Implementation of PV Self-Consumption with Ramp-Rate Control Algorithm using a Day-to-Day Forecast battery charging, with a Vanadium Redox Flow Battery

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Nomenclature
API – Applications Programming Interface;
BAPV – Building Applied Photovoltaics;
BCR – Battery charge ratio;
BESS – Battery energy storage systems;
DSO – Distributor system operator;
EG – Energy from the grid;
EMS – Energy management strategy;
FBU - Overall from battery use;
FGU – Overall from grid use;
GRF – Grid relief factor;
MA – Moving average;
OBU – Overall battery use;
RR – Ramp rate (\%/min per nameplate capacity);
SCM – Self-consumption maximization;
SCM+RR - Self-consumption maximization with Ramp-rate control;
SCM+RR+WF - Self-consumption maximization with Ramp-rate control with weather forecast battery charging;
SCR – Self-consumption ratio;
SoC – State of charge (%);
SSR – Self-sufficiency ratio;
TBU - Overall to battery use;
TGU - Overall to grid use;
TSO – Transmission system operator;
VRE – Variable Renewable Energy;
VRFB – Vanadium Redox Flow Battery.
Abstract

The variability of solar resource by cloud passing can cause rapid power fluctuations on the output of photovoltaic systems. These fluctuations can negatively impact the electric grid, and smoothing techniques can be used as attempts to correct it. This work is focused on using a battery energy storage unit to manage – absorb or inject – the power output from the PV system, maintaining the ramp rate (RR) within a non-violation value, and an appropriate battery state of charge (SoC) for this RR management. For this purpose, the authors explore the vanadium redox flow battery (VRFB) technology for the experimental implementation of this strategy at real scale. A comparison among three energy management strategies (EMS) is carried out, namely a self-consumption maximization (SCM); SCM with a ramp-rate strategy (SCM+RR), and also this last strategy combined with night battery charging based on the day ahead weather forecast (SCM+RR+WF). The weather forecast allows a battery SoC management, preparing it for the next day power ramp rate control demands. These strategies are developed considering the physical and technical battery characteristics. Finally, the EMSs are evaluated and compared with the most suitable key performance indicators, including the self-consumption rate and the battery use, in one week.

Keywords: Photovoltaic solar energy; energy storage; self-consumption; ramp rate

1. Introduction

In the end of 2019, the global installed renewable capacity reached 2 537 GW, more 176 GW over the past year [1]. Wind and solar accounted for 90% of the global newly added capacity. In 2019 the solar PV had a representation in the world generation mix of 3%, with a 2050 forecast of 23% [2].

Limitations for variable renewable energy (VRE) are needed once there is a significant share of renewable energy [3]. The technical requirements relevant for the VRE integration are regulations which take into account limits for the electricity exchanged to the grid. The controlled electricity factors are the voltage and frequency operating ranges, power quality, reactive power capability for voltage control, frequency support, fault behaviour, active power gradient limitations, simulation models, active power management, communication and protection. Grid power injection ramps are a concern for the active power gradient limitations. These ramps are caused by fluctuating primary energy from the renewable generation. The increase of this VRE could be solved through the creation of a ramp limit. A ramp is a change in active power output over a defined period of time. Limit ramp values have been defined and imposed in the legislation of some countries around the world [3].

The ramps limitation contributes to a more balanced energy system management through the DSO, contributing for the systems increased efficiency. Countries with a significant number of solar photovoltaic (PV) installations have feed-in limitations of power injection into the grid. The ramps are generally classified using a minute timeframe, considering the PV power nameplate capacity.

The ENTSO-E (European Network of Transmission System Operators) requires that the ramp rate (RR) limit should be specified by regional TSO if necessary. General grid codes for PV integration are studied in [4]. Some of the detailed active power limitation regulations for VRE currently established are highlighted below for several countries:

- Germany - Since 2012, for PV generators under 30kW which cannot be remotely controlled, a feed-in limitation of 70% of the system’s peak power is needed. If the installed capacity is bigger than 1 MVA, the RR limit is 10% of the rated power per minute; for wind energy, if generators trip due to grid fault or frequency, the ramp rate is limited to go back online, to 10-20% of rated power per minute;
- Puerto Rico – In 2012, the Puerto Rico Electric Power Authority (PREPA) imposed a 10% nameplate capacity per minute as a ramp rate limitation of grid injection [5];
- Denmark – Wind power plants connected to high voltage grid (HV) have no constraints on active power gradients, but the generators must be able to constraint their ramp rate if demanded by grid operator [3]. Also, a maximum ramp-rate of 100 kW/s is required [6];
- Ireland – EirGrid Plc establishes that the wind farm power station must be able to control the ramp rate of its active power output over a range of 1-100% of its nominal capacity per minute. Wind turbines must be able to restrict ramping [3]. Also, it has a positive ramp-up limit of 30 MW per minute;
- Philippines – It is required to limit active power during over-frequency; large plants must be able to limit ramping;
- China – the National Standard for the maximum ramp range of PV power station requires it to be less than 10% of the installed capacity per minute [4].

Short-term power fluctuations are directly related to the PV plant area and its geographical dispersion, thus, the normally small area of a domestic/services photovoltaic installation become especially prone to have extreme PV power fluctuations [7].

The ramp rate limitation can be conducted through the operation of the PV system below its nominal capacity, through the deviation of the MPP [8], or through the use of a battery energy storage system (BESS) to absorb or inject the excess PV power when the ramp limit is violated [9]. The smoothing methods are mainly divided in two categories: filter methods and gradient methods. The study made in [6] presents the comparison of different ramp smoothing filter techniques, using a BESS. In this work the authors choose to focus on the moving average (MA) filter type, which is considered the most traditional filter technique, although it is also mentioned that it could lead to increased battery cycling.

This is also the motive why for the present study it was chosen to apply the MA filter to a Vanadium Redox Flow Battery (VRFB). This BESS technology, although being a battery with a moderate energy density, allows (if needed) a high number of cycles without significantly reducing its performance, capacity, or lifetime.

The application timeframe of the MA technique is a very important issue and must be carefully chosen. In [10] the author’s study is made considering a 15 minutes timeframe. In [6] the authors explore timeframes of 2.5, 5, 7.5 and 10 minutes, evaluating the number of fluctuations and its impact on the technique application. This study [10] shows that a shorter timeframe results in a higher number of controlled ramps successfully.

Taking into account this conclusion and the technical limits of the microgrid used for the experimental validation of the present study, it was chosen to use a period of 20s for the MA. Further details are presented in the next section.

Nowadays, PV for self-consumption is the most studied and applied strategy to operate a PV system with or without a battery (depending on the load consumption). In Portugal, mostly in the context of the legislation DL 169/2019 in force, and, because of that, it is one of the starting points of this work. Previous studies regarding this topic, and including the usage of a BESS, include the study in [11], with a real time implementation on a VRFB of the University of Évora (UEvora), exploring the real time operation conditions of this battery, implementing successfully a PV self-consumption maximization; and the study in [12] where not only the PV self-consumption is studied, but also the way of making PV generation forecast, in order to improve the battery system operation. Also, this study [12] used the Germany specific grid feed-in limitations to relieve the grid from the VER.

In this work, Section 2 will present the methodology, including previous solar PV data analysis (2.1), an overview of the used Energy Management Strategies (EMS) (2.2), the description of the used data (2.3), a brief summary about the battery model (2.4), the weather forecast data process (2.5), data analysis and timeframe selection for the MA (2.6), the definition of ramp rate and MA functions (2.7) and, finally, in 2.8, the selected Key Performance Indicators (KPI) are introduced, in order to assess the results of this study.

In Section 3, the simulation and the implementation details are presented, focusing on the simulation of the studied EMSs, and on the implementation for validation in the real microgrid, consisting of a PV system and a VRFB, its programming and control. Section 4 presents the results regarding the simulations, the KPIs and the battery SoC, followed by its discussion. The conclusions for this work are presented in Section 5.
2. Methodology

2.1. A variability analysis of the solar PV data of the UÉvora

The ramp rate control is a measure which should not be observed through a quantitative-only analysis, since its negative impact is related with matters like the extension of household appliances lifetime, and to contribute to the grid stability, helping the DSOs and TSOs. As an example, a calculation was made for the ramp rate, in an interval of one minute, for the nameplate capacity of one of the UÉvora Building Attached PV (BAPV) systems, for one year of PV monitored data, shown in Figure 1.

Figure 1 - Rooftop photovoltaic system with 6740 W installed power, in one of the University of Évora’s microgrids

The nominal power of the PV system is 6740 W, and its monitoring data was collected with an in-house developed software in LabVIEW environment, with a timeframe of 2 seconds, collecting data from a precision power analyser (Circutor CVM-1D [13]) and the PV inverter. The data was compiled in samples of one minute, and the ramp rates were calculated for the entire year of 2018. The RR results summary is shown in Table 1.

| Ramp rates (%/min) in the year of 2018 | Percentage of total RR in one year (%) |
|----------------------------------------|---------------------------------------|
| < 5 %/min                              | 78.47                                 |
| ≥ 5 %/min                              | 8.090                                 |
| ≥ 10 %/min                             | 5.161                                 |
| > 10 %/min                             | 4.833                                 |
| ≥ 50 %/min                             | 0.650                                 |

It can be observed that almost 79% of the ramp rates are low (below 5%/min), which is an expected result and will probably have low or no impact on the grid. The values of 5% and 10% were used as references, being 10% the most frequent current limit in the grid codes which apply to this type of ramp rate limitation. In 2018, RR higher or equal to 10 %/min of the installation’s nameplate capacity, occurred in 5% of ramps, giving, in this situation, a quantitative reference of the number of ramps to be controlled.

It should be noted that, in order to increase the degree of confidence of these results, this analysis requires a substantially longer data period, ideally several years. The existence of systems with monitoring of long-term PV production data with high frequency (e.g. datalogging at 2s) is rare and should be an effort to be implemented in the future of experimental installations.

Similar to the analysis of solar radiation meteorological data, and due to the direct relationship between this solar radiation data and the occurrence of power ramps, the results in the previous table are only representative for the location and specifications (tilt, azimuth, etc.) of this photovoltaic system.
2.2. PV+battery energy management strategies

In this section, three energy management strategies are presented. These EMS are explored in this work.

The self-consumption maximization (SCM – strategy 1) is a very simple strategy which is applied to maximize the usage of the PV generation throughout the day, made available by a PV system. The user installation can benefit from a battery to increase this PV generation utilization. This strategy is usually the most applied overall, in the industry and in residential solutions, due to its simple application and improved match with the consumption demands.

The second strategy is the self-consumption maximization with a ramp-rate control (SCM+RR – strategy 2). As previously explained, the continuous increase of PV system installations worldwide will have impacts on the grid management, due to its intermittency and variability characteristics, probably requiring for ramp-rate limitations. Applying these ramp limitations (either for up or down ramps), will strengthen the SC maximization strategy. In this case, the self-consumption is carried out by the PV system with the help of the battery, although when the ramp is violated, the battery unit is used primarily to control the ramp. In this strategy, the ramp is calculated as a percentage per minute over the nominal PV power. When a violation of this value occurs (when the RR achieve its limit), and the battery presents suitable capacity (SoC) and power to deal with it, the RR algorithm is activated: the battery absorbs the surplus PV power/energy, or injects the power lacking due to a ramp-down fluctuation. When there is no violation of the ramp limit, the PV self-consumption maximization strategy is used. In this strategy, a SoC control is not carried out. This decision was made in order to evaluate the extent of the impact of not having a SoC control.

The third strategy studied in this work is a Self-consumption maximization with Ramp-rate control and a battery charging based on a weather forecast (SCM+RR+BCF – strategy 3). One of the most important factors in the ability to use a ramp rate algorithm with a battery is the battery SoC when needed.

In this sense, ramp control is a concurrent objective with the maximization of self-consumption for the use of the battery. In the average load curve characteristic of a domestic or services installation, a peak consumption at the end of the day often occurs after sunset or at night. Supplying this night-time consumption, in order to maximize photovoltaic self-consumption, has the consequence that the battery SoC can reach the next morning close to its minimum limit.

Similarly, a summer day with high solar radiation and a clean sky, and/or low consumption power in the user installation, can charge the battery up to the upper limit of SoC.

Due to the Power-SoC characteristics of the BESS technologies (e.g. lithium-ion, vanadium redox flow, sodium-nickel chloride, etc.), the available power to charge/discharge is severely constrained near the upper and lower SoC limits, respectively. These available power technical restrictions prevent the full control of power ramps.

In the last strategy, a SoC control is implemented, with a battery charging-discharging command target conditioned to the weather forecast for the next 12h for the site. The meteorological forecast categories that best could indicate the probability of the occurrence of ramps were selected. More details about this method are presented in section 2.5.

This control technique allows that, if the weather forecast indicates, the battery will start the next day with its SoC close to 50%, range where it presents its maximum power available for charging or discharging, and thus, controlling the occurrence of extreme ramps.

2.3. Sampled data – PV and loads

The PV profile corresponds to the real data obtained with the UÉvora’s PV system (Figure 1), during one week from 1st to the 7th day of January of 2018, with 2 second intervals data logging. The load curve used (consumption profile) is made available by EDP Distribuição – Portuguese DSO company – with 15 minutes average load consumption data for the year of 2018 [14]. This data was previously treated, with the help of the MATLAB software, in the way of corresponding to the PV data sampled timeframe. The used data can be seen below, in Figure 2, where a)
presents the collected data, PV and consumption profiles, for the first seven days of January of 2018, and b) for a single day of January, the 1\textsuperscript{st}.

2.4. VRFB modelling

The VRFB (60/5 kWh/kW) is integrated in a microgrid, presented in Figure 3, which is currently exclusively devoted for its testing and systems operation study, and integration with the building at a real scale. This microgrid is equipped with a PV system with 3.5 kWp of polycrystalline technology, and 3.2 kWp of monocrystalline technology, precision monitoring equipment and a control system.
The VRFB is physically constituted by two tanks of electrolyte, two pumps which allow the electrolyte flowing, and a stack: the energy conversion unit. The stack is a dynamic system, and its performance depends on multiple effects: electrochemical, fluid dynamics, electric and thermal. Different oxidation states of dissolved vanadium ions in the electrolyte ($V^{2+}$, $V^{3+}$, $V^{4+}$, $V^{5+}$) store or deliver electric energy through a reversible chemical reaction.

This VRFB was the object of study in previous works, and the most recent include the battery full electrical modelling, developed and validated on a real scale, considering its general operating conditions. This model is fully detailed in the research conducted in [15]. In Figure 4 it is shown the VRFB's stack voltage comparison among the operation data and the modelling simulation results, carried out in MATLAB software.

Considering the small relative error of this model when calculating the battery SoC and taking into account the availability of power (charge/discharge), a battery operating range between 20% and 70% of its SoC was selected. The presented VRFB model [15] was implemented in the control algorithm and energy management strategies. This consideration not only helps the
implementation of the controls in real time, but also helps the use of this model with the smallest possible error.

2.5. Battery charging with weather forecast

In strategy 3 SCM+RR+BCF, the battery will be charged to values near the 50\% SoC when needed, with data input from weather forecast (ramp-rate occurrence), using data forecast produced by IPMA (Instituto Português do Mar e da Atmosfera).

IPMA is a Portuguese public body, which is responsible for, among other many tasks, forecast the states of the weather and sea for all necessary needs. The forecast data associated with the geographical sites, and seismic events location, in the JSON format, are made available in their API (application programming interface) [16]. The data is obtained automatically through a forecast statistic process with forecasts of two numerical models – ECMWF [17] and AROME [18]. These forecasts are updated two times per day, at 00 UTC (available at 10am) and 12 UTC (available at 8pm). In summertime, the Portuguese legal hour is UTC+1, and in winter is equal to UTC.

In this API it can be found online daily meteorological data forecast up to 5 consecutive days by region, and daily meteorological data forecast up to 3 consecutive days with aggregated information per day. Each Portuguese region has a global code id, which identifies it. Every twelve hours the forecast information is updated in the website, for each region. IPMA forecasts roughly 41 regions, both onshore and offshore. The website makes available the following daily weather indicators: precipitation probability (no precipitation, weak, moderate or strong), minimum and maximum temperatures in °C, wind direction (N, NE, E, SE, S, SW, W, NW), id weather type (0 to 27 weather description states), wind speed class (weak, moderate, strong, very strong). In this work we choose to give relevance to the id weather type, for which a number is attributed, corresponding to a weather description, which can be observed in Table 2.

| Number | Correspondence          | Number | Correspondence            |
|--------|-------------------------|--------|---------------------------|
| ---    | -99                     | 14     | Intermittent heavy rain   |
| 0      | No information          | 15     | Drizzle                   |
| 1      | Clear sky               | 16     | Mist                      |
| 2      | Partly cloudy           | 17     | Fog                       |
| 3      | Sunny intervals         | 18     | Snow                      |
| 4      | Cloudy                  | 19     | Thunderstorms             |
| 5      | Cloudy (High cloud)     | 20     | Showers and thunderstorms |
| 6      | Showers                 | 21     | Hail                      |
| 7      | Light showers           | 22     | Frost                     |
| 8      | Heavy showers           | 23     | Rain and thunderstorms    |
| 9      | Rain                    | 24     | Convective clouds         |
| 10     | Light rain              | 25     | Partly cloudy             |
| 11     | Heavy rain              | 26     | Fog                       |
| 12     | Intermittent rain       | 27     | Cloudy                    |
| 13     | Intermittent ligth rain |        |                           |
In this work, the selected relevant information periodically obtained is the latest information per region, regarding the weather forecast for the following day. With the help of this information, the battery SoC is prepared for the next day, as needed. The preparation is made through battery charging during the night hours (in general there is very low energy consumption from domestic users during those hours), and for that reason, this control type is optimal for the Portuguese bi-hourly and tri-hourly household tariffs, with lower electricity price during the night [19]. Every day at 1:30 am, the algorithm consults the IPMA API looking for the “idWeatherType” number correspondence, in order to know if it should act on the power command of the battery. The command will be a charging only command, since it is expected that the battery at the end of the day, to be near its lowest SoC (limit), given the load curve profiles used. If none of the conditions is satisfied (near lowest limit SoC, or “bad” weather day), the SoC of the VRFB will be only dependent of the self-consumption objective.

2.6. Time frame

The moving averaging timeframe is an aspect that should be sensibly weighted. The study developed in [20] researches carefully the PV time averages impacts on the small and medium-sized PV installations. The authors conclude that a timeframe of 15-minute averages describes these ramps poorly. Because of this concern, an adequate time frame to apply in this work evaluation was considered. For the one week of PV data considered in this study, the theoretical controlled ramps were calculated, using the 10%/min RR, with average of different time periods of PV intervals. The obtained values are presented in Table 3.

| Time frame       | Controlled ramps in the chosen week (RR ≥ 10%/min) |
|------------------|----------------------------------------------------|
| 2 s (without averaging) | 5716                                               |
| 10 s             | 5751                                               |
| 20 s             | 5660                                               |
| 30 s             | 5570                                               |
| 60 s (1 min)     | 5039                                               |
| 300 s (5 min)    | 364                                                |
| 600 s (10 min)   | 0                                                  |
| 900 s (15 min)   | 0                                                  |

The corresponding PV averaging to these timeframes can be observed in Figure 5, presented below.
Figure 5 – PV average of the timeframes studied and presented in Table 3. The 2s corresponds to the raw data extracted from the PV installation in study. Remaining timeframes are the PV averaging correspondent to each of that timeframe.

The results obtained support the study previously referred, for the domestic PV installations. The main conclusion is that as the average timeframe increases, the less ramps are detected and controlled. Alternatively, if the average timeframe is too small, the impact will be short. In any way, a careful sensitivity analysis of this parameter must be carried out. The simple moving average, being simple to implement and with low computational effort, can let through unexpected artefacts such as peaks in the results.

In accordance, the timeframe of 20 seconds was chosen. This PV averaging timeframe can be observed in Figure 6, from the 12:00h to the 14:00h (to be appropriately visible) of the 1st of January of 2018.

Figure 6 – (a) PV average with a timeframe of 20 seconds, and (b) correspondent Ramp-rate calculus; for the first day of January of 2018, obtained through the 2 s measurement data of the PV system of 6740 W (UÉvora).
2.7. Ramp calculus with MA technique

In general, the classic way of representing the ramp rate is defined as $RR_{\text{classic}}$, as presented in Eq. (1),

$$
RR = \frac{P_{PV}(t) - P_{PV}(t - \Delta t_R)}{P_N \Delta t_R} \times 100
$$

(1)

Where,

$RR$ – Ramp rate (%);
$P_{PV}$ – PV power (W);
$t - \Delta t_R$ – Time differential of the ramp rate, typically equal to the unit (min).

The MA was the method used in this study as the power smoothing technique, for the reasons previously referred. In this way, at each iteration, the RR calculated is defined as $RR_{MA}$. In this way, the difference is that the variable $P_{PV}(t - \Delta t_R)$ is the average of the PV power defined in the desired interval, in our case, for the previous 20 seconds. This method functions with the averaging of the previous PV measurements, in a chosen period, t, and the battery command is easily calculated from Eq. (2) below,

$$
P_{\text{battery}}(t) = \sum_{i=0}^{w-1} \frac{P_{PV}(t - i) \cdot w}{w} - P_{PV}(t)
$$

(2)

For more details regarding the ramp rates calculations, the work made by the authors of [6] may be consulted, where this is presented in detail.

2.8. Key-performance indicators

To properly evaluate the application of the strategies studied, a calculation is done of suited key-performance strategies indicators. All the parameters are based in the sum of the energy consumed/used in the 7 days of the strategy implementation. Its explanation is detailed in the following Table 4.

| KPI                  | Definition                                                                 | Formula                                                                 | Variables description |
|----------------------|---------------------------------------------------------------------------|------------------------------------------------------------------------|-----------------------|
| SCR - Self-consumption ratio | Share of the PV consumed by the installation of the total PV energy generated. The PV produced energy is consumed directly in all the studied strategies, and indirectly by the battery in the first strategy (including its losses). | $SCR = \frac{E_{PV \text{consumed}}}{E_{PV \text{generated}}}$ | $E_{PV \text{consumed}}$ - PV energy generation consumed directly or indirectly $E_{PV \text{generated}}$ - Total PV energy generated by the PV system |
| SSR - Self-sufficiency ratio | Share of the consumed PV energy generation in the total load consumption needs | $SSR = \frac{E_{PV \text{consumed}}}{E_{Load}} = \frac{E_{Load} - E_{Grid}}{E_{Load}}$ | $E_{Load}$ - Total load consumption needs $E_{Grid}$ - Energy injected and extracted from the grid |
| GRF - Grid-relief factor | Measure of the total energy of the installation consumption which is not exchanged with the grid. | $GRF = \frac{E_{Load} - E_{Grid}}{E_{Load}}$ | - |
| OBU - Overall battery use | Amount of energy used to charge and discharge the battery unit, over the overall installation consumption needs | \[ \frac{E_{\text{charge}} + E_{\text{discharge}}}{E_{\text{Load}}} \] |
|--------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|
| BCR - Battery charge ratio | Total energy used to charge the battery, over the overall energy sent and received to/by the battery. | \[ \frac{E_{\text{charge}}}{E_{\text{battery}}} \] |
| EG - Energy from the grid | Amount of energy extracted from the grid, considering the total energy exchanged with the grid | \[ \frac{E_{\text{fromGrid}}}{E_{\text{Grid}}} \] |
| FGU - Overall from grid use | Amount of energy extracted from the grid in the overall installation consumption needs | \[ \frac{E_{\text{fromGrid}}}{E_{\text{Load}}} \] |
| TGU - Overall to grid use | Amount of energy injected into the grid in the overall installation consumption needs | \[ \frac{E_{\text{toGrid}}}{E_{\text{Load}}} \] |
| FBU - Overall from battery use | Amount of energy extracted from the battery in the overall installation consumption needs | \[ \frac{E_{\text{fromBattery}}}{E_{\text{Load}}} \] |
| TBU - Overall to battery use | Amount of energy sent to the battery in the overall installation consumption needs | \[ \frac{E_{\text{toBattery}}}{E_{\text{Load}}} \] |
| Number of Controlled Ramps Rate (NCRR) | Rate of the number of the ramps up and downs controlled with the use of the battery in the current strategy, and the number of ramps up and down without any strategy | \[ \frac{N_{\text{ramps}}}{N_{\text{original}}} \] |

For the reader to be fully engaged with the key-performance indicators presented, the best-case scenario for the prosumer is shared, i.e., the best case from the point of view of the self-consumption user/installation owner. This reference value can help the reader to understand how close or distant a strategy is from its ideal (best-case) scenario. It should be considered that the best-case for one indicator could imply the worst case of another. The week chosen in this study can also have influence in some of the KPIs. The KPIs best case scenarios are shown in Table 5.

**Table 5 - Best case-scenarios of the KPIs, considering the SCM strategy.**

| KPI                  | Ideal best value | Direct meaning, from the point of view of the prosumer     |
|----------------------|------------------|------------------------------------------------------------|
| SCR - Self-consumption ratio | 1                | Amount of PV energy produced which meets with the one consumed. |
| SSR - Self-sufficiency ratio | 1              | How much PV energy is consumed in the overall consumption demand. |
| GRF - Grid relief factor | 1 | How independent from the grid is the user (if equal to 1, there is no energy going into the grid). |
|-------------------------|---|--------------------------------------------------------------------------------------------------|
| OBU - Overall battery use | Battery-PV profiles dependent. For this case, in the SCM point of view is 31% | How much energy is exchanged with the battery (Charge/Discharge) in the overall consumption (considering the PV generation, and the studied week of January). |
| BCR - Battery charge ratio | Equal to 0.5, with a battery efficiency of 1 | How much energy is used to charge the battery |
| EG - Energy from the grid | 1 (should be weighted) | Offers a quantification of the amount of energy that is coming from the grid or going to the grid. |
| FGU - Overall from grid use | 0 | Equal to 1 means that all the overall consumed energy comes from the grid. |
| TGU - Overall to grid use | 0 | Equal to 1 means that the energy injected to the grid is equal to the energy consumption. |
| FBU - Overall from battery use | 1 | Equal to 1 means that all the consumed energy comes from the battery. |
| TBU - Overall to battery use | 0 | Equal to 1 means that all the energy sent to the battery (charge) is equal to the consumption energy needs. |
| NCRR -Number of Controlled Ramps Rate | 1 | All ramps that violate the RR reference are controlled. |

3. Simulation and Experimental validation in the VRFB

In this section, the real time operation of the SCM+RR+WF (strategy 3) and experimental validation details are presented.

As previously referred, the study made in [11], validated the SCM (strategy 1) using the same experimental setup and battery. The strategy number 2 is a simplification of the strategy number 3. Being the SCM+RR+WF (strategy 3) the most complex strategy, when compared to strategy 1 and strategy 2, it was decided to implement the SCM+RR+WF and validate it at full scale and real operating conditions in the experimental microgrid of the VRFB.

All strategies (SCM, SCM+RR and SCM+RR+WF) were simulated in MATLAB environment, with the same input data (loads, PV power and battery model), to obtain KPI results and to be compared with the experimental validation results of the SCM+RR+WF strategy.

In previous studies the VRFB was entirely characterized and the optimal conditions were defined [15]. The chosen SoC operating range was from 20% to 70%, given the operational available power of charge and discharge. Its energy capacity is 60 kWh, which means it is operating with 30 kWh of useful capacity (for the chosen SoC range). The maximum power of charge/discharge is 5000 W, the VRFB nominal power, available throughout all the SoC chosen range. In the battery room, a controlled ambient temperature of 25°C is maintained. In all the validation tests the VRFB started with a SoC of 50%, and all strategies are tested in a frame of one week, with datalogging period of 2 seconds. The inverters energy consumption, in stand-by mode, of 30 W is also considered in the modelling. The SoC of the battery is calculated through the manufacturer’s curve, as shown in the work developed in [11].

The first strategy is a PV self-consumption maximization with the help of the battery. The PV generated energy, which is sent to the battery for later consumption, has losses accounted for inverters losses and battery efficiency. In the second strategy, the self-consumption is carried out for the PV power with the help of the battery, and the battery will perform the ramp control when a RR limit is violated. The ramp is calculated for each minute. In the third strategy, the main difference from the previous one is that the battery will charge at night (only interesting for bihourly and trihourly tariffs), to reach 50% SoC, up to a maximum charging duration during the night (i.e. a limit of maximum charging hours at night is imposed). This night charging will only happen when the next day forecast indicates a cloudy day, considering the map developed in Table 2, and thus with higher probability of occurrence of PV power ramps violating the RR limit. The flowchart of this algorithm part (part I) is presented in Figure 7. The RR algorithm is activated when its real-time calculated result is equal or larger than the 10 %/min RR value. The algorithm of
SCM+RR+WF (strategy 3), when the RR limit is not violated is shown in Figure 8. In Figure 9 the algorithm performing RR control (when the RR limit is violated) is presented. Thus, the three flowcharts presented below constitute the global algorithm for SCM+RR+WF.

Figure 7 – Algorithm Flowchart of the weather forecast with the IPMA API and SoC control, implemented in LabVIEW environment.

Figure legend:
Time_target – Initial hour for the beginning of the night charge (h);
SCM or RRC – Self-consumption maximization or Ramp-rate control;
SoCt – State of charge target (%), set as 50%, in the above flowchart example;
Pcomm – Power command value sent/received to/from the battery (W);
P_charge – Battery charge power in nightly hours, generally a constant value (W).

Figure 8 – Flowchart of Self-consumption maximization algorithm, using a battery.
Figure legend:
PVaverg – Average of the PV values (W);
PVcurr – Current iteration PV value (W);
Ppv – PV power;
Pload – Power of the consumption load (W);
SoCmin – Minimum SoC limit (%);
SoCmax – Maximum SoC limit (%);
Pmin – Minimum power limit (W);
Pmax – Maximum power limit (W);
Pn – PV installation nameplate capacity (W);
Ecacity – Nominal energy capacity of the ESS (Wh);
P_charge – Battery charge power (W);
P_discharge - Battery discharge power (W).

Figure 9 - Ramp-rate control algorithm flowchart.

The algorithm was then programmed in LabVIEW environment and implemented, successfully achieving a control cycle time of 2 seconds. The designed LabVIEW user interface is shown below, in Figure 10.
4. Results

This section is devoted to the presentation of the main results of the simulations and the experimental validation.

4.1. Simulation and experimental implementation – SoC results

The three strategies were programmed and simulated in a MATLAB environment. Given its importance, the SoC evolution of the battery was compared for each one, which is shown in Figure 11.

Figure 11 – Simulation of the battery SoC for the three strategies over the same week.
Regarding the strategy of SCM+RR+WF, the battery SoC evolution in the MATLAB simulation was also compared with the experimental validation. For the chosen week (1-7 January 2018), the IPMA API weather forecast was consulted for the next day forecasts, resulting in an active SoC control (night battery charge) in the day 2, 3, 4 and 5. In the days 1, 6 and 7, due to the weather forecast, the active SoC control was not activated.

The night battery charging power setpoint was defined to 2700 W, with a battery SoC target of 50%.

In Figure 12 the evolution of Soc is shown, comparing the simulation results and the experimental results for the strategy of SCM+RR+WF.

![Figure 12 – SoC evolution over the week: SCM+RR+WF simulation vs real-time implementation results.](image)

4.2. Key-performance indicators

For each of the strategies studied, the key-performance indicators were calculated, and the results can be observed in Table 6, presented below.

| Strategy / Indicators | 1 SCM | 2 SCM+RR | 3 SCM+RR+WF |
|-----------------------|-------|----------|-------------|
| SCR                   | 58.6  | 58.7     | 59.2        |
| SSR                   | 21.8  | 22.9     | 21.8        |
| GRF                   | 57.9  | 63.3     | 60.8        |
| OBU                   | 31.1  | 26.4     | 49.2        |
| BCR                   | 38.7  | 37.4     | 40.9        |
| EG                    | 98.8  | 95.2     | 94.9        |
| FGU                   | 57.2  | 60.2     | 57.7        |
| TGU                   | 0.71  | 3.06     | 3.09        |
| FBU                   | 13.2  | 10.8     | 22.2        |
Table legend:
SCR - Self-consumption ratio
SSR - Self-sufficiency ratio
GRF - Grid-relief factor
OBU - Overall battery use
BCR - Battery charge ratio
EG - Energy from the grid
FGU - Overall from grid use
TGU - Overall to grid use
FBU - Overall from battery use
TBU - Overall to battery use
NCRR - Number of Controlled Ramps Rate

In order to improve the readability of these indicators for each of the strategies, their graphical representation is also presented in Figure 13, compared to the best-case for each KPI.

![Figure 13 - KPIs representation for each of the strategies studied.](image)

4.3. Discussion

The analysis made concerns one week in the Portuguese winter season, a season usually characterized by many daily fluctuations in the PV power production and being the time of the year with the lowest average daily global solar radiation. Figure 2 depicts the PV power production over the studied period, showing days with high variability in the photovoltaic power production (with the exception of the day 6 and the afternoon of the day 7), posing a challenging scenario with regard to power ramps.

Figure 11 presents the simulation SoC results of the three strategies. It can be seen the night battery charging (SCM+RR+WF) on some days and that the battery SoC never exceeds 50% for any strategy throughout the week. This is due to the seasonality of the photovoltaic production, being this week in winter. The difference between the SCM and SCM+RR strategies is smaller, which points to a low energy consumption of the system in tasks of Ramp Rate Control. This fact can also be seen through the TGU indicator (or EG), where there is a small growth from the simplest to the most complex strategy, pointing a small increase in the energy injected into the grid, for controlling power ramp rates.

Regarding the SoC results presented in Figure 12, the simulation presents low error (absolute average of 3.5 % over the period of study) when compared with the experimental validation. This fact points to a model with good representation of the battery and with the ability to simulate the VRFB behaviour with the necessary precision. Additional improvement on it will be carried out in order to further reduce the existing error.

From the KPI results, it can be concluded that, for all the strategies, the Self-Consumption Ratio (SCR) is very similar. For the week under study, the SCR value is far from its theoretical maximum due to a production of photovoltaic energy greater than the global consumption, a relationship that will vary throughout the year with the variation in the availability of solar radiation and the loads profile curve.

The system energy (PV or battery) used for ramp control tasks is rather low, when compared with the loads consumption, so the implementation of this objective does not greatly penalize the self-consumption ratio (SCR).

Given the profiles of consumption studied and the PV generation, the GRF is marginally higher for the strategy 2 (SCM+RR). This KPI is related to the energy which is extracted from the grid and the energy of load consumption. The fact that the battery charges at night could justify thinking that the energy extracted from the grid is the highest. Although, using strategy 1 (SCM), for this week period, induction a lower energy consumption from the grid, in comparison with strategy 2, since the PV production is low during the middle days of the week.

EG accounts for the energy extracted from the grid, in the overall grid energy exchange. Once again, the pre-conception of definitions could foster misleading results. However, with the profiles used to test these strategies, the strategy with higher EG, in the overall grid use is Strategy 1 (SCM), mainly due to a lower weekly total of energy exchanged with the grid.

Finally, regarding the KPI for the number of controlled ramps (NCRR), comparing the results for the 3 strategies, it is shown that the SCM+RR+WF strategy, with the implementation of SoC control dependent on the weather forecast (and, indirectly, the potential occurrence of extreme power ramps) can successfully control all power ramps, imposing an RR limit of 10%/min. Otherwise, implementing a simple RR control strategy could only control about 86% of the total power ramps occurring in the test period.

The objective of this work was not to evaluate economic KPIs, but its importance is recognized. However, it was intended to minimize the cost of charging the battery (to control SoC, when needed) overnight using the cheapest electricity tariffs (for the bi-hourly or tri-hourly tariffs).

For the purpose of ramp control, the implementation of a Soc control algorithm also causes an increase in the battery utilization rate, as expected, which can be seen in the increase in the indicators TBU and FBUB. In the case of this battery technology, this additional usage will not reduce its lifetime or increase its degradation, which happens, for example, in lithium-ion battery technology.
5. Conclusion

In this work, a residential/services system was studied, considering a PV installation, an electricity storage unit – a VRFB –, and a load profile over one week of winter, with data from January 2018. Three energy management strategies were evaluated, with the aim of obtain a result improvement of the main KPIs related to the self-consumption maximization and power ramp rate control.

Strategy 1, SCM, perform only simple self-consumption maximization of the PV power production; strategy 2, SCM+RR, additionally performed a ramp rate control, trying to impose a 10%/min of the PV nameplate capacity ramp rate limit, providing stability to the grid interaction. Strategy 3, SCM+RR+WF, add a weather forecast (IPMA API) for the next day, in order to implement a SoC control, able to prepare the battery to better deal with the next day power ramps.

Based on local data for the year 2018, it is shown that about 5% of the photovoltaic power ramps that occurred are above the rate of 10%/min of the PV nameplate capacity. However, to improve the confidence of this ramp rate occurrence distribution, it is necessary to collect data from a larger period, in a similar way to a typical meteorological year.

Based on the obtained results, it can be concluded that the strategy of SCM+RR+WF presents a good approach in order to perform a SoC control to accommodate the next day ramp-rates. The night battery charging presented a simple solution to follow in the winter season, conditioned to SoC at the end of the day, and it should be noted that for summer, probably, the opposite should take place – a nightly discharge.

The strategy 2 (SCM+RR) proven to be insufficient to control all power ramps violating the RR defined limit.

Despite the challenging scenario of occurrence of power ramps in the selected week, the SCM+RR+WF strategy demonstrated to be able to control 100% of the ramps with rates above 10%/min, without significantly reducing the photovoltaic self-consumption rate, successfully achieving the proposed objective.

The development of multi-objective management strategies, often with competing goals such as the SCM+RR+WF, present different system needs for power, energy, usage cycles or response time, can thus probably benefit from the use of hybrid battery systems, combining the strengths of different technologies, which presents itself as a path for future research work.

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