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Development, Evaluation, and Deployment of Bidirectional DC–DC Converters for Hybrid Energy Storage Systems in DC Microgrid Applications

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Abstract

This study introduces an improved bidirectional multi-input DC–DC converter (MIPC) tailored for hybrid energy storage systems (HESS) in DC microgrid environments. Traditional batteries exhibit limited charge and discharge rates, which can impose high current stresses, thereby reducing their operational lifespan. Supercapacitors (SCs), due to their high power density, respond rapidly to sudden load variations, mitigating these limitations; however, they are unsuitable for long-term energy storage. Combining batteries with SCs in a HESS leverages their complementary properties, creating an efficient energy storage solution. The proposed MIPC links the HESS to the DC microgrid, enabling independent regulation of battery and SC power as well as efficient energy transfer among storage units. A unified control strategy was developed to manage both charging and discharging of the HESS. A model predictive control (MPC) scheme demonstrated superior DC bus voltage restoration during step changes in photovoltaic (PV) generation and load conditions, compared with conventional proportional-integral (PI) controllers. The MPC reduces current stress, prolongs battery lifespan, and improves overall system performance, ensuring rapid DC grid voltage stabilization. Simulation and experimental tests under varying PV output and load profiles confirmed enhanced DC-link voltage regulation.

Keywords Power converter, DC microgrid, Battery, Supercapacitor, Power quality

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Introduction

Renewable energy sources are increasingly relied upon to satisfy a growing portion of global electricity demand due to their sustainability and reduced environmental footprint [1]. Among these, solar energy remains one of the most prominent options. Energy storage systems (ESSs) are critical for stabilizing power generation from renewable sources, and combining batteries with supercapacitors (SCs) in a hybrid energy storage system (HESS) provides exceptional performance, capable of managing the variability of sources such as photovoltaic (PV) panels and wind turbines [2]. ESSs are evaluated based on their energy storage capacity, power density, lifespan, and cost-effectiveness [3]. Fluctuations in PV output and heavy nonlinear loads often cause deep cycling and irregular charging patterns in batteries, which can degrade performance and increase maintenance costs [4]. Balancing factors such as response time, power delivery, durability, and energy density is essential, and SCs play a key role in achieving optimal system responsiveness.

HESS architectures are typically categorized as either passive or active based on their power conversion approach [5]. Active configurations utilize one or more DC–DC converters to integrate storage devices with the DC bus [6]. An effective HESS requires both a power conditioning unit and an energy management system (EMS). Multi-input converters (MICs) offer a cost-efficient, compact solution for DC–DC converters, enabling intelligent and flexible storage system configurations [7]. Designs featuring simple topologies, bidirectional power control, and unified management of storage elements improve system consistency while reducing size and manufacturing cost. Coordinated control of SC and battery power flow is vital to maximize efficiency and enhance operational capability [8].

A variety of advanced control strategies have been applied to HESSs, including artificial intelligence (AI)-based methods, fuzzy logic control (FLC), artificial neural networks (ANNs), and genetic algorithms (GAs) [9]. Within these approaches, batteries typically support low-frequency energy demands, whereas SCs handle high-frequency power fluctuations [10]. Optimizing battery usage by minimizing peak currents reduces internal voltage drops, heating, and energy losses, thereby lowering dynamic stress on the system. This work proposes an enhanced MPC-based controller for an MIPC, applied to both current and voltage control loops. The MIPC is modeled alongside the PV system, and the HESS comprises both a battery and an SC.

Figure 1 illustrates a standard DC microgrid configuration. PV modules naturally generate DC power, whereas wind turbines produce AC power. The integration of multiple renewable sources necessitates the use of power electronic converters, such as AC–DC and DC–DC converters, to connect these generation units to the DC network. These converters provide the necessary flexibility and control to optimize the power output from the renewable energy sources.



Figure 1. DC microgrid configuration.

Energy storage systems (ESSs) play a crucial role in DC microgrids to address supply-demand imbalances. In recent years, integrating multiple ESS types has become increasingly prevalent, as hybrid energy storage systems (HESSs) can combine the strengths of different storage technologies to enhance overall system stability.

DC microgrids can operate in either an autonomous (standalone) mode or a connected mode to the main grid. In standalone mode, local loads are supported by renewable energy sources (RES) and the HESS. When grid-connected, power exchange between the DC and AC networks enables greater flexibility and control over energy flows from both RES and storage units. The stability of the system governs the maintenance of power balance, particularly under fluctuations in PV generation and load demand. Reference [11] provides an extensive review of control strategies and energy management approaches for both AC and DC microgrids. Rapid DC bus voltage regulation is essential to cope with volatility in PV output and load demand, and effective power-sharing mechanisms between RESs and HESSs are critical. This study explores various bidirectional converter topologies and control techniques for HESSs in DC microgrid applications. The proposed control strategies aim to maintain DC bus voltage, manage battery charge/discharge rates, and appropriately distribute power between batteries and supercapacitors.

Recent Research Works: A Brief Review

Numerous studies have focused on preserving battery life within HESS configurations by incorporating supercapacitors (SCs). A few representative works are summarized below.

Karthikeyan and Gupta [12] analyzed a multi-input configuration of an isolated, bidirectional, dual-active-bridge DC–DC converter (MIBDC) for battery-based power storage, demonstrating the feasibility of series-combining inputs even with low-voltage sources. Aktas *et al.* [13] implemented a smart energy management algorithm (SEMA) for HESS integration in three-phase, four-wire PV systems, testing a battery–ultracapacitor setup for solar PV applications. Kwon and Choi [14] presented an ESS paired with a bidirectional DC–DC converter (BDC) to address switching-mode challenges, enabling both short- and long-term energy support while maintaining high-quality DC microgrid operation. Lai *et al.* [15] developed a BDC for hybrid electric vehicles, capable of step-up and step-down operation and bidirectional power control, while independently managing power flow between two low-voltage sources.

Deihimi *et al.* [16] proposed an expandable multi-input step-up DC–DC converter (MISUC) suitable for multiple RES inputs, offering improved output-voltage regulation and enhanced HESS performance through simultaneous monitoring and control of all input sources.

Traditional proportional-integral (PI) controllers used for HESSs have limitations, including complex parameter tuning and the need for additional filtering to handle both high- and low-frequency power fluctuations [17–21]. This paper presents a comparative analysis between conventional PI and model predictive control (MPC) approaches for controlling MIPCs in HESS-based DC microgrids. The MPC strategy predicts future system behavior using a discrete system model and current states, selecting optimal control actions at each sampling instance. The proposed MPC-based control aims to regulate DC bus voltage, manage battery charge/discharge rates, and coordinate power sharing between batteries and SCs. The main objectives include:

- Reducing computational complexity
- Employing a straightforward double-loop control structure with an outer voltage loop generating dynamic references and an inner current loop that tracks these references without low-pass filters using MPC principles
- Enhancing dynamic performance and minimizing DC bus voltage deviations compared to traditional PI control.

HESS-Supported RES Configuration

Figure 2 illustrates the two-input bidirectional converter setup for an HESS-supported renewable energy system described in this section. The system consists of an off-grid PV array and a hybrid storage bank combining batteries and SCs. PV generation remains a key RES for DC microgrids. A boost converter extracts maximum power from the PV array and links it to the DC bus. The HESS, comprising a battery–SC combination, reacts rapidly to maintain DC bus voltage when mismatches occur between PV generation and load demand.

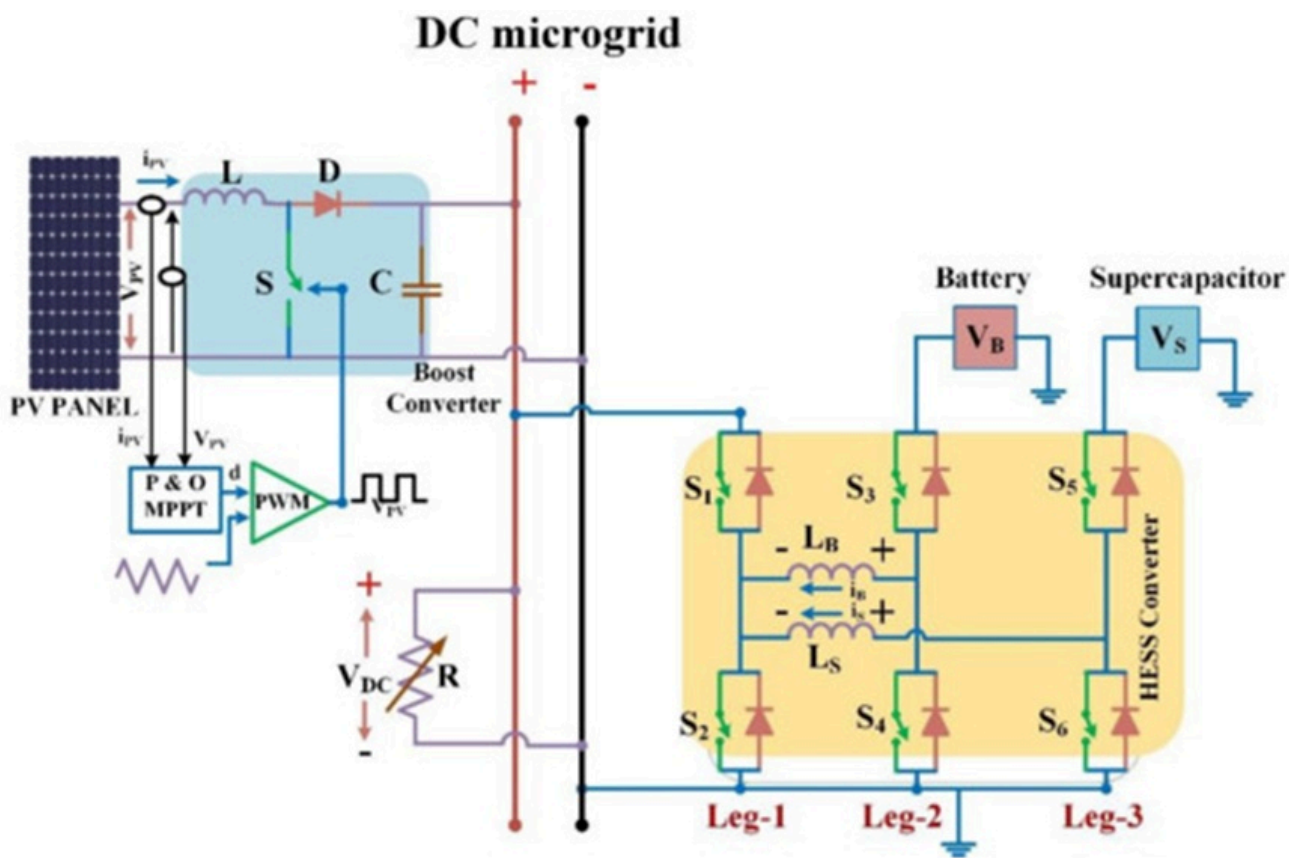


Figure 2. DC microgrid setup with HESS and PV integration

The operational strategies for this system are comprehensively discussed in Ref. [22]. The focus here is on a revised converter topology with three independently switched legs. In this configuration, Leg 2 and Leg 3 connect to the battery (V_B) and supercapacitor (V_S) units, respectively, while Leg 1 interfaces directly with the DC microgrid (V_{DC}). The design ensures that the battery voltage remains higher than the SC voltage but still below the DC bus voltage. Each leg incorporates a dedicated high-frequency inductor— L_B for the battery and L_S for the supercapacitor. The following subsections detail the converter's multiple operating modes.

Energy flow from HESS to DC bus

The power semiconductor switches operate according to a time-based sequence summarized in **Table 1**. For the supercapacitor leg, switches S_5 and S_2 are modulated using the duty cycle d_S , while the complementary duty cycle is applied to switches S_6 and S_1 . For the battery leg, duty cycle d_B controls S_3 , and its complement governs S_4 , ensuring proper bidirectional power flow from the HESS to the DC bus.

Table 1. Switching operation in various time intervals.

Time Scale	T_1	T_2	T_3

Operating switches	(S ₂ –S ₃ –S ₅)	(S ₂ –S ₄ –S ₅)	(S ₁ –S ₄ –S ₆)
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In a DC microgrid, any mismatch between the PV array’s power output and the load’s power consumption causes the system voltage to deviate from its steady-state operating point. A reduction in solar irradiance or a sudden increase in load demand results in a decline in the DC bus voltage. To correct this power imbalance, the battery–supercapacitor hybrid energy storage system (HESS) injects power into the DC microgrid, as illustrated in **Figures 3a–3c**.

At the instant $t = t_0$, switches S2, S3, and S5 are activated simultaneously. This causes the inductor currents i_B and i_S to ramp up linearly at rates determined by V_B/L_B and V_S/L_S , respectively.

When t reaches t_1 , switch S3 is turned off, creating a freewheeling path for the battery current (**Figure 3b**). Once the appropriate dead time between S3 and S4 has elapsed, switch S4 is turned on.

At $t = t_2$, switches S2 and S5 are deactivated. The supercapacitor current then circulates through its body diodes, decreasing with a slope of $-V_{DC}/L_S$, while the battery current i_B flows through the body diode of S1, also decreasing at a slope of $-V_{DC}/L_B$, as shown in **Figure 3c**.

At $t = t_3$, switches S1, S4, and S6 are turned off. To keep the inductor currents continuous, the body diodes of S2, S3, and S5 start conducting, allowing i_B and i_S to rise again with positive slopes of V_B/L_B and V_S/L_S . After the dead-time interval, the gate pulses are reapplied to switches S2, S3, and S5. During this interval, switch S3 operates at duty cycle d_B , while switches S2 and S5 operate at duty cycle d_S .

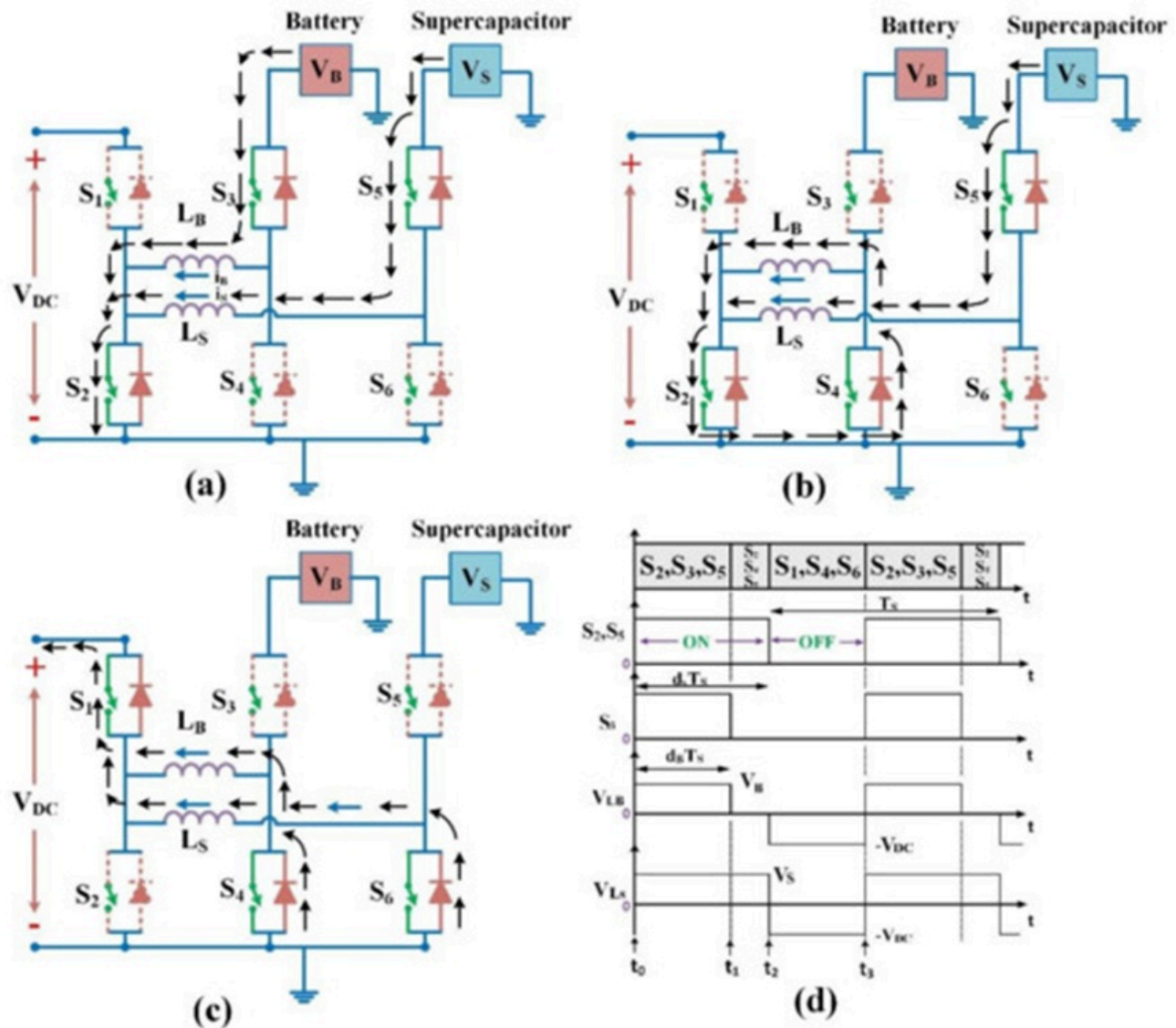


Figure 3. The equivalent circuit of the two-input bidirectional converter: Subfigure (a) shows the configuration with switches S₂, S₃, and S₅ conducting, (b) depicts the case with switches S₂, S₄, and S₅ active, (c) illustrates operation using switches S₁, S₄, and S₆, and (d) displays the steady-state waveforms during the discharging mode.

The duty ratio d_B is always kept lower than d_S because the battery voltage V_B exceeds the supercapacitor voltage V_S . Independent adjustment of d_B and d_S enables precise control of the power exchange among the battery, the supercapacitor, and the DC microgrid.

Power transfer from DC Grid to HESS

When the PV array generates more power than the load requires, or when the load demand suddenly decreases, surplus energy appears in the DC microgrid. This excess causes the DC bus voltage to rise. The additional power from the PV source is then directed into the battery and supercapacitor for storage. Consequently, power flows from the DC microgrid toward the hybrid energy storage system (HESS) under these conditions.

The converter's behavior during this charging process can be described using equivalent circuits over three distinct switching intervals, as depicted in **Figures 4a–4d**. The specific switches that are active during each interval are summarized in **Table 2**.

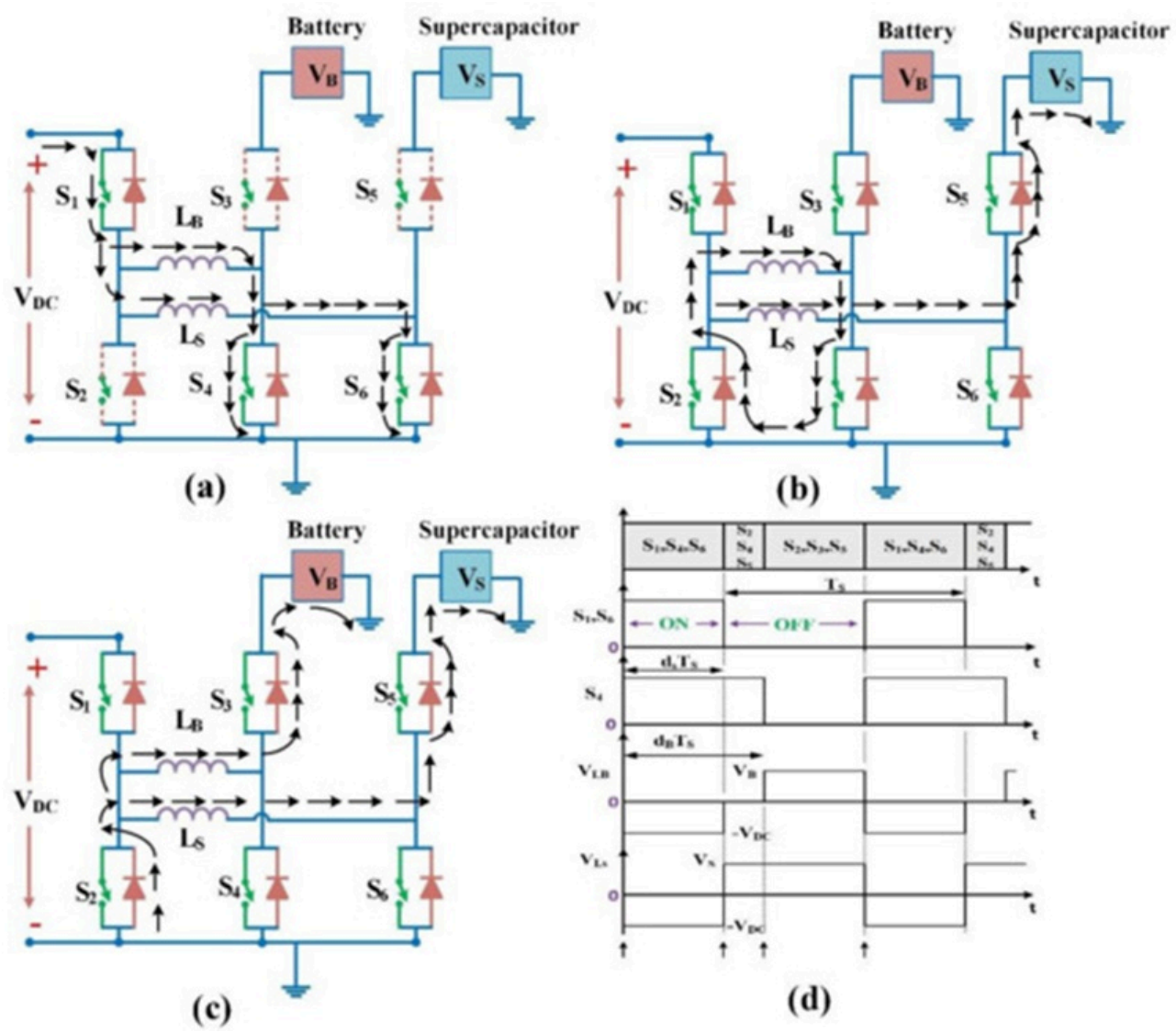


Figure 4. The equivalent circuits of the two-input bidirectional converter in various operating states: Part (a) represents the mode where switches S_1, S_4 , and S_6 are turned on, part (b) shows the configuration with switches S_2, S_4 , and S_5 conducting, part (c) illustrates the case with switches S_2, S_3 , and S_5 active, and part (d) provides the steady-state waveform diagrams for the discharging mode.

Table 2. Changing states at various times.

Time Scale	T_1	T_2	T_3
Operating switches	$(S_1-S_4-S_6)$	$(S_2-S_4-S_5)$	$(S_2-S_3-S_5)$

Table 3 presents the correlation between the DC bus voltage and the voltages across the battery and supercapacitor after the volt-second balance is achieved for inductors L_B and L_S .

Table 3. Relationship between different voltages.

S. No	Mode of operation	Transfer function
1	Power transfer from Battery–SC bank to the DC grid	$V_{DC}=dS_1-dS \cdot V_S$, $V_{DC}=dB_1-dS \cdot V_B$
2	Power transfer from DC grid to Battery–SC	$V_S=dS_1-dS \cdot V_{DC}$, $V_B=dS_1-dB \cdot V_{DC}$
3	Energy exchange mode	$V_S=d \cdot V_B$

At the moment $t = t_0$, the converter activates switches S1, S4, and S6. This action drives both inductor currents i_B and i_S upward in the reverse direction, following slopes of $-V_{DC}/L_B$ for the battery side and $-V_{DC}/L_S$ for the supercapacitor side. Between t_0 and t_1 , the inductors accumulate energy from the DC grid.

When t reaches t_1 , switches S1 and S6 are deactivated. To prevent any discontinuity in the supercapacitor inductor current i_S , the body diodes of S2 and S5 immediately take over conduction. At this stage, the energy stored in the inductor L_S is released and used to charge the supercapacitor. Simultaneously, the battery-side inductor current i_B circulates freely through the body diode of switch S2.

At instant $t = t_2$, switch S4 is turned off. The supercapacitor inductor current i_S then continues through the body diode of switch S3, now changing at a slope determined by V_S/L_S . At the same time, the energy stored in inductor L_B is transferred to charge the battery.

Finally, at $t = t_3$, switches S2, S3, and S5 are deactivated. To sustain continuous current flow through the inductors, the body diodes of switches S1, S4, and S6 begin conducting.

The volt-second balance applied to inductors L_B and L_S determines the steady-state voltage ratios between the DC bus, the battery, and the supercapacitor. These relationships are summarized in [Table 3](#), where dB stands for the duty cycle of switch S4, and dS represents the common duty cycle of switches S1 and S6.

Power transfer from battery bank to SC (Energy exchange mode)

A supercapacitor excels at delivering high-power bursts but cannot supply prolonged, steady energy like a battery. To ensure reliable performance of the overall hybrid energy storage system (HESS), the supercapacitor must be regularly recharged from the battery. In this mode, power is deliberately transferred from the battery bank to the supercapacitor.

Figure 5 presents both the equivalent circuit diagram and the corresponding steady-state waveforms that characterize the energy exchange operation between the battery and the supercapacitor.

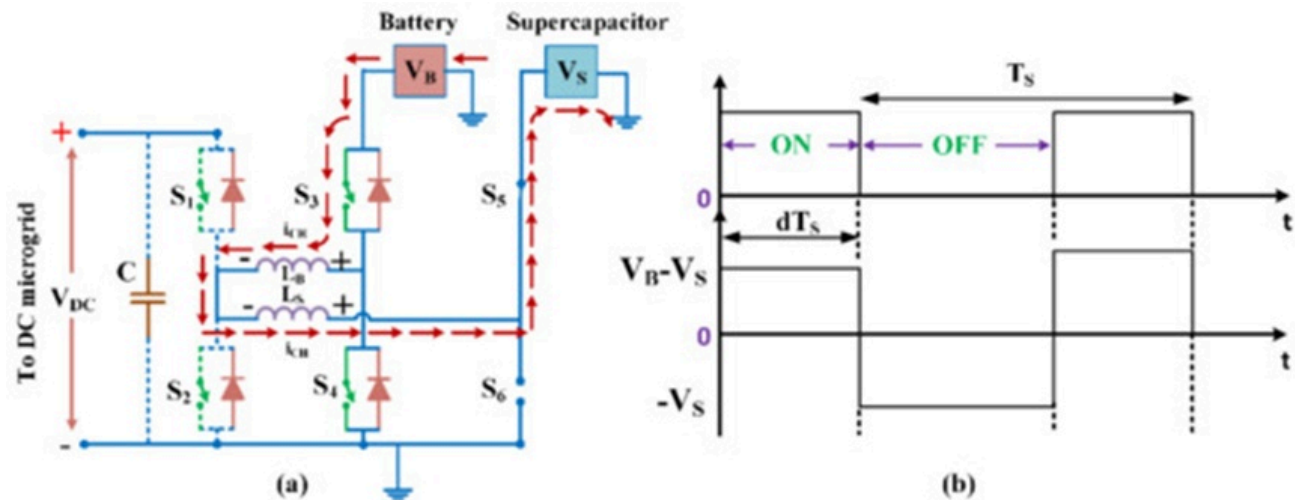


Figure 5. The operating principle of the HESS during the energy exchange mode: (a) the equivalent circuit configuration and (b) the corresponding steady-state waveforms.

In this energy exchange mode, switches S_1 and S_2 remain open, effectively isolating the DC microgrid from the hybrid energy storage system (HESS). The switching pairs S_3/S_4 and S_5/S_6 operate in a complementary manner. As shown in **Figure 5**, switch S_5 stays continuously on, while switch S_6 remains fully off. Switch S_3 operates with a duty cycle denoted as d , and switch S_4 is kept constantly conducting. This arrangement enables power to transfer from the battery to the supercapacitor, functioning similarly to a buck converter. Connecting the two inductors in series helps minimize current ripple. The amount of power delivered from the battery to the supercapacitor can be precisely adjusted by varying the duty cycle d . **Figure 5** also presents the detailed switching sequence of the converter during supercapacitor charging and discharging processes. **Table 3** provides the voltage relationship between the battery and the supercapacitor once the volt-second balance is established across the equivalent inductance L_{eq} (where $L_{eq} = L_B + L_S$).

PI Control System Scheme of HESS

Figure 6 presents the block diagram of the PI-based control strategy for the HESS. The PI controller is designed to deliver strong closed-loop performance while maintaining stability despite variations in converter dynamics and external disturbances. In this approach, the measured DC link voltage (V_{DC}) is compared against a reference value ($V_{DC, ref}$). The resulting error signal is fed to the PI controller, which produces the total reference current (i_{tot}) required by the energy storage system. As depicted in **Figure 6**, this total current is then separated into its low-frequency component (i_{LOW}) and high-frequency component (i_{HIGH}). These components serve as reference currents for the battery and supercapacitor control loops, respectively. Within the PI control scheme, the battery current reference corresponds to the low-frequency portion, whereas the supercapacitor current reference is assigned the high-frequency portion.

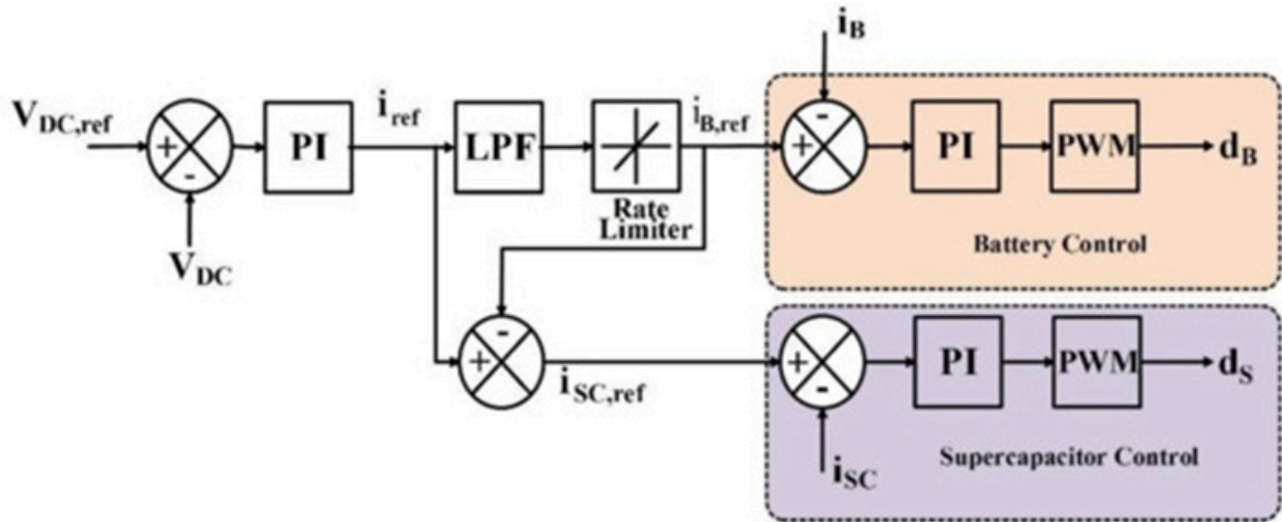


Figure 6. A complete overview of the control approach employed to divide the current demand between the supercapacitor and the battery within the PI regulation framework.

PI controller design for HESS

The control architecture for the hybrid energy storage system is presented in **Figure 7**. It comprises two distinct sections: a fast inner loop that regulates the supercapacitor current and a slower outer loop that controls DC voltage, as detailed in **Figure 7a**. Separately, **Figure 7b** outlines the generation of the reference signal for the battery current.

The supercapacitor current loop is intentionally tuned with a substantially wider bandwidth than the battery current loop. This design choice ensures a faster response from the supercapacitor side. Because the inner current regulation acts much faster than the outer voltage regulation, the bandwidth of the current loops is deliberately maintained higher than that of the voltage loop. For this implementation, the converter's switching frequency was fixed at 10 kHz.

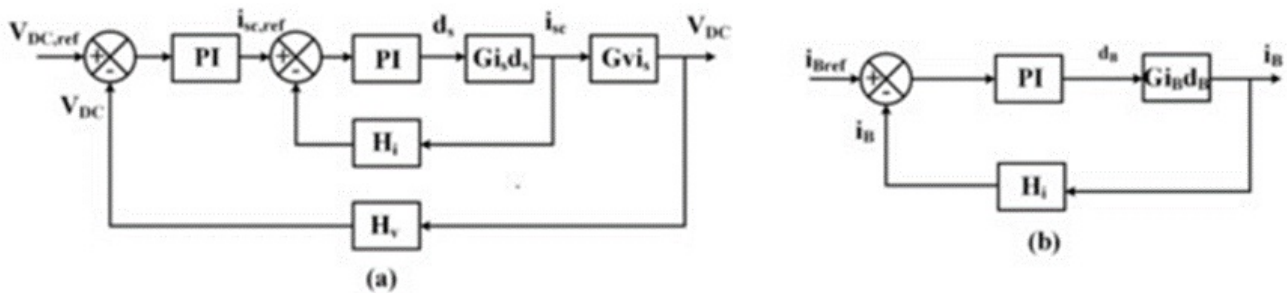


Figure 7. The complete block diagram of the control system: (a) the structure for supercapacitor current regulation and (b) the structure for battery current regulation.

SC current control loop design

Table 4 lists the small-signal transfer functions derived for the supercapacitor current control loop parameters. In this table, V_{DC} denotes the DC bus voltage, i_B represents the battery current, i_{SC} denotes the supercapacitor current, d_B denotes the duty cycle of the battery current controller, and d_{SC} denotes the duty cycle of the supercapacitor current controller.

The open-loop transfer function $G_{iSC}d_{SC}$ was used to determine the compensated parameters for the current controller. The proportional gain K_p , SC , and the integral gain K_i , SC of the supercapacitor current PI controller are also provided in

Table 4. These controller settings were designed to achieve a bandwidth of 1.6 kHz and a phase margin of 60°. Using the MATLAB SISO toolbox, the calculated compensated values for the SC current loop were obtained as $K_p, SC = 0.4124$ and $K_i, SC = 2291$.

Table 4. Linear averaged transfer functions for small signals.

S. No.	Parameter	Transfer Functions
1	SC current transfer function control	$G_{iscdsc} = \frac{i_{sc}(s)}{d_{sc}(s)} = \frac{V_{DC}(1 + d_{sc})}{R(1 - d_{sc})^3} \left[\frac{1 + S \frac{RC}{(1 + d_{sc})}}{S^2 - \frac{L_{SC}C}{(1 - d_{sc})^2} + S \frac{L_{SC}}{R(1 - d_{sc})^2} + 1} \right]$
2	SC current to transfer function output voltage	$G_{VDCisc} = \frac{V_{DC}(s)}{i_{sc}(s)} = \frac{R(1 - d_{sc})}{(1 + d_{sc})} \left[\frac{1 - S \frac{d_{sc}L_{SC}}{R(1 - d_{sc})^2}}{1 + S \frac{RC}{1 + d_{sc}}} \right]$
3	Control to battery current transfer function	$G_{ibdb} = \frac{i_b(s)}{d_b(s)} = \frac{V_{DC}}{d_b R(1 - d_{sc})^2} \cdot \left[\frac{1 + SRC}{S^2 \frac{L_B C}{(1 - d_{sc})^2} + S \frac{L_B}{R(1 - d_{sc})^2} + 1} \right]$
4	Inner SC current loop PI controller transfer function	$G_{pi,SC} = K_{p,SC} + \frac{K_{i,SC}}{S}$
5	The transfer function of the battery current loop was controlled by a PI controller	$G_{pi,BAT} = K_{p,b} + \frac{K_{i,b}}{S}$
6	Outer voltage control loop PI controller transfer function	$G_{pi,v} = K_{p,v} + \frac{K_{i,v}}{S}$

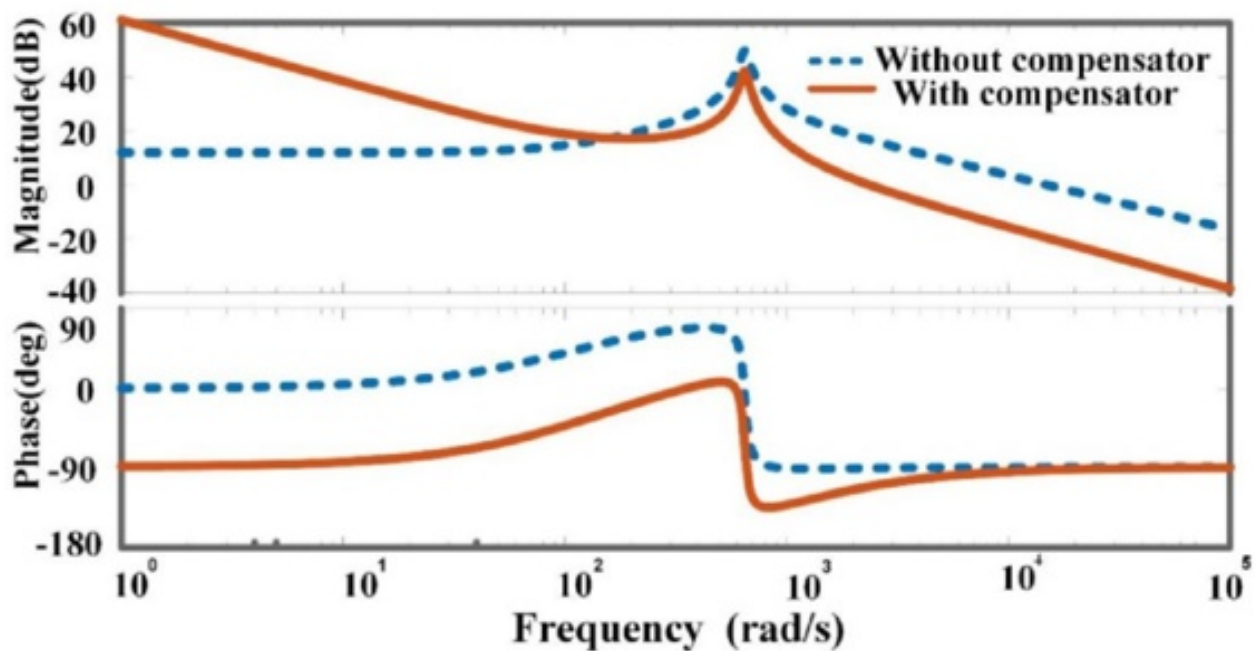


Figure 8. with and without compensation, a Bode plot of the inner SC current logic.

System stability for supercapacitor (SC) current regulation was evaluated by calculating open- and closed-loop transfer functions.

$$G_{ol_SC} = G_{pi_sc} \cdot G_{isc_dsc} H_{SC} \quad (1)$$

$$G_{cl_SC} = \frac{G_{pi_sc} \cdot G_{isc_dsc}}{1 + G_{pi_sc} \cdot G_{isc_dsc} H_{SC}} \quad (2)$$

In these expressions, G_{ol_SC} corresponds to the open-loop transfer function, G_{cl_SC} indicates the closed-loop transfer function, and H_{SC} represents the feedback gain applied in the SC current control loop. **Figure 8** displays the Bode plots of the SC current control loop in its original, uncompensated state and after controller application. Analysis of these plots verifies that the implemented controller delivers stable behavior, supported by adequate gain and phase margins.

Battery current control loop design

Table 4 presents the small-signal transfer functions for the battery current regulation loop. Controller gains were determined from the open-loop transfer function G_{iBdB} . In this control scheme, $K_{p,b}$ and $K_{i,b}$ denote the proportional and integral gains, respectively. These parameters were selected to achieve a phase margin of 59.2 degrees and a bandwidth of 1 kHz. Application of the MATLAB SISO toolbox yielded the final gain values $K_{p,b} = 1.971$ and $K_{i,b} = 7300$.

$$G_{ol_B} = G_{pi_B} \cdot G_{iBdB} \cdot H_B \quad (3)$$

$$G_{cl_B} = \frac{G_{pi_B} \cdot G_{iBdB}}{1 + G_{pi_B} \cdot G_{iBdB} \cdot H_B} \quad (4)$$

In the given formulas, G_{ol_B} denotes the open-loop transfer function of the battery control loop, and H_B denotes its feedback gain. **Figure 9** illustrates the Bode plots of the open-loop transfer functions for both the compensated and uncompensated cases. The results from these diagrams demonstrate that the suggested controller ensures stable operation while maintaining suitable gain margin and phase margin.

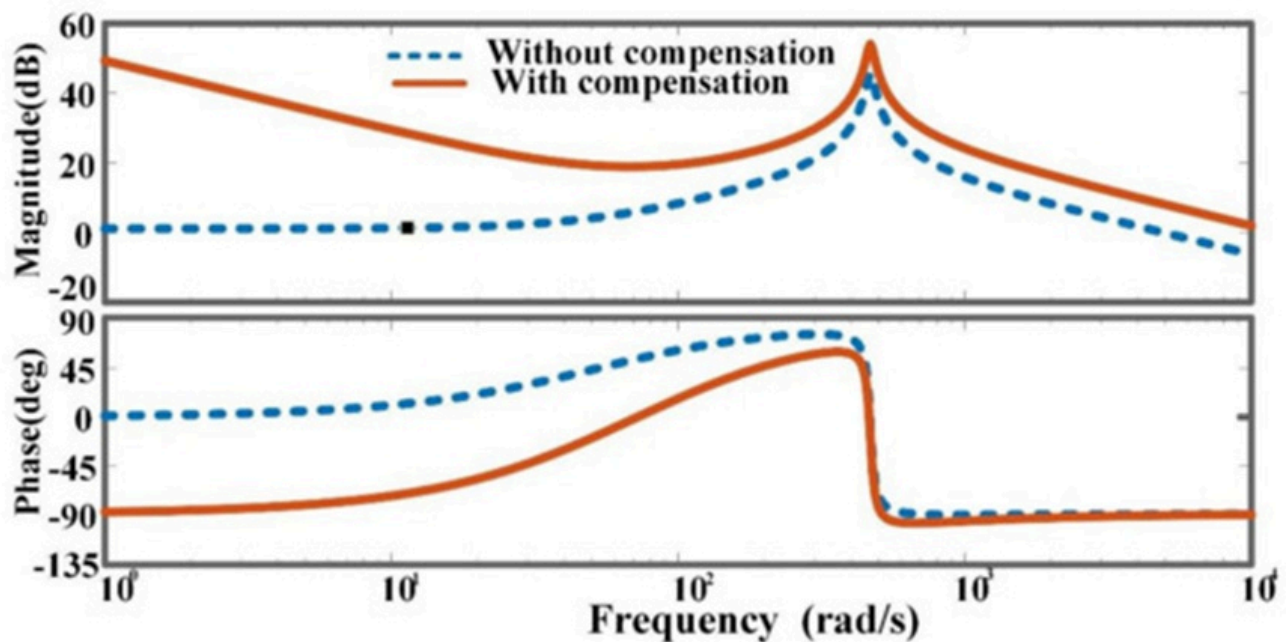


Figure 9. The open-loop Bode diagram of the battery current control scheme is presented in both its corrected and uncompensated forms.

Overall outer voltage control loop

Designing the voltage regulation loop relies on input signals that are modified according to the battery and SC current responses. The outer loop was configured to operate with a bandwidth of 200 Hz while maintaining a phase margin of 60°. The controller parameters for this loop were selected as $K_{p,v} = 0.5054$ and $K_{i,v} = 266$. Based on these settings, the open-loop transfer function corresponding to the outer voltage loop was derived as follows.

$$G_{ol_vDC} = G_{pi,v} \cdot G_{cl_SC} \cdot G_{vISC} \cdot H_V \quad (5)$$

The expression G_{ol_vDC} was used to assess the system's stability characteristics, where H_V denotes the voltage loop's feedback gain. **Figure 10** shows the open-loop frequency response of the voltage control system under both compensated and uncompensated conditions. From the Bode plot, it can be observed that the system remains stable at the chosen operating point, satisfying the required phase and gain margin criteria.

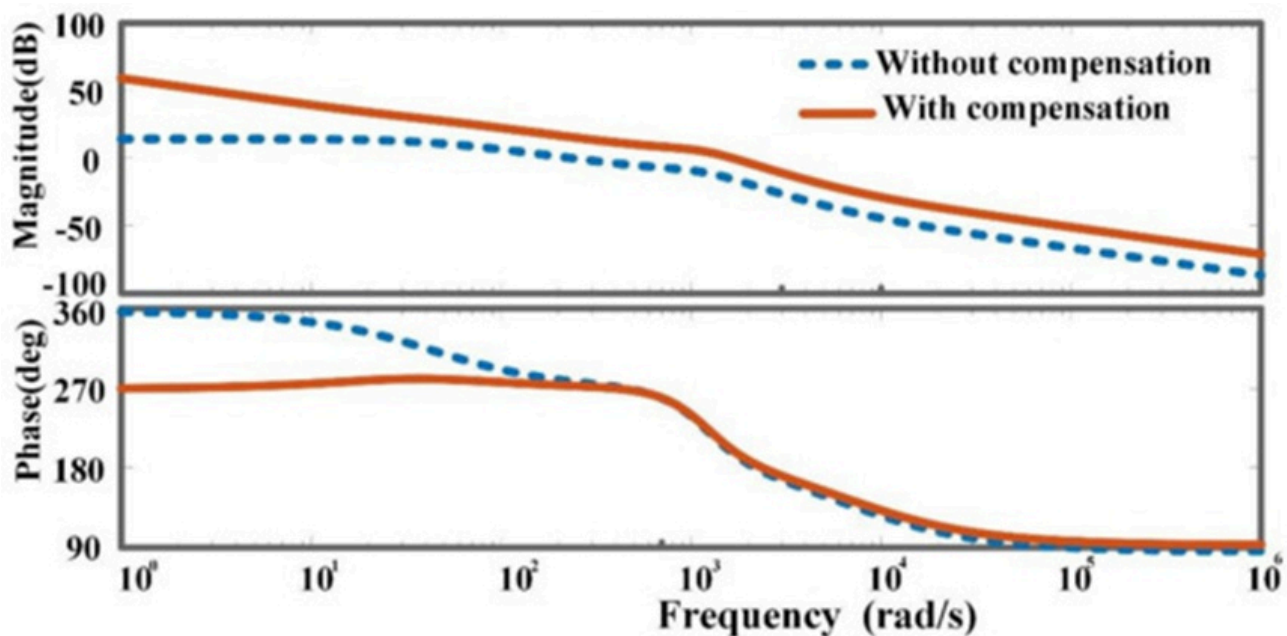


Figure 10. The open-loop frequency response of the outer voltage control scheme is depicted through Bode plots for both compensated and uncompensated cases.

MPC control strategy

The implemented control framework was organized into two hierarchical layers to stabilize the DC grid voltage, consisting of an outer voltage regulation loop and an inner current regulation loop. The primary function of the outer loop was to generate a time-varying reference current for the HESS, enabling effective voltage regulation of the DC grid. Subsequently, a power management scheme allocated this reference current, thereby reducing battery discharge stress while improving the equilibrium between load demand and PV generation.

For control execution, system behavior was predicted using a discrete-time representation of the DC–DC converter, which facilitated the estimation of battery and supercapacitor inductor currents. This predictive approach selected control actions by minimizing the deviation between the predicted currents and their corresponding reference values. **Figure 11** provides a schematic block representation of the MPC-based control strategy.

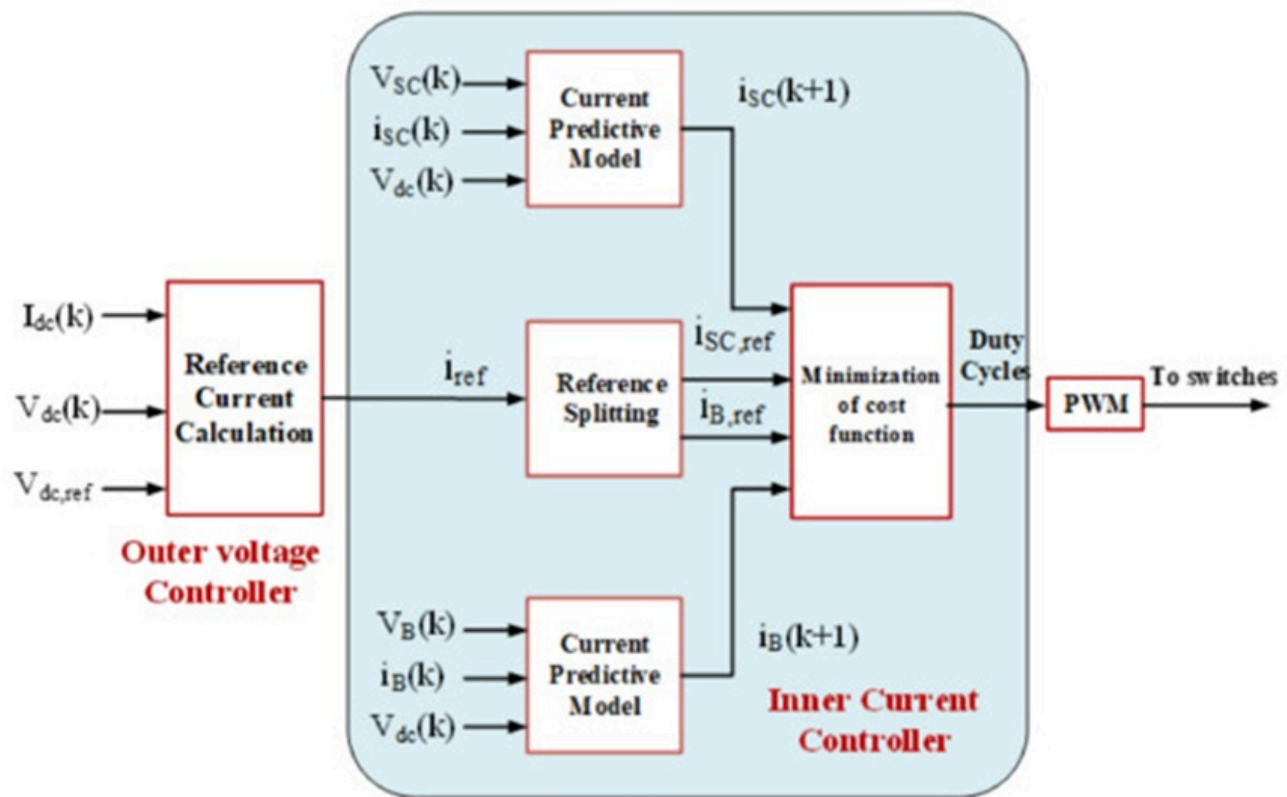


Figure 11. The block diagram of the model predictive control (MPC) approach applied to the hybrid energy storage system (HESS).

Outer voltage control loop

The current flowing through the DC-link capacitor can be expressed by the given equation, where the capacitor charging current (i_c) is influenced directly by fluctuations in the DC grid voltage.

$$i_c = C \frac{dV_{dc}}{dt} \quad (6)$$

This equation can be expanded for a small sampling period by applying Euler's forward difference method.

$$i_c(k) = C \times \frac{V_{dc}(k) - V_{dc}(k-1)}{T_s} \quad (7)$$

Here, T_s represents the sampling interval, $V_{dc}(k)$ denotes the DC grid voltage at the present sample, and $V_{dc}(k-1)$ refers to the voltage from the previous sample.

$$i_c(k+1) = C \times \frac{V_{dc}(k+1) - V_{dc}(k)}{T_s} \quad (8)$$

To achieve $V_{dc}(k+1)$ equal to the reference voltage V_{ref} , the required $i_c(k+1)$ obtained from the prior relation would initially be excessively large. To limit this, an integer coefficient N was introduced as the prediction horizon.

$$i_c(k+1) = C \times \frac{V_{ref} - V_{dc}(k)}{N * T_s} \quad (9)$$

For regulating the DC grid voltage, the overall reference current that the HESS must supply is expressed as:

$$i_{ref}(k+1) = i_c(k+1) + i_{dc}(k) \quad (10)$$

Where $i_{dc}(k)$ corresponds to the total load current.

Inner current control

An average voltage balance equation was developed across the inductors (L_b) to predict the currents in the battery and supercapacitor (SC) inductors.

$$L_b \frac{di_b}{dt} = V_b d_b - V_{dc} (1 - d_b) \quad (11)$$

Applying Euler's difference method yields:

$$L_b \frac{i_b(k+1) - i_b(k)}{T_s} = V_b(k) d_b(i) - V_{dc}(k) (1 - d_b(i)) \quad (12)$$

From this, the battery inductor current at the next step, $i_b(k+1)$, is obtained.

Similarly, the supercapacitor inductor current model was established as follows:

From this relation, $i_{sc}(k+1)$ is derived.

$$i_b(k+1) = \frac{T_s}{L_b} \times [V_b(k) d_b(i) - V_{dc}(k) (1 - d_b(i))] + i_b(k) \quad (13)$$

The cost functions defined for controlling the battery and SC currents are:

$$L_{sc} \frac{di_{sc}}{dt} = V_{sc} d_{sc} - V_{dc} (1 - d_{sc}) \quad (14)$$

From the derived equation, the supercapacitor inductor current at the subsequent sampling instant, $i_{sc}(k+1)$, is obtained.

$$i_{sc}(k+1) = \frac{T_s}{L_{sc}} \times [V_{sc}(k) d_{sc}(i) - V_{dc}(k) (1 - d_b(i))] + i_{sc}(k) \quad (15)$$

The objective (cost) functions used for battery and supercapacitor current regulation are given by:

$$J_b = ((i_{bref} - i_b(k+1))^2) \tag{16}$$

$$J_{SC} = ((i_{SCref} - i_{SC}(k+1))^2) \tag{17}$$

Employing the predicted currents $i_b(k+1)$ and $i_{SC}(k+1)$, the duty cycles d_b and d_{sc} were systematically varied from 0 to 1 in steps of 0.01. In every sampling period, each generated duty cycle pair was assessed against the respective reference currents i_{bref} and i_{SCref} . The combination yielding the smallest cost function value was ultimately selected as the optimal switching command.

Results and Discussion

This section presents the performance outcomes of the developed system, which integrates a multi-input power converter (MIPC), a PI controller, model predictive control (MPC), a battery, a supercapacitor (SC), and a DC source. The entire configuration was modeled and simulated in MATLAB/Simulink 7.10.0 (R2021b, Torrance, CA, USA) using a PC with an Intel Core i5 processor and 8 GB RAM. A complete Simulink model was built to implement the proposed scheme, incorporating both PI and MPC controllers to generate the gating signals for the MIPC. The designed approach effectively maintained stable DC-link voltage despite load and source disturbances. The MIPC switching was managed by the proposed controller to achieve reliable DC-link voltage regulation.

The nominal parameter values employed for the simulation study are summarized in [Table 5](#).

Table 5. Simulation study system parameters.

S. No	Parameters	Value
1	MPPT voltage (V_{mppt})	31.95 V
2	MPPT current (I_{mppt})	3.05 A
3	MPPT power (P_{mppt})	96.05 W
4	SC voltage (V_{SC})	32 V
5	SC storage inductance (L_S)	0.365 mH
6	Battery voltage (V_B)	24 V
7	Battery storage inductance (L_B)	0.35 mH
8	Boost converter inductance (L)	4.2 mH
9	Load resistance (R)	24 Ω
10	DC grid voltage (V_{DC})	48 V
11	Output capacitance (C)	400 μ F

Performance of PI controller during sudden PV power variation

Figure 12 illustrates the dynamic response of the system under PI control when the photovoltaic (PV) source experiences a sudden power change. At $t = 0.2$ s, the PV array power jumped from 96 W to 192 W due to changing environmental conditions, then dropped back to 96 W at $t = 0.4$ s. This was accompanied by a corresponding rise in PV current from 3 A to 6 A, which later fell back to 3 A.

Throughout the test, the connected load remained steady at 96 W. When the PV generation suddenly exceeded the load requirement by 96 W at $t = 0.2$ s, the DC-link voltage climbed noticeably above the nominal 48 V. The supercapacitor responded rapidly, absorbing the entire surplus power, providing fast compensation until the battery restored the DC-link voltage to the 48 V reference. In accordance with the energy management strategy, both storage units were charged appropriately to restore and sustain the DC bus voltage at the target level.

Analysis of the results revealed settling times of 110 ms during the PV power increase at $t = 0.2$ s and 120 ms during the power reduction at $t = 0.4$ s.

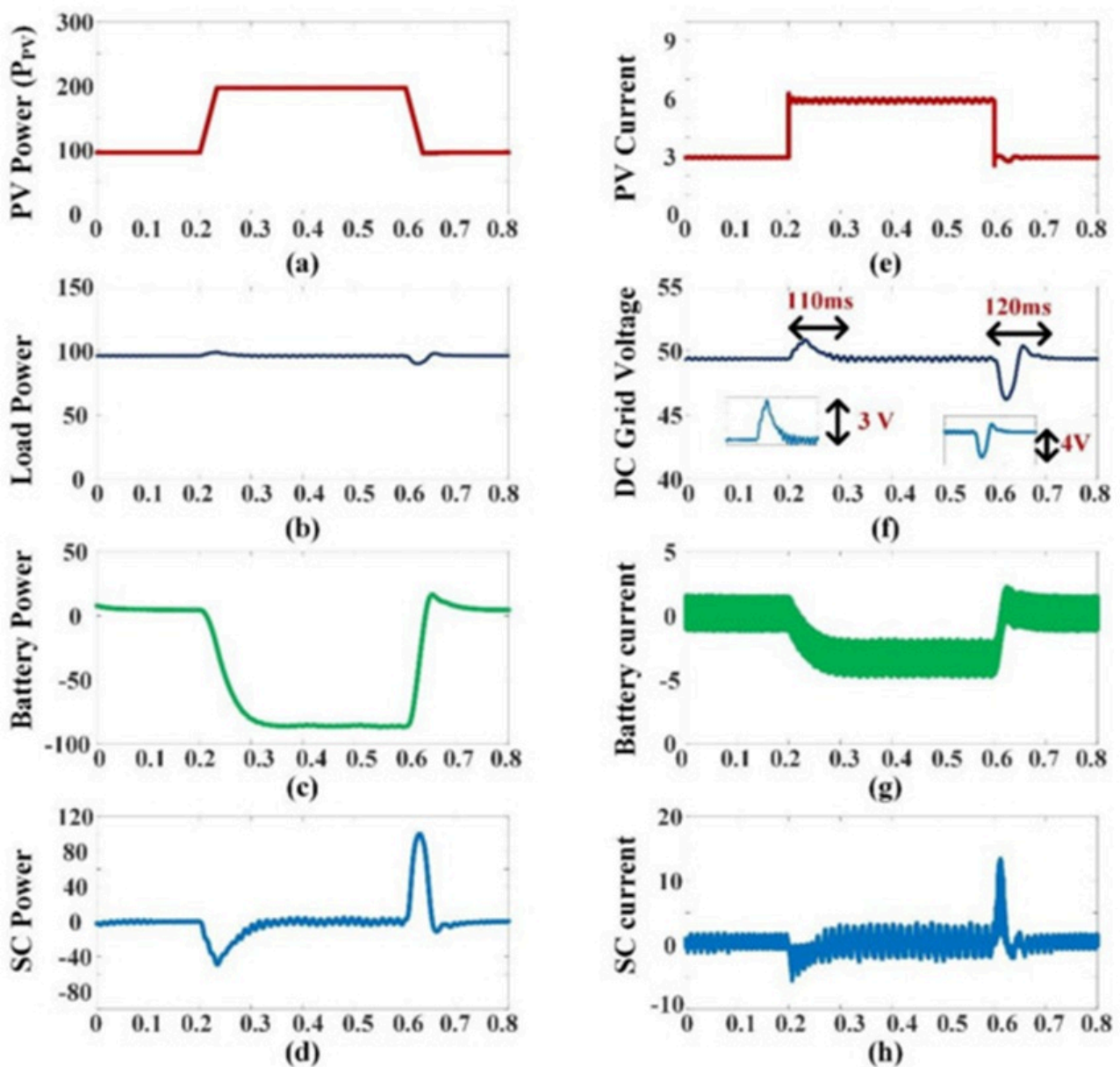


Figure 12. Simulated waveforms depicting the system's reaction to PV power fluctuations with the PI controller in place: (a) Photovoltaic power, (b) load demand power, (c) battery power flow, (d) supercapacitor power flow, (e) PV output current, (f) DC microgrid bus voltage, (g) battery current, and (h) supercapacitor current.

PI controller behavior under abrupt load demand increase

Figure 13 presents the dynamic waveforms obtained during a sudden rise in load power. At $t = 0.2$ s, the connected load power demand was stepped up sharply from 96 W to 192 W. Consequently, the load current rose from 2 A to 4 A. During this entire period, the PV source continued supplying a fixed current of 3 A.

This sudden load increase at $t = 0.2$ s pushed the power demand well beyond the PV array's capacity.

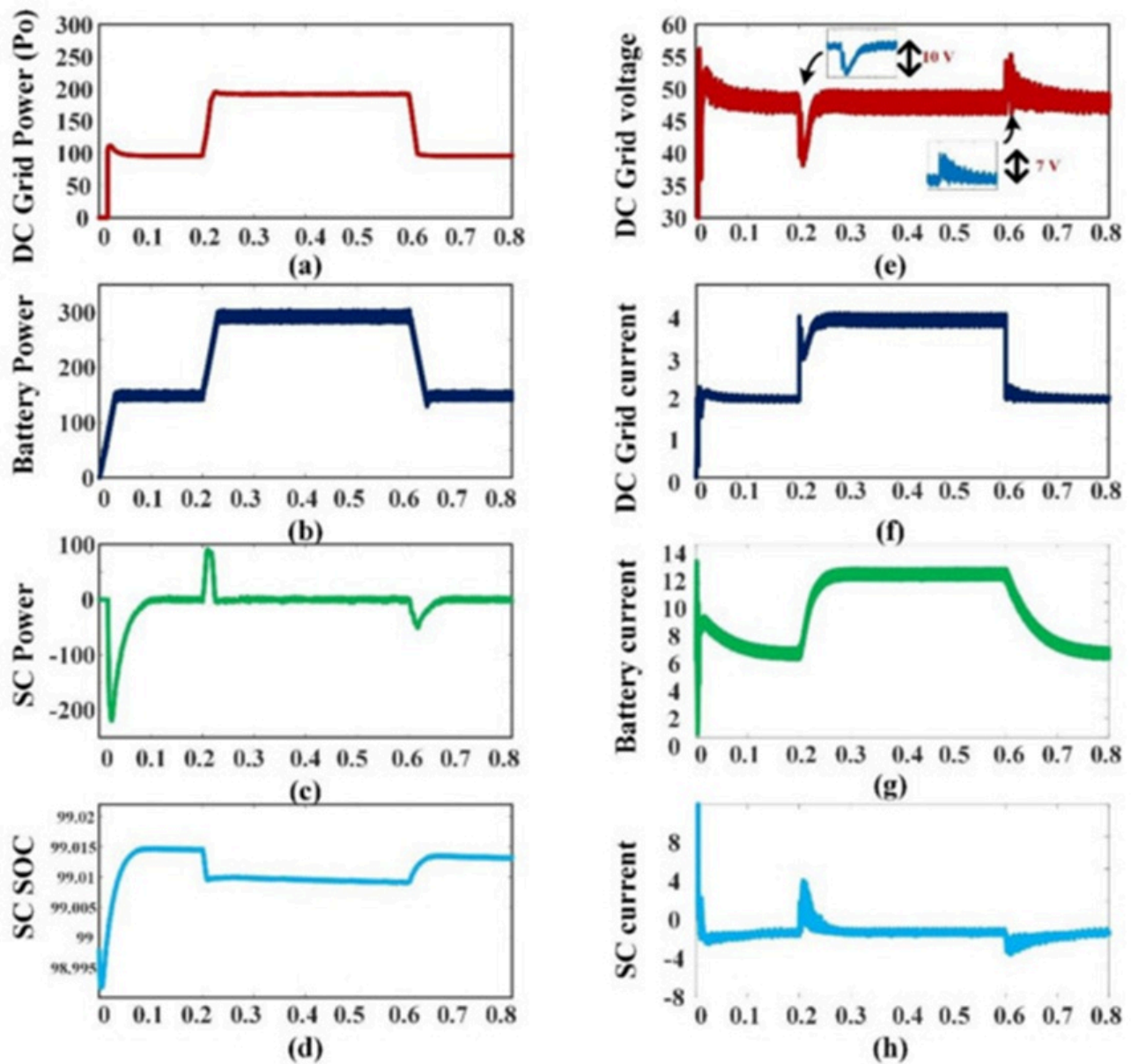


Figure 13. Simulated results illustrating the system response to a sudden load power variation: (a) DC microgrid power, (b) battery power, (c) supercapacitor (SC) power, (d) SC state of charge (SOC), (e) DC microgrid voltage, (f) DC microgrid current, (g) battery current, and (h) SC current.

This sudden increase in load created an imbalance between available generation and the load's demand. Such abrupt load changes directly impact the DC bus voltage. To compensate for the power deficit in the DC microgrid, the hybrid energy storage system (HESS) responds promptly to these disturbances. The supercapacitor handles the high-frequency transient components, while the battery manages the low-frequency steady-state power requirements. The DC microgrid voltage recovered within 60 ms after the load step at $t = 0.2$ s, and within 110 ms after the change at $t = 0.4$ s.

MPC performance during step change in PV generation

Figure 14 displays the simulation waveforms for a sudden PV output variation when using the model predictive control (MPC) strategy. Due to changing weather conditions, the PV array power rose from 96 W to 192 W at $t = 0.2$ s and then dropped back to 96 W at $t = 0.4$ s. These power steps also produced corresponding step changes in PV current at the same instants.

Despite these variations, the DC microgrid voltage remained nearly steady at the nominal 48 V, with very small settling times of only 2 ms and 5 ms at $t = 0.2$ s and $t = 0.4$ s, respectively. Compared to the conventional PI controller, the MPC approach demonstrated noticeably faster response and considerably reduced voltage overshoot.

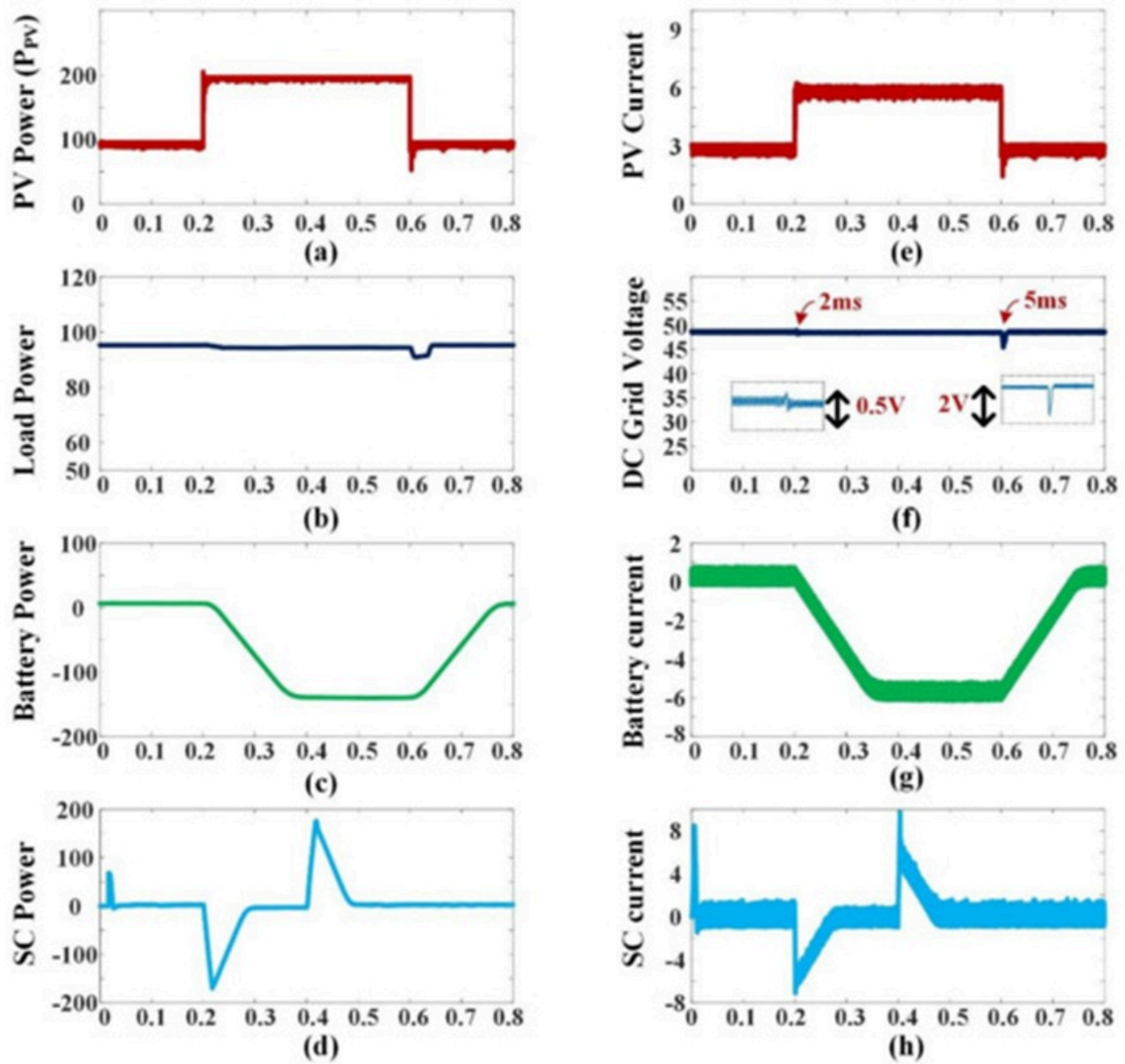


Figure 14. Simulated waveforms under MPC during a step variation in PV generation: (a) PV power output, (b) load power requirement, (c) battery power, (d) supercapacitor (SC) power, (e) PV current, (f) DC microgrid voltage, (g) battery current, and (h) SC current.

MPC response to sudden load demand increase

Figure 15 presents the system performance when the load experiences a step change under the model predictive control (MPC) strategy. The PV source was operating at its maximum available power of 96 W. At $t = 0.2$ s, the load power demand was suddenly increased to 192 W.

This abrupt rise created a significant power shortfall between the PV generation and the load consumption, causing the DC microgrid voltage to drop below the nominal 48 V. The proposed MPC scheme effectively commanded the bidirectional converter to deliver an additional 96 W from the hybrid energy storage system to compensate for the deficit and regulate the DC bus voltage back to 48 V.

The voltage restoration time achieved with MPC ranged from 3 to 10 ms, approximately 10 times that of the PI controller.

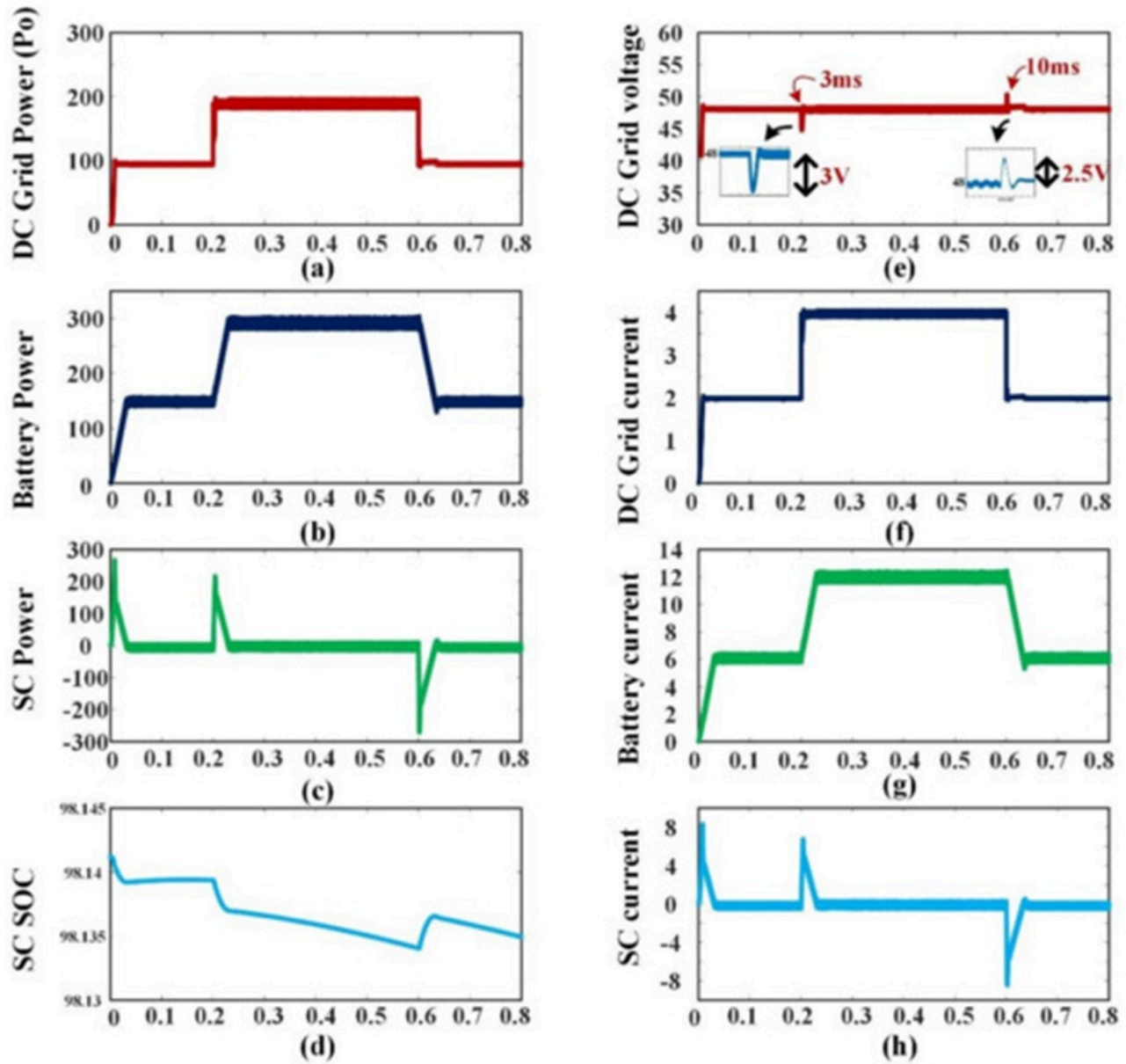


Figure 15. Simulation results for a load demand step change: (a) DC microgrid power, (b) battery power contribution, (c) supercapacitor power contribution, (d) supercapacitor state of charge (SOC), (e) DC microgrid voltage, (f) DC grid current, (g) battery current, and (h) SC current.

Performance comparison between MPC and PI controllers

The effectiveness of the model predictive control (MPC) strategy was benchmarked against the conventional PI controller under abrupt variations in both PV generation and load power. The evaluation focused primarily on two key dynamic metrics: maximum voltage overshoot and the time required to bring the DC bus voltage back to its reference value.

$$\%MP = \frac{|V_{DC,ref} - V_{max}|}{V_{DC,ref}} \times 100 \quad (18)$$

Figures 16 and 17 provide a direct visual comparison of the transient responses for both controllers. The MPC method clearly outperformed the PI controller by achieving notably faster voltage stabilization and considerably smaller peak deviations. Thanks to the predictive approach, the supercapacitor efficiently absorbed the rapid transients, giving the battery sufficient time to assume the steady-state power balance. As a result, the MPC-based system delivers superior voltage regulation speed and greater overall robustness in the DC microgrid.

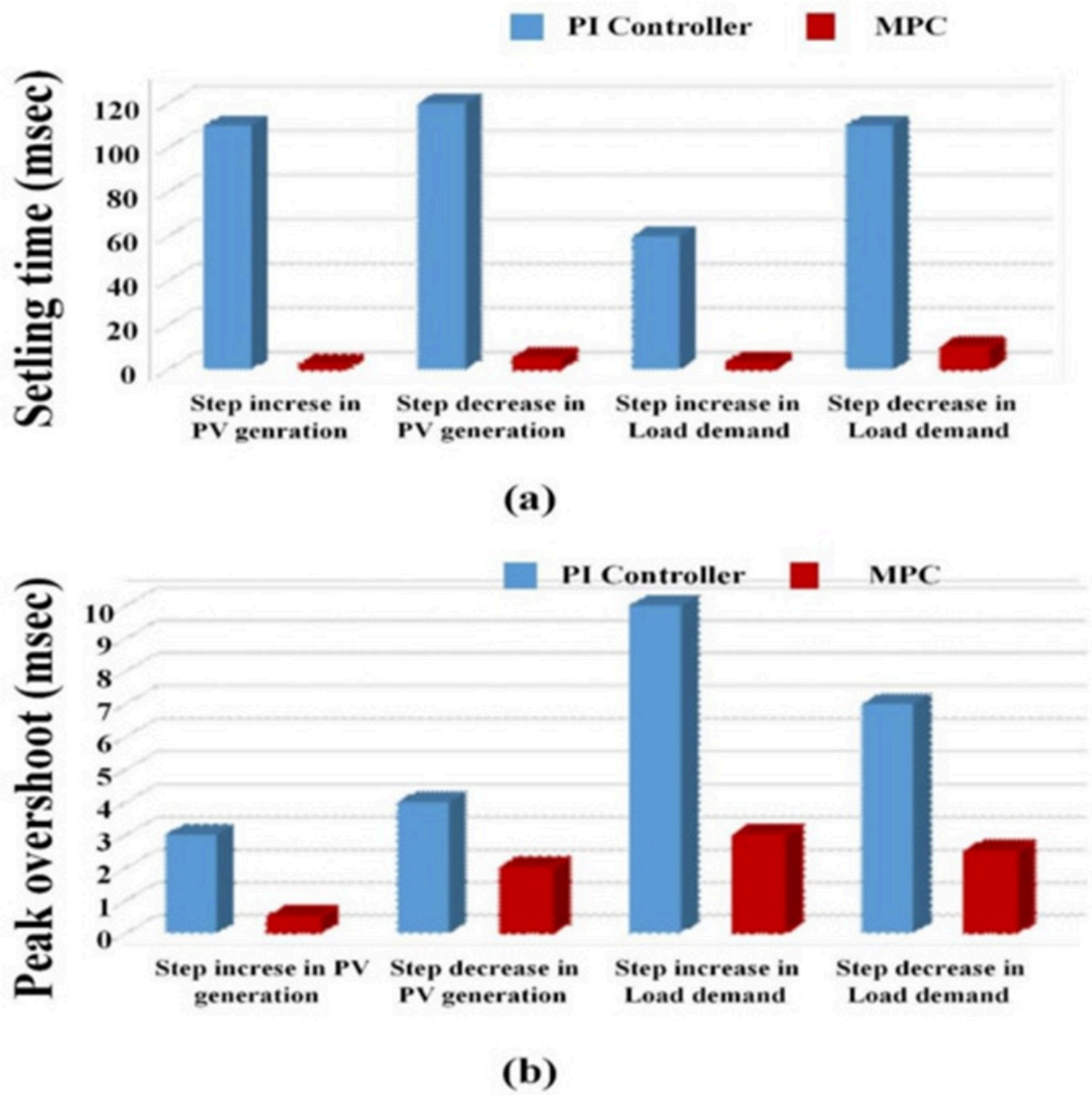


Figure 16. Visual comparison of dynamic performance between the PI and MPC controllers: (a) voltage settling time and (b) maximum peak overshoot.

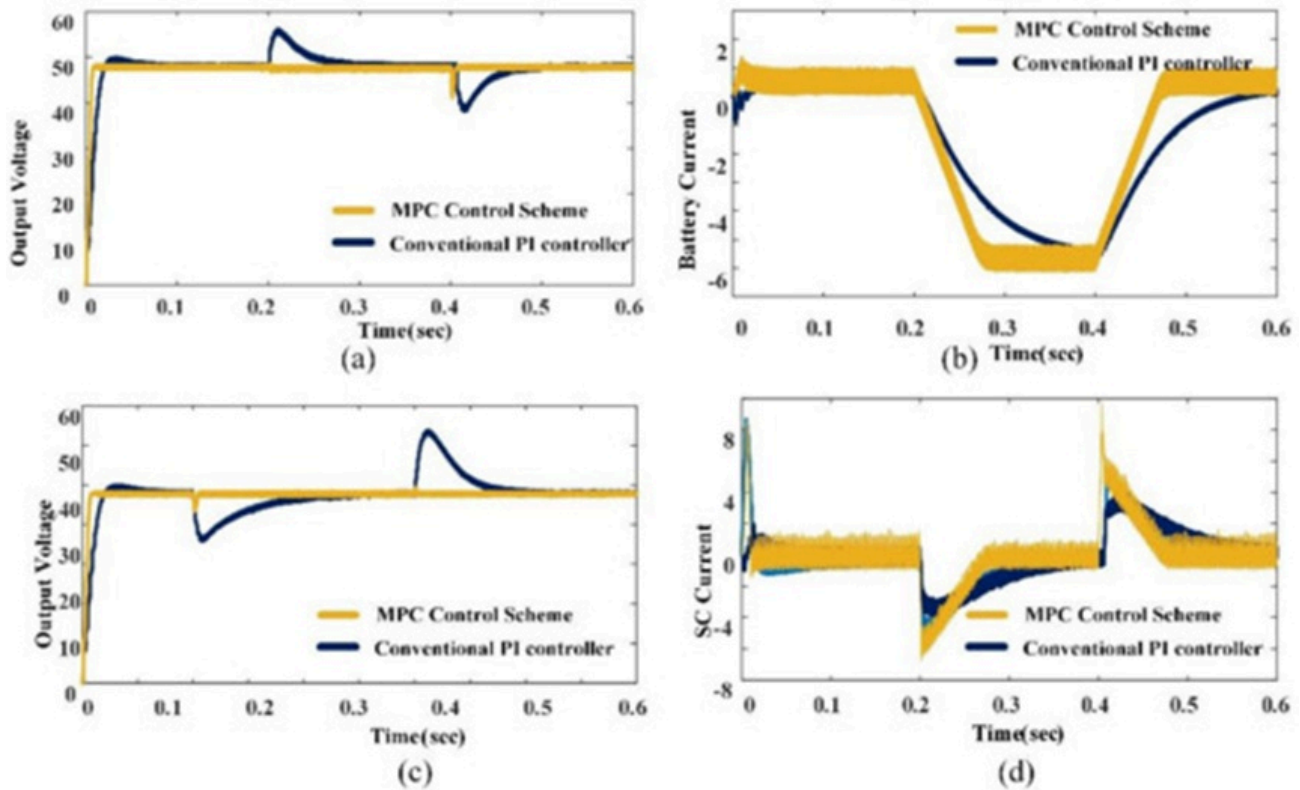


Figure 17. Performance comparison highlighting the behavior of the PI controller relative to MPC: (a) PV input subjected to a step disturbance, (b) battery current response, (c) load demand applied as a step variation, and (d) supercapacitor (SC) current response.

Experimental Results

The proposed MPC scheme was substantiated through laboratory testing on a low-power, scaled prototype, as depicted in [Figure 18](#). Control implementation was carried out using a dSPACE-DS1104 real-time platform. During experimentation, electrical quantities were acquired using an LA 55-P current sensor and an LV 25-P voltage sensor. To replicate photovoltaic behavior, a regulated power supply (RPS) in conjunction with a current-regulated boost converter was used as a PV emulator. The hybrid energy storage system (HESS), provided by Safe Power Exide Chloride, consisted of a 12 V, 7 Ah lead–acid battery paired with a Maxwell BMOD0058 supercapacitor rated at 16 V and 58 F. Additionally, the dual-input bidirectional converter topology incorporated six IRF540N MOSFET switches.

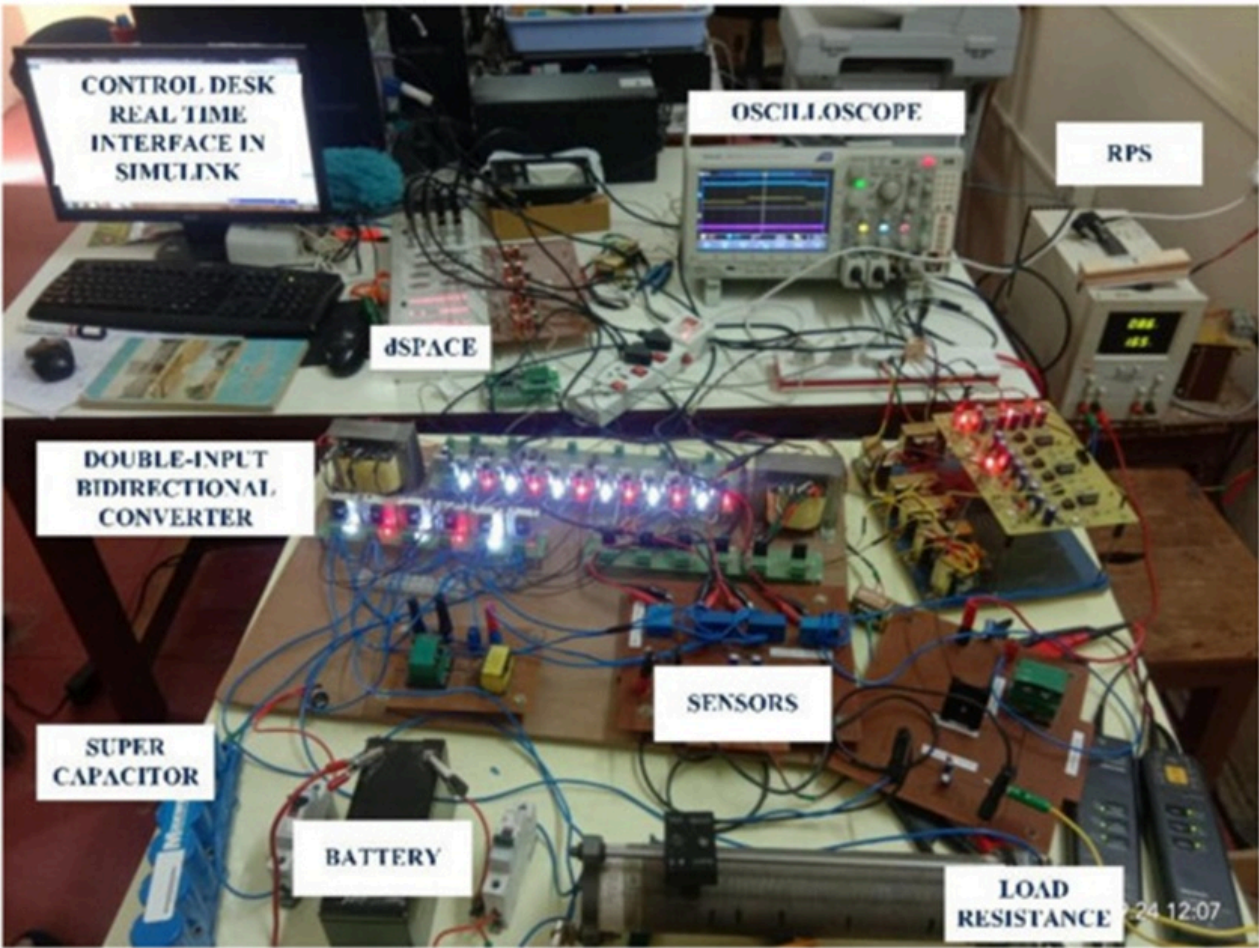


Figure 18. Physical setup of the HESS hardware prototype.

The behavior of the DC microgrid, supplied by a PV emulator and backed by the HESS, was evaluated under two conditions: (1) sudden variations in PV output and (2) abrupt changes in load demand. The DC grid specifications are summarized in [Table 6](#), with the microgrid operating at a nominal voltage of 20 V.

Table 6. Parameters for implementing a DC microgrid.

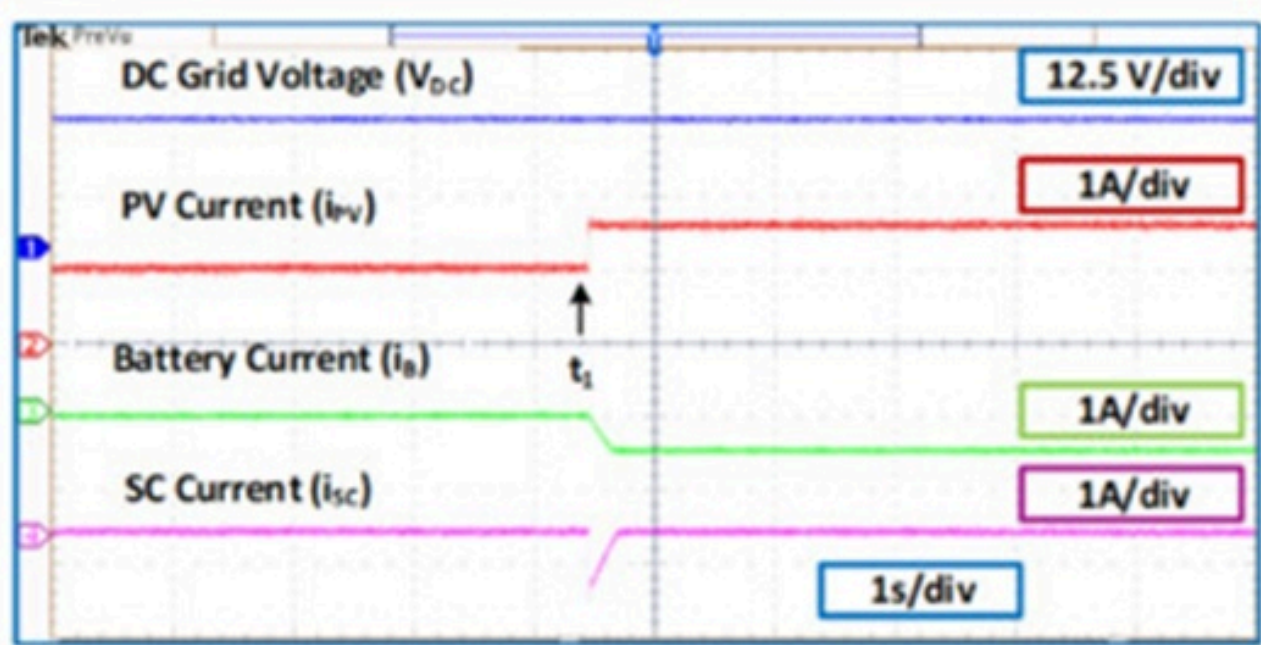
S. No	Parameters	Value
1	SC component voltage (V_{SC})	10 V
2	SC component inductance (L_S)	1.43 mH
3	Battery component voltage (V_B)	12 V
4	Battery inductance (L_B)	4.8 mH
5	Boost converter inductance (L)	4.1 mH
6	Load resistance (R)	25 Ω
7	DC microgrid voltage (V_{DC})	20 V
8	Filter capacitance (C)	150 μ F

Experimental response to step change in PV generation

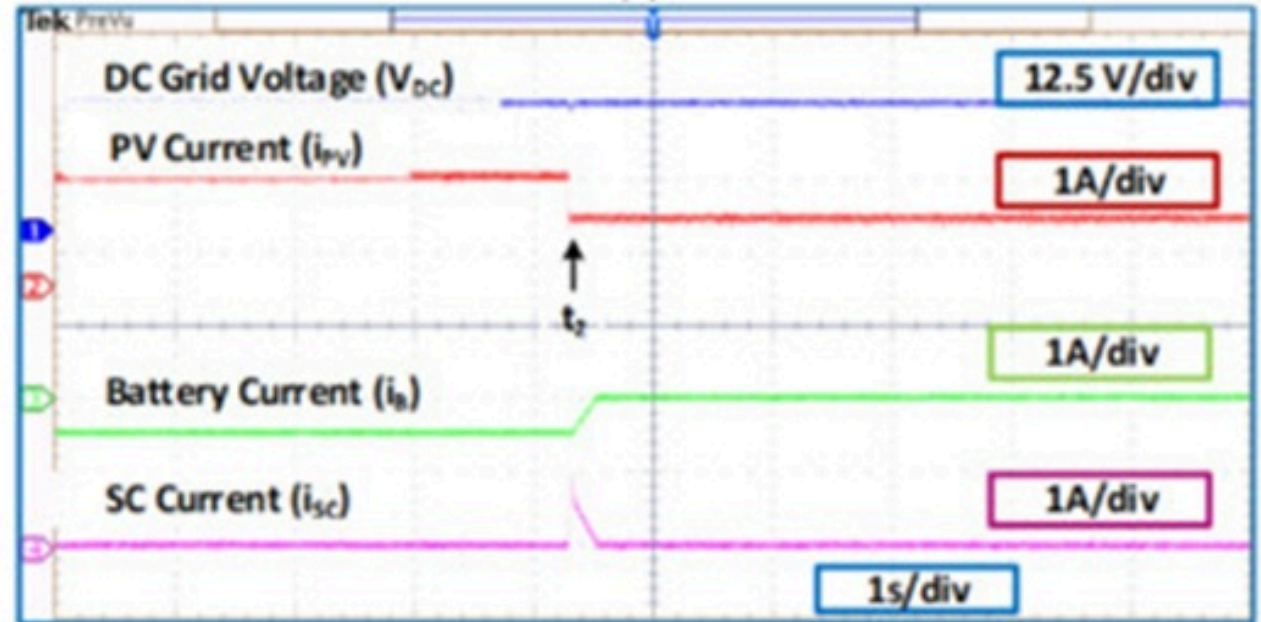
Figure 19 illustrates the hardware results obtained during a sudden variation in PV output. In this test, the load power demand was kept constant throughout.

To introduce the step increase, the PV emulator current was raised from 1 A to 1.5 A at instant t_1 (**Figure 19a**). Subsequently, at instant t_2 , the PV current was reduced back from 1.5 A to 1 A (**Figure 19b**). **Figure 19c** shows the overall experimental waveforms capturing both the upward and downward PV power steps.

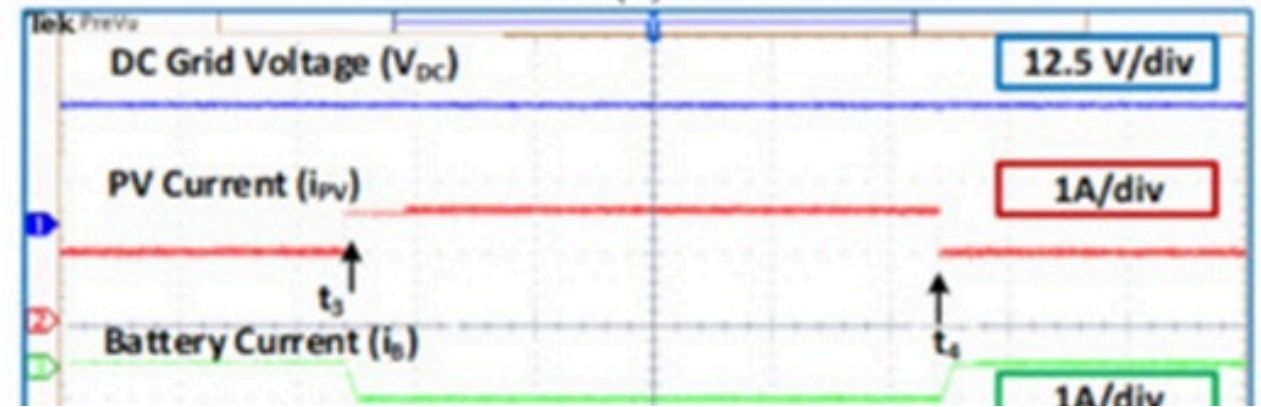
In both scenarios, the supercapacitor effectively handled the high-frequency transient power components, while the battery supplied the steady-state power requirement. This coordinated operation successfully maintained stable DC microgrid voltage under the sudden PV variations.

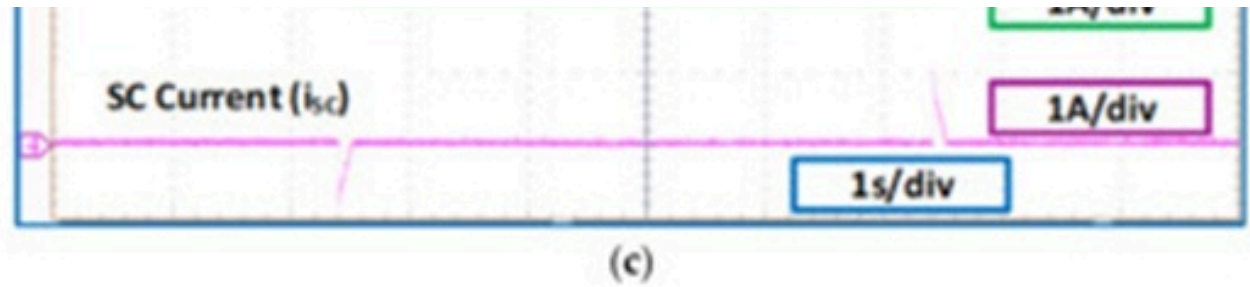


(a)



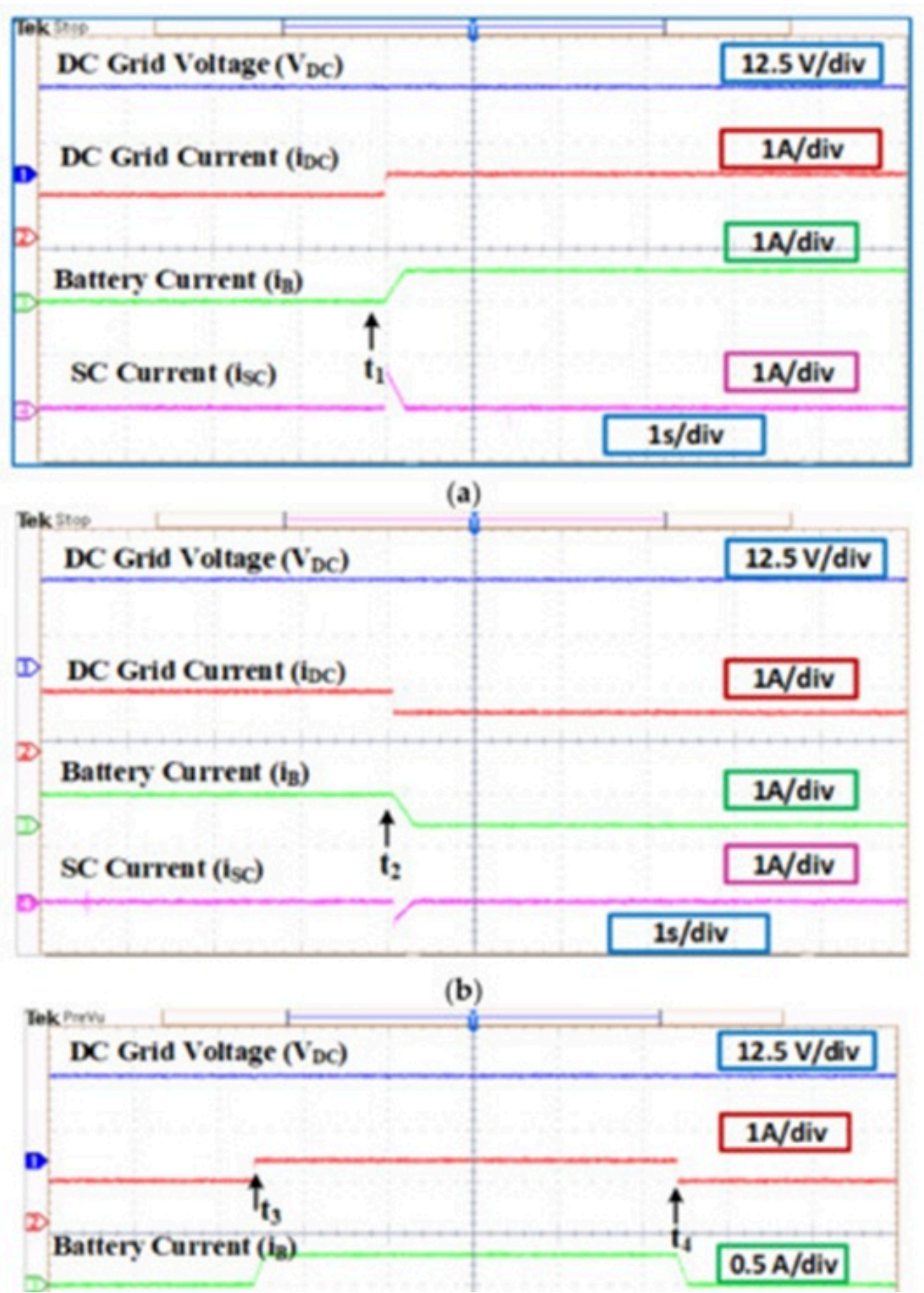
(b)

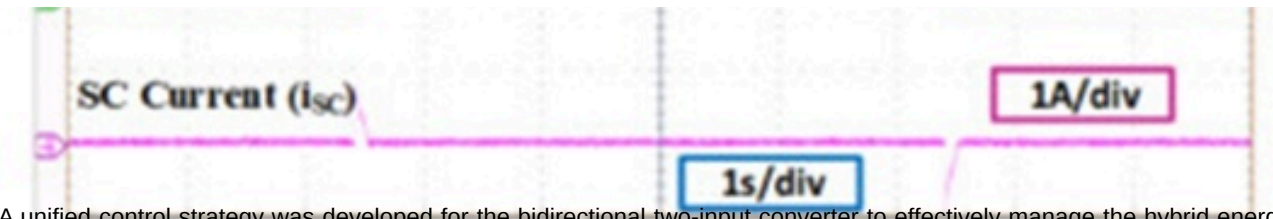




20b). Figure 20c displays the complete experimental waveforms for both the load-increase and load-decrease cases.

Such abrupt load changes create an immediate power mismatch between the PV source and the load. The hybrid energy storage system (HESS) reacts swiftly to correct this imbalance and stabilize the DC microgrid voltage. The supercapacitor absorbs the fast-transient power components, while the battery provides sustained steady-state power.





A unified control strategy was developed for the bidirectional two-input converter to effectively manage the hybrid energy storage system (HESS) in a DC microgrid. The proposed controller was thoroughly tested under multiple operating conditions to ensure reliable DC bus voltage regulation. It demonstrated excellent capability to maintain stable microgrid voltage despite disturbances from both PV generation fluctuations and abrupt load variations.

The control scheme cleverly exploits the supercapacitor’s fast response to handle sudden transients, while the battery handles sustained power requirements. The single controller successfully handled both charging and discharging modes of the HESS. Furthermore, it enabled fully decoupled, independent regulation of power flow for the supercapacitor and the battery, including seamless energy exchange between them.

The proposed system can also be extended to hybrid electric vehicle applications where multiple power sources are integrated. Additionally, the converter’s operating modes for maintaining the supercapacitor’s state of charge (SOC) within safe limits were successfully validated.

Nomenclature

RES	Renewable energy source
ANN	Artificial neural network
PWM	Pulse width modulation
EMS	Energy management scheme
EV	Electric vehicle
ESS	Energy storage systems
PV	Photovoltaic
HESS	Hybrid energy storage system
HEV	Hybrid electric vehicle
LPF	Low-pass filter
MISO	Multi-input single output
PI	Proportional integral
SC	Supercapacitor
SOC	State of charge

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Conflict of interest

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Ethics statement

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