from the point of view of firmware integration, since the output voltage and selected operating parameters can be configured directly through the controller. However, its current margin is more limited when the device operates in boost mode from the low-voltage supercapacitor source.

The TPS61288 is a synchronous boost converter designed for high-current conversion from low input voltages. It can operate from input voltages as low as 2.0 V and provides a high switch-current capability, making it more suitable for the short-duration power peaks expected on the supercapacitor branch.

Table 3.2: Comparison of the boost-converter candidates analysed for the supercapacitor branch.

Parameter	MP8859	TPS61288
Converter topology	Synchronous buck-boost converter	Synchronous boost converter
Input-voltage range	2.8–22 V	2.0–18.0 V
Output-voltage adjustment	Digitally programmable	External feedback network
Digital interface	Native I2C interface	External I2C-controlled potentiometer
Output-current capability	Up to 3 A	Higher current capability in boost operation
Current limit	3 A output current or 4 A input current	Up to 15 A switch current
Maximum efficiency	High, load-dependent	Up to 96.9%
Switching frequency	500 kHz	500 kHz
Integrated protection	Thermal and current-limit protection	Overcurrent, overvoltage, and thermal protection
Main advantage	Direct firmware programmability	High-current operation from low input voltage
Main limitation	Lower current margin in boost operation	Requires an external network for programmable output control
Prototype application	Analysed candidate	Final integrated prototype

The comparison highlighted a trade-off between direct digital programmability and high-current boost capability. The MP8859 provides a simpler interface with the firmware, whereas the TPS61288 offers a wider operating margin for the transient power demands expected on the supercapacitor branch.

The TPS61288 was therefore adopted in the final integrated prototype. Its output voltage was configured through an external feedback network and a digitally controlled potentiometer, preserving firmware-based adjustment through the I2C bus. The corresponding network dimensioning is described in Section 3.6.1.

3.4 Evaluation of Alternative Supercapacitors

The supercapacitor represents the auxiliary energy-storage element of the HESS and is required to supply short-duration high-power transients through the dedicated boost-converter branch.

Its selection was mainly driven by the following parameters:

- capacitance;
- rated voltage;
- equivalent series resistance;
- discharge-current capability;
- usable stored energy;
- compatibility with the available integration space;
- compatibility with the charging and boost-converter stages.

The initial modular prototype employed the Eaton TV1020-3R0605-R device, with a capacitance of 6 F and a rated voltage of 3.0 V. Although this component was suitable for preliminary validation of short assist events, additional devices were analysed to investigate possible improvements in terms of stored energy and transient-support duration.

Three commercial supercapacitors were considered:

Table 3.3: Supercapacitor devices considered for the HESS platform.

Device	Capacitance	Rated voltage	ESR
Eaton TV1020-3R0605-R	6 F	3.0 V	35.0 mΩ
Eaton TV1325-3R0156-R	15 F	3.0 V	24.0 mΩ
KYOCERA/AVX SCMU33F156SRBB0	15 F	5.5 V	90.0 mΩ

A first comparison was performed by estimating the usable energy within the voltage range compatible with the boost converter. Since the supercapacitor is connected to the load through the boost stage, the useful energy cannot be evaluated down to zero voltage, but only between the maximum charging voltage and the minimum input voltage required for correct converter operation.

The usable energy referred to the load side was estimated as:

$$E_{\text{out}} = \eta_{\text{boost}} \frac{1}{2} C \left(V_{\text{SC,max}}^2 - V_{\text{SC,min}}^2 \right) \quad (3.1)$$

where:

- C is the supercapacitor capacitance;
- $V_{\text{SC,max}}$ is the maximum charging voltage;
- $V_{\text{SC,min}}$ is the minimum voltage allowed by the boost converter;
- η_{boost} is the assumed boost-converter efficiency.

For the comparison, the minimum operating voltage was set to 2.0 V. The maximum charging voltage was set to 2.85 V for the 3.0 V devices and to 5.35 V for the 5.5 V device, preserving a safety margin below the rated voltage. A nominal boost-converter efficiency of 95% was assumed for the comparative estimate.

This estimate does not explicitly account for the voltage drop and dissipative losses associated with the supercapacitor ESR, which become increasingly relevant at high discharge currents.

The resulting usable-energy values are reported in Table 3.4.

Table 3.4: Estimated usable energy for the considered supercapacitors.

Device	C	$V_{SC,max}$	E_{out}
Eaton TV1020-3R0605-R	6 F	2.85 V	11.75 J
Eaton TV1325-3R0156-R	15 F	2.85 V	29.37 J
KYOCERA/AVX SCMU33F156SRBB0	15 F	5.35 V	175.44 J

The comparison shows that the Eaton 6 F device is suitable for the validation of short-duration assist events, while the 15 F alternatives provide a larger energy reserve and a longer theoretical support duration.

The Eaton TV1325-3R0156-R increases the available energy while preserving the same nominal voltage range and reducing the ESR with respect to the original 6 F device. This makes it a comparatively straightforward alternative from the point of view of system compatibility.

The KYOCERA/AVX SCMU33F156SRBB0 provides the highest estimated usable energy because of its higher rated voltage. However, its larger ESR, different charging-voltage requirement, and compatibility with the remaining power stages must also be considered before integration.

The analysed devices therefore represent alternative solutions with different trade-offs among stored energy, ESR, voltage range, charging requirements, and integration constraints.

To estimate the theoretical assist duration, the discharge time was computed under the conservative assumption that the supercapacitor supplies the entire load power:

$$t_{SC} = \frac{E_{out}}{P_{load}} \quad (3.2)$$

Three load-power levels were considered: 5.5 W, 13.5 W, and 18 W. The corresponding discharge times are summarized in Table 3.5.

Table 3.5: Estimated discharge time assuming that the supercapacitor supplies the entire load power.

Device	5.5 W	13.5 W	18 W
Eaton TV1020-3R0605-R	2.14 s	0.87 s	0.65 s
Eaton TV1325-3R0156-R	5.34 s	2.18 s	1.63 s
KYOCERA/AVX SCMU33F156SRBB0	31.90 s	13.00 s	9.75 s

The Eaton TV1020-3R0605-R remained suitable for the initial prototype and for the validation of short transient events. However, the analysis identified the Eaton 15 F and KYOCERA/AVX 15 F devices as possible alternatives for extending the assist duration.

The adoption of a different supercapacitor would require a corresponding adaptation of the charging subsystem, particularly in terms of maximum charging voltage and current regulation. The evaluation of the charging architecture is therefore discussed in the following section.

3.5 Supercapacitor Charger Analysis

The supercapacitor charging stage is responsible for restoring the energy extracted during assist operation. Since the charging current is supplied by the battery branch, the charger must provide controlled and safe recharge while limiting the additional load imposed on the battery and avoiding interference with the regulated load supply.

Two charger architectures identified within the NerveRepack research activities were analysed: the BQ25173 linear charger and the BQ24640 switching charger, both manufactured by Texas Instruments.

The comparison considered:

- input- and output-voltage compatibility;
- adjustable charging-current range;
- conversion efficiency;
- thermal behaviour;
- circuit and PCB complexity;
- compatibility with programmable current control;
- suitability for repeated supercapacitor recovery cycles.

The BQ25173 is a linear charger specifically intended for capacitive storage elements. Its output voltage is configured through an external feedback divider, while the charging current is set by the resistor connected to the ISET pin. The device supports charging currents from approximately 10 mA to 800 mA and requires a limited number of external components.

This solution was used in the initial modular prototype, where the evaluation board was configured for a maximum supercapacitor voltage of 2.85 V and a charging current of approximately 400 mA. These values provided a safety margin below the 3.0 V rated voltage of the original supercapacitor and represented a compromise between recharge time and current drawn from the battery.

The main limitation of the linear architecture is its conversion efficiency. The voltage difference between the battery supply and the supercapacitor is dissipated by the charger, resulting in increased thermal losses. This effect becomes particularly relevant during repeated recovery cycles or when higher charging currents are required.

The BQ24640 is a synchronous switching charger controller based on a buck-converter architecture. It supports a wider input- and output-voltage range and

significantly higher charging currents. Its switching operation reduces the power dissipated within the charging stage and improves efficiency.

The main characteristics of the two analysed devices are summarized in Table 3.6.

Table 3.6: Comparison of the supercapacitor charger solutions analysed for the HESS prototype.

Parameter	BQ25173	BQ24640
Charging architecture	Linear charger	Synchronous buck charger controller
Input-voltage range	3–18 V	5–28 V
Maximum output voltage	10.5 V	26 V
Maximum charging-current capability	0.8 A	Up to 10 A, depending on the external power stage
Implemented charging-current range	Approximately 400 mA in the initial prototype	Approximately 50–570 mA in the final prototype
Charging-current adjustment	External ISET resistor	External current-sense resistor and ISET network
Conversion efficiency	Limited by the linear voltage drop	Higher due to switching conversion
Thermal behaviour	Higher dissipation for large input-output voltage differences	Reduced dissipation at equivalent charging power
External component count	Reduced	Higher
PCB integration complexity	Low	Higher
Programmable current control	Possible through the ISET network	Possible through the ISET network
Suitability for repeated recovery cycles	Limited at high charging current	More suitable
Prototype application	Initial modular prototype	Final integrated prototype

The BQ25173 provided a compact and simple solution for the preliminary validation of the supercapacitor charging process at moderate current. However, its linear operating principle results in increased power dissipation when the voltage difference between the battery and the supercapacitor is large.

The BQ24640 was adopted in the final integrated prototype because its switching

architecture offers improved efficiency and thermal behaviour during repeated recovery cycles. Its charging-current regulation network was subsequently dimensioned to enable firmware-controlled adjustment through an I2C digital potentiometer, as described in Section 3.6.2.

3.6 Feedback-Network for Programmable Control

Following the definition of the final hardware architecture, the feedback and regulation networks associated with the supercapacitor boost converter and charger were dimensioned to enable firmware-controlled operation.

Since the TPS61288 and BQ24640 do not provide a native digital interface for the direct adjustment of their operating setpoints, external digital potentiometers were introduced into the corresponding regulation networks. These devices are controlled through the I2C bus and allow the controller to modify the boost-converter output voltage and the supercapacitor charging current during operation.

The resistive networks were designed to provide both a programmable operating mode and a fixed standalone configuration. Selectable jumpers allow the digital potentiometers to be bypassed when firmware-independent operation is required.

The digital potentiometer was modelled as an ideal variable resistance. The calculations therefore neglect the wiper resistance and the tolerance of the nominal end-to-end resistance, which may introduce small deviations between the theoretical and experimentally obtained voltage and current ranges.

3.6.1 Boost-Converter Feedback Network

The output voltage of the TPS61288 boost converter is defined by the feedback relation

$$V_{\text{BOOST}} = V_{\text{REF}} \left(1 + \frac{R_{\text{TOP}}}{R_{\text{BOT}}} \right), \quad (3.3)$$

where $V_{\text{REF}} = 0.6 \text{ V}$ is the internal feedback reference voltage, R_{TOP} is the resistance connected between the output and feedback nodes, and R_{BOT} is the equivalent resistance connected between the feedback node and ground.

In the implemented circuit, the upper feedback resistance was selected as

$$R_{\text{TOP}} = R_{38} = 270 \text{ k}\Omega. \quad (3.4)$$

Two alternative bottom-feedback networks were introduced through a selectable jumper.

In the fixed-output configuration,

$$R_{\text{BOT}} = R_{41} = 30 \text{ k}\Omega, \quad (3.5)$$

which results in

$$V_{\text{BOOST}} = 0.6 \left(1 + \frac{270}{30} \right) = 6.0 \text{ V}. \quad (3.6)$$

This configuration provides a fixed 6 V output independently of firmware control.

In the programmable configuration, the bottom resistance consists of a fixed resistor connected in series with a 5 k Ω digital potentiometer:

$$R_{\text{BOT}}(N) = R_{40} + R_{\text{DIG}}(N), \quad (3.7)$$

with

$$R_{40} = 27.4 \text{ k}\Omega \quad (3.8)$$

and

$$R_{\text{DIG}}(N) = 5 \text{ k}\Omega \frac{N}{1023}, \quad (3.9)$$

where N is the 10-bit digital code, ranging from 0 to 1023.

The programmable output voltage is therefore given by

$$V_{\text{BOOST}}(N) = 0.6 \left[1 + \frac{270 \text{ k}\Omega}{27.4 \text{ k}\Omega + 5 \text{ k}\Omega \frac{N}{1023}} \right]. \quad (3.10)$$

For $N = 0$,

$$R_{\text{BOT},\text{min}} = 27.4 \text{ k}\Omega, \quad (3.11)$$

and the maximum output voltage is

$$V_{\text{BOOST},\text{max}} = 0.6 \left(1 + \frac{270}{27.4} \right) \simeq 6.51 \text{ V}. \quad (3.12)$$

For $N = 1023$,

$$R_{\text{BOT},\text{max}} = 27.4 \text{ k}\Omega + 5 \text{ k}\Omega = 32.4 \text{ k}\Omega, \quad (3.13)$$

and the minimum output voltage is

$$V_{\text{BOOST},\text{min}} = 0.6 \left(1 + \frac{270}{32.4} \right) \simeq 5.60 \text{ V}. \quad (3.14)$$

The resulting programmable range is therefore approximately

$$5.6 \text{ V} \leq V_{\text{BOOST}} \leq 6.5 \text{ V}. \quad (3.15)$$

This interval enables the voltage difference between the supercapacitor and battery branches to be adjusted during operation. The boost voltage can be increased to promote the supercapacitor contribution during assist operation and progressively reduced during the transition back to battery-dominated operation.

3.6.2 Charging-Current Regulation Network

The BQ24640 charging current is determined by the voltage applied to the ISET pin according to

$$I_{\text{CHG}} = \frac{V_{\text{ISET}}}{20R_{\text{SR}}}, \quad (3.16)$$

where R_{SR} is the current-sense resistance.

In the implemented circuit,

$$R_{\text{SR}} = 100 \text{ m}\Omega. \quad (3.17)$$

The ISET voltage is generated by a resistive divider supplied by a 3.3 V reference:

$$V_{\text{ISET}} = V_{\text{CTRL}} \frac{R_{\text{BOT,eq}}}{R_{\text{TOP}} + R_{\text{BOT,eq}}}, \quad (3.18)$$

where

$$V_{\text{CTRL}} = 3.3 \text{ V}. \quad (3.19)$$

and

$$R_{\text{TOP}} = R_{21} = 10 \text{ k}\Omega. \quad (3.20)$$

The equivalent bottom resistance consists of a fixed resistor connected in series with a 5 k Ω digital potentiometer:

$$R_{\text{BOT,eq}}(N) = R_{28} + R_{\text{DIG}}(N), \quad (3.21)$$

with

$$R_{28} = 316 \text{ }\Omega \quad (3.22)$$

and

$$R_{\text{DIG}}(N) = 5 \text{ k}\Omega \frac{N}{1023}. \quad (3.23)$$

By combining Equations 3.16 and 3.18, the charging current becomes

$$I_{\text{CHG}}(N) = \frac{V_{\text{CTRL}}}{20R_{\text{SR}}} \frac{R_{28} + R_{\text{DIG}}(N)}{R_{21} + R_{28} + R_{\text{DIG}}(N)}. \quad (3.24)$$

For $N = 0$,

$$R_{\text{BOT,eq}} = 316 \, \Omega, \quad (3.25)$$

resulting in

$$V_{\text{ISET}} = 3.3 \frac{316}{10000 + 316} \simeq 0.101 \, \text{V} \quad (3.26)$$

and

$$I_{\text{CHG,min}} = \frac{0.101}{20 \cdot 0.1} \simeq 50.5 \, \text{mA}. \quad (3.27)$$

For $N = 1023$,

$$R_{\text{BOT,eq}} = 316 \, \Omega + 5 \, \text{k}\Omega = 5316 \, \Omega, \quad (3.28)$$

resulting in

$$V_{\text{ISET}} = 3.3 \frac{5316}{10000 + 5316} \simeq 1.145 \, \text{V} \quad (3.29)$$

and

$$I_{\text{CHG,max}} = \frac{1.145}{20 \cdot 0.1} \simeq 572 \, \text{mA}. \quad (3.30)$$

The resulting programmable charging-current range is therefore approximately

$$50 \, \text{mA} \leq I_{\text{CHG}} \leq 570 \, \text{mA}. \quad (3.31)$$

This range enables the charging current to be adapted according to the operating state of the system. A lower current can be used to reduce the additional demand imposed on the battery, whereas a higher value shortens the supercapacitor recovery time when sufficient power margin is available.

As for the boost stage, selectable jumpers were included to allow the programmable regulation network to be bypassed and replaced by fixed-resistance configurations during standalone hardware testing.

3.7 Final HESS Prototype

Following the definition of the final architecture within the NerveRepack research activities, the component-analysis and circuit-dimensioning work described in the previous sections supported the implementation of the integrated HESS prototype.

The final board integrates the main power-conversion, charging, switching, sensing, and communication circuits required for the operation of the battery-supercapacitor system. Compared with the initial modular prototype, the use of a single PCB reduces the number of external connections and provides a more compact and repeatable platform for control development and experimental validation.

The MP8859 converter supplies the regulated 6 V bus from the battery branch, while the TPS61288 transfers energy from the supercapacitor to the same load bus during assist operation. The BQ24640 restores the energy stored in the supercapacitor after the transient event, with a charging current that can be adjusted through the I2C-controlled regulation network described in Section 3.6.2.

The boost-converter feedback network also allows the output voltage of the supercapacitor branch to be modified through firmware. This feature was used during the subsequent control-development activities to regulate the contribution of the supercapacitor and to investigate different load-sharing and branch-transition strategies.

The main power branches are monitored through INA228 voltage and current sensors. These devices provide the measurements required to evaluate the battery, supercapacitor, and load electrical quantities and to implement the energy-management logic.

The external control platform is connected to the HESS board through the available I2C and GPIO interfaces. In the experimental implementation adopted in this work, the control and acquisition firmware was executed on an external ESP32-S3 development board. The ESP32-S3 is therefore not physically integrated into the HESS PCB.

The assembled board constituted the hardware platform used for the activities described in the following chapters. These included the implementation of the PMS, real-time monitoring of the main electrical quantities, subsystem verification, and experimental testing under pulsed resistive loads and robotic-hand operating conditions.

Figures 3.1 and 3.2 show the top- and bottom-side 3D renderings of the final HESS PCB.

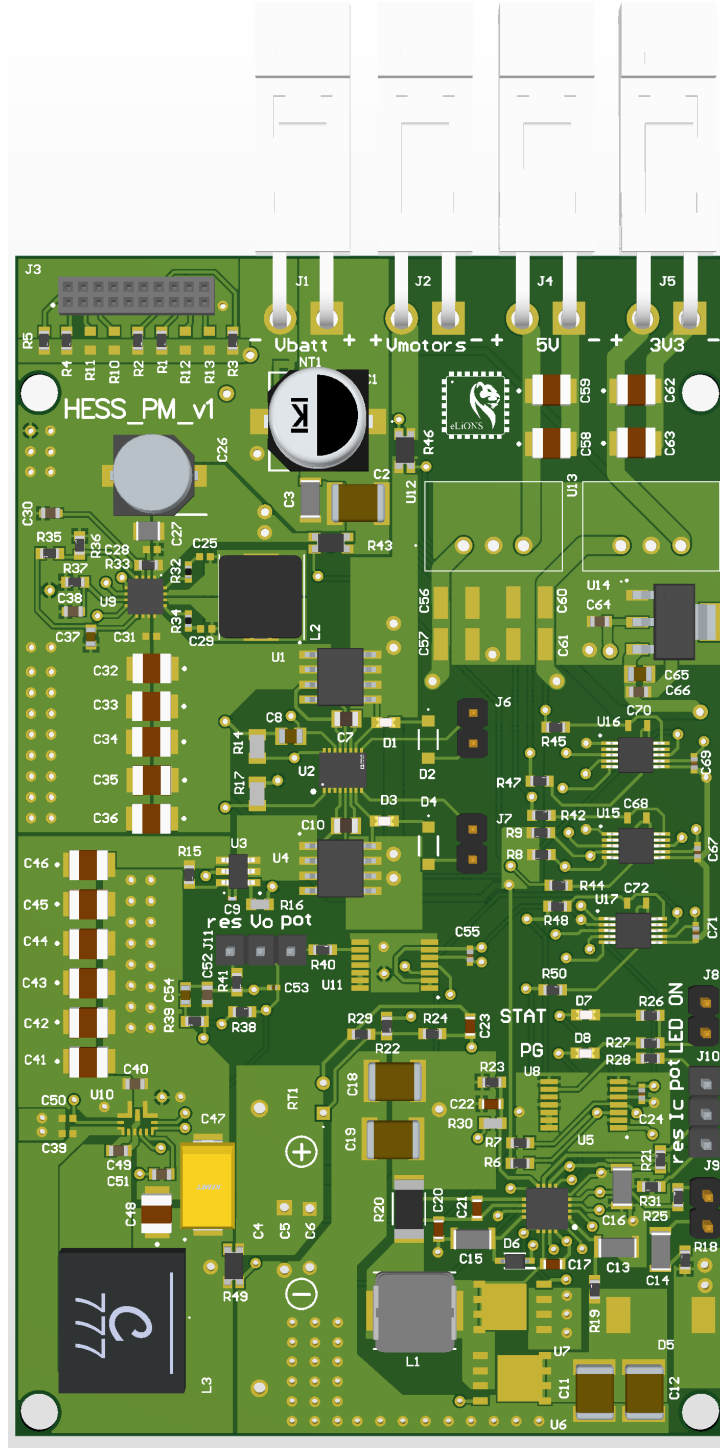


Figure 3.1: Top-side 3D rendering of the final HESS PCB.

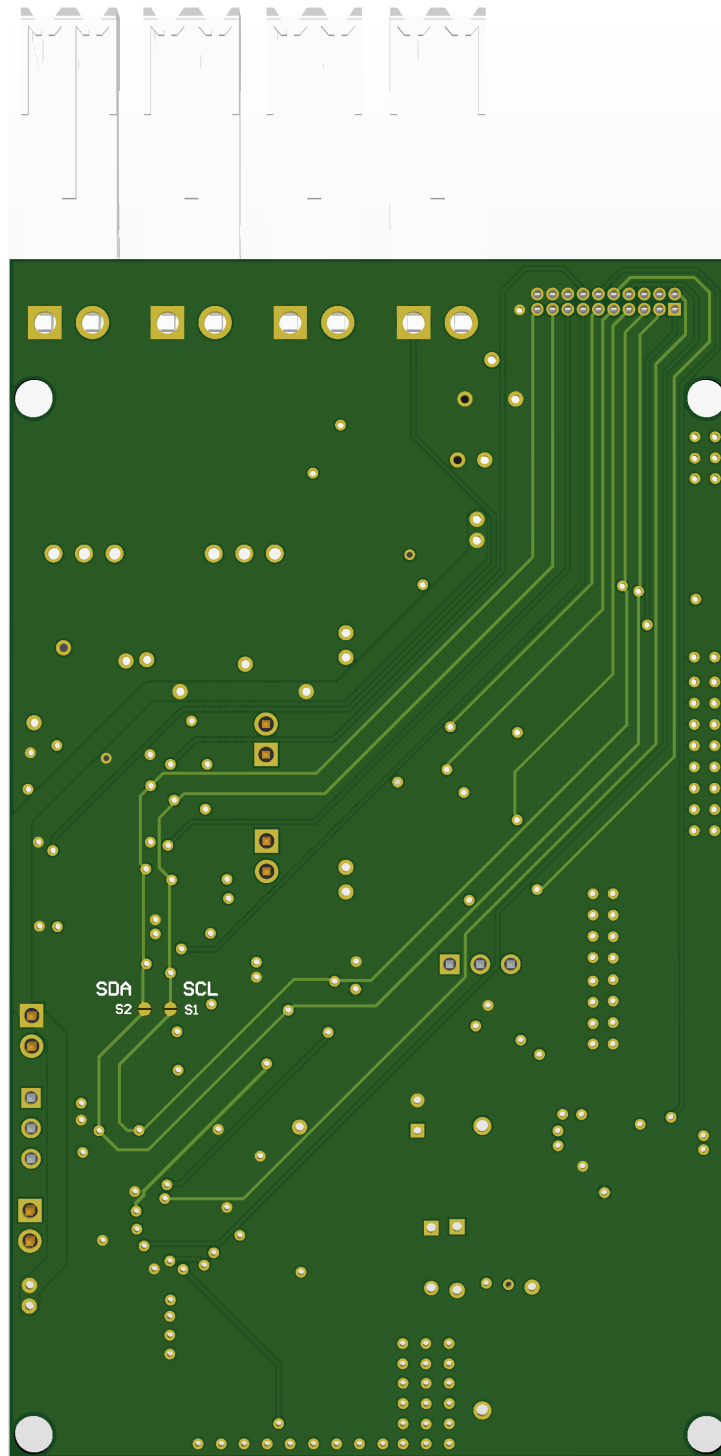


Figure 3.2: Bottom-side 3D rendering of the final HESS PCB.

Chapter 4

Energy Management and Control Strategy

4.1 Introduction

The HESS architecture presented in Chapter 3 provides the hardware platform required for the implementation of the proposed energy-management strategy. However, the overall performance of the system does not depend solely on the electrical characteristics of the individual components, but also on the capability of the controller to coordinate the power flows between the battery, the supercapacitor, and the robotic load.

The main objective of the Power Management System is to preserve the stability of the regulated 6 V load bus while reducing the electrical stress imposed on the battery during short-duration power peaks. To achieve this objective, the controller continuously monitors the relevant electrical quantities and dynamically coordinates the activation of the supercapacitor branch, the charging process, and the operating state of the power converters.

The control strategy is implemented through a finite-state-machine architecture. Each state corresponds to a specific operating condition of the HESS and defines the associated control actions, transition conditions, and protection constraints. Particular attention is given to the detection of high-power transients, the activation of the supercapacitor contribution, the controlled recovery of the storage element, and the prevention of unstable switching between operating modes.

This chapter first presents the embedded control and monitoring architecture. The finite-state-machine implementation is then described, followed by the transition conditions, control thresholds, and adaptive load-sharing strategy adopted during assist operation.

4.2 Embedded Control and Monitoring Architecture

4.2.1 Embedded Control Platform

The controller represents the supervisory unit of the HESS. Its main functions are to acquire the electrical measurements provided by the distributed sensing infrastructure, execute the PMS algorithms, coordinate the programmable power stages, and transmit diagnostic data to the external monitoring software.

The ESP32-S3 was selected as the experimental control platform used to implement and validate the proposed control strategy. Compared with conventional Arduino-based platforms, it provides higher computational performance, larger memory resources, multiple communication interfaces, and native USB connectivity.

These characteristics are particularly relevant in the proposed application, where measurement acquisition, finite-state-machine execution, converter configuration, and serial communication must be performed concurrently and with limited control latency.

Table 4.1 summarizes the main characteristics considered during the platform selection.

Table 4.1: Main characteristics of the Arduino Uno and ESP32-S3 platforms.

Feature	Arduino Uno	ESP32-S3
CPU frequency	16 MHz	Up to 240 MHz
Processor architecture	8-bit AVR	32-bit dual-core Xtensa LX7
RAM	2 kB	512 kB
Flash memory	32 kB	Board-dependent, up to 16 MB
Native USB	No	Yes
Communication interfaces	UART, SPI, I ² C	Multiple UART, SPI, and I ² C interfaces
Suitability for concurrent control and monitoring	Limited	High

The ESP32-S3 communicates with the INA228 power-monitoring devices and the programmable control components through the I²C bus. The same interface is used to acquire the electrical quantities required by the EMS and to update the operating setpoints of the programmable feedback networks.

Dedicated GPIO signals are instead used for time-critical control actions, including the activation of the boost converter, the connection of the supercapacitor

branch, and the enabling of the charging circuit. This separation allows converter configuration and measurement acquisition to be handled through the serial bus, while critical switching operations are executed through direct digital control lines.

Figure 4.1 illustrates the logical of the control workflow.

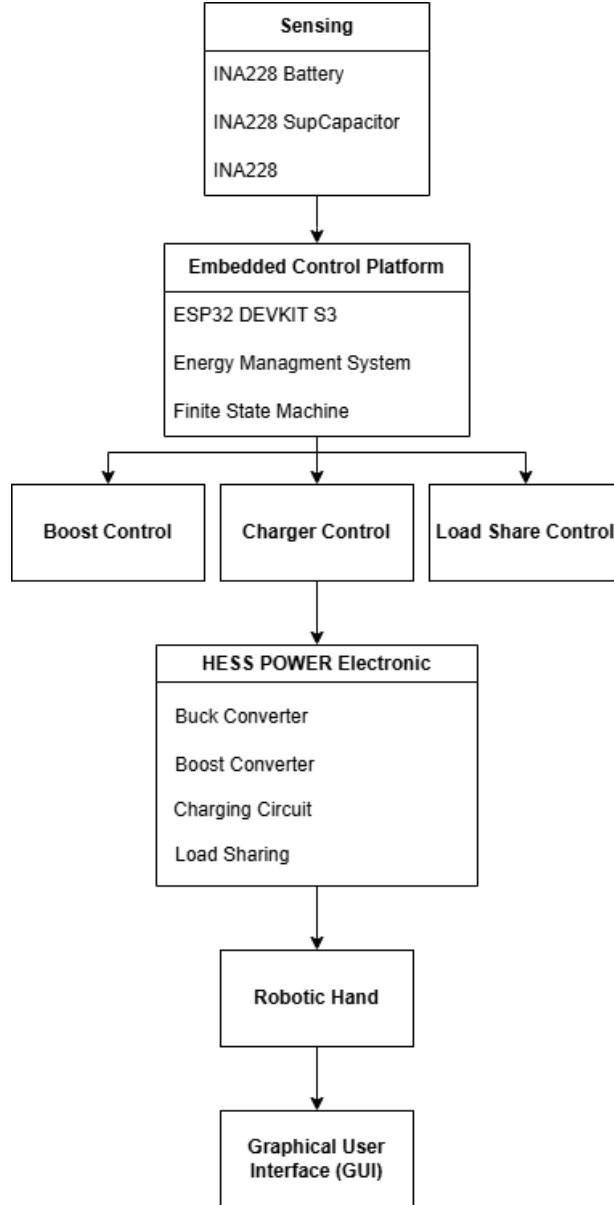


Figure 4.1: Logical of the control workflow implemented on the ESP32-S3.

The developed firmware performs the following main tasks:

- acquisition of battery-, supercapacitor-, and load-side measurements;

- execution of the finite-state-machine control logic;
- activation and deactivation of the power-conversion stages;
- update of the programmable boost-voltage and charging-current setpoints;
- supervision of operating limits and protection conditions;
- transmission of measurements and diagnostic information to the monitoring interface.

4.2.2 Real-Time Monitoring Infrastructure

The real-time monitoring infrastructure provides the electrical measurements required by both the PMS and the experimental validation activities. The architecture is based on three INA228 power monitors, respectively assigned to the battery branch, the supercapacitor branch, and the regulated load bus.

Each device measures the local bus voltage and the voltage drop across a dedicated current-sense resistor. The corresponding current and power values are then computed by the device and made available to the ESP32-S3 through the I²C interface.

The monitored quantities are:

- battery voltage, current, and power;
- supercapacitor voltage, current, and power;
- load-bus voltage, current, and power.

The sign convention adopted for the current measurements distinguishes the direction of the power flow. In the supercapacitor branch, positive current identifies discharge toward the load, whereas negative current identifies charging from the battery-side power path.

The acquired measurements are used by the controller for three main purposes:

- evaluation of the operating state of the HESS;
- detection of load transients and protection conditions;
- transmission of real-time diagnostic data to the external graphical interface.

The monitoring system also computes derived quantities used during system analysis, including the instantaneous load power, the power delivered by each storage element, the overall conversion efficiency, and the fraction of the load power supplied by the supercapacitor.

The supercapacitor contribution is evaluated as:

$$\text{SC}_{\text{share}} = \frac{P_{\text{SC}}}{P_{\text{LOAD}}} \times 100, \quad (4.1)$$

where P_{SC} is the power delivered by the supercapacitor branch and P_{LOAD} is the power absorbed by the regulated load bus. This definition is preferred to a ratio based on the total battery and supercapacitor input powers, since the battery branch also supplies the auxiliary 5 V and 3.3 V outputs.

Figure 4.2 summarizes the measurement and data-flow architecture.

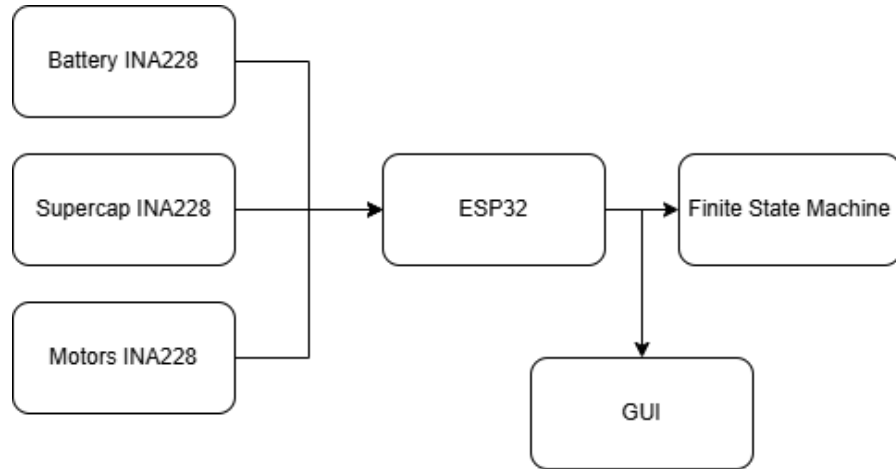


Figure 4.2: Real-time monitoring architecture based on three INA228 power monitors and the ESP32-S3 controller.

4.3 Finite State Machine Based PMS

The PMS of the HESS is implemented through a Finite State Machine. This approach was selected because it provides deterministic behavior, low computational complexity and direct compatibility with real-time embedded control on the ESP32-S3 platform.

The objective of the finite state machine is to coordinate the interaction between the battery branch, the supercapacitor branch, the boost converter and the charging subsystems according to the instantaneous operating condition of the robotic load. The controller continuously evaluates the electrical quantities acquired from the sensing infrastructure, including load power, power variation, supercapacitor voltage, battery voltage, external-power availability and fault conditions.

At each control cycle, the ESP32-S3 reads the monitored electrical variables, evaluates the current operating state and applies the corresponding control actions to the power-management hardware. In the switch-based configuration considered in this section, the main control outputs include the activation of the boost converter, the connection of the supercapacitor branch through the dedicated power switch, and the activation of the supercapacitor and battery charging functions.

The battery branch remains continuously available to the load-sharing stage. The PMS therefore directly controls only the insertion or removal of the supercapacitor branch, while the actual power contribution of the two sources depends on their relative output voltages and on the behavior of the ideal-diode controller.

The implemented state machine is composed of six main operating states:

- **INIT**: initialization state executed at system startup;
- **BATT**: normal battery-powered operation with the boost converter maintained in pre-assist condition;
- **ASSIST**: transient support using the supercapacitor branch;
- **RECOVERY**: controlled recharge of the supercapacitor;
- **PROTECT**: protection state used in case of unsafe operating conditions;
- **BATT_CHARGE**: dedicated smart-battery charging state.

The operating states together with their main entry and exit conditions and the control actions associated with each operating state are summarized in Table 4.2 and Table 4.3.

Table 4.2: Finite State Machine states and main transition conditions.

State	Name	Entry condition	Exit condition
S0	INIT	System startup or reset after fault clearance or battery-charge completion.	Transition to BATT after successful initialization and bus stabilization. Transition to BATT_CHARGE when battery charging is requested. Transition to PROTECT if a fault is detected.
S1	BATT	Default normal operating condition.	Transition to ASSIST after a valid assist request, to RECOVERY when supercapacitor recharge is required, to BATT_CHARGE when battery charging is requested, or to PROTECT after fault detection.
S2	ASSIST	High load power or rapid load-power variation with sufficient supercapacitor voltage.	Transition to BATT when the assist request ends or when the supercapacitor reaches its minimum operating voltage, to BATT_CHARGE when battery charging is requested, or to PROTECT after fault detection.
S3	RECOVERY	Supercapacitor voltage below the recovery threshold under admissible load conditions.	Transition to BATT when the target voltage is reached, to ASSIST after a valid assist request, to BATT_CHARGE when battery charging is requested, or to PROTECT after fault detection.
S4	PROTECT	Fault or unsafe operating condition detected.	Transition to INIT after fault clearance and reset.
S5	BATT_CHARGE	External power present and battery voltage below the charging activation threshold.	Transition to INIT when the battery reaches the charging deactivation threshold or when external power is removed. Transition to PROTECT if a fault is detected.

Table 4.3: Control actions associated with each FSM state in the switch-based configuration.

State	Boost	SC switch	SC charger	Batt. charger	Power flow
INIT	OFF	OFF	OFF	OFF	The controller initializes the sensing, communication, and power-management interfaces, while the battery branch remains available to the load.
BATT	ON	OFF	OFF	OFF	The battery supplies the load, while the boost converter remains active in pre-assist condition and the supercapacitor branch remains disconnected.
ASSIST	ON	ON	OFF	OFF	The supercapacitor branch is connected to the common bus. The resulting contribution of each source depends on the relative branch voltages and on the ideal-diode controller.
RECOVERY	OFF	OFF	ON	OFF	The battery supplies the load while the supercapacitor branch is disconnected and the supercapacitor is recharged.
PROTECT	OFF	OFF	OFF	OFF	The boost converter, supercapacitor switch and charging functions are disabled. The battery branch remains physically connected to the load-sharing stage.
BATT_CHARGE	OFF	OFF	OFF	ON	The battery-charging function is enabled, while the boost converter, supercapacitor switch and supercapacitor charger are disabled. The battery branch remains available to the load.

A simplified representation of the implemented control logic is reported in Figure 4.3. The diagram refers to the switch-based implementation and includes normal battery-powered operation, transient assistance, supercapacitor recovery, battery charging, protection conditions and the corresponding transition priorities.

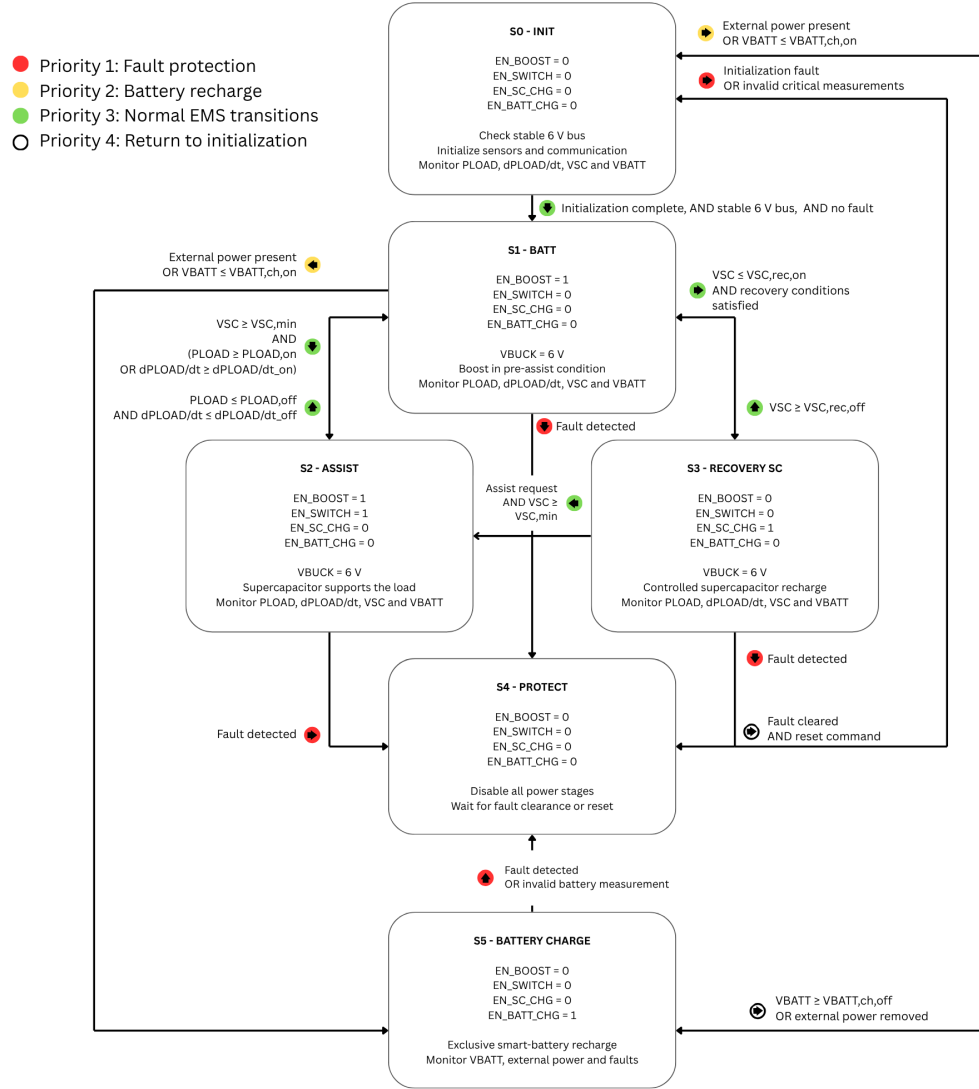


Figure 4.3: State-transition diagram of the switch-based PMS, including the transition-priority hierarchy.

The transition conditions are evaluated according to a predefined priority hierarchy. If multiple conditions are simultaneously satisfied, the transition with the highest priority is executed. Fault handling has the highest priority, followed by

battery charging, normal operating transitions and return-to-initialization transitions.

The adopted hierarchy is:

1. **Priority 1:** transition to PROTECT;
2. **Priority 2:** transition to BATT_CHARGE;
3. **Priority 3:** transitions among BATT, ASSIST, and RECOVERY;
4. **Priority 4:** return to INIT.

The system starts from the INIT state, where peripherals, communication interfaces and sensing devices are initialized. After the initialization phase, if no fault is detected and the power bus is stable, the controller enters the BATT state.

The BATT state represents the default operating condition of the HESS. In this state, the battery-powered buck converter supplies the load and remains the only source connected to the common bus. In order to reduce the response delay during transient events, the boost converter is maintained in a pre-assist operating condition. However, the supercapacitor does not contribute to the load because the dedicated switch located downstream of the boost converter remains open.

The controller continuously monitors the load power and its time derivative in order to detect rapid power variations generated by the robotic actuators. When an assist condition is detected, the supercapacitor branch can be connected to the load bus without waiting for the complete startup of the boost converter, improving the dynamic response of the HESS.

When a high-power transient or a rapid increase in load demand is detected and the supercapacitor voltage is above the minimum operating threshold, the controller enters the ASSIST state. In this condition, the boost converter remains enabled and the dedicated power switch connects the supercapacitor branch to the load-sharing stage.

Once both branches are available, the actual power distribution is not directly imposed by the controller. Instead, it depends on the relative output voltages of the buck and boost converters, the equivalent impedance of the two paths and the behavior of the ideal-diode controller. The source with the higher instantaneous output voltage tends to provide the dominant contribution to the load.

Once the transient event terminates, or when the load power returns below the selected threshold, the controller exits the ASSIST state and returns to BATT. From this state, if the supercapacitor voltage is below the recovery activation threshold and the load demand is sufficiently low, the controller subsequently enters RECOVERY.

In the RECOVERY state, the supercapacitor switch and boost converter are disabled, while the dedicated supercapacitor-charging subsystem is enabled. During this phase, the battery continues to supply the load through the buck converter and a controlled amount of energy is transferred to the supercapacitor. If a new transient load event is detected during recovery and the supercapacitor voltage is

sufficient, the charging process is interrupted and the controller gives priority to the **ASSIST** state.

The **PROTECT** state is entered whenever unsafe operating conditions are detected, such as converter faults, invalid critical measurements, or excessive voltage or current values. In this state, the controller disables the boost converter, the supercapacitor switch and both charging functions. However, because the battery branch is not equipped with a dedicated firmware-controlled disconnection element in the switch-based configuration, it remains physically available to the load-sharing stage.

An insufficient supercapacitor voltage does not represent a fault condition. In this case, assist activation is inhibited or terminated, and the system returns to battery-powered operation. Supercapacitor recovery is subsequently evaluated from the **BATT** state when the charging conditions are satisfied.

In the **BATT_CHARGE** state, the battery-charging function is enabled, while the boost converter, the supercapacitor switch and the supercapacitor charger are disabled. The state therefore prevents the simultaneous activation of the supercapacitor-related power paths during battery charging. Nevertheless, the battery branch remains connected to the load in the switch-based implementation.

The resulting finite state machine enables deterministic and robust control of the HESS. By assigning each operating condition to a specific state, the controller can clearly define which subsystems must be active and which transitions are allowed. This organization simplifies firmware development, improves system reliability and provides a clear framework for the experimental validation described in the following chapter.

Table 4.4 reports the low-level control signals associated with the switch-based implementation.

Table 4.4: Low-level control signals associated with each EMS state in the switch-based configuration.

State	EN_BOOST	EN_SWITCH	EN SC_CHG	EN BATT_CHG
INIT	OFF	OFF	OFF	OFF
BATT	ON	OFF	OFF	OFF
ASSIST	ON	ON	OFF	OFF
RECOVERY	OFF	OFF	ON	OFF
PROTECT	OFF	OFF	OFF	OFF
BATT_CHARGE	OFF	OFF	OFF	ON

The control signals reported in Table 4.4 represent the low-level hardware commands generated by the EMS. The `EN_BOOST` signal activates the boost converter associated with the supercapacitor branch, `EN_SWITCH` connects the boost-converter output to the load-sharing stage, `EN_SC_CHG` enables the supercapacitor-charging circuit, and `EN_BATT_CHG` enables the battery-charging function.

Implementation note. In the switch-based configuration, the dedicated power switch controls only the connection of the supercapacitor branch. The battery branch remains continuously available to the load-sharing stage and cannot be actively disconnected through the same firmware commands.

Therefore, the `PROTECT` and `BATT_CHARGE` states disable the controlled supercapacitor path and the charging subsystems, but they do not provide complete isolation of the battery from the load. A complete source-disconnection function would require an additional controllable element on the battery branch or the use of the enable-based load-sharing configuration investigated separately.

This organization separates the logical state of the EMS from the physical activation of the controllable power paths. As a result, each operating state is associated with a deterministic set of hardware actions, reducing the possibility of ambiguous configurations such as simultaneous charging and discharging of the supercapacitor branch.

4.3.1 Initialization State (INIT)

The `INIT` state represents the startup phase of the PMS and is executed immediately after power-up, after fault clearance, or following the completion or interruption of the battery-charging process.

The primary objective of this state is to ensure that all hardware peripherals, sensing devices, and communication interfaces are correctly initialized before normal operation begins. During this phase, the controller configures the communication buses, initializes the monitoring devices, and restores the operating parameters required by the power-management circuitry.

To guarantee a controlled startup sequence, the boost converter, the supercapacitor switch and both charging functions remain disabled during initialization. The battery branch remains physically available to the load-sharing stage. The controller also verifies the availability of valid battery, supercapacitor and load measurements and checks the stability of the regulated power bus.

During `INIT`, the controller evaluates the system conditions according to the predefined transition-priority hierarchy. If a fault or an invalid critical measurement is detected, the controller transitions immediately to `PROTECT`.

If no fault is present and an external power source is detected together with a valid battery-charging request, the controller enters the `BATT_CHARGE` state.

Otherwise, once the initialization sequence has been completed successfully and

the regulated bus has reached a stable operating condition, the PMS transitions to the **BATT** state.

The **INIT** state therefore acts as a controlled synchronization phase between startup, fault recovery, battery charging and normal HESS operation, ensuring that all hardware resources are correctly configured before the appropriate power-management state is activated.

4.3.2 Battery State (**BATT**)

The **BATT** state represents the default operating condition of the HESS and corresponds to the normal operating mode during most of the system lifetime.

In this state, the battery branch supplies the load through the programmable buck converter, which regulates the common bus voltage at the nominal value required by the robotic platform. Under steady-state conditions, the battery therefore supports the complete load demand, while the supercapacitor remains available as an auxiliary high-power source for future transient assistance events.

The boost converter is maintained in a pre-assist operating condition rather than being completely disabled. Its output is regulated to a predefined voltage so that the supercapacitor branch can be connected rapidly when an assist request is detected.

Although the boost converter remains enabled, the supercapacitor branch is disconnected from the load bus because the corresponding power switch remains open. As a result, the supercapacitor does not deliver power during normal battery operation, while the boost converter remains ready for rapid branch insertion.

During this state, the controller continuously monitors the electrical quantities acquired by the sensing infrastructure, including the load power, its rate of variation, the supercapacitor voltage, the battery voltage, and the availability of the external power source.

The controller evaluates the load power and its rate of variation to detect both sustained high-power demands and rapid actuator-generated transients.

The system remains in **BATT** while the load demand is within the normal operating range and no higher-priority transition condition is detected.

A transition to **ASSIST** occurs when a valid assist request is detected and the supercapacitor voltage is sufficient for safe operation. The corresponding activation conditions are described in Section 4.3.3.

A transition to **RECOVERY** occurs when the supercapacitor voltage falls below the recharge activation threshold and the load conditions are compatible with charging. This transition is permitted only when no valid assist request is present.

The **BATT** state also represents the mandatory intermediate state following the end of an assist event. Therefore, the controller always returns from **ASSIST** to **BATT** before evaluating a possible transition to **RECOVERY**.

Fault and battery-charging conditions are evaluated before the normal operating transitions. Consequently, a detected fault causes an immediate transition to **PROTECT**, while the presence of external power together with a valid battery-charging request causes a transition to **BATT_CHARGE**.

The **BATT** state therefore represents the nominal supervisory condition of the HESS. From this state, the controller coordinates transient supercapacitor assistance, subsequent energy recovery, exclusive battery charging, and fault handling.

4.3.3 Assist State (**ASSIST**)

The **ASSIST** state represents the core operating mode of the HESS. In this state, the supercapacitor branch actively contributes to the load demand, allowing the system to support high-power transient events while reducing the instantaneous current stress imposed on the battery.

The transition to the **ASSIST** state occurs when the measured load power exceeds the activation threshold or when a sufficiently rapid increase in load demand is detected:

$$P_{\text{LOAD}} \geq P_{\text{LOAD,on}} \quad \vee \quad \frac{dP_{\text{LOAD}}}{dt} \geq \left(\frac{dP_{\text{LOAD}}}{dt} \right)_{\text{on}}. \quad (4.2)$$

The transition is allowed only if the supercapacitor voltage remains above the minimum voltage required for safe operation:

$$V_{\text{SC}} \geq V_{\text{SC,min}}. \quad (4.3)$$

Since the boost converter is already maintained in a pre-assist condition during the **BATT** state, the activation of the assist mode does not require its complete startup. The controller enables the switch connecting the supercapacitor branch to the load-sharing stage, thereby reducing the delay between transient detection and supercapacitor contribution.

Once the supercapacitor branch is connected, both energy sources contribute to the load demand. The battery continues supplying power through the buck converter, while the supercapacitor injects additional power through the boost converter.

The approximate power balance during the assist phase can be expressed as

$$P_{\text{LOAD}} \approx P_{\text{BATT,out}} + P_{\text{SC,out}}, \quad (4.4)$$

where $P_{\text{BATT,out}}$ and $P_{\text{SC,out}}$ are the output powers delivered by the battery and supercapacitor branches to the common load bus, respectively.

This relation refers to the power delivered at the regulated load bus and does not include the auxiliary 5 V and 3.3 V outputs, which remain supplied by the battery branch.

A key advantage of this operating mode is the reduction of battery current peaks. A portion of the transient load demand is supplied by the supercapacitor, thereby reducing the instantaneous current stress imposed on the battery.

During the assist phase, the controller continuously monitors the load power, its rate of change, the battery and supercapacitor contributions, and the supercapacitor voltage. These measurements are used to supervise the power-sharing process and determine when the assist condition is no longer required.

The controller remains in **ASSIST** while the transient condition persists and sufficient supercapacitor energy is available. The normal assist-exit condition is evaluated using the corresponding deactivation thresholds:

$$P_{\text{LOAD}} \leq P_{\text{LOAD,off}} \quad \wedge \quad \frac{dP_{\text{LOAD}}}{dt} \leq \left(\frac{dP_{\text{LOAD}}}{dt} \right)_{\text{off}}. \quad (4.5)$$

The use of separate activation and deactivation thresholds introduces hysteresis and prevents repeated transitions between **BATT** and **ASSIST** when the measured load power fluctuates close to the decision boundary.

When the assist request ends, the controller always returns to the **BATT** state. The supercapacitor branch is disconnected and the battery resumes normal load supply.

If, once the system is in **BATT**, the supercapacitor voltage is below the recharge activation threshold and the load conditions permit charging, the controller subsequently transitions to the **RECOVERY** state.

If the supercapacitor voltage reaches the minimum safe operating limit during assist, its contribution is disabled and the controller returns to the **BATT** state. This condition does not independently represent a system fault. Supercapacitor recovery is evaluated only after the transition to **BATT**, when the load conditions are compatible with charging.

Fault and battery-charging conditions are evaluated before the normal assist transitions. Therefore, a transition to **PROTECT** or **BATT_CHARGE** overrides the normal exit logic of the **ASSIST** state.

The **ASSIST** state therefore enables the hybrid functionality of the energy-storage system by providing rapid transient support from the supercapacitor while maintaining coordinated operation with the battery branch.

4.3.4 Recovery State (**RECOVERY**)

The **RECOVERY** state is responsible for restoring the energy previously extracted from the supercapacitor during assist events. Its primary objective is to recharge

the supercapacitor and re-establish the energy reserve required for future transient power support.

The controller enters the **RECOVERY** state when the supercapacitor voltage falls below the recharge activation threshold and the load demand is sufficiently low to allow the charging process without compromising the operation of the robotic platform. Entry into this state is therefore permitted only when no valid assist request is present and no fault condition has been detected.

The transition to **RECOVERY** is enabled when

$$V_{SC} \leq V_{SC,rec,on} \quad (4.6)$$

and the load power remains below the recovery-enabling threshold.

During this state, the battery continues supplying the load through the buck converter, while the dedicated charging subsystem transfers energy from the battery branch to the supercapacitor. The supercapacitor boost converter and the load switch are disabled, while the supercapacitor charger is enabled.

The charging process is continuously supervised by the PMS through the measurement of the supercapacitor voltage. The controller monitors the charging progress and compares the measured voltage against the predefined recovery thresholds.

As the supercapacitor voltage increases, the stored energy increases according to

$$E_{SC} = \frac{1}{2}CV_{SC}^2, \quad (4.7)$$

where C is the supercapacitor capacitance and V_{SC} is the measured supercapacitor voltage.

The recovery process continues until the supercapacitor reaches the recovery completion threshold:

$$V_{SC} \geq V_{SC,rec,off}. \quad (4.8)$$

Once this condition is satisfied, the charging subsystem is disabled and the controller transitions back to the **BATT** state.

The controller continuously monitors the load demand also during the recovery phase. If a new valid assist request is detected while the supercapacitor is being recharged, the charging process is immediately interrupted and the controller transitions to the **ASSIST** state, provided that the supercapacitor voltage remains above the minimum threshold required for safe assist operation.

The recovery transition is evaluated only after fault and battery-charging conditions. Therefore, a transition to **PROTECT** or **BATT_CHARGE** overrides the normal supercapacitor-recovery logic.

The charging current is regulated according to the limits imposed by the charging circuitry and by the selected supercapacitor operating conditions. This ensures safe operation while avoiding excessive stress on both the battery and the supercapacitor.

The **RECOVERY** state therefore acts as an energy-restoration phase that prepares the HESS for subsequent assist events while maintaining continuous operation of the robotic platform. By replenishing the energy extracted during transient support, the controller ensures that the supercapacitor remains available as a high-power auxiliary energy source for future load peaks.

4.3.5 Protection State (PROTECT)

The **PROTECT** state represents the safety-oriented operating mode of the PMS. Its purpose is to prevent unsafe operation of the HESS whenever abnormal or potentially damaging conditions are detected.

The controller enters the **PROTECT** state when one or more monitored quantities exceed the predefined safety limits or when a critical fault is detected. These conditions may include excessive current, abnormal battery or load voltage levels, converter fault conditions, communication errors with the sensing infrastructure, invalid critical measurements, or other unsafe operating conditions identified by the embedded control system.

An insufficient supercapacitor voltage is not independently treated as a system fault. Instead, it inhibits the activation of the supercapacitor-assisted branch or causes the controller to terminate the assist phase and return to battery-powered operation. Supercapacitor recharge is subsequently evaluated from the **BATT** state when the load conditions permit it.

When the system enters the **PROTECT** state, the controlled power paths are disabled in order to avoid uncontrolled energy transfer between the battery, the supercapacitor, and the load bus. In particular, the boost converter, the supercapacitor switch, the supercapacitor-charging subsystem, and the battery-charging function are disabled.

The main control actions performed in the **PROTECT** state are:

- disable the boost converter;
- open the supercapacitor-assisted power path;
- disable the supercapacitor-charging subsystem;
- disable the battery-charging function;
- prevent further assist activation;

During this state, the controller continues monitoring the electrical quantities acquired from the sensing infrastructure in order to verify whether the fault condition has been cleared. The system does not automatically resume normal operation immediately after a temporary recovery of the monitored quantities.

A confirmed fault-clear condition and a reset command are required before leaving the **PROTECT** state. Once these conditions are satisfied, the controller transitions back to **INIT**. This ensures that the sensing infrastructure, communication interfaces, and power-management subsystems are correctly reinitialized before

normal operation resumes.

The transition to PROTECT has the highest priority within the finite state machine. Therefore, a detected fault overrides battery charging, assist activation, supercapacitor recovery, and all other normal operating transitions.

The PROTECT state therefore provides a safety layer for the HESS architecture. By forcing the system into a controlled configuration during abnormal conditions, it prevents uncontrolled power flow and reduces the risk of damage to the energy-storage devices, the power converters, and the robotic platform.

4.3.6 Battery-Charge State (BATT CHARGE)

The BATT_CHARGE state implements a dedicated smart-battery recharging mode. It is entered when an external power source is detected and the battery voltage falls below the charging activation threshold.

During this state, the supercapacitor boost converter, the dedicated power switch, and the supercapacitor charger are disabled, while the battery-charging function is enabled. In the switch-based implementation, the battery branch remains physically available to the load-sharing stage and is not actively isolated from the load.

The state-entry condition is:

$$P_{\text{ext}} = 1 \quad \wedge \quad V_{\text{batt}} \leq V_{\text{batt,ch,on}}, \quad (4.9)$$

where P_{ext} indicates the presence of the external power source.

The state is exited when the battery reaches the charging deactivation threshold,

$$V_{\text{batt}} \geq V_{\text{batt,ch,off}}, \quad (4.10)$$

or when the external power source is removed.

If a fault or an invalid critical battery measurement is detected during charging, the controller transitions to the PROTECT state. After normal completion or interruption of the recharge process, the system returns to INIT before restoring normal operation.

The BATT_CHARGE transition has higher priority than the normal operating transitions among BATT, ASSIST, and RECOVERY, but lower priority than fault handling.

4.4 Threshold Selection and Control Mechanisms

The behavior of the finite state machine is governed by a set of voltage, power and timing thresholds implemented within the embedded firmware. These parameters

define the conditions for assist activation, supercapacitor recovery, battery charging, low-energy protection, and safe state transitions.

The thresholds were selected considering both the electrical limits of the hardware and the experimental behavior observed during prototype testing. Particular attention was dedicated to avoiding undesired oscillations between states, ensuring rapid transient response and preventing excessive discharge of the supercapacitor.

4.4.1 Supercapacitor Voltage Thresholds

The supercapacitor voltage is one of the most important variables used by the control strategy, since it provides direct information about the available energy reserve and determines whether the auxiliary branch can safely support the load during transient events.

In the current prototype, the control thresholds were defined for the Eaton TV1020-3R0605-R supercapacitor, rated at 6 F and 3.0 V. The same voltage limits can also be applied to the Eaton TV1325-3R0156-R, rated at 15 F and 3.0 V, since both devices share the same nominal voltage range. According to the Eaton TV series datasheet, these devices have a maximum working voltage of 3.0 V and a surge voltage of 3.3 V. Therefore, the maximum recovery voltage used in the firmware was intentionally set below the nominal voltage rating in order to preserve a safety margin during charging.

The lowest safety threshold is the supercapacitor undervoltage limit, defined as $V_{SC,UV} = 2.00$ V. When the measured supercapacitor voltage falls below this value, the auxiliary energy source is considered no longer suitable for safe assist operation. This threshold is mainly related to the boost converter operating limits. The TPS61288 boost converter supports an input voltage range starting from 2.0 V, while its undervoltage lockout thresholds are located around the same low-voltage region. For this reason, operation close to 2.0 V is treated as the lower boundary of the usable supercapacitor voltage range. This prevents the boost converter from operating too close to its minimum input-voltage limit and avoids excessive supercapacitor discharge.

To prevent repeated transitions around the undervoltage boundary, an exit threshold is also defined as $V_{SC,UV,exit} = 2.25$ V. This hysteresis avoids rapid switching caused by small voltage rebounds associated with the equivalent series resistance of the supercapacitor.

The availability of the supercapacitor for assist operation is managed using a second hysteresis window. The supercapacitor is considered available for assist when its voltage is above $V_{SC,OK,on} = 2.50$ V, while assist availability is disabled when the voltage falls below $V_{SC,OK,off} = 2.15$ V.

The value of $V_{SC,OK,on} = 2.50$ V was selected to keep a margin above the boost converter startup and UVLO region, ensuring that the boost converter can operate

reliably when the assist branch is enabled. Conversely, $V_{SC,OK,off} = 2.15 \text{ V}$ allows part of the stored energy to be used during the transient event while still preventing operation too close to the absolute lower limit.

The recovery process is controlled by a dedicated voltage window. For the 3.0 V supercapacitor configuration, the controller requests supercapacitor recharge when the voltage falls below $V_{SC,rec,on} = 2.55 \text{ V}$ and terminates the recovery phase when the voltage reaches $V_{SC,rec,off} = 2.85 \text{ V}$.

The upper recovery threshold $V_{SC,rec,off} = 2.85 \text{ V}$ corresponds to the selected maximum charging voltage for the prototype supercapacitor. This value maintains a margin of approximately 150 mV below the nominal 3.0 V voltage rating of the Eaton device, reducing the risk of overvoltage during charging and measurement fluctuations. The lower threshold $V_{SC,rec,on} = 2.55 \text{ V}$ was selected to avoid unnecessary recharge activation caused by small voltage variations and to start recovery only after a meaningful amount of energy has been extracted.

The same control structure can be adapted to the alternative KYOCERA/AVX SCMU33F156SRBB0 supercapacitor module, rated at 15 F and 5.5 V. This device belongs to the 5.5 V SCM series and provides a significantly higher voltage rating than the Eaton 3.0 V devices. As a consequence, the upper recovery threshold can be increased while preserving the same design principle based on a safety margin below the rated voltage.

For the 5.5 V configuration, the maximum recovery threshold can be set to $V_{SC,rec,off} = 5.35 \text{ V}$. This value maintains approximately the same 150 mV safety margin used for the 3.0 V devices. The corresponding recovery entry threshold can be set to $V_{SC,rec,on} = 5.05 \text{ V}$, maintaining a 300 mV recovery hysteresis window equivalent to the one adopted in the current prototype.

The lower boost-related thresholds do not necessarily need to be increased when using the 5.5 V supercapacitor, because they are mainly imposed by the minimum input-voltage capability of the TPS61288 boost converter rather than by the rated voltage of the storage device. Therefore, $V_{SC,UV} = 2.00 \text{ V}$, $V_{SC,UV,exit} = 2.25 \text{ V}$, $V_{SC,OK,on} = 2.50 \text{ V}$ and $V_{SC,OK,off} = 2.15 \text{ V}$ can be maintained as absolute lower operating limits also for the 5.5 V configuration.

However, from a practical control perspective, the higher-voltage supercapacitor would normally operate well above these lower thresholds. This is advantageous because, for the same output power delivered to the load, a higher supercapacitor voltage reduces the input current required by the boost converter. As a result, the voltage drop caused by the equivalent series resistance is reduced, improving the dynamic behavior of the assist branch during high-power transient events.

Table 4.5 summarizes the voltage thresholds for both the current 3.0 V configuration and the possible 5.5 V configuration.

Table 4.5: Supercapacitor voltage thresholds for the 3.0 V and 5.5 V configurations.

Threshold	3.0 V SC	5.5 V SC
$V_{SC,UV}$	2.00 V	2.00 V
$V_{SC,UV,exit}$	2.25 V	2.25 V
$V_{SC,OK,on}$	2.50 V	2.50 V
$V_{SC,OK,off}$	2.15 V	2.15 V
$V_{SC,rec,on}$	2.55 V	5.05 V
$V_{SC,rec,off}$	2.85 V	5.35 V

The undervoltage and assist-availability thresholds are kept unchanged in the two configurations because they are mainly imposed by the minimum operating voltage of the boost converter. Conversely, the recovery thresholds are adapted to the rated voltage of the selected supercapacitor. For the 3.0 V Eaton devices, the recovery process is completed at 2.85 V, while for the 5.5 V KYOCERA/AVX module the recovery completion threshold can be increased to 5.35 V, preserving a safety margin below the rated voltage.

Overall, the selected thresholds are based on two different constraints. The lower thresholds are mainly determined by the minimum operating region of the TPS61288 boost converter, while the upper recovery thresholds are determined by the nominal voltage rating of the selected supercapacitor. This separation allows the same control logic to be reused with different supercapacitor configurations by modifying only the recovery voltage window.

4.4.2 Battery-Charging Thresholds

The transition to the `BATT_CHARGE` state is controlled through a voltage-hysteresis strategy applied to the smart-battery voltage.

Battery charging is requested when an external power source is available and the measured battery voltage falls below the activation threshold:

$$V_{\text{batt,ch,on}} = 7.50 \text{ V}. \quad (4.11)$$

The charging process is terminated when the battery voltage reaches the upper threshold:

$$V_{\text{batt,ch,off}} = 8.20 \text{ V}. \quad (4.12)$$

The difference between the two thresholds prevents repeated activation and deactivation of the battery charger due to small voltage fluctuations close to the decision boundary.

The corresponding transition conditions are:

$$P_{\text{ext}} = 1 \quad \wedge \quad V_{\text{batt}} \leq V_{\text{batt,ch,on}} \quad \Rightarrow \quad \text{BATT_CHARGE}, \quad (4.13)$$

and

$$V_{\text{batt}} \geq V_{\text{batt,ch,off}} \quad \vee \quad P_{\text{ext}} = 0 \quad \Rightarrow \quad \text{INIT}. \quad (4.14)$$

During battery charging, the PMM240 charging-current limit is configured to 500 mA, while the external input-current limit is set to 1 A.

Table 4.6: Battery-charging control parameters.

Parameter	Implemented value
Charging activation threshold	$V_{\text{batt,ch,on}} = 7.50 \text{ V}$
Charging deactivation threshold	$V_{\text{batt,ch,off}} = 8.20 \text{ V}$
Battery charging-current limit	500 mA
External input-current limit	1 A
External-power detection	PMM240 GPIO signal
Invalid battery measurement	Transition to PROTECT or charging inhibition

4.4.3 Load Power and Power-Derivative Thresholds

The transition from the **BATT** state to the **ASSIST** state is based on both the absolute load power and the rate of change of the load demand.

The load power is evaluated as $P_{\text{load}} = V_{\text{load}} \cdot I_{\text{load}}$. In addition, the controller estimates the power derivative, dP_{load}/dt , in order to detect rapid load variations generated by the robotic actuators.

The assist request is activated when the load power exceeds $P_{\text{load,on}} = 6.0 \text{ W}$ or when the power derivative exceeds $(dP/dt)_{\text{on}} = 13.0 \text{ W/s}$.

The first condition allows the controller to detect sustained high-power operation, while the second condition allows the system to react rapidly to impulsive load variations even before the absolute power reaches a high value.

To avoid chattering during state transitions, lower deactivation thresholds are used. The assist condition is released when the load power decreases below $P_{\text{load,off}} = 2.5 \text{ W}$ and the power derivative falls below $(dP/dt)_{\text{off}} = 7.0 \text{ W/s}$.

Table 4.7: Load-power and power-derivative thresholds used for assist activation and deactivation.

Threshold	Value
$P_{\text{load,on}}$	6.00 W
$P_{\text{load,off}}$	2.50 W
$\left(\frac{dP_{\text{load}}}{dt}\right)_{\text{on}}$	13.0 W/s
$\left(\frac{dP_{\text{load}}}{dt}\right)_{\text{off}}$	7.00 W/s

The use of different ON and OFF thresholds introduces hysteresis and prevents repeated transitions between **BATT** and **ASSIST** when the load power oscillates around the activation boundary.

4.4.4 Recovery Activation Logic

The supercapacitor recovery process is activated exclusively from the **BATT** state. This prevents the charging subsystem from being enabled while the supercapacitor is still connected to the load or while an assist event is active.

After an assist event, the controller first returns to **BATT**, disconnecting the supercapacitor branch from the load. Once normal battery-powered operation has been restored, the controller evaluates whether the supercapacitor requires recharge.

The transition from **BATT** to **RECOVERY** is enabled when the supercapacitor voltage falls below the recovery activation threshold:

$$V_{\text{SC}} \leq V_{\text{SC,rec,on}}, \quad (4.15)$$

provided that the load demand is compatible with the charging process and no valid assist request is present.

The recovery-enabling condition can therefore be expressed as

$$V_{\text{SC}} \leq V_{\text{SC,rec,on}} \quad \wedge \quad P_{\text{LOAD}} \leq P_{\text{REC,max}} \quad \wedge \quad \neg R_{\text{ASSIST}}, \quad (4.16)$$

where $P_{\text{REC,max}}$ is the maximum load power compatible with supercapacitor charging and R_{ASSIST} represents a valid assist request.

During **RECOVERY**, the controller continuously monitors the load demand. If a valid assist request is detected and the supercapacitor voltage is sufficient for safe operation, the charging process is interrupted and the controller transitions directly to **ASSIST**.

The recovery process is completed when

$$V_{SC} \geq V_{SC,rec,off}, \quad (4.17)$$

after which the supercapacitor charger is disabled and the controller returns to **BATT**.

The use of separate activation and deactivation thresholds introduces voltage hysteresis and prevents repeated transitions between **BATT** and **RECOVERY** when the supercapacitor voltage fluctuates close to the charging boundary.

Fault and battery-charging conditions are evaluated before the recovery logic. Consequently, a transition to **PROTECT** or **BATT_CHARGE** overrides the transition from **BATT** to **RECOVERY**.

4.4.5 Timing Thresholds and Anti-Chattering Mechanisms

In addition to voltage and power thresholds, the firmware implements timing constraints to improve the robustness of the PMS and prevent false state transitions caused by measurement noise, short disturbances, or rapid oscillations around the decision thresholds.

At startup, the system remains in the **INIT** state for a stabilization interval equal to

$$T_{INIT} = 800 \text{ ms}. \quad (4.18)$$

This interval allows the regulated power rails, sensing infrastructure, communication interfaces, and power-management peripherals to stabilize before normal operation begins.

During assist operation, a minimum residence time equal to

$$T_{ASSIST,min} = 300 \text{ ms} \quad (4.19)$$

is enforced. This prevents the controller from immediately leaving the **ASSIST** state because of short-term fluctuations in the measured load power and ensures that the supercapacitor branch remains active long enough to support the transient event.

The normal transition from **ASSIST** to **BATT** is therefore evaluated only after the minimum assist residence time has elapsed. However, fault conditions and battery-charging requests are evaluated according to the global transition-priority hierarchy and may override the normal residence-time constraint when required.

Similarly, the **RECOVERY** state includes a minimum residence time equal to

$$T_{RECOVERY,min} = 500 \text{ ms}. \quad (4.20)$$

This constraint avoids very short charging activations and repeated transitions between **BATT** and **RECOVERY** when the supercapacitor voltage or load power fluctuates close to the corresponding thresholds.

During recovery, the controller also monitors the effectiveness of the charging process. The supercapacitor voltage is expected to increase by at least

$$\Delta V_{SC,min} = 0.10 \text{ V} \quad (4.21)$$

within a monitoring interval equal to

$$T_{RECOVERY,timeout} = 10 \text{ s.} \quad (4.22)$$

If the expected voltage increase is not detected within this interval, the charging process is considered ineffective. The supercapacitor charger is disabled and the controller returns to the **BATT** state in order to preserve continuity of service.

An ineffective recovery process does not independently cause a transition to **PROTECT**. The protection state remains reserved for critical faults, invalid measurements, or unsafe operating conditions.

The use of timing constraints together with separate activation and deactivation thresholds provides both temporal and amplitude hysteresis. This combination improves the stability of the finite state machine and reduces unnecessary switching among the operating states.

Table 4.8 summarizes the timing parameters implemented in the control firmware.

Table 4.8: Timing thresholds implemented in the HESS control firmware.

Parameter	Value	Function
T_{INIT}	800 ms	Initial stabilization interval.
$T_{ASSIST,min}$	300 ms	Minimum residence time in the ASSIST state.
$T_{RECOVERY,min}$	500 ms	Minimum residence time in the RECOVERY state.
$T_{RECOVERY,timeout}$	10 s	Monitoring interval used to verify the effectiveness of supercapacitor charging.
$\Delta V_{SC,min}$	0.10 V	Minimum expected supercapacitor-voltage increase during recovery.

4.5 Load Sharing Control Strategy

The load-sharing strategy represents the control mechanism used during the **ASSIST** state to coordinate the interaction between the battery and supercapacitor branches.

Its main objective is to reduce the instantaneous current stress imposed on the battery during rapid load transients, rather than to enforce an exact and constant current split between the two energy sources.

In the HESS, the battery is connected to the common 6 V load bus through the buck converter, while the supercapacitor is connected through the boost converter, the controlled switching stage, and the LTC4353 ideal-diode power-path controller.

During normal operation, the battery supplies the load and the supercapacitor branch remains disconnected from the load bus. However, the boost converter is maintained in a pre-assist operating condition in order to reduce the response delay when an assist event is detected.

When the system enters the **ASSIST** state, the supercapacitor branch is connected to the common load bus. The original design objective was to obtain a simultaneous contribution from the battery and supercapacitor, with the battery supplying the base power demand and the supercapacitor providing the additional power required during transient actuator events.

The actual power distribution is not directly imposed by the controller. Instead, it depends on the relative output voltages of the buck and boost converters, the equivalent impedance of the two branches, the conduction characteristics of the external MOSFETs, and the behaviour of the LTC4353 ideal-diode controller.

When the two converter output voltages are closely matched, both branches may conduct simultaneously. However, experimental characterization showed that the simultaneous-conduction region is narrow and highly sensitive to small voltage differences.

If the boost-converter output voltage is slightly higher than the buck-converter voltage, the supercapacitor branch tends to become the dominant source. Conversely, if the boost-converter output voltage is slightly lower, its contribution decreases rapidly and the battery supplies most or all of the load demand.

The observed behaviour is therefore closer to a voltage-dependent source takeover than to a stable and accurately regulated current-sharing condition. Small variations caused by converter regulation accuracy, switching ripple, wiring resistance, connector losses, supercapacitor ESR, and instantaneous changes in the load can significantly modify the contribution of each branch.

For this reason, the implemented strategy must be interpreted as a voltage-guided power-distribution mechanism. The controller adjusts the output-voltage setpoint of the boost converter to influence the supercapacitor contribution, but it does not directly regulate the current supplied by each source.

The load-bus power balance during the assist phase can be approximated as

$$P_{6V} \approx P_{\text{BATT,load}} + P_{\text{SC,load}}, \quad (4.23)$$

where $P_{\text{BATT,load}}$ and $P_{\text{SC,load}}$ represent the powers delivered by the battery and supercapacitor branches to the main 6 V load bus.

The supercapacitor contribution is evaluated with respect to the power delivered to the main load bus. The corresponding supercapacitor share is defined as

$$SC_{\text{share}} = \frac{P_{\text{SC,load}}}{P_{6\text{V}}} \cdot 100. \quad (4.24)$$

This formulation excludes the auxiliary 5 V and 3.3 V loads, which are supplied only by the battery branch and therefore must not be included in the evaluation of the supercapacitor contribution to the main 6 V load.

The boost-converter voltage command can be updated using small voltage increments in order to avoid abrupt variations in the power flow. Conceptually, the dynamic command can be expressed as

$$V_{\text{boost,cmd}}(k+1) = V_{\text{boost,cmd}}(k) + \Delta V_{\text{boost}}, \quad (4.25)$$

where the sign and magnitude of ΔV_{boost} depend on the desired variation of the supercapacitor contribution.

In the implemented firmware, the boost-converter output voltage is constrained within a limited operating window. These limits prevent excessive voltage commands and reduce the risk of forcing the supercapacitor branch into an uncontrolled dominant-source condition.

Nevertheless, the experimental results showed that maintaining a stable intermediate sharing ratio through voltage adjustment alone is difficult. Because the simultaneous-conduction region of the LTC4353 is narrow, even small disturbances can move the operating point toward battery-dominant or supercapacitor-dominant operation.

Therefore, the control action is not intended to guarantee a precise sharing percentage. Its purpose is instead to activate the supercapacitor branch during high-power transients and reduce the corresponding battery current peak.

Although the observed source-takeover behaviour differs from the original objective of stable load sharing, it remains compatible with the primary function of the HESS. When the supercapacitor branch becomes dominant during a rapid transient, it supplies a substantial portion of the instantaneous load demand and consequently reduces the electrical stress imposed on the battery.

The experimental limitations of the LTC4353-based power path and the resulting source-takeover behaviour are analysed in detail in Chapter 5.

4.5.1 Conceptual Load Sharing Behaviour

Figure 4.4 conceptually illustrates the desired evolution of the load power and of the contributions provided by the battery and supercapacitor branches during assist operation. Before the assist event, the battery supplies the full load demand. When the assist condition is detected, the supercapacitor contribution increases

and part of the load demand is transferred from the battery to the auxiliary branch. As a result, the battery power decreases during the transient interval, while the supercapacitor supports the load.

At the end of the assist interval, the auxiliary contribution is not removed instantaneously. Instead, it is progressively reduced so that the battery can smoothly recover the load demand. This behavior reflects the intended operation of the implemented control logic and the role of the load sharing strategy in reducing battery stress during short-duration power peaks.

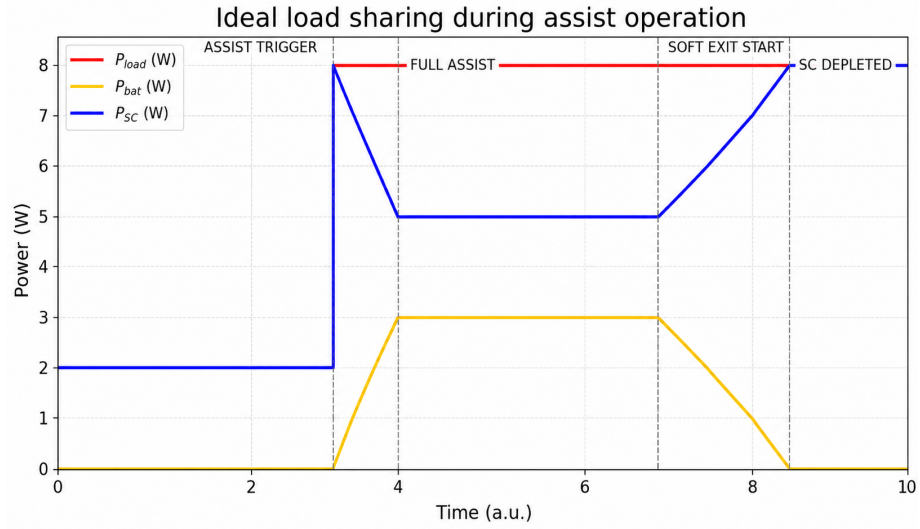


Figure 4.4: Ideal evolution of the load power and of the battery and supercapacitor contributions during assist operation.

Figure 4.4 highlights the main objective of the strategy: the supercapacitor is not intended to replace the battery, but to temporarily support it during transient events. In this way, the battery remains the main energy source of the system, while the supercapacitor provides high-power assistance only when required by the load dynamics.

4.5.2 Conceptual Evolution of the Boost Command

The boost converter command also plays a central role in the load sharing strategy. During battery-only operation, the boost converter is not fully disabled, but maintained in a pre-enabled standby condition. This allows the system to react rapidly to assist requests, without the delay associated with converter startup and output-voltage stabilization.

During assist operation, the boost command is increased in order to promote

a higher contribution from the supercapacitor branch. At the end of the assist interval, the auxiliary contribution is progressively reduced before the controller returns to the **BATT** state, allowing the battery branch to recover the load demand more smoothly.

Figure 4.5 conceptually illustrates the desired evolution of the boost converter command during the different phases of operation. The plot shows the standby condition during **BATT**, the increase of the command during **ASSIST**, and the gradual reduction preceding the transition from **ASSIST** to **BATT**.

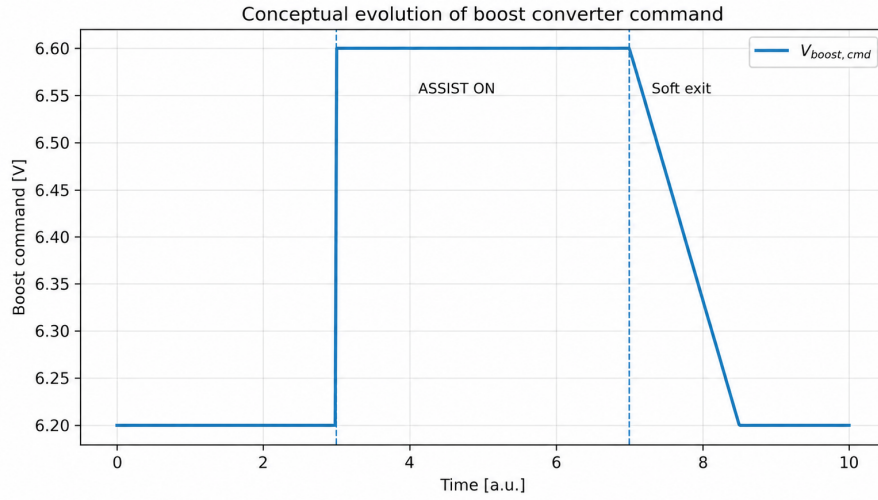


Figure 4.5: Conceptual evolution of the boost converter command during standby, assist operation and soft exit.

This conceptual behavior is consistent with the implemented control philosophy. The boost converter is used not only as a power-conversion stage, but also as an actuator through which the controller can indirectly regulate the power contribution of the supercapacitor branch.

4.5.3 Soft Exit from Assist Operation

A dedicated soft-exit mechanism was implemented to improve the transition from the **ASSIST** state back to the **BATT** state. Without this mechanism, the supercapacitor branch would be disconnected abruptly as soon as the assist condition is no longer detected. This could cause a sudden transfer of the load demand back to the battery branch, producing current peaks and reducing the effectiveness of the hybrid support strategy.

For this reason, the controller does not immediately disable the supercapacitor-assisted path when the assist-exit condition is satisfied. Instead, the boost-converter setpoint is progressively reduced before opening the supercapacitor switch. This gradual reduction decreases the contribution of the supercapacitor and allows the battery branch to recover the load demand more smoothly.

During the soft-exit phase, the boost-voltage command is decreased step by step within the allowed operating window. As the boost setpoint is reduced, the voltage difference between the supercapacitor and battery branches decreases, progressively reducing the current supplied by the supercapacitor through the ideal-diode power-path stage.

The soft-exit mechanism can be summarized as follows:

- the controller detects the end of the assist request;
- the supercapacitor switch remains temporarily closed;
- the boost-voltage setpoint is gradually reduced;
- the supercapacitor contribution decreases progressively;
- once the boost command reaches the predefined pre-assist value, the supercapacitor switch is opened;
- the controller transitions to the **BATT** state.

After the transition to **BATT**, the controller evaluates whether the supercapacitor requires recharge. If its voltage is below the recovery activation threshold and the load conditions are compatible with charging, a subsequent transition from **BATT** to **RECOVERY** is performed.

The soft-exit mechanism therefore does not define an independent finite-state-machine state and does not introduce a direct transition from **ASSIST** to **RECOVERY**. It represents an internal exit procedure executed before the transition from **ASSIST** to **BATT**.

This strategy reduces abrupt power-flow variations and limits the instantaneous current transferred back to the battery. It also complements the hysteresis implemented in the assist thresholds: the hysteresis determines when the assist state can be exited, while the soft-exit procedure determines how the supercapacitor contribution is progressively removed from the load bus.

Chapter 5

Experimental Tests and Validation

The experimental validation of the HESS was carried out through a progressive testing approach aimed at verifying both the correct operation of the developed hardware platform and the effectiveness of the implemented PMS. The validation activity was organized in successive steps, starting from the verification of the individual PCB subsystems and gradually moving toward full-system tests under dynamic load conditions.

First, preliminary tests were performed to validate the main hardware blocks of the PCB, including the voltage rails, sensing infrastructure, communication interfaces, supercapacitor charging circuit and DC-DC conversion stages. Then, the complete HESS was tested under controlled pulsed-load conditions in order to evaluate the finite-state machine behaviour, the activation of the supercapacitor assistance and the recovery phases in a repeatable way.

The validation was subsequently extended to the robotic hand, where the system was tested under realistic electromechanical operating conditions characterized by transient current peaks and variable power demand. Finally, the firmware was expanded to include smart-battery monitoring and charge management through SMBus communication.

Overall, the chapter presents the experimental setup, the measured quantities used for data analysis, the preliminary PCB and subsystem validation, the EMS tests under pulsed-load and robotic-hand operation, the experimental refinement of the switch-based power-path strategy, and the final integration and validation of the smart-battery charging logic.

5.1 Validation Strategy and Experimental Setup

The experimental setup was designed to validate the HESS under operating conditions representative of the target exoprosthesis application. The objective of the setup was to reproduce the electrical behaviour of the complete power chain, from the battery-side supply to the final electromechanical load, while allowing real-time monitoring of the main electrical quantities involved in the energy management process.

The validation bench integrates the developed HESS prototype, the ESP32-S3 development board used for embedded control and data acquisition, the battery and driver subsystem, and the robotic hand used as final electromechanical load. In addition, controlled resistive and pulsed-load configurations were adopted during the intermediate validation phases in order to test the system under repeatable and progressively more demanding operating conditions.

The experimental results presented in this chapter mainly refer to the switch-based configuration. In this implementation, the battery branch remains continuously available to the load-sharing stage, while the supercapacitor branch is connected or disconnected through the dedicated power switch located downstream of the boost converter.

Figure 5.1 shows the complete experimental setup adopted during the validation activity.

The battery and driver subsystem provides the main electrical supply to the platform and interfaces the actuation electronics of the robotic hand. The HESS board implements the hybrid battery-supercapacitor power architecture, including the battery-side conversion stage, the supercapacitor branch, the boost converter, the switching stage, the auxiliary DC-DC converters and the distributed sensing infrastructure. The ESP32-S3 development board executes the embedded control logic, manages the communication with the sensing devices and transmits the acquired measurements to the monitoring interface. Finally, the robotic hand represents the final load and allows the system to be evaluated under realistic actuation profiles characterized by transient current peaks, non-uniform load profiles and rapid variations in the requested power.

The main elements of the experimental validation setup are summarized in Table 5.1.

The experimental validation was carried out through a progressive sequence of tests aimed at assessing the behaviour of the HESS at increasing levels of complexity. The procedure was not limited to a single operating condition, but was structured as an iterative process in which the experimental observations were used to refine both the firmware implementation and the energy management strategy.

In the first phase, the individual hardware subsystems of the PCB were verified. The main voltage rails were measured under no-load conditions, the sensing module

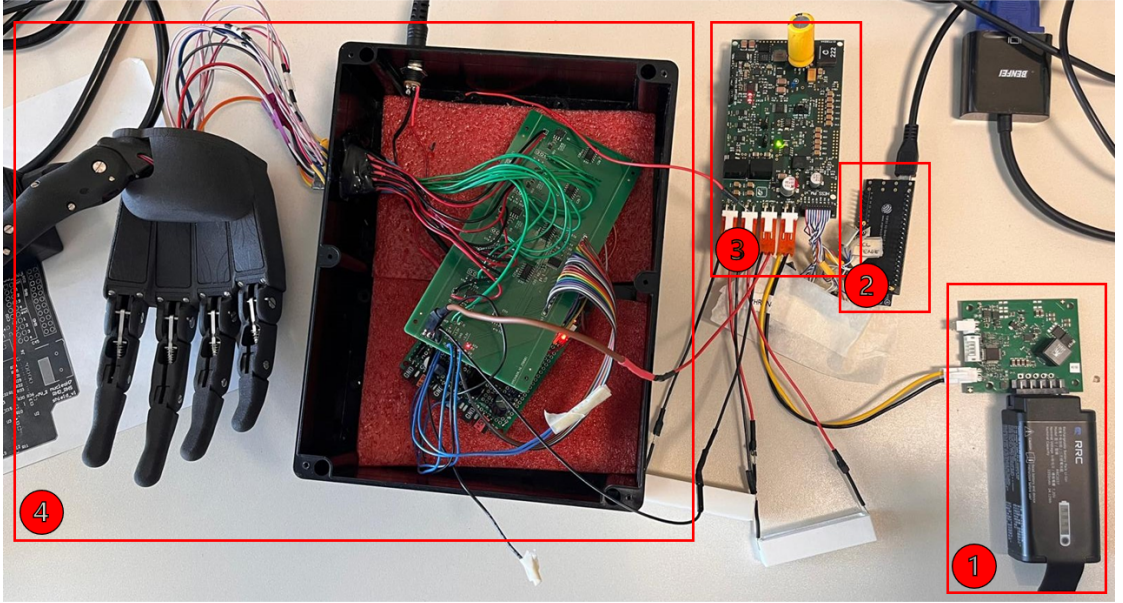


Figure 5.1: Experimental setup used for the validation of the HESS prototype: (1) battery and driver subsystem, (2) ESP32-S3 development board, (3) HESS board, and (4) robotic hand used as electromechanical load.

Table 5.1: Main elements of the experimental validation setup.

Label	Element	Function
1	Battery and driver sub-system	Provides the main supply and interfaces the robotic hand actuation electronics.
2	ESP32-S3 development board	Executes the embedded control logic, manages data acquisition and communicates with the monitoring interface.
3	HESS board	Implements the hybrid battery-supercapacitor power architecture, the power conversion stages and the sensing infrastructure.
4	Robotic hand load	Represents the final electromechanical load used to validate the system under realistic actuation profiles.

was validated using a known external resistive load, and the I2C communication between the controller and the sensing devices was tested. The effective sampling frequency of the acquired data was also evaluated in order to verify the capability of the monitoring system to capture fast variations in the load profile. The supercapacitor charging circuit was then tested by controlling the digital potentiometer through the firmware, while the buck converter, boost converter and auxiliary DC-DC converters were experimentally checked under representative operating conditions.

After the preliminary PCB validation, the complete HESS was tested under controlled pulsed-load conditions. This configuration was selected because it provides a repeatable and challenging load profile for the energy management algorithm. In particular, it allowed the finite-state-machine transitions, the activation of the supercapacitor-assisted branch, the return to battery-powered operation, and the subsequent recovery phase to be evaluated before testing the system with the robotic hand.

The validation activity was then extended to the robotic hand. In this phase, the system was tested under realistic motor-driven operating conditions, where the load demand is characterized by transient current peaks, non-uniform power profiles, and rapid variations caused by actuator activation. The control thresholds were adapted on the basis of the experimental load characterization of the robotic hand, while the interaction between the battery branch, the switch-controlled supercapacitor branch, and the LTC4353-based power-path stage was evaluated during actual hand actuation.

During the experiments, the HESS prototype generated the regulated load bus used to supply the external load. The battery branch acted as the primary energy source, while the supercapacitor branch was connected during assist operation through the dedicated power switch. Once connected, the actual contribution of the two sources depended on their relative output voltages and on the behavior of the ideal-diode power-path controller.

After each assist event, the controller first returned to the **BATT** state. If the supercapacitor voltage was below the recovery threshold and the load conditions were compatible with charging, the controller subsequently entered the **RECOVERY** state.

During each test, the main electrical quantities were acquired in real time through the distributed sensing system implemented on the HESS board. The monitored variables included the battery-side voltage and current, the load-side voltage and current, the supercapacitor voltage, the supercapacitor current, the boost converter operating condition and the control states generated by the finite-state machine. The auxiliary 5 V and 3.3 V output powers were not acquired through the onboard sensing infrastructure. They were measured separately using external instrumentation and subsequently treated as constant values in the offline

power-balance and efficiency calculations. These measurements were transmitted to the graphical monitoring interface, where they were visualized and subsequently saved for offline analysis.

Particular attention was paid to the transient response of the system. Since the target application involves robotic prosthetic actuation, the most critical operating conditions are not represented by steady-state loads, but by rapid variations in load power caused by motor activation. Therefore, the validation focused on the ability of the EMS to detect transient events, connect the supercapacitor branch, maintain the regulated load bus, avoid unnecessary recharge cycles, and return deterministically to battery-powered operation once the transient demand had ended.

As a final step, the firmware was extended to integrate the monitoring and control of the smart battery charging process through SMBus communication. This allowed the battery charging behaviour to be monitored directly by the controller and represents an additional step toward the integration of the HESS architecture into the final prosthetic system.

Overall, the adopted setup enabled the evaluation of the HESS behaviour in different operating conditions, including subsystem-level operation, controlled pulsed-load operation, battery-only supply, supercapacitor-assisted operation, post-transient recovery and final robotic hand actuation. This progressive validation strategy made it possible to assess not only the electrical performance of the hardware platform, but also the effectiveness and robustness of the implemented energy management strategy.

5.2 Measured Quantities and Data Processing

During the experimental tests, the main electrical quantities of the HESS were acquired through the INA228 sensing devices integrated on the board. The monitored variables included the battery voltage and current, the supercapacitor voltage and current, and the load-bus voltage and current.

The corresponding instantaneous powers were calculated as

$$P_{\text{LOAD}} = V_{\text{LOAD}} I_{\text{LOAD}}, \quad (5.1)$$

$$P_{\text{BATT}} = V_{\text{BATT}} I_{\text{BATT}}, \quad (5.2)$$

and

$$P_{\text{SC}} = V_{\text{SC}} I_{\text{SC}}, \quad (5.3)$$

where P_{LOAD} is the power delivered to the main 6 V load bus, P_{BATT} is the power measured on the battery branch, and P_{SC} is the power measured on the supercapacitor branch.

The supercapacitor contribution was evaluated with respect to the main 6 V load power according to

$$SC_{\text{share}} = \frac{P_{\text{SC}}}{P_{\text{LOAD}}} \cdot 100. \quad (5.4)$$

This definition was adopted because the supercapacitor branch contributes only to the main 6 V load bus, while the auxiliary outputs remain supplied by the battery branch.

The auxiliary 5 V and 3.3 V output powers were not acquired through the onboard sensing infrastructure. They were measured separately using external instrumentation and subsequently treated as constant values in the offline power-balance and efficiency calculations.

The total useful output power was therefore calculated as

$$P_{\text{OUT,tot}} = P_{\text{LOAD}} + P_{5\text{V}} + P_{3.3\text{V}}, \quad (5.5)$$

where $P_{5\text{V}}$ and $P_{3.3\text{V}}$ are the externally measured constant powers associated with the auxiliary outputs.

The system efficiency was evaluated as

$$\eta_{\text{SYS}} = \frac{P_{\text{OUT,tot}}}{P_{\text{BATT}} + P_{\text{SC}}} \cdot 100. \quad (5.6)$$

During battery-dominated operation, P_{SC} is approximately zero and the denominator is mainly determined by the battery contribution. During assist operation, both the battery and supercapacitor powers are included in the total input power.

In addition to the electrical quantities, the digital variables associated with the PMS were recorded. These included the active finite-state-machine state, the boost-converter command, the supercapacitor-switch command, the supercapacitor-charger command, the battery-charging request, and the external-power status.

The combined analysis of the electrical measurements and control variables made it possible to verify whether the state transitions and power-path commands were consistent with the actual operating conditions of the load.

The acquired data were stored in CSV format and subsequently processed offline. For the characterization of the robotic hand, multiple acquisitions performed under the same operating condition were temporally aligned and superimposed. This procedure was used to assess the repeatability of the load profiles and the dispersion among consecutive tests.

5.2.1 Graphical User Interface for Real-Time Monitoring

A dedicated graphical user interface was developed to support the real-time monitoring and experimental validation of the HESS. The interface receives the data transmitted by the ESP32-S3 through the serial communication link and provides an immediate graphical representation of the main electrical quantities acquired during system operation.

The first version of the GUI was primarily designed to monitor the electrical behaviour of the battery, supercapacitor, and load branches. In particular, it displayed the measured voltages, currents, and corresponding instantaneous powers, together with the calculated system efficiency. This initial implementation provided four main graphical panels dedicated to voltage, current, power, and efficiency monitoring.

The monitored quantities included the battery voltage and current, the supercapacitor voltage and current, and the voltage and current associated with the main 6 V load bus. The corresponding power values were calculated from the acquired measurements and displayed in real time, allowing the interaction among the battery branch, the supercapacitor branch, and the load to be observed during the different operating conditions.

In addition to the electrical quantities, the operating state generated by the control loop was transmitted by the firmware and included in the recorded dataset. This information made it possible to associate each electrical transient with the corresponding state of the PMS.

The control-loop state was particularly useful during offline analysis, since it allowed the activation of the **ASSIST** and **RECOVERY** states to be verified after each acquisition. The recorded state could therefore be compared with the measured load power, its time derivative, and the supercapacitor voltage in order to determine whether the expected transition conditions had been correctly detected by the controller.

The GUI also provided data-recording functionality. The acquired electrical quantities and the corresponding control state were stored in CSV format for subsequent processing. The recorded files were used to analyse transient events, compare repeated acquisitions, evaluate the timing of the state transitions, and verify the consistency between the control decisions and the actual operating conditions of the system.

The auxiliary 5 V and 3.3 V output powers were not acquired in real time through the onboard sensing infrastructure. These values were measured separately using external instrumentation and subsequently treated as constant parameters in the offline power-balance and efficiency calculations.

This first version of the GUI therefore represented the main monitoring and diagnostic tool during the preliminary validation of the PCB and the PMS. Its

functionality was later extended to include the smart-battery parameters and the variables associated with the battery-charging subsystem, as described in Section 5.8.

Figure 5.2 shows the first version of the graphical interface used during the experimental tests.

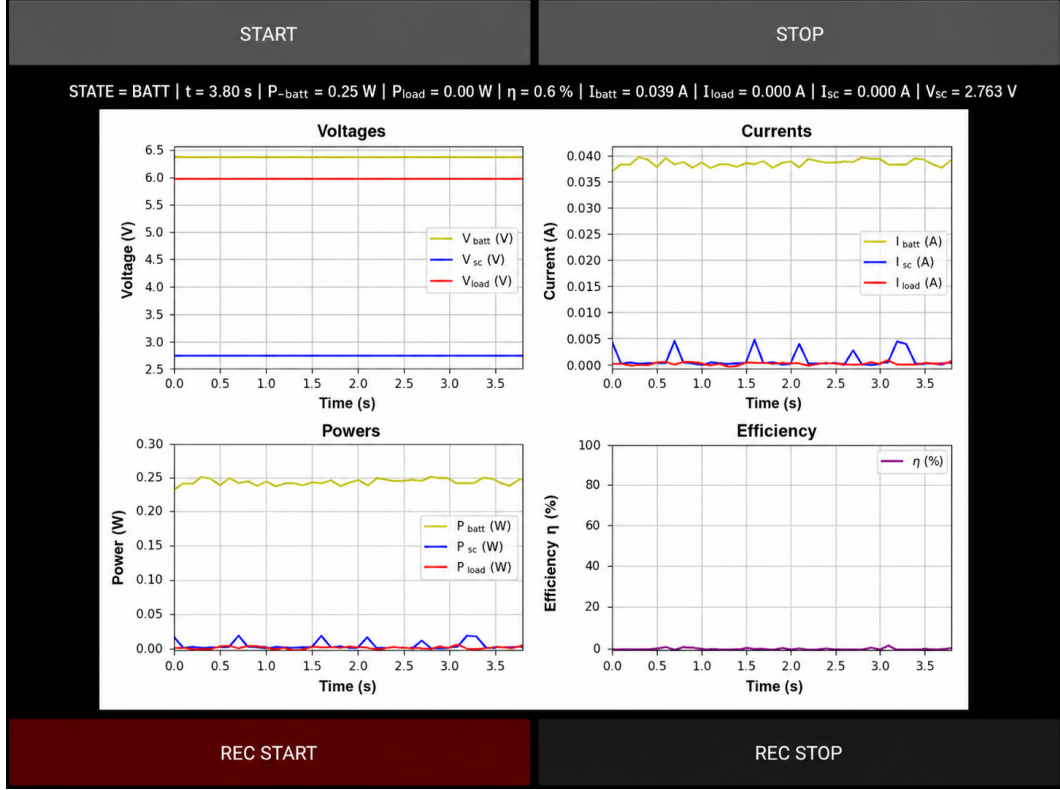


Figure 5.2: First version of the graphical user interface developed for real-time visualization of voltages, currents, powers, and system efficiency. The control-loop state was also stored in the recorded dataset for offline verification of the EMS transitions.

5.3 Preliminary PCB and Subsystem Validation

Before testing the complete HESS under dynamic operating conditions, a preliminary validation campaign was performed on the developed PCB. The objective of this phase was to verify the correct operation of the main hardware subsystems, identify possible deviations from the expected design values and ensure that the board could be safely used for the subsequent energy management tests.

This preliminary activity was organized at subsystem level. First, the main

voltage rails generated by the board were measured under no-load conditions. Then, the sensing infrastructure was validated using a known external resistive load, comparing the measured values with the theoretical ones. The communication between the ESP32-S3 controller and the sensing devices was also verified, with particular attention to the effective sampling frequency of the acquired data. Finally, the supercapacitor charging circuit, the digital potentiometer interface and the main DC-DC conversion stages were experimentally checked.

This validation step was essential because the correct operation of the EMS strongly depends on the reliability of the acquired electrical measurements and on the proper actuation of the power conversion stages. In particular, wrong current or voltage readings, communication delays or unstable converter outputs could lead to incorrect state transitions in the finite-state machine and compromise the interpretation of the following experimental tests.

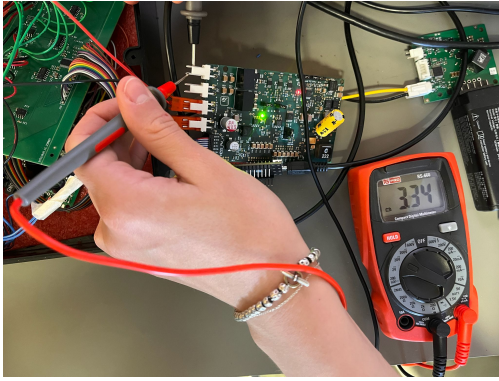
5.3.1 Voltage Rails and No-Load Verification

The first verification concerned the output voltages generated by the HESS board under no-load conditions. With the robotic hand disconnected, the auxiliary voltage rails and the regulated outputs of the main power conversion stages were measured using a digital multimeter.

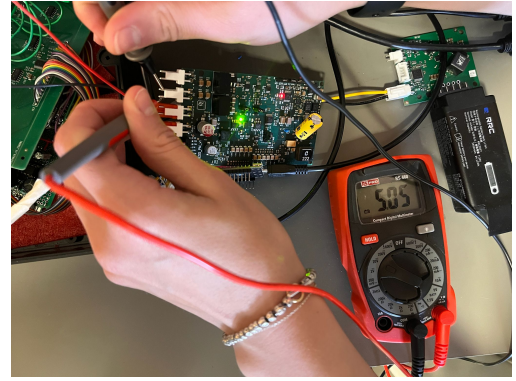
In particular, the following voltage rails were checked:

- the 3.3 V auxiliary line, used to supply low-voltage electronic components;
- the 5 V auxiliary line, used for auxiliary electronic subsystems;
- the regulated output of the buck converter;
- the regulated output of the boost converter associated with the supercapacitor branch.

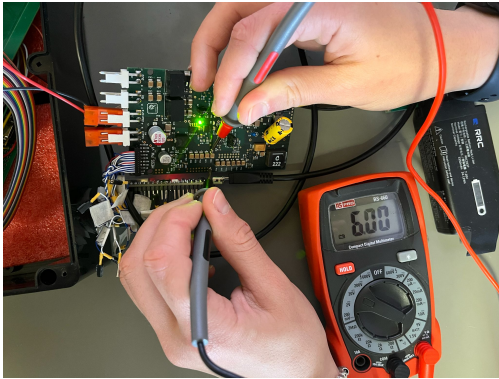
This test was performed to confirm that the board was able to correctly generate all the supply voltages required by the control electronics, the sensing system and the load-side power architecture before proceeding with dynamic load testing.



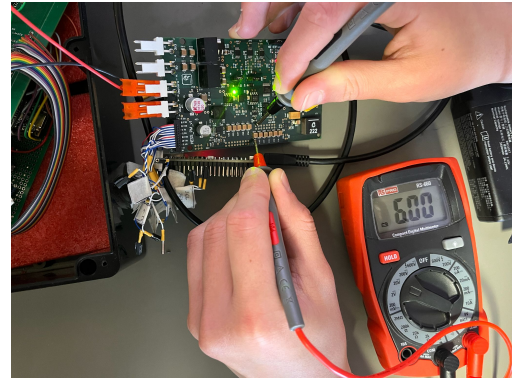
(a) 3.3 V auxiliary line.



(b) 5 V auxiliary line.



(c) Buck converter output.



(d) Boost converter output.

Figure 5.3: Preliminary validation of the main output voltages generated by the HESS board under no-load conditions.

The multimeter measurements confirmed that the generated voltages were consistent with the expected design values. This result verified the correct operation of the main voltage regulation stages of the board and provided the necessary confidence to proceed with the validation of the sensing infrastructure and the power conversion subsystems.

5.3.2 Sensing Module Validation under Resistive Load

After the no-load verification, the sensing system was validated under a fixed resistive load condition. A nominal $10\ \Omega$ power resistor was connected to the regulated load output of the board, while the supercapacitor branch was disabled. This configuration allowed the load current measured by the INA228 sensing device to be compared with the theoretical current calculated from Ohm's law and with the voltage measured directly across the load using a digital multimeter.

Before performing the test, the real value of the nominal 10 Ω load resistor was experimentally measured. By applying a known DC voltage and measuring the corresponding current, the actual resistance was calculated as:

$$R_{load} = \frac{V_R}{I} \quad (5.7)$$

Using the measured values $V_R = 1.95$ V and $I = 0.198$ A, the real resistance was found to be:

$$R_{load} = \frac{1.95}{0.198} \approx 9.85 \Omega \quad (5.8)$$

This experimentally measured resistance value was then used to calculate the theoretical current expected during the sensing validation test. During the test, the voltage measured with the multimeter across the load was approximately 5.98 V. Therefore, the theoretical current was:

$$I_{theoretical} = \frac{V_R}{R_{load}} = \frac{5.98}{9.85} \approx 0.607 \text{ A} \quad (5.9)$$

The INA228 sensing system measured a load voltage of 6.005 V and a load current of 0.61 A. The relative error between the measured current and the theoretical value was calculated as:

$$\varepsilon_I = \frac{I_{measured} - I_{theoretical}}{I_{theoretical}} \cdot 100 \quad (5.10)$$

Substituting the experimental values:

$$\varepsilon_I = \frac{0.61 - 0.607}{0.607} \cdot 100 \approx 0.5\% \quad (5.11)$$

The low relative error confirmed a good agreement between the theoretical value, the multimeter-based measurement and the INA228 acquisition. The observed deviation can be attributed to residual resistor tolerance, shunt tolerance, sensor offset, parasitic wiring resistance and measurement quantization.

This result validated the sensing chain under a simple and repeatable load condition, confirming that the current and voltage measurements could be reliably used for the subsequent dynamic tests and for the implementation of the EMS control logic.

5.3.3 I2C Communication and Sampling Frequency

The sensing devices integrated on the HESS board communicate with the ESP32-S3 controller through the I2C bus. Since the EMS decisions are based on real-time voltage and current measurements, the reliability and speed of this communication

Table 5.2: Effective acquisition frequency measured for different register-reading configurations.

Configuration	Period	Frequency
Three-register acquisition	1.234 ms	809.9 Hz
Voltage and current acquisition	822.6 μ s	1.215 kHz

As expected, the acquisition frequency increased when the number of read registers was reduced. In particular, limiting the measurement routine to the voltage and current registers allowed the loop frequency to increase from approximately 809.9 Hz to 1.215 kHz. This confirmed the direct influence of the I2C reading sequence on the effective sampling rate of the control loop.

The oscilloscope measurements confirmed that the I2C communication and the acquisition routine were stable and repeatable. Both measured sampling frequencies were considered suitable for the monitoring requirements of the HESS control strategy, allowing the controller to acquire the electrical quantities with sufficient temporal resolution for the detection of fast variations in load power.

This result validated the complete measurement chain before the execution of the pulsed-load and robotic hand tests, where the EMS must detect transient events and activate the supercapacitor assistance when required.

5.3.4 Supercapacitor Charging Circuit and Digital Potentiometer Control

A further preliminary test was dedicated to the validation of the supercapacitor charging circuit. This subsystem is responsible for restoring the supercapacitor voltage after assist events and therefore plays a fundamental role in the recovery phase of the EMS.

The charging current is set through a digital potentiometer controlled by the firmware. Consequently, the validation of this subsystem involved both the electrical charging circuit and the communication interface used to configure the digital potentiometer. The objective was to verify that the ESP32-S3 could correctly send the control commands and that the resulting charging behaviour was consistent with the selected current setting.

During the test, the supercapacitor charging current was set to 380 mA through the firmware. The test was performed on the Eaton TV1020-3R0605-R supercapacitor, while the supercapacitor voltage was monitored using the oscilloscope. This allowed the voltage increase during the charging phase to be directly observed and used as an experimental verification of the charging circuit operation.

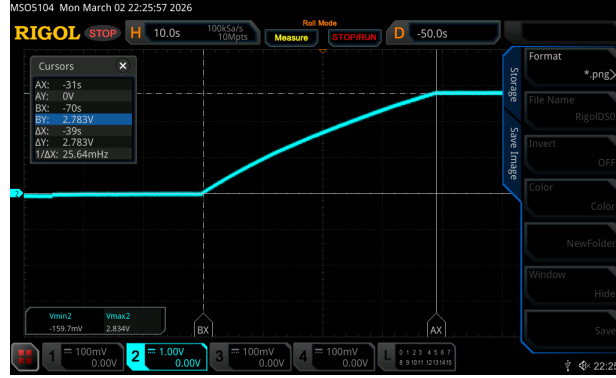


Figure 5.5: Oscilloscope acquisition of the supercapacitor charging transient with the charging current set to 380 mA through the digital potentiometer control.

As shown in Figure 5.5, the supercapacitor voltage increases progressively during the charging phase, reaching approximately 2.8 V. The observed charging profile confirms that the charging circuit is able to transfer energy to the supercapacitor in a controlled way once the current reference is imposed through the digital potentiometer.

This test confirmed the correct interaction between the embedded firmware, the digital potentiometer and the supercapacitor charging circuit. The validation of this subsystem was necessary before implementing the automatic recovery logic, since an incorrect charging current could either slow down the restoration of the supercapacitor voltage or impose unnecessary stress on the battery branch.

The successful charging test demonstrated that the supercapacitor branch could be recharged under firmware control, enabling the implementation of the recovery state of the EMS in the following validation phases.

5.4 Robotic Hand Load Characterization

After the preliminary validation of the HESS board and its main subsystems, an experimental characterization of the robotic hand load profile was performed. This step was necessary to identify the real electrical demand generated by the prosthetic actuators and to define the initial operating thresholds of the PMS on the basis of experimental measurements.

The robotic hand represents a highly dynamic electromechanical load. Unlike a purely resistive load, the power required by the motors is not constant, but varies significantly during actuation. In particular, current peaks can occur during motor start-up, finger motion and grasping phases. For this reason, the control strategy was not defined only from nominal motor specifications, but from direct experimental load measurements.

The tests were carried out by acquiring the load voltage, load current and instantaneous load power using the INA228 sensing devices integrated on the HESS board. Data acquisition and visualization were performed through the graphical monitoring interface developed for the platform. For each operating condition, multiple consecutive acquisitions were recorded and compared in order to evaluate the repeatability of the measured load profiles.

The characterization campaign considered the following operating conditions:

- idle condition, with the robotic hand connected but without motor actuation;
- activation of each individual finger;
- full-hand movement without external load.

The following subsections describe the main results obtained during the robotic hand load characterization and explain how these measurements were used to define the initial EMS load-power thresholds.

5.4.1 Idle Condition

The first test was performed under idle conditions, with the robotic hand connected to the system but without motor actuation. This measurement was used to estimate the baseline electrical consumption of the electronics and of the connected load in the absence of mechanical movement.

For this test, four consecutive acquisitions were recorded and superimposed in order to evaluate the repeatability of the baseline consumption. The monitored quantities were the battery current I_b and the battery power P_b , as shown in Figure 5.6.

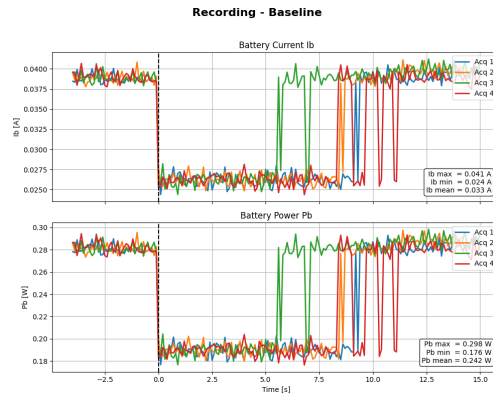


Figure 5.6: Superimposed acquisitions of the battery current and battery power under idle conditions, with the robotic hand connected but without motor actuation.

Under this condition, the absorbed power remained low and relatively stable. The average absorbed power was approximately 0.24 W, while the maximum value was about 0.30 W. The battery current remained within a low-current range, with an average value of approximately 0.033 A. This confirmed that the idle consumption of the system is significantly lower than the power levels associated with actuator operation.

As visible in Figure 5.6, the acquisitions show an initial transition followed by a stable low-power region. This behaviour was used as the reference baseline for the following measurements. Any significant increase in the measured load power during the subsequent tests could therefore be attributed to motor activation rather than to the static consumption of the electronics.

5.4.2 Single-Finger Actuation

After the idle characterization, single-finger actuation tests were performed. The objective of these tests was to evaluate the power demand associated with each individual actuator and to identify possible differences among the fingers.

The index, middle, ring and thumb fingers showed comparable electrical behaviour. Their average absorbed power was between approximately 2.7 W and 3.0 W, with peak values close to or slightly above 3 W. These results indicate that the actuation of a single finger generally produces a moderate power demand, although short transient peaks may still occur during motion.

A different behaviour was observed for the little finger. In this case, the average absorbed power was approximately 5.6 W, with peak values reaching about 6.5 W. This result highlighted that the electrical demand of the robotic hand is not uniformly distributed among the actuators and that some single-finger movements can be significantly more demanding than others.

The temporal profiles acquired for the individual fingers are shown in Figure 5.7. For each actuator, multiple consecutive acquisitions were superimposed in order to compare the energetic behaviour of the different fingers and to verify the repeatability of the measured power demand.

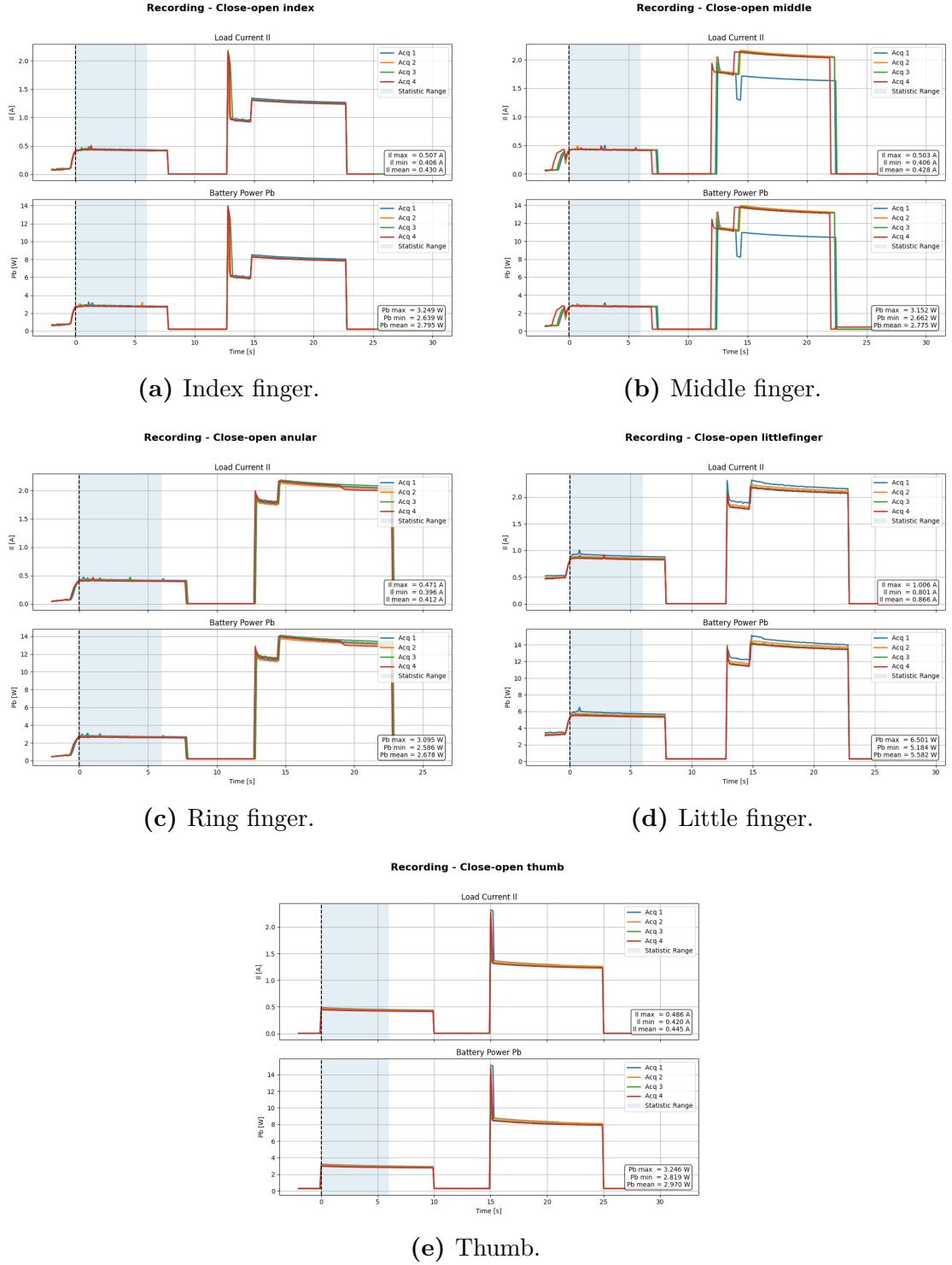


Figure 5.7: Superimposed acquisitions of the load profiles associated with the actuation of the individual fingers of the robotic hand.

5.4.3 Full-Hand Movement

Full-hand movement tests were then performed in order to evaluate the combined effect of simultaneous actuator activation. This condition is more representative of the actual use of the robotic hand, since several fingers may be activated during closing or grasping movements.

The full-hand test was carried out without external load. This condition represents the dynamic baseline of the robotic hand during free movement. The measured profile was characterized by an initial transient associated with the activation of the actuators, followed by a more stable power absorption region.

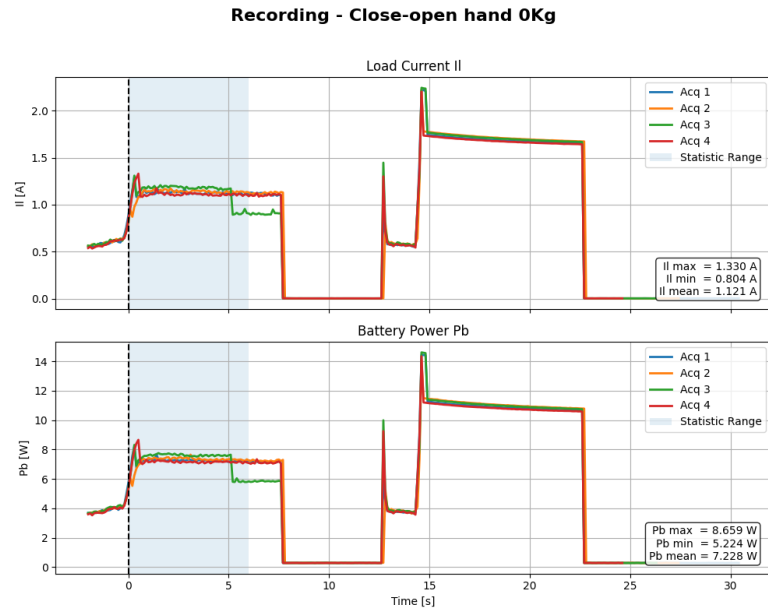


Figure 5.8: Load power profile during full-hand movement without external load, corresponding to the 0 kg load condition.

In this operating condition, the average absorbed power was approximately 7.2 W, while the maximum value reached approximately 8.7 W. This result shows that even in the absence of an external mechanical load, the simultaneous activation of the actuators generates a dynamic and non-negligible power demand.

The main experimental results obtained during the robotic hand characterization are summarized in Table 5.3.

Table 5.3: Summary of the robotic hand load characterization tests.

Operating condition	Average power [W]	Peak power [W]	Average current [A]
Idle condition	0.24	0.30	0.033
Index finger	2.795	3.249	0.430
Middle finger	2.775	3.152	0.428
Ring finger	2.678	3.095	0.412
Little finger	5.582	6.501	0.866
Thumb	2.970	3.246	0.445
Full-hand movement without external load	7.228	8.659	1.121

The results confirmed that the robotic hand behaves as an impulsive and highly variable load. Even when the average power remains moderate, short power peaks can occur during motor activation. This behaviour supports the use of a hybrid energy storage architecture, where the battery supplies the average energy demand while the supercapacitor branch is activated to support the most demanding transient events.

5.4.4 Definition of EMS Control Thresholds

The experimental characterization of the robotic hand was used as the basis for the initial definition of the main load-power thresholds implemented in the EMS. The objective was to select threshold values able to distinguish between idle operation, moderate actuator activity and demanding motor events requiring supercapacitor assistance.

The measured profiles showed that the idle power remained below approximately 0.3 W, while most single-finger movements required average powers close to 3 W. The little finger represented a more demanding single-actuator condition, with peak power values above 6 W. Full-hand movement without external load produced an average absorbed power of approximately 7.2 W and peaks close to 8.7 W.

Based on these results, the assist activation threshold was selected in order to make the supercapacitor intervention selective. The threshold had to be high enough to avoid unnecessary activation during low-power or moderate single-finger operation, but low enough to detect the most demanding motor events. For this reason, the load power threshold for assist activation was set to:

$$P_{LOAD_ON} = 6.0 \text{ W} \quad (5.12)$$

This value is higher than the average power measured for most single-finger movements, but close to the demand of the little finger and lower than the power

required during full-hand actuation. Therefore, the assist strategy is mainly activated during the most demanding movements, while avoiding unnecessary supercapacitor intervention during low-power operation.

To prevent unstable switching around the activation threshold, a lower load power threshold was introduced for assist deactivation:

$$PLOAD_OFF = 2.5 \text{ W} \quad (5.13)$$

The difference between $PLOAD_ON$ and $PLOAD_OFF$ provides a hysteresis margin, reducing the risk of rapid oscillations between the battery-only and supercapacitor-assisted states when the load power decreases after a transient event.

The two load-power thresholds adopted at this stage are summarized in Table 5.4.

Table 5.4: Load-power thresholds initially defined from the robotic hand characterization.

Parameter	Function	Value
$PLOAD_ON$	Activation threshold for supercapacitor assistance	6.0 W
$PLOAD_OFF$	Deactivation threshold for assist exit and hysteresis	2.5 W

These thresholds provided the initial load-power criteria for the finite-state machine. Additional dynamic criteria based on the derivative of the load power were then introduced and refined during the following control validation phase, in order to improve transient detection and smooth the transition between the battery and supercapacitor branches.

5.5 EMS Validation under Pulsed Load Conditions

After the preliminary validation of the PCB and the characterization of the robotic hand load, the complete EMS was tested under controlled pulsed-load conditions. This intermediate validation step was introduced before the final robotic hand tests in order to evaluate the behaviour of the control logic under repeatable and challenging dynamic load profiles.

The pulsed-load test was selected because it reproduces one of the most critical operating conditions for the HESS: a sudden increase in load power followed by a lower-power interval. This type of profile is representative of motor-driven applications, where short current peaks can occur during actuator start-up or rapid

load variations. At the same time, the use of a controlled pulsed load allowed the system response to be evaluated more clearly than with the robotic hand, whose actuation profile is less repeatable and depends on the mechanical movement.

The objective of this validation phase was to verify the correct activation of the finite-state machine, the intervention of the supercapacitor branch during load peaks, the recovery of the supercapacitor after assist events and the effect of the auxiliary outputs on the overall power balance.

5.5.1 Pulsed Load Test Configuration

The pulsed-load validation was performed by connecting the HESS output to a dynamic load profile characterized by alternating high-power and low-power phases. This configuration was used to force the EMS to detect transient events and activate the supercapacitor assistance when the load demand exceeded the selected thresholds.

The assist shut-off thresholds were adjusted for operation with a pulsed load having a baseline power consumption of approximately 4 W, in order to redefine the baseline and validate the control system under the most demanding conditions for the battery.

During the test, the battery branch represented the primary energy source of the system, while the supercapacitor branch was enabled by the EMS during the assist phase. The buck converter supplied the regulated load bus during normal operation, whereas the boost converter associated with the supercapacitor branch was activated when the control logic detected a demanding transient event.

In addition to the main pulsed load, the auxiliary outputs of the PCB were connected to fixed resistive loads. This choice was introduced to include the contribution of the auxiliary electronic subsystems in the experimental power balance. In particular, the 5 V auxiliary rail supplied approximately 2.5 W, while the 3.3 V rail supplied approximately 1.089 W. Therefore, the HESS was tested not only as a supply stage for the main load, but also as a complete power platform including the auxiliary consumption expected in the final application.

The quantities monitored during the test included the battery voltage and current, the supercapacitor voltage and current, the load voltage and current, the auxiliary output powers, the total output power, the efficiency and the active state of the finite-state machine. The complete recording of the pulsed-load test is shown in Figure 5.9.

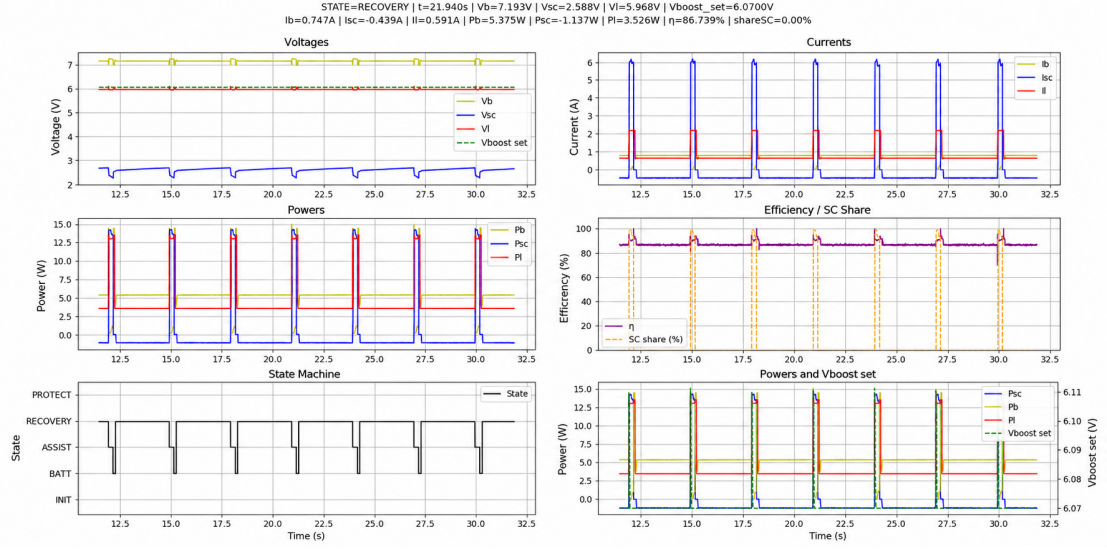


Figure 5.9: Experimental recording of the HESS under pulsed-load conditions. The plots show the voltage profiles, current redistribution between battery and supercapacitor branches, corrected power flows, system efficiency, supercapacitor power share and finite-state-machine transitions.

5.5.2 Finite-State Machine Behaviour

The first objective of the pulsed-load test was to verify the correct behaviour of the finite-state machine under dynamic load conditions. The EMS was expected to remain in a low-demand operating state during the intervals between pulses, switch to the ASSIST state when a load peak was detected and then manage the recovery of the supercapacitor after each assist event.

As shown in Figure 5.9, the finite-state machine followed the imposed pulsed-load profile in a repeatable way. During the low-power intervals, the system remained in the recovery or low-demand operating condition, while the supercapacitor branch did not contribute to the main load. When a load pulse occurred, the EMS detected the increase in load demand and activated the ASSIST state.

The state transitions were synchronized with the load pulses. Each high-power event produced a corresponding transition toward the ASSIST state, followed by a return to the recovery condition after the end of the pulse. This confirmed that the implemented control logic was able to detect repeated transient events and coordinate the operating modes of the HESS without losing synchronization with the load profile.

The pulsed-load test therefore validated the basic sequencing of the EMS and confirmed that the finite-state-machine transitions were consistent with the measured electrical conditions.

5.5.3 Supercapacitor Assistance during Load Peaks

A key objective of the pulsed-load validation was to verify the effectiveness of the supercapacitor assistance during high-power events. During the ASSIST state, the supercapacitor branch was expected to support the load transient and reduce the instantaneous current stress imposed on the battery.

The experimental results confirmed this behaviour. During the load peaks, the supercapacitor current rapidly increased, reaching values significantly higher than the battery current. In the recorded operating point reported in Figure 5.9, the battery current was approximately 0.535 A, while the supercapacitor current reached approximately 6.486 A. The corresponding battery power was about 4.168 W, while the supercapacitor branch supplied approximately 15.379 W.

The experimental results confirmed that the supercapacitor branch effectively supported the load during transient operation. However, the observed power distribution did not correspond to a fixed or balanced 50/50 sharing condition. Due to the behaviour of the LTC4353 ideal-diode controller and to the small voltage difference between the outputs of the two converters, the supercapacitor branch became the dominant source during the assist interval.

This operating condition can therefore be described as a partial or near-complete source takeover rather than as an accurately regulated current split. Although this behaviour differed from the initial load-sharing objective, it remained beneficial for the target application because it substantially reduced the instantaneous current demanded from the battery during the load peak.

Based on these experimental observations, the control objective was revised. Rather than maintaining a predefined sharing ratio, the final strategy was aimed at ensuring rapid intervention of the supercapacitor branch, stable operation of the 6 V load bus, and a controlled handoff of the load demand back to the battery after the transient event.

5.5.4 Power Flow and Efficiency Evaluation

The pulsed-load test was also used to evaluate the power flow within the HESS and to assess the overall efficiency of the system under dynamic operating conditions.

The battery power was calculated from the measured battery voltage and current, while the supercapacitor power was calculated from the corresponding supercapacitor measurements. The useful output power was obtained by summing the power delivered to the main 6 V load and to the auxiliary rails.

During the pulsed-load validation, the auxiliary outputs were connected to fixed resistive loads in order to include their contribution in the total power balance. This was important because, in the final prosthetic application, the HESS must supply not only the main actuator load, but also the auxiliary electronic subsystems.

The auxiliary powers were treated as useful output power. In the tested configuration, the 5 V rail supplied:

$$P_{5V} = 2.500 \text{ W} \quad (5.14)$$

while the 3.3 V rail supplied:

$$P_{3.3V} = 1.089 \text{ W} \quad (5.15)$$

The total useful output power was therefore calculated as:

$$P_{out,tot} = P_{6V} + P_{5V} + P_{3.3V} \quad (5.16)$$

where P_{6V} is the power delivered to the main pulsed load, while P_{5V} and $P_{3.3V}$ are the powers delivered by the auxiliary output rails.

During the assist pulse shown in Figure 5.9, the main 6 V load power reached approximately:

$$P_{6V} = 14.073 \text{ W} \quad (5.17)$$

Therefore, the total useful output power was:

$$P_{out,tot} = 14.073 + 2.500 + 1.089 = 17.662 \text{ W} \quad (5.18)$$

Including the auxiliary output powers in the analysis was necessary to avoid underestimating the useful output power delivered by the PCB. This is especially important during low-load intervals, where the auxiliary consumption represents a significant part of the total power delivered by the system.

During the representative assist condition shown in Figure 5.9 the total input power was approximately:

$$P_{in} = 19.547 \text{ W} \quad (5.19)$$

resulting in a system efficiency of:

$$\eta_{sys} = 90.36\% \quad (5.20)$$

The corresponding power loss was approximately:

$$P_{loss} = 1.885 \text{ W} \quad (5.21)$$

These values confirmed that the HESS maintained a high efficiency during supercapacitor-assisted pulsed operation. The measured efficiency is also consistent with the preliminary efficiency characterization of the individual DC-DC converters, summarized in Table 5.5.

Table 5.5: Experimental efficiency characterization of the main DC-DC converters.

Converter	P_{in} [W]	P_{out} [W]	η [%]	Expected η [%]
Buck converter, $V_{in} = 7.0$ V	3.861	3.528	91.379	90–93
Buck converter, $V_{in} = 7.4$ V	3.838	3.540	92.242	90–93
Buck converter, $V_{in} = 8.0$ V	3.734	3.528	94.501	90–93
Boost converter	4.018	3.564	88.691	88–92
5 V converter	2.832	2.500	88.268	91–92
3.3 V converter	1.250	1.086	86.873	89–91

The buck converter showed measured efficiencies between approximately 91.4% and 94.5%, in good agreement with the expected range. The boost converter efficiency was approximately 88.7%, also consistent with the theoretical expected range. The auxiliary converters showed slightly lower measured efficiencies than the expected values, with approximately 88.3% for the 5 V converter and 86.9% for the 3.3 V converter. This difference can be attributed to the specific operating point, measurement uncertainty and the effect of fixed losses, which become more relevant at relatively low output powers.

Overall, the pulsed-load validation confirmed that the EMS was able to manage the main power flows of the HESS in a controlled way. The battery branch supplied the average power demand, the supercapacitor branch supported the transient peaks, and the auxiliary outputs were correctly included in the useful output power. This test therefore provided a repeatable validation of the EMS before the final experimental tests with the robotic hand.

5.6 EMS Validation with the Robotic Hand

After the preliminary validation of the PCB subsystems and the controlled pulsed-load tests, the experimental activity was extended to the robotic hand. This phase represented the application-oriented validation of the Hybrid Energy Storage System, since the electrical demand was generated directly by the electromechanical actuators rather than by a predefined resistive load.

Unlike the controlled pulsed-load configuration, the robotic hand produces non-uniform and only partially repeatable power profiles. The instantaneous electrical demand depends on several factors, including motor starting conditions, finger

synchronization, mechanical friction, contact conditions, and the external load applied to the grasping mechanism. Therefore, the validation focused not only on the maximum power demand, but also on the capability of the Energy Management System to detect rapid load variations, activate the supercapacitor branch, maintain the regulated load bus, and restore the supercapacitor energy after each assist event.

The tests were performed by repeatedly closing and opening the robotic hand under three different loading conditions:

- 0 kg, corresponding to free hand motion without an external mechanical load;
- 1 kg, corresponding to an intermediate grasping load;
- 2 kg, corresponding to the most demanding tested mechanical condition.

Four acquisitions were recorded for each load condition in order to evaluate the repeatability of the measured profiles and the response of the control algorithm to consecutive actuation events. For each acquisition, the battery, supercapacitor, and load voltages and currents were monitored together with the corresponding power flows, system efficiency, supercapacitor contribution, boost-converter voltage reference, and active finite-state-machine state.

The auxiliary 5 V and 3.3 V outputs were also included in the total useful output power. Their contribution was maintained constant during the tests in order to reproduce the additional electrical demand associated with the embedded electronic subsystems of the final application.

5.6.1 Adaptation of the Control Thresholds

The initial control thresholds were defined on the basis of the robotic-hand characterization described in Section 5.4. The previous measurements showed that the idle consumption remained below approximately 0.3 W, while most single-finger movements required average power levels close to 3 W. Higher values were observed during the actuation of the little finger and during full-hand motion, where the measured power exceeded 6 W.

Based on these observations, the load-power threshold for assist activation was set to

$$P_{\text{LOAD,ON}} = 6.0 \text{ W}, \quad (5.22)$$

while the deactivation threshold was set to

$$P_{\text{LOAD,OFF}} = 2.5 \text{ W}. \quad (5.23)$$

The difference between the two thresholds introduced a hysteresis margin intended to prevent repeated transitions between the *BATT* and *ASSIST* states when the measured load power fluctuated around the activation boundary.

During the tests with the robotic hand, the absolute load-power threshold alone was found to be insufficient for detecting all motor-induced transients. Some events were characterized by a rapid increase in load demand but reached the steady-state power threshold only after the initial current peak. Therefore, the load-power derivative was also included in the assist activation logic.

The final assist request was generated when either the absolute load power exceeded the selected threshold or a sufficiently rapid positive variation in load power was detected. This combined criterion improved the responsiveness of the PMS and allowed the supercapacitor branch to be activated during fast actuator transients before the maximum load power was reached.

The derivative thresholds and the additional timing parameters were refined experimentally in order to avoid false activations caused by measurement noise and to improve the stability of the transitions between operating states. The final values adopted in the control loop are reported in Table 5.4.

5.6.2 Battery-Dominated Operation

During low-demand intervals, the PMS remained in the *BATT* state and the battery branch acted as the main energy source of the system. In this condition, the supercapacitor-assisted path remained disconnected from the load bus and the measured supercapacitor current was approximately zero.

The boost converter was maintained in a pre-enabled standby condition at the selected voltage reference. However, since the supercapacitor switching path remained open, no significant power contribution was delivered to the load bus. The battery therefore supplied both the robotic hand and the auxiliary 5 V and 3.3 V outputs.

Across the acquisitions performed at 0 kg, 1 kg, and 2 kg, the regulated load voltage remained close to the nominal 6 V value during battery-dominated operation. This confirmed that the battery-side buck converter was able to maintain the required supply voltage during idle and low-power operating intervals.

When the robotic hand started closing or opening, the battery current increased according to the instantaneous actuator demand. If the measured load power or its derivative exceeded the selected activation threshold, the controller requested the transition from *BATT* to *ASSIST*. Therefore, battery-dominated operation represented the default condition from which the transient support mechanism was activated.

5.6.3 Supercapacitor-Assisted Operation

During hand closing and opening, the simultaneous activation of multiple actuators generated rapid variations in load current and power. When the absolute power threshold or the derivative-based condition was exceeded, the PMS entered the *ASSIST* state and connected the supercapacitor branch to the common load bus.

The experimental acquisitions showed a rapid increase in supercapacitor current at the beginning of the most demanding actuation events. At the same time, the battery contribution remained lower than the total instantaneous power demand, confirming that part of the transient load was transferred to the auxiliary storage branch.

The observed power distribution was not characterized by a constant or accurately regulated sharing ratio. The actual contribution of each source depended on the relative output voltages of the buck and boost converters, the equivalent impedance of the two power paths, and the behaviour of the LTC4353 ideal-diode controller. In several assist events, the supercapacitor branch became the dominant source, consistently with the source-takeover behaviour described in Section 5.7.3.

The 0 kg tests showed that supercapacitor assistance could already be activated during free full-hand motion. Even without an external mechanical load, motor starting and finger synchronization generated sufficiently rapid power variations to trigger the assist condition.

Under the 1 kg and 2 kg conditions, the actuator demand generally remained elevated for longer intervals. The supercapacitor branch therefore contributed not only during the initial current peak, but also during part of the subsequent grasping phase, depending on the duration of the movement and on the available supercapacitor voltage.

A strictly monotonic increase in the measured peak current was not observed between the 0 kg, 1 kg, and 2 kg test conditions. This result is consistent with the non-deterministic behaviour of the robotic hand, since the instantaneous electrical demand depends not only on the applied mass, but also on finger synchronization, motor starting conditions, mechanical contact, and movement duration.

Despite the variability among repeated acquisitions, all three loading conditions showed the same overall operating principle. The battery supplied the baseline energy demand, while the supercapacitor branch responded to rapid power transients and reduced the instantaneous electrical stress imposed on the battery.

Throughout the assist events, the load-bus voltage remained close to the nominal 6 V level, with only limited transient variations. This result confirmed that the combined action of the boost converter, the ideal-diode power path, and the embedded control strategy was able to preserve the supply continuity required by the robotic hand.

Figure 5.10 shows a representative acquisition obtained during full-hand closing and opening without an external mechanical load.

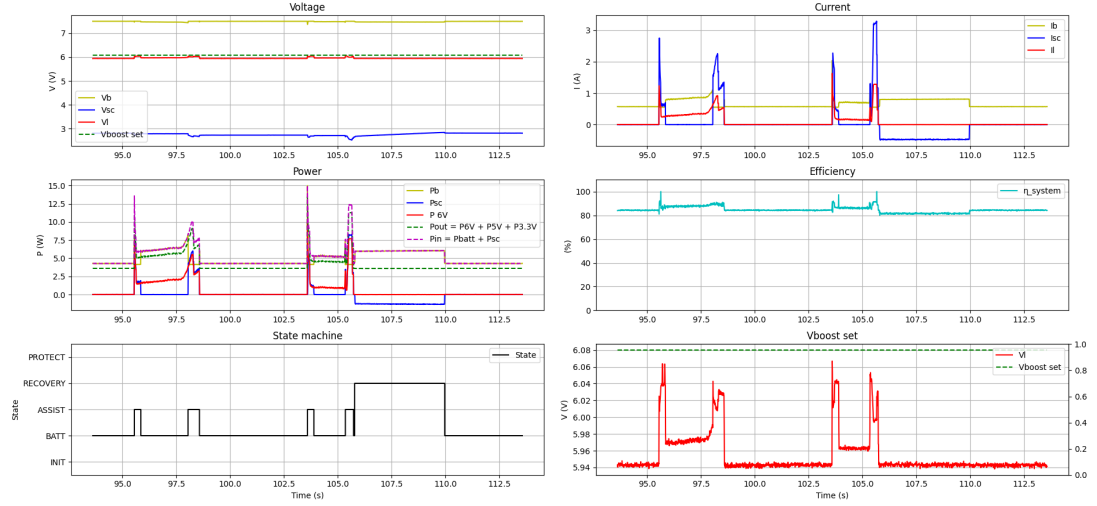


Figure 5.10: Representative HESS acquisition during robotic-hand closing and opening without an external mechanical load.

Figure 5.11 shows a representative acquisition obtained during full-hand closing and opening under the 1 kg loading condition.

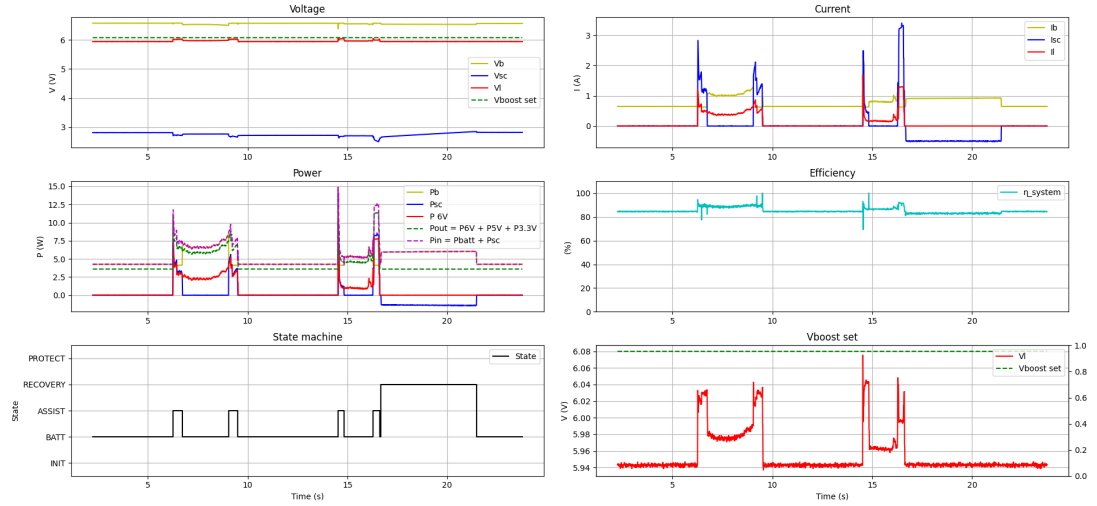


Figure 5.11: Representative HESS acquisition during robotic-hand closing and opening with a 1 kg external load.

Figure 5.12 shows a representative acquisition obtained during full-hand closing and opening under the 2 kg loading condition.

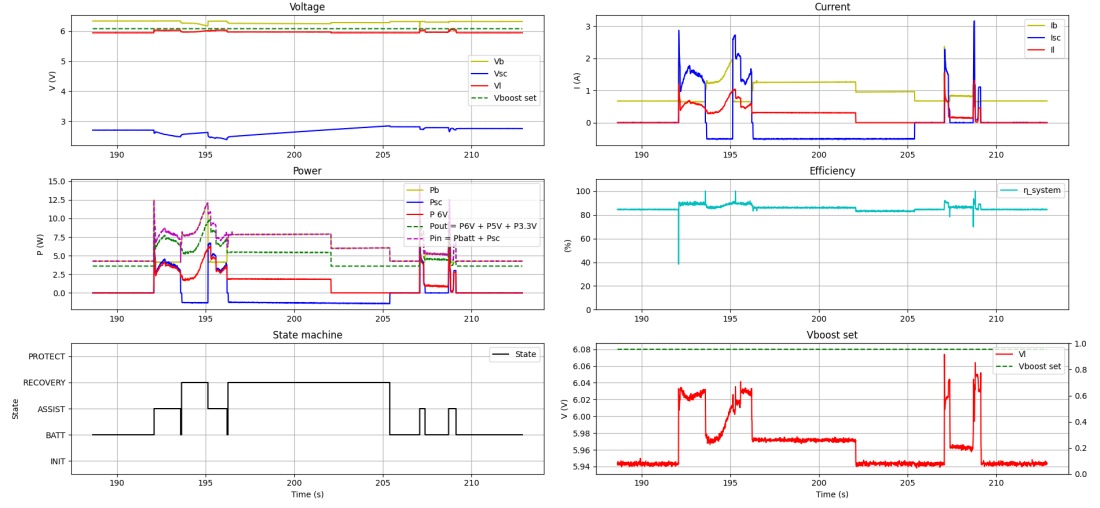


Figure 5.12: Representative HESS acquisition during robotic-hand closing and opening with a 2 kg external load.

5.6.4 Recovery Behaviour after Assist Events

After each assist event, the supercapacitor voltage decreased according to the energy delivered to the load. If the measured voltage fell below the selected recovery threshold and the load demand returned to a sufficiently low level, the PMS entered the *RECOVERY* state.

During recovery, the supercapacitor-assisted load path was disconnected and the dedicated charging circuit was enabled. The battery continued to supply the robotic hand and the auxiliary electronic loads while simultaneously transferring energy to the supercapacitor.

The recovery condition was clearly visible in the experimental acquisitions as a negative supercapacitor current, corresponding to power entering the storage element. At the same time, the battery current increased because the primary energy source had to supply both the external load and the charging subsystem.

The supercapacitor voltage progressively increased during the recovery interval until the upper recovery threshold was reached. Once this condition was satisfied, the charging circuit was disabled and the system returned to the *BATT* state.

The experimental results also confirmed that the recovery process was interrupted whenever a new assist request occurred. In this condition, the control algorithm gave priority to transient load support, disabled the charger, and reconnected the supercapacitor branch to the load bus. This behaviour ensured that the charging process did not delay the system response to a new actuator event.

During the first validation tests, the interaction between the recovery thresholds, the supercapacitor terminal-voltage rebound, and the finite-state-machine logic produced repeated transitions between *BATT*, *ASSIST*, and *RECOVERY*. These observations motivated the subsequent refinement of the recovery hysteresis and low-energy management strategy described in Section 5.7.

Overall, the robotic-hand tests confirmed that the PMS was able to coordinate battery-dominated operation, supercapacitor-assisted transient support, and post-event recovery under realistic electromechanical load conditions. The experiments also highlighted the importance of threshold tuning, source-takeover management, and controlled handoff between the two energy branches.

5.7 Control Strategy Refinement and Experimental Optimization

The final control strategy was obtained through an iterative experimental process. The initial objective was to achieve a controlled contribution from both the battery and supercapacitor branches during transient load conditions. However, the interaction among the regulated DC–DC converters, the load-switching stage, and

the LTC4353 ideal-diode controller introduced several non-ideal effects that could not be completely predicted from the nominal component behaviour.

Different hardware-control configurations and firmware strategies were therefore tested during the experimental campaign. Each iteration was used to identify the limitations of the implemented power-path architecture and to refine the Energy Management System. The final operating strategy resulted from a trade-off among response speed, load-bus stability, electrical isolation of the power branches, supercapacitor utilization, and current redistribution between the two energy sources.

5.7.1 Initial Load-Sharing Objective

The initial objective of the HESS control strategy was to obtain a simultaneous contribution from the battery and supercapacitor branches during the *ASSIST* state. In the desired operating condition, the battery would continue supplying part of the load demand, while the supercapacitor would provide the additional power required during transient actuator events.

A nominal sharing target close to 50/50 was initially considered as a useful reference for evaluating the interaction between the two branches. The output voltage of the boost converter was therefore adjusted within a narrow interval around the buck-converter output voltage in order to promote simultaneous conduction through the LTC4353 ideal-diode stage.

The experimental tests showed, however, that the effective current distribution was extremely sensitive to the voltage difference between the two converter outputs. Differences of only a few millivolts were sufficient to significantly modify the contribution of each source and, in several operating conditions, to cause one branch to become dominant.

Consequently, an accurately regulated and repeatable 50/50 power split could not be maintained through voltage matching alone.

5.7.2 Load-Switch Enable Control and Branch-Isolation Limitations

A first refinement consisted of directly using the enable signals associated with the load-switching stage to control the connection of the battery and supercapacitor branches. The objective was to reduce the delay associated with the supercapacitor intervention and obtain a more deterministic activation of the auxiliary power path.

In this configuration, the main switching stage was maintained active, while the individual branch-enable signals were used to determine which source was connected to the common load bus. This approach allowed the supercapacitor

branch to enter more rapidly than with a strategy based only on the converter startup sequence.

However, the experimental results showed that the enable-based control did not provide sufficient electrical isolation between the two power paths. Residual interaction between the battery and supercapacitor branches was observed during both assist and recharge operation.

In particular, voltage drops appeared on the regulated load bus when the supercapacitor branch was connected and during activation of the charging subsystem. These effects indicated that the load-switching stage could not behave as an ideal source selector under all operating conditions. The incomplete isolation of the branches introduced undesired current paths and disturbed the regulated bus during transitions among *BATT*, *ASSIST*, and *RECOVERY*.

Although the enable-based strategy improved the intervention speed of the supercapacitor, the resulting voltage disturbances and interaction between the power branches were not considered sufficiently robust for the final robotic-hand application. Therefore, this configuration was not retained as the definitive control solution.

5.7.3 Ideal-Diode Takeover and Load-Sharing Instability

The experimental analysis of the LTC4353-based power path showed that the ideal-diode controller naturally tended to operate as a source-selection mechanism rather than as a stable current-sharing element.

When the boost-converter output voltage was slightly higher than the buck-converter voltage, the supercapacitor branch rapidly became the dominant source. Conversely, when the boost output voltage was slightly lower, the supercapacitor contribution decreased sharply and the battery branch supplied almost the entire load demand.

A limited transition region existed in which both branches simultaneously conducted. However, this interval was very narrow and strongly affected by:

- converter output-voltage regulation accuracy;
- switching ripple and measurement noise;
- MOSFET conduction losses;
- wiring and connector resistance;
- supercapacitor equivalent series resistance;
- instantaneous variations in the robotic-hand load.

As a result, maintaining the two sources inside the simultaneous-conduction region proved difficult and poorly repeatable. Small disturbances were sufficient to move the operating point from battery-dominant to supercapacitor-dominant operation, or vice versa.

The source-takeover behaviour was nevertheless beneficial during rapid actuator transients. When the supercapacitor branch became dominant, the battery current was substantially reduced and the auxiliary storage element supplied most of the instantaneous power demand. Therefore, although the observed behaviour differed from the original load-sharing objective, it remained compatible with the main purpose of the HESS, namely the reduction of transient battery stress.

5.7.4 Soft-Handoff Experimental Evaluation

A soft-handoff strategy was subsequently investigated in order to avoid an abrupt transfer of the load demand from the supercapacitor branch back to the battery at the end of the assist phase.

The implemented algorithm progressively reduced the boost-converter voltage reference once the transient condition had ended. The objective was to gradually decrease the supercapacitor contribution and force the system to pass through the small simultaneous-conduction region of the LTC4353.

The load-power derivative was used to identify the end of the fast transient. When the derivative remained below the selected stability threshold, the controller began reducing the boost-voltage command in small increments.

Although this approach reduced the abruptness of the voltage command, the experimental tests revealed instability within the narrow voltage interval required for load sharing. Minor variations in converter output voltage and load demand caused repeated transitions between battery-dominant and supercapacitor-dominant operation.

Rather than producing a controlled current redistribution, the slow reduction of the boost reference increased the time spent inside an electrically sensitive operating region. Oscillations were consequently observed in the current contribution of the two branches and in the behaviour of the load-switching stage.

The experimental results therefore showed that the implemented hardware was not suitable for maintaining a stable soft handoff over an extended interval. For this reason, the strategy was not retained as the primary mechanism for obtaining an accurate power split.

A faster and more deterministic transition was preferred in the final implementation, reducing the time spent within the unstable simultaneous-conduction region.

5.7.5 Comparison between Switch-Based and Enable-Based Control

Two strategies were experimentally evaluated to control the connection of the supercapacitor branch to the common load bus.

In the *switch-based configuration*, the battery branch remained connected to the load-sharing stage, while the supercapacitor branch was connected and disconnected through the dedicated power switch placed downstream of the boost converter.

In the *enable-based configuration*, the dedicated switch was maintained active and the enable inputs of the two load-sharing channels were used to select the active branch. The input polarity was experimentally verified, with a low logic level enabling the corresponding channel and a high logic level disabling it.

Both strategies successfully activated the supercapacitor during high-power events. The enable-based configuration provided a slightly faster response and avoided the additional series element introduced by the external switch. However, disabling a branch through the load-sharing enable inputs did not always ensure complete electrical isolation. Conversely, the switch-based configuration provided a clearer physical disconnection of the supercapacitor branch. This improved branch isolation, reduced undesired current paths, and produced more robust behaviour during recharge and fault conditions.

Table 5.6 summarizes the main differences between the two configurations.

Table 5.6: Qualitative comparison between enable-based and switch-based supercapacitor control.

Aspect	Enable-based control	Switch-based control
Supercapacitor activation	Through the enable inputs of the load-sharing stage.	Through the dedicated switch on the supercapacitor branch.
Branch isolation	Electronic isolation.	Physical disconnection of the supercapacitor branch.
Behaviour during recharge	Residual interactions with the common bus could occur.	More robust because the branch could be physically disconnected.
Reverse-current protection	Mainly entrusted to the ideal-diode stage.	Improved by the additional physical isolation.
Experimental response	Slightly faster median response.	Slightly slower response, but improved robustness and isolation.

The final comparison therefore considered not only the response time, but also load-bus stability, branch isolation, reverse-current protection, recharge behaviour, and fault management.

5.7.6 Timing Characterization under Pulsed-Load Operation

The dynamic response of the enable-based and switch-based configurations was characterized using the controlled pulsed-load setup.

The pulsed load was selected because its activation instant was known and repeatable, allowing the different contributions to the supercapacitor intervention delay to be separated. Tests performed with the robotic hand were instead used for functional validation, since the exact beginning of the motor transients depended on the movement, mechanical load, and motor synchronization.

Four relevant time instants were recorded:

- t_{load} : physical activation of the pulsed load;
- t_{request} : generation of the request to enter the **ASSIST** state;
- t_{command} : application of the command to the enable inputs or to the dedicated switch;
- t_{SC} : instant at which the supercapacitor current exceeded the selected threshold.

The **ASSIST** detection delay was defined as:

$$t_{\text{detection}} = t_{\text{request}} - t_{\text{load}}. \quad (5.24)$$

The software delay was defined as:

$$t_{\text{software}} = t_{\text{command}} - t_{\text{request}}, \quad (5.25)$$

while the hardware delay was calculated as:

$$t_{\text{hardware}} = t_{\text{SC}} - t_{\text{command}}. \quad (5.26)$$

The total response delay from the **ASSIST** request to the effective supercapacitor contribution was therefore:

$$t_{\text{response}} = t_{\text{SC}} - t_{\text{request}} = t_{\text{software}} + t_{\text{hardware}}. \quad (5.27)$$

The supercapacitor contribution was considered active when:

$$I_{\text{SC}} > 0.10 \text{ A}, \quad (5.28)$$

thus preventing measurement noise and small current fluctuations from being classified as valid intervention events.

Since isolated outliers were present, the median was used as the main comparison parameter. The resulting values are reported in Table 5.7.

Table 5.7: Median timing results obtained under controlled pulsed-load operation.

Timing quantity	Enable-based control	Switch-based control
ASSIST detection delay	2.450 ms	3.162 ms
Software delay	0.805 ms	0.805 ms
Hardware delay	19.805 ms	22.633 ms
Response delay	20.980 ms	23.438 ms

The software delay was practically identical in the two configurations because the same acquisition and state-machine logic was used. The main difference was therefore associated with the hardware response, which was slightly faster in the enable-based configuration.

The ASSIST detection delay also differed between the two datasets, but this quantity did not depend directly on the selected switching strategy. It was mainly influenced by different conditions.

The distributions also showed isolated low- and high-delay events in both configurations, indicating that part of the variability was associated with the converter dynamics, the ideal-diode takeover, the sampling phase, and the current threshold used to identify the supercapacitor intervention.

Figure 5.13 shows the timing boxplot obtained for the enable-based configuration.

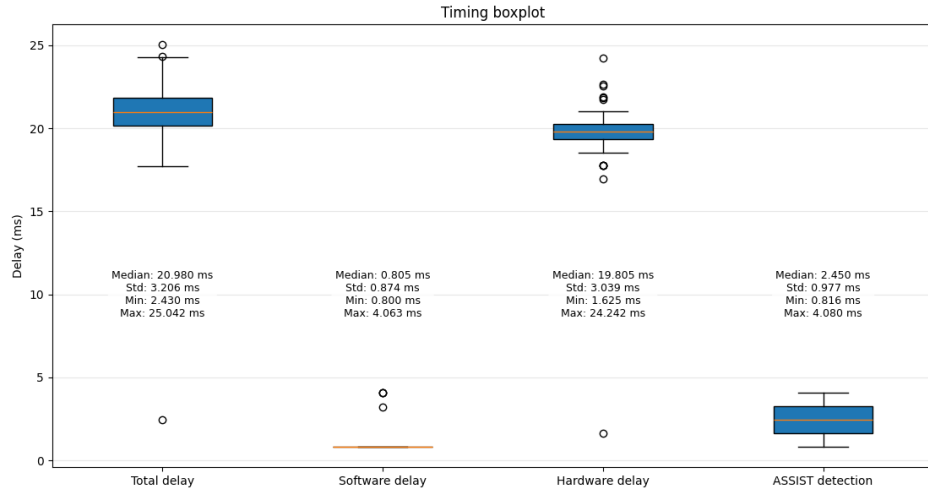


Figure 5.13: Timing boxplot obtained under controlled pulsed-load operation for the enable-based configuration.

Figure 5.14 shows the corresponding timing boxplot for the switch-based configuration.

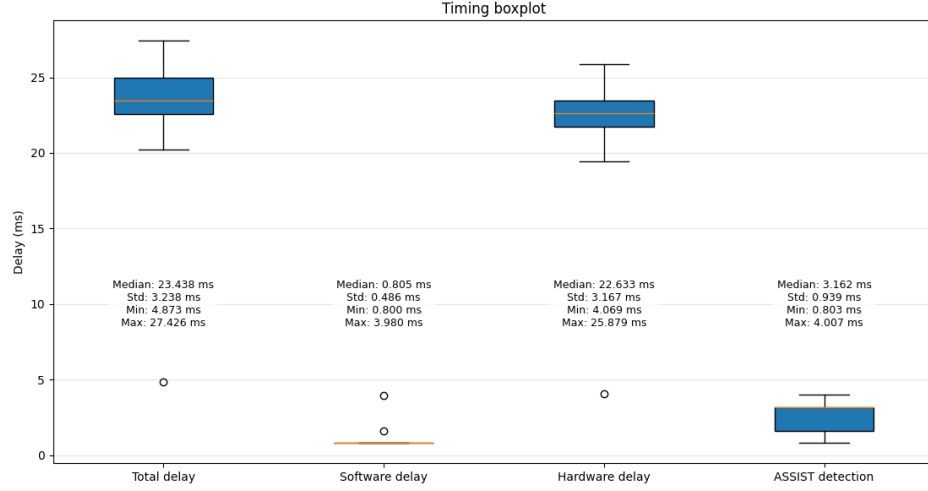


Figure 5.14: Timing boxplot obtained under controlled pulsed-load operation for the switch-based configuration.

The complete timing distributions are compared in Figure 5.15.

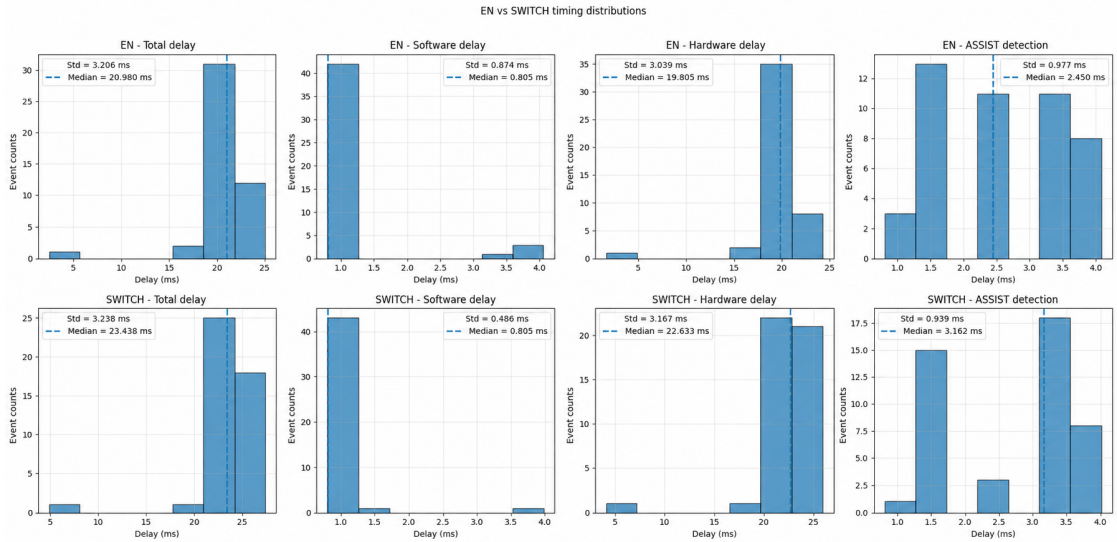


Figure 5.15: Comparison of the timing distributions obtained with the enable-based and switch-based control strategies. The dashed lines indicate the median values.

The enable-based configuration therefore exhibited a moderate timing advantage. However, the difference of a few milliseconds was not sufficient to compensate for the weaker branch isolation and the less robust behaviour observed during supercapacitor recharge.

5.7.7 Recharge Current Selection

The supercapacitor recharge current was also experimentally adjusted in order to obtain a suitable compromise between recovery time and battery stress.

A high recharge current reduces the time required to restore the supercapacitor energy reserve. However, it also increases the battery current during the *RECOVERY* state and may produce additional voltage disturbances on the shared power architecture.

Conversely, a lower recharge current reduces the instantaneous demand imposed on the battery but increases the interval during which the supercapacitor is not fully available for a new assist event.

Different charging-current settings were evaluated through the programmable digital potentiometer. The experimental analysis showed that the selected current had to satisfy three main requirements:

- restore the supercapacitor voltage within a reasonable time;
- avoid excessive battery-current demand during recovery;
- preserve the stability of the regulated load bus.

The final charging-current setting was therefore selected as an experimental trade-off rather than by considering recharge speed alone. This choice ensured that the recovery process remained compatible with continuous operation of the robotic hand and with the power demand of the auxiliary electronic loads.

5.7.8 Recharge Hysteresis Optimization

During the early validation stages, the supercapacitor recharge strategy showed an undesired oscillatory behaviour between the *BATT* and *RECOVERY* states.

The initial voltage hysteresis between recharge activation and deactivation was too narrow. As a consequence, small variations in the supercapacitor terminal voltage were sufficient to repeatedly activate and disable the charging circuit.

These variations were associated with measurement noise, supercapacitor relaxation, and the voltage rebound occurring after changes in charging or discharging current. The resulting repeated transitions caused unnecessary energy transfer from the battery and increased the average battery demand even when the robotic load was inactive.

To address this issue, the recharge thresholds were revised by increasing the hysteresis window. The recovery activation threshold was reduced, while the upper threshold used to terminate charging was maintained close to the target supercapacitor voltage.

The revised strategy prevented the charger from being activated by minor voltage fluctuations and allowed a larger portion of the stored supercapacitor energy to be used before initiating a new recovery cycle.

The optimization reduced unnecessary recharge requests and improved the stability of the finite-state-machine operation. It also ensured that the supercapacitor was recharged only after a meaningful amount of energy had been extracted.

5.7.9 Final Control Philosophy

Based on the experimental observations, the final control philosophy was revised with respect to the initial objective of achieving a balanced current distribution between the battery and the supercapacitor.

The tests showed that prolonged simultaneous conduction of the two branches could lead to unstable source interaction because the current distribution was strongly influenced by small voltage differences, converter tolerances, and the dynamic behaviour of the ideal-diode stage. For this reason, an accurately regulated 50/50 power split was no longer considered a primary control objective.

The comparison between the enable-based and switch-based configurations also showed that the fastest response did not necessarily correspond to the most robust operating condition. The enable-based strategy provided slightly lower median intervention delays, but it did not always guarantee complete isolation of the disabled branch. This limitation was particularly relevant during supercapacitor recharge and during transitions between operating states.

The switch-based configuration was therefore selected for the final implementation. Although it introduced a small additional conduction resistance and a slightly longer response time, it ensured a clearer physical disconnection of the supercapacitor path, improved fault handling, and reduced undesired interactions between the two power branches.

The final control priorities were defined as follows:

- stable operation of the regulated 6 V load bus;
- rapid and reliable activation of the supercapacitor during actuator transients;
- reduction of the instantaneous battery-current demand;
- physical isolation of the supercapacitor branch during recharge and fault conditions;

- deterministic transitions among the finite-state-machine states;
- avoidance of prolonged operation within the unstable simultaneous-conduction region.

During normal operation, the battery supplied the average energy demand and the auxiliary electronic loads. When a high-power event was detected, the supercapacitor switch was closed and the supercapacitor branch was allowed to take over a substantial portion of the transient load.

The load-sharing stage remained responsible for preventing reverse current and for managing the source takeover after connection of the supercapacitor branch. However, the control algorithm did not attempt to impose an exact sharing percentage. Instead, the supercapacitor was allowed to become the dominant source during the **ASSIST** state.

At the end of the transient, the supercapacitor contribution was progressively reduced before opening the switch, in order to avoid abrupt current transfer and load-bus disturbances. The branch was then physically disconnected before the beginning of the recharge phase.

The final strategy therefore prioritized load-bus stability, battery peak-current reduction, and robust branch isolation over minimum activation time and exact current sharing. This operating principle was considered more suitable for the target prosthetic application, where continuity of operation and protection of the battery are more important than maintaining a predefined power-sharing ratio.

5.7.10 System Efficiency Evaluation

The overall efficiency of the HESS was evaluated throughout the experimental campaign using the real-time measurements acquired from the distributed sensing infrastructure.

The total useful output power was calculated by considering the power delivered to the main 6 V load and to the auxiliary 5 V and 3.3 V outputs:

$$P_{\text{out,tot}} = P_{6\text{V}} + P_{5\text{V}} + P_{3.3\text{V}}. \quad (5.29)$$

During battery-powered and supercapacitor-assisted operation, the total input power was evaluated as the sum of the power provided by the active energy sources:

$$P_{\text{in,tot}} = P_{\text{batt}} + P_{\text{SC}}, \quad (5.30)$$

where P_{batt} is the power supplied by the battery branch and P_{SC} is the power supplied by the supercapacitor branch. During discharge, P_{SC} is positive because energy is delivered to the load, whereas during recharge it becomes negative because energy is transferred toward the supercapacitor.

The system efficiency was calculated as

$$\eta_{\text{sys}} = \frac{P_{\text{out,tot}}}{P_{\text{in,tot}}} \cdot 100. \quad (5.31)$$

Particular attention was required during the *RECOVERY* state. In this condition, part of the power provided by the battery is intentionally transferred to the supercapacitor. This contribution is not delivered directly to the external load, but it is not dissipated as heat and therefore should not be interpreted as a system loss.

For this reason, the efficiency analysis was revised in order to distinguish between actual conversion losses and energy intentionally stored in the supercapacitor. This correction provided a more representative evaluation of the overall HESS performance and avoided an artificial reduction of the calculated efficiency during charging intervals.

A representative analysis was then performed under the most demanding pulsed-load condition considered for the target prosthetic application. This test reproduced repeated high-power transient events and therefore represented the most significant condition for evaluating both the transient-support capability and the energy efficiency of the HESS.

Figure 5.16 reports the complete experimental acquisition.

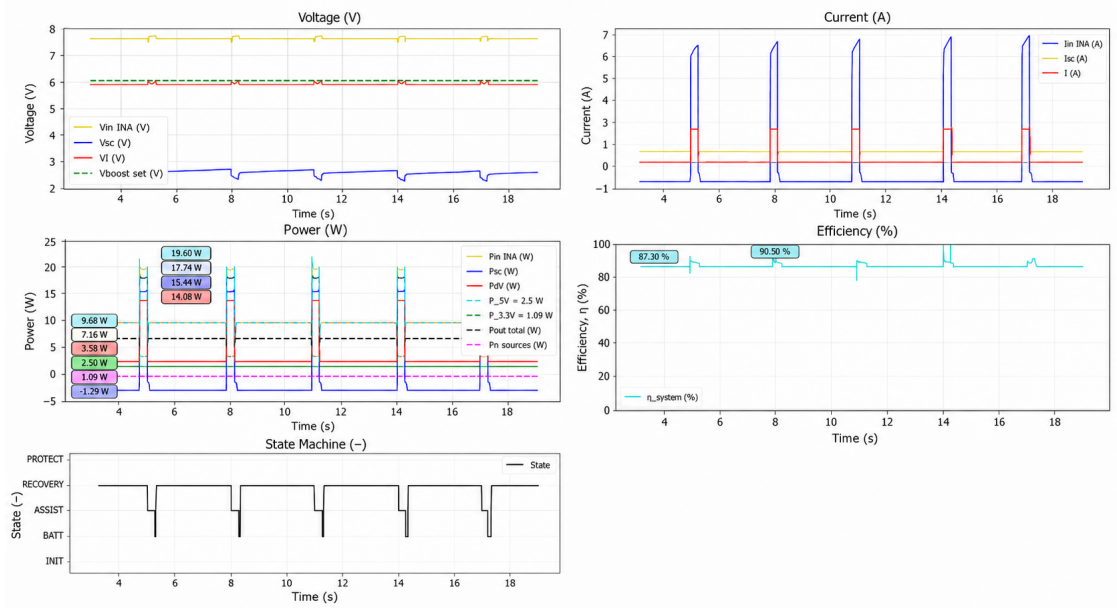


Figure 5.16: Efficiency evaluation under the most demanding pulsed-load condition representative of the target prosthetic application. The figure reports the main electrical quantities together with annotated power and efficiency values during repeated transient events.

As highlighted by the annotations in Figure 5.16, the total input power provided by the active sources reached approximately

$$P_{\text{in,tot}} \simeq 19.60 \text{ W}, \quad (5.32)$$

while the total useful output power was approximately

$$P_{\text{out,tot}} \simeq 17.74 \text{ W}. \quad (5.33)$$

The main 6 V pulsed load absorbed approximately

$$P_{6\text{V}} \simeq 14.08 \text{ W}, \quad (5.34)$$

while the auxiliary output contributions were

$$P_{5\text{V}} = 2.50 \text{ W} \quad (5.35)$$

and

$$P_{3.3\text{V}} = 1.09 \text{ W}. \quad (5.36)$$

During the recharge intervals, the supercapacitor power reached approximately

$$P_{\text{SC}} \simeq -1.29 \text{ W}, \quad (5.37)$$

where the negative sign indicates energy flowing into the storage element.

The measured system efficiency remained between approximately 87.3% and 90.5% during the repeated pulsed-load events. These values confirmed that the HESS maintained a high energy-transfer efficiency even under the most severe transient condition considered for the prosthetic application.

The efficiency variations observed during the test were mainly associated with changes in the active power paths and in the operating point of the DC–DC converters. During high-power intervals, the fixed losses of the control and conversion stages represented a smaller fraction of the transferred power, and the system efficiency approached the upper part of the measured range. Conversely, during lower-power intervals, the relative contribution of fixed converter losses and auxiliary electronic consumption became more significant.

The measured efficiency values were consistent with the individual characterization of the buck, boost, and auxiliary conversion stages. They also confirmed that the integration of the supercapacitor branch did not introduce prohibitive energy penalties, while providing substantial benefits in terms of transient power support and battery-current reduction.

Overall, the experimental results demonstrated that the HESS can support repeated high-power transients while maintaining an average efficiency compatible

with the requirements of wearable robotic applications. The most demanding pulsed-load test therefore represents a conservative validation of the system performance under operating conditions comparable to the peak demand of the target hand exoprosthesis.

5.8 Smart Battery Monitoring and Charge Control

As a final integration step, the embedded firmware was extended to include the monitoring and charge control of the smart lithium-ion battery through the System Management Bus (SMBus). This functionality allowed the battery charging process to be supervised directly by the ESP32-S3 and integrated into the same real-time monitoring infrastructure used for the HESS.

The smart-battery interface was implemented on a dedicated I2C-compatible bus, physically separated from the communication network used by the INA228 sensing devices and programmable HESS peripherals. The bus connected the controller to both the smart battery and the PMM240 power-management module.

The smart battery was addressed according to the Smart Battery System specification and provided direct access to the main internal battery variables, including:

- battery terminal voltage;
- charging or discharging current;
- state of charge;
- remaining capacity;
- battery temperature;
- internal status information.

Unlike the voltage measured by the INA228 on the external power path, the battery voltage acquired through SMBus represents the value directly reported by the battery-management electronics. This measurement was therefore used as the main variable for supervising the charging process.

5.8.1 SMBus Communication and Battery Data Acquisition

The ESP32-S3 periodically reads the battery voltage, current, state of charge, remaining capacity, and temperature through dedicated Smart Battery System

commands. The acquired data are validated before being used by the charge-control logic.

If an SMBus transaction fails, the controller maintains the previous charging state rather than immediately enabling or disabling the charger. This behaviour prevents temporary communication errors from producing undesired charge commutations.

The battery data are also transmitted through the serial interface and made available to the graphical user interface. This enables the user to monitor the battery condition together with the HESS voltages, currents, power flows, finite-state-machine state, and supercapacitor contribution.

5.8.2 Battery Charge-Control Logic

The charging process is managed through the PMM240 power-management module. The controller programs two main parameters:

- the input-current limit of the external power supply;
- the maximum current allocated to battery charging.

In the implemented configuration, the PMM240 input-current limit was set to

$$I_{\text{in,lim}} = 1000 \text{ mA}, \quad (5.38)$$

while the requested battery charge-current limit was set to

$$I_{\text{chg,lim}} = 500 \text{ mA}. \quad (5.39)$$

The PMM240 gives priority to the user application. Therefore, the current available for battery charging may be reduced when the HESS and the robotic hand require a significant fraction of the available input power.

The charge enable command is controlled using the battery voltage and state of charge acquired through SMBus. Charging is requested when the measured battery voltage falls below the lower activation threshold:

$$V_{\text{batt,ch,on}} = 7.20 \text{ V}. \quad (5.40)$$

Once charging has been enabled, the process remains active until the battery reaches either the upper voltage threshold

$$V_{\text{batt,ch,off}} = 8.20 \text{ V}, \quad (5.41)$$

or the selected state-of-charge threshold:

$$\text{SoC}_{\text{off}} = 95\%. \quad (5.42)$$

This latch-based logic prevents the charger from being repeatedly enabled and disabled when the battery voltage fluctuates around a single threshold.

A minimum residence time and a multi-sample confirmation mechanism were also introduced before changing the charging state. These constraints reduce the sensitivity of the control logic to measurement noise, temporary voltage variations, and isolated SMBus communication errors.

The presence of the external charger is verified through a dedicated PMM240 status signal. If the external supply is not detected, the battery charge command is disabled independently of the measured battery voltage.

When charging is disabled, the PMM240 input-current limit is set to zero. Since the PMM240 charge-current register does not accept a zero-current value, its charge-current limit is maintained at the minimum valid setting, while the zero-input-current command effectively prevents energy transfer to the battery.

The PMM240 configuration commands include a Packet Error Code (PEC), calculated according to the SMBus CRC-8 polynomial. The firmware verifies the result of each write operation and reports the communication status to the monitoring interface.

5.8.3 GUI Integration

The graphical user interface was extended to display the variables acquired from the smart battery and the status of the charging subsystem. In particular, the interface reports:

- battery voltage measured through SMBus;
- battery current;
- battery state of charge;
- charge-enable status;
- external-charger presence;
- result of the PMM240 configuration command.

The integration of these quantities into the HESS monitoring interface made it possible to observe the interaction among battery charging, robotic-hand operation, supercapacitor assistance, and recovery events within a single acquisition.

Figure 5.17 shows a representative acquisition of the complete HESS control system with smart-battery monitoring enabled.

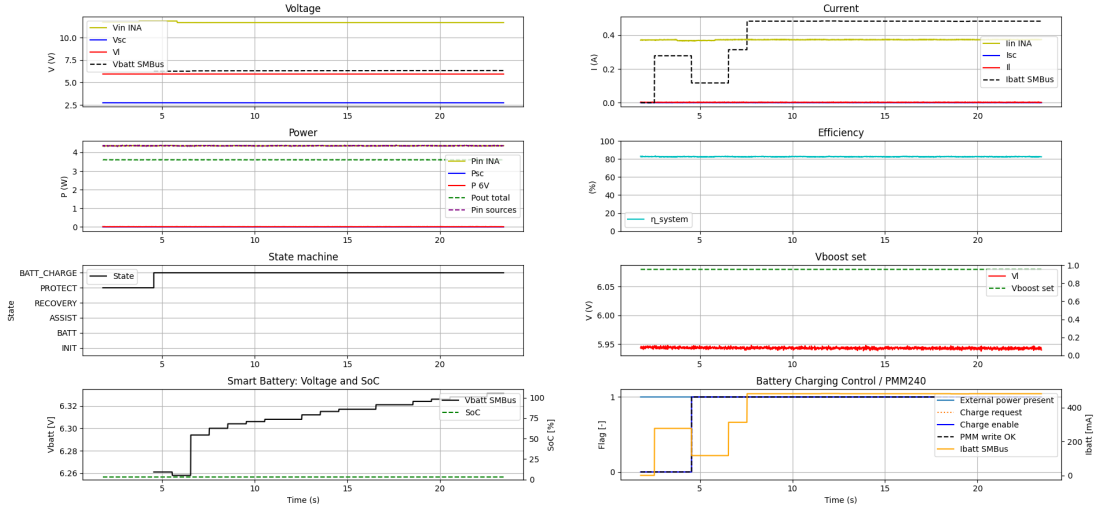


Figure 5.17: Integrated monitoring of the HESS and smart-battery charging subsystem. The plots include the electrical quantities of the main power branches, the finite-state-machine transitions, the battery voltage and state of charge acquired through SMBus, and the PMM240 charge-control signals.

The acquisition shows that the smart-battery variables can be monitored simultaneously with the HESS operating states. The battery charge command remains active according to the implemented voltage and state-of-charge conditions, while the PMM240 current allocation is updated without preventing the EMS from entering the *ASSIST* or *RECOVERY* states.

The charging subsystem therefore operates as an additional supervisory layer and does not replace the HESS finite-state machine. The EMS continues to manage the interaction between the battery, supercapacitor, and robotic load, while the smart-battery controller supervises the restoration of the main energy source.

5.8.4 Experimental Battery-Charging Profile

A complete battery-charging acquisition was performed in order to verify the evolution of the main smart-battery variables during the charging process. Figure 5.18 reports the battery voltage, charging current, state of charge, remaining capacity, and temperature.

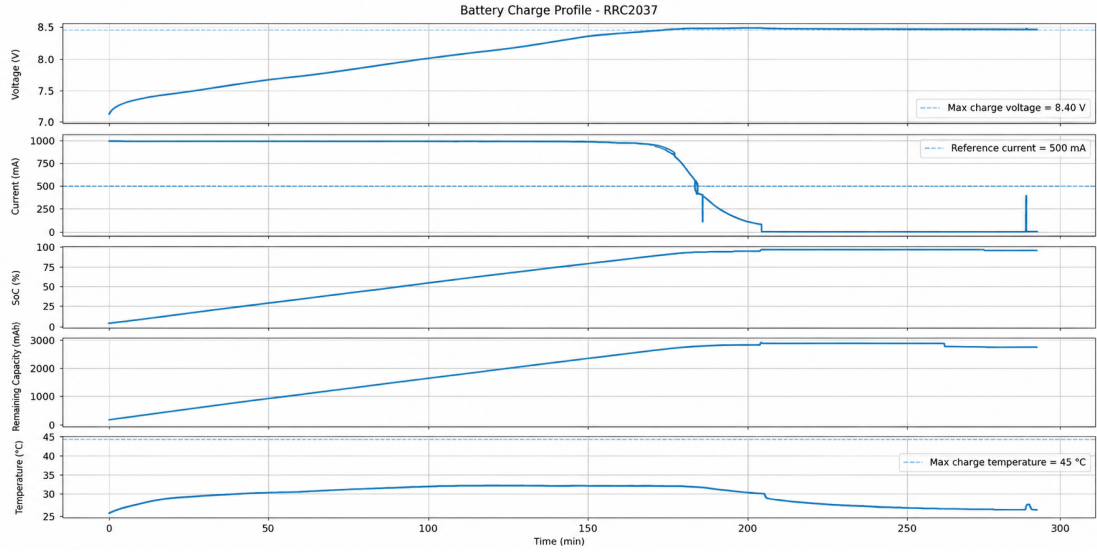


Figure 5.18: Complete charging profile of the RRC2037 smart battery acquired through SMBus, including battery voltage, charging current, state of charge, remaining capacity, and temperature.

The battery voltage progressively increased toward the maximum charging value of approximately 8.4 V. During the first part of the process, the charging current remained approximately constant. As the battery voltage approached its maximum value, the current progressively decreased, indicating the transition toward the final constant-voltage charging phase.

The state of charge and remaining capacity increased throughout the charging process and reached their maximum values near the end of the acquisition. The battery temperature remained well below the selected maximum charging temperature of 45 °C, confirming that no critical thermal condition occurred during the test.

The isolated current variations observed near the end of the acquisition can be associated with charger supervision, communication updates, or internal battery management operations. They did not produce significant variations in battery voltage or temperature.

Overall, the experimental results confirmed the correct acquisition of the smart-battery variables and the successful integration of the PMM240 charge-control commands into the HESS firmware and graphical monitoring interface. This functionality completes the power-management architecture by combining transient power support through the supercapacitor with supervised recharge of the primary battery.

Chapter 6

Conclusions and Future Developments

The work was carried out within the broader NerveRepack research activity, starting from a previous hardware prototype developed by the research team.

Within this framework, the thesis focused on the experimental optimization of the HESS operation, with particular attention to the implementation and refinement of the embedded Power Management System (PMS), the tuning of the control thresholds and power-path transitions, the improvement of the real-time monitoring infrastructure, and the experimental validation of the system under controlled and application-oriented operating conditions.

The system combines a lithium-ion battery, used as the main energy source, and a supercapacitor, employed to support short-duration actuator transients. The control strategy was implemented on an ESP32-S3 through a finite state machine managing battery-powered operation, supercapacitor assistance, recovery, protection, and smart-battery charging.

The experimental activity confirmed the correct operation of the main power stages, sensing infrastructure, communication interfaces, and charging circuits. The optimized acquisition routine reached an effective sampling frequency of approximately 1.2 kHz, which was sufficient to detect the rapid load variations generated by the robotic hand.

The hand load was characterized under idle, single-finger, and full-hand conditions. The measurements confirmed a strongly variable and impulsive power profile, supporting the use of a hybrid battery–supercapacitor architecture. The results were then used to tune the load-power and power-derivative thresholds of the PMS.

The system response was characterized more accurately through a controlled pulsed load, whose activation instant was known and repeatable. This allowed the total intervention time to be separated into ASSIST detection, software, and

hardware contributions.

Two control configurations were compared. The enable-based strategy showed a slightly faster response, with a median total delay of 20.980 ms, compared with 23.438 ms for the switch-based strategy. However, the enable-based configuration did not always guarantee complete electrical isolation of the inactive branch, especially during recharge and state transitions.

The switch-based configuration was therefore retained in the final implementation because it provided clearer physical isolation, more robust recharge behaviour, and more deterministic fault management. The final choice was thus based on overall system stability and reliability rather than on response time alone.

The experimental tests also showed that the LTC4353-based load-sharing stage did not provide a stable and repeatable 50/50 current split. The effective power distribution was highly sensitive to small voltage differences between the buck and boost outputs. In practice, the system often operated through source takeover, with the supercapacitor becoming dominant during assist events.

Although this differed from the initial load-sharing objective, it still achieved the main purpose of the HESS by reducing the instantaneous battery-current demand during fast load transients.

Under the most demanding pulsed-load conditions, the overall system efficiency was approximately 87%–90%, while the regulated 6 V load bus remained stable with variations in the order of tens of millivolts.

The validation with the robotic hand confirmed the same general behaviour under real electromechanical conditions. The battery supplied the average demand, while the supercapacitor supported the most demanding transients and was subsequently recharged through the dedicated recovery state.

The firmware and graphical interface were also extended to include the RRC2037 smart battery. Voltage, current, state of charge, remaining capacity, and temperature were acquired through SMBus communication. A dedicated charging state was added to the finite state machine, allowing the PMM240 charging path to be controlled according to the external power presence and battery condition.

The complete battery-charging profile confirmed the expected charging behaviour, with progressive voltage increase, current reduction near full charge, increasing state of charge, and temperature maintained below the selected safety limit.

Overall, the experimental results confirmed the feasibility of the considered HESS architecture for robotic prosthetic applications. The final control strategy prioritizes:

- stability of the regulated 6 V load bus;
- rapid supercapacitor support during actuator transients;
- reduction of battery-current peaks;

- reliable branch isolation during recharge and fault conditions;
- deterministic state transitions;
- supervised charging of the supercapacitor and smart battery.

Future Developments

Future developments should first address the limitations of the current load-sharing stage. A different power-path controller, or an actively regulated converter architecture, could provide more accurate control of the battery and supercapacitor contributions.

A particularly relevant option would be to combine the enable-based and switch-based strategies rather than treating them as mutually exclusive. In a more advanced architecture, the enable inputs could be used for fast and flexible source coordination, while the external switch could preserve physical isolation during recharge, startup, shutdown, protection, and persistent fault conditions.

Such an EN-switch combination could exploit the main advantage of each configuration:

- faster actuation and direct power-path control through the enable signals;
- robust electrical isolation and deterministic safety through the external switch.

This solution would require a more complex control logic, including interlocks, dead times, and additional checks to prevent invalid switching configurations. Its adoption should therefore depend on the future requirements of the NerveRepack project, including the selected robotic platform, actuator power levels, safety constraints, and integration with the central control system.

The supercapacitor subsystem could also be improved by adopting a higher capacitance or higher voltage device. A larger energy reserve would extend the duration of assist events and reduce the boost-converter input current, although the charging stage and voltage thresholds would need to be adapted accordingly.

From the control perspective, the current strategy is reactive because the supercapacitor is activated after the load transient has been detected. Future work could use motor commands or higher-level robotic control information to anticipate actuator activation and pre-enable the auxiliary branch.

Adaptive thresholds based on battery state of charge, temperature, supercapacitor voltage, expected movement, and recent load history could also improve system efficiency and responsiveness.

Further tests should include longer operating sequences, repeated grasping cycles, different battery states of charge, and validation with the complete NerveRepack electronic platform.

Finally, energy harvesting may be investigated as a complementary source for low-power electronics or auxiliary charging. It is not expected to replace the battery for actuator supply, but it could contribute to reducing the overall energy demand and extending system autonomy.

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