MICROGRID ENERGY MANAGEMENT CONTROL WITH A VANADIUM REDOX FLOW AND A LITHIUM-ION HYBRID BATTERY SYSTEM FOR PV INTEGRATION

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ABSTRACT**:** Hybrid energy storage systems combine multiple energy storage technologies, to improve the overall storage's performance and lifetime expectancy, compared to a single storage unit. This work proposes an online power/energy sharing management control of a hybrid energy storage system and a simulation tool developed by the authors. The hybridized system is composed of two PV installations (3.6 kWp and 6.7 kWp), a vanadium redox flow battery (VRFB) (5.0 kW /60 kWh) and a lithium-ion battery (LIB) (3.3 kW useful /9.8 kWh). The software simulation architecture is designed using MATLAB, where three hypothetical operation scenarios are simulated, with the aim of optimizing the energy usage according to its technical characteristics, current state operation and PV generation, with a 1-year time frame. The system's overall performance is evaluated through three technical key-performance indicators. The combination of different energy storage technologies is a feasible solution that depends on the application goals and on the assurance of the accuracy and reliability of the system and its control strategy.

Keywords: Hybrid Energy Storage System, Energy Management, Vanadium-Redox Flow Battery, Lithium-ion battery, Solar Photovoltaic.

1 INTRODUCTION

The installed capacity for decentralized renewable energy production has been increasing. Photovoltaic (PV) self-consumption maximization is one of the most popular management strategies in the solar photovoltaic sector nowadays. Renewable energy mini-grids are new grids that combine renewable energy and loads to operate on a self-sustained basis (matching discharge time within the time frame needs) [1]. Energy storage systems (ESS) help to make this match, giving additional stability to these grids. World is looking for ESS solutions that are preferentially scalable, modular, flexible, but also cheap and reliable.

Electricity storage contributes to a flexible power system. Storage can be conceived to be applied on meeting the demand and reliability in the grid peak hours; liberalized electricity markets can benefit from price arbitrage, capacity credit, ancillary resources or having customer side benefits [2]; shifting electricity from low demand to peaks, giving support to intermittent renewable energy sources, distributed generation, or smart grid initiatives, and provide alternative solutions to increase flexibility – as, demand-side management (DSM) or flexible power demand, or even smart charging strategies for Electric vehicles (EV) [3].

The energy management strategies can help in the execution of grid services such as peak shaving and curtailment avoidance, or simply balancing of loads through the power command management. Establishing the optimal technical and economic combination of different strategies and/or services is a complex task, highly dependent on the power consumption and generation profiles, market factors, applied tariffs, the existence of a grid connection to the system, general system costs, among others.

This value-stacking approach of simultaneous usage of different energy management strategies requires making trade-offs between energy needs, power needs, battery life and degradation, specific acquisition or O&M costs, etc. The hybrid energy storage system (HESS) can effectively present advantages to this multigoal task. For instance, the vanadium redox flow batteries are well suited for low power, long discharge applications, and the lithium-ion batteries in higher power applications. A Hybrid ESS can alleviate peak power stress, allowing to optimize the lifetime of these assets. Considering other fundamental technical characteristics of these systems, such as the physical limits of the technologies (State of Charge, operation temperature, etc.), allow to achieve an improved operation that, sometimes, can have competing goals.

This work presents the online operation control of a hybrid battery system VRFB-LIB, based on power-sharing techniques, for PV integration. The use of power-sharing to allocate power is studied to achieve reasonable energy distribution between the batteries and improve the utilization of energy. In the literature, several power management methods can be found as in [4]–[8]. In this work, the control strategy is proposed in three main approaches, and its effectiveness is verified through the technic key-performance indicators results, based on one-year simulation profiles. The control considers both batteries states of charge (SOC), performance, dynamics characteristics (assured by the used battery models), charge and discharge patterns. The simulation results show the improved use of energy storage devices.

The paper is organized as follows. First, the proposed hybridization of VRFB-LIB ESS is presented in Section 2. In Section 3, the methodology used to simulate the power-sharing of the hybrid solution is explained. In Section 4, the simulation results are presented. Finally, Section 5 draws the conclusions of the present work.

2 HYBRIDIZATION OF BATTERIES

2.1 Interconnection of batteries

In the case of energy storage system technologies, hybridization directly uses to the combination of more than one unit and generally is established in a single grid network. The combination is made to answer to a certain application usage case, to attend to specific needs. Hybrid battery technologies are being studied in the literature, given the distinct characteristics of each one, that can be complementary to each other. This approach can be applied for any project that combines multiple energy generation, storage, or load control technologies, co-located either physically or virtually.

Hybrid control could optimize the EMSs, allow the delivery of multiple services ("stacked"), and consider different planning horizons.

A review on Energy Storage Systems is conducted by the authors of [9], where Hybrid Energy Storage Systems (HESS) are detailed. These systems are combined considering their costs, performance, and environmental factors, emphasizing the benefits of individuals. Nevertheless, the state of the art presents gaps in the development of management strategies for these systems validated with parameters and real technical restrictions in an experimental environment.

In this work, a LIB and a VRFB with different energy and power capabilities, integrated into the microgrid of the Renewable Energies Chair of the University of Évora, are studied. Table I presents the main general characteristics of each of the energy storage technologies under study. The interconnection of different energy storage systems could result in a complementary characteristics solution, to result in an overall increase of the system's performance. The selection of a specific storage type is a result of technical and/or economic optimization.

Table I: Technical characteristics of ESS systems [3][6].

Battery/ Characteristic	VRFB	Lithium-ion
Power range (MW)	0.03-3	Up to 0.01
Discharge time	s-10h	m-h
Overall efficiency Power	0.65-0.85	0.85-0.95
Power density (W/kg)	166	50-2000
Energy density (Wh/kg)	10-35	150-350
Storage durability	h-months	Min-days
Self-discharge (per day)	Small	0.1-0.3 %
Lifetime (year)	10-20	5-15
Life cycles (cycles)	10000-13000	1500–4500
Response time	Fast	Very fast
Self-discharge	Null	Low

HESS interconnection can be achieved using different approaches. The simplest and most cost efficient is through a direct DC-connection on the battery terminals, although it lacks energy management or controllability. An alternative approach is through an active power electronics interface between the different storages to a more flexible and efficient HESS [10] across the AC grid.

3 METHODOLOGY

In this section, the methodology which allowed the one-year simulation of the proposed hybrid configurations evaluation is explained.

3.1. Microgrid constraints

The HESS is a result of the combination of the LG Chem RESU 10 lithium-ion battery (LIB) of 5.0 kW /9.8 kWp, and the redT vanadium redox flow battery (VRFB) system of 5.0 kW /60 kWh, as shown in Figure 1, and the microgrid architecture is represented in Figure 2, presented below. Since the LIB inverter has a nominal power capacity of 3.3 kW, this is the assumed maximum capacity that can be retrieved from the LIB system. These technologies were chosen to be an object for this study, due to their distinct characteristics as energy capacity, efficiency, lifetime, and response time.

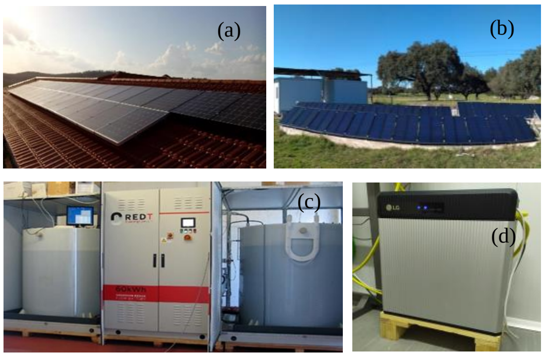


Figure 1: (a) Solar photovoltaic installation 6.7 kWp; (b) Solar photovoltaic installation 3.2 kWp; (c) VRFB redT 60 kWh; (d) LIB LG Chem Resu 10, 9.8 kWh.

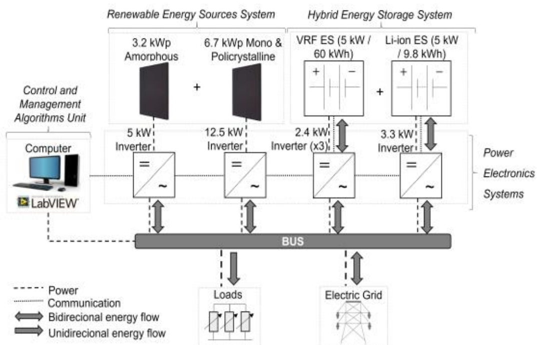


Figure 2: Scheme of the hybrid battery integration within the Renewable Energies Chair of the University of Évora's microgrid.

The power electronics efficiency of the VRFB was previously calculated and included in the developed model of the VRFB developed in [11], discussed below. In the case of the VRFB, the minimum value (limit) of the voltage is settled by the power inverter. Further development of lower voltages operation of power electronics should help the use of the battery at its fullest energy capacity. In addition, a value of 30 W total of the standby mode of the inverters was considered. The algorithms time of application is on a 1-minute basis.

2.2. PV and load consumption treatment output

One of the input variables is photovoltaic production. In this work, the actual PV generation curves were used, a complete year of data (2019) of the two installed PV systems (see Figure 3). The data from the two installations were treated separately and gathered for the results. The raw registered data is obtained with a 1- and 2-seconds interval, although, for this paper, a 1-minute average was achieved.

The load profile used is made available by the Portuguese DSO company E-REDES, with 15 minutes averaging of load data for the year 2019, for each of the Portuguese consumption sectors, in this case, for the BTN B sector, which corresponds to the overall consumption in buildings [12]. The data were treated to correspond to the 1-minute data sampled time frame for the PV.

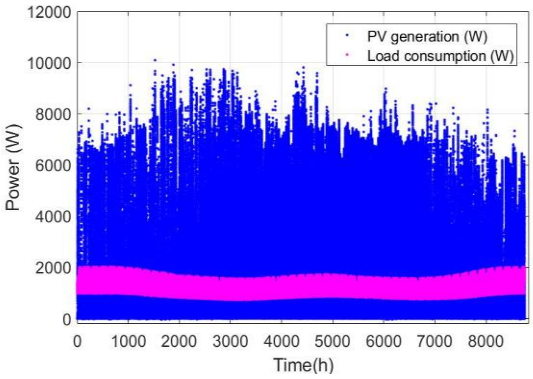


Figure 3: PV generation and load power profiles for the period of one year (2019) [12].

3.2. Modeling tool description

The model was developed with the help of the MATLAB programming tool, as a first approach to discuss the hybrid battery performance. The model was built to reproduce the operation of the batteries, describing their behaviour, also considering the inverters and general microgrid losses, computing the energy management systems' algorithms, and delivering the evaluation of the overall system, based on the selected key performance indicators (KPIs). In the studied scenarios, this tool provides information to evaluate whether the control offers a technically attractive solution to be considered for cost-effectiveness.

The developed model architecture was designed to be flexible to the addition of different battery units, data inputs, and model management of the overall system. The developed model allows the batteries to be operated together, to evaluate the overall HESS operation. For this purpose, the work main contribution is on the design algorithm to define HESS operation and control, the development of the energy routine for better energy performance, and the possibility of operating the HESS in a way to carry out multiple tasks.

3.3. Battery modelling

The operation of each BESS is achieved through its simulation model. Each battery was previously tested experimentally through characterization tests in each general operating conditions. The batteries physical constraints must be included in the model, as boundaries, such as the maximum allowable power and capacity, SOC or depth of discharge (DOD) limits, efficiencies, lifetime. Other constraints are related to the model initial definitions, being batteries-related as well. These constraints are enunciated in Table II, below.

Table II: Values of key technic parameters of the LIB and VRF batteries for modelling inputs [13].

Quantity	Value	Value reference
VRFB Maximum power (W)	5000	According to power-SOC relation and nominal power
VRFB nominal energy capacity (kWh)	60	Nominal energy capacity
VRFB SOC range (%)	10-95	According to lifetime strategy
VRFB operating voltage range (V)	50-60	Manufacturer and inverter dependent
LIB Maximum power (W)	3300	According to power-SOC relation and nominal power
LIB SOC range (%)	15-95	According to lifetime strategy
LIB nominal energy capacity (Ah)	189	Nominal energy capacity
LIB operating voltage range (V)	48-61	Manufacturer and inverter dependent
Initial SOC of both LIB and VRFB	50	Strategy starts at the middle interval
Temperature (ºC)	20-35	General operating condition

Battery lifetime depends strongly on the operation conditions: temperature, state of charge and total energy throughput (electrochemical operating windows) and charge and discharge rates. Ageing depends on technology, usage conditions, storage conditions, and operation (temperature, charge/discharge rates, voltage operation limits). The knowledge currently available on these matters results from a vast combination of experimental and modelling approaches [14]. In this work, the time frame evaluation is of one year, and for that reason, no battery degradation was assumed.

3.3.1. VRFB modelling

The VRFB is integrated with the building at a real scale, in a microgrid exclusively devoted for its testing and systems operation study. The nonlinear Nernst-Plank equation is one of the modelling approaches used to describe the multiphysics of the VRFB. The model is considered an equivalent circuit that describes the major reaction occurring in real-time operation, with reduced complexity and satisfying results. The VRFB was firstly fully experimentally characterized, and the model was validated with an energy management strategy, developed in the work in [13]. The model includes thermal effects, transients, dynamic SOC, and auxiliary consumption determination.

3.3.2. Lithium-ion modelling

The LIB models currently have an emphasis on the research field, most of them developed for the automotive sector. The authors of the present work developed a model of the lithium-ion battery integrated into the microgrid. Taking the bibliographical references regarding the LIB modelling for grid applications, the simple electrical equivalent model and the modified Shepperd model were used to describe the battery of this microgrid, considering the experimental characterization results, previously achieved.

3.4. EMS and Power command – HESS Allocation Method

In this work, the energy management strategy controls the connected power-inverters and operate the units according to the pre-defined set of rules. The goal is to have a power profile smoothing to be exchanged with the grid and the maximization of self-consumption while simultaneously protecting the battery SOC to be around the defined operational limits and the power profile limits.

A coordination block is created to virtually distribute power among the operation of the system. The filter-based power provides power splitting, as shown in Figure 4. The power-sharing strategy assigns higher power ramps to the LIB and the baseload power to the VRFB. The LIB energy capacity is lower compared with the VRFB, and its SOC can reach its extremes more often, which limits battery usability. The power-sharing ratio among the energy storage system could be dynamically adjusted for SOC regulation. The systems architecture is designed to operate the VRFB as the primary energy component, and the LIB has the primary power component. The power adjustment is achieved through the inverter control power command.

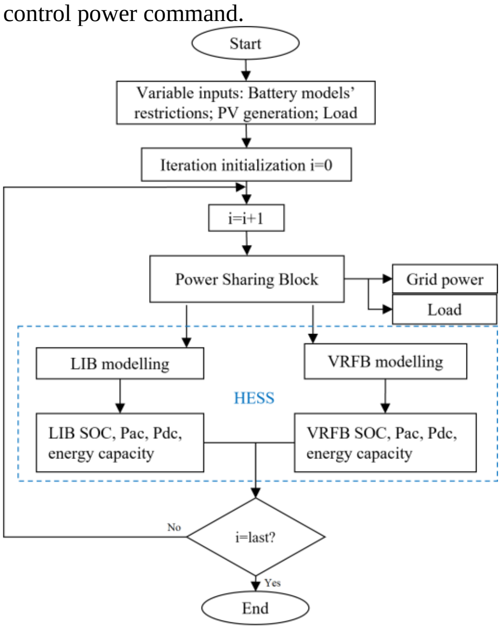
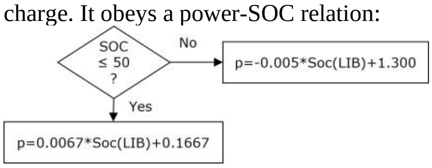


Figure 4: Modelling scheme of the hybrid energy storage system for the 3 scenarios.

The energy management strategy of self-consumption maximization is based on the HESS power allocation control. Different scenarios for the power allocation method are researched:

- **Scenario I** – The power-sharing is distributed with a fixed power ratio for each of the batteries. In this scenario, 75% of the total power is requested/retrieved from VRFB, and the rest is requested/retrieved from LIB.
- **Scenario II** – Scenario I with variable ratios. HESS is operated depending on the LIB state of charge. It obeys a power-SOC relation:



With p as the percentage. The remaining power is requested/retrieved from VRFB.

- **Scenario III** – Dynamic variability power command for LIB and fixed value for VRFB. It is the realization of two services for each battery (as if LIB executes a peak shaving strategy).

3.5. Key-Performance Indicators

The evaluation of the HESS power allocation control will be evaluated for a one-year time frame, using the key-performance indicators enunciated below.

- **Self-consumption ratio (SCR)** – Share of the PV generation consumed by the installation from the total of the PV energy generation.

$$SCR = \frac{E_{PVconsumed}}{E_{PVgenerated}} \tag{1}$$

- **Grid-relief factor (GRF)** – The grid relief factor offers a measure of the total grid use in the overall load consumption needs.

$$GRF = \frac{E_{Grid}}{E_{Load}} \tag{2}$$

- **Overall battery use (BU)** – Share of energy of the power battery command in the overall energy consumption

$$BU = \frac{E_{fromBattery} + E_{toBattery}}{E_{Load}} \tag{3}$$

The parameters are based on the sum of the energy used throughout the days of the strategy application. The indicators are calculated for the overall strategy output results, although the BU is calculated separately for each battery.

4 SIMULATION RESULTS

The initial state of charge is 50% for both batteries, and the simulation sample time is of 1 minute, over an entire year. The simulation tool allows for obtaining the energy fluxes that occur at each moment, which, in turn, allow for the calculation of the technical performance indicators, as the example of Figure 5, shown below.

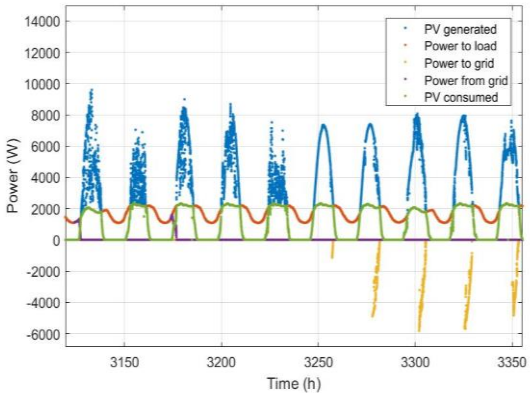


Figure 5: Output of the simulation tool, where the sum of the energy fluxes of the simulated year allows the calculation of the technical performance indicators.

The impact of the power-sharing in the studied scenarios is presented in Table III, where the calculated key-performance indicators results are shown.

Table III: Simulation results of power and energy exchange with the loads and utility grid using different power-sharing scenarios, a yearly basis.

Scenario	SCR	GRF	BU LIB	BU VRFB
I	0.53	0.35	0.55	0.67
II	0.53	0.27	0.63	0.64
III	0.53	0.36	0.54	0.64

The state of charge impact is shown in Figures 6 in (a), (b) and (c), and the AC power requested to the inverter (charge or discharge the battery) is shown in Figure 7, in (a), (b) and (c).

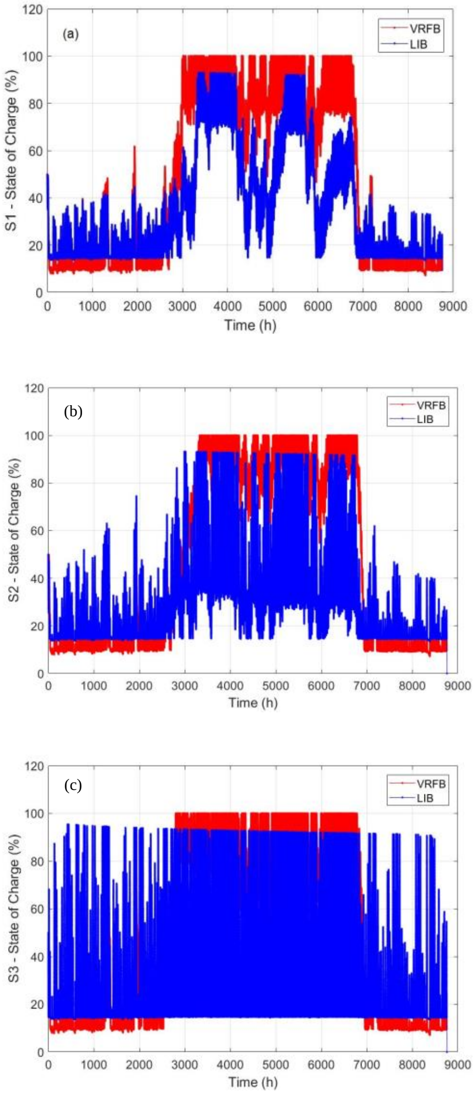


Figure 6: Output of the simulation tool: SOC evolution for both batteries for Strategy 1 (a), Strategy 2 (b) and Strategy 3 (c).

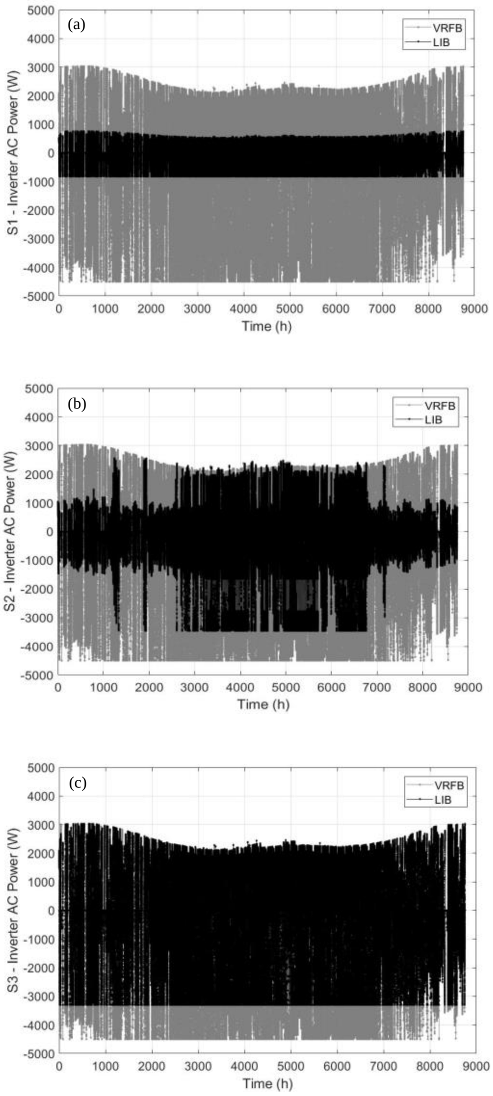


Figure 7: Output of the simulation tool: AC Power of the inverter of both batteries for Strategy 1 (a), Strategy 2 (b) and Strategy 3 (c).

5 CONCLUSIONS

A robust control can improve system dynamics, minimizing extreme SOC states and power levels, or peak temperatures caused by high C-rate operation. Scenario I is a rough approach as HESS power-sharing method. Scenario II improves the systems dynamic, by lowering extreme power SOC states. Scenario III offer the efficient realization of different tasks.

SCR is maintained in the three scenarios, the GRF is the smallest for Scenario II given the better batteries exploitation. VRFB executes the baseload in all the scenarios, shown by its BU indicator. The LIB BU indicator presents a higher use in Scenario 2 even though the LIB operation is controlled by the SOC-power profile. Summer-Winter differences are present regarding BU, and Scenario 3 presents a smaller LIB BU due to a smoothing of the grid power exchange operation.

Further conclusions should be drawn regarding a technical-economic analysis of this scenario comparison and considering battery ageing. Initial investment costs (CAPEX) should be considered for complete analysis as well as a seasonal results analysis. A robust cost analysis constitutes an important goal of future work.

ACKNOWLEDGEMENTS

The authors would like to thank the support of this work, developed under the European POCITYF project, financed by 2020 Horizon under grant agreement no. 864400. This work was also supported by the PhD. Scholarship (author Ana Foles) of FCT – Fundação para a Ciência e Tecnologia –, Portugal, with the reference SFRH/BD/147087/2019.

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