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Article

Optimized Power Management Approach for Photovoltaic Systems with Hybrid Battery-Supercapacitor Storage

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Abstract: The paper addresses the ongoing and continuous interest in photovoltaic energy systems (PESs). In this context, the study focuses on an isolated photovoltaic system with hybrid battery-supercapacitor storage (HBSS). The integration of supercapacitors (SCs) in this system is of particular importance because of their high specific power density. In photovoltaic (PV) systems, multi-storage systems use two or more energy storage technologies to enhance system performance and flexibility. When batteries and supercapacitors are combined in a PV system, their benefits are maximized and offer a more reliable, efficient, and cost-effective energy storage option. In addition, effective multi-storage power management in a PV system needs a solid grasp of the energy storage technologies, load power demand profiles, and the whole system architecture. In this work, battery-supercapacitor storage system (HBSS) is established by combining batteries and supercapacitors. The primary objective is to devise a novel management algorithm that effectively controls the different power sources. The algorithm's purpose is to regulate the charge and discharge cycles of the HBSS, ensuring that the state of charge (SOC) of both batteries and supercapacitors remains within the desired range. The proposed management algorithm is designed to be simple, efficient, and light on computational resources. It efficiently handles the energy flow within the HBSS, optimizing the usage of both batteries and supercapacitors based on real-time conditions and energy demands. By maintaining the SOC of these energy storage components within the specified limits, the proposed method ensures their longevity and maximizes their performance. Simulation results obtained from applying the management strategy are found to be satisfactory. These results show that the proposed algorithm maintains the SOC of batteries and supercapacitors within the desired range, leading to improved energy management and enhanced system efficiency.

Keywords: photovoltaic; power management control; batteries; supercapacitor; hybrid energy storage

1. Introduction

In remote areas the adoption of renewable energy systems is rising [1--5]. In order to keep the source energy and the charge demand in an optimal power balance, the energy storage system is essential [6, 7]. In photovoltaic (PV) systems, energy storage is used to store excess solar energy produced during the day so that it can be used at a later time when the sun is not shining or when

electricity demand is high. There are several types of energy storage technologies that can be used in photovoltaic (PV) systems, including batteries, supercapacitors, Flywheels, pumped hydroelectric storage, thermal energy storage and fuel cells. Batteries are the most widely used storage technology for PV systems, as they are relatively inexpensive and can be easily installed in residential and commercial settings. Supercapacitors, also known as ultracapacitors, store electrical energy as an electrostatic charge. They have a high-power density, meaning they can charge and discharge quickly, making them well-suited for applications that require high power output. While supercapacitors have some advantages over batteries, such as faster charging times and longer lifetimes under certain conditions; they also have some limitations that may make them less practical for some PV system applications. The different drawbacks are low energy density, high cost, limited lifespan, voltage limitations and leakage current [8, 9].

The best combination will be determined by the system requirements and the resources at hand. It will be determined by various criteria, including the system's precise requirements, the available budget, and the tradeoffs between the advantages and downsides of each technology. The combination of batteries and supercapacitors has various advantages. Batteries can store significant quantities of energy for extended periods of time, but supercapacitors may discharge fast and give high-power bursts for brief periods of time. This combination has the potential to assist balance the load on the PV system, particularly during high energy demand periods. When a PV system produces extra energy, the batteries may be charged and when power demand is high, the stored energy in the batteries can be released. However, Batteries have a limited discharge rate and are susceptible to voltage loss during high-power demands. Supercapacitors, however, discharge fast, giving extra power to meet high power demands, and they can also maintain a constant voltage output during periods of high-power demand. Combining batteries and supercapacitors has the added benefit of extending the life span of both power sources. Supercapacitors can absorb high power bursts, lowering battery burden and reducing battery cycling. This helps preventing battery damage, increasing their life span. Supercapacitors are more costly than batteries, but they are capable of reducing the capacity required for the battery system. However, there are some potential disadvantages, such as higher costs, complex control systems, maintenance issues, safety concerns, and limited scalability.

Power management of multi-storage in a PV system is a crucial aspect to ensure that the different energy storage technologies work together effectively and efficiently. Additionally, continuous monitoring of the SOC ensures that the storage systems operate within their optimal range, by ensuring optimized utilization and maximum system efficiency. Power management of photovoltaic (PV) systems with multi storage technologies has been the subject of several research papers [10-19]. The power management of PV systems with multi storage technologies involves controlling the power flow between different energy storage technologies, such as batteries and supercapacitors, while also ensuring that the load is supplied. The goal is to optimize the use of each storage technology and maximize the overall system efficiency.

The purpose of this study is to introduce a management power control which permits the control of the charge and discharge process of storage. The application is demonstrated in Berjaya an area with a significant potential for solar irradiation, using four different day patterns. The validity and usefulness of the suggested power management approach are shown in this study through simulation results. On a real-time simulator (RT Lab), a number of experimental tests were carried out to assess the suggested control algorithms.

2. Biometrical study on storage in renewable energies

The integration of biometrics in renewable energy's storage of freshen handed security, improved use reexperience, and increased efficiency in managing renewable energy systems. A research has been made based on different keywords (energy storage, renewable energy, batteries, photovoltaic, Figure 1 visually depicts the network of relationships between terms, represented by lines connecting one term to another. This figure illustrates the clusters associated with different aspects of renewable energy research. Notably, recent developments in the field are prominently

related to storage systems, photovoltaic, hybrid renewable energies, and electric vehicle charging. This figure can be a reference for future researchers to identify relevant themes within the renewable energy domain. The findings reveal a total of 741 items related to renewable energy. These items are organized into six distinct clusters as follows:

1. Cluster 1 (Red) - Contains 234 items.
2. Cluster 2 (Green) - Contains 192 items.
3. Cluster 3 (Blue) - Contains 158 items.
4. Cluster 4 (Yellow) - Contains 82 items.
5. Cluster 5 (Purple) - Contains 65 items.
6. Cluster 6 (Cyan) - Contains 11 items.

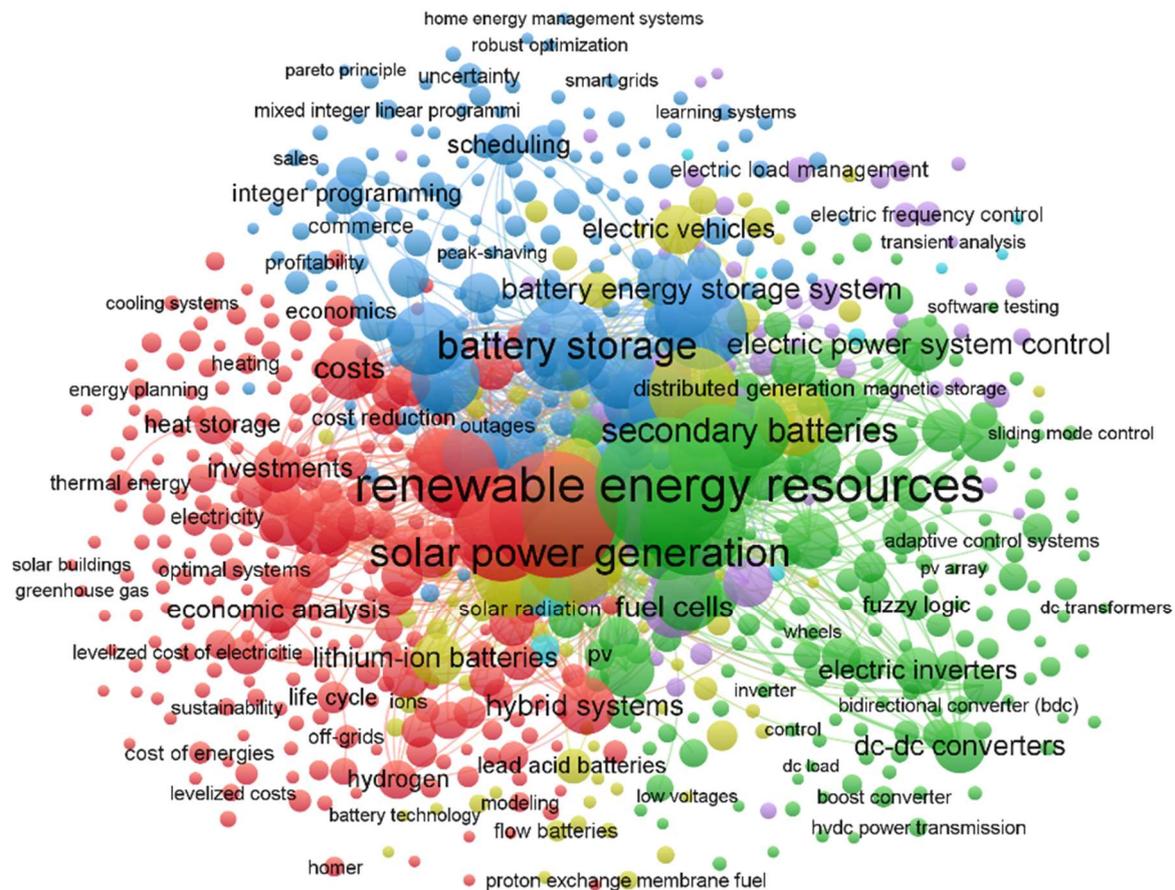


Figure 1. Network visualisation of renewable energy keyword.

Each cluster represents a group of related terms, and a colored circle is assigned to each term within the clusters. The size of the circles is proportional to the frequency of occurrence of the terms in the titles and abstracts. Larger circles and letters indicate more frequent appearances of the terms.

3. Proposed PV hybridstoragesystem

PV panels, a DC/DC converter, and (batteries/supercapacitors)storage system are all components of the system under study (Figure 1). Long-term energy storage is possible with battery technology. Supercapacitors can quickly absorb current variation, lowering the risk to the batteries. The voltage of the solar panels can be raised by connecting a boost converter to them. Due to the connection of supercapacitors and batteries to the DC bus, electrical power from the PV panels, batteries, and supercapacitors can all be used to power the load simultaneously.

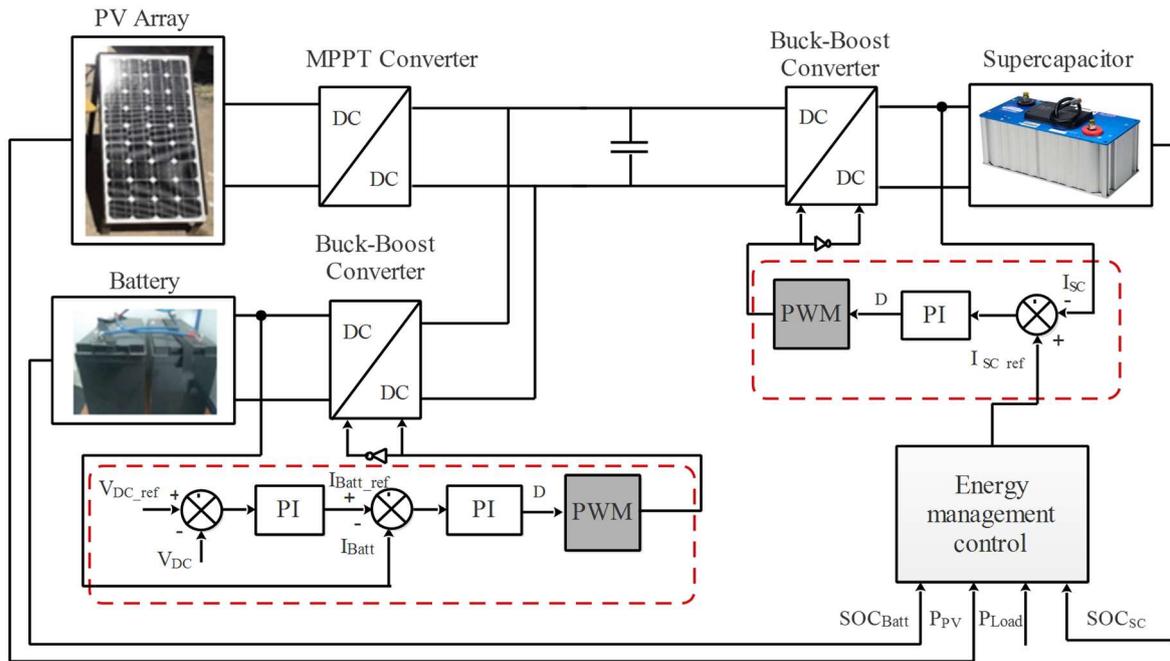


Figure 2. Proposed PV based hybrid storage scheme.

3. CONTROLLER DESIGN

3.1. Photovoltaic panel modeling

The electrical current is [6,20-25]:

$$I_{pv} = I_{ph} - I_0 \times \left[\exp\left(\frac{q \times (V_{pv} + R_s \times I_{pv})}{A \times N_s \times K \times T_j}\right) - 1 \right] - \frac{V_{pv} + R_s \times I_{pv}}{R_{sh}} \quad (1)$$

Where: I_{ph} , I_d and I_{Rsh} are respectively photo-current, diode-current and shunt resistance current.

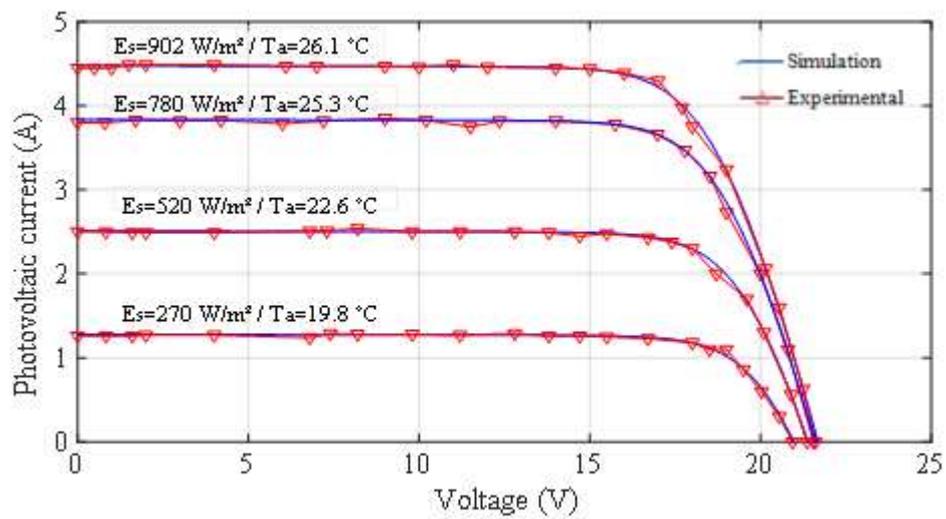
Various tests (Experimental and simulations) have been performed in order to identify the different PV panel characteristics (Figure 3) under three distinct solar irradiation and ambient temperature levels: low, medium and high as pointed out in Table 1. The established experimental bench is highlighted in Figure 4

Table 1. PV identification tests.

Tests	E_s (W/m ²)	T_a (°C)
Test 1	750.00	28.00
Test2	410.00	27.50
Test 3	158.00	21.00



Figure 3. Experimental test bench.



(a) $I_{pv}=f(V_{pv})$

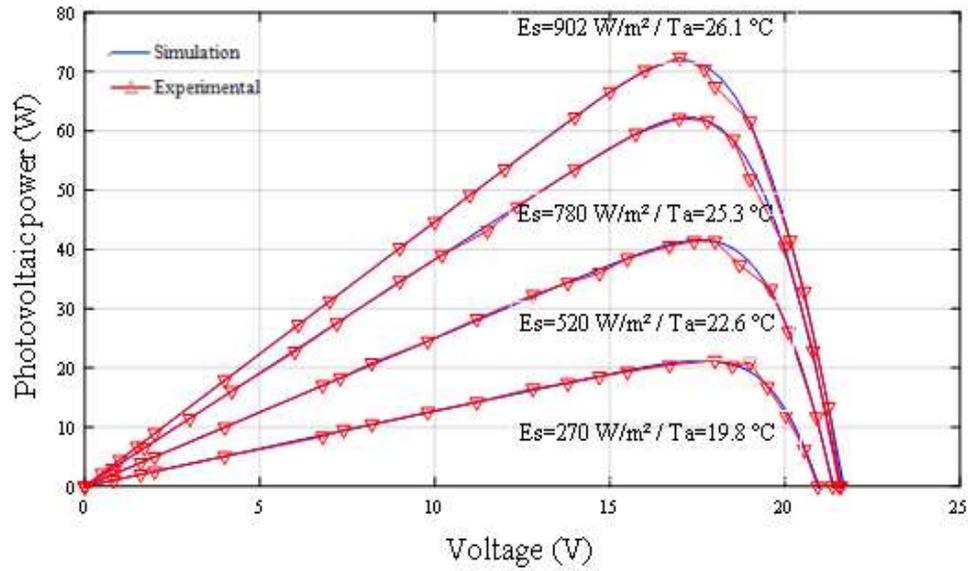
(b) $P_{pv}=f(V_{pv})$

Figure 4. Electrical characteristics.

3.2. Battery modeling

The following model (Figure 5) has been employed in our work using various voltage and charge state equations [1,7].

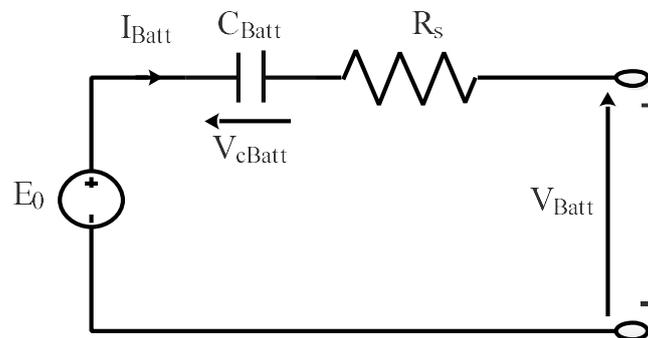


Figure 5. R-C model of the battery.

$$\begin{cases} V_{Batt} = E_0 - R_{Batt} \cdot I_{Batt} - k \cdot \int \left(\frac{I_{Batt}}{Q} \right) \cdot dt \\ SOC = 1 - \frac{I_{Batt} \cdot t}{C_{Batt}} \end{cases} \quad (2)$$

In this study, a 12 V-100 Ah battery is used as a storage device as shown in Figure 6. Identification is performed to determine the battery impedance (Z_{Batt}).

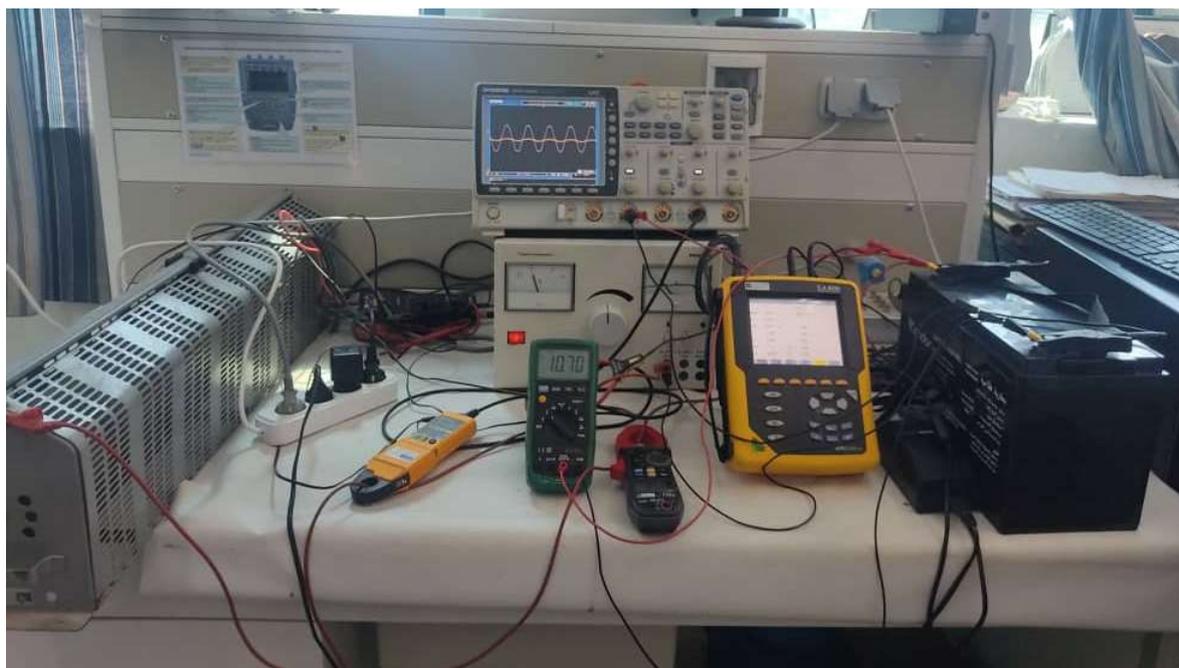


Figure 6. Battery identification test bench.

The phase shift of these two signals gives the impedance Z_{Batt} . And then internal resistance R_{Batt} , and the capacitive reactance X_{Batt}

$$\begin{cases} Z_{Batt} = \frac{U_{batt}}{I_{Batt}} \\ R_{Batt} = Z_{Batt} \cdot \cos \rho \\ X_{Batt} = Z_{Batt} \cdot \sin \rho \\ C_{Batt} = \frac{1}{(X_{batt} \cdot 2 \cdot \pi \cdot f)} \end{cases} \quad (3)$$

With: f the frequency, (Hz)

The different calculated results are:

$R_{Batt}=0.795 \Omega$, $X_{Batt}=0.07 \Omega$ and $C_{Batt}=44.96 \text{ mF}$

All of these identified variables were included in simulation models to establish realistic mathematical models that were as near to the experiment as possible. Figure 7 shows the different curves obtained while proceeding to the identification of the battery. It shows that there exist a phase shift of 3 degrees between voltage and current (voltage is lagging)



Figure 7. Battery voltage and current curves.

3.3. Supercapacitors model

Different models for simulating a supercapacitor (SC) have been put forth in the literature [26 - 36]. The corresponding electric circuit with two RC branches (Figure 8) is the model utilized in our research.

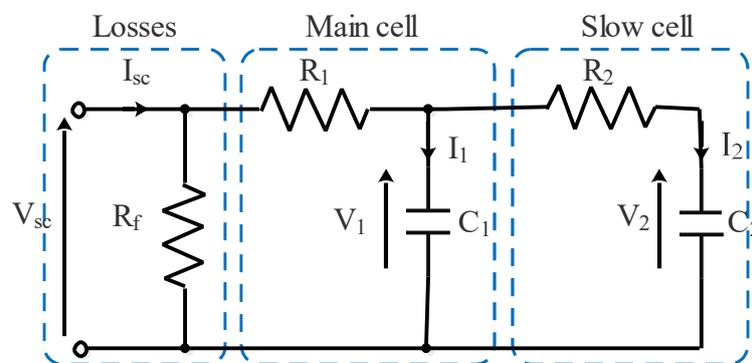


Figure 8. SC model.

There are two branches to it. The supercapacitor's immediate behavior during quick charge and discharge cycles with in seconds is defined by the R1C1 branch [8, 9]. The sluggish branch is the second branch R2C2. The model [8] is described by the equations below:

$$\begin{aligned}
 U_{SC} &= N_{SC-s} \cdot V_{SC} = N_{SC-s} (V_1 + R_1 \cdot I_{SC}) \\
 &= N_{SC-s} \left(V_1 + R_1 \cdot \frac{i_{SC}}{N_{SC-p}} \right)
 \end{aligned} \tag{4}$$

The SC's pack voltage and current are represented as U_{sc} and I_{sc} , respectively. The fundamental supercapacitor voltage and current are V_{sc} and i_{sc} , respectively.

The secondary capacity C_2 's secondary voltage V_2 is determined by:

$$\begin{aligned}
 V_2 &= \frac{1}{C_2} \int i_2 \cdot dt \\
 &= \frac{1}{C_2} \int \frac{1}{R_2} (V_2 - V_2) \cdot dt
 \end{aligned}
 \tag{5}$$

Q_2 is the instantaneous charge of C_2 , we have:

$$Q_2 = \int i_2 \cdot dt \tag{6}$$

The current i_1 in the main capacitor C_1 is given as:

$$i_1 = i_{sc} - i_2 \tag{7}$$

There are three main techniques to characterize a supercapacitor as listed in Table 3 shown below:

Table 3. Different supercapacitor identification techniques.

Technique	Description	Advantages	Drawbacks
Electrochemical impedance spectroscopy	Supercapacitor impedance is measured as a function of frequency	Identifies several supercapacitor electrical properties such as capacitance, resistance, and frequency-dependent behavior	Expensive equipment required.
Cyclic voltammetry	Various voltages are applied to the supercapacitor and the resulting current is measured.	Provides information about the supercapacitor's capacitance, charge/discharge behavior, and electrochemical stability.	High degree of interpretation and practical skills are required
Charge-Discharge Cycling	The capacitor is charged to a set voltage, then it is discharged through a load while measuring the resulting voltage and current.	Fast and relatively easy way to determine the capacitance and resistance of supercapacitors	The accuracy of the results can be influenced by the quality of measurement equipments, the accuracy of the voltage and current measurements

Galvanostatic charge-discharge cycling, potentiation charge-discharge cycling, and constant current charge-discharge cycling are just a few of the methods that can be used to describe supercapacitors. The exact properties of the supercapacitor being tested and the data needed for the application determine the technique to use. Charge-discharge cycling was employed in this study to evaluate the supercapacitor (Figure 9). Table 4 displays the various supercapacitor's researched parameters.

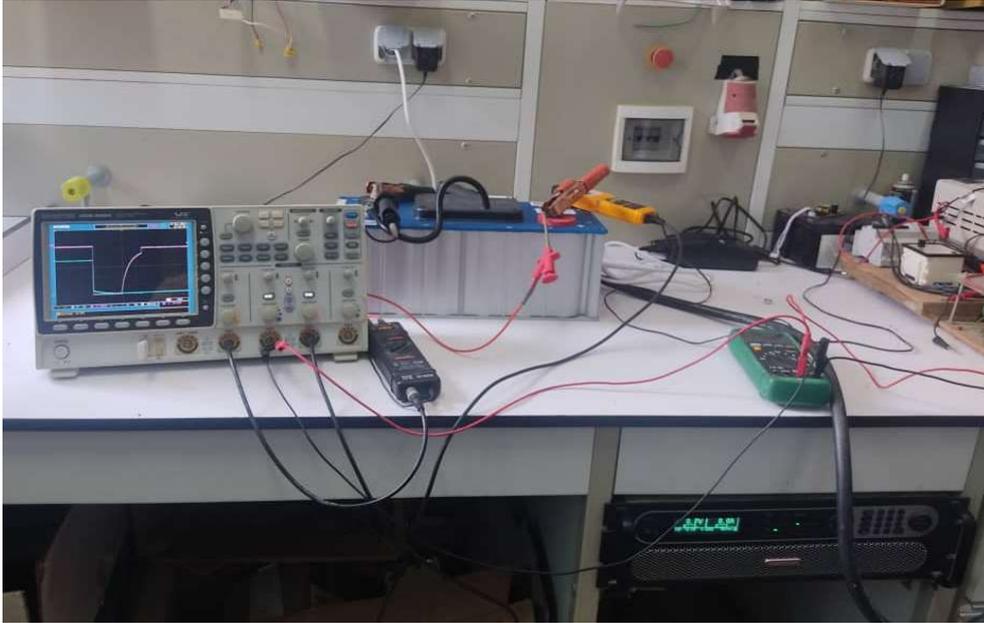


Figure 9. Supercapacitor identification test bench.

Table 4. Supercapacitor parameters.

Paramètres	Values
Rated capacitance	165 F
Maximum ESR _{DC} initial	60 m Ω
Test current for capacitance and ESR _{DC}	100A
Rated voltage	48 V
Stored energy	53 Wh
Absolute maximum voltage	51 V
Absolute maximum current	1,900 A
Maximum series voltage	750V
Capacitance of individuel cells	3,000 F
Storage Energy, individuel cell	3.0 Wh
Number of cells	18

During charge and for a current of 10A, we obtain the following response (Figure 10). The resistance R_1 is the cause of the drop in the load voltage at the initial moment. C_1 is determined directly from the constant current load characteristic of the cell: $C_1 = I / ((\Delta V) / (\Delta t)) = 10 / ((20 - 2) / ((300 - 10))) = 161F$.



Figure 10. Tests under charge and discharge.

The different identified parameters are given in Table 5.

Table 5. Obtained identified parameters.

Parameters	Values
R ₁	1,8Ω
R ₂	0,5Ω
C ₁	161F
C ₂	102F

4. Proposed Power management control

Two DC/DC converters that are set up as buck-boost converters are employed by the power management system, which also employs a power flow control method. To make sure the system runs smoothly and effectively, these converters regulate the flow of power. These are the load power requirements:

$$P_{loadcalc} = P_{pv} + (P_{Batt} + P_{Sc}) \quad (8)$$

Where ΔP is the power demand variation

$$\Delta P = P_{load} - P_{pv} \quad (9)$$

According to Table 6, there are eleven possible modes. the flowchart (Figure 11) shows how it works.

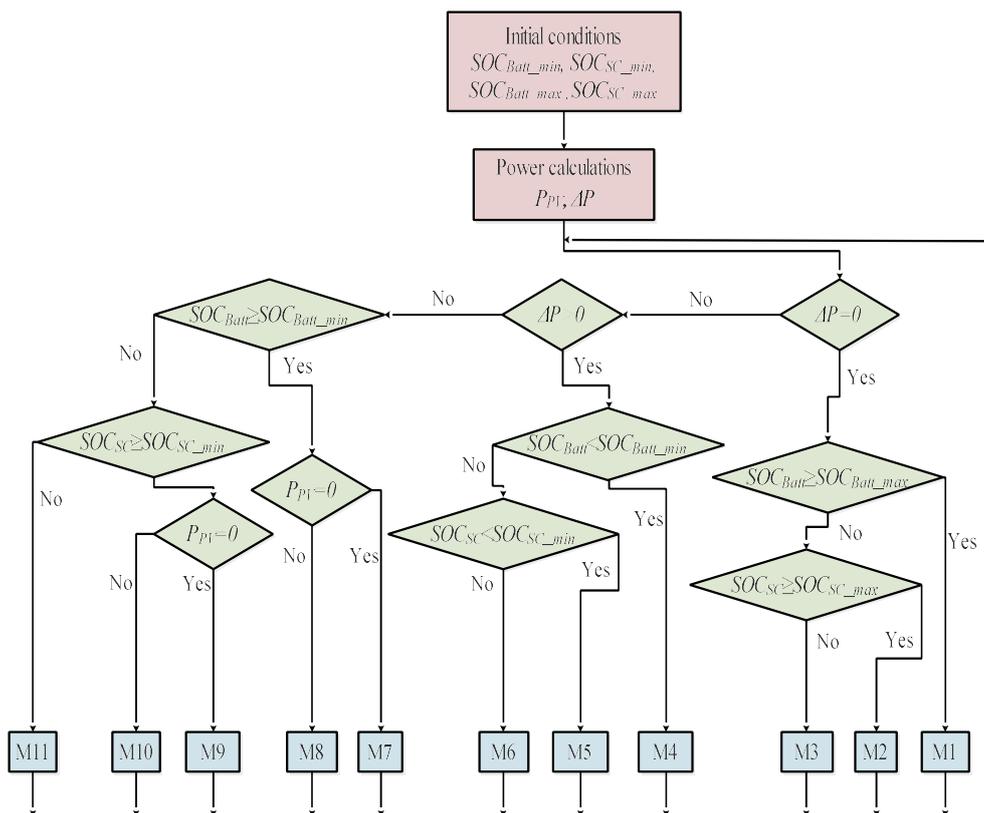
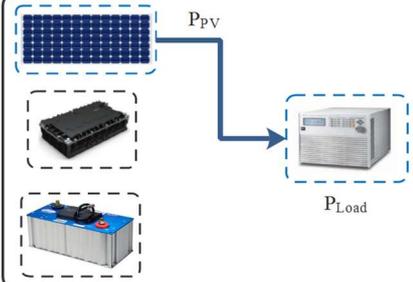
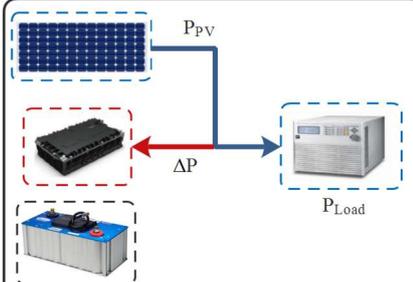
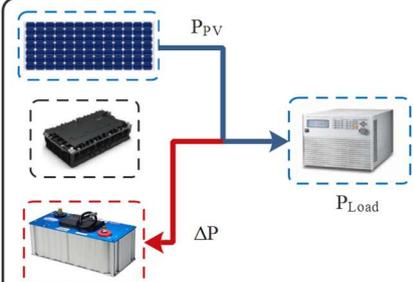
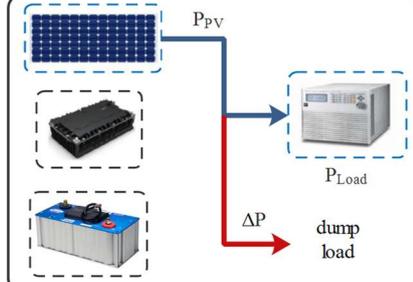
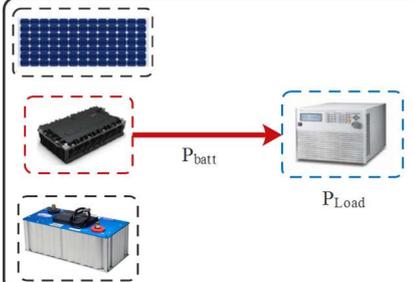


Figure 11. Photovoltaic system energy management flowchart.

Table 6. The different possible modes.

Modes	description	Equations	Scheme
M1	We disconnected the batteries because they are fully charged.	$\begin{cases} \Delta P = 0 \\ P_{load} = P_{pv} \\ SOC_{Batt} \geq SOC_{Batt_max} \end{cases}$	
M2	We disconnected the the supercapacitors because they are fully charged.	$\begin{cases} \Delta P = 0 \\ P_{load} = P_{pv} \\ SOC_{SC} \geq SOC_{SC_max} \end{cases}$	

M3	<p>When the batteries and supercapacitors are depleted and disconnected, the load is powered by PV power.</p>	$\begin{cases} \Delta P = 0 \\ P_{load} = P_{pv} \\ SOC_{Batt} < SOC_{Batt_min} \\ SOC_{SC} < SOC_{SC_min} \end{cases}$	
M4	<p>The generated photovoltaic power will be used to supply the load since it is greater than what is needed by the load.</p> <p>The extra power recharge the batteries..</p>	$\begin{cases} \Delta P > 0 \\ P_{load} = P_{pv} \\ SOC_{Batt} \leq SOC_{Batt_min} \end{cases}$	
M5	<p>The generated photovoltaic electricity will be used to supply the load because it is greater than the load power.</p> <p>The extra power charge the supercapacitors.</p>	$\begin{cases} \Delta P > 0 \\ P_{load} = P_{pv} \\ SOC_{SC} \leq SOC_{SC_min} \end{cases}$	
M6	<p>PV powers the load, and any extra power is sent to a backup load while the batteries and supercapacitors are charged</p>	$\begin{cases} \Delta P > 0 \\ P_{load} = P_{pv} \\ SOC_{Batt} \leq SOC_{Batt_min} \\ SOC_{SC} \leq SOC_{SC_min} \end{cases}$	
M7	<p>The batteries are charged, the load is supplied, and the photovoltaic power is zero</p>	$\begin{cases} \Delta P < 0 \\ P_{pv} = 0 \\ P_{load} = P_{Batt} \\ SOC_{Batt} > SOC_{Batt_min} \end{cases}$	

M8	As long as the batteries are charged, since the PV power is not zero, they will fill up the power gap and supply the load.	$\begin{cases} \Delta P < 0 \\ P_{pv} \neq 0 \\ P_{load} = P_{pv} + P_{Batt} \\ SOC_{Batt} > SOC_{Batt_min} \end{cases}$	<p>The diagram shows a PV panel (P_{pv}) and a battery (P_{batt}) connected to a load (P_{Load}). A blue arrow labeled P_{pv} points from the PV panel to the load. A red arrow labeled P_{batt} points from the battery to the load. The PV panel and battery are enclosed in dashed boxes.</p>
M9	Since there is no PV power in this scenario, charged SCs will be used to feed the load.	$\begin{cases} \Delta P < 0 \\ P_{pv} = 0 \\ P_{load} = P_{SC} \\ SOC_{SC} > SOC_{SC_min} \end{cases}$	<p>The diagram shows a supercapacitor (P_{sc}) connected to a load (P_{Load}). A red arrow labeled P_{sc} points from the supercapacitor to the load. The supercapacitor is enclosed in a dashed box.</p>
M10	The load is provided by SCs and PV power because the SCs are charged and the PV power is not zero.	$\begin{cases} \Delta P < 0 \\ P_{pv} \neq 0 \\ P_{load} = P_{pv} + P_{SC} \\ SOC_{SC} > SOC_{SC_min} \end{cases}$	<p>The diagram shows a PV panel (P_{pv}) and a supercapacitor (P_{sc}) connected to a load (P_{Load}). A blue arrow labeled P_{pv} points from the PV panel to the load. A red arrow labeled P_{sc} points from the supercapacitor to the load. Both the PV panel and supercapacitor are enclosed in dashed boxes.</p>
M11	We disconnected the batteries and SCs. The load could not be supplied by the PV because of the low batteries and SCs levels of SOC.	$\begin{cases} \Delta P < 0 \\ P_{pv} \neq 0 \\ P_{load} = 0 \\ SOC_{Batt} \leq SOC_{Batt_min} \\ SOC_{SC} \leq SOC_{SC_min} \end{cases}$	<p>The diagram shows a PV panel (P_{pv}) and a load (P_{Load}). A dashed blue arrow labeled P_{pv} points from the PV panel to the load, indicating a disconnected connection. The PV panel is enclosed in a dashed box.</p>

It is worth mentioning that the proposed energy management strategy has eleven different modes and this increases the HESS system reliability and reduces the stress applied on the batteries.

5. Simulation results

The studied system is simulated under MATLAB/Simulink to verify the suggested control and energy management technique. The simulation's findings have been presented and analyzed. The measured profiles of solar irradiation and ambient temperature are respectively given in Figure 12 and Figure 13. DC bus voltage tracks well its reference (Figure 14). Voltage battery and supercapacitor are represented in Figure 15.

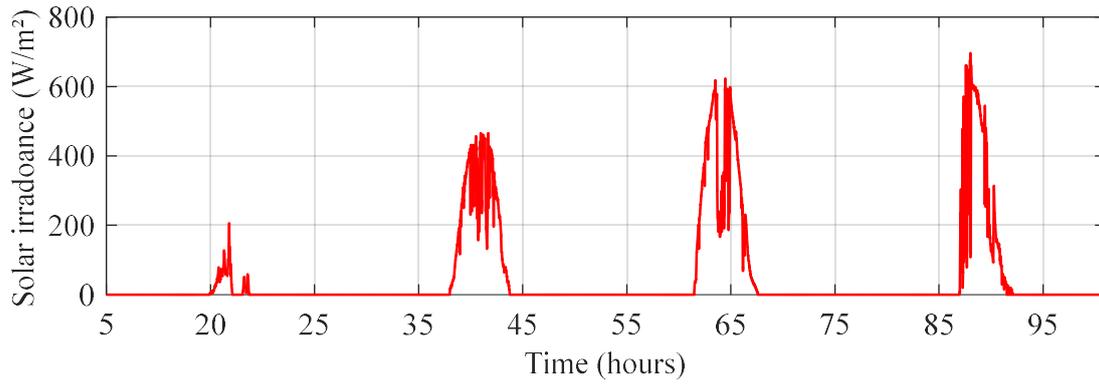


Figure 12. Measured solar irradiance.

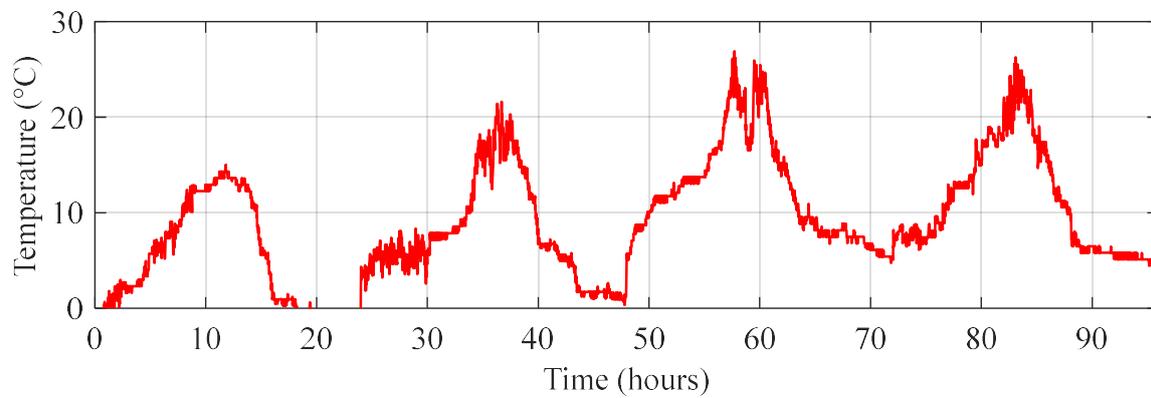


Figure 13. Ambient temperature.

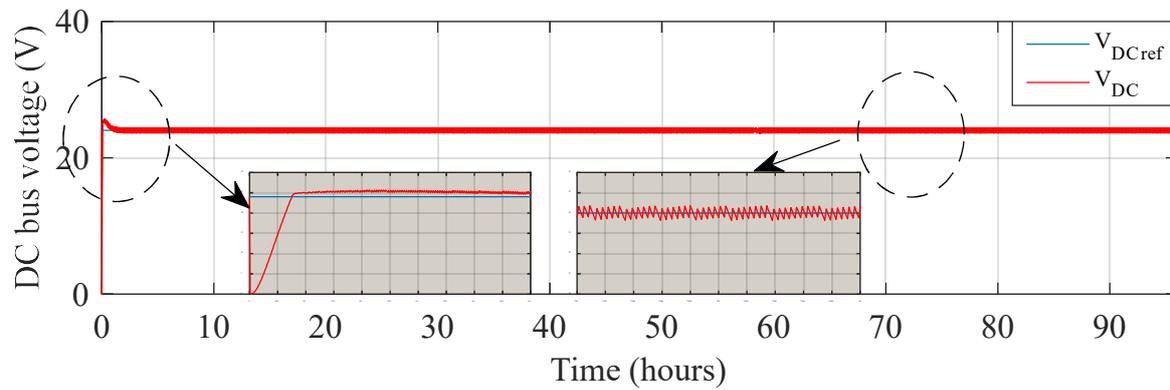


Figure 14. DC bus voltage.

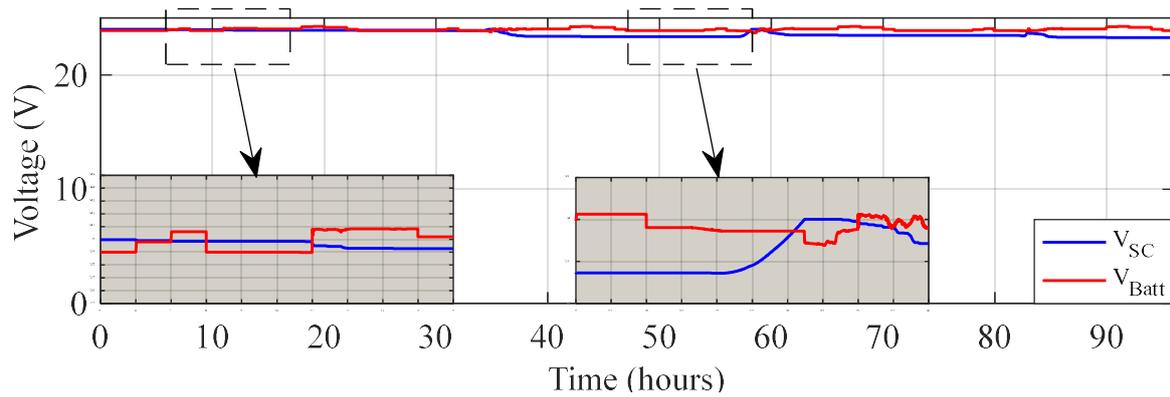


Figure 15. Voltage battery and supercapacitor.

It is shown in Figure 16, battery SOC is maintained between 82.85% and 90% while supercapacitor SOC varies between 58.05% and 90%. Figure 17 shown below points out the battery and supercapacitor currents. The different resulting modes are given in the Figure 18. The battery, supercapacitor and the PV powers are simultaneously depicted in Figure 19. The power per day of all power sources corresponding to four distinct days are shown in Figure 20. The reference load power and the sum of power developed by all the power sources are respectively shown in Figure 21. The zoom of this last mentioned figure for four distinct days is shown in Figure 22.

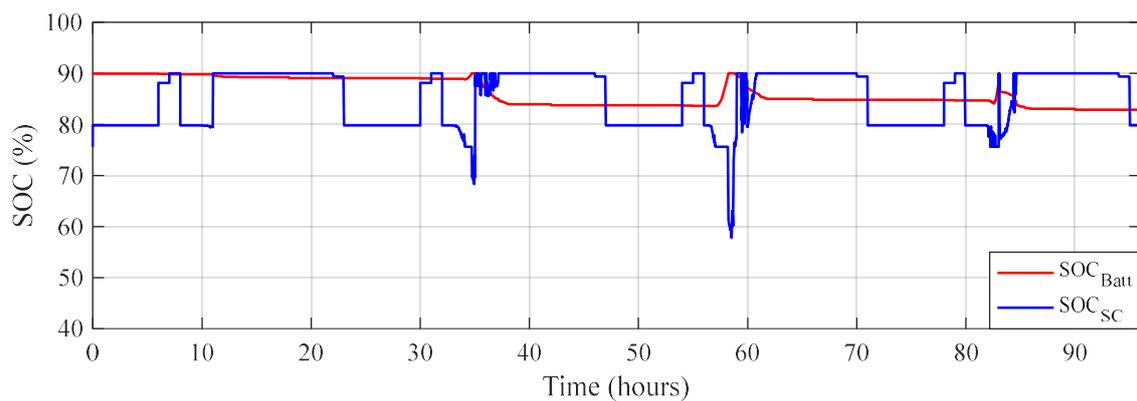


Figure 16. Battery and supercapacitor SOC.

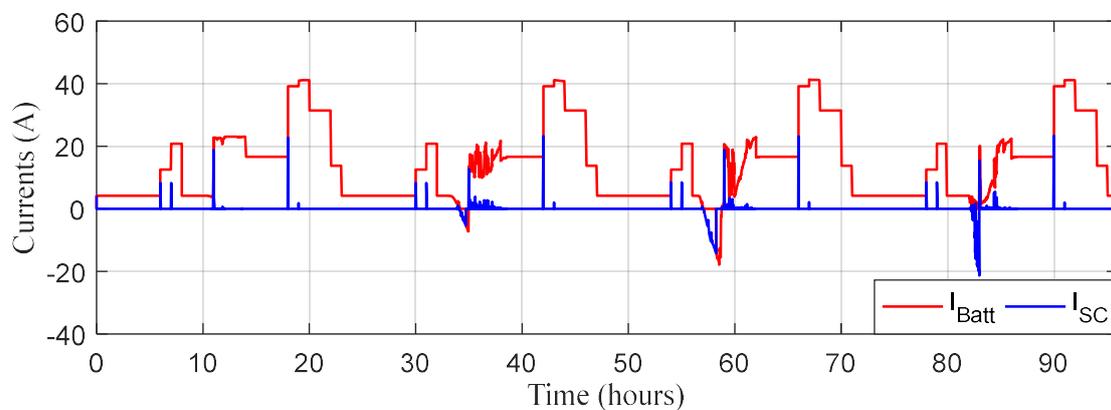


Figure 17. Battery and supercapacitor currents.

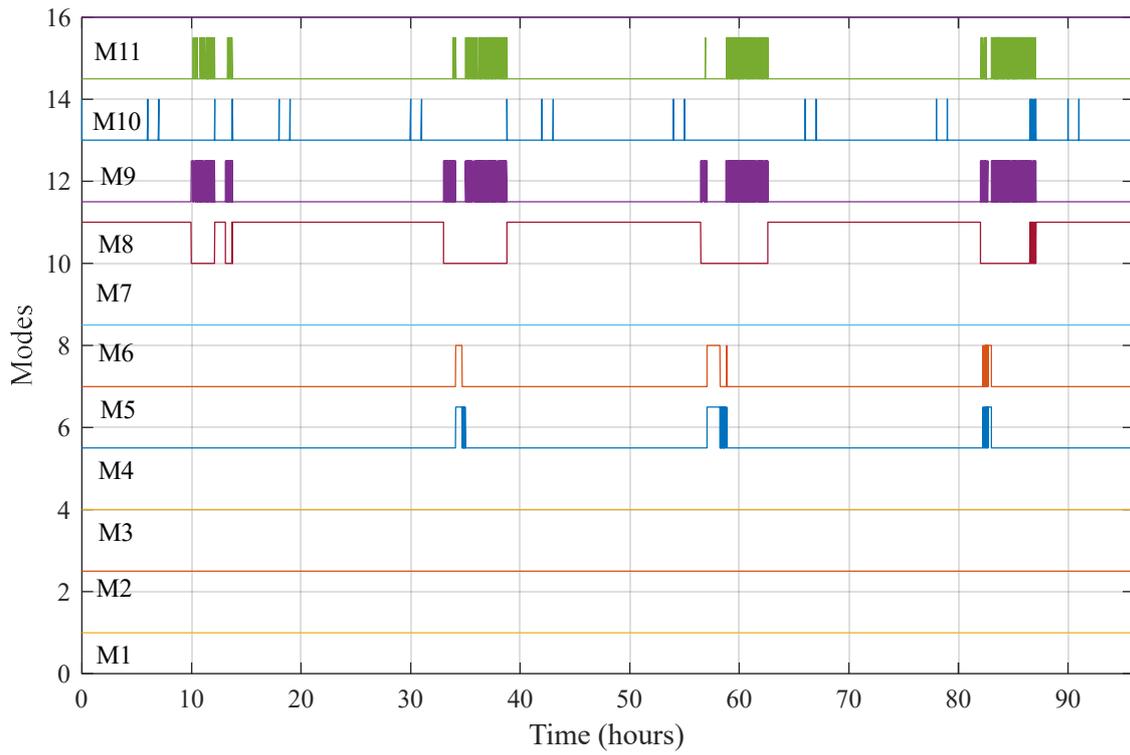


Figure 18. Differentobtainedmodes.

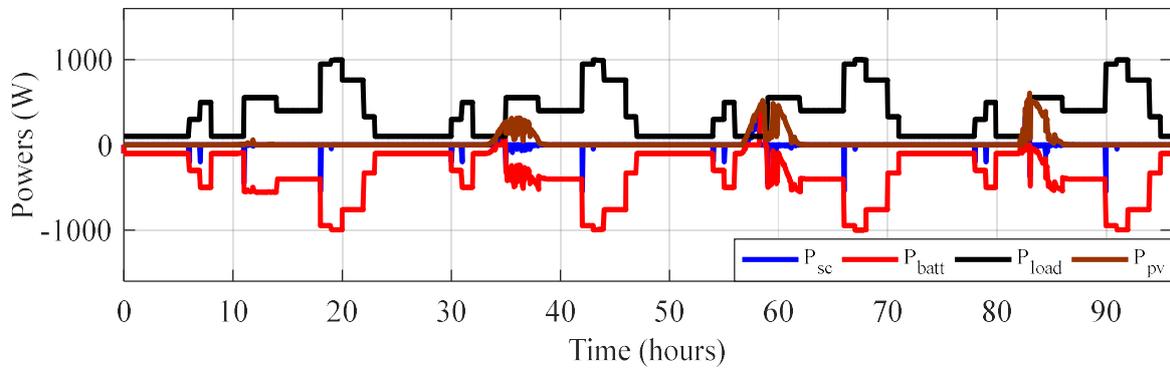
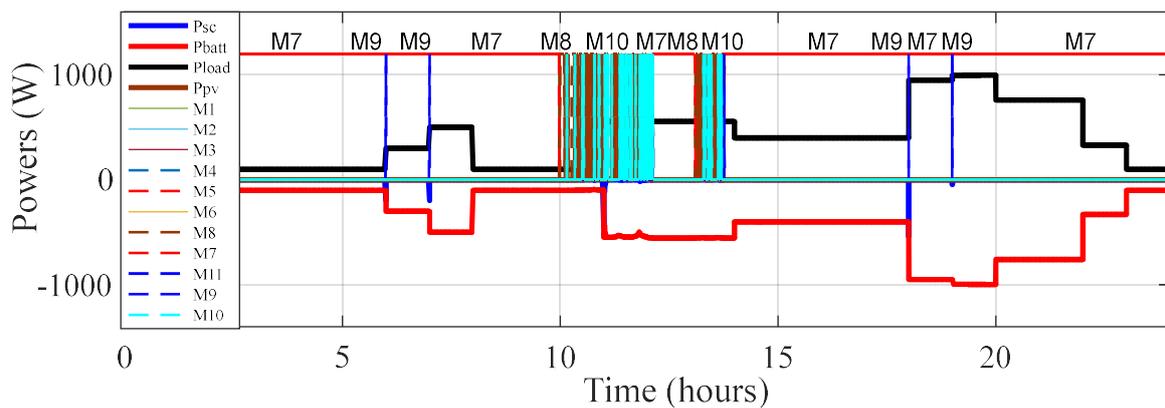


Figure 19. The different powers.



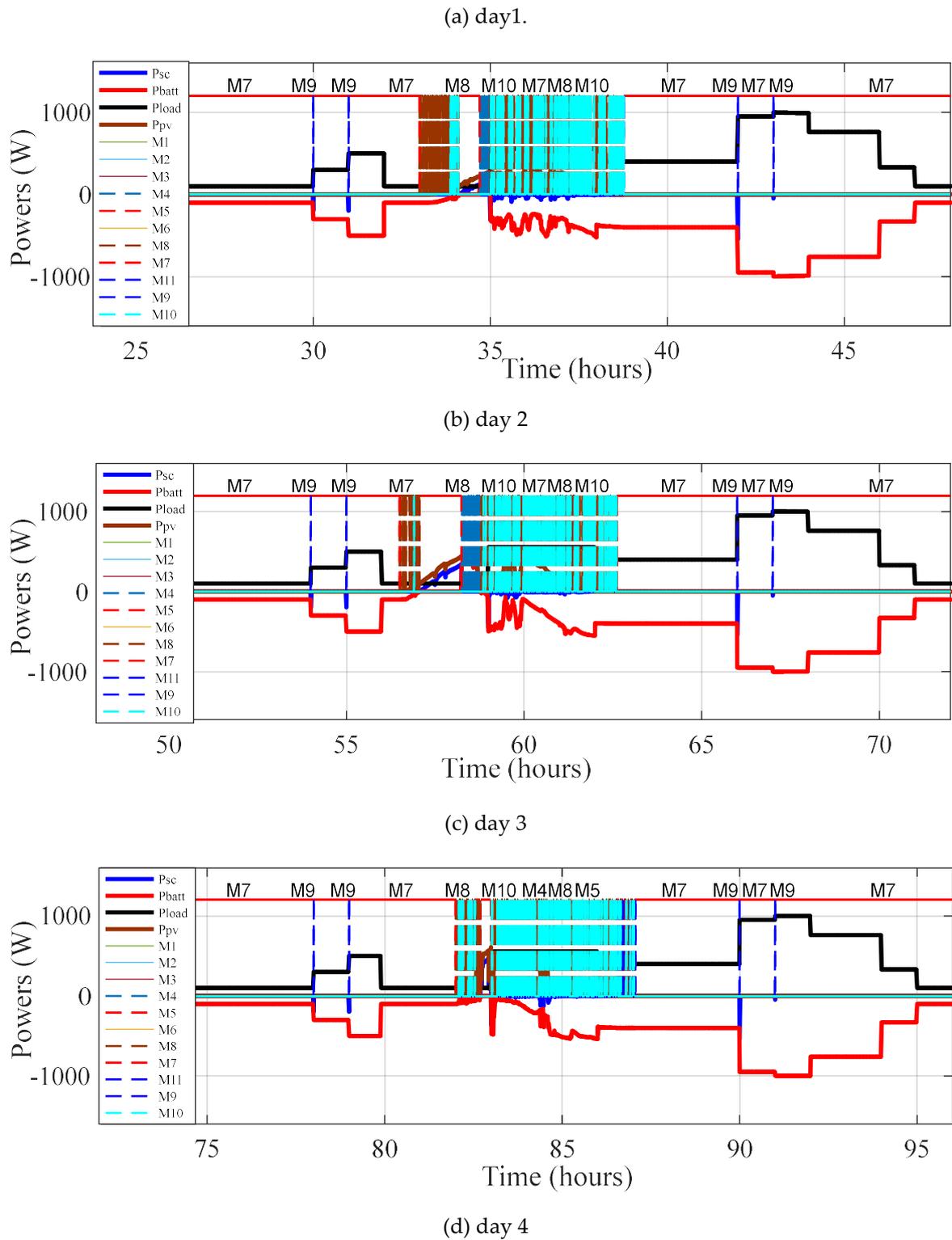


Figure 20. Powers per day with the different modes.

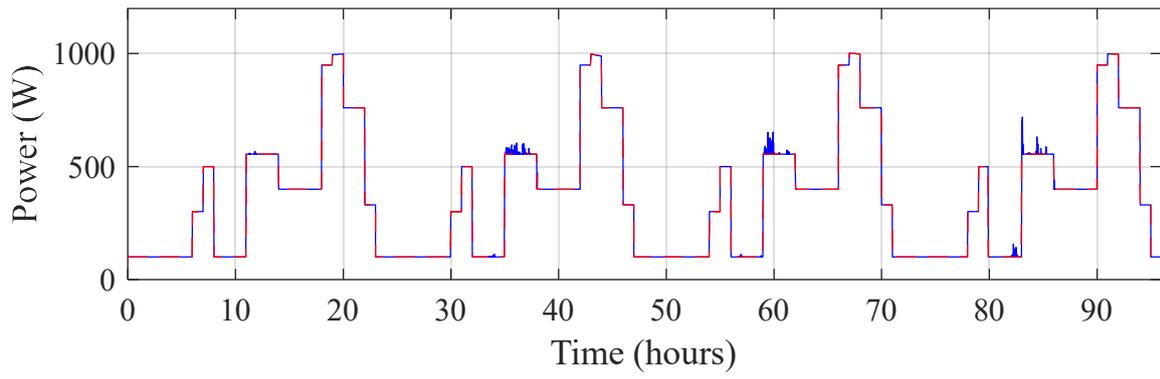
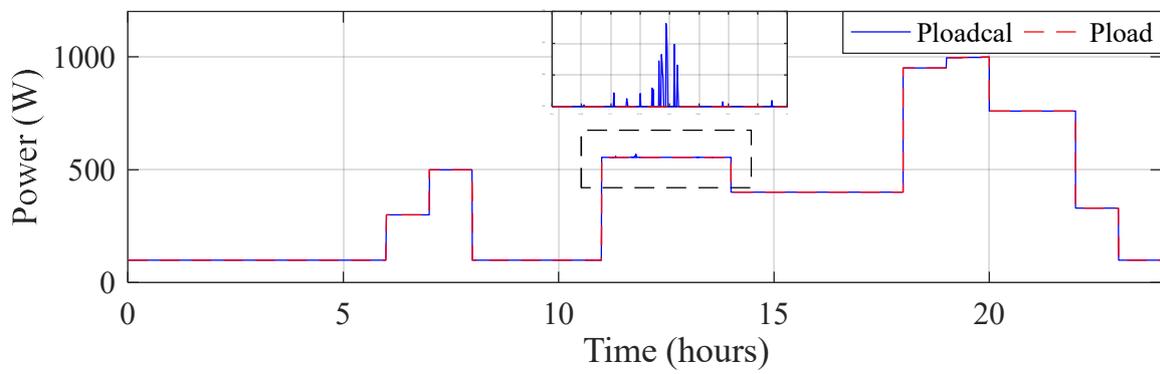
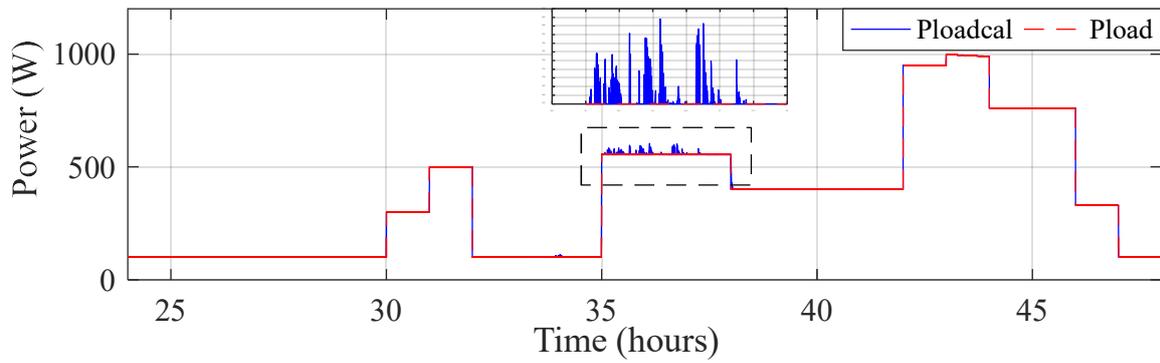


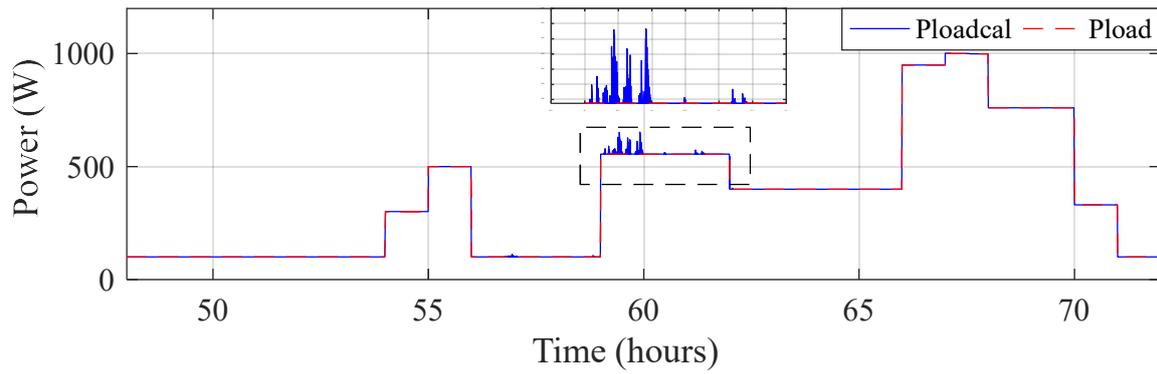
Figure 21. Calculated $P_{loadcal}$ and developed P_{load} power.



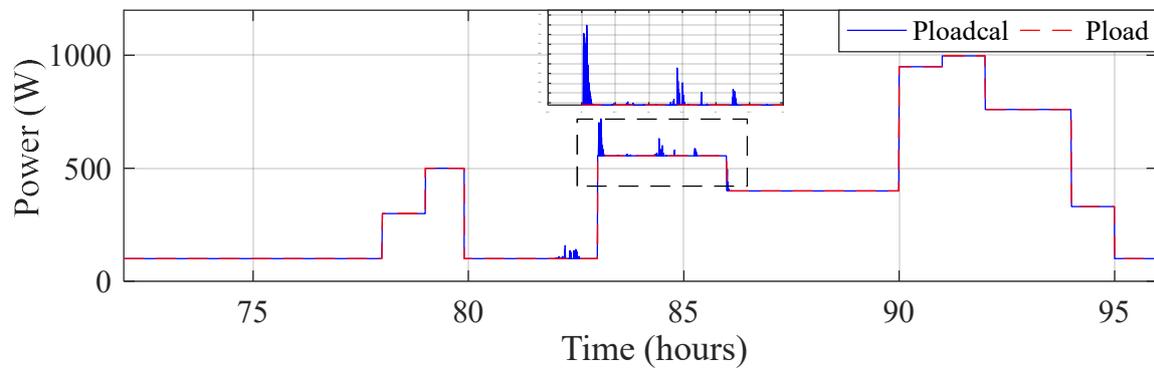
(a) day 1



(b) day 2



(c) day 3



(d) day 4

Figure 22. Zoomson calculated and developed load power.

6. Real-Time simulation

On a real-time simulator (RT Lab), a number of experimental tests were carried out to assess the suggested control algorithms. The system parameters remained the same as those used in the MATLAB/Simulink numerical simulation. A host PC, a real-time digital simulator (OP5700), an HIL controller, an OP8660 data collection interface, and a digital oscilloscope make up the real-time simulation bench (Figure 23).

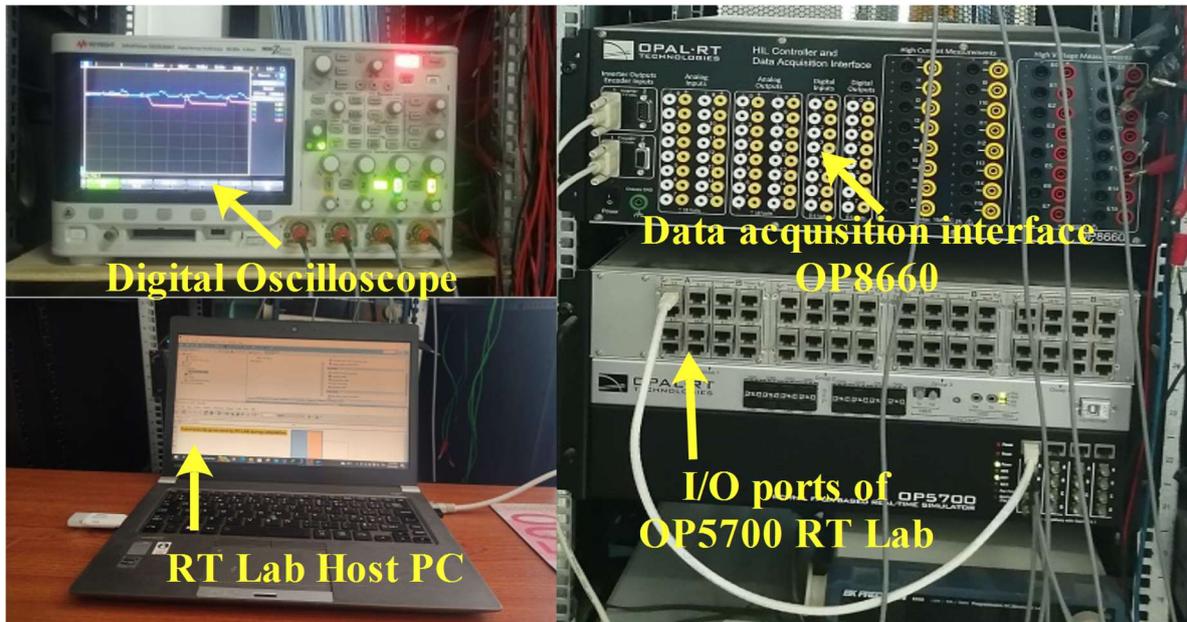
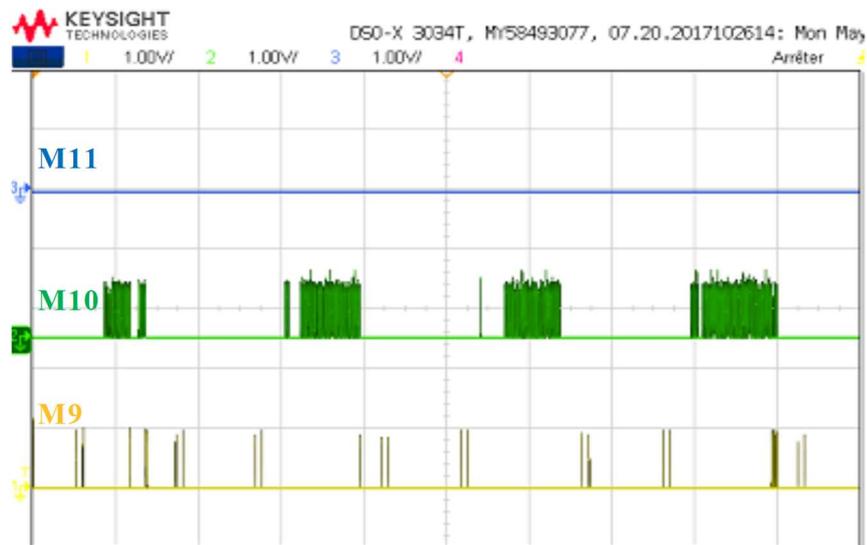


Figure 23. RT Lab real-time simulator work bench.

Figure 24 shows the different obtained modes when the energy management strategy is run using the RT LAB real time simulation platform. The scheduled modes from 1 to 11 are highlighted to demonstrate the efficacy of the suggested management.



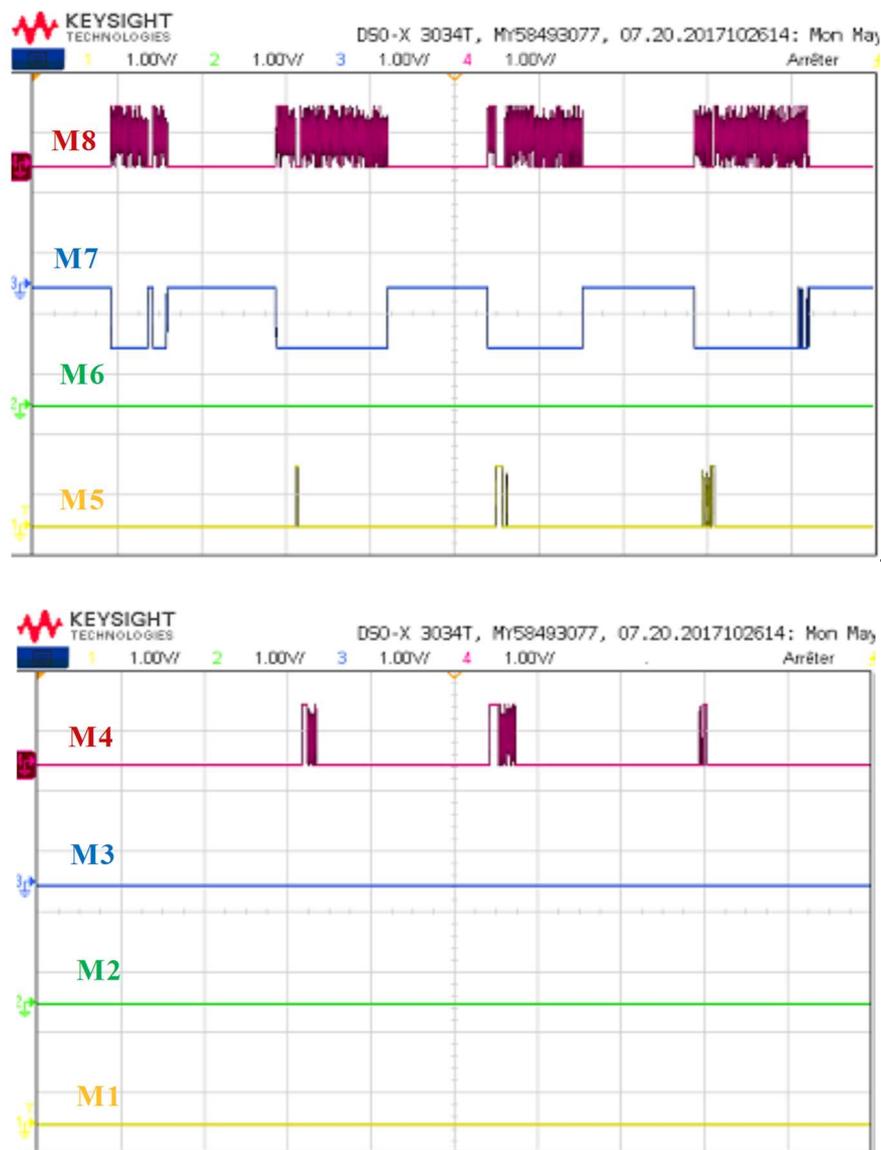


Figure 24. Different modes obtained in RTlab.

Battery and supercapacitor voltages and their corresponding zooms are highlighted in Figure 25. The SOC of both supercapacitor and battery are shown in Figure 26. The zoom in this same figure confirms that the SOC of the previously mentioned power sources is kept within safe limits during all these simulation periods.

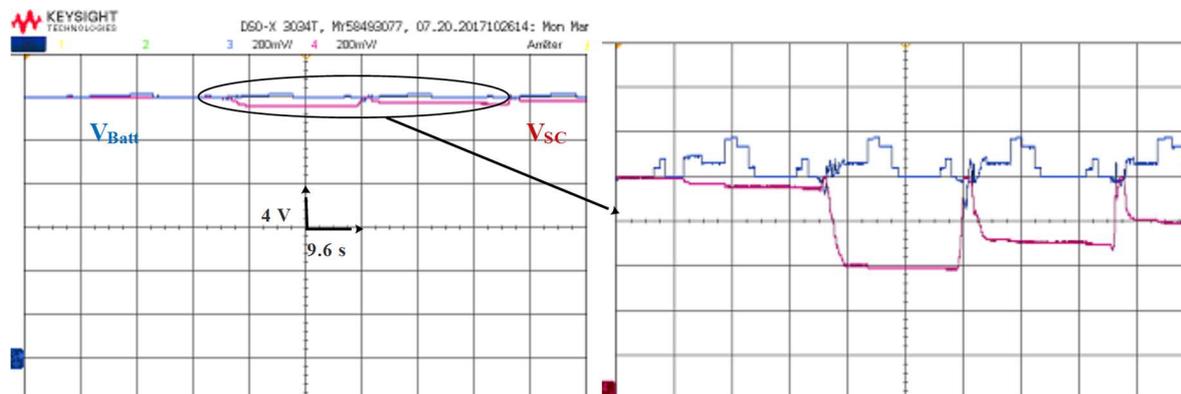


Figure 25. Battery voltage.

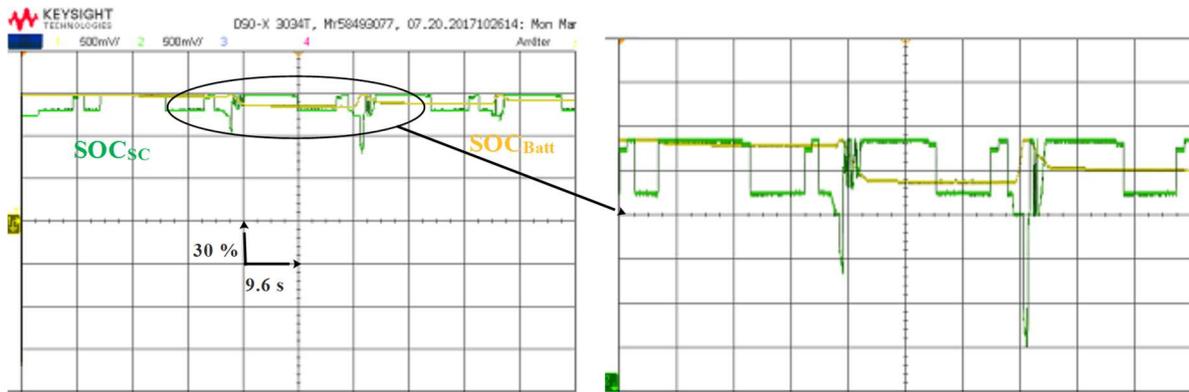


Figure 26. Battery-supercapacitor SOC and their zoom.

The battery and supercapacitor currents are shown in Figure 27. It can be seen that the battery is used during low and medium power demands. However, during fast and peak load demands, the supercapacitor is used because of its rapid transient dynamics.

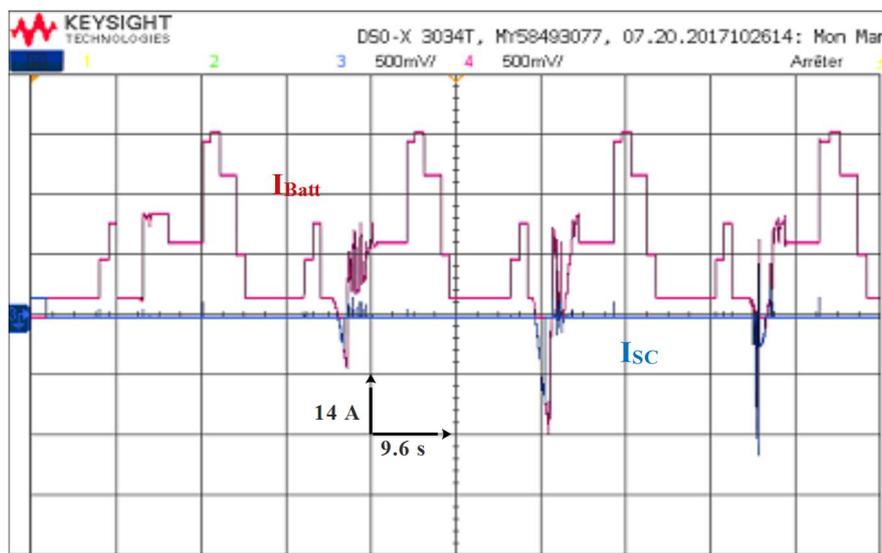


Figure 27. Battery-supercapacitor currents.

Figure 28 shows the reference DC bus voltage, its reference and a zoom of the aforementioned quantity. It can be seen clearly that V_{DC} follows precisely its reference. Note also that the voltage ripple band is small and tolerable.

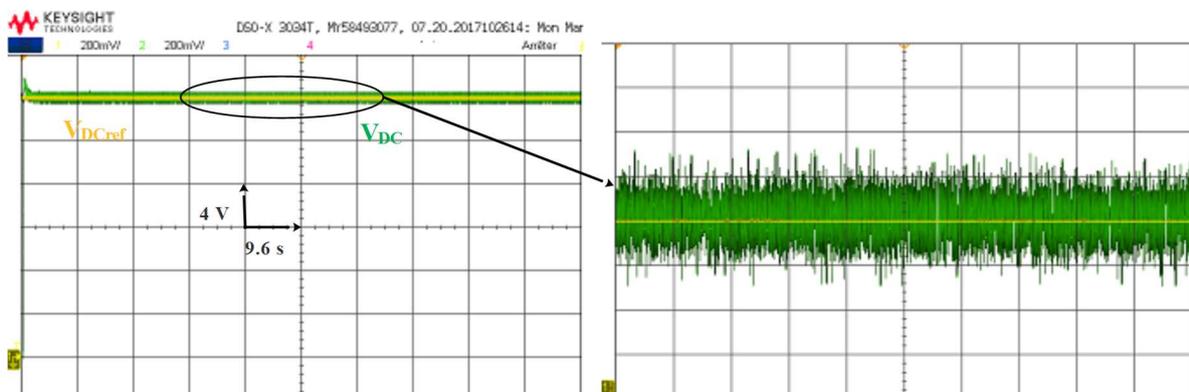


Figure 28. DC bus voltage and its zoom.

The power developed by each energy source is shown separately in Figure 29. As shown in Figure 30, the load power equals the developed power. Out of Figure 31, one can notice that the hybrid energy storage system produces a power that is equivalent to the total demand with a little excess as illustrated in the different subfigures of Figure 31 illustrated below:

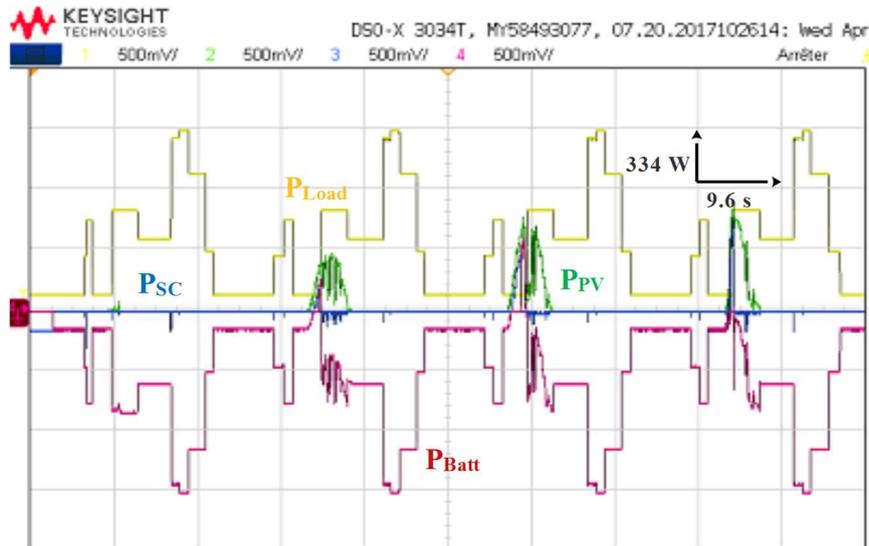


Figure 29. Different energy sources powers.

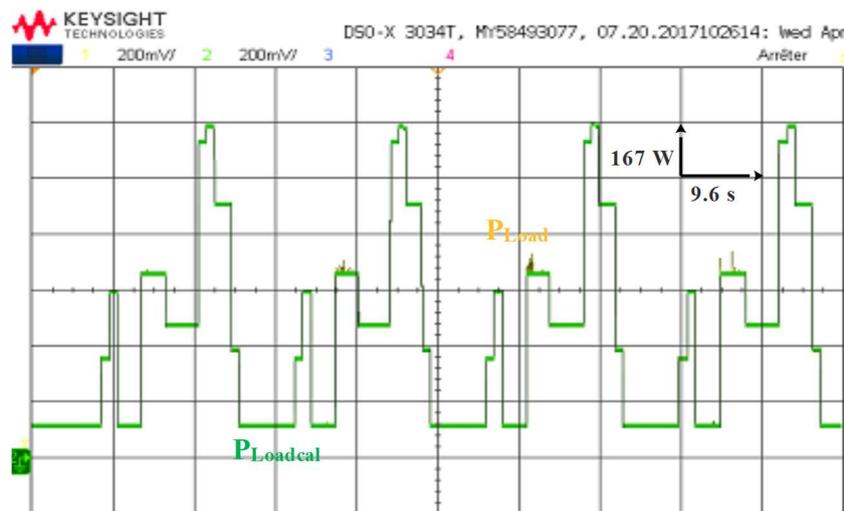
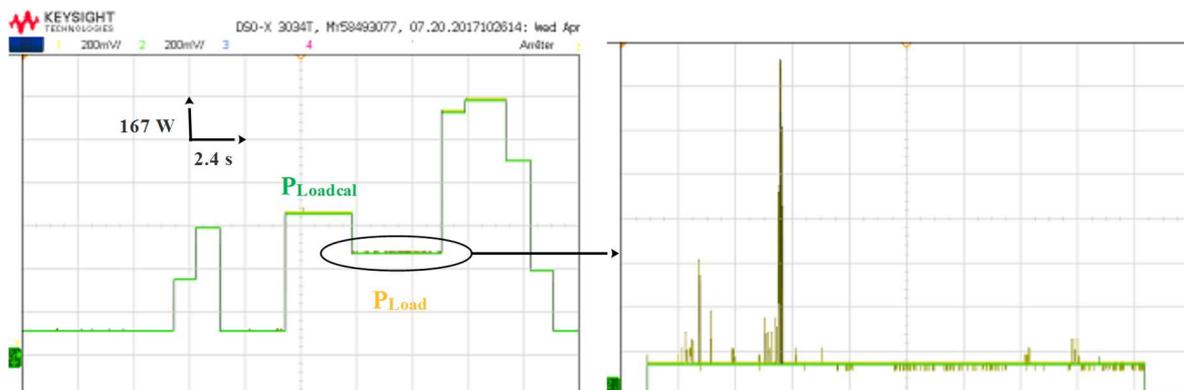
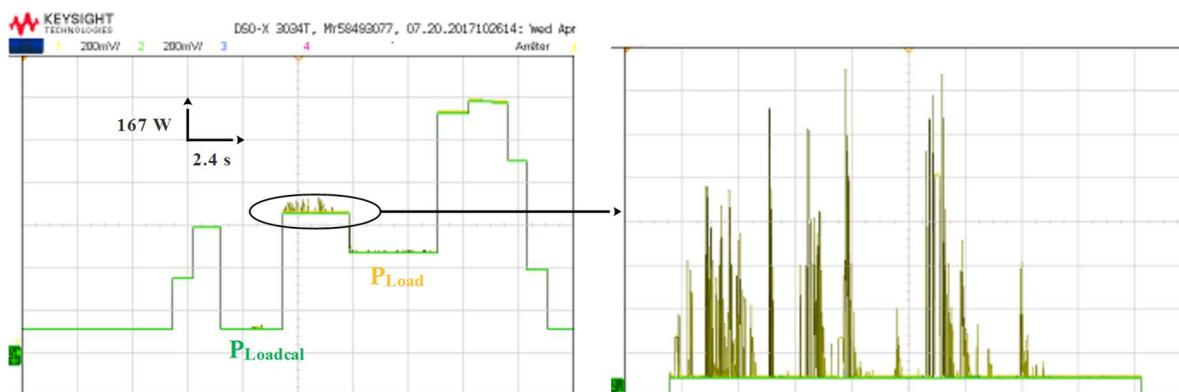


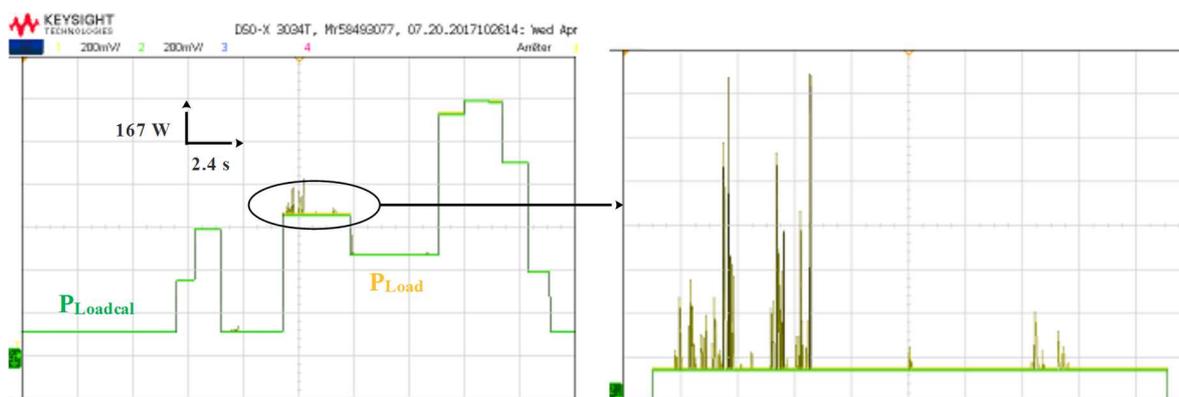
Figure 30. Total developed power and desired one.



(a) day 1.



(b) day 2



(c) day 3



(d) day 4

Figure 31. Zooms on calculated and developed load power in RTlab.

5. Conclusion

This paper discusses an energy management strategy for multi storage (Battery/SC) applied in photovoltaic system has been proposed. The used control technique is based on current regulation of two energy sources through the use of proportional integral (PI) regulators. The findings were verified by simulation with MATLAB/Simulink, and they were also put to the test in real-time with the RT LAB simulation platform. This means that the control used is efficient and allows the flow of energy appropriately and this ensures good and optimal system operation. The power management techniques covered in this paper enable the system to operate as effectively as possible with high photovoltaic system performance, regardless of the weather conditions. As a further work,

it is planned to apply intelligent control methods to extend the lifespan of energy sources while ensuring their efficient and optimal utilization.

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