Energy Management System in an Electrical Microgrid with Hybrid Storage and a Multi-Objective Approach

Pérez-Aballe, Osmany R.[1,*]; Nicolas-Martin, Carolina[2]; González-García, Jorge[3]; Flores-Martín, Pablo[2,4]; Santos-Martin, David[2]

[1]University of Moa, Department of Electrical Engineering, Holguín, Cuba
[2]Universidad Carlos III de Madrid, Department of Electrical Engineering, Leganés (Madrid), Spain
[3]Universidad Carlos III de Madrid, Department of Aerospace Engineering, Leganés (Madrid), Spain
[4]CT Engineers A.A.I. S.L, Getafe (Madrid), Spain

Abstract: This article presents an innovative Energy Management System (EMS) for microgrids with Hybrid Energy Storage Systems (HESS), designed to optimize power dispatch, minimize premature degradation of components, and ensure DC bus voltage stability (±2 %) under stochastic disturbances. The EMS, implemented in the MATLAB/Simulink Stateflow environment, adopts a multi-objective strategy to regulate the DC bus, manage current limits across the HESS, and compensate for ultra-fast fluctuations (<500 ms) in both generation and demand. Validation combines software-in-the-loop (SiL) simulations with experimental validation on a real prototype subjected to dynamic power cycles. Results demonstrate that the EMS maintains the DC bus voltage within ±1.7 % of its nominal value, reallocates loads without exceeding the defined current limits for each storage element, and reduces stress on critical components by 20 %. The hierarchical coordination between Li-ion batteries and supercapacitors extends storage system lifetime by prioritizing supercapacitors for fast transients and batteries for sustained power demands. Furthermore, the EMS handles energy surpluses through controlled export or dissipation, preventing overvoltages on the DC bus. Experimental validation confirmed the theoretical model, demonstrating the robustness of the EMS in both isolated and interconnected microgrids, as well as its effectiveness which enables the integration of intermittent renewable sources such as airborne wind energy systems.

Keywords*:* Energy management system, Hybrid energy storage, Microgrids, Power electronic converters

Sistema de Gestión de Energía en Microrred Eléctrica, con Almacenamiento Híbrido y Enfoque Multiobjetivo

Resumen: Este artículo presenta un Sistema de Gestión de Energía (EMS) innovador para microrredes con almacenamiento híbrido (HESS), diseñado para optimizar el despacho de energía, reducir la degradación prematura de los dispositivos y asegurar la estabilidad de la tensión en el bus DC (±2 %) bajo perturbaciones estocásticas. El EMS, implementado en el entorno Stateflow de MATLAB/Simulink, utiliza un enfoque multiobjetivo que regula el bus DC, controla los límites de corriente en los HESS y compensa fluctuaciones ultrarrápidas (<500 ms) en generación y demanda. La validación combina simulaciones software-in-the-loop (SiL) y pruebas experimentales en un prototipo real, con ciclos de potencia dinámicos. Los resultados muestran que el EMS mantiene la tensión del bus DC en ±1,7 % de su valor nominal, redistribuye cargas sin superar los límites de corriente establecidos para cada elemento de almacenamiento y reduce el estrés en los componentes críticos en un 20 %. La coordinación jerárquica entre baterías de Li-ion y supercondensadores optimiza la vida útil del almacenamiento, priorizando los supercondensadores para transitorios rápidos y las baterías para demandas estables. Además, gestiona excedentes mediante exportación o disipación controlada para evitar sobretensiones en el bus de DC. La validación experimental corroboró el modelo teórico, lo que confirmó la robustez del EMS en microrredes aisladas o interconectadas, y su aplicación en la integración eficiente de fuentes renovables intermitentes, como los sistemas eólicos aerotransportados.

Palabras clave: Almacenamiento híbrido de energía, Convertidores electrónicos de potencia, Microrredes, Sistema de Gestión de energía

1. INTRODUCTION

The global transition towards decentralized and resilient energy systems, driven by the massive integration of

*aballeperez83@gmail.com
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intermittent renewable sources such as solar and wind, has solidified microgrids as critical infrastructures for decarbonizing electrical grids to ensure operational security (Abbasi, 2023; Alasali, 2023; Jing, 2017). According to the IEEE Std. 2030-7 (2018) definition, microgrids are systems composed of interconnected loads and distributed energy resources that operate within defined electrical boundaries. As microgrids gain prominence, new challenges related to efficient energy management emerge, particularly regarding Hybrid Energy Storage Systems (HESS), which combine complementary technologies such as lithium batteries (high energy density) and supercapacitors (high power density) (Azega et al., 2024; Guevara-Calderón, 2024; Kazerani, 2014; Vukajlović et al., 2020; Wang et al., 2023).

Shahzad et al. (2022) proposed a pioneering framework to manage HESS microgrids using linear programming and model predictive control (MPC), reducing operational costs by 18 %. This approach is limited by the use of outdated technologies, the omission of storage device degradation, and the lack of integration of dynamic weather forecasts, which hinder proper microgrid control. More recent studies, such as Hadi et al. (2024), address these limitations by incorporating artificial intelligence (AI), HESS with supercapacitors, and electrochemical-thermal models, laying the groundwork for more efficient autonomous systems in modern DC microgrids.

The coexistence of complementary storage technologies in HESS presents additional integration challenges, as synchronizing dynamic responses across heterogeneous time scales (from milliseconds to hours) requires advanced and adaptive control strategies that must integrate energy efficiency and storage longevity considerations (Naderi, et al., 2023; Nazaripouya et al., 2019; Wu et al., 2024; Zhang et al., 2021). In this context, Energy Management Systems (EMS) have become the technological core for harmonizing microgrid operations.

Several studies have emphasized the importance of adopting a multi-objective approach to microgrid management, particularly those that consider DC bus regulation, thermal and current limits in storage devices, and real-time compensation for ultrafast fluctuations (<500 ms) in generation and demand (Hadi et al., 2024; Zhang et al., 2021). Classical models that prioritize battery use for stable demands are insufficient in scenarios with high renewable energy penetration, as they increase thermal stress on components and may reduce the lifespan of storage elements by 15-20 % (Zaher, 2018; Zhao et al., 2023). This underscores the need to implement dynamic load distribution strategies that not only optimize energy efficiency but also ensure the resilience of microgrids and their components in extreme conditions (Zia et al., 2018).

Although various strategies have been proposed for energy management in microgrids with HESS, many of them present critical limitations. In particular, some EMS prioritize grid stability without considering economic aspects and storage degradation, which could compromise the long-term viability of the systems (Elalfy et al., 2024). Additionally, many of these approaches are validated only in simulated environments, without considering real-world disturbances and non-linearities (Hadi et al. 2024). This gap between simulation and real experimentation limits the applicability of the proposed solutions in operational microgrid environments (Casolino, Russo, & Varilone, 2018). Thus, there is an increasing urgency for studies that validate energy management strategies both in simulation and experimental environments.

Current EMS models tend to focus on optimizing instantaneous power flow, neglecting aspects such as adaptability to internal failures, energy generation variability, or microgrid scalability (Tello & Marulanda, 2017). Moreover, some approaches use Machine Learning algorithms to forecast demand, but they rely on large volumes of historical data and high computational capacity, which can pose a barrier to implementation in emerging microgrids with limited operational information (Panda et al., 2024). In this context, the approach proposed in this article, based on closed-loop feedback and real-time optimization, eliminates the need for accurate predictions, offering a more robust and adaptable solution to the changing conditions of microgrids (Maddineni et al, 2024).

Moreover, recent research, such as Jacho et al. (2024), has proposed the use of data-driven controllers (DDC), eliminating the need for predefined mathematical models and reducing power fluctuations in solar microgrids. However, this approach still needs to be extended to industrial environments and must incorporate sustainability considerations, a crucial aspect that remains limited in many studies (Bordons et al., 2015). Meanwhile, the review by Zaher (2018) on energy management strategies in microgrids with storage systems shows that HESS technologies are essential to manage fluctuations across multiple time scales, achieving a reduction of up to 40 % in battery degradation and 30 % in voltage variations. Despite these advances, the work highlights several gaps, such as the lack of standardization in evaluation metrics and the limited validation of models in large-scale microgrids (Benavides-Padilla, 2024).

Despite recent progress in energy management for microgrids with HESS, several critical gaps remain in the literature. These include: limited experimental validation of proposed models, a lack of adaptive strategies that account for storage degradation under real-world conditions, and reliance on predictive approaches that demand extensive historical data and high computational resources. Furthermore, many current EMS solutions do not incorporate robust mechanisms to handle stochastic disturbances, nor do they address long-term sustainability considerations.

This article proposes an innovative EMS with a multi-objective approach that integrates critical variables such as DC bus regulation, thermal and current limits in HESS, and real-time compensation for ultrafast fluctuations in generation and demand, designed for microgrids with HESS and renewable energy sources. The system is designed to meet three interdependent objectives: (1) optimize energy dispatch under operational constraints, (2) mitigate premature degradation of storage devices, and (3) ensure voltage stability on the DC bus (±2 %) under stochastic disturbances. To achieve this, the EMS is implemented in the MATLAB/Simulink Stateflow environment, where the system dynamically optimizes energy routing through the use of an adaptive algorithm that prioritizes the use of supercapacitors for millisecond transients and batteries for stable demands, ensuring a stable power supply in the face of renewable energy variability. The strategy is validated through a software-in-the-loop (SiL) simulation that replicates the target microgrid architecture, followed by tests in a real microgrid where realistic power cycles are injected, positioning the system as a robust solution for microgrids, addressing critical gaps identified in the current literature.

2. METHODOLOGY

Current microgrids incorporate distributed energy components, HESS, controlled power converters, and control devices. Among the distributed generation technologies are photovoltaic solar panels, land-based wind turbines, fuel cells, conventional generation units, and the emerging Airborne Wind Energy Systems (AWES). A fundamental element in achieving microgrid resilience is the use of HESS—such as batteries and supercapacitors—which play a critical role in balancing fluctuations between supply and demand and in maintaining power quality, particularly in the presence of intermittent generation sources (Fagiano & Milanese, 2012; Jing et al., 2017).

Power converters, as the core of energy management, regulate voltage levels and control current flow from HESS components. Some DC/DC converters can operate bidirectionally, enabling smooth integration between subsystems (Carpintero-Rentería et al., 2019). In an islanded mode, microgrids operate independently from the main grid, relying solely on distributed generation units and the local HESS to maintain system stability. Therefore, robust EMS solutions are essential, capable of adapting to various operational scenarios within the microgrid (Guerrero et al., 2021).

Figure 1 presents the conceptual structure diagram of a typical microgrid, which integrates: HESS, dynamic loads, and time-varying generation sources. This diagram shows how the EMS is the central operational core of the microgrid, coordinating and controlling the energy flow between components to ensure stable and efficient operation.

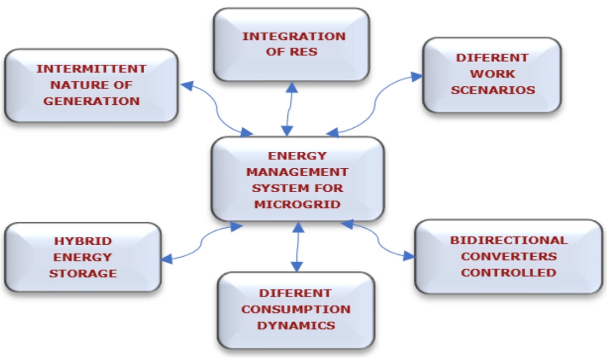


Figure 1. Conceptual structure of the proposed microgrid

2.1 Microgrid Object of Study

Figure 2 illustrates the proposed electrical topology for the microgrid. The power architecture is designed so that all electrical components, including energy conversion and storage subsystems, are arranged around a 600 V ±2 % direct current (DC) bus. This DC bus serves as the central node, which enables efficient interconnection of all microgrid elements.

Through the use of bidirectional power converters, the DC bus supports the integration of renewable energy sources such as photovoltaic and wind under system conditions in direct current, as well as a HESS composed of batteries and supercapacitors. These converters are responsible for adapting the electrical characteristics of each source, ensuring coordinated and stable operation within the microgrid (Pérez-Aballe et al., 2025).

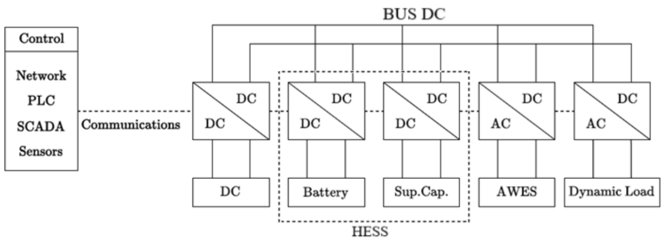


Figure 2. Microgrid Object of Study

The HESS is composed of two complementary technologies: (1) a lithium-ion battery bank with a nominal capacity of 5.5 kWh, of which 4.4 kWh are usable under an 80 % Depth of Discharge (DoD). These batteries operate within a voltage range of 48 to 54 VDC; and (2) a supercapacitor module rated at 166 F ±5%, with a nominal voltage of 48.6 VDC, an energy capacity of 54 Wh, and a peak power output of 118 kW.

For energy management, bidirectional interleaved DC/DC converters are used, each rated at 5.5 kW and achieving over 96 % efficiency at 50 % load. These converters are distributed as follows: two are dedicated to the HESS, to manage power flow between the DC bus and the storage devices, and a third 25 kW external DC interface converter, with a voltage range of 400–800 VDC, enables bidirectional connection with external systems such as DC loads or adjacent microgrids. All converters employ adaptive Pulse Width Modulation (PWM) strategies designed to minimize current ripple, keeping it below 3 % peak-to-peak.

The system management is carried out through a hierarchical control layer. An industrial Programmable Logic Controller (PLC), with a cycle time of up to 1 ms, handles the real-time management of the converters and protections, such as overcurrent and phase imbalance protection. Additionally, a PC-based SCADA system, under system conditions the OPC UA protocol, is integrated.

For the simulation, models from the Matlab libraries (Fetene, 2025) were used for the converters, batteries, and supercapacitors, adapted to the real data of the laboratory microgrid. Control circuits with closed-loop PID controllers were designed for each converter, successfully emulating the dynamic behavior of the real microgrid.

DC/DC Converter Configuration:

- DC/DC Converter G1: Connects the energy supply battery and system control. This converter has voltage and current control on the high side.

- DC/DC Converter G2: Handles the connection of the supercapacitor to the system. It features voltage control on the low side, to ensure that the voltage stays within the appropriate parameters for the supercapacitor.

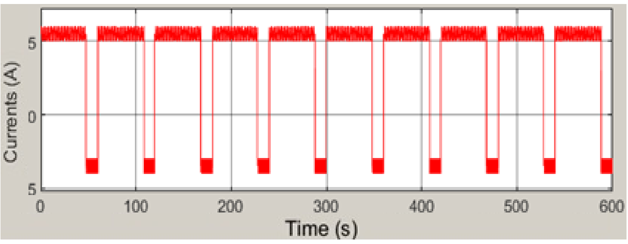
- DC/DC Converter G3: Has two defined modes: one for protection against bus overloading and another for voltage control on the low side.

In the microgrid simulation, the 600 V DC bus and the associated components are highlighted, including the bidirectional converters and HESS.

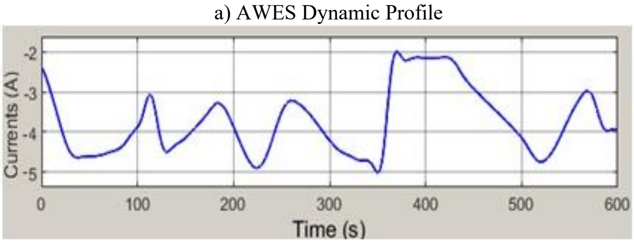
2.2 Dynamic Load Blocks

The AWES block simulates the operating cycle of an airborne system. Based on the methodology presented by Fagiano et al. (2022), the mechanical power at the motor shaft was used to generate a current signal that replicates the behavior of the AWES cycle, as illustrated in Figure 3a.

Figure 3 b) shows the current waveform injected into the bus. This simulates a dynamic load over time, with data obtained from real microgrid tests conducted in the laboratory.



a) AWES Dynamic Profile



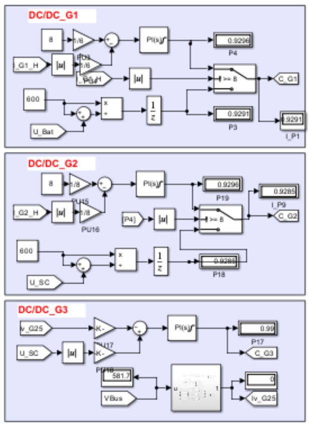
b) Dynamic Load Profile
Figure 3. Dynamic Loads Connected to the Microgrid

2.2.1 DC/DC Converter Control

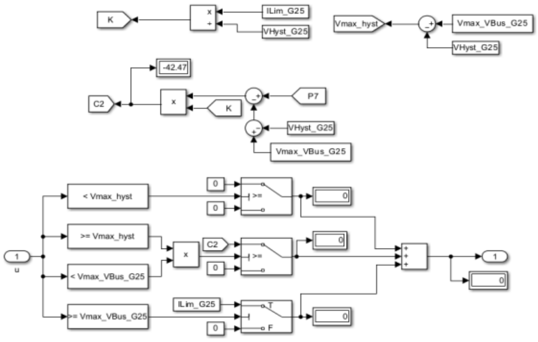
The control circuit for the DC/DC converters is detailed in Figure 4 a). The main objective of the control strategy is to monitor the current on the high side of the converter. Depending on the current value, the system operates in one of the following modes:

1. Voltage Control Mode: If the current does not exceed the 8 A threshold on the high side, the converter adjusts its duty cycle to maintain the bus voltage at 600 V.
2. Current Control Mode: If the current exceeds the 8 A threshold, the PI controller takes over, limiting the current to the set reference value (8 A) to protect the system.

This design ensures flexible and robust operation, adapting to the demands of the microgrid while protecting critical components.



a) Control Circuit for Converters G1, G2, and G3 (General)



b) Control Circuit for Converter G3
Figure 4. DC/DC Converter Control Circuit

The DC/DC Converter G3 has two predefined functions: (1) connection to an external DC bus or (2) as an energy dissipator with voltage drop control. The control circuits for the converter are detailed in Figure 4 b). These include a comparator that continuously monitors the DC Bus voltage. This system dynamically switches between two control modes:

- Overload Protection for the DC Bus: When the bus voltage exceeds 670 V and up to 685 V, the current flow towards a resistor at its output gradually increases according to the current control curve, proportional to the bus voltage, until reaching a maximum power transfer of 8 kW.

- Voltage Control on the Low Side: In this mode, it keeps the DC output voltage within the established limits as per the installation requirements to which it is connected.

This dual approach, combining both control methods, ensures stable and safe system operation, dynamically adjusting in real-time to load and power generation conditions.

2.3 Energy Management for Microgrid with AWES System

The laboratory microgrid, which includes a dynamic load and generation from the AWES system, is used to evaluate the EMS. It operates under two well-defined modes and follows a set of priorities, with a "master" control logic overseeing the entire system to ensure proper functioning. The configuration is as follows:

1. Generation Mode: The reluctance machine generates power for 48 seconds using mechanical energy supplied by the induction machine.

2. Motorization or Consumption Mode: The reluctance machine operates and consumes energy for 12 seconds using mechanical energy provided by the induction machine.

Operation:

- Priority 1: Store the energy generated by the reluctance machine through DC/AC_1 into the supercapacitors via DC/DC_G2.

- Priority 2: Store any excess energy into the battery through DC/DC_G1.

- Priority 3: Supply the energy required by the reluctance machine in motorization mode, through DC/AC_1 from the supercapacitors via DC/DC_G2.

- Priority 4: Feed any surplus or stored energy from the supercapacitors or battery (in that order) to the external three-phase grid through the DC/AC connection converter or from the DC/DC_G3 converter to an external DC grid, depending on demand.

- Priority 5: To protect system stability, dissipate remaining energy into the internal load resistor through the DC/AC_1 chopper in case the batteries and supercapacitors are fully charged and unable to deliver energy to the external grid.

2.4 Stateflow Diagrams in MATLAB for System Modeling

The priority-based control logic described in the previous section has been implemented as a flowchart or control diagram using the Stateflow tool in MATLAB/Simulink. The diagrams developed are automatically translated into Structured Control Language (SCL) through the PLC Coder add-on in Simulink. The generated code is then deployed to the microgrid control system through the use of TIA Portal, Siemens' platform for programming and configuring PLCs. Figure 5 presents the integrated system validation interface, designed to verify the microgrid's behavior prior to physical implementation. This architecture enables comprehensive system verification by combining the accuracy of physical modeling in Simulink with the adaptive control capabilities of Stateflow within a unified simulation environment.

Structure in Stateflow, Composition:

- In the central upper region, there is the "Control Panel", which presents elements for real-time interaction: buttons to enable or disable the converters and displays for monitoring voltage and current at critical nodes of the microgrid.

- In the right region, the control logic of Stateflow is located, displaying the operation diagram of the microgrid in an energy management algorithm based on state transitions related to charge states and voltage and current levels at specific nodes, as well as operational priorities.

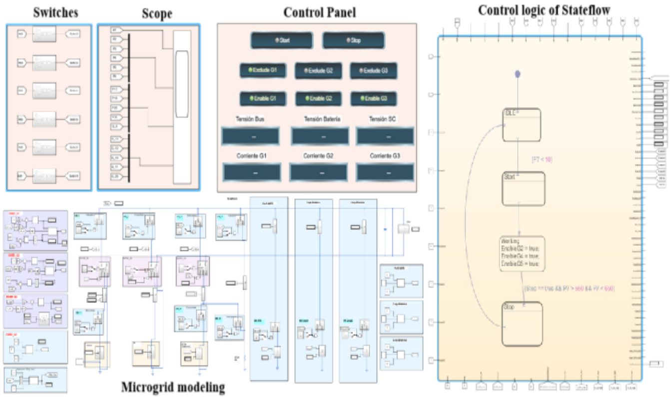


Figure 5. Stateflow in MATLAB of the Microgrid

- In the lower-left region, the schematic provides a detailed representation of the microgrid through a system model.

2.5 Energy Management of the AWES Microgrid: Operational Procedure

This subsection describes the operation of the microgrid in four sequential phases, to ensure proper system functionality:

1. System Initialization: The State of Charge (SOC) of the HESS is verified, requiring a minimum of 40 % for the energy battery and 10 % for the supercapacitor, to ensure sufficient capacity to handle initial transients through battery support. All system breakers must remain open at the beginning of the startup process. Next, the DC bus precharge sequence starts by closing the breakers that connect converter G1 and activate the precharge resistor. G1 is set to a controlled ramp mode (0 → 600 V in 15 s, 40 V/s), limiting the inrush current to 5 A to avoid thermal stress on the converter capacitors. Once the DC bus voltage reaches 600 V ±2 %, it is energized by sequentially closing all relevant switches from G1 to G3. After stable operation is confirmed, G1 switches to autonomous control mode (600–625 V) to regulate and maintain the bus voltage.

2. Normal Operation – Generation-Motorization Cycle: During the generation mode (48 s), the induction machine, driven by the ABB ACS880-1 converter, powers the synchronous reluctance machine (SRM) as a generator, injecting energy into the DC bus through the AC/DC_1 converter. This setup emulates the operation of the AWES cycle in the laboratory through the use of these machines and converters. The main priority is to store energy in the

supercapacitors via G2, configured in low-voltage control mode (45 V) with an 8 A current limit. Excess energy is redirected to battery B_1 through G1, which charges the energy storage battery under constant current conditions (8 A). During the motorization phase (12 s), the SRM operates as a load powered by the DC bus. The supercapacitors SC_1, via G2 in discharge mode (at 15 V), supply primary energy through AC/DC_1 operating as an inverter. If the SOC of the supercapacitors drops below 25 %, the battery supplements the demand through DC/DC_G1 under system conditions in current control mode, to ensure uninterrupted operation.

3. Hierarchical Management of Excess Energy: When the battery reaches an SOC ≥80 % and the supercapacitors an SOC ≥90 %, the surplus energy is exported through G3 to an external DC grid (400–800 V). In case of a DC bus overvoltage condition (>670 V) with no export path available, the internal chopper of AC/DC_1 is activated, dissipating up to 8 kW proportionally (670–685 V), while G3 acts as the final safeguard against critical voltages exceeding 685 V.

4. Controlled Shutdown: The shutdown sequence begins with a forced discharge of the supercapacitors through the use of G2 in 15 V mode until their SOC drops below 10 %. Then, the converters are sequentially deactivated in the following order: AC/DC_1 → G3 → G2 → G1, with a 2 s delay between each step to prevent transient disturbances. Finally, the discharge resistor is activated for 10 s until the DC bus voltage falls below 10 V, after which all breakers are opened, electrically isolating the system.

2.6 Flowchart of the AWES Microgrid

The implementation of the Energy Management System (EMS) within the AWES microgrid is realized through a state-based control logic developed in MATLAB/Simulink using Stateflow. This graphical programming environment allows for the modeling of event-driven systems using finite state machines and flowcharts. Based on the detailed operational procedure outlined in Section 2.5, the EMS has been structured to reflect the four main operational phases of the microgrid: initialization, normal operation, hierarchical energy management, and controlled shutdown. Each phase is represented by a distinct state within the Stateflow diagram, with defined transition conditions driven by real-time measurements such as State of Charge (SOC), voltage levels, and system priorities.

The core structure of the flowchart includes an initial verification state that checks SOC thresholds for both the battery and supercapacitors. Upon successful verification, the system transitions into a precharge sequence, gradually energizing the DC bus to the target voltage of 600 V. Subsequent states control the alternation between energy generation and motorization modes, replicating the AWES operational cycle using laboratory equipment. Transitions between states are governed by timer conditions and SOC limits, ensuring that the supercapacitors and battery are used optimally and safely.

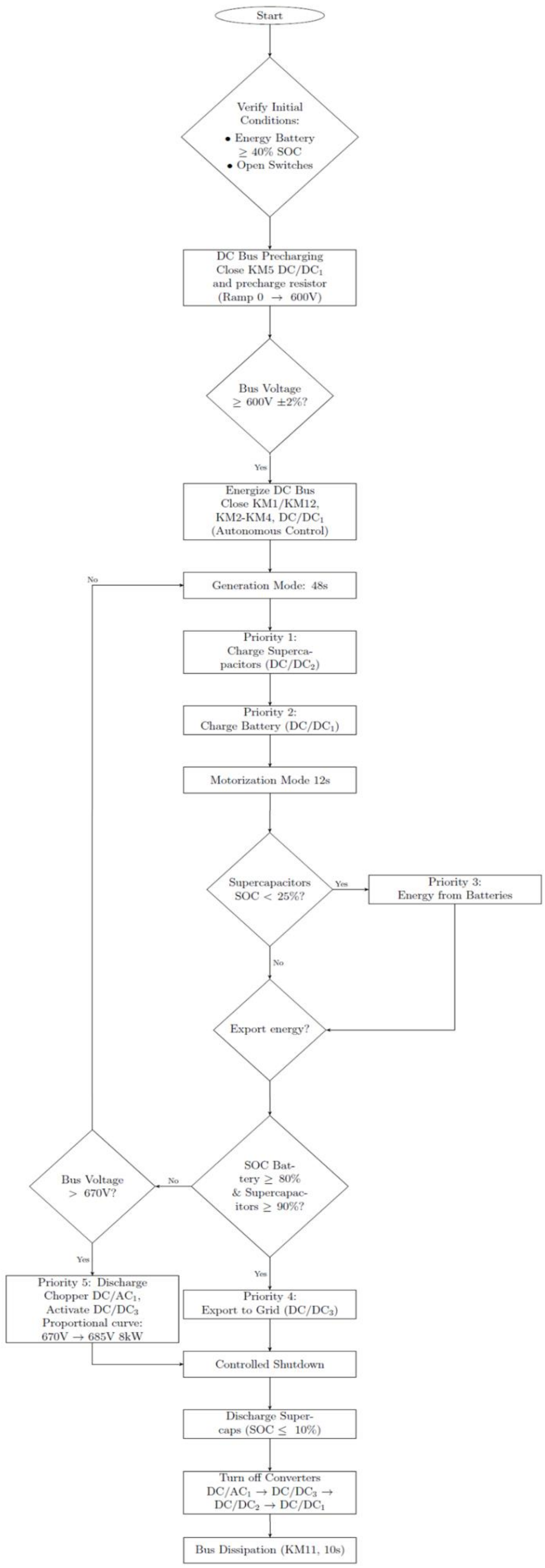


Figure 6. Microgrid operation flowchart

In addition, the flowchart includes logic for exporting surplus energy to an external DC grid and for activating protection mechanisms such as the internal chopper in overvoltage scenarios. The final states manage a safe and gradual system shutdown, ensuring that all converters are deactivated in a sequenced manner and that residual energy is dissipated through a controlled discharge. This comprehensive flowchart, shown in Figure 6, is ultimately converted into Structured Control Language (SCL) and deployed to a PLC via Siemens TIA Portal, enabling real-time execution of the EMS on the physical microgrid.

3. DISCUSSION OF RESULTS

3.1 Simulations in Simulink Software

Following the directives of the flowchart from the previous section, the following performance tests were conducted. Figure 7 presents the graphs corresponding to the system initialization, DC bus energization and the supercapacitor charge phase. These signals reflect the dynamic behavior of the bidirectional DC/DC converters in the microgrid with the hybrid storage system.

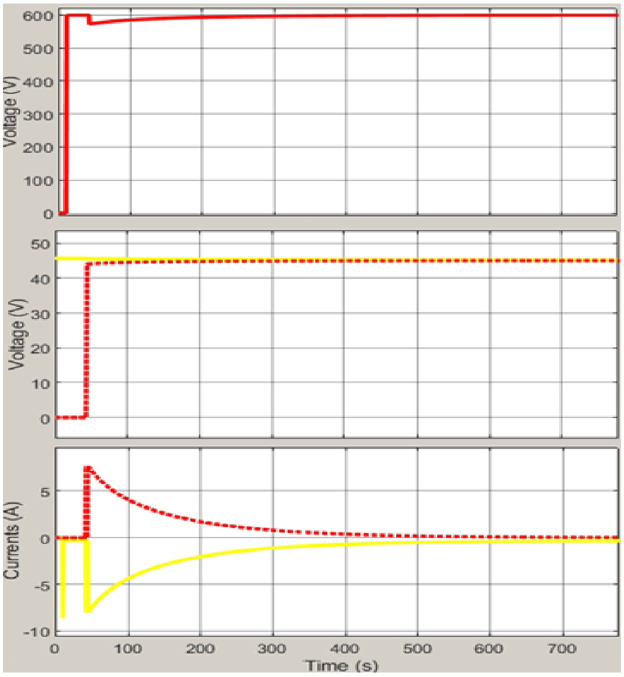
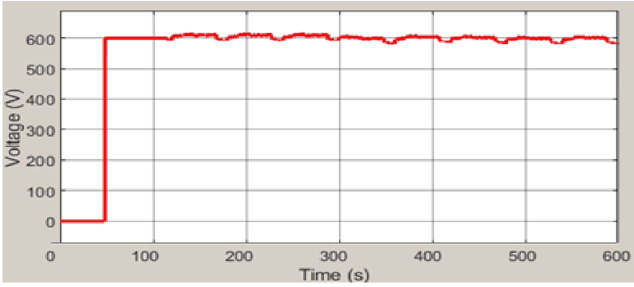


Figure 7. Microgrid operation diagram

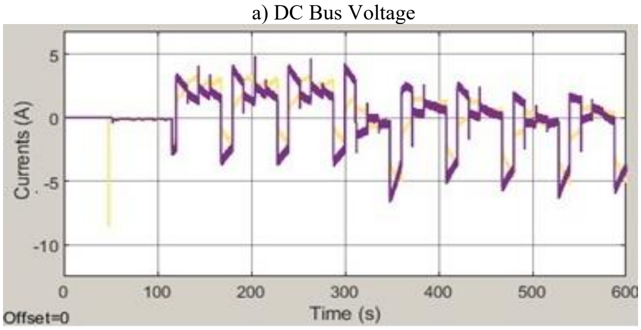
- Upper quadrant: The DC bus voltage is monitored. During the initial energization phase, a slight overshoot of 1.72 V is recorded, with a delay of 0.22 s to reach 600 V. This is followed by a maximum voltage drop of 4.66 % when the supercapacitors are connected, which gradually stabilizes as they charge. This behavior is typical in systems with capacitive loads and results from the transition between pre-charge and steady-state operation.

- Middle quadrant: The battery voltage is displayed in yellow, while the supercapacitor voltage is shown in red. These signals make it possible to verify the dynamic response of the system during the charging and discharging phases of the storage devices.

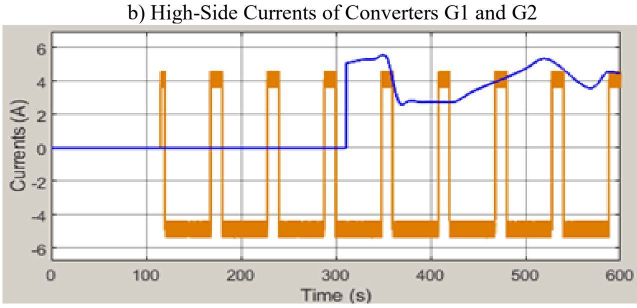
- Lower quadrant: The currents on the high-voltage side of the converters connected to the DC bus are shown. In yellow, a current peak of 8.45 A lasting 0.22 s is observed, corresponding to the contribution of the battery to energize the bus. In red, the charging current of the supercapacitor is displayed, with a peak of 7.22 A that gradually decreases until reaching zero at around 500 s, when the target voltage of 45 V is attained. Meanwhile, the energy supplied by the battery to support this charging process is reflected in the yellow trace.



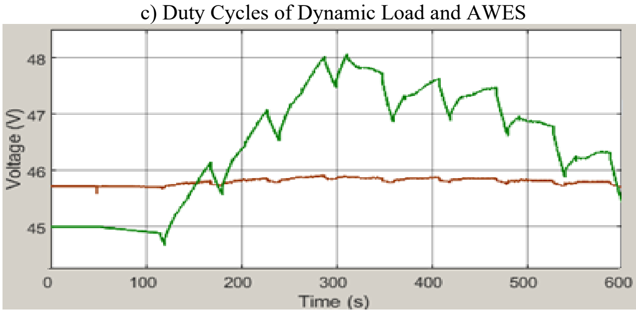
a) DC Bus Voltage



b) High-Side Currents of Converters G1 and G2



c) Duty Cycles of Dynamic Load and AWES



d) Battery and Supercapacitor Voltage

Figure 8. Microgrid AWES operation diagram across ten work cycles

3.2 Operation with External AWES Source and Dynamic Load

Figure 8 expands the analysis by including the connection of an external power source and a dynamic load profile that simulates the behavior of an AWES microgrid. The analyzed values correspond to average data from the 9 cycles shown in the figures.

Section a): The DC bus voltage shows a 2.8 % overshoot compared to its base value (600V) during 48 s, corresponding to positive energy injection.

Section b): The high-side currents of the converters show the following behavior:

- Battery B1 (yellow): Contributes 3.2 A to the system with an oscillating component of ±0.6 A for 12 s and recharges with -2.37 A and an oscillation of ±0.7 A for 48 s.
- Supercapacitors (violet): Contributes 3.82 A to the system with an oscillating component of ±0.3 A for 12 s and recharges with -2.53 A and an oscillation of ±0.7 A for 48 s.

Section c): Dynamic charging currents are shown:

- In ochre color, the current flowing to the bus during the AWES cycle is displayed; during 48 s, it contributes 5.02 ±0.9 A, and during 12 s, it consumes 4.01 ±0.9 A from the system.

- In blue color, the current consumed by the dynamic load connected to the bus is shown, exhibiting an oscillating behavior of 4.0 ±1 A.

Section d): The battery and supercapacitor voltages show variations corresponding to the charging and discharging cycles:

- Batteries (Brown): During the charging phase (48 s), the base voltage of 45.8 V increases by 0.2 V, while during the consumption phase (12 s), it decreases by 0.2 V relative to the reference of 46 V.
- Supercapacitors (Green): During the charging phase, the base voltage of 45 V increases by 3.2 V, and during the consumption phase, it decreases by approximately the same amount, returning close to its initial value. This behavior occurs because the energy accumulated during the AWES cycle, minus the energy consumed by the dynamic load, results in a positive balance. As a result, the final voltage of the supercapacitor remains slightly higher than the initial value.

3.3 Microgrid Operation Analysis in a Duty Cycle

Figure 9 provides an extended analysis of the results obtained in a stable duty cycle of the microgrid.

Table 1 shows the simulation results of an AWES cycle in a steady-state under system conditions. The voltage and current values presented display two distinct oscillating operating states: (1) when the AWES cycle supplies energy to the DC bus (48 s) and (2) when it consumes energy from the DC bus (12 s).

3.4 Results Analysis

DC Bus Stability: The voltage variations (spikes and drops) do not exceed 1.7 % under system conditions, remaining within operational limits, which confirms the effectiveness of the energy management system, regardless of the presence of two dynamic sources over time: (1) the AWES generation system and (2) the dynamic load.

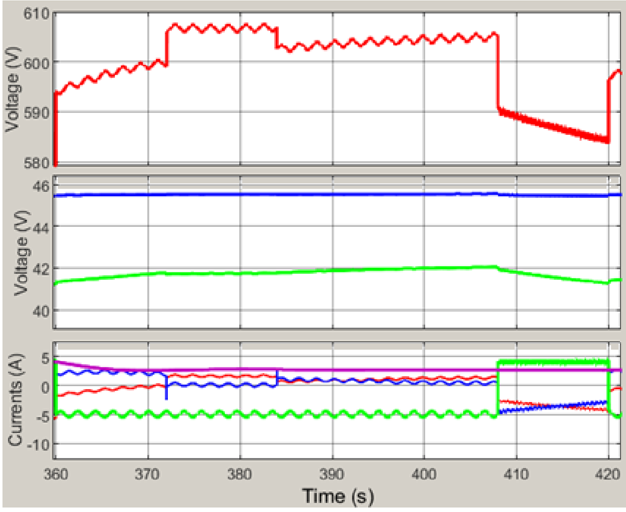


Figure 9. Operation diagram of the AWES microgrid in a duty cycle

Table 1. Data obtained from a simulation cycle

	T1(s)	V1(V)	T2 (s)	V2 (V)	ΔV (V)
V_{Bus}	375.00	607.48	375.9	606.05	1.41
	415.10	585.76	415.31	586.92	1.16
V_{Bat}	375.00	45.54	375.9	45.54	0.0043
	415.10	45.48	415.31	45.48	0.0037
V_{SC}	375.00	41.79	375.9	41.73	0.0135
	415.10	41.49	415.31	41.50	0.0018
	T1(s)	**I1(A)**	**T2 (s)**	**I2 (A)**	**ΔI (A)**
I_{AWES}	375.00	-5.34	375.9	-4.41	0.930
	415.10	4.51	415.31	3.62	0.892
I_{CDin}	375.00	2.74	375.9	2.76	0.026
	415.10	2.73	415.31	2.73	0.0008

HESS Behavior and Supercapacitor Role: The current and voltage signals from the converters managing the energy flow between the battery and supercapacitor reveal coordinated and efficient operation, dynamically adjusting to charge and discharge cycles. The supercapacitor stands out for its high responsiveness, rapidly absorbing and supplying energy to the DC bus, especially during the motoring phase of the SRM, to compensate for load variations and maintain voltage stability. Its role is particularly critical under rapid load or generation fluctuations, such as those induced by the AWES cycles. However, its energy capacity of 54 Wh restricts its operation to just a few seconds, although it can handle peak power levels up to 118 kW. To prevent overloading and accelerated wear, the EMS enforces a maximum current limit of 8 A. The supercapacitor is prioritized to manage fast transients, but when its State of Charge (SOC) drops below 25%, the battery takes over to support the load.

Dynamic Load and AWES Generation Profile: Both faithfully replicate the expected behavior of a real AWES microgrid, thus validating the Simulink model.

4. CONCLUSIONS

This article presents an innovative EMS for microgrids with HESS, demonstrating its ability to balance efficiency, durability, and stability in realistic energy environments.

The EMS successfully maintained the DC bus voltage at 600 V with minimal variations (±1.7 %), even under sudden fluctuations in generation (AWES Cycle) or demand (Dynamic Load). Intelligent coordination between the HESS elements ensures the stability of the DC bus: Supercapacitors absorb energy spikes in milliseconds (such as during rapid load changes), while the batteries manage constant demands over longer periods, in order to reduce wear.

The system showed excellent adaptability and managed energy effectively in accordance with the AWES Microgrid Flow Diagram embedded in Stateflow. It adhered to the five priorities of energy management for microgrids. This flexibility is essential in microgrids with intermittent renewable sources, such as airborne wind energy, where sudden changes are cyclical and frequent.

Dual validation, with digital simulations in Matlab and physical experimental validation in a laboratory microgrid, not only confirmed the EMS's effectiveness but also corrected inconsistencies between theoretical models and reality, such as effects from non-ideal components during initial transients. This reinforces its applicability in real-world environments, whether in isolated communities or grids interconnected with an external network.

In essence, this work not only solves technical challenges but also brings microgrids closer to a more sustainable future. By optimizing how energy is stored and used, the integration of renewables is facilitated, and the lifespan of equipment is extended, in order to reduce costs and increasing reliability. Future steps could explore scaling this solution to larger grids or combining artificial intelligence with real-time control to further enhance energy management.

CONFLICTS OF INTEREST:

The authors declare no conflict of interest.

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REFERENCES

Abbasi, M. E. A., Aguilera, L., Li, R. P., Lu, D., & Wang, F. (2023). Review on the microgrid concept, structures, components, communication systems, and control methods. Energies *16*(1), 484. https://doi.org/10.3390/en16010484

Azega, R. K., Smith, A. D., Chowdhury, N. R., Vyas, A., Li, Q., Haque, M., Xun, Q., Zhang, X., Thurakkal, S., Thiringer, T., Enoksson, P., & Lundgren, P. (2024). Supercapacitors and rechargeable batteries, a tale of two technologies: Past, present and beyond. *Sustainable Materials and Technologies, 41*, e01111. https://doi.org/10.1016/j.susmat.2024.e01111

Alasali, F., Saad, S. M., Saidi, A. S., Itradat, A., Holderbaum, W., El-Naily, N., & Elkuwafi, F. F. (2023). Powering up microgrids: A comprehensive review of innovative and intelligent protection approaches for enhanced reliability. Energy Reports, 10, 1899–1924. https://doi.org/10.1016/j.egyr.2023.08.068

Benavides-Padilla, D. J. (2024). Estrategias de operación de sistemas de almacenamiento para la integración de energías renovables en una microrred. https://produccioncientifica.uca.es/documentos/6620101c62f14c04d839301a

Bordons, C., García-Torres, F., & Valverde, L. (2015). Gestión Óptima de la Energía en Microrredes con Generación Renovable. Revista Iberoamericana de Automática e Informática Industrial, *12*(2), 117–132. https://www.elsevier.es/es-revista-revista-iberoamericana-automatica-e-informatica-331-articulo-gestion-ptima-energia-microrredes-con-S1697791215000023

Carpintero-Rentería, M., Santos-Martín, D. & Guerrero, J. M. (2019). Microgrids literature review through a layers structure. *Energies*, *12*(22), ttps://doi.org/10.3390/en12224381

Casolino, G. M., Russo, M., & Varilone, P. (2018). Hardware-in-the-loop validation of energy management systems for microgrids: A short overview and a case study. Energies, *11*(11), 2978. https://doi.org/10.3390/en11112978

Elalfy, D. A., Gouda, E., Kotb, M. F., Bureš, V., & Sedhom, B. E. (2024). Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends. *Energy Strategy Reviews, 54*, 101482. https://doi.org/10.1016/j.esr.2024.101482

Fagiano, L. & Milanese, M. (2012). Airborne wind energy: An overview. American Control Conference (ACC). IEEE, pp. 3132–3143. https://doi.org/10.1109/ACC.2012.6314801

Fagiano, L., Quack, M., Bauer, F., Carnel, L., & Oland, E. (2022). Autonomous Airborne Wind Energy Systems: Accomplishments and Challenges, Annu. Rev. Control Robot. Autonom. Syst., 5, 603–631, https://airbornewindeurope.org/archivos/7891

Fetene, Y. (2025). DC-DC Boost Converter Design SIMULINK. GitHub. Recuperado 28 febrero, 2025. https://github.com/yes42d/DC-DC-Boost-Converter-Design-SIMULINK

Guerrero, J. M., & Kandari, R. (Eds.). (2021). *Microgrids: Modeling, control, and applications*. Academic Press. https://vbn.aau.dk/en/publications/microgrids-modeling-control-and-applications

Guevara-Calderón, M. P. V. (2024). Exploración de Estrategias Tecnológicas en la Integración de Fuentes Renovables con Sistemas Electromecánicos. Polo de conocimiento, *9*(92), 1448-1463. https://doi.org/10.23857/pc.v9i7.7576

Hadi H. Awaji, H., Alhussainy, A. A., Alobaidi, A. H., Alghamdi, S., Alghamdi, S., & Alruwaili, M. (2024). Real-time energy management simulation for enhanced integration of renewable energy resources in DC microgrids [Original Research]. Frontiers in Energy Research, 12. https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2024.1458115

IEEE Std. 2030-7. (2018). IEEE Standard for the specification of microgrid controllers. IEEE Std. 2030-7-2018, 1–43. https://doi.org/10.1109/IEEESTD.2018.8340204

Jacho, A., Echeverría, D., Chamba, S., Lozada, C., & Sánchez, W. (2024). Aplicación del Control Formador de Red en Microrredes con Sistemas de Almacenamiento de Energía para la Regulación Primaria de Frecuencia, Caso de Estudio: Islas Galápagos. Revista Técnica "energía", *21*(1), 94–104. https://revistaenergia.cenace.gob.ec/index.php/cenace/article/view/662

Jing, W., Hung C., Shung L. & Ling M. (2017). Battery-supercapacitor hybrid energy storage system in standalone dc microgrids: A review. *IET Renewable Power Generation*, 11(4), 461–469, 2017. https://ietresearch.onlinelibrary.wiley.com/doi/epdf/10.1049/iet-rpg.2016.0500

Kazerani, K. Z. M. (2014). Development of a hybrid energy storage system (HESS) for electric and hybrid electric vehicles. IEEE Transportation Electrification Conference and Expo (ITEC), 1-5. https://doi.org/10.1109/ITEC.2014.6861868

Maddineni, V. K., Koganti, N. B., & Damacharla, P. (2024). Enhancing microgrid performance prediction with attention-based deep learning models. https://doi.org/10.48550/arXiv.2407.14984

Naderi, M., Khayat, Y., Shafiee, Q., Blaabjerg, F., & Bevrani, H. (2023). Dynamic modeling, stability analysis and control of interconnected microgrids: a review. Appl. Energy 334, 120647. https://doi:10.1016/j.apenergy.2023.120647

Nazaripouya, H., Chung, Y. W., & Akhil, A. (2019). Energy storage in microgrids: challenges, applications and research need. *Int. J. Energy Smart Grid, 3*(2), 60–70. https://doi.org/10.23884/IJESG.2018.3.2.02

Panda, S. P., Genest, B., Easwaran, A., Rigo-Mariani, R., & Lin, P. (2024). Methods for mitigating uncertainty in real-time operations of a connected microgrid. https://arxiv.org/pdf/2409.19568

Pérez-Aballe, O., Ruiz-Chavarría G., Vázquez-Seis Dedos L., & Columbié-Navarro O. (2025). Diseño de convertidor DC/DC bidireccional dual para gestión de almacenamiento híbrido de energía en microrredes. Minería Y Geología, *41*(1), 83–101. https://revista.ismm.edu.cu/index.php/revistamg/article/view/2701

Shahzad, S., Abbasi, M. A., Chaudhary, M. A., & Hussain, M. (2022). Model Predictive Control Strategies in Microgrids: A Concise Revisit. IEEE Access, 10, 122211–122225. https://doi.org/10.1109/ACCESS.2022.3223298

Tello, J., & Marulanda, A. R. (2017). Modelos de optimización para sistemas de potencia en la evolución hacia redes inteligentes: Una revisión. DYNA, *84*(202), 102-111. https://repositorio.unal.edu.co/handle/unal/60366

Vukajlović, N., Milićević, D., Dumnić, B., & Popadić, B. (2020). Comparative analysis of the supercapacitor influence on lithium battery cycle life in electric vehicle energy storage. Journal of Energy Storage, 31, 101603. https://doi.org/10.1016/j.est.2020.101603

Wang, L., Chen, B., & Patel, R (2023). Advances in hybrid energy storage systems: Bridging the gap between supercapacitors and lithium-ion batteries. Energy Conversion and Management, 278, 116734. https://doi.org/10.1186/s40807-024-00120-4

Wu, Y., Cui, J. Z., & Liu, C. (2024). State-of-the-art review on energy management systems, challenges and top trends of renewable energy based microgrids. *EAI Endorsed Trans. Energy*. http://dx.doi.org/10.4108/ew.4124

Zaher, G. R. (2018). Una solución híbrida de almacenamiento de energía de forma distribuida aplicado a microgeneración en microrredes redes eléctricas: diseño del sistema electrónico de potencia y control. Recuperado de https://portalinvestigacion.uniovi.es/documentos/5e4e722c2999524eaa94e5d1

Zhang, J., Cho, H., & Mago, P. J. (2021). "Energy conversion systems and energy storage systems," in Energy services fundamentals and financing. Editor D. Borge-Diez (Academic Press), 155–179. https://doi.org/10.1016/B978-0-12-820592-1.00007-5

Zhao, J., Zhou, J., Wang, L., & Zhao, Y. (2023). An energy management strategy to reduce the comprehensive cost of hybrid energy storage systems in electric vehicles [Original Research]. *Frontiers in Energy Research*, 11. https://doi.org/10.3389/fenrg.2023.1191565

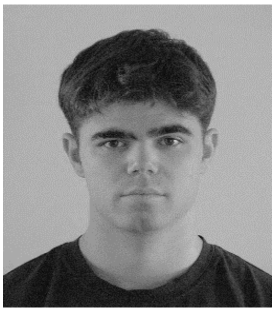
Zia, M. F., Elbouchikhi, E., & Benbouzid, M. (2018). Microgrids energy management systems: a critical review on methods, solutions, and prospects. *Appl. Energy,* 222, 1033–1055. https://doi.org/10.1016/j.apenergy.2018.04.103

BIOGRAPHIES

Osmany R, Pérez-Aballe, is a research professor at the University of Moa in Cuba, specializing in Electronics and Renewable Energy. He is pursuing a PhD in Electromechanics, focusing on Energy Management in Electric Microgrids with airborne wind energy systems (AWES). His previous work includes designing a dual bidirectional DC/DC converter for hybrid energy storage in microgrids. With 18 years of experience in Power Electronics, he has served as Degree Director, Head of the Electrical Engineering program, and Head of the Electronics department. He is currently involved in research projects with UC3M, Spain, on KITE2GRID and AWES generation.

Carolina, Nicolás-Martín, is a researcher and lecturer at Universidad Carlos III de Madrid, specializing in electric machine control and renewable energy systems. She is pursuing a PhD in Electrical Engineering, focusing on airborne wind energy systems (AWES), supported by a prestigious FPU grant. Her prior work includes energy management for electric vehicles and photovoltaic modeling. Carolina has authored several peer-reviewed publications and presented at international conferences. With a strong background in teaching and academic innovation, she has received excellence awards and contributed to curriculum development. She is fluent in English, Spanish, and Galician, with intermediate proficiency in German.

Jorge, González-García, Received his Bachelor's degree in mechanical engineering and his Master's degree in engineering research from Universidad de Extremadura, Spain. He worked as a Development Engineer in the automotive sector in private industry. In 2023, he joined the Department of Aerospace Engineering at Universidad Carlos III de Madrid, Spain, as a predoctoral researcher. His main research focuses on the design, control, and testing of airborne wind energy systems (AWES)



Pablo, Flores-Martín, is a final-year Energy Engineering student at Universidad Carlos III de Madrid, specializing in microgrid energy management and renewable energy integration. He is developing the Energy Management System for the Airborne Wind Energy Systems project, central to his thesis and an upcoming ICREPQ paper. He has participated in an academic exchange at Concordia University in Canada and excels in courses like Aero-thermochemical Systems and Electric Power Generation. Proficient in MATLAB, Simulink, and Siemens TIA Portal, Pablo is fluent in Spanish and English, with intermediate German skills.

David, Santos-Martin, received the B.Sc. degree in electrical and electronic engineering from E.T.S. Industrial Engineering of Madrid (ETSII-UPM), Madrid, Spain, in 1997, the M.S. degree in control engineering from The École Supérieure d'Électricité (SUPÉLEC-Paris), Paris, France, and the Ph.D. degree in electrical engineering from the University Carlos III of Madrid, Madrid, Spain. Currently, he is an Assistant Lecturer with the Department of Electrical Engineering, University Carlos III of Madrid. Prior to this, he was with Iberdrola from 2001 to 2007 and with Ecotecnia-Alsthom from 2000 to 2001. His research interests include power electronics, application of power electronics to power systems, and advanced control techniques applied to renewable energy.