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*Article*

# Experimental Study on Heuristics Energy Management Strategy for Hybrid Energy Storage System

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**Abstract:** Energy management strategy (EMS) is a decision-making algorithm for effective power allocation between storage devices in a hybrid energy storage system (HESS). Source voltages, state-of-charge (SOC), terminal voltage of load, and rate of change of battery current must be considered while implementing EMS and hence they are termed as performance indicators. This paper presents the development of an EMS designed to manage the performance indicators of the sources and ensure efficient power distribution through a shared bus topology. A shared bus topology employs individual converters for each source, offering efficient control over these sources. Rule-based fuzzy logic control ensures efficient power distribution between batteries and ultracapacitors. Additionally, hardware has been developed to validate the power-allocation strategy and regulate the DC-link voltage in the Energy Management System (EMS). The dSPACE MicroLabBox is utilized for the implementation of real-time control strategies. A battery and an ultracapacitor bank are utilized in a Hybrid Energy Storage System. The simulation outcomes have been corroborated by experimental data, affirming the efficacy of the proposed energy management strategy.

**Keywords:** battery; energy management strategy; energy storage; ultracapacitor

## 1. Introduction

The energy and power densities of a source are responsible for the effective performance of a standalone load that is not connected to the grid [1]. For example, in a battery electric vehicle (BEV), the battery suffers from many short-term transients which require colossal power [2–4]. Being a single source and due to these transients, the battery's performance gets degraded [5,6]. In literature, multiple storage is identified as the only option to safeguard the battery. The ultracapacitor (UC) technology is one of the best hybridization sources due to its favorable properties [7–12].

To control the power transaction between the sources and the load, various EMSs are reported in the literature as rule-based and optimization-based. Being simple in nature, easily understandable, and real-time implementable, the rule-based EMS is preferred widely [13–16]. A review on intelligent energy management system for electrified vehicles is presented in [13] where characteristics of rule-based EMSs are discussed. In [14], a novel rule-based approach has been devised to achieve effective power balance between battery and supercapacitor. The supercapacitor is in a charged state at the end of each cycle in this method. On board transaction strategy is discussed in [15]. Reference [16] shows how rule-based EMS can be applied to solar, fuel cell and biomass energy storage systems. Classical EMSs are widely available in the literature [11,17–19]. Dc-link voltage regulation is considered as a prime controlling factor in microgrid systems in [11]. UC voltage and battery current rate regulation are taken as essential criterion in [17]. In [18], a diesel generator, a battery, and a photovoltaic system are utilized as HESS to provide power supply in critical circumstances. The management of the energy is dependent on fuzzy rules-based EMS. Multiple sources like battery,

UC, photovoltaic (PV) panel, and fuel cell (FC) and their integration in a specific manner are presented in [20] with a power tracking control mechanism. For battery-UC hybrid energy storage system (HESS), a control algorithm based on energy is presented in [21] for a grid system. Reference [22] has demonstrated that the UC's SOC is a controlling factor for generating the battery's reference current. Fuzzy logic controllers are also reported for controlling UC voltage, battery peak power, power allocation, and energy level handling [23–25].

The way of interconnection between the battery and UC decides the topologies. These topologies are important in regulating the source parameters. A passive topology lacks any control over performance indicators as converters are not present [26]. In a semi-active topology, only one converter is utilized, and the performance indicators of the other source remain uncontrolled. This strategy increases the current of the controlled source. In this strategy, the current of the controlled source increases [27]. Cascade topology is also employed to enhance battery life. However, as a series connection, the control is intricate and frequent charging of the UC is necessary [28]. Multiport topologies have been developed that are both compact and complex, capable of utilizing multiple sources [29,30]. The existing and proposed topologies are compared and presented in [31]. The shared bus topology is widely used to control performance indicators because it employs individual converters for the sources, making the control process straightforward [32,33].

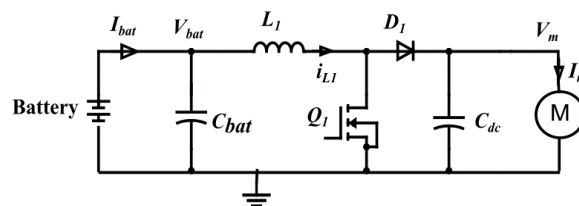
Rule-based EMSs suffer in pinpoint power distribution, but they ease in real-time implementation. Optimization-based EMS overcomes this limitation, but its real-time implementation is complex. Also, limited work is verified through hardware development. In [26], a review of different EMSs is presented. The conventional and modified rule-based EMS (MRB-EMS) is presented in [34,35] with DC-link voltage compensation. Accurate power allocation with a fuzzy logic controller is presented in [36].

In this experimental study, a hardware setup is developed with the help of the dSPACE MicroLabBox controller, converters, sources, level shifters, driver circuits, and sensors. Two different modes of power-sharing strategy are examined here. These modes are low and high-power-demand modes. DC-link voltage or load voltage is regulated to 48V irrespective of load power variations. Battery current rate limiter is also implemented and examined. The results analyzed after a detailed experimental study concur with the simulation results and confirm the effectiveness of the proposed power allocation strategy.

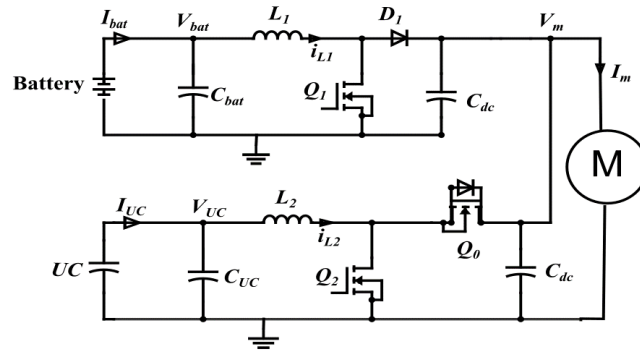
This paper is organized as follows. The circuit topology and its operation are discussed in Section - 2. Section 3 gives an overview of EMS and its development. The component design and selection of ratings are presented in Section – 4. The experimental setup and its discussion are given in section – 5. The performance analysis is provided in Section – 6, and Section – 7 presents the conclusion.

## 2. Topology and Modes of Operation

The performance indicators are effectively controlled by shared bus topology. It consists of a boost and one bidirectional dc-dc converter. The boost converter controls the power flow between the battery and the load, whereas the bi-directional converter controls the power transaction between UC and the load. The circuit topologies are shown in Figures 1 and 2. The working patterns of the switches Q1, Q2, and Q0, decide their modes of operation. For experimental study purposes, two modes are explored and studied.



**Figure 1.** Battery-boost converter for LPDM.



**Figure 2.** Shared bus topology for HPDM.

### 2.1. Mode I – Low Power Demand Mode (LPDM)

In this mode, the required load power is less than the base power. The battery alone is sufficient to tackle the load requirement. After analyzing the complete power profile, base power is defined. The base power should be such that the battery should be able to provide it easily. It is a transient free power. The circuit configuration for LPDM is presented in Figure 1. It shows the battery voltage ( $V_{bat}$ ), battery current ( $I_{bat}$ ), load voltage ( $V_m$ ), load current ( $I_m$ ), input capacitor ( $C_{bat}$ ), Inductor ( $L_1$ ), Inductor current ( $i_{L1}$ ), switch ( $Q_1$ ), diode ( $D_1$ ), and dc-link capacitor ( $C_{dc}$ ), all related to the boost converter circuit.

Expression for load voltage for this mode is given by Equation (1).

$$V_m(t) = \frac{1}{C_{dc}} \int i_{L1}(t) dt \quad (1)$$

### 2.2. Mode II – High Power Demand Mode (HPDM)

In this mode, the power required by the load is more than the base power. This additional requirement of power is fulfilled by the UC bank. Figure 2 represents the circuit configuration for this mode of operation. It shows the UC voltage ( $V_{UC}$ ), UC current ( $I_{UC}$ ), input capacitor ( $C_{UC}$ ), inductor ( $L_2$ ), inductor current ( $i_{L2}$ ), and switches ( $Q_2$  and  $Q_0$ ), all related to the bi-directional converter circuit.  $d_{Q1}$  and  $d_{Q2}$  are the duty ratios of the two pulses generated for  $Q_1$  and  $Q_2$  switches respectively. In this mode, both converters operate together to provide the required power to the load.

Equations (2) – (6) represent the operation of this mode. Here, two pulses are generated for the switches  $Q_1$  and  $Q_2$  simultaneously for the operation.

$$V_m = \frac{V_{bat}}{1-d_{Q1}} = \frac{V_{UC}}{1-d_{Q2}} \quad (2)$$

$$i_m(t) = i_{L1}(t) + i_{L2}(t) \quad (3)$$

$$i_{L1}(t) = \frac{1}{L_1} \int v_{bat}(t) d_{Q1} dt \quad (4)$$

$$i_{L2}(t) = \frac{1}{L_2} \int v_{UC}(t) d_{Q2} dt \quad (5)$$

$$v_m(t) = \frac{1}{C_{dc}} \int (i_{L1}(t) + i_{L2}(t)) dt \quad (6)$$

## 3. Energy Management Strategy

A modified EMS for effective control over performance indicator is presented in [31]. A fuzzy logic controller is used to allocate the power between the battery and UC. In this experimental study, DC-link voltage regulation, power allocation, and rate limiter functionality are the main focus of the investigation. The control strategy used for the experimental verification is shown in Figure 3.

The total load power ( $P_m$ ) is calculated from load voltage ( $V_m$ ) and load current ( $I_m$ ). The fuzzy logic controller allocates power commands to the battery ( $P_{bat}$ ). The UC power ( $P_{UC}$ ) allocation is obtained from load and battery power. Based on  $P_{bat}$  and  $P_{UC}$ , current signals  $I_{bat}^*$  and  $I_{UC}^*$  are generated by dividing the power by voltages. Error in battery and UC current is generated by the difference





The expression of energy with respect to time ( $E_n(t)$ ) is given by Equation (12). This expression is used to calculate the total energy transfer and percentage of energy saved.

$$E_n(t) = \int V_{bat}(t) * I_{bat}(t)dt \quad (12)$$

4. Rating Selection and Design

4.1. Selection of Battery Rating

Equation (12) provides the energy requirement of the load. The battery should be able to deliver this energy requirement for a load running at 48V with current 25A for 1.5 hours, the energy required will be 1.8kWh. To meet this requirement, the selected battery rating is 24V and 100Ah.

4.2. UC Rating Selection

UC is used to protect the battery during peak power demand mode. This UC should drive and accept the energy from load.

The rating of the UC is calculated based on total energy required ( $W_{uc}$ ) and is tabulated in Table 1.

Table 1. UC specifications.

| Parameters         | Rating       | Parameters | Rating           |
|--------------------|--------------|------------|------------------|
| Single-cell rating | 2.7 V, 500F. | Main. UC.  | 24.3V., 55.55 F. |
| Total cell         | 9.           | Capacity.  | kJ               |

4.3. Converter Rating Selection

Converters are the medium of power exchange. A well-designed converter provides better efficiency. Converter component rating selection is done through Equations (13) – (17) [38].

$$L_1 = \frac{T_s * R_a * (1 - d_1)^2 * d_1}{2} \quad (13)$$

$$L_2 = \frac{T_s * (1 - d_2) * V_m}{2 * I_m} \quad (14)$$

$$d_1 = 1 - \frac{V_{c_{in\_min}}}{V_m} \quad (15)$$

$$C_{uc} = \frac{\Delta i_{L2} * T_s}{8 V_{uc}} \quad (16)$$

$$C_{bat} = \frac{d_1 * V_m * T_s}{R_a * \Delta V_m} \quad (17)$$

The converter efficiency is  $\eta_c$ , and the ripples in voltage and current are  $\Delta V_m$  and  $\Delta i_{L2}$ , respectively. The duty cycle for the boost converter is  $d_1$ , and for the bidirectional converter, it is  $d_2$ . The input capacitance for the battery and UC are  $C_{uc}$  and  $C_{bat}$ , respectively.  $f_s$  is the switching frequency. The parameters of the converter are shown in Table 2. The inductor value is taken as 1.5 mH and the input capacitor as 1200  $\mu$ F. The value of the output capacitor is 1200  $\mu$ F.

TABLE 2. Converter Specifications.

| Parameters                                  | Values         | Parameters                         | Values         |
|---------------------------------------------|----------------|------------------------------------|----------------|
| Minimum input voltage ( $V_{in\_min}$ )     | 24V.           | Current ripple ( $\Delta i_{L2}$ ) | 20% of $I_a$ . |
| Load voltage ( $V_m$ )                      | 48V.           | Voltage ripple( $\Delta V_m$ )     | + -2%.         |
| Converter efficiency ( $\eta_c$ )           | 80%.           | Load resistance ( $R_a$ )          | 2.5 Ohm.       |
| Switching period ( $T_s$ )                  | 1/10000 s      | $C_{uc}$                           | 1200 $\mu$ F.  |
| Rated motor current ( $I_m$ )               | 25A.           | $C_{bat}$ )                        | 1200 $\mu$ F.  |
| DC-link voltage ( $V_{dc}$ )                | 48V.           | Boost converter inductor ( $L_1$ ) | 14.44 $\mu$ H. |
| Bi-directional converter inductor ( $L_2$ ) | 40.32 $\mu$ H. | Switching frequency( $f_s$ )       | 10 kHz.        |

5. Experimental Setup

For experimental verification, dSPACE MicroLabBox is used as a controller. The complete experimental setup is shown in Figure 4. Six analog signals (load voltage and current, battery voltage and battery-boost inductor current, UC voltage, and UC-bidirectional inductor current) are used to develop the EMS for the converters in the real-time interface with dSPACE MicroLabBox. Two digital output pulses are developed for the triggering of converter modules. These two digital pulses have a level of 3.3V, but for the triggering of IGBT, the pulse level should be 15V. A level shifter shifts the pulse level from 3.3V to 15V. The level shifter is powered by 20V AC, which is provided by a 20-0-20 single-phase step-down transformer.

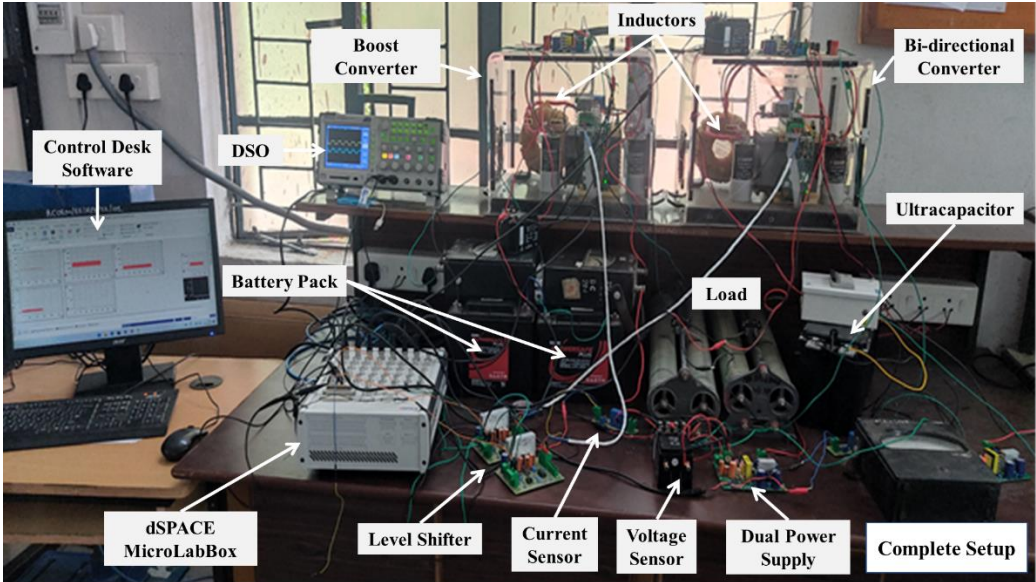


Figure 4. Experimental setup.

The analog input pin interface of the controller is used to develop the control strategy in real-time environment for the converters. Three current sensors for the inductor current and load current are used for both converters. The conversion ratio of these current sensors is 1A/1mA. Three voltage sensors, each for load voltage, battery voltage, and UC voltage, are used to give the analog signal input to the controller. 10kHz switching frequency is used for the operation of the converters. Shared bus topology is used for the effective control of the performance indicators. The components used in the hardware development are presented in Table 3.

TABLE 3. Component Ratings.

| Sr. No | Component                                 | Description                                   | Unit |
|--------|-------------------------------------------|-----------------------------------------------|------|
| 01     | dSPACE MicroLabBox and auxiliary assembly | 1. Highly efficient and high-speed controller | 01   |
|        |                                           | 2. Analog inputs crocodile pin                | 06   |
|        |                                           | 3. Digital output pulse wire                  | 02   |
|        |                                           | 4. Level shifter (two outputs – 3.3V to 15V)  | 01   |
|        |                                           | 5. Dual power supply (+-15V)                  | 04   |
|        |                                           | 6. Current sensors (LA55P)                    | 04   |
|        |                                           | 7. Voltage transducers (LEM CV3-500)          | 03   |
| 02     | Battery                                   | 12V, 100Ah battery                            | 02   |
| 03     | Ultracapacitor                            | 24.3V, 250F                                   | 01   |
| 04     | Converter Module                          | 1. Inductor – 1.5 mH, 60 A                    | 02   |
|        |                                           | 2. IGBT module – Semikron, 75A                | 02   |
|        |                                           | 3. Output capacitor – 3000 $\mu$ F, 100 V     | 02   |
|        |                                           | 4. Input capacitor – 1200 $\mu$ F, 50 V       | 02   |
| 05     | Load                                      | 500 watts (Resistive)                         | 01   |

A variable resistor is used by keeping the DC-link voltage constant to achieve variable power. Operation of the converters are in boost mode.

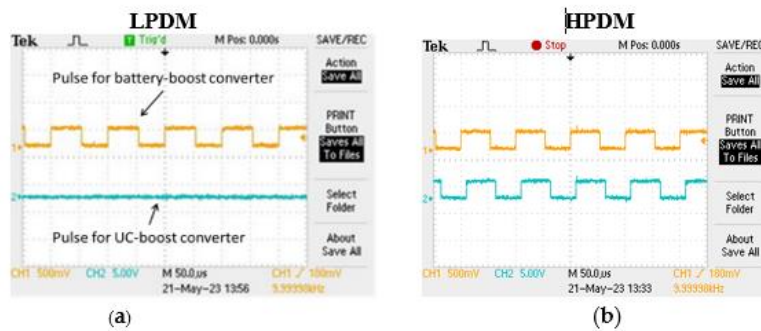
The main concern in this verification model is the real-time power-sharing strategy for different load conditions. In this experiment, the base power selected is 70 watts. If the total load power requirement is below the base power, the battery will provide the power required by the load. If the power of load needed is higher than the base power, then UC will assist the battery with the increased load power, and both will satisfy the required load power. LPDM and HPDM are two different load conditions used for power-sharing verification.

## 6. Performance Analysis

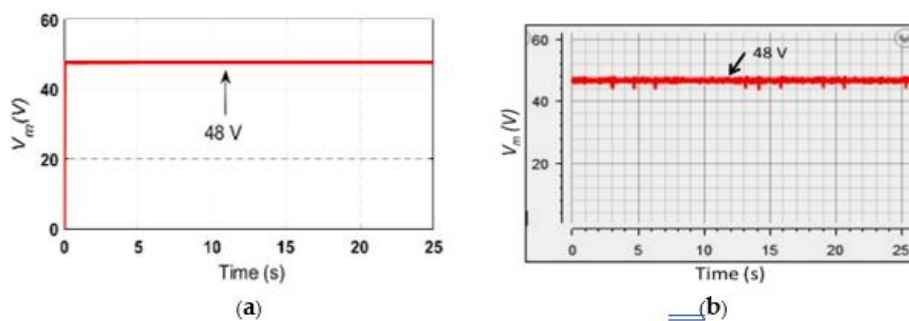
In this section of research work, the real-time output results are discussed in context with the power-sharing and DC-link voltage regulation. A comparative analysis of results are performed on the results obtained on the basis of the power demanded mode.

### 6.1. Analysis for Low Power Demand Mode

The pulses are generated in real-time for both modes and are shown in Figure 5. In Figure 5a, the pulse is generated for switch  $Q_1$  only because in LPDM, the battery alone operates. In Figure 5b, the pulses are generated for both switches  $Q_1$  and  $Q_2$  because of the high power demanded. Here, UC supports the battery. The pulse frequency can be seen as 10kHz in real time on a digital oscilloscope. DC-link voltage or load voltage ( $V_m$ ) is shown in Figure 6. In Figure 6a,b, for low power demand conditions, dc-link voltage is constant at 48 V for simulated and experimental environment. The ControlDesk software is used to extract all the waveforms in a real-time environment. A voltage sensor captures the DC-link voltage at the load side. The LEM-CV3-500 voltage transducer is used for voltage measurement and its close-loop feedback. An internal loop is used for the compensation of DC-link voltage and is shown in Figure 3 in the EMS section.



**Figure 5.** Generated pulse for (a) battery-boost converter (switch  $Q_1$ ), (b) shared bus configuration (switches  $Q_1$  and  $Q_2$ ).



**Figure 6.** Load voltage profile during LPDM for (a) simulation and (b) Experimentation.



The load current ( $I_m$ ) for LPDM is displayed in Figure 7. The load current is 0.93 A in simulation environment for the power requirement of 47.2 watts as shown in Figure 8. This simulated result is closely matched with the experimental result as shown in Figure 7b which is 0.91 A for the same power requirement. In order to capture the load current, a current sensor (LA55P) at the load side is used. Its conversion factor is used in the real-time interface of dSPACE Simulink.

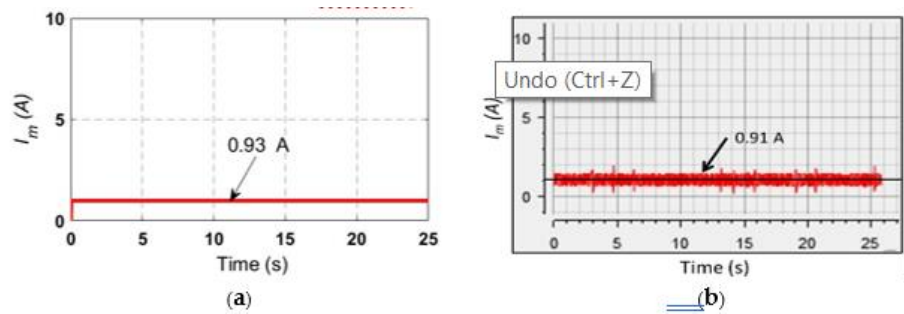


Figure 7. Load current profile during LPDM for (a) simulation and (b) Experimentation.

The load power profile  $P_m$  for LPDM is presented in Figure 8. During simulation, load power profile is 47.2 watt as shown in Figure 8a, whereas during experimentation, average power is 47 watts as shown in Figure 8b. The base power selected is 70 watts. So, in LPDM, load power required is 47.2 watt. This load requirement is completely fulfilled by the battery only as shown in Figure 9a,b during simulation and experimental verification respectively. As, in LPDM, battery alone is handling the load, contribution of the UC is negligible as presented in Figure 10a,b during simulation and experimentation respectively.

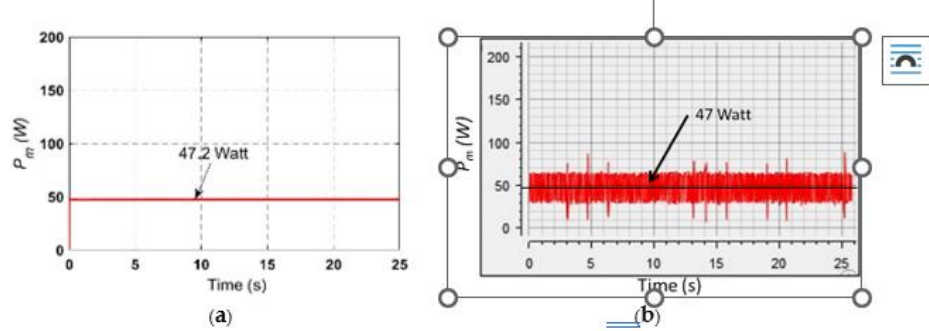


Figure 8. Load power profile during LPDM for (a) simulation and (b) Experimentation.

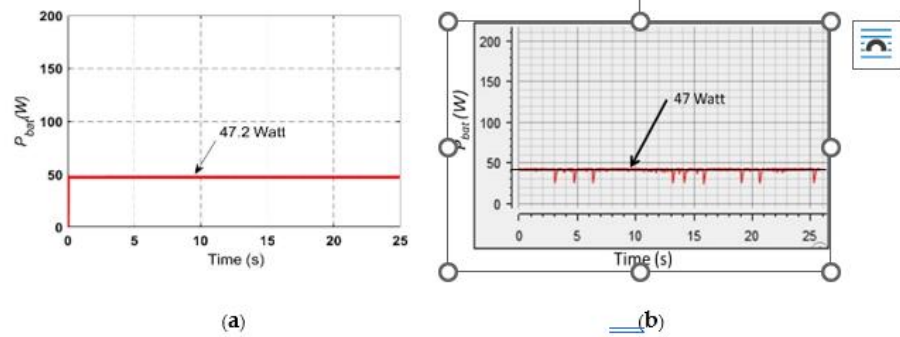
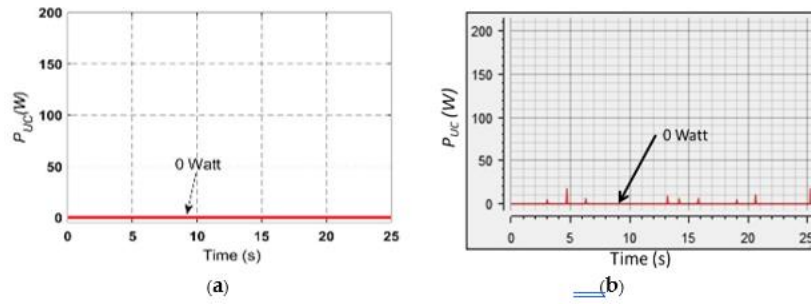


Figure 9. Battery power profile during LPDM for (a) simulation and (b) Experimentation.

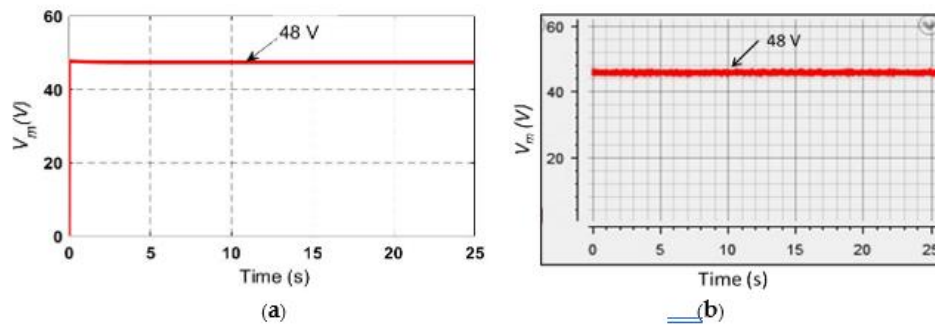


**Figure 10.** UC power profile during LPDM for (a) simulation and (b) Experimentation.

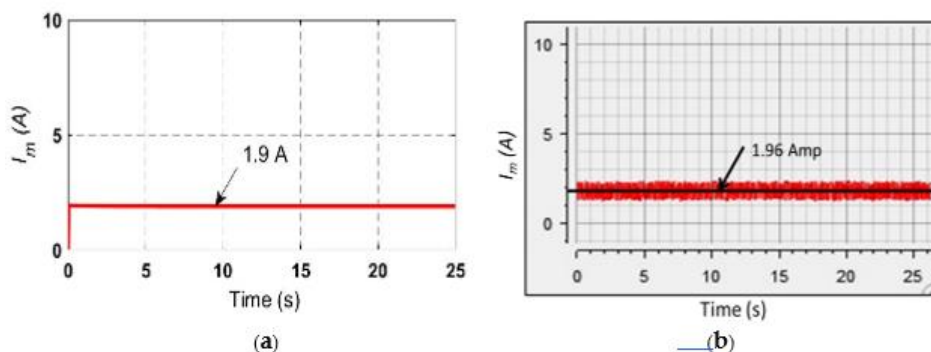
So, during the low power demand mode, the proposed strategy is effective in allocating the power.

## 6.2. Analysis for High Power Demand Mode

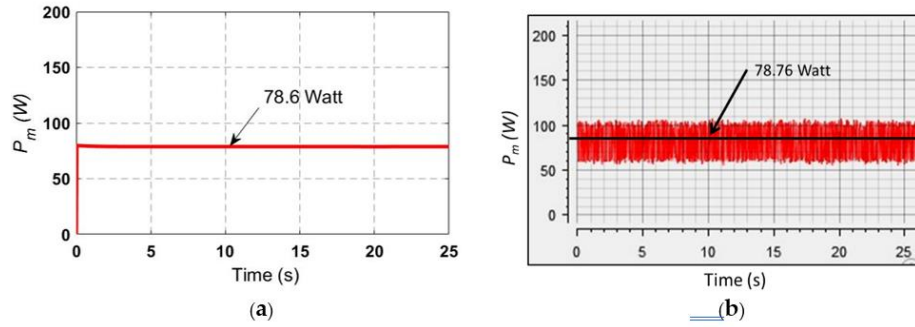
After successful verification of the LPDM, its time to validate the control strategy for the high-power demand mode (HPDM). In this mode, total load power required is 78.6 watts during simulation. For this load, dc-link voltage is constant at 48V as shown in Figure 11 for both the verification methods (simulation and experimental). To handle this load, the simulated load current is 1.9A which is very close to experimental result which is 1.96A as shown in Figure 12a and Figure 12b respectively. The battery handles only 70 watts of power out of 78.6 watt, rest is carried out by UC as per the proposed control strategy and is validated by simulation and experimental results as shown in Figures 13–15. As the UC assists the battery with the increased load power from its base power, the UC delivers 8.76 watts of power. UC, being the high-power density, it safeguards the battery from peak power demand. Selection of UC rating is critical as it has to provide the increased load requirement.



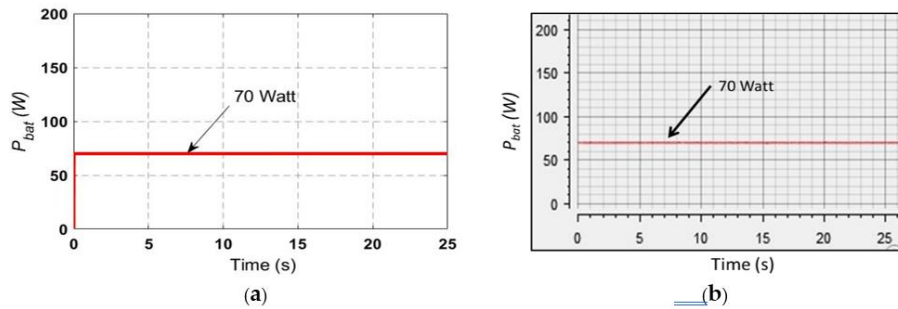
**Figure 11.** Load voltage profile during HPDM for (a) simulation and (b) Experimentation.



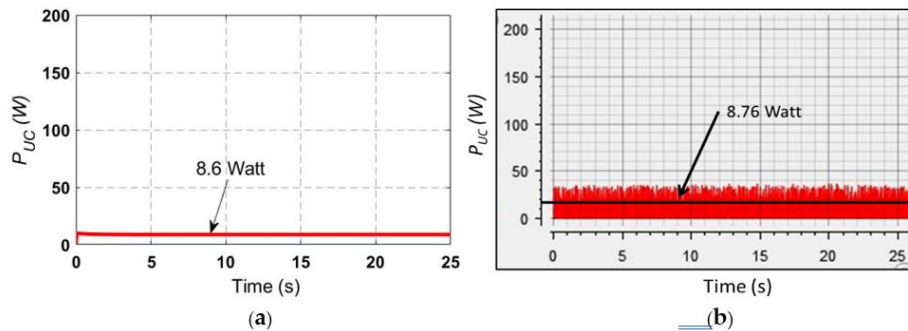
**Figure 12.** The load current profile during HPDM for (a) simulation and (b) Experimentation.



**Figure 13.** The load power profile during HPDM for (a) simulation and (b) Experimentation.



**Figure 14.** The battery power profile during HPDM for (a) simulation and (b) Experimentation.



**Figure 15.** The UC power profile during HPDM for (a) simulation and (b) Experimentation.

## 7. Conclusions

In this paper, the experimental study is carried out to analyze the power-sharing strategy, and regulation of DC-link voltage. A shared bus topology with modified EMS is used to verify the above indicators. The control strategy is developed in the dSPACE real-time interface (RTI) window. A dedicated RTI library is used for interfacing the hardware dSPACE MicroLabBox.

To create this control strategy in the real-time interface (RTI) window, signals from current and voltage sensors are connected to six analog pins. After processing these signals as per requirement, two pulses are generated for the switches  $Q_1$  and  $Q_2$ . The switching frequency for the pulse width modulation generation is 10kHz. The designed rating of the converter module is 1.2 kW and a load of 500 watts.

This experimentation is carried out for the two operational modes, LPDM and HPDM. The base power for this experiment is taken as 70 watts. The battery provides power only up to base power, and this strategy is also verified by experimentation. For high power demand (87.78 watts), both sources should provide the power to the load in real-time, and it is verified from RTI waveform

Figure 13b to Figure 15b. Irrespective of the load conditions, dc-link voltage is constant as shown in RTI waveform Figures 6b and 11b.

From the experimental study, the proposed EMS proved its effectiveness in real-time. The DC-link voltage regulation and power-sharing strategy are also verified. It can be employed in various applications including electric vehicle and microgrids.

**Author Contributions:** Conceptualization, A.R. and S.B.; methodology, A.R., A.B. and G.G; software, A.R. and S.B.; validation, A.R., G.G.; formal analysis, S.B.; investigation, S.B.; resources, A.B.; data curation, S.T.; writing—original draft preparation, A.R.; writing—review and editing, A.R.; visualization, S.T.; supervision, S.B.; project administration, S.B.; funding acquisition, S.B. and G.G. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

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