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Original Articles

Comparative study of dynamic response by three types of energy storage systems for grid studies: A Microgrid Laboratory experimental-based study

Estudio comparativo de la respuesta dinámica de tres tipos de sistemas de almacenamiento de energía para estudios de red: Experimentos reales en un laboratorio de Micro-Red

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Abstract

Implementing Energy Storage Systems (ESS) is increasingly significant in power electrical systems. This is attributed to their ability to store surplus electricity generated by renewable energy sources such as wind and solar, contributing to the balance between generation and demand. Literature studies indicate that this practice enhances network stability and diminishes the need for expensive redesigns in infrastructure. This paper presents an exhaustive experimentation-based study of the dynamic response provided by three energy storage system technologies: supercapacitors, Lithium-Ion batteries, and Vanadium redox flow batteries, technologies with significant academic, research, and industrial interests nowadays. The objective of this research is the experimental evaluation of the performance of such technologies in real electrical system operations, focusing on determining the efficiency of charge and discharge, as well as the tracking of active and reactive power achieved through the associated grid interface. The experimental tests performed in a microgrid laboratory show these technologies' advantages and limitations in different grid-integration applications, with the Lithium-Ion battery-based ESS demonstrating the highest efficiency and faster power response. The results achieved and reported in the article can serve as an essential input for

Summary: Introduction, Materials and Methods, Results and Discussion and Conclusions.

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researchers and technology developers to feed their models with more precise parameters and data that might provide results closer to the actual behaviour of the studied prototypes. The methodological framework used in this research is descriptive, experimental, and quantitative.

Keywords: EESs, Lithium-Ion batteries, Vanadium-redox flow batteries, Supercapacitors, Microgrids.

Resumen

La implementación de sistemas de almacenamiento de energía (SAE) está adquiriendo una creciente relevancia en los sistemas eléctricos de potencia. Esto se debe a su capacidad para almacenar el excedente de electricidad generado por fuentes de energía renovable, como la eólica y la solar, y contribuir al equilibrio entre la generación y la demanda. Estudios documentados en la literatura muestran que esta práctica mejora la estabilidad de la red y reduce la necesidad de realizar costosos rediseños en la infraestructura. En este artículo, se presenta un estudio exhaustivo basado en la experimentación de la respuesta dinámica proporcionada por tres tecnologías de SAE: supercapacitores, baterías de iones de litio y baterías de flujo de Vanadio redox; tecnologías de gran importancia en la academia, investigación e industria en la actualidad. El objeto de esta investigación es la evaluación experimental del desempeño de tales tecnologías en operaciones reales de un sistema eléctrico, centrándose en la determinación de eficiencia de carga y descarga, así como en el seguimiento de potencia activa y reactiva conseguido por la interfaz de conexión a la red asociada. Los resultados de los experimentos realizados en un laboratorio de microrred muestran las ventajas y limitaciones de estas tecnologías en diferentes aplicaciones, demostrando ser la más eficiente y rápida en respuesta de potencia el SAE basado en baterías de iones de litio. Los resultados alcanzados y reportados en el artículo sirven como insumo esencial para que los investigadores y desarrolladores de tecnología alimenten sus modelos con parámetros y datos más precisos que brinden resultados más cercanos al comportamiento real de los prototipos estudiados. La metodología utilizada en esta investigación es descriptiva, experimental y cuantitativa.

Palabras clave: SAEs, baterías de iones de litio, baterías de flujo de Vanadio redox, supercapacitores, microrredes.

Introduction

Overview

The production of electricity from renewable sources such as solar and wind energy is highly dependent on weather conditions. Solar energy is available only from dawn to dusk, and cloudy conditions can cause variations in energy production during this time. Likewise, in the case of wind energy, wind speed is highly variable in both on-shore and off-shore wind farms, resulting in varying levels of energy production. This variability is a problem for electrical power systems since energy must be supplied to consumers (residential, commercial, and primarily industrial) in compliance with rigorous quality standards concerning voltage level and frequency.

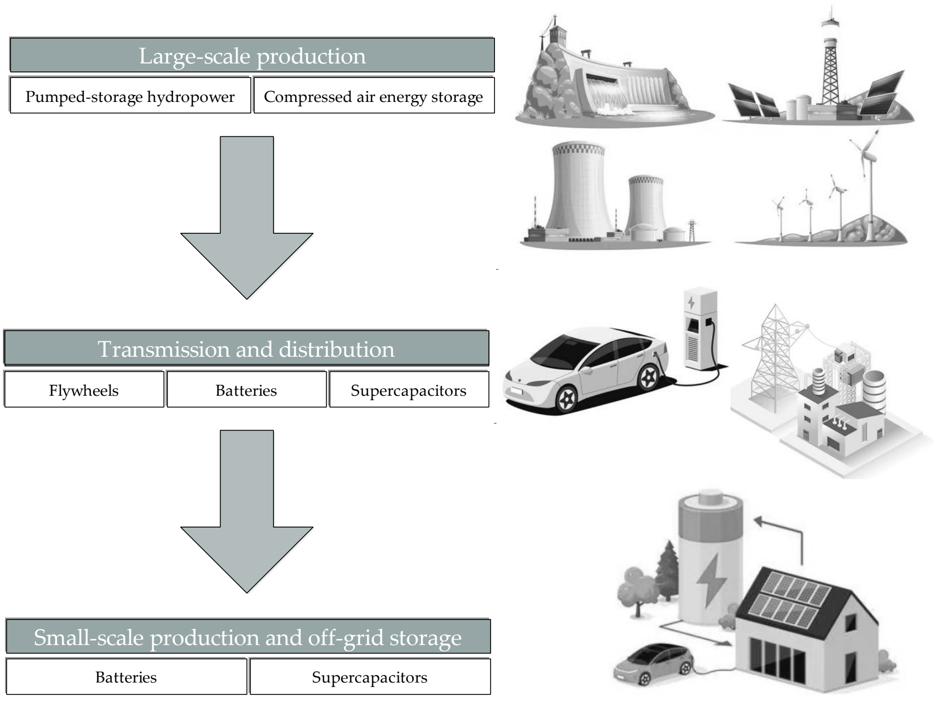
In this context, there is a clear need to mitigate the variability intrinsic to intermittent renewable energy sources (IRE) and improve the reliability of the electricity supply in terms of its continuity. One of the ways currently used to fulfil these purposes is toemploy energy storage systems (ESS) interconnected to the electric-electronic equipment of the generation plants that take advantage of IRE and at specific strategic points of the electric grid (Ochoa & Martinez, 2021); (Silva, 2018).

According to (Shukla et al., 2000), two fundamental ways to store electrical energy exist. The first is indirect, involving batteries, where the storage (charge) is in the form of chemical energy and is recovered (discharged) through a redox process of the electroactive reagents of the device. The second is direct since the energy is stored in electrostatic form as positive and negative charges on the plates of a capacitor with very high capacitance (hundreds or thousands of Farads), known as a supercapacitor or ultracapacitor.

Figure 1 shows the uses of batteries, supercapacitors, and other energy storage mechanisms employed at different scales within electrical systems (Aneke & Wang, 2016).

Figure 1

Usage of energy storage systems at different scales in electrical systems. Source: own elaboration based on [4]



State-of-the-art review

There is an important academic, research, and industrial interest in energy storage, given its performance and technological maturity, which is why it is possible to find many scientific contributions that have led to countless applications in the literature. In (Hassan et al., 2022), an evaluation study of using supercapacitors as a fast response energy storage unit to improve energy self-consumption and self-sufficiency to compensate for intermittent photovoltaic generation is presented. The results show that this combined use improves specific parameters related to power quality and leads to an appreciable increase in the total monthly energy supplied by the installation.

In this line, research reported in (Şahin et al., 2022) and (Gao et al., 2023) shows that the performance of supercapacitors can be considerably improved when hybridized with other battery-based storage technologies. Apart from providing a better energy cushion, the hybrid solution is an interesting alternative from a techno-economic point of view due to its increased lifetime (Subasinghage et al., 2022); (Dikmen & Karadağ, 2022).

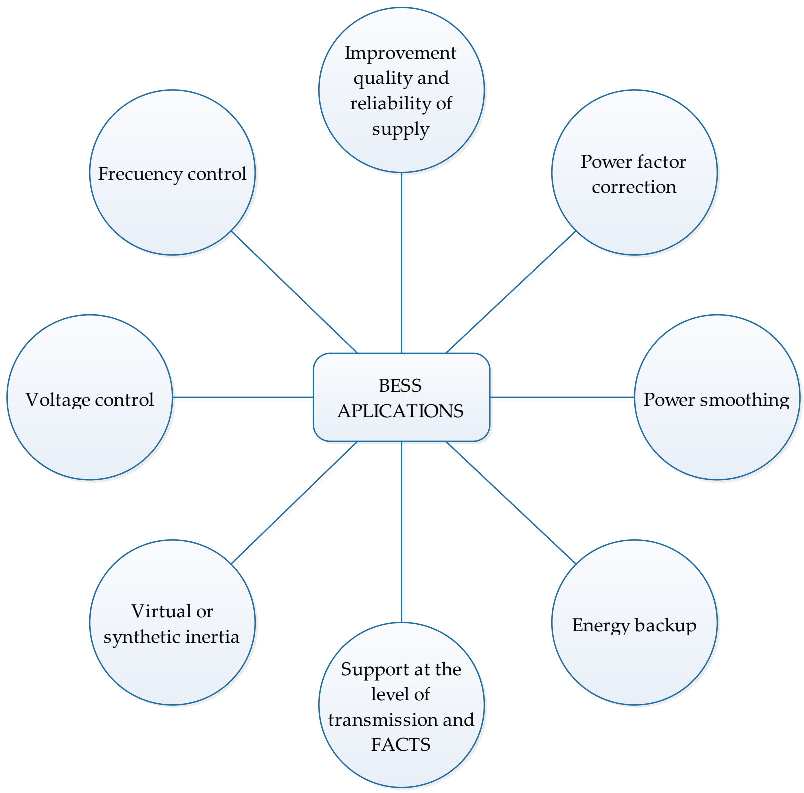
In addition, these works explore the opportunities provided by the concept of "second life" of electrochemical systems decommissioned in their original applications (e.g., discarded batteries of electric vehicles) with the consequent reduction of the carbon footprint (Mostert et al., 2018). Today, the predominant applications of storage based on lithium-ion batteries are in the electromobility sector and grid energy support (Şahin et al., 2022). The latter is the subject of interest for this research, providing support for the grid in contingency and loss of supply risk situations (Lee et al., 2022) and the contribution to the proper integration of intermittent renewable generators to the grid, thanks to the fast response in power terms and the high storage capacity offered by lithium-ion batteries.

This property facilitates the absorption of fluctuations of wind and photovoltaic generators in weak and isolated power systems, improving the reliability and quality of the power supply (Mancuso et al., 2019). A third storage technology that has attracted current scientific attention is the storage system based on Vanadium Redox Flow Batteries (VRFB). Its high storage capacity and long (theoretically infinite) electrochemical life cycle (Arribas et al., 2016) make this technology very attractive for reliable energy supply applications in isolated microgrids (Suvire et al., 2017) and for backup power supply of critical loads in industries and hospitals(Do Nascimento Ricardo & Fthenakis, 2017); (Li et al., 2017).

Apart from the applications mentioned here, energy storage systems provide a more comprehensive range of implementation opportunities in electrical power systems to provide support in fundamental activities such as frequency and voltage control in a power grid (Zecchino et al., 2021); (Ochoa et al., 2022), power factor correction (Niwas & Singh, 2016), power smoothing (Benavides et al., 2023), improving the resilience of the power system through the concept of virtual or synthetic inertia (Pazmiño et al., 2021), (Pazmiño et al., 2022), flexible alternating current transmission systems or FACTS (Kljajić et al., 2020), among many others. Figure 2 schematizes the main applications of battery energy storage systems (BESS) found in this literature review.

Figure 2

Applications of battery energy storage systems in power systems



Aim of the study

This research aims to experimentally evaluate the performance of ESS technologies in actual power systems operations, explicitly focusing on determining the efficiency of charge and discharge processes and analysing the active and reactive power set-point tracking dynamics achieved through the associated network interface. The study involves an exhaustive examination, based on experimentation, of the dynamic response provided by three energy storage systems (ESS) working on a power system: ESS based on supercapacitors, ESS based on lithium-ion batteries, and ESS based on Vanadium Redox Flow Batteries, three technologies of great current interest in the academic, research and industrial fields. The laboratory tests are designed to yield characteristic curves and times of the charge and discharge processes of the different technologies, as well as active and reactive power set-point-tracking dynamics.

Materials and Methods

First of all, this section describes the materials used for conducting the proposed validations. Subsequently, the developed methodology and the design of the experiments, which will lead to the achievement of the research objectives, are outlined.

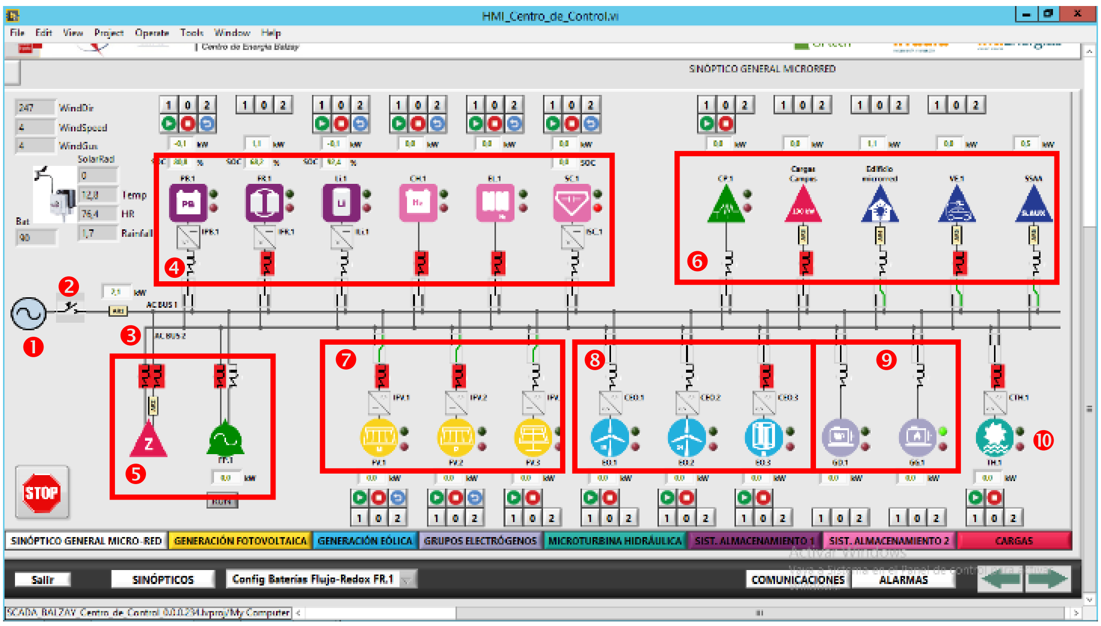
Materials: Energy storage systems under study

Microgrid Laboratory of the CCTI-B

The experimental work is conducted in the Microgrid Laboratory of the Centro Científico Tecnológico y de Investigación Balzay (CCTI-B) of the Universidad de Cuenca. This laboratory has a variety of energy generation, consumption, and storage agents and can work connected to the main distribution network or in island mode. Figure 3 shows a schematic representation of the main components of the laboratory.

Figure 3

Schematic representation of components of the Microgrid Laboratory: 1. Main grid, 2. Grid connection bus bar (B-01), 3. Energy storage components, 5. Programmable loads and sources, 6. Other loads, 7. Solar photovoltaic generation, 8. Wind generation, 9. Thermal generation, 10. Hydraulic generation



Within the scope of the present study, the Microgrid Laboratory of Universidad de Cuenca has the following energy storage systems, which constitute the materials used in the current research (Espinoza et al., 2017):

- ESS based on supercapacitors (Supercapacitors- ESS)
- ESS based on lithium-ion batteries (Li-Ion BESS)
- ESS based on Vanadium Redox Flow Battery (Vanadium Redox Flow - BESS)

Supercapacitors–ESS

Supercapacitors (SCs) are storage devices capable of holding more energy (charge) than a conventional capacitor and releasing energy (discharge) much faster than a battery (Castro-Gutiérrez et al., 2020). Additionally, their high number of charge/discharge cycles and long-term stability position SCs as an attractive option for implementing ESSs. Compared to batteries, their main disadvantage is their low specific energy or gravimetric energy density (watt-hours per unit mass - Wh/kg). SCs are classified into three categories (Libich et al., 2018): Electric double-layer capacitors (EDLC) with liquid electrolyte make up the first. They store energy by electrostatic interaction in the Helmholtz electric double layer at the phase interface between the electrode surfaces and the electrolyte (known as the electrostatic storage principle), which gives them a high-power density (very high discharge current). They have high durability and a lifetime (cyclability) of millions of charge/discharge cycles. They are also the most common and widely marketed.

The second category is pseudo-SCs or faradaic SCs, which do not store energy in the double dielectric layer. They are like batteries since redox reactions and energy transfer between electrodes and the electrolyte occur during the charging and discharging. This feature provides approximately twice as much higher specific energy than EDLCs (Libich et al., 2018). However, the electrodes degrade faster, causing an increase in the SC's internal resistance and lower stability and cyclability. Their use and commercialization are limited.

Finally, hybrid SCs are in the third category. These combine the properties of EDLCs and pseudo-supercapacitors through a faradaic reaction at one electrode and an electrostatic interaction at the other. It is the most modern and advanced technology, providing higher specific energy (approximately 36 times more than EDLCs and 18 times more than pseudo-SCs, according to (Libich et al., 2018) and higher power density. In a study of trends in hybrid (SC-Battery) energy storage devices (Benoy et al., 2022), the authors state that hybrid SC applications are increasing significantly in the industrial sector of energetically hybrid vehicles.

Among the most critical applications of SCs are: load-levelling function; hybridization with rechargeable batteries in drive systems and regenerative braking systems for partial recharging in electric vehicles; short-term power backup (for safe shutdown of systems or switching to permanent backup systems); control of transients or power fluctuations (power smoothing), among others.

In the Microgrid Laboratory, a supercapacitor bank comprises ten electric double-layer capacitors (EDLC) connected in series of 130 F and 56 V_{DC} each, BOOSTCAP model BMOD0130, from the USA manufacturer Maxwell Technologies. The bank's terminal voltage is 560 V_{DC}, and its total energy storage capacity is 0.57 kWh. The power converter connected to this equipment is 30 kW rated (Figure 4).

Figure 4

Supercapacitors-ESS of the Microgrid Laboratory: supercapacitor bank (left), a cabinet containing the power electronic converter (right)

Li-Ion BESS

Lithium-ion (Li-ion) battery cells consist of a cathode, anode, electrolyte, and separator (a safety component that prevents a short circuit between the anode and cathode, which is permeable to lithium ions). They use non-metallic lithium in the cathode, i.e., chemical compounds called lithium metal oxides capable of providing lithium ions (Li+), hence their commercial name and their varieties. The ions are transported through the electrolyte between two electrodes in a reversible chemical reaction from the cathode to the anode during charge and discharge (Zubi et al., 2018). They are characterized by having an "unmatched combination of high energy density and high power density" (Nitta et al., 2015).

There are six commercially available lithium-ion batteries (Beltran et al., 2020), with significantly different technical characteristics depending on the lithium metal oxide they employ. These are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese cobalt oxide (NMC), and lithium titanate (LTO).

According to (Zubi et al., 2018), LCO lithium-ion batteries have high specific energy (up to 190 Wh/kg), long life (up to 1000 cycles), and their main disadvantage is their low level of safety due to the thermal instability of cobalt oxide. Their applicability is in mobile electronic devices. Lithium-Ion LMO has a relatively high-power density, higher durability (up to 1500 cycles), lower specific energy (up to 140 Wh/kg), and the higher thermal stability of manganese oxide makes them safer. Their applications are in e-bikes, medical devices, and power tools. Lithium-Ion LFP has higher durability (2000 cycles), is safe, relies on environmentally friendly materials, and tolerates operation over a wide range of state of charge (SoC) 15-100% with consistent performance. However, it has low specific energy (up to 140 Wh/kg). It has the potential for application in electric power systems (EPS) and has been successful in e-bikes. Lithium-ion NCAs stand out for their high specific energy (250 Wh/kg) and high-power density. They have high durability (up to 1500 cycles). They are used in electric vehicles (EVs), particularly in Tesla models. Lithium-Ion NMC has lower specific energy (up to 200 Wh/kg) and higher durability (up to 2000 cycles); the proportions of their chemical components can be modified according to the application to provide tailor-made solutions. They are the dominant technology in EVs and plug-in hybrid electric vehicles

(PHEV). Finally, Lithium-ion LTOs are characterized by using nanotechnology to integrate lithium titanate nanocrystals on the anode surface (Campoverde-Pillco et al., 2024). They have very high-power density, which allows them to deliver a discharge current that is ten times higher (approx.) than that provided by other lithium-ion technologies. They have high durability (20,000 cycles) and safely support fast charges (in the order of minutes). Regarding its applications, it has great potential for energy storage in EPSs integrating IRE.

Electrical energy storage in lithium-ion batteries currently has three main applications (Zubi et al., 2018). The first one is in mobile electronic devices (cell phones, tablets, and laptops, among others), where it is the dominant technology. The second is in electric vehicles (EVs, e-bikes, and e-scooters, among others) as the primary energy source. Finally, they can contribute to integrating intermittent renewable energies into the system in EPSs. In this last application, the batteries store surplus energy to be injected into the grid when the natural resource is unavailable (sunlight or wind) or is technically and economically convenient.

The rechargeable lithium-ion battery bank of the Microgrid Laboratory shown in Figure 5 consists of 11 cells of 58.36 V_{DC}, connected in series, model ELPT392- 0002, Samsung brand. The bank's output voltage is 642 V_{DC}, with a power of 88 kW and an energy storage capacity of 44 kWh. The bank is connected to an 80-kW power converter.

Figure 5

Li-Ion BESS from the Microgrid Laboratory: cell bank (left), a cabinet containing the power electronic converter (right)

Vanadium Redox Flow – BESS

A redox flow battery (RFB) consists of two reservoirs, one with charged electrolyte and the other with discharged electrolyte, an electrochemical energy conversion system (stacks connected in series or parallel), a hydraulic pumping system to make the electrolyte flow through the conversion system, and the electrical system for interconnection with the load and the electrical power source (Skyllas-Kazacos et al., 2011). The current state-of-the-art identifies two types of RFBs: 1) standard or pure flow and 2) hybrid. Figure 6 shows the Vanadium Redox Flow Battery bank of the Microgrid Laboratory.

Figure 6

Vanadium Redox Flow - BESS of the Microgrid laboratory: Container housing the vanadium cells (left), double cluster of power electronic converters (right)

Standard or pure flow batteries, among which the vanadium redox flow battery (VRFB) stands out, provide the independence or decoupling between storage capacity and power as one of the leading technical characteristics (Lourenssen et al., 2019). Their capacity depends on the amount of electrolyte stored in the system, the concentration of active components, the voltage of the electrochemical cells, and the number of stacks. In contrast, the power depends on the active components' behaviour and the electrodes' size. This decoupling provides advantages such as modular and flexible design, excellent scalability, moderate maintenance costs, and extended durability. Its energy density is 25-35 Wh/L, which is still very low compared to lithium-ion batteries (250 Wh/L or more). Its cyclability is far superior to other types of batteries, with a range of 15000-20000 complete cycles (Sánchez-Díez et al., 2021). According to market statistics, VRFB is currently the most commercially successful (Transparency Market Research, 2023).

On the other hand, hybrid RFB saves at least one solid electroactive material, such as the zinc-bromine redox flow batteries (ZBFB), the second most important technology on the market (Transparency Market Research, 2023). Their decoupling between power and energy storage capacity is limited due to the presence of the solid electrode. Commercially available models have a specific energy range of 60-85 Wh/kg, with an estimated lifetime of 11-14 years (Suvire et al., 2017). Their main application is large-scale energy storage in EPSs for IREintegration, where they are intended to meet the requirements of a long lifetime (cyclability and calendar years), low cost, and high round-trip efficiency.

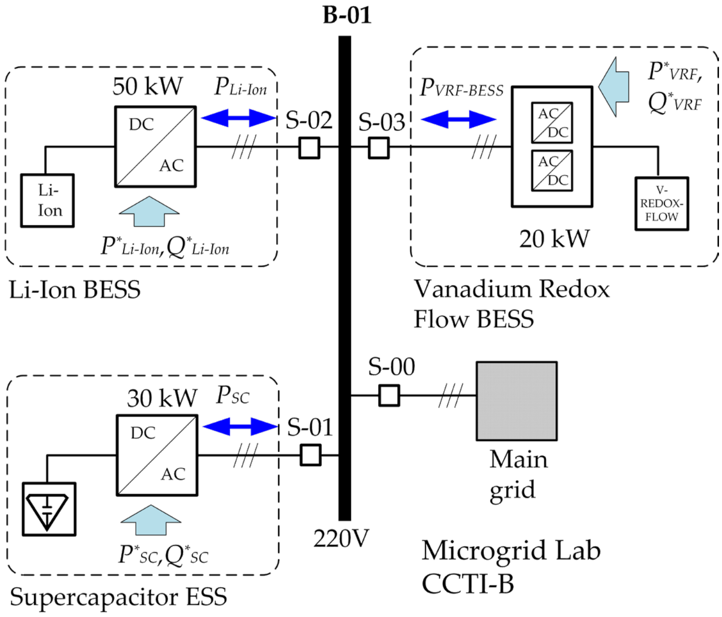
The Microgrid Laboratory has a VRFB model CELLCUBE FB 20-100 from the Austrian manufacturer GILDEMEISTER Energy Solutions, with an output power of 20 kW and an energy storage capacity of 100 kWh in 12 electrochemical stacks. The battery is equipped with two clusters of power converters (3 converters per cluster, one master, and two slaves) to connect to any of the two three-phase bus bars available in the Microgrid Laboratory.

Methodology: Design of the laboratory test bench

Figure 7 shows the schematic representation of the test bench set up in the laboratory. All the energy storage agents under study will be connected to the main bus bar of the microgrid (B-01), which is connected, in turn, to the main distribution network.

Figure 7

One-line diagram of the test bench



The ESSs will all be subjected to the same operating conditions to facilitate a comparative analysis between the different storage technologies. Due to the significant amount of energy handled in such tests, both the charge/discharge tests and the dynamic tests of active and reactive power set point tracking will operate one technology at a time. The following is a description of the test plan to be carried out in this study, which constitutes the methodological basis of this research:

Charge and discharge tests. Each technology will be subjected to charge and discharge tests under constant active power conditions. This first experiment aims to determine the storage capacity and energy backup time provided by each system studied. With this information, the round-trip efficiency will be calculated, a parameter of great importance in ESSs since it quantifies the electrical energy that can be extracted from an ESS compared to the amount of electrical energy spent in its charging process. In addition, to respect the maximum and minimum operating limits of all ESS components, it was ensured that the charging and discharging tests were performed with an SoC between 20 and 80 %.

Active and Reactive Power tracking tests. To evaluate the short-term response in terms of active and reactive power provided by the different ESS technologies under study, these will be forced to follow the same power time profile in charge and discharge situations. The control of the set point signals applied to the power electronic converters (PEC) associated with each ESS will be performed from the laboratory's Supervisory Control and Data Acquisition (SCADA) system. This test will gauge the efficiency of each ESS technology in tracking the imposed power set points in terms of its response time, power tracking error in dynamic and steady-state, and the effect of the power tracking on the SoC.

Results and Discussion

Charge and discharge tests

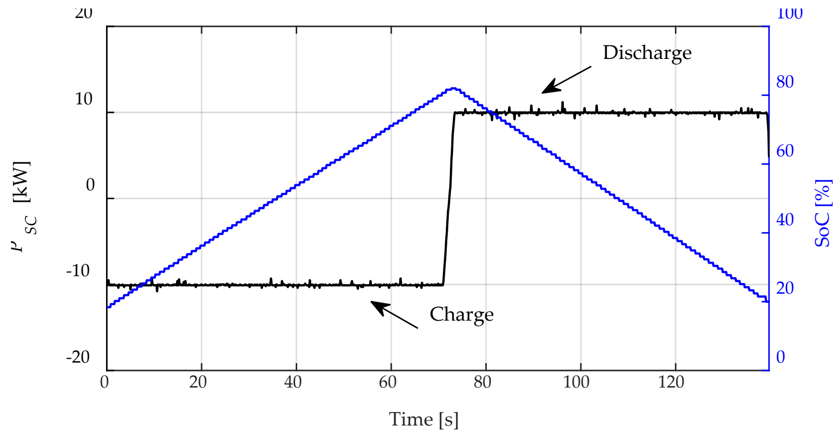
This section presents the results obtained in the laboratory during the charge and discharge tests of the different ESS technologies considered. To have comparable cases in the three experiments, each ESS is subjected to a constant power condition of 10 kW so that the corresponding SoC varies from 20 to 80% (charging stage) and then from 80 to 20% (discharging stage) in a sustained manner. In Figures 8, 9, and 10, black curves represent the active power at which the ESS is charged/discharged (in kW), and the blue curve represents the evolution of its state of charge (in %).

Tests applied to Supercapacitors-ESS

Figure 8 shows the complete charging and discharging process of the Supercapacitor-ESS. In this test, the correct operation of the power electronic converters associated with this technology to track the pre-set active power is evident: ±10 kW constant. In its charging stage, the SoC of the Supercapacitor-ESS goes from 20 to 80%, in a sustained manner, in 72.6 seconds. This process is associated with an expenditure of 0.202 kWh of electrical energy from the grid. Once this ESS reaches 80% of the load, the power setpoint applied to the inverter is reversed to start the discharging stage, as shown in the figure. The tests show that going from a state of charge of 80% to 20% with a power of 10 kW takes 67.1 seconds, delivering 0.189 kWh of electrical energy. The findings reveal that, in this type of ESS, to extract 0.189 kWh of electrical energy, it is necessary to use 0.202 kWh during battery charging. The ratio between the first and second quantities is called round-trip efficiency (RTE), which in the case of the Supercapacitor-ESS is 92.4%, an expected value in terms of efficiency for this technology. An intriguing observation from the results is that the dynamics presented by the SoC in the charging and discharging process have a linear nature.

Figure 8

Charge and discharge test performed on the Supercapacitor-ESS

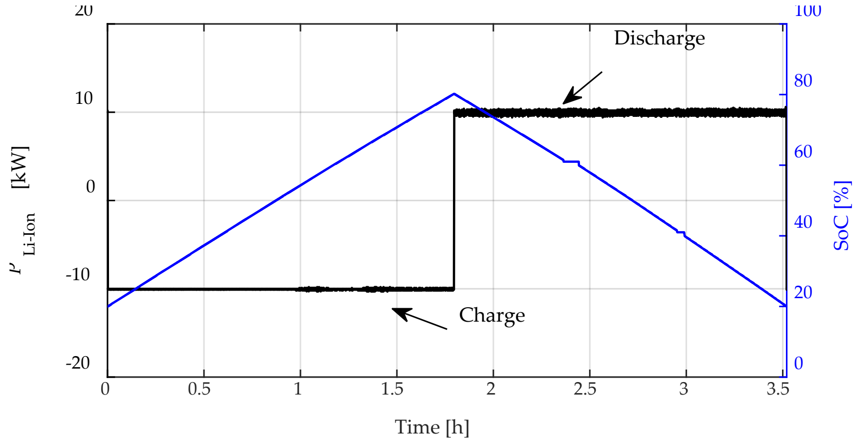


Tests applied to Li-Ion BESS

The complete charging and discharging process of the Lithium-Ion BESS is shown in Figure 9. It is observed that, in its charging stage, the SoC goes from 20 to 80% in 107.8 minutes, requiring 17.96 kWh of electrical energy. Likewise, in the previous case, it is observed that once this ESS reached 80% of the load, the power setpoint is reversed to start with the discharge process to 20% of SoC at a constant power of 10 kW. The discharge, on the other hand, lasts 105.2 minutes and delivers 17.54 kWh of electrical energy. In this case, the RTE efficiency is 97.7%, meaning the electrical energy extracted from this ESS technology penalizes only 3% of the energy needed to charge the battery. Note that the dynamics adopted by the SoC of this ESS in its charging and discharging process have a linear characteristic.

Figure 9

Charge and discharge test applied to Lithium- Ion BESS



Tests applied to Vanadium Redox Flow – BESS

The Vanadium Redox Flow-BESS presents a charge and discharge cycle, as shown in Figure 10. Its charging process (SoC from 20 to 80%) takes about 13.5 hours, and the temporal evolution of the SoC presents a non-linear dynamic. As expected, sustaining a charging power of 10 kW for a long time involves an investment of 135.3 kWh of electrical energy. This characteristic makes this technology the one with the highest storage capacity of the three studied here. The results reveal that this battery can sustain a power supply of 10 kW for at least 7.8 hours, representing an energy extraction of 77.8 kWh. It is evident here that, although this battery provides a reasonably large energy cushion compared to the previous two, its RTE efficiency is the lowest: 57.5%.

Figure 10

Charge and discharge tests applied to Vanadium Redox Flow-BESS

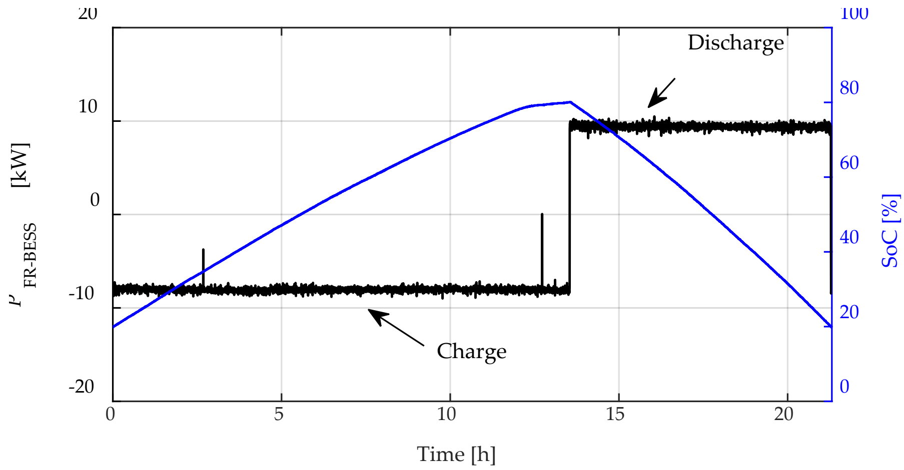


Figure 11 shows the results obtained in this first part of the tests, including the round-trip efficiency calculations for the three ESS technologies studied.

Figure 11

Round-trip efficiency of the three ESS technologies studied

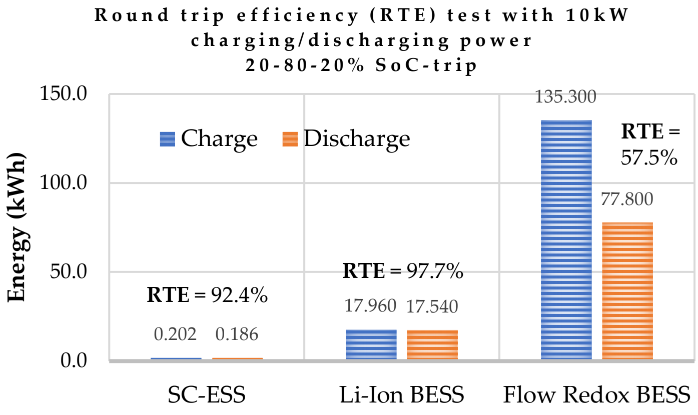
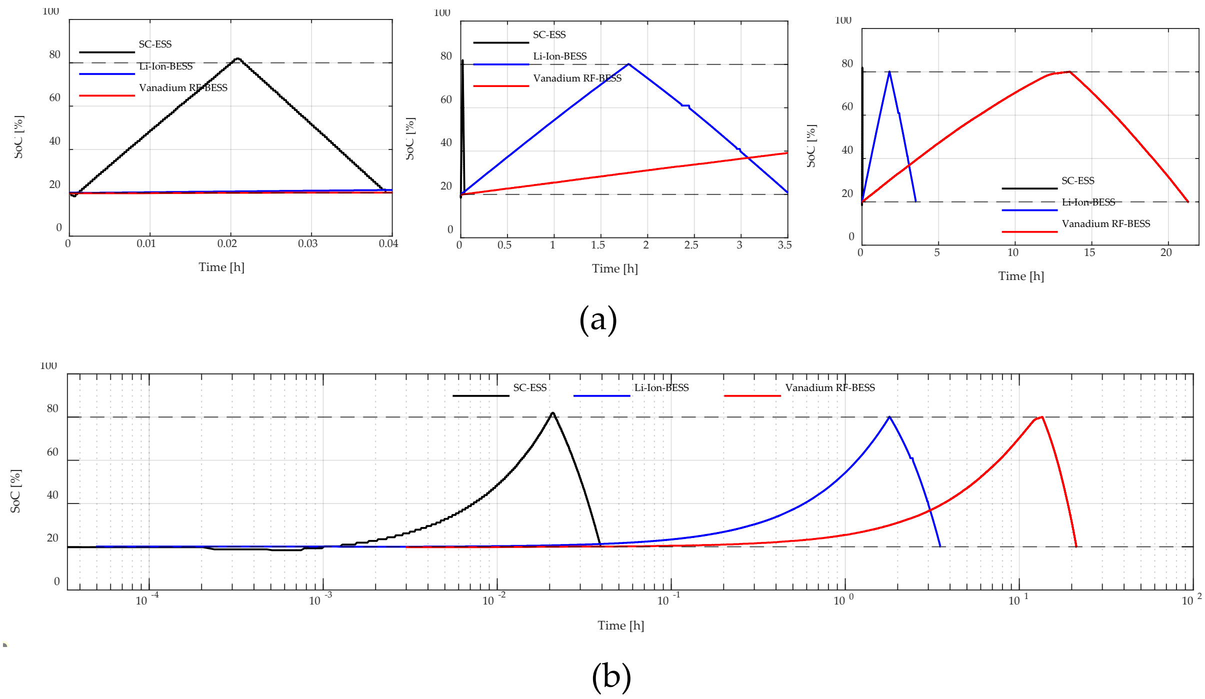


Figure 12 (a) shows the charge and discharge cycles of the ESSs studied over the same time scale. In this, the short-term response of the Supercapacitor-ESS compared to that of the Li-Ion BESS is evidenced, and how, in turn, the time response of the latter is short if compared to the Vanadium Redox Flow-BESS. Complementarily, a superposition of the three charging and discharging characteristics of the ESSs on a logarithmic time scale is given in Figure 12 (b).

Figure 12

Comparison of charge and discharge characteristics of ESSs under constant 10 kW



Finally, for completeness, the tests described above have been repeated to obtain the charging and discharging characteristics of the ESSs but for different power values. Table 1 shows the results obtained in the experimental tests. In each case, the round-trip efficiency becomes a characteristic value of each ESS technology and varies very little for each charging and discharging power level. Thus, the round-trip efficiency of Supercapacitor-ESS is 92%, the Li-Ion BESS is between 95-97%, and the Vanadium Redox Flow-BESS is 57%.

Table 1

Charge and discharge tests applied to the ESS studied: 20-80-20% SoC-trip

Power [kW]	SC-ESS			Li-Ion BESS			FR-BESS		
	Time [s]		RTE [%]	Time [min]		RTE [%]	Time [h]		RTE [%]
	Charge	Discharge		Charge	Discharge		Charge	Discharge	
5.0	116.50	107.80	92.53	245.60	240.00	97.72	-	-	-
10.0	72.60	67.10	92.42	107.76	105.24	97.66	13.53	7.78	57.50
15.0	30.50	28.00	91.80	70.00	66.67	95.24	-	-	-
20.0	23.00	21.00	91.30	42.03	40.00	95.16	-	-	-

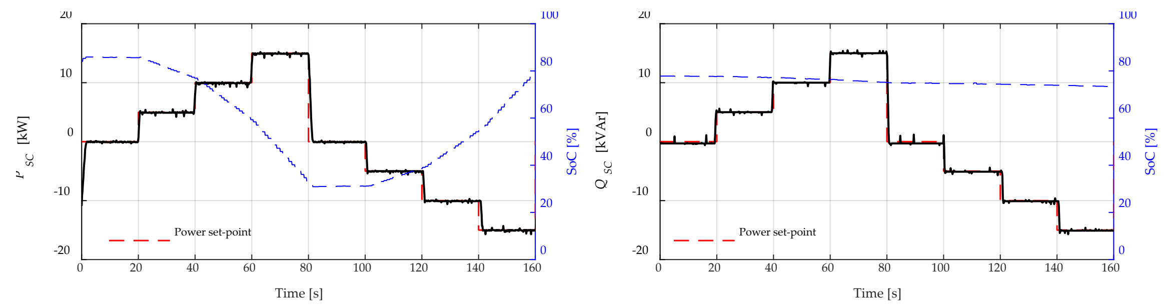
Active and Reactive Power setpoint tracking tests

Next, the studied ESSs are subjected to variable active and reactive power conditions to evaluate their short-term dynamic response. For this purpose, power profiles have been prepared, taking the values 0, 5, 10, and 15 kW (and kVAR) in steps of 20 seconds each. These profiles were loaded into the algorithm commanding the inverters associated with the ESS in the laboratory's SCADA.

Figure 13 (a) depicts the response provided by the Supercapacitor-ESS. The graph demonstrates the correct performance of this ESS since it successfully reaches the active power setpoint values in both transient and steady-state regimes. However, it is worth noting the volatility of the SoC of this technology in terms of active power injection and absorption requirements. This characteristic is expected since the Supercapacitor-ESS is the technology with the lowest energy storage capacity of the three studied here. In addition, regarding reactive power tracking (Figure 13 (b)), the Supercapacitor-ESS correctly achieves the setpoints imposed with a negligible consumption of useful energy (SoC). With these two tests, the usefulness of this ESS in applications requiring fast power response and its low energy consumption is evident.

Figure 13

Power tracking of the Supercapacitor-ESS



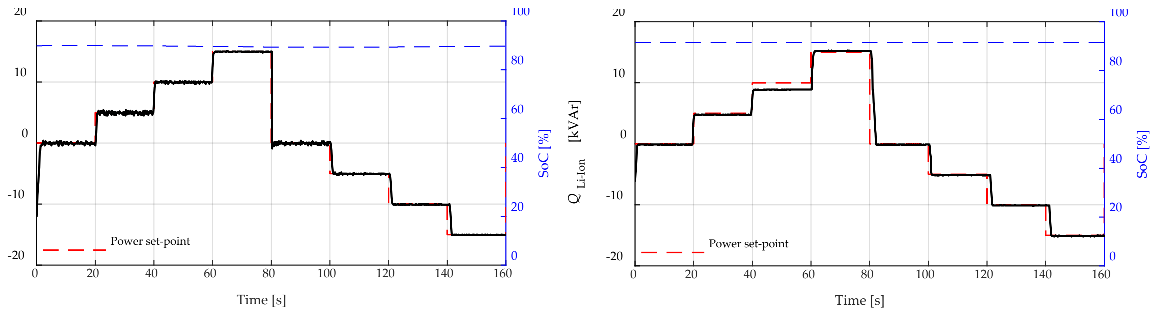
(b)

Next, regarding the response presented by the Li- Ion BESS, Figure 14 (a) shows the high effectiveness in active power setpoint tracking of the lithium-ion battery in transient and permanent regimes, shown in Figure 14 (b).

In this test, it is evident that when the ESS is subjected to an active power requirement of short duration, the useful energy handled is small and almost does not affect the SoC level for the plotted time scale. A similar situation occurs in the reactive power control (Figure 14 (b)), in which the reactive power tracking is performed very efficiently while the SoC does not show an appreciable reduction over time. In this second test, the inverter associated with the ESS presents a correct performance in short-term power tracking tasks and, in turn, provides operation for relatively long times due to its significant energy storage capacity.

Figure 14

Power tracking of the Li-Ion BESS



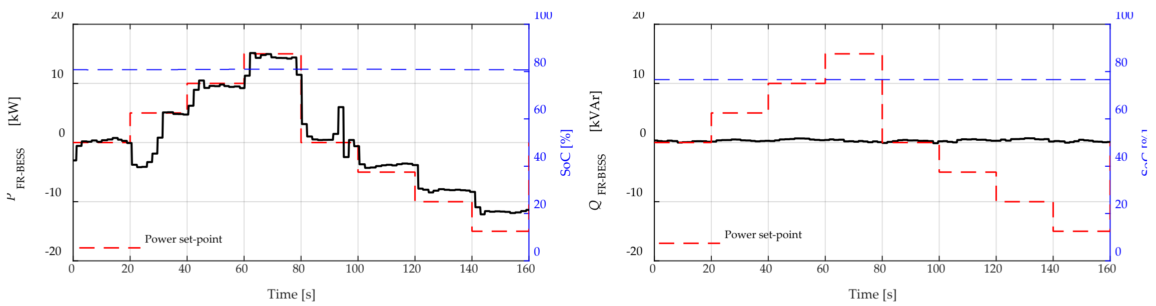
(a) (b)

Finally, Figure 15 shows the performance of the Vanadium Redox Flow-BESS in power-tracking tasks. Figure 15 (a) shows the poor response of this technology in terms of short-term active power. On the other hand, when long-term power transitions are required, this ESS can respond adequately to such demands (See Figure 10). Finally, regarding reactive power control, Figure 15 (b) shows a null response from the ESS. This is because the actual prototype in the laboratory does not have the reactive power control enabled by default.

The results presented here offer insights into the advantages and limitations of the three types of ESSs examined in terms of their required time response. In addition, they confirm the different applications of such technologies in their interaction with the electric power system, as discussed in section 2 of this paper.

Figure 15

Power tracking of the Vanadium Redox Flow-BESS



(a) (b)

Conclusions

In this study, a comprehensive study has been carried out to obtain the dynamic responses of three ESS technologies: supercapacitors, lithium-ion batteries, and Vanadium redox flow batteries. The work has been done on actual commercial models with industrial characteristics available in the Microgrid Laboratory of Universidad de Cuenca. In align with the research objectives aimed at evaluating the performance of energy storage systems in terms of their efficiency and dynamics of active and reactive power for applications in power systems, two tests were devised: 1) charge and discharge and 2) active and reactive power set point tracking. The most relevant results are presented below:

Supercapacitor-ESS: the results of charge and discharge tests showed that this energy storage medium has the lowest storage capacity: 1/90 of the capacity of Li-Ion BESS and 1/670 of the capacity of Vanadium Redox Flow-BESS but with very high current density since it allows swift responses in terms of active and reactive power with practically imperceptible error margins. From these tests, it is concluded that this ESS is ideal for applications whose power demands have a very short-term variability, such as power smoothing, frequency and voltage control in electrical systems, and voltage dips suppressor when switching from a primary supply source to a backup source during a contingency. Its round-trip efficiency is around 92%.

Li-Ion BESS: Tests performed on this commercial model showed that its storage capacity allows it to sustain significant power for at least a few hours, which, added to its high current density, allows practically instantaneous transitions of active and reactive power, allowing this ESS technology to be implemented in applications similar to that of Supercapacitor-ESS. In addition, its long autonomy allows it to be used as a backup system when the primary energy supply is lost in an electrical installation, widening the range of applications concerning the previous technology. Experimental results showed this technology has a 95-97% round-trip efficiency.

Vanadium Redox Flow BESS: after conducting charge and discharge tests on this type of battery, it was found to have the highest capacity of the three ESSs studied. This technology enables the sustenance of significant power load requirements during tens of hours of uninterrupted operation. From the experimental results, it is concluded that this ESS is ideal to be implemented as a reliable and long-duration power backup system in applications where the primary supply source presents a high risk of unavailability or in base load applications. However, this ESS is unsuitable for applications where high-speed tracking of load power is required due to the electrochemical constraints of the tested commercial model. The round-trip efficiency is around 57%, the lowest of the three technologies studied.

In addition to the conclusions presented here, the results of this study provide charge and discharge charts of the different ESSs and values of charge and discharge times at different power levels. These data enable the elaboration of characteristic power vs. charging time curves, which help feed mathematical ESS models. Integrating mathematical ESS models in the grid studies facilitates obtaining numerical results that closely resemble the actual operation of these prototypes, thereby enhancing accuracy when sizing the energy storage facilities for various applications within the electrical power system framework.

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