**UNIVERSIDAD POLITÉCNICA DE
MADRID**

**ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA
Y SISTEMAS DE TELECOMUNICACIÓN**

**STORAGE SIZE FOR PV POWER RAMP
RATE CONTROL**

PhD THESIS

Aitor Makibar Puente

**Ingeniero en Organización Industrial
Master en Ingeniería de la Energía**

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A mis padres.

“El hombre rinde el máximo de su capacidad cuando adquiere la plena conciencia de sus circunstancias. Por ellas comunica con el universo.”

“¡La circunstancia! ¡Circum-stantia! ¡Las cosas mudas que están en nuestro próximo derredor! Muy cerca, muy cerca de nosotros levantan sus tácitas fisonomías con un gesto de humildad y de anhelo, como menesterosas de que aceptemos su ofrenda y a la par avergonzadas por la simplicidad aparente de su donativo. Y marchamos entre ellas ciegos para ellas, fija la mirada en remotas empresas, proyectados hacia la conquista de lejanas ciudades esquemáticas.”

José Ortega y Gasset

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Abstract

During the next years, a large share of PV power is expected to be integrated in worldwide electricity grids by virtue of the increase of its competitiveness against conventional energy sources earlier than expected. In order to achieve a large-scale integration of PV, grid-stability and power quality problems must be avoided, whereas the role of PV power in the grid must be shifted to becoming an active agent. In particular, short-term PV power fluctuations caused by clouds are raising the attention of operators of grids with high renewable energy penetration rates, leading them to impose ramp rate limitations. Such fluctuations are mitigated coupling modern energy storage systems such as batteries, but these devices still have a high cost and their use may hinder the feasibility of PV projects. In this context, the success of a project lies in the correct sizing of the battery and in creating advanced strategies and techniques to minimise the storage requirements.

This thesis addresses the sizing of energy storage systems used for mitigating short-term power fluctuations of PV plants to comply with a prescribed ramp rate limitation. The study is based on the fact that strong fluctuations scarcely occur, so battery power and capacity requirements must be minimised according to a trade-off between an adequate grade of compliance and a practical battery size. It analyses the effects of reducing the size of a battery designed to absorb every fluctuation by taking into consideration, both, the fluctuation occurrence and the penalties in case of non-compliance of the ramp-rate limitation.

A deep analysis assesses the relation between size reduction and ramp rate compliance, obtaining as result a model for predicting the probability of non-compliances with a reduced battery. Additionally, the size reduction analysis is applied to the particular grid code currently proposed for Puerto Rico, implementing three alternatives. The potential for reducing the size without falling into penalties is high, but it increases if part of the fluctuations can be absorbed by limiting PV inverters during upwards fluctuations. Therefore, an advanced control strategy has been created to team up PV inverter limitations with a reduced battery in order to improve the ramp rate compliance of the plant. Besides, PV array oversizing technique is studied as an alternative to mitigate part of the fluctuations. The results show that for the same storage size, a proper combination of these solutions increases the yearly PV production, creating new tools for selecting a battery with reduced power and energy capacity.

Finally, the reduced size battery control strategy is implemented and validated in a laboratory, addressing the accuracy and control response required for implementing the method in a utility-scale PV plant.

Resumen

Durante los próximos años, se espera integrar una gran cuota de energía fotovoltaica (FV) en redes eléctricas de todo el mundo, gracias al incremento de su competitividad frente a fuentes de energía convencionales. Para alcanzar una integración de FV a gran escala, los problemas de estabilidad y calidad de suministro deben evitarse y su papel en la red tiene que evolucionar hasta convertirse en un agente activo. En concreto, las fluctuaciones de potencia FV causadas por nubes están llamando la atención de operadores de redes con alta tasa de penetración de energías renovables, llevándoles a imponer limitaciones de rampas de potencia. Dichas fluctuaciones se mitigan acoplando sistemas de almacenamiento de energía como baterías, pero todavía tienen un alto coste y su uso puede entorpecer la viabilidad de proyectos FV. En este contexto, el éxito de un proyecto radica en un correcto dimensionado de la batería y en la creación de estrategias y técnicas avanzadas para minimizar los requisitos de almacenamiento.

Esta tesis aborda el dimensionado de sistemas de almacenamiento de energía aplicados a mitigar fluctuaciones de potencia de centrales FV para cumplir con una limitación de rampa prescrita. El estudio se basa en el hecho de que las fluctuaciones críticas apenas ocurren, por lo que los requisitos de potencia y capacidad de batería deben minimizarse equilibrando un grado de cumplimiento adecuado y un tamaño de batería práctico. Analiza los efectos de reducir el tamaño de una batería diseñada para absorber todas las fluctuaciones, teniendo en cuenta la ocurrencia de fluctuaciones y la penalización en caso de incumplimiento de rampas.

Un análisis exhaustivo evalúa la relación entre la reducción del tamaño y el cumplimiento de rampas, obteniendo como resultado un modelo para predecir la probabilidad de incumplimientos con una batería reducida. Además, el análisis de reducción de tamaño se aplica a la normativa propuesta para Puerto Rico, implementando tres alternativas. El potencial para reducir el tamaño sin incurrir en penalizaciones es alto y sube más si parte de las fluctuaciones ascendentes se absorben limitando los inversores FV. Por lo tanto, se ha creado una estrategia de control avanzada para coordinar la limitación de inversores con una batería reducida, con el propósito de mejorar el índice de cumplimiento de rampas de la central FV. Posteriormente, la técnica de sobredimensionado del generador FV se ha estudiado como solución para mitigar parte de las fluctuaciones. Los resultados muestran que para un mismo tamaño de batería, una combinación adecuada de estas soluciones incrementa la producción FV anual, creando nuevas herramientas para seleccionar una batería de potencia y capacidad reducidas.

Por último, la estrategia de control de batería reducida se ha implementado y validado en un laboratorio, abordando aspectos de precisión y de respuesta de control requeridos para implementar el método en una central FV utility-scale.

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Nomenclature

Parameter	Description	Unit
C_{BAT}	Battery energy capacity	kWh
$C_{\text{BAT,MAX}}$	Maximum battery energy capacity required along a year	kWh
$C_{\text{BAT,N}}$	Nominal battery capacity, data of manufacturer	kWh
$C_{\text{BAT,rec}}$	Useful battery capacity, recommended by manufacturer	kWh
$C_{\text{BAT,WF}}$	Battery capacity requirement according to WF model	kWh
C_{ESS}	BESS energy capacity	kWh
Cu_w	Curtailment imposed to PV plant during week w	%
DR_{INV}	Inverter-to-PV array ratio	p.u.
ΔP_{RR}	Allowable output power variation between two consecutive scans	kW
Δt	Monitoring / scan time-step	s
Δt_{R}	Time differential of the ramp rate	s
E_{BAT}	Energy charged to / discharged from the battery along an interval	kWh
$E_{\text{BAT}}(t)$	Energy which is stored in the battery at a given instant	kWh
$E_{\text{BAT,MAX}}$	Maximum energy supplied by the battery	kWh
$E_{\text{BAT,MIN}}$	Maximum energy stored into the battery	kWh
$E_{\text{BAT,ref}}$	Reference value of the energy stored in the battery	kWh
$E_{\text{ESS}}(t)$	Energy managed at BESS output, AC side of converter	kWh

$E_{\text{ESS,DC}}(t)$	Energy managed at DC side of BESS converter	kWh
E_{GRID}	Energy produced by the PV plant and fed into the grid	MWh
$E_{\text{PVi,Cu}}$	Energy loss associated with PV inverters limitation	kWh
ε_{ESS}	Error between set-point and measured BESS power	%
$\varepsilon_{\text{GRID}}$	Error between set-point and measured power fed into the grid	%
$\eta_{\text{CNV}}(t)$	Converter efficiency, instantaneous	p.u. %
$\bar{\eta}_{\text{CNV}}$	Average converter efficiency	p.u. %
η_{BAT}	Battery round-trip efficiency	p.u. %
η_{ESS}	Energy storage system round-trip efficiency	p.u. %
$G_{\beta,\alpha}(t)$	Irradiance incident on the inclined plane	W/m ²
$I_{\text{BAT}}(t)$	Battery current	A
K	Proportional control parameter	-
k_c	Battery capacity reduction factor	p.u.
k_{os}	PV array oversizing factor	p.u.
k_p	Battery power reduction factor	p.u.
OF	Battery operating factor	p.u.
OF_c	Battery charge operating factor	p.u.
OF_d	Battery discharge operating factor	p.u.
P_{BAT}	Battery power requirement	kW
$P_{\text{BAT}}(t)$	Battery charge/discharge power, instantaneous	kW
$P_{\text{BAT,MAX}}$	Maximum battery power required along a year	kW
$P_{\text{BAT,set}}(t)$	Set-point of battery power	kW
$P_{\text{BAT,WF}}$	Battery power requirement according to Worst Fluctuation model	kW
P_{ESS}	BESS power requirement	kW
$P_{\text{ESS}}(t)$	BESS output power, instantaneous	kW
$P_{\text{ESS,DC}}(t)$	BESS DC side power, instantaneous	kW
$P_{\text{ESS,set}}(t)$	Set-point of BESS power	kW
$P_{\text{GRID}}(t)$	Power fed into the grid	kW

P_N	PV plant nameplate power	kW
P'_N	Oversized PV plant nameplate power	kW
$P_{PV}(t)$	PV plant output power	kW
$P'_{PV}(t)$	Oversized PV plant output power	kW
$P_{PV,DC}(t)$	PV array output power	kW
$P'_{PV,DC}(t)$	Oversized PV array output power	kW
$P_{PV,p}$	PV array peak power	kW
$P'_{PV,p}$	Oversized PV array peak power	kW
$P_{PV,w}$	Allowable maximum PV plant output power during week w	kW
$P_{PVi,Cu}(t)$	PV inverters power limitation	kW
RR	PV power ramp rate	$\%P_N/\text{min}$
RR_{LIM}	Ramp rate limitation imposed by a grid code	$\%P_N/\text{min}$
RRC	PV plant ramp rate compliance	%
RRC_w	PV plant ramp rate compliance of week w	%
S	Area of PV plant	ha
SF	Battery energy significant events fraction	p.u.
SOC	State Of Charge of an energy storage system	%
T_s	Control execution time-step	s
τ	WF model time constant	s
τ'	Oversized WF model time constant	s
τ_d	Control response delay	s
$V_{BAT}(t)$	Battery voltage	V

Abbreviations

BESS	Battery Energy Storage System
BMS	Battery Management System
DER	Distributed Energy Resources
DSM	Demand Side Management

DSO	Distribution System Operator
EMS	Energy Management System
ESS	Energy Storage System
FSM	Finite-State Machine
HIL	Hardware-In-the-Loop
I/O	Input / Output
I&C	Instrumentation and Control
LCOE	Levelised Cost Of Electricity
MPP	Maximum Power Point of inverter
MTR	Minimum Technical Requirements
N_{ON}	Number of scans when PV plant is generating
NC	Non-compliance
NC_C	Non-compliant scan, due to reduced battery capacity
NC_P	Non-compliant scan, due to reduced battery power
NMC	Nickel-Manganese-Cobalt oxide
PCC	Point of Common Coupling
PLC	Programmable Logic Controller
PREPA	Puerto Rico Electric Power Authority
PV+BESS	PV plant coupled to a battery energy storage system
RES	Renewable Energy Sources
RT	Real-Time
RTOS	Real Time Operating System
TSO	Transmission System Operator
WF	Worst Fluctuation (model)

CHAPTER 1

Introduction

1.1 Energy paradigm shift and distributed generation blast

Traditional electricity grid is a centralised system designed to connect large and centralised generating units to large consumers or to substations that deliver power to smaller consumers and households. Most of power stations of such a classic system are characterised by using fossil fuels as raw material and the ground for creating a centralised system was to improve the efficiency of those thermal power plants. The power capacity of these generators is directly related to the volume of their steam boiler, whereas their thermal losses are mainly related to the surface area of the latter. Hence, with respect to the size of the boiler, the power increases with a cubic relation, while the losses increase only to the square. As a consequence, the total efficiency of the system increases with the size of the power plant; so, conventional power plants are designed to be as large as possible and the electricity system must evacuate their production to usually distant consumption areas.

However, the need to avoid irreversible climate change effects has led worldwide countries in general and European countries in particular to commit to reducing greenhouse gas emissions, mainly by increasing the share of renewable energy sources (RES) like photovoltaic (PV) power in their electricity mix. By nature, these technologies are distributed energy resources (DER) rather than centralised. The efficiency of PV systems is independent of their size, which grants them a modular nature. This attribute allows for installing them close to the consumers, reducing the losses caused by power transmission. The massive connection of clean technologies to the grid both at distribution and transmission level will result in a paradigm shift, transforming the traditional centralised electricity system to a more decentralised one. The grid needs to integrate the rise of distributed generation like PV electricity, which will play a key role in worldwide electricity mix given its competitive trajectory.

PV electricity is expected to be competitive against conventional electricity in several market segments across Europe by the end of this decade (EPIA, 2012). The learning curve of this technology decreases the price of all system components, resulting in a levelised cost of electricity (LCOE) that makes this technology competitive earlier than expected. As it becomes

a mature and mainstream technology, PV will need to massively integrate into the electricity grid in a distributed way, not only avoiding grid stability or power quality problems, but also offering ancillary services like conventional technologies do.

In this context, several studies supported by the EU have investigated the technical challenges that PV power is going to face in the coming years to achieve its grid-integration seamlessly. More precisely, the deep study carried out by the former European Photovoltaic Industry Association in its report (EPIA, 2012) outputted interesting guidelines that should be followed by researches working at massive deployment of PV systems. The challenges identified in that report help us to focus on the problems to be solved and on the technological solutions needed to be developed for contributing to large-scale grid integration of PV power.

1.2 Challenges of large-scale grid integration of PV

Transmission system operators (TSOs) have slowly adapted and reached the high level of reliability of the electricity system that is evident today. Their primary task is to ensure the stability of the system in the control zone they manage, which is the cornerstone of electricity system development. In order to ensure safe grid operation and high power quality, the electricity frequency must be maintained close to its nominal value, which in Europe is 50 Hz. The frequency is determined by the balance of demand and generation. An imbalance immediately results in a deviation from the target value, decreasing when demand exceeds generation and increasing when generation is higher than demand. Therefore, TSOs balance supply and demand at all times contracting reserve energy and calling for balancing power in case of imbalances. This power can be positive and negative depending on what imbalance is seen. According to (ENTSOE-UCTE, 2009), against a frequency disturbance caused by a given incident, the frequency is controlled in the following way: After the inertial response of the grid, primary control reserve is activated in few seconds to stabilise the frequency, still out of its nominal value. After around 30 s, secondary reserve is activated to progressively bring the frequency back to its nominal value, elapsing around 10 min. Finally, tertiary reserve restores the secondary reserve and if the frequency is not in the target value yet, it supplements the regulation operation, being able to participate during hours.

Figure 1.1: Principle frequency deviation and subsequent activation of reserves. Against an event with a frequency disturbance, primary reserve stabilises it in around 30s and secondary reserve restores its nominal value. Source: (ENTSOE-UCTE, 2009)

Traditional electricity system includes a great proportion of dispatchable power plants that eases the balancing task as well as the stability conservation. However, several challenges arise with the integration of distributed and weather-dependent variable RES. These concerns have been relatively minor with a low penetration of PV in the past, but in the future they must be reconsidered as high levels of penetration are reached. The development of the future smart grid must be carried out adopting cost-effective solutions that help to solve the challenges presented by an increasing share of PV. EPIA identified different challenges and the respective solutions to face them, allowing a stable operation of the electricity system and ensuring security of energy supply even with a high penetration of PV. The identified challenges are the following:

- Turning variable into predictable
- Security of supply
- Ensuring flexibility
- Avoiding excess generation
- Voltage limitation and equipment overload avoidance in distribution grid

1.2.1 Turning variable into predictable

PV power includes a unique generation characteristic because solar irradiance has a variable nature and other weather conditions affect the PV production. Variability usually implies uncertainty and it must be reduced for a high penetration of PV into the electrical system. Traditionally, the variability of the demand has been one of the most important challenges faced by the power system. This challenge is addressed so far by aggregating the load and by using dispatchable power plants to ensure system operation, so a similar technique can be used to reduce the uncertainty associated with the variability of PV generation.

Long-term variability of PV, such as seasonal or daily variation of solar resource, is insignificant for high PV penetration; TSOs can schedule the required dispatchable generation to compensate it. However, for reliable PV grid integration, short-term variability is the factor that raises the most concern. Fast changes of PV production need to be taken into account to secure the supply and maintain a balanced system at the required frequency by means of ancillary services, especially in grids with low or null level of interconnection. In those cases the network operator has to be able to balance the demand in a cost effective way, so the following specific challenges are detected:

1) Forecast of PV production

Prediction of the output power of a single PV plant can be a hard challenge as the variability of a single PV plant can be very high, leading to great prediction errors. Fortunately, when forecasting the aggregated power of a fleet of PV plants in a certain region belonging to the same section of the electrical system, the variability is reduced, leading to lower errors. In any case, the development of accurate prediction tools leading to low errors is a challenge for high penetration of PV. An accurate forecast enables reliability and reduces costs by allowing more efficient and secure management of electricity grids.

2) Smoothing of forecasted PV generation in large balancing areas

Prediction allows the system operator to prepare the required reserve power but this means, in most of the cases, high costs. So, procedures for mitigating the PV variability appear as another key challenge. High power interconnection between the different European electrical systems allows the virtual aggregation of PV generation, but this solution depends not only on technical aspects but mainly on political ones that can take decades to be solved. Therefore, the development of alternative smoothing procedures not requiring high investments in transport interconnections is identified as a key technical challenge.

Besides, in some cases the geographical aggregation is limited. In these cases, the high frequency variability caused by the intermittency of solar resource can be smoothed by means of energy storage systems (ESS).

1.2.2 Security of supply

Security of supply is the capability of the power system as a whole to provide electricity to end-users in all circumstances. Two challenges are identified regarding this issue:

1) Secure generation adequacy

As PV generates electricity when the sun shines, additional back-up energy sources, either renewable, conventional or storage, are needed to achieve generation needs in any circumstance and to ensure the security of supply. The back-up required to support RES is named as residual load. With increasing penetration of PV, the power system will have to be secured at all times. In order to reduce the need for conventional power running on a standby mode, additional solutions will be required that compensate for the time when PV is not producing; or that shift part of the PV production from midday to the evening peak, or that shift demand. These solutions could be respectively storage or demand side management (DSM).

2) Secure network adequacy

Congestion of important transmission lines may isolate parts of the grid, separating PV power plants from flexible balancing resources, reducing opportunities to share those resources with another part of the grid (IEA, 2011). The most direct way of overcoming these bottlenecks is by reinforcing the interconnection of transmission lines to ensure that every consumer has access to a secure electricity supply. Interconnection is proving to be a valuable tool to facilitate the integration of variable RES produced in remote areas. The increasing maturity of high- and ultra-high voltage (HV-UHV) transmission technology, with over 250 GW commissioned globally and 200 GW in the pipeline, potentially opens up entirely new interconnection possibilities and transportation corridors (IEA, 2016a). However, its cost must be taken into account and the political barriers to deploy this solution continent-wide are important. On the contrary, if PV systems are installed close to consumption areas, where the grid is robust, the use of the transmission network will be limited. Focusing on dense consumption areas would reduce by almost 75% the need to transfer the excess generation. This implies the challenge of integrating PV systems in the homes and buildings of these dense areas, facing the technical problems associated to highly disperse and decentralised PV generation.

1.2.3 Ensuring flexibility

Flexibility is the key requirement for planning and operating the power system with a large share of variable RES connected to it (IEA, 2011). It expresses the capability of the system to maintain security of supply when rapid changes occur in production and/or demand. In general, operational flexibility comprises fast start-up and shutdown of generators, forecasting of fast load changes and the required frequency control by means of ancillary services. Apart from traditional solutions as flexible conventional generation, flexibility can be provided by interconnections, storage and DSM, and only a proper mix of all four solutions will enable a cost-effective transition to a flexible grid with a high share of PV. If only flexible generation were implemented, the high costs for maintaining the full power fleet on-line while operating them during a limited time would hinder large-scale deployment of PV systems.

Furthermore, in a high PV penetration scenario, PV generators will have to participate in the frequency control. In a traditional power system, the stability of the frequency is reinforced by its inertia, which is inherent of a system based on rotating generators and determines the immediate frequency response in case of power imbalances. When frequency changes due to an imbalance, first the inertia will dampen the effect, which is known as inertial response, and in a second phase, frequency is restored as explained before in Figure 1.1. So, the lower the inertia of the system, the more rapid the frequency reacts on sudden changes in generation or load. However, PV systems inject energy through inverters that decouple the generators electrically from the grid, so no inertial response is delivered by them against a frequency event. Under a high PV penetration scenario, the lack of inertia would be especially noticeable during low load situations, when conventional power fleet which do have inertia would only operate in standby mode. Therefore, PV generators will have to participate in the frequency control to solve this problem, by providing virtual inertia or primary reserve in combination with storage.

It must be noted that according to EPIA, the generation adequacy must also face an additional challenge in the future; the need to follow high and steep residual load ramps by flexible sources. In the near future this issue does not present problems and in fact these ramps can be easily met by currently installed flexible sources. However, to achieve RES penetration foreseen in 2030, additional flexibility will be required so as to reduce the periods during which part of the conventional power fleet will have to be operated in standby mode to respond quickly to any balancing needs (EPIA, 2012). Additional flexibility can increasingly be provided by a combination of dispatchable RES (hydro, biomass, geothermal, etc.) as well as innovative storage options and DSM. Particularly, PV plant output power fluctuations occurred in the time-window of the primary-secondary reserves could be smoothed by coupling an ESS to the plant.

1.2.4 Avoiding excess generation

High PV penetration could produce problems in the electrical system when PV generation exceeds the demand and export capacities. It is expected that, in an early scenario PV power together with other variable sources like wind will be higher than the minimum load in some European countries. This could be solved with interconnections reinforcement, curtailment of generation and storage or DSM.

Regarding the first one, apart from the costs and regulatory problems already mentioned, there are some technical issues that prevent the countries from exporting excess PV generation. Part of the European conventional power stations such as nuclear power plants are inflexible, which means that they have to feed in as base load. So even with strong interconnections, in the event of continent-wide minimum loads part of excess PV power could not be exported to countries running inflexible plants.

Regarding curtailments, it represents energy losses and, therefore, reduction of economical turnover. Furthermore, it is not allowed in several regulations.

Finally, energy storage solutions could shave the peak PV production and shift it to evening peak demand hours, or on the contrary, DSM solutions could shift peak demand to noon, when the highest PV production occurs. On the one hand, energy storage shifts generation to match with demand. Storage can flatten the residual load curve by significantly reducing the peak demand and avoiding excess generation. The former effect has a positive impact on the reduction of flexible standby capacity; the latter is a significant solution to excess generation. On the other hand, DSM shifts demand to match with generation. The scheduling of demands to modulate load curves is not new and has been implemented, for example, by means of the night-day electricity tariffs of large consumers. To successfully manage a significant amount of load, aggregation techniques must be applied either managing small fleets of large consumers without complexity or coordinating large fleets of household-size customers with smart-meters and information and communication technology (ICT).

1.2.5 Voltage limitation and equipment overload avoidance in distribution grid

Until now, the main role of the distribution grids was to ensure the electricity supply to every final consumer, being the bridge between transmission network and users on lower voltage levels. Distribution is managed by distribution system operators (DSO). The frequency is the responsibility of the TSOs, but the DSOs must manage the second important aspect of power quality, the voltage level.

Traditional electricity systems were designed to transport power in a unidirectional flow from high voltage (HV) levels to the end user on low voltage (LV) levels. Voltage of the line decreases relative to the distance and the level of consumption at the feeder. Therefore, transformers and lines are designed taking into account the most distant consumption point from the transformer. Usually, transformers allow so-called tapping to set the voltage level of the line. This allows controlling the voltage along the line in a certain bandwidth and ensures that the voltage of the final consumer is above the lower limit.

But with high distributed RES such as PV being connected in the distribution grid, the scenario has changed. Electricity flows in both directions and this presents new challenges in the management of distribution grids. When the power consumed in the distribution line is lower than the produced, a reverse flow occurs. The power flows from the distributed generator to other consumers or to the higher voltage level. As the distribution grid has not been built to host distributed generation, reverse power flows may create grid bottlenecks that lead to some problems.

First, the voltage can increase, in particular when DERs are installed in regions with low consumption. In some cases, the electricity may change direction and flow through the transformer to the higher voltage. As a consequence, DSOs ensure that the voltage will not exceed the limits of each side under the worst-case scenario, taking into account every consumer and every distributed producer.

Second, the distribution system equipment such as lines or transformers can overload. This is caused by the thermal limitation due to high current reverse flow through those devices, originally designed for a current flow from the centralised generation to the consumers.

Therefore, the PV hosting capacity of a distribution grid is determined by those two factors and it varies widely depending on the characteristics of the distribution grid itself. For example, urban grids supply many households in a small area so the transformer capacity is high and the length of the line is short. With such a configuration, overvoltage problems due to PV barely occur. However, rural grids are characterised by fewer but dispersed consumers which require lower transformer capacity and longer lines, so overvoltage is more probable.

The traditional approach to face this challenge is based on three alternatives: temporary limitation of the power via PV curtailments, connection to a stronger point of the grid, or reinforcement of the network with new transformers and lines. These measures either waste energy or cause additional costs, so smart solutions need also to be included. First, distribution grids may be monitored real-time through smart-meters to guarantee security of supply and a better distributed PV integration. Second, depending on the voltage situation at a given instant, the voltage at an intelligent feeding transformer can be lowered or raised in order to avoid upper voltage limit along the line. Third, PV inverters can support frequency and voltage by providing active and reactive power control. Fourth, distributed storage is becoming a good option to keep current and voltage limits by means of different strategies. ESS located at the end of a heavily loaded line may improve voltage drops by discharging active power or may reduce voltage rises by charging (IEC, 2011). Besides, distributed power production has no impact on the distribution grid as long as the power is locally consumed, so, by means of storage, the self-consumption is enhanced. As their costs decrease, storage systems will become a valuable alternative to grid reinforcement.

1.3 Energy storage as a disruptive element

Among every solution to face the challenges of previous section, such as reinforcing interconnections, deploying DSM or installing additional flexible generation; energy storage is presented as a key for facing almost every challenge of large-scale grid integration of PV power. Depending on the storage technology, it can be considered as the most flexible and independent option. It can be used in every type of grids, from strong and interconnected ones like those of European countries, to isolated and/or weak ones of small countries or islands. Besides, according to the recent perspectives stated in (IEA, 2016b), reinforcement of interconnections is expected to be effective only up to a limit in the share of variable RES (PV and wind). With large penetration, DSM or storage will be necessary to avoid curtailments during excess generation.

Given its synergies with RES and other sectors like transportation industry, electrical energy storage is starting to be considered as a disruptive element of the energy sector, which will enable the large-scale integration of PV power in worldwide electricity grids. Traditionally, the electricity grid was understood as a non-buffered system, with the main restriction of consuming the generated energy simultaneously and with few centralised storage systems. With the development of distributed and cost-effective storage systems, the paradigm is expected to shift. On the following, main technologies and applications are going to be described, based on deep review works carried out by the International Electrotechnical Commission and the International Energy Agency (IEA, 2014; IEC, 2011).

1.3.1 Electrical energy storage technology

Currently, there are several technologies available at many levels of development. The selection of the appropriate one depends mainly on two different criteria. First, the suitability for a particular application needs to be assessed, focusing on the power density, energy density, efficiency and other technical issues. Second, the cost of the solution, usually given in a ratio per kWh of storage capacity, needs to be taken into account. The cost usually decreases according to the maturity of the technology, so the traditional solutions usually are the cheapest ones at the moment. Main electrical energy storage technologies available are the following:

a) Pumped hydro storage (PHS)

These plants use two water reservoirs at different elevations to pump water during off-peak hours from the lower to the upper reservoir (charging). When required, the water flows back from the upper to the lower reservoir, powering a turbine with a generator to produce electricity (discharging). Typical discharge times range from several hours to a few days. The efficiency is in the range of 70 % to 85 %. Advantages are the long lifetime and practically unlimited cycle stability of the installation. Main drawbacks are the dependence on topographical conditions and large land use. The main applications are nonspinning reserve and supply reserve.

b) Compressed air energy storage (CAES)

Electricity is used to compress air and store it in either an underground structure or an above-ground system of vessels or pipes. When needed, the compressed air is mixed with natural gas, burned and expanded in a modified gas turbine to produce electricity. The advantage is its large capacity and disadvantages are low round-trip efficiency and geographic limitation of locations.

c) Flywheel energy storage (FES)

Rotational energy is stored in an accelerated rotor, which is a massive rotating cylinder coupled to a motor/generator. The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in the speed results in a higher amount of energy stored. The main advantages are the cycle stability and long life, little maintenance, high power density and the use of environmentally inert material. However, they have a high level of self-discharge due to air resistance and bearing losses.

d) Double-layer capacitors (DLC)

They fill the gap between classical capacitors used in electronics and general batteries. Two main features are the extremely high capacitance and the possibility of very fast charges and discharges due to extraordinarily low inner resistance, features not available with conventional batteries. They can reach a specific power density which only very-high-power lithium batteries can reach and are suited especially to applications with a large number of short charge/discharge cycles. However, they are not suitable for storing energy over longer periods of time, because of their high self-discharge rate, low energy density and high investment costs.

e) Superconducting magnetic energy storage (SMES)

The energy is stored in the magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature enabled by a cryogenically cooled refrigeration system. It provides very high power instantaneously but for a short period of time and it is characterised by its high overall round-trip efficiency (85% - 90%). However, the overall reliability depends crucially on the complex refrigeration system.

f) Chemical storage - Hydrogen (H₂) and synthetic natural gas (SNG)

Hydrogen storage system consists of an electrolyser which splits water with the help of electricity into oxygen and hydrogen, which is stored under pressure. To generate electricity, both gases flow again into a fuel-cell where an electrochemical reaction produces water, heat and electricity. In addition to fuel cells, gas motors, turbines and combined cycles of gas and steam turbines are in discussion for power generation. In this context, synthetic natural gas obtained from hydrogen can also be burned. Hydrogen can react with carbon dioxide to obtain methane. The main advantage of this approach is the use of an already existing gas grid infrastructure, where hydrogen can be fed into up to a certain concentration. The main disadvantage is the low efficiency due to the conversion losses in electrolysis, methanation, storage, transport and the subsequent power generation.

g) Redox flow batteries (RFB)

In these batteries two liquid electrolyte dissolutions containing dissolved metal ions as active masses are pumped to the opposite sides of an electrochemical cell. The electrolytes at the negative and positive electrodes are called anolyte and catholyte respectively. Anolyte and catholyte flow through porous electrodes, separated by a membrane which allows the electron transfer process. During the exchange of charge a current flows over the electrodes. During discharge, the electrodes are continually supplied with the dissolved active masses from the tanks and the resulting product is removed to the tank. Charging is the inverse process. Main advantage is the ability to do full charge-discharge cycles, with 100% of depth of discharge. However, hazardous liquids are pumped along pipes and given the environmental risk, the system must be protected to avoid dangerous leakage.

h) Secondary batteries – Lead acid (LA), NiCd, NiMH and Li-ion

Different types of batteries have been widely used for mobile and stationary applications. Lead acid batteries are the most widely used ones and commercially deployed for more than a century. They have a favourable cost/performance ratio, easy recyclability and a simple charging technology. Main disadvantages are that effective capacity decrease when high power is discharged and also the low energy density. Nickel-based batteries have a higher power

density, a slightly greater energy density and the number of cycles is higher, so NiCd batteries were developed as an alternative. However, because of the toxicity of cadmium, NiMH batteries were developed to replace them. Indeed, NiMH batteries have all the positive properties of NiCd batteries, except for the maximal nominal capacity which is much less.

Recently, lithium-ion batteries have become the most important storage technology in the areas of portable and mobile. They have higher cell voltage levels which mean that the number of cells in series and the associated connections and electronics can be reduced to obtain the target voltage. Another advantage of Li-ion batteries is their high gravimetric energy density, and the prospect of large cost reductions through mass production. They have a very high efficiency, typically in the range of 95 % - 98 %. Nearly any discharge time from seconds to weeks can be realized, which makes them a very flexible and universal storage technology. Standard cells with high cycle rates are possible depending on the materials used for the electrodes. The main obstacle is the high cost due to special packaging and overcharge protection circuits. They are thermally unstable and can decompose at elevated temperatures, releasing oxygen which can lead to a thermal runaway. Since lithium ion batteries are currently still expensive, they compete with lead acid batteries in those applications which require short discharge times.

1.3.2 Energy storage applications

According to the challenges identified in section 1.2, energy storage can play different roles. As a general classification, the applications of storage systems can be divided in energy applications and power applications:

Energy applications: High capacity - long-term storage

- PV production shifting: Displacing excess production to times when there is high demand and low production (peak shaving).
- Load-following: It manages system imbalances on a time frame that can range from 15 minutes to 24 hours.
- Smoothing load curves / Arbitrage. Storage is charged at off-peak times when the prices are low and discharged at peak times when prices are higher. The customer is more predictable for the grid operator.
- Self-consumption: When consuming locally the produced PV electricity, voltage disturbance is avoided and transmission network bottlenecks are avoided.

Power applications: High power - short-term storage

- Improve power quality: Providing ride-through capability and securing frequency until generation adequacy is brought up (primary reserve).
- Frequency regulation: Providing services of secondary reserve on a minute-to-minute (or shorter) basis.
- Voltage support: Injecting or absorbing reactive power to correct voltage level of transmission and distribution system.
- Supporting the grid against disturbances and faults: Due to its fast response times and high flexibility, storage prevent black-outs and costly equipment damage.

- Face solar resource intermittency: Smoothing the fluctuating output of PV plants, mitigating rapid output changes. This solution mitigates frequency disturbances during the first instants, until secondary reserve is fully operative.

In order to select the appropriate technology for each application stated above, Figure 1.2 shows the ranges of power and energy that each technology can manage and the associated duration of discharge.

Figure 1.2: Comparison of rated power and energy of different energy storage system technologies. Source: (IEC, 2011).

Given the distributed nature of PV power, in this work only distributed energy storage solutions are going to be addressed, which usually are coupled to PV systems. A distributed storage must comply with high grade of availability, independent of geographical or environmental aspects. The solutions that best suit these requirements with high efficiency and reliability are the electrochemical storage technologies. They are modular solutions and can be installed almost everywhere. In particular, given the high power and energy density shown in Figure 1.2 and the potential for cost-reduction that they are experiencing during the last years, batteries are normally used for supplying storage solutions to PV systems.

Among other battery technologies, Li-ion batteries are earning the attention of worldwide industrial and energy sectors, mainly due to the synergies with other industries like the automotive. The disruption of the electric vehicle is expected to develop economies of scale, which should decrease the cost of Li-ion batteries. They are undergoing an intense development in their technological features, especially in the electrochemistry of the electrodes (Thackeray et al., 2012; Yoo et al., 2014). Their high specific energy, efficiency and durability, are placing them as one of the most promising actors in the field of ESS technology. The highly reactive nature of the lithium is the main reason of those good electrochemical properties (Scrosati and Garche, 2010; Subburaj et al., 2015). The lowering of their production costs will allow the wide application of these technology and several studies identify key points which will help on this matter (Gallagher et al., 2011; Wood et al., 2015).

But due to the current high battery costs, the deployment of batteries for enabling the large-scale grid integration of PV power requires strategies to reduce their size. The use of storage has an impact on the competitiveness of PV power and each application identified here requires estimating when the cost of a storage system will be outweighed by the benefits provided to either electricity system, PV plant owner or the final consumer; ultimately, to PV electricity. Therefore, the large-scale grid integration of PV systems will only be feasible if the overall costs of using a battery are reduced. This can be achieved by means of the following alternatives:

- a) To reduce the cost of battery technology: Developing new materials, production processes and economies of scale that enable shaping a steep learning curve.
- b) To provide multiple services: Developing battery control strategies that allows for addressing various applications, those that have the highest cost of opportunity.
- c) To reduce battery requirements: Developing advanced control strategies and complementary techniques that enable reducing the size required for a specific application.

1.4 Problem to solve and objective of the thesis

As explained along this chapter, the large-scale grid integration of PV power will face important challenges during the following years and decades. For every challenge identified in section 1.2 normally more than one solution was proposed. However, in certain regions of the world with low interconnected and/or weak grids such as islands, the use of energy storage systems is the only reliable solution. In these scenarios, the large-scale integration of PV power is a challenge of today, since installing utility-scale PV plants in such small grids means increasing considerably their share in the electricity mix. Facing the challenges of today in isolated grids will prepare us for facing the challenges of the future for large-scale grid integration of PV power in the European electricity system.

In this context, several TSOs have started to propose strict grid codes with technical requirements in order to reduce the short-term output power fluctuations of utility-scale PV plants caused by clouds covering them. One of the most popular code was proposed by the Puerto Rico Electric Power Authority (PREPA, 2012). The requirements of that code limit maximum allowed power variations that are injected to the grid and it is compulsory to install an energy storage system (ESS) to smooth such fluctuations. The smoothing of these fluctuations by means of an ESS such as a battery is called PV power ramp rate (RR) control. Here, the battery cost is not an issue that prevents it from being a commercial solution; its use is an imperative technical requirement instead. However, the storage requirement is a key factor that can reduce the feasibility of a PV project to be developed under such a strict regulation.

Given current battery costs, the battery required for PV power ramp rate control results rather large and expensive. In order to boost the economic feasibility of this solution, the battery size must be properly assessed and reduced. As a consequence, **the objective of this thesis is to reduce the size of the battery in terms of power and capacity requirements, by creating techniques and tools for minimising the adverse effects and ensuring an appropriate PV power ramp rate control.**

The research works that allow us for achieving that objective are structured as follows:

- The research methodology used in this thesis is presented first. It starts with a review of state-of-art techniques used for characterising and mitigating PV power fluctuations. Then, the methodology used for carrying out deep theoretical studies is explained, describing the database of a real PV plant used to feed extensive simulation exercises. Finally, the laboratory designed for validating the outputs of the theoretical studies is presented, including the characterisation of a Li-ion battery (Chapter 2).
- With the extensive simulations, the relation between battery size and ramp rate limitation is studied, obtaining a model for predicting the ramp rate compliance of reduced batteries. Then, the concept is applied to a specific grid code and a method to assess the battery size reduction potential is presented (Chapter 3).
- The battery size reduction assessment is applied to a scenario where PV power ramp rate control is performed by a novel control strategy that teams up the battery with the limitation of PV inverters. Besides, the possibility of smoothing part of the fluctuations by oversizing the PV array of a plant is studied as an alternative (Chapter 4).
- The battery size reduction concept and the different control strategies developed in the theoretical part are implemented in the controller of the laboratory, testing them in a Li-ion battery and validating the results for their use in utility-scale PV plants coupled to batteries (Chapter 5).
- Finally the conclusions and the future research lines are discussed (Chapter 6).

CHAPTER 2

Research methodology

In order to fulfil the objective of this thesis, a methodology that includes theoretical and applied studies is used. It is based, first, on detailing the previous works that have been used as starting point for this one, second, on the use of a unique experimental database for theoretical studies, and third, on the implementation of an ad-hoc laboratory to test the developed solutions.

2.1 Starting point: PV power variability characterisation and mitigation

In previous works, procedures have been proposed to characterise PV power fluctuations and to size batteries for complying with a certain power ramp rate (RR) limitation. An appropriate short term PV power variability analysis is necessary for describing the behaviour of a PV plant under intermittent irradiance conditions, for detecting the problems that it could cause to the grid and to propose solutions. In this context, several techniques have been proposed in the literature and have been used as a starting point of this work.

2.1.1 PV power fluctuations characterisation

Early studies characterised irradiance variability. The most classical references had a lack of measurements in order to carry out their research, so for instance in (Chowdhury and Rahman, 1987; Chowdhury, 1992) artificial irradiance data series were created for simulating PV plants variability. Later, measured irradiance data was used in order to characterise irradiance fluctuations precisely and to study the behaviour of PV systems against them. (Otani et al., 1997) addressed the irradiance fluctuations and their spectral density by correlating data measured at nine stations, giving importance to the area of incidence. In (Woyte et al., 2007a, 2007b, 2006) pseudorandom time series of irradiance dataset was used, obtained with measured data of clearness index. Moreover, this author addresses the importance of the analysis of the irradiance series in the domain of the frequency and proposes the treatment of such fluctuating

time series as realizations of a stochastic, locally stationary, wavelet process. (Tomson and Tamm, 2006) also studied irradiance fluctuations in a statistical way, modelling the series as exponential distribution functions.

Currently PV plant output power fluctuations are characterised directly, using statistical methods. Several authors quantify the variability of PV power depending, among others, on the size of the PV plant and the speed of the clouds that cover the arrays (Hoff and Perez, 2010; Lave and Kleissl, 2013; Marcos et al., 2011a, 2011b). Other authors analyse statistically the ramp-rate of the output power in different size PV plants, obtaining empirical models of power fluctuations frequency distributions (Mazumdar et al., 2014; Mills et al., 2009; Van Haaren et al., 2014).

Particularly, in (Marcos et al., 2011a) PV power fluctuations are characterised in the domain of the frequency and studying their probability of occurrence along a given year. With the results, an empirical model is obtained, showing that the frequency distribution can be modelled as an exponential decay function. It must be pointed out that the model demonstrates that the occurrence of medium-to-strong size fluctuations during a yearly operation of a utility-scale PV plant is very low. Besides, with those results the authors propose an interesting model that predicts the output PV power of a PV plant using data of incident irradiance, which is explained in (Marcos et al., 2011b). The model is a low pass filter of the incident irradiance that smooths down high frequency fluctuations, whose cut-off frequency is in function of the surface area of the PV plant. This tool is really interesting for studies that need reliable artificial data series that include this smoothing phenomenon, for instance when studying storage requirements of a simulated PV plant.

2.1.2 Methods to mitigate PV power fluctuations

There are two types of techniques to smooth part of the power fluctuations at the output of a PV plant. First one takes into account the nature of the fluctuations and the influence of design parameters of a PV plant, such as the area of its PV array or the configuration with respect to other PV plants. The studies of (Marcos et al., 2011a) show that as the area of the PV array increases, both the maximum power fluctuation registered and the 90th percentile of every fluctuations are reduced exponentially.

In line with that issue, fluctuations can also be smoothed by geographically dispersing PV plants. When several plants are separated but still located inside the same region to aggregate their power, the probability that a cloud front covers all of them simultaneously is highly reduced. As a consequence, each plant compensates the fluctuations occurred in another plant separated by sufficient distance. In (Murata and Otani, 1997; Murata et al., 2009), simulated and measured PV power data are used for analysing the smoothing effect of distributing a large number of PV plants along a country-level region. They obtained a correlation between output power fluctuations and the distances between the locations of the plants. A similar work was done in (Hoff and Perez, 2010; Lave et al., 2012; Marcos et al., 2012; Mills et al., 2009) either theoretically or experimentally. The literature demonstrates that, for a certain aggregated power, fluctuations are smoothed as the number of dispersed PV plants increases. The studies confirm that if the plants are separated by sufficient distance to consider the short-term fluctuations of each plant as independent, the smoothing caused by the dispersion is more important than the

smoothing caused by the size of the plants. Recently, following a previous procedure, in (Marcos et al., 2016) the authors proposed a model to simulate the fluctuations generated by a fleet of dispersed PV plants using the irradiance data measured at a single location.

However, in some regions the potential for smoothing the fluctuations by aggregation of dispersed PV plants is intrinsically limited. This is the case of isolated grids, such as islands. In these regions, the strict grid regulations demand buffering capabilities to individual PV plants. Accomplishing such regulations requires a battery energy storage system (BESS), able to inject (absorb) power when the PV power decreases (increases) faster than the prescribed limit. Figure 2.1a shows the configuration of a PV plant supported by a BESS on its point of common coupling (PCC). In such a configuration, the result is a ramp shaped injection to the grid for highly fluctuating periods. Figure 2.1b shows for a period of around 30 min the output power of a multi-MW PV plant, $P_{PV}(t)$, and the power injected to the grid, $P_{GRID}(t)$, applying ramp rate control by means of the BESS. It can be seen that when a cloud front passes over the plant, the PV power falls suddenly, failing the required downwards ramp rate limitation, RR_{LIM} , of 10% of PV plant nameplate power per minute. It also can be seen that once the front passes by, instant power increases beyond the allowed upwards ramp. In a day with medium clearness index and high wind speed like the one shown in the figure, this process occurs time after time. That leads to the question of the size of the corresponding battery, in terms of power and energy capacity, for accomplishing such regulations. These requirements are given by both PV power downwards and upwards fluctuations that exceed a given ramp rate limitation, evaluating required battery power, $P_{BAT}(t)$, and energy, E_{BAT} , for each fluctuating event. Figure 2.2 shows a sample of these events and battery power and energy requirements to manage them.

Figure 2.1: PV power fluctuations smoothing by means of BESS. (a) The battery is connected on the point of common coupling (PCC) in order to absorb PV power fluctuations and to inject power to the grid, $P_{GRID}(t)$, in a required 10%/min ramp rate (b). In a day with medium clearness index and high wind speed, downwards and upwards fluctuations occur time after time.

Figure 2.2: Modulation of $P_{\text{GRID}}(t)$ following the prescribed RR limit. When a cloud passes over the plant and $P_{\text{PV}}(t)$ decreases below RR_{LIM} , battery is discharged at a certain power $P_{\text{BAT}}(t)$ supplying required energy E_{BAT} . When the cloud is gone and $P_{\text{PV}}(t)$ is recovered faster than RR_{LIM} , the battery absorbs excess power and extra energy is stored in it. Both discharge and charge events start ($t_{\text{D,start}}$ and $t_{\text{C,start}}$) when $P_{\text{PV}}(t)$ exceeds RR_{LIM} and end when either fluctuation sign changes ($t_{\text{D,end}}$) or when RR_{LIM} is kept again ($t_{\text{C,end}}$).

By analysing PV power fluctuations statistically, in (Perez and Hoff, 2013; van Haaren et al., 2015) the use of energy storage systems for fluctuations mitigation is addressed. In line with this and based on one second long-term observations at PV plants of different sizes, a model for the “worst fluctuation” (WF) was proposed in Marcos et al., 2014b. Roughly, it corresponds to the darkening of the PV array (from clear sky irradiance to diffuse irradiance) by a cloud moving at about 80-90 km/h, which is also confirmed by (Lave and Kleissl, 2013). Providing the battery can be fully recharged between two consecutive fluctuations by means of a state of charge (SOC) driven control, the WF model allows sizing the battery for full compliance of ramp-rate limits (Marcos et al., 2014a). As a next step, more recent studies focused on reducing the storage requirements. Several control strategies have been developed in order to optimise the usage of batteries, combining its operation with other techniques (de la Parra et al., 2016, 2015; Ina et al., 2004; Marcos et al., 2014a).

2.2 Experimental database

The theoretical research is carried out by carefully analysing high quality data of a multi-MW PV plant available for this work. In the framework of a research project financed by the Spanish TSO Red Eléctrica de España (REE) and executed by UPM and UPNa, a database of a monitored PV plant fleet belonging to Acciona was built up. Since 2008, multiple parameters of six utility-scale PV plants rating between 1 MWp - 9.4 MWp and located in the North of Spain were monitored. The sampling frequency of 1 s makes from this database a unique information source for analysing PV power fluctuations with experimental measurements.

The database is used for feeding simulation tools; so that the behaviour of a BESS coupled to a PV plant can be modelled, allowing us to develop advanced energy management strategies and PV+BESS plant configuration alternatives.

2.2.1 Real PV plant description and associated database

Extensive simulation exercises are performed using as input one second power values recorded at the PCC of a 7.2 MW PV power plant located in Milagro, Northern Spain. The PV plant under analysis is equipped with vertical axis trackers with an inclination of 45° and covering an area of 52 ha. High quality PV plant output power data was collected by means of a power meter at the point of common coupling and recorded by a PLC.

Besides, other relevant parameters such as horizontal and tilted irradiance were measured by calibrated modules and recorded by the PLC. Irradiance data was really useful in order to detect some power measurement errors. At first glance, some sudden power decays were detected in the dataset, which were initially studied as power fluctuations caused by clouds because they were not identified as data logging common faults. However, after comparing irradiance and power data, they turned out to be errors and were filtered out from the dataset. For instance, an inverter of a certain PV plant section can suffer a sudden disconnection fault and the subsequent reconnection, which can resemble a power fluctuation. Therefore, a process which correlates irradiance vs. power data prevents us from sizing a battery for absorbing false fluctuations.

Table 2.1 shows the main configuration parameters of the Milagro PV plant, as well as the electrical and meteorological parameters that are monitored by the instrumentation system and recorded by the PLC. Due to its function as a test bench for a wide range of research topics, many magnitudes are registered every second. The electrical parameters recorded at the PCC are the voltage (U), current (I) and the active (P) and reactive (Q) powers. One of the calibrated PV modules is installed on the ground and the other one tilted and installed on a tracker to monitor the incident irradiance. Besides, the cell temperature (T_c), ambient temperature (T_a) and wind speed at 3m height (V_w) are measured.

Table 2.1: Main characteristics and monitored parameters of Milagro PV plant, the base of the theoretical research.

Peak power $P_{PV,p}$ (kWp)	Nameplate power P_N (kW)	Area (ha)	Location (lat., lon.)	Tracker	Inclination β ($^\circ$)	Monitored parameters
9500	7243	52	42°15'28"N 1°46'30"W	Vertical axis	45	$U, I, P, Q,$ $G(0^\circ), G(45^\circ), T_c, T_a, V_w$

The high sampling frequency, with a time step of $\Delta t = 1$ s, converts this database into a valuable resource for assessing the behaviour of PV plants under irradiance fluctuations caused by clouds. In this context, the same database was used in several works for effectively characterising PV power fluctuations and proposing first techniques for mitigating them by means of BESS (Marcos et al., 2014b, 2011b). Therefore, its choice for the present work is a good decision as its validity in this research topic is widely contrasted.

2.2.2 Simulation of a BESS coupled to a PV plant

An advanced simulation toolbox has been created in order to emulate the operation of a BESS coupled to Milagro PV plant. It has been developed and implemented in Matlab® code given that this environment allows writing code in a fast, flexible and modular way, as well as it is optimised for working with matrices.

The database explained in the previous section is cleaned, filtered out from errors and adapted appropriately in order to have a PV power data series to be used as input of the toolbox. The toolbox accepts input data with sampling resolutions multiple to $\Delta t = 1$ s; so it is easily adjusted to simulate PV+BESS systems which operate under the scans monitoring requirements proposed by different grid codes.

PV+BESS systems operate under different control strategies, so in order to study the relation between battery size and ramp rate compliance under them, the toolbox must allow implementing various controllers, different types of analysis and different scopes of simulation. On the following, the computing requirements of the simulation toolbox to fulfil the objectives of this research are described:

a) Calculation of instant battery power and energy

The simulator must smooth the input PV power data series and give as an output the power fed into the grid that complies with a given RR_{LIM} . For this, it must calculate the time series of the instant battery power that supports an excessive PV power variation occurred between two consecutive scans of input data series. This will cause a variation in the energy stored in the battery, so a time-series of this parameter must be calculated too. Depending on the control strategy, additional time-series of other relevant parameters may be calculated, so the toolbox needs to be easily adaptable.

b) Implementation of control strategies

A flexible control core is needed so that different control strategies are easily reprogrammed. Depending on the strategy, the battery is recharged after the fluctuation event in a different way, changing the time series of power and energy.

c) Simulation of the operation with a specific battery configuration

Alternatively, the toolbox must allow specifying a pre-sized battery configuration, entering nameplate power and energy capacity parameters. This will allow simulating how a particular PV+BESS system will react to the input PV power data and it will serve as test-bench for different size batteries.

d) Simulation of singular constraints

The system must be adapted to scenarios with singular operation modes, in order to study the behaviour of a PV+BESS system under complex regulations. For instance, the toolbox must simulate how a system with a reduced power or capacity battery would behave, which would not be able to comply with a prescribed RR_{LIM} . These events need to be appropriately assessed and some quality indexes must quantify the goodness of the operation under these singularities.

e) Scope of analysis

Time series may change dynamically due to calculations made after intermediate scopes of simulation. Some calculations like instant battery power or energy are going to be done immediately at every scan; but, at the end of a day, a week or a month, different processes may require to assess partially a given output time-series in order to check the goodness of the system response. Therefore, the toolbox must be structured in a way that the execution loop permits to take into consideration other time magnitudes of execution larger than the Δt of the input data. In this context, each element of the input PV power data series must be synchronised with a time value. This value tags the power data with the instant when the sample was taken, and will be used as the time of the simulation. The timestamp used is the “Matlab Time” because it is easy to obtain the number of the day, week or month from it.

f) Output and analysis of results

Output time-series are stored in vectors, but the toolbox is also prepared for giving quality-indicators of sequential simulations, which need to be stored in matrices. The toolbox must be able to perform annual simulations under different configurations of the BESS, storing the indicators obtained in each simulation in a position of a matrix. This way multiple-factors analysis can be done, performing sensitivity analysis of each parameter of BESS configuration and knowing their influence in the quality indicators. For example, an annual simulation is carried out for a battery sized by a particular combination of nameplate power and capacity. The toolbox is able to perform one simulation for each power and capacity combination and, by storing different quality indexes obtained from it in a position reserved for each configuration; multiple sensitivity analysis can be done. After the simulation process, the result matrices are available for functions that can access the quality indexes obtained in each of them. Some example of these quality indexes are annual PV energy production, energy loss respect to the maximum, the compliance with RR_{LIM} , etc.

2.3 PV - Battery integration laboratory

In the framework of this PhD thesis a laboratory to develop and test advanced real-time (RT) energy management strategies for grid-connected PV+BESS systems has been created. The laboratory is composed of two rooftop PV generators, a Li-ion battery energy storage system, controllable loads in a Smart Home and a powerful instrumentation & control (I&C) equipment. It is prepared for developing both rooftop and utility-scale PV+BESS control strategies, with a powerful RT controller that can implement any control algorithm.

Here the components used for developing and testing RR control strategies are going to be described. So, instead of using the rooftop PV installations of the laboratory, the PV plant is going to be emulated using the PV power database explained in section 2.2. Control strategies designed to smooth PV power fluctuations need real scale data to test their behaviour against the latter and it is not possible to use downscaled PV installations; so, given the characteristics of the laboratory, this part is necessarily simulated. This fact involves that the tests are conducted combining hardware and simulated equipment, which, in practice, means that we will follow the *hardware-in-the-loop* concept. The controller receives simulated PV input, but it commands a real I&C system that runs a real BESS. As a consequence, the BESS, the measurement

instrumentation and the RT controller are the physical devices used for our research activities.

In this section the methodology to carry out experimental tests is going to be described. First, the laboratory layout and I&C equipment that monitor and govern the devices are going to be explained; and, second, the BESS is going to be characterised and tested for RR control tasks. Finally, the methodology for testing PV+BESS systems in the created laboratory is going to be explained.

2.3.1 Instrumentation & Control infrastructure of the laboratory

PV generator and BESS of the laboratory are connected to the local grid by means of their respective AC/DC converter. The connection of both systems is in the 230V AC single-phase line.

In order to guarantee correct measurement of all parameters involved in the operation of the system, high resolution digital power instruments have been used, either AC or DC digital power meters for measuring at each side of the converters. The instrumentation equipment used for this experiment is manufactured by CIRCUTOR and it must follow certain resolution and quality specifications. DC meters are two DH96-CPM model unidirectional panel indicators, each one monitoring respectively charge and discharge energy flow. They measure voltage and current with a precision of 0.2% (± 1 digit), obtaining power and energy values from those two parameters. AC meters are CVM-1D model single-phase power analysers that measure voltage and current with a precision of 0.5% and active and reactive power with 1% (± 1 digit in both cases). When we run downsized tests in the laboratory, the equipment must be as precise as possible, because the measurement error in laboratory scale is translated to a utility-scale error multiplied by the scale factor. The instruments are equipped with physical communications interface, via RS-485 in half-duplex configuration and according to Modbus/RTU protocol. Each meter sends measurements of relevant parameters to the controller in real-time.

The controller that collects the data of the instrumentation and rules the system is a NI-PXIe industrial controller, where a LabVIEW® Real-Time application implements the control algorithms. By means of an input/output sever (I/O server) it manages the data received by the communication system and sends back the set-point parameters to the actuators of the laboratory. The control algorithm receives as input the parameters monitored by AC and DC digital meters and the PV plant output power; then it processes them according to the implemented strategy; and, finally, it commands the BESS converter and PV inverter, sending power set-point values accordingly through the I/O server. In our case, the PV plant is simulated and the power dataset is used as input of the controller while the set-point values sent to the PV inverters are just registered.

Figure 2.3 shows the layout of the laboratory, placing the components explained above and connecting them through the electrical and communication wiring diagram.

Figure 2.3: Layout of the PV-Battery integration laboratory. DC and AC power and other electrical parameters are measured and transmitted via RS 485 with Modbus/RTU protocol to a RT industrial controller, which commands PV and BESS converters accordingly.

The NI-PXIe controller has a real-time operating system (RTOS), which allows executing control applications with strict time constraints and with a high reliability. RTOS are focused on the tasks demanded by the control algorithm, without falling into interruptions or background tasks like conventional operating systems do. In real-time computing, the tasks to be completed inside a control algorithm are schedulable; which means that tasks are accepted by the system and completed as specified by the task deadline. The deadline is defined as the time required for a particular process to be processed. In a critical operation, every task must be processed in the time specified by the deadline. For the control strategies to be developed in this thesis, the deadline will be set to no less than one second, which in RT environment is a very affordable target. The tasks are periodical, which means that every execution time-step, elapsed T_s , a new cycle of the tasks-schedule must be performed. Because of all these strict control requirements, the selected NI-PXIe controller is a good option for our laboratory.

In this context, a LabVIEW application that implements each I&C requirement has been developed. The application is designed in different functional blocks. Each of them has a particular instrumentation, communication, control or monitoring function and thanks to its modular architecture, the system is prepared to add new blocks easily if the system must be eventually upgraded. Besides, it is prepared to implement different control strategies in the control core block. The control core can be seen as a slot where different strategies are inserted, whereas the rest of the system barely requires small adjustments. This architecture will allow as developing and testing different ramp rate control strategies in a fast and robust I&C infrastructure. Figure 2.4 shows the modular architecture followed to develop and implement the control system in the I&C infrastructure, organised as a LabVIEW project.

Figure 2.4: Modular architecture of the control system implemented in the NI-PXIe controller of the I&C infrastructure, developed in a LabVIEW RT application.

2.3.2 BESS characterisation and efficiency test

In order to create an accurate test bench for RR control strategies, it is necessary to know the behaviour of the BESS in real operation. In this section, a commercial Li-ion battery used for storing and managing PV power in distributed generation systems will be characterised. This way, the performance model of the battery can be obtained and implemented inside the algorithm of the controller, allowing it to operate the BESS accordingly. A method and the results for testing round trip efficiencies of a modern Li-ion battery based ESS, as well as its effective capacity and operation limits, are described. For further details, the reader is addressed to (Makibar and Narvarte, 2015).

2.3.2.1 Li-ion battery and converter specifications

The selected BESS option is a Cegasa battery solution, which consists of a stationary NMC prismatic pouch lithium cells string, operated by a Battery Management System (BMS) module and connected to the local grid of the laboratory by an Ingeteam converter (Cegasa, 2014; Ingeteam, 2013). It is formed by two energy modules connected in series, each containing 36 cells in series, divided in 6 strings of 6 cells. Thanks to the modular architecture, with this solution the required capacity of the BESS is achieved adding extra modules. The following table describes the electrical specifications of the storage system.

Table 2.2: Specifications of the Li-ion battery used in the laboratory, provided by the manufacturer. Voltage values are distinguished according to maximum available values (SOC 100 - 0 %) and values recommended by the manufacturer (rec.).

Electric parameter	Value	Electric parameter	Value
Nominal voltage	266.4 V	Nominal discharge current I_C	40 A
Maximum voltage (SOC 100%)	302.4 V	Max. discharge / charge current	50 A
Minimum voltage (SOC 0%)	194.4 V	Maximum constant power, P_{BAT}	6.4 kW
Max. cell voltage, $V_{CELL,max}$ (rec.)	4.05 V	Peak power (2 min)	6.9 kW
Min. cell voltage, $V_{CELL,min}$ (rec.)	3.3 V	Peak power (3 sec)	7.9 kW
Maximum voltage (rec.)	291.6 V	Nominal capacity, $C_{BAT,N}$	10.6 kWh
Minimum voltage (rec.)	237.6 V		

The converter is the responsible for the operation of the battery. Our model is a single-phase EMS Home 5TL, connected to the BMS via CANopen communication interface and to the controller of the laboratory via RS 485 with Modbus/RTU protocol and half-duplex configuration. It teams up with the BMS to watch out not only operation parameters such as battery voltage, current or SOC, but also critical parameters such as battery temperature or minimum/maximum voltage of the cells. Depending on the SOC of the battery, it runs under constant current or constant voltage modes. Depending on the voltage of the battery, it demands the required current in order to match the AC power set-point demanded by the controller. Main electrical specifications are displayed on Table 2.3.

Table 2.3: Specifications of BESS converter used in the laboratory, provided by the manufacturer.

Electric parameter	Value
AC power, P_{ESS}	5 kW
AC voltage, V_{ESS}	220-250 V
Max. AC current, I_{ESS}	22 A
Frequency	50/60 Hz
DC voltage, V_{BAT}	96-330 V
Max. DC current, I_{BAT}	50 A

2.3.2.2 BESS efficiency

In order to characterise the whole BESS, it is necessary to test the efficiency taking into account its two subsystems, the battery and the converter. On the one hand, the manufacturer does not specify the efficiency of the battery but, in the specific literature, there are different values for this parameter. For example, in reference (Qian et al., 2011) it is explained that when operating a LiFePO4 battery between SOC limits of 30-70%, the efficiency is 95%. But given that the strategies that are going to be developed in this thesis will operate between other limits and the battery type is NMC, it is necessary to test its efficiency in our laboratory following the applicable standard. In this context, the test must be carried out according to the conditions explained in IEC61427-2, which rules the conditions and procedures for testing a battery used for renewable energy storage in different conditions. It relates to batteries used in ESS applications and the associated methods of test, which are proposed for the verification of endurance, performance and their reaction to specified or anomalous occurrences during operation (IEC, 2013).

On the other hand, the real efficiency of the converter used in the tests must also be taken into account. This type of power electronics device has been widely tested and, for example, in

reference (Qian et al., 2011) it is said that their efficiency is usually around 97-98% working at nominal power. However, in order to characterise the BESS of our laboratory, it is necessary to analyse the behaviour of our converter working together with the specific Li-ion battery of the laboratory. This is achieved by calculating the efficiency of the converter during the complete charge and discharge process of the battery efficiency test.

The BESS efficiency is calculated as the combination of battery and converter efficiencies during a complete process of charging and discharging the stored energy. Figure 2.5 illustrates the modelling of BESS round-trip efficiency and the role of its components in the energy losses.

Figure 2.5: BESS round-trip efficiency, modelled as the combination of the round-trip efficiency of the Li-ion battery and the efficiency of the converter during both charge and discharge operations of the battery.

2.3.2.3 Efficiency test according to IEC61427-2

According to the standard, the battery is fully discharged and immediately charged, using the effective full-capacity of the battery along a day. Following the specifications of the manufacturer and the standard, the appropriate discharge/charge DC power rate is configured. By monitoring the DC energy flow along the whole process and registering battery voltage and current by means of I&C equipment, round-trip efficiencies for different discharge/charge rates can be calculated and $V_{BAT}(t)$ and $I_{BAT}(t)$ curves can be drawn.

Given that our purpose is to characterise the whole BESS, in addition to the parameters specified by IEC61427-2 the instant converter efficiency $\eta_{CNV}(t)$ needs to be calculated during the same test. This parameter is calculated as the ratio between instant converter AC power and battery power. Therefore, in addition to all DC parameters of the battery, the AC power of the BESS must also be monitored during our test. The parameters to monitor are listed in Table 2.4.

Table 2.4: Parameters of the BESS monitored during the efficiency test. All DC parameters are required by IEC61427-2, while AC power of the BESS is required to test the converter efficiency.

Test parameter	Variable name
Total discharged energy (DC)	E_{BAT}^D (kWh)
Total charged energy (DC)	E_{BAT}^C (kWh)
Battery discharge/charge power (DC)	P_{BAT} (kW)
BESS discharge/charge power (AC)	P_{ESS} (kW)
Battery voltage (DC)	$V_{BAT}(t)$ (V)
Battery current (DC)	$I_{BAT}(t)$ (A)

The manufacturer does not recommend using all of the nominal capacity. Each cell has a maximum and a minimum recommended voltage and surpassing or going below these limits can involve damage of their electrochemical properties. Moreover, beyond these limits the battery turns very inefficient and charging beyond a maximum or discharging below a minimum SOC will result in a low useful energy exchange compared to the generated losses. As a consequence, the test will also characterise the effective capacity under recommended conditions.

Considering a full-charge and equalised battery as the initial state, the test starts with the following discharge/charge sequence, carried out in an uninterrupted way:

- 1) Discharge for 480 minutes at constant DC power P_{BAT}^D until $V_{BAT}(t)$ reaches its lower limit, which is registered when the voltage of the most discharged cell equals $V_{CELL,min}$. The SOC indicated by the BMS at that instant is the lowest value recommended by the manufacturer, named as SOC_{low} . In order to perform a full discharge during that time, the constant power must be configured following Eq. (2.1). x and n parameters configure the so-called *test object battery* downsized from the full-size battery, and are explained in (IEC, 2013). In our case, the required values are 1 and 3 respectively.

$$P_{BAT}^D = \frac{x \cdot 3}{n} = 1 \text{ kW} \mid x = 1 ; n = 3 \quad (2.1)$$

- 2) Charge for around 480 minutes at constant DC P_{BAT}^C , equal to P_{BAT}^D but with opposite sign. When the most charged cell reaches $V_{CELL,max}$, the converter captures the value of $V_{BAT}(t)$ and decreases the charging current in order to keep constant the voltage. When the current reaches a minimum value (2A), the process stops and battery reaches its maximum SOC. Owing to the losses, if the charge is performed at the same power rate as the discharge, the time for achieving initial SOC will be longer than discharge time.
- 3) The efficiency η_{BAT} is defined as the ratio between net energy discharged and total energy charged. Apart from the internal losses, this ratio takes into account the auxiliary energy consumption of the BMS, necessary for the right operation of the battery.

$$\eta_{BAT} = \frac{E_{BAT}^D}{E_{BAT}^C} \quad (2.2)$$

Therefore, in the particular case of our battery this test is a full discharge/charge cycle test at $P_{BAT} = \pm 1$ kW DC power set-point value. The converter measures $V_{BAT}(t)$ and calculates the required current for discharging (charging) P_{BAT} power from (into) the battery, supplying AC power to (from) the grid at the corresponding P_{ESS} . That current is kept constant for short periods in steps, because the converter does not make that calculation in real time. That means that the power is not exactly constant along the test and it varies in a small range of 16W (1.6%) during discharge and 12W (1.2%) during charge. However, as $V_{BAT}(t)$ decreases (increases) considerably, the converter updates the current setting it upper (lower), in order to try to keep constant the power supplied by (to) the battery. Figure 2.6 shows the discharge-charge process of the efficiency test, displaying the battery voltage and current measured during the same. The discharge process is carried out at $P_{BAT}^D = 1$ kW and it is ended when the most discharged cell

voltage reaches $V_{\text{CELL,min}}$, which in this test occurs when the measured battery voltage is $V_{\text{BAT}}(t) = 240.9$ V. Immediately the charge process starts, operating at $P_{\text{BAT}}^{\text{D}} = -1$ kW. The process and the test ends when the voltage of the most charged cell reaches $V_{\text{CELL,max}}$, which occurs when the measured battery voltage is $V_{\text{BAT}}(t) = 291.5$ V. Table 2.5 shows the results of the test, with values of the parameters measured at the end of discharge and charge processes.

Figure 2.6: Battery voltage and current measured during the efficiency test. The discharge cycle that brings the battery to SOC_{low} is elapsed 480 min at $P_{\text{BAT}} = 1$ kW (a), whereas the charge cycle that recovers SOC_{high} is enlarged around extra 30 min at $P_{\text{BAT}} = -1$ kW (b), in order to overcome the internal losses of the battery and the auxiliary consumption of the BMS among others.

Table 2.5: Values of the parameters monitored during the BESS efficiency test. Converter efficiency values corresponding to discharge and charge processes are mean values of the instant ones monitored along each process.

Test parameter	Discharge	Charge
$V_{\text{BAT}}(t_{\text{start}}); V_{\text{BAT}}(t_{\text{stop}})$	291.9 , 240.9 V	241.1 , 291.5 V
$I_{\text{BAT}}(t_{\text{start}}); I_{\text{BAT}}(t_{\text{stop}})$	3.4 , 4.2 A	-4.1 , -3.4 A
$P_{\text{BAT}}^{\text{D}}$ range (kW)	0.99 , 1.015 kW	-1.009 , -0.997 kW
$E_{\text{BAT}}^{\text{D}}$ (kWh)	8.75 kWh	9.19 kWh
$\bar{\eta}_{\text{CNV}}$	93.15 %	93.13 %
$\text{SOC}_{\text{low}} / \text{SOC}_{\text{high}}$	5%	90%

Battery round-trip efficiency is calculated taking into account all energy flows supplied from and into the battery. In charging process, the DC power supplied by the converter and monitored by the DC indicator is used for charging the battery, but after some losses the effective energy is lower. Both in charge and discharge processes, some energy is lost as heat and another part consumed as auxiliary energy by the BMS unit. In discharge process, the battery supplies effective DC power monitored by DC indicator. This value is the available energy after battery losses, so in order to find the round-trip efficiency of the battery, the effective discharging energy must be compared with the total charging energy. If we replace the values of Table 2.5 in the above mentioned Eq. (2.2), we obtain the efficiency:

$$\eta_{\text{BAT}} = \frac{8.751}{9.194} = 0.9518 \rightarrow 95.18\% \quad (2.3)$$

The instant efficiency of the converter is the relation of its AC and DC bus powers at every monitored scan, measured by the AC and DC meters. But in order to characterise a value for the whole test, the mean value of instant efficiencies is calculated as follows. Being n the total number of scans monitored during the test, converter efficiency in discharge and in charge processes respectively is modelled following Eqs. (2.4) - (2.5). Given that the test is performed at constant power, a simple average is adequate. The values are also included in Table 2.5.

$$\eta_{\text{CNV}}^{\text{D}}(t) = \frac{P_{\text{ESS}}^{\text{D}}(t)}{P_{\text{BAT}}^{\text{D}}(t)} ; \quad \eta_{\text{CNV}}^{\text{C}}(t) = \frac{P_{\text{BAT}}^{\text{C}}(t)}{P_{\text{ESS}}^{\text{C}}(t)} \quad (2.4)$$

$$\eta_{\text{CNV}}^{\text{D}} = \frac{\sum \eta_{\text{CNV}}^{\text{D}}(t)}{n} = 93.15\% ; \quad \eta_{\text{CNV}}^{\text{C}} = \frac{\sum \eta_{\text{CNV}}^{\text{C}}(t)}{n} = 93.13\% \quad (2.5)$$

2.3.2.4 BESS characterisation

Following the model of Figure 2.5 and using the results obtained in previous test, we can model the Li-ion battery based ESS using an efficiency that gives the effective energy that can supply the BESS in AC bus compared to the energy previously stored in it:

$$\eta_{\text{ESS}} = \frac{E_{\text{ESS}}^{\text{D}}}{E_{\text{ESS}}^{\text{C}}} = \frac{E_{\text{BAT}}^{\text{D}} \cdot \eta_{\text{CNV}}^{\text{D}}}{E_{\text{BAT}}^{\text{C}} / \eta_{\text{CNV}}^{\text{C}}} = \frac{E_{\text{BAT}}^{\text{D}}}{E_{\text{BAT}}^{\text{C}}} \cdot \eta_{\text{CNV}}^{\text{C}} \cdot \eta_{\text{CNV}}^{\text{D}} = \eta_{\text{BAT}} \cdot \eta_{\text{CNV}}^{\text{C}} \cdot \eta_{\text{CNV}}^{\text{D}} \quad (2.6)$$

Using the values obtained in the test and displayed in Table 2.5:

$$\eta_{\text{ESS}} = 0.9518 \cdot 0.9313 \cdot 0.9315 = 0.8257 \rightarrow 82.57\% \quad (2.7)$$

The effective capacity of the battery following minimum recommendations of the manufacturer, named as $C_{\text{BAT,rec}}$, can be obtained applying SOC_{low} and SOC_{high} values of Table 2.5 to the nominal capacity given by the manufacturer:

$$C_{\text{BAT,rec}} = (\text{SOC}_{\text{high}} - \text{SOC}_{\text{low}}) \cdot C_{\text{BAT,N}} = 9.01 \text{ kWh} \quad (2.8)$$

However, due to auxiliary energy consumption of internal devices, when the battery is unused during long periods, it can be autodischarged. If this occurs when SOC is in the minimum range, it can be dangerous for the cells. Besides, in order to avoid large depth of discharges (DOD) that would increase cycling degradation of the battery dramatically, further SOC restrictions beyond the minimum recommendation of the manufacturer must be set. A common restriction often used in the literature is a maximum DOD = 80%. So maximum SOC is kept equal to the one given by the manufacturer at 90%, but we propose a typical discharge limit of $\text{SOC}_{\text{min}} = 20\%$. Therefore, the effective battery capacity used in every strategy that is going to be implemented in the laboratory is set by Eq. (2.9), being the 70% of the nominal capacity.

$$C_{\text{BAT}} = (\text{SOC}_{\text{high}} - \text{SOC}_{\text{min}}) \cdot C_{\text{BAT,N}} = 0.7 \cdot 10.6 = 7.42 \text{ kWh} \quad (2.9)$$

Therefore, Eqs. (2.7) and (2.9) characterise the round-trip efficiency, operation limits and the effective capacity of the battery. These values must be taken into account in the tests to be carried out in chapter 5, and also to model the battery when the controller is designed.

2.3.3 Methodology for testing downscaled utility-scale PV+BESS plants

Utility-scale PV+BESS plants require control strategies to operate according to a given grid code but, before they are implemented in a large plant, they need to be tested in a laboratory. Given the size of the target plant, downscaled BESS laboratory tests must be carried out to successfully check the behaviour of the control strategies. On the following, the considerations taken into account in this thesis to design, implement and validate PV power ramp rate control strategies in a laboratory are going to be explained.

2.3.3.1 Scale factor

The size of every test object component at a given test must be in accordance with the hardware of the laboratory and, in this case, the battery is the device that imposes the sizing reference. As explained in previous section, this device is rated $P_{\text{BAT}} = 5 \text{ kW}$ (limited by the power of the converter) and $C_{\text{BAT,N}} = 10.6 \text{ kWh}$. The nominal relation corresponds to 0.5C rate.

However, the nameplate power of Milagro PV plant is 7.2 MW, so the required BESS power to face the fluctuations is expected to be in the order of 5 MW. Taking into account the ratio between the powers of the utility-scale battery and the laboratory battery, a scale factor of

1:1000 is considered the most appropriate for the tests. This means that 1kW of the test is translated to 1 MW of the real system and identically with the energy values; 1 kWh of the test is translated to 1 MWh of the real system. Therefore, the battery of the laboratory is able to test downscaled operation powers of up to 5MW and discharge/charge energies of up to 10.6 MWh. This way, the controller understands that when the instrumentation monitors power and energy values, it must consider them augmented by the scale factor.

2.3.3.2 Sizing of downscaled batteries

Once the scale factor is defined, the test battery must emulate the sizing of the utility-scale battery. This is achieved by taken into account the C-rates of both the utility-scale and the test battery. In our case, the C-rate of the laboratory is low and for testing utility-scale batteries of high C-rates, firstly the power requirements of both batteries must be matched. Let us consider a 10C battery for a particular operation in a utility-scale PV plant, assuming that the power requirement of such battery is $P_{\text{BAT,real}} = 5000 \text{ kW}$ and the capacity is $C_{\text{BAT,real}} = 500 \text{ kWh}$. By means of the scale factor, $P_{\text{BAT,real}}$ is translated to the full-power of the test battery $P_{\text{BAT,test}} = 5 \text{ kW}$. Then, the C-rate of the utility-scale battery is taken into account for emulating the capacity. In this case, the test battery has a 0.5C rate so the capacity used in the test must be limited to $C_{\text{BAT,test}} = 500 \text{ Wh}$ in order to emulate a 10C, i.e. considering non-usable the rest of the effective capacity characterised by Eq. (2.9).

The emulation of capacity limits is achieved by operating in between the limits of the downscaled capacity, accurately monitoring the energy discharged and charged from the battery at every instant of the test. For this, the energy flow must be measured and monitored with high precision in order to know the emulated SOC of the utility-scale battery. It is important to create an advanced controller that monitors the energy at every point of the BESS, i.e. at the AC side of the converter (BESS energy), DC side of the converter (battery input) and effective energy of the battery (considering battery round-trip efficiency).

However, limiting the capacity in that way prevents us from including some phenomena of a Li-ion battery. For instance, the behaviour of a discharge/charge curve shown in Figure 2.6 becomes distorted and it cannot be emulated. Consequently, the battery efficiency variation when operating at different SOC levels cannot be emulated neither. As a proposal for future research, a test battery of the same C-rate as the utility-scale battery would improve the emulation, since the discharge/charge curve and the efficiency would react in a more similar way.

2.3.3.3 About precision errors and auxiliary consumptions of downscaled systems

When we run downsized scale tests in the laboratory, the instrumentation equipment must be as precise as possible, because the measurement error in laboratory scale is translated to a utility-scale error multiplied by the scale factor. Besides, the error between the response of the converter power and the set-point power commanded by the controller is also scaled up by the same factor. Therefore, the controller must take into account such incongruences and must be able to distinguish between an error due to a bad control and an error caused by the scale factor.

In line with that issue, the auxiliary consumptions and standby losses of the converter can be misunderstood too. When the converter of the laboratory is in standby, the AC power meter measures a consumption of 40-50W, which cannot be directly scaled-up by $\times 1000$. A good technique to overcome this problem is the following: To detect when the system is in standby and, instead of scaling up the consumption, to replace it with a typical auxiliary consumption value of a commercial utility-scale BESS converter (Ingeteam, 2017). To that end, if the measured AC power is between 10-50W, the controller checks if the set-point AC power and the measured DC power of the BESS are zero (standby). If so, the scaled-up measured AC power of the BESS is replaced by 60W, typical standby consumption of a 1MVA converter.

CHAPTER 3

Sizing of batteries applied to PV power fluctuations mitigation

Cloud passing over PV generators translates into short-term -seconds or few minutes- PV power fluctuations, which represent troubles for maintaining the frequency and voltage stability in electric grids including PV plants (Marcos et al., 2011b). This issue becomes particularly relevant in relatively small grids, such as islands or scarcely interconnected regions, because smoothing effects derived from the aggregation of geographical dispersion are intrinsically limited (Lave et al., 2012; Marcos et al., 2012). Not surprisingly, a growing number of such small grid regulations are imposing ramp-rate limits to the power injected by PV plants at the point of common coupling. The door for such limitations has been opened in (PREPA, 2012) by the Puerto Rico Electric Power Authority, PREPA, by imposing a 10% of plant nameplate PV power per minute ramp rate limitation, $RR_{\text{LIM}} = 10\%$ per minute. Other TSOs are also concerned about this matter, with even more restrictive ramp rates (CRE, 2012; HECO, 2014; NERC, 2012).

Accomplishing such regulations requires a battery energy storage system (BESS), able to inject (absorb) power when the PV power decreases (increases) faster than the prescribed limit. In previous works, procedures have been proposed to characterise PV power fluctuations and to size batteries for complying with a certain power ramp rate limitation. Despite part of the fluctuations can be smoothed by geographically dispersing PV plants (Lave et al., 2012; Marcos et al., 2012; Murata et al., 2009), strict grid regulations demand buffering capabilities to individual PV plants. By analysing PV powers fluctuations statistically, in (Perez and Hoff, 2013; van Haaren et al., 2015) the fluctuations mitigation is addressed by means of energy storage systems. In line with this and based on one second long-term observations at PV plants of different sizes, a model for the “worst fluctuation” (WF) was proposed in (Marcos et al., 2014b). Roughly, it corresponds to the darkening of the PV array (from clear sky irradiance to diffuse irradiance) by a cloud moving at about 80-90 km/h, which is also confirmed by (Lave and Kleissl, 2013). Providing the battery can be fully recharged between two consecutive fluctuations by means of a SOC driven control, the WF model allows sizing the battery for full compliance of ramp-rate limits (Marcos et al., 2014a).

Adhering exclusively to ramp rate control requirements, it leads to rather large and expensive batteries which are likely impractical because such worst fluctuation seldom occurs and even in case of occurrence its consequences are not necessarily catastrophic. Although, batteries are undergoing an intense development in their technological features, leading them to a fall in their cost (Gallagher et al., 2011; Wood et al., 2015; Yoo et al., 2014), they are still rather expensive. As a consequence, smaller batteries, able to absorb the majority but not all the fluctuations, are likely more practical. In this context, some authors have pointed out the need of reducing the storage requirements for ramp rate applications. For instance, in (van Haaren et al., 2015) the authors proposed two algorithms for smoothing power fluctuations, simulating ramp rate failures of a PV plant with different storage sizes up to smoothing 99% of fluctuating events.

However, there is a gap in the current state of the art about the analysis of size reduction for different ramp rate limits and power data sampling requirements. It is necessary to deeply address the effects of limiting the battery power and energy capacity requirements, which would allow boosting the economic feasibility of using them in large PV plants. This chapter addresses the sizing of practical batteries by taking into consideration, both, the fluctuation occurrence and the penalties in case of non-compliance of the prescribed ramp-rate limitations (Makibar et al., 2017). In this context, the objective of this chapter is double:

- To model the ramp rate limit failures derived from the reduction of battery power and capacity requirements, considering different ramp rate limits and the sampling time used for evaluating it.
- To apply the battery reduction analysis to the Puerto Rico grid code requirements, taking into account the specific conditions and power curtailments imposed as penalty.

3.1 Relation between battery size and ramp rate limitation compliance

A ramp is defined by the sudden variation of the output of a PV plant caused by an irradiance fluctuation. When power output falls suddenly due to cloud cover, a ramp occurs. The rate of change of power output due to an irradiance fluctuation which lasts a specific duration, is called the facility's ramp rate (RR) and it can be expressed as a percentage of the plant's nominal power per unit of time differential, defined in Eq. (3.1).

$$RR = \frac{[P_{PV}(t) - P_{PV}(t - \Delta t_R)]/P_N}{\Delta t_R} \quad (3.1)$$

where $P_{PV}(t)$ is the PV plant output power at a given instant t , P_N is the PV plant nameplate power capacity and Δt_R is the time differential of the ramp rate, typically equalling to 1 min.

3.1.1 Method for calculating P_{BAT} and E_{BAT} series and battery size

Figure 3.1 shows a typical downwards PV power fluctuation caused by a cloud passing over a PV generator and the corresponding evolution of the power required from the battery to preserve a given ramp-rate limitation, RR_{LIM} . For a given fluctuation, battery power, $P_{\text{BAT}}(t)$, is given by the difference between allowable power to be injected to the grid, $P_{\text{GRID}}(t)$, and the power from the PV plant, $P_{\text{PV}}(t)$. $P_{\text{GRID}}(t)$ is calculated as an increase or decrease of PV power limited to the maximum allowable variation, ΔP_{RR} , in each studied time step. This is described by Eqs. (3.2) - (3.4). Considering Δt the time step of the analysed production data series, the ramp rate defined in Eq. (3.1) is adapted to each step. The process is the same for upwards fluctuations, but in this case with the opposite sign. As a matter of convenience, battery discharge (downwards fluctuation) is considered as positive $P_{\text{BAT}}(t)$, while battery charge (upwards fluctuation) is considered as negative $P_{\text{BAT}}(t)$.

$$\Delta P_{\text{RR}} = P_{\text{N}} \cdot \frac{RR_{\text{LIM}}}{\Delta t_{\text{R}}/\Delta t} \quad (3.2)$$

$$P_{\text{GRID}}(t) = P_{\text{GRID}}(t - \Delta t) + \min(P_{\text{PV}}(t) - P_{\text{PV}}(t - \Delta t), \Delta P_{\text{RR}}) \quad (3.3)$$

$$P_{\text{BAT}}(t) = P_{\text{GRID}}(t) - P_{\text{PV}}(t) \quad (3.4)$$

Figure 3.1: Battery power and capacity characterisation in order to comply with a given RR and smooth fluctuations.

The displayed downwards fluctuation starts at $t_{\text{start}} = 400$ s and stops at $t_{\text{end}} = 850$ s and it represents the maximum battery power ($P_{\text{BAT}} = 5132$ kW) and capacity ($C_{\text{BAT}} = 336$ kWh) requirement of a 7.243 MW PV plant in northern Spain observed in a particular year, for $RR = 10\%/min$.

Extending the exercise along a representative period (one full year in our case), yields the time series of required battery power of every fluctuation event. The nominal battery power requirement for full ramp rate compliance, $P_{\text{BAT,MAX}}$, is calculated as the maximum of the $P_{\text{BAT}}(t)$ time series, defined in Eq. (3.5).

$$P_{\text{BAT},\text{MAX}} = \max(|P_{\text{BAT}}(t)|) \quad (3.5)$$

The energy managed by the battery during each downwards (upwards) fluctuation is calculated by the integral of the battery power curve defined between the limits of each discharge (charge) event, $t_{\text{D},\text{start}}$ and $t_{\text{D},\text{end}}$ ($t_{\text{C},\text{start}}$ and $t_{\text{C},\text{end}}$) respectively as shown in Figure 2.2. Note that, despite the downwards-upwards symmetry of the PV power, the net annual energy flow from the battery is negative, i.e. the battery SOC decreases. Because of that, a battery managed just to absorb PV power fluctuations tends to progressively discharge along the year. However, it has been shown that such loss of charge can generally be compensated by recharging the battery from the PV array before the next fluctuation occurs (de la Parra et al., 2015; Marcos et al., 2014a). We will here adhere to this practice, because it just minimizes the battery size requirements. Hence, the energy requirement E_{BAT} for absorbing a complete fluctuation event, either downwards or upwards fluctuation, is given by the following equations, where D or C define a battery discharge or charge operation respectively.

$$E_{\text{BAT}}^{\text{D}} = \int_{t_{\text{D},\text{start}}}^{t_{\text{D},\text{end}}} P_{\text{BAT}}(t) dt \quad (3.6)$$

$$E_{\text{BAT}}^{\text{C}} = \int_{t_{\text{C},\text{start}}}^{t_{\text{C},\text{end}}} P_{\text{BAT}}(t) dt \quad (3.7)$$

The series of battery energy requirements for each discharge and charge event are calculated by integrating the battery power along each fluctuation event, defined as the period between two consecutive battery power changes of sign. The maximum value of discharge events, $E_{\text{BAT},\text{MAX}}^{\text{D}}$, represents the maximum energy supplied by the battery during the most energy-restrictive downwards fluctuation, while the absolute value of the minimum of charge events, $|E_{\text{BAT},\text{MIN}}^{\text{C}}|$, is the maximum energy stored in the battery during the most energy-restrictive upwards fluctuation. The finally required battery energy capacity for full ramp rate limitation compliance, $C_{\text{BAT},\text{MAX}}$, is given by the maximum of both discharge and charge energy requirement values, defined in Eq. (3.8).

$$C_{\text{BAT},\text{MAX}} = \max(E_{\text{BAT},\text{MAX}}^{\text{D}}, |E_{\text{BAT},\text{MIN}}^{\text{C}}|) \quad (3.8)$$

However the energy capacity requirement also depends on the implemented control algorithm. In (Marcos et al., 2014b) a basic control was presented in order to continuously recover battery SOC to its reference point. This algorithm restores the battery to $\text{SOC} = 50\%$ before the start of every new fluctuation, being able to discharge it completely to smooth a sudden maximum downwards fluctuation, or on the contrary to leave enough capacity to charge the excess of a maximum upwards fluctuation. For this algorithm, this is achieved by doubling $C_{\text{BAT},\text{MAX}}$.

Figure 3.2 shows the control diagram of the strategy. $P_{\text{BAT}}(t)$ output of the system is a controlled variable, thanks to the input of a manipulated variable to the plant. The output

variable is adapted by a feedback element to obtain the required feedback signal. In this case, the battery power is integrated in order to obtain the energy stored in the battery after supporting the fluctuation, $E_{BAT}(t)$. This energy is compared to the reference input, which is the desired battery energy to be maintained after each fluctuation event. The error between them is the actuating signal which is sent through the feedback loop to the feedback controller. This element amplifies the actuating signal by a proportional factor K in order to add the response to the disturbance and to calculate the manipulated input variable of the system. The higher the K factor, the faster will be the SOC recovery.

Figure 3.2: Basic SOC control diagram. The output of the RR limiter is controlled by a feedback loop SOC controller, in order to recover the SOC of the battery to its reference point after each fluctuation.

Implementing the strategy in the simulation, consecutive fluctuations are considered as independent, so the energy requirements of discharge and charge events can be considered independently. Hence, for a given RR and Δt combination, the study of battery size reduction is carried out by analysing the histogram of the resulting battery power time series and the histogram of the resulting series of battery energy requirements of each event.

3.1.2 Results and discussions

a) Battery size for 100% fluctuations smoothing

In most cases, given the high value of the maximum power, it makes sense to suppose that $P_{BAT,MAX}$ and $C_{BAT,MAX}$ will correspond to the same fluctuation event. For instance, Figure 3.1 shows an event in which maximum power and energy requirement of the year are fully used, in this case discharging. However, this is not necessarily always like this, as energy requirement also depends on the length of the event. Therefore both power and capacity sizing must be calculated independently. For a given PV plant and location, the result of this exercise depends on the values of RR_{LIM} and Δt . Given that $P_{PV}(t)$ data were recorded with one second sampling time, we can extend the exercise to any Δt being multiple of 1 s, depending on the monitoring requirements of each particular grid code. Table 3.1 shows $P_{BAT,MAX}$ and $C_{BAT,MAX}$ values for absorbing 100% of fluctuations of the studied year, in order to comply with RR values of 5, 7.5, 10, 20 and 30%/min and considering $\Delta t = 2$ s.

Table 3.1: Battery size for full compliance of different ramp rate limits at Milagro PV plant.

RR in %/min	Power in kW (% of P_N)	Capacity in kWh (min)
5	5447 (75.21)	765 (6.3)
7.5	5287 (73)	471 (3.9)
10	5132 (70.86)	336 (2.78)
20	4634 (64)	160 (1.3)
30	4170 (57.6)	95 (0.8)

In order to generalise the model for its suitability along different years, instead of using the full battery sizing expressions of Eqs. (3.5) and (3.8), the maximum battery storage requirements, given by the so called “worst fluctuation model”, WF, are used. (Marcos et al., 2014b).

The model states that the worst downwards power fluctuation observed at the output of a PV plant follows an exponential decay function, starting at P_N , just before the instant when the cloud approaches, and falling to $0.1P_N$, instant when the cloud totally covers the PV array. The worst upwards fluctuation is just the inverse, an exponential rise from $0.1P_N$ to P_N . Figure 3.3 shows the WF model, including the allowable ramp injected to the grid (10%/min in this case) and the resulting function of the battery power required to match it.

Figure 3.3: Worst Fluctuation model, used for sizing the battery to absorb the strongest fluctuation that could be observed at the output of a PV plant, developed in (Marcos et al., 2014b).

The equations that rule the model are the following:

$$P_{PV,WF}(t) = 90 e^{\left(-\frac{t}{\tau}\right)} + 10 \quad (3.9)$$

$$P_{GRID,WF}(t) = 90 - r_{\max} t + 10 \quad (3.10)$$

$$P_{BAT,WF}(t) = P_{PV,WF}(t) - P_{GRID,WF}(t) \quad (3.11)$$

Where $r_{\max}$ is the maximum allowed ramp in (%/s). The time constant τ is empirically correlated with the shortest dimension of the perimeter of the PV plant, l , so, the larger its size, the slower the power decay, which in practice means that the fluctuation is smoother.

$$\tau = 0.042 \cdot l - 0.5 \quad (3.12)$$

For every size PV plant, the instant values are calculated multiplying the nameplate capacity P_N by the Eqs. (3.9) - (3.11). As shown, the instant value of the battery power for absorbing the fluctuation is given by $P_{\text{BAT,WF}}(t)$, which can be developed to the following expression:

$$P_{\text{BAT,WF}}(t) = \frac{P_N}{100} \left[90 \left(1 - e^{-t/\tau} \right) - r_{\max} t \right] \quad (3.13)$$

Obtaining the maximum of that function, the maximum battery power requirement is calculated:

$$P_{\text{BAT,WF}} = \frac{P_N}{100} \left[90 - \tau \cdot r_{\max} \left(1 + \ln \left| \frac{90}{\tau \cdot r_{\max}} \right| \right) \right] \quad (3.14)$$

where $P_{\text{BAT,WF}}$ is defined in (kW), $r_{\max}$ in (%/s) and τ in (s). In order to calculate the required energy capacity to face the fluctuation, Eq. (3.13) must be integrated along the time span that lasts from the beginning of the worst fluctuation to the instant when the ramp reaches $0.1P_N$, defined as $T_R = 90/r_{\max}$.

$$C_{\text{BAT,WF}} = \int_0^{T_R} P_{\text{BAT,WF}}(t) dt = \frac{0.9 P_N}{3600} \left[\frac{90}{2 \cdot r_{\max}} - \tau \right] \quad (3.15)$$

where $C_{\text{BAT,WF}}$ is given in (kWh). Therefore, the maximum battery power and capacity requirements to absorb every fluctuation along different years are $P_{\text{BAT,WF}}$, and $C_{\text{BAT,WF}}$ respectively. For the different ramp rate values considered in this work, the design battery power and capacity values are displayed in Table 3.2.

Table 3.2: Battery size for full compliance of different ramp rate limits at Milagro PV plant, as given by the Worst Fluctuation model.

<i>RR in %/min</i>	<i>Power in kW (% of P_N)</i>	<i>Capacity in kWh (min)</i>
5	5713 (78.9)	925 (7.7)
7.5	5416 (74.8)	600 (5)
10	5148 (71.1)	437 (3.6)
20	4262 (58.8)	192 (1.6)
30	3558 (49.1)	111 (0.9)

As it can be seen, the values are similar to the ones obtained in the previous analysis. Most of the values of Table 3.1 are slightly lower because they are derived from the fluctuations of a single year, while WF model describes the worst case possible. As mentioned in section 3.1.1, depending on the control algorithm applied to the operation of the battery, its capacity $C_{\text{BAT,WF}}$ should be doubled. However, there are methods for avoiding this, for example by absorbing the upwards fluctuations moving the operation point of the plant inverters out of the MPP, which involves some PV energy loss virtually insignificant. This issue will be analysed separately in section 4.1. The present work is focused on the relation between ramp rate compliance and battery size reduction, analysing statistically the power and energy requirements of every downwards and upwards fluctuation event as a fraction of reference values, i.e. $P_{\text{BAT,WF}}$ and $C_{\text{BAT,WF}}$ of Table 3.2.

b) Calculation of histograms of P_{BAT} and E_{BAT} series

For analysing battery size reduction, 10 iterative simulations were carried out, one for each RR and Δt combination, obtaining the respective P_{BAT} and E_{BAT} series as explained in section 3.1.1. If we split into bins of a histogram the resulting data of battery power or energy series, we can define certain power or energy intervals. For the whole series, any P_{BAT} and E_{BAT} of any fluctuation event lies in between one of those intervals, considering them as fractions of full-size $P_{\text{BAT,WF}}$ and $C_{\text{BAT,WF}}$, defined in Eqs. (3.16) and (3.17):

$$P_{\text{BAT}} = k_p \cdot P_{\text{BAT,WF}} \quad (3.16)$$

$$E_{\text{BAT}} = k_c \cdot C_{\text{BAT,WF}} \quad (3.17)$$

where k_p and k_c are the interval limits ranging from 0 to 1. The core purpose is to predict the occurrence of battery power and energy values along the year higher than P_{BAT} and E_{BAT} , with which the reduced battery could not cope.

Figure 3.4 shows for a full year the histograms of P_{BAT} and E_{BAT} , for RR values of 5, 7.5, 10, 20 and 30%/min and Δt values of 2 s and 30 s. For the sake of simplicity, only discharge power (left) and energy (right) histograms have been displayed (downwards fluctuations) and the explanation will focus on these parameters. However, histograms of P_{BAT} and E_{BAT} for upwards fluctuations have also been analysed with the same method.

Moreover, looking for presentation clarity, the histograms of Figure 3.4 consider only the range higher than a threshold $u = 0.1\%$, ($P_{\text{BAT}} > u \cdot P_{\text{BAT,WF}}$ and $E_{\text{BAT}} > u \cdot C_{\text{BAT,WF}}$). This makes sense as it corresponds to neglecting signal values below the measurement equipment resolution.

Figure 3.4: Battery discharge power (left) and energy (right) histograms along a full year, for $RR = 5, 7.5, 10, 20$ and $30\%/min$ and for $\Delta t = 2$ s (a,b) and $\Delta t = 30$ s (c,d).

This way, normalising these distributions to their respective integrals on the interval $[u, 1]$ equalling to 1, cumulative frequencies for any given P_{BAT} can be calculated, which can be understood as the conditional probability density functions of P_{BAT} given $P_{BAT} > u$. In turns, the probability of $P_{BAT} > u$ is given by the ratio between the time the battery is operating beyond the threshold to the total time the battery is operating, $T_{P_{BAT} > u} / T_{P_{BAT} > 0}$. This ratio also depends on applicable RR and Δt .

c) Analytical expressions of distributions

Looking for an analytical expression for the histograms of Figure 3.4, it was found that the most appropriate fit was an exponential function as the one described in Eq. (3.18). It keeps a good balance between a high goodness of fit and simplicity. The goodness of the fit of each RR - Δt combination distribution is proven later on in Table 3.3 with its respective R^2 index.

$$f(x)_{|P_{BAT} > u} = ae^{-bx} \quad (3.18)$$

In the case of power distribution, x corresponds to the power fraction $P_{BAT}/P_{BAT,WF}$. Assuming $u \ll 1$ and given that the area below each frequency distribution equals to 1:

$$\begin{aligned}
F(x=1)_{|P_{\text{BAT}}>u} &= \int_u^1 f(x)_{|P_{\text{BAT}}>u} dx = a \int_u^1 e^{-bx} dx \\
&= \frac{a}{b} (e^{-bu} - e^{-b}) \approx \frac{a}{b} e^{-bu} = 1 \rightarrow a = be^{bu}
\end{aligned} \tag{3.19}$$

Resulting in a simplification of Eq. (3.18) to only one parameter:

$$f(x)_{|P_{\text{BAT}}>u} = be^{-b(x-u)} \tag{3.20}$$

Table 3.3 shows the curve fitting parameter b and the goodness of the fit for each histogram of every combination of RR and Δt . As it can be seen, R^2 values range between 0.948 and 0.998.

Table 3.3: Curve fitting parameter and goodness of fit index for each RR_{LIM} and Δt combination.

Δt	Fit	RR (% P_N /min)									
		P_{BAT} (discharge)					E_{BAT} (discharge)				
		5	7.5	10	20	30	5	7.5	10	20	30
2	b	17.57	17.63	18.08	20.31	21.15	69.56	66.62	64.38	60.54	58.05
	R^2	0.948	0.952	0.956	0.960	0.960	0.995	0.993	0.993	0.993	0.992
30	b	10.54	9.92	9.41	8.20	7.10	56.82	52.03	51.09	47.49	35.07
	R^2	0.980	0.990	0.995	0.998	0.997	0.991	0.990	0.988	0.987	0.998

d) Model of ramp rate limitation non-compliance as a function of the battery size.

The model could be used as a frequency distribution tool to predict with good accuracy the occurrence of a certain battery power and the energy managed by the battery during a fluctuation event. As a consequence, the cumulative frequency of a certain charge power value of being higher than a given $P_{\text{BAT}}/P_{\text{BAT,WF}}$ fraction, defined as k_p , is given by integrating Eq. (3.20) defined in the range higher than this fraction. Note that $u \ll 1$ assumption is also taken into account, which results in an easy analytical expression.

$$F(x > k_p)_{|P_{\text{BAT}}>u} = \int_{k_p}^1 f(x)_{|P_{\text{BAT}}>u} dx = \int_{k_p}^1 be^{-b(x-u)} dx = e^{-b(k_p-u)} \tag{3.21}$$

The previous equation is also valid for expressing charge power cumulative frequency and even for discharge or charge energy cumulative frequency, using appropriate b parameter in each case and replacing k_p with k_c in the cases of energy. Note that Eq. (3.21) represents the conditional probability given $P_{\text{BAT}} > u$. In order to calculate the total probability related to the time when PV plant is injecting power, it is necessary to take into account the battery discharging time supporting downwards fluctuations and the battery discharging time beyond the threshold u . These time periods are defined in Table 3.4 while their relationship as operating factors, for different RR and Δt , are explained in Table 3.5. These tables include the definitions

for charge power times. Subscript d is used in operating factors for discharge and c is used for charge.

Table 3.4: Yearly PV plant and battery operation periods.

Period	Description
T_D	Time while PV plant is generating (4084h)
$T_{P_{BAT} \neq 0}$	Total battery operating time
$T_{P_{BAT} > 0}$	Battery discharging time, downwards fluctuations
$T_{P_{BAT} < 0}$	Battery charging time, upwards fluctuations
$T_{P_{BAT} > u}$	Battery discharging time, beyond threshold
$T_{P_{BAT} < -u}$	Battery charging time, beyond threshold

Table 3.5: Yearly battery operating factors for 2 s and 30 s sampling time and 5, 7.5, 10, 20 and 30% P_N/min ramp rate limitations.

Operating factors	Δt	$RR (\%P_N/\text{min})$				
		5	7.5	10	20	30
$OF = \frac{T_{P_{BAT} \neq 0}}{T_D}$	2	0.229	0.167	0.128	0.054	0.026
	30	0.175	0.121	0.088	0.030	0.012
$OF_d = \frac{T_{P_{BAT} > 0}}{T_D}$	2	0.116	0.085	0.065	0.027	0.013
	30	0.089	0.062	0.045	0.015	0.006
$OF_c = \frac{T_{P_{BAT} < 0}}{T_D}$	2	0.113	0.083	0.063	0.027	0.013
	30	0.086	0.059	0.043	0.015	0.006
$OF_{d,u} = \frac{T_{P_{BAT} > u}}{T_{P_{BAT} > 0}}$	2	0.925	0.937	0.950	0.957	0.963
	30	0.986	0.988	0.989	0.990	0.990
$OF_{c,u} = \frac{T_{P_{BAT} < -u}}{T_{P_{BAT} < 0}}$	2	0.920	0.933	0.946	0.957	0.964
	30	0.986	0.988	0.990	0.991	0.994

So, total probability of occurrence of an instant with battery discharge power higher than a given reduced fraction k_p is calculated by means of the following expression:

$$F(x > k_p) = OF_d \cdot OF_{d,u} \cdot F(x > k_p)_{|P_{BAT} > u} = OF_d \cdot OF_{d,u} \cdot e^{-b(k_p - u)} \quad (3.22)$$

However, the previous equation cannot be directly used for capacity reduction analysis. Operating factor parameters of Table 3.4 are calculated by taking into account battery operating times against PV plant production times. It means that the cumulative frequency is defined for the time domain, representing the probability of occurrence of a battery power requirement higher than k_p in a given PV power generating instant of the year. But battery energy histogram is defined for discharge (charge) events rather than for time domain. Like this, each discharged (charged) energy amount is associated to a single fluctuation event, being the frequency distribution related to the total amount of fluctuation events of its type. Consequently, the approach for capacity reduction analysis is different. The model will give a probability of occurrence of an event with a required capacity higher than a given $E_{BAT}/C_{BAT,WF}$. In other words, it gives information about how likely it is not to have enough capacity for absorbing the complete fluctuation event, once immersed in it. Eq. (3.23) describes the probability for

discharging energy events (downwards fluctuations). In order to consider only significant energy flows higher than the threshold u , the fraction of the significant events observed in the studied year, SF , is applied to Eq. (3.21). Significant events description and significant events fractions for different RR and Δt are shown in Table 3.6 and Table 3.7 respectively. Subscript d is used for fractions of discharge events and c is used for charge ones.

$$F(x > k_c) = SF_d \cdot F(x > k_c)_{|E_{BAT} > u} = SF_d \cdot e^{-b(k_c - u)} \quad (3.23)$$

Table 3.6: Significant battery energy events definition, with energy transfer beyond threshold u .

Significant events	Description
$E_{BAT} > u$	Events with discharged energy beyond threshold
$E_{BAT} < -u$	Events with charged energy beyond threshold

Table 3.7: Significant battery energy events fraction, for 2 s and 30 s sampling time and 5, 7.5, 10, 20 and 30 % P_N /min ramp rate limitations.

Significant events fraction	Δt	RR (% P_N /min)				
		5	7.5	10	20	30
$SF_d = \frac{E_{BAT} > u}{E_{BAT} > 0}$	2	0.372	0.437	0.475	0.537	0.574
	30	0.780	0.848	0.889	0.951	0.971
$SF_c = \frac{E_{BAT} < -u}{E_{BAT} < 0}$	2	0.366	0.439	0.476	0.542	0.587
	30	0.758	0.826	0.880	0.947	0.982

The results of the model are in accordance to previous studies carried out, both in terms of fluctuations characterisation and in terms of battery size assessment for facing them. The battery requirements model developed in the present study follows an exponential function similar to the one developed in (Marcos et al., 2011a) for fluctuations description. This makes sense, as the battery size reduction is correlated with the fluctuations size and their occurrence. In a similar way, the model also follows the exponential behaviour of the non-compliances function described in (van Haaren et al., 2015), for both battery power and capacity requirements of a PV plant with a nameplate power capacity similar to the one used in this work.

e) Example of application

Finally, as an illustrative example, in Table 3.8 and Table 3.9 the probability of not complying with different ramps with certain reduced battery is explained. In terms of battery discharge power for downwards fluctuations, the probability of incurring in instants with battery power requirements higher than 10% and 20% of $P_{BAT,WF}$ is shown in Table 3.8, both as conditional probability given that power is higher than u and as total probability. In terms of battery discharge capacity, the probability of a discharge event to need more capacity than 5% and 10% of the design battery capacity $C_{BAT,WF}$ is shown in Table 3.9. Again, left part of the table shows the conditional probability for discharge events with $E_{BAT} > u$, while right part is the total probability for every discharge event. In order to have a global view, the exercise has also been extended to power charge instants and energy charge events, not included here for simplicity reasons.

Table 3.8: Probability of occurrence of non-compliances with two different battery power fractions, relative and absolute.

$P_{BAT}/P_{BAT,WF}$	Δt	$F(x > k_p)_{ P_{BAT}>u} \cdot 100$ (%)					$F(x > k_p) \cdot 100$ (%)				
		5	7.5	10	20	30	5	7.5	10	20	30
0.1	2	17.6	17.5	16.7	13.4	12.3	1.9	1.4	1.0	0.4	0.2
	30	35.2	37.4	39.4	44.4	49.5	3.1	2.3	1.8	0.7	0.3
0.2	2	3.0	3.0	2.7	1.8	1.5	0.3	0.2	0.2	0.1	0.0
	30	12.3	13.9	15.4	19.6	24.3	1.1	0.9	0.7	0.3	0.1

Table 3.9: Probability of occurrence of non-compliances with two different battery capacity fractions, relative and absolute.

$E_{BAT}/C_{BAT,WF}$	Δt	$F(x > k_c)_{ E_{BAT}>u} \cdot 100$ (%)					$F(x > k_c) \cdot 100$ (%)				
		5	7.5	10	20	30	5	7.5	10	20	30
0.05	2	3.3	3.8	4.3	5.2	5.8	1.2	1.7	2.0	2.8	3.3
	30	6.2	7.8	8.2	9.8	17.9	4.8	6.6	7.3	9.3	17.4
0.1	2	0.1	0.1	0.2	0.2	0.3	0.0	0.1	0.1	0.1	0.2
	30	0.4	0.6	0.6	0.9	3.1	0.3	0.5	0.6	0.9	3.0

The model proves that the potential for reducing the battery size given by the worst fluctuation model is high. The number of failures in terms of RR limitation compliance of a battery with a power 20% of $P_{BAT,WF}$ and a capacity 10% of $C_{BAT,WF}$ is scarce, following the low occurrence of sudden fluctuations.

3.2 Case study: Optimal battery size in Puerto Rico considering penalties

Taking into account current grid codes, optimal battery size from the viewpoint of the PV plant owner results from a trade-off between battery investment costs and applicable penalties in case of non-compliance with RR regulations. The larger the battery size, the larger the compliance. Hence, the cheaper the unitary cost of battery and the larger the penalties are, the larger the optimal battery is.

The only penalties proposal known to date is included in the regulation prepared by the Puerto Rico Electric Power Authority (PREPA). This organisation has established minimum technical requirements (MTR) for interconnection of photovoltaic power plants, developed with the support of different public authorities like US Department of Energy, NREL and the association of renewable energy producers of Puerto Rico (APER) (Gevorgian and Booth, 2013; PREPA, 2012). Despite they are out of the scope of the present work, it is worth mentioning that the code includes other features apart from RR limitations. It gives specifications about voltage fault ride-through and short-circuit ratio, frequency ride-through and frequency response, power quality criteria and voltage and reactive power regulation through power factor.

In the particular case of RR limitation, the proposal considers penalties through PV power curtailment for complete week periods, as a function of RR non-compliance observed the week before. This code limits the RR to 10%/min. For this scenario, the application of the battery size reduction assessment will be carried out taking into consideration the specific conditions, adapting the simulation process accordingly.

3.2.1 Methodology

The simulation implements a SOC control algorithm explained in section 3.1.1, with the full-size battery power and capacity reference values given by the WF model (Table 3.2) and corresponding to $P_{\text{BAT,WF}}$ and $2 \cdot C_{\text{BAT,WF}}$ respectively. Therefore, a full-size battery will operate up to a maximum rated $P_{\text{BAT,WF}}$ in each fluctuation event. However, the capacity reserved at the beginning of each type of fluctuation (downwards or upwards) will be $C_{\text{BAT,WF}}$, i.e. half of the reference capacity for each type.

The practical implementation procedure, based on the regulation proposal, consists on the following steps:

1) PV plant injected power monitoring

P_{GRID} is scanned at 2 seconds rate ($\Delta t = 2$ s) during all the time the PV plant is injecting power into the grid.

2) Ramp rate compliance evaluation of the scans

For each scan, the ramp rate compliance, RRC, is evaluated with a scan differential method for measuring the RR . For example, a RR of 10%/min will be traduced to 10%/30 for $\Delta t = 2$ s, evaluating accordingly every 2 s scan of an entire week during producing hours of the plant. Like this, for every week both compliant and non-compliant scans are aggregated to calculate weekly RRC.

Reducing the battery power in a certain magnitude k_p will prevent the battery from absorbing some fluctuations, lowering RRC of the scans involved in them. If the required instant power $P_{\text{BAT}}(t)$ (see Eq. (3.4)) to be managed by the battery in either downwards or upwards fluctuations exceeds its reduced power (Eq. (3.16)), the step is non-compliant for power (NC_P), which is done evaluating the following expression:

$$|P_{\text{BAT}}(t)| \geq P_{\text{BAT,WF}} \cdot k_p \quad (3.24)$$

The weekly non-compliance grade of the PV plant in terms of power $NC_P(\%)$ is obtained expressing the non-compliant scans as a percentage of total scans during generation periods, N_{ON} .

$$NC_P(\%) = 100 \cdot \frac{NC_P}{N_{\text{ON}}} \quad (3.25)$$

Reducing battery capacity by a certain magnitude k_c will prevent the battery from absorbing some fluctuations, lowering RRC . The analysis counts the battery energy flow of every 2 s step by integrating $P_{\text{BAT}}(t)$ in every fluctuation (see Eqs. (3.6) and (3.7)). If the cumulative sum of the energy of every step at a point of the fluctuation overflows the reduced battery capacity (Eq.

(3.17)), either in a charge or discharge process, this step (and as a consequence the rest of the following steps of the fluctuation) will be marked as non-compliant for capacity (NC_C). This process is cumulative, which means that for a step which lasts from $t = n$ to $t = n + \Delta t$, all energy managed previously since the start of the fluctuation ($t = 0$) must be considered. This is evaluated with the following equation:

$$\left| \int_0^t P_{\text{BAT}}(t) dt + \int_t^{t+\Delta t} P_{\text{BAT}}(t) dt \right| \geq C_{\text{BAT,WF}} \cdot k_c \quad (3.26)$$

The weekly non-compliance grade of the PV plant in terms of capacity $NC_C(\%)$ is obtained expressing the number of non-compliant scans as a percentage of total scans during generation periods.

$$NC_C(\%) = 100 \cdot \frac{NC_C}{N_{\text{ON}}} \quad (3.27)$$

3) Weekly RRC calculation

For each week, a RR compliance index (RRC_w) is calculated with the following expression:

$$RRC_w(\%) = 100 \cdot \left(1 - \frac{NC}{N_{\text{ON}}} \right) \quad (3.28)$$

where NC is the number of non-compliant scans, obtained adding NC_P and NC_C scans and being careful of not adding twice a single scan that is simultaneously non-compliant in terms of power and capacity.

4) Weekly curtailments calculation

In the particular case of Puerto Rico, there are linked dynamics of RRC and curtailment which justify the need of a weekly assessment of the effects derived from reducing battery size, instead of the annual analysis explained in section 3.1. Due to statistical factors such as tolerance, metering accuracy or latency, the weekly minimum compliance to avoid curtailments is proposed as $RRC_{\text{min}} = 98.5\%$. Consequently, if in a weekly basis less than 98.5% of the production scans comply with the proposed RR_{LIM} , grid operator will impose a curtailment for the next week. Curtailments of a given week Cu_w are as follows:

$$Cu_w = (Cu_{w-1} - (RRC_{\text{min}} - RRC_{w-1})) \quad (3.29)$$

$$P_{\text{PV},w} = P_N \cdot Cu_w \quad (3.30)$$

where Cu_{w-1} and RRC_{w-1} are respectively the curtailment and ramp rate compliance calculated for the previous week, while $P_{PV,w}$ is the weekly maximum injection power. Note that the curtailment factor is cumulative; which means that for correcting it for a given week, previous week RRC must be better than the minimum one. As a result, $P_{PV,w}$ for each week is calculated applying the correspondent curtailment factor to the PV plant nominal power P_N .

5) Yearly PV energy production calculation

In order to evaluate the effect of combining both battery power reduction and capacity reduction, the most objective indicator is the yearly produced PV energy. This value is obtained performing a yearly simulation for each k_p and k_c combination. Assessing RRC and the involved curtailments along the full year of each simulation, the power injected into the grid for each combination of k_p and k_c , $P_{GRID,k_p,k_c}(t)$ is obtained. Integrating each of these time series for the total scans of the year n , total yearly energy injected to the grid for every combination is obtained.

$$E_{GRID,k_p,k_c} = \int_0^n P_{GRID,k_p,k_c}(t) dt \quad (3.31)$$

This parameter is useful for selecting a proper combination of k_p and k_c .

3.2.2 Results and discussions

Figure 3.5 illustrates the linked dynamics of RRC and curtailment corresponding to the same Milagro PV power time series of the previous section, using a battery whose power is just 10% of $P_{BAT,WF}$. Figure 3.5a shows the $P_{PV}(t)$ evolution along a day of week 31 (last week of July 2009) without (blue) and with $Cu_{31} = 60\%$ weekly curtailment factor (red). This value results from the previous week RR compliance, RRC_{30} , and the accumulated Cu_{30} (week 30: $RRC_{30} = 97.5\% \mid Cu_{30} = 0.61$). From the beginning of the year, the accumulated curtailment dropt to $Cu_{30} = 61\%$, so adding the 1% of under-compliance incurred in week 30, Cu_{31} is reduced in this amount. Figure 3.5b shows the corresponding battery power required for full RRC of that week at full available $P_{PV}(t)$ (blue) and if plant injects with curtailed limit of $P_{PV,31}$ (red). The direct link between curtailment and RR compliance becomes evident. Battery requirements for full RR compliance are lower for the curtailed PV plant than for the non-curtailed one. Figure 3.5c and d show yearly evolution of RRC and power curtailment.

Figure 3.6 shows the corresponding evolution of weekly energy loss, caused by reducing P_{BAT} to 10% of $P_{BAT,WF}$ and keeping full $C_{BAT,WF}$, with respect to maximum generation obtained with full power battery. Figure 3.6b makes evident that the loss evolution follows the curtailment imposed as shown in Figure 3.5d.

Figure 3.5: Relation between curtailment and RR compliance, showing PV generation (a) and battery operation (b) during a day of week 31 of 2009 with reduced battery design power of $P_{BAT} = 0.1 \cdot P_{BAT,WF}$. Battery requirements for full RRC are lower for curtailed PV generation $P_{PV,CU}(t)$, than for the non-curtailed one $P_{PV}(t)$. Fluctuations are smaller due to curtailed $P_{PV,31} = 0.6 \cdot P_N$ (d) derived from bad RRC along the first weeks of the year (c), so battery operates less times.

Figure 3.6: (a) Weekly produced energy evolution for full power battery and 10% $P_{BAT,WF}$ battery. (b) Weekly energy loss with respect to full power battery, associated to the curtailment evolution caused by weekly RRC.

Therefore, some loss limits must be established in order to clear the way for business models with a balance between cost savings derived from battery size reduction and incomes reduction owing to production loss. Figure 3.7 extends the simulation exercise to different power and capacity battery sizes, showing, for every k_p and k_c combination, the annual energy loss with respect to full battery size. The first relevant result obtained from this graph is that there is no energy loss beyond 30% $P_{BAT,WF}$ - 15% $C_{BAT,WF}$ combination, placed in the corner. Reducing below these limits, the losses increase exponentially. It is also worth mentioning that if one of the parameters is kept high, the other one can be slightly reduced below those limits without any additional energy loss. Moreover, it is shown that the losses are limited to around 48.7% of the maximum generation. However, it makes sense to affirm that the grid operator should not accept a $k_p = 0$ or $k_c = 0$ case, as it is likely to assume that there would be an explicit requirement of installing a battery.

Figure 3.7: Annual energy loss with respect to full-size battery case, in function of power and capacity reduction factors k_p and k_c .

Figure 3.8 shows the combinations of reduction of power and capacity of battery that leads to a set of yearly PV plant productions, limited by four lines: 100%, 97%, 95% and 80% of the maximum achievable production. The 100% curve expresses the limit of the region containing possible k_p and k_c combinations that lead to 100% PV plant production, which, therefore, should be seen as the set of combinations that minimise the size of the battery for 100% PV plant production.

Looking for battery design the so called C-rate (the ratio between P_{BAT} and C_{BAT}) of available batteries must be taken into account, so some lines that keep the C-rate relations have been added to Figure 3.8. The intersections of previous lines and these C-rate lines, give information about the annual produced energy using batteries with different C-rates available in the market (Saft, 2016; Samsung SDI, 2016) and for different gradual reductions of the battery power and capacity, showing the potential use of this study for designers of PV plants with batteries.

Two examples are going to be explained. On the one hand, the reduction of the battery rating 5.9C is going to be assessed, which corresponds to the one obtained as ideal for PV plant 100% RRC at its full-size. As explained before, for a $RR = 10\%/min$ and $\Delta t = 2$ s, this battery is rated

$P_{\text{BAT,WF}} = 5148 \text{ kW}$ (71.1% P_N) and $2 \cdot C_{\text{BAT,WF}} = 874 \text{ kWh}$ (7.2 min). However, if the aim of the sizing is to achieve the 100% annual production reducing battery size to the maximum, k_p & k_c combination must be pointed on the cross between 5.9C-rate line and 100% production limit curve, resulting $k_p = 0.29$ and $k_c = 0.29$. This corresponds to $P_{\text{BAT}} = 1493 \text{ kW}$ (20.6% P_N) and $C_{\text{BAT}} = 254 \text{ kWh}$ (2.1 min).

Figure 3.8: Different annual production percentage limits with respect to maximum achievable one, depending on k_p and k_c combinations. Dotted lines represent k_p and k_c combinations that keep C-rates of commercial batteries, being them in reference to WF model battery C-rate (5.9C) dash-dot line. 9C is also included following PREPA-AEE minimum battery requirement.

On the other hand, a commercial 4C battery reduction is going to be assessed. The point which fulfils the maximum RRC according to the graph of Figure 3.8 is rated $P_{\text{BAT}} = 3493 \text{ kW}$ (48.2% P_N) and $C_{\text{BAT}} = 874 \text{ kWh}$ (7.2 min). However, 100% annual production by reducing battery size to the maximum is achieved with $k_p = 0.25$ and $k_c = 0.38$, corresponding to $P_{\text{BAT}} = 1313 \text{ kW}$ (18.1% P_N) and $C_{\text{BAT}} = 328 \text{ kWh}$ (2.7 min).

Table 3.10 describes the most significant points of Figure 3.8 corresponding with different C-rate batteries available in the market, regarding 100% and 97% annual PV generation targets. It can be seen that Figure 3.8 and Table 3.10 are tools that open the door to project designers for optimising the battery selection for the particular case of Puerto Rico, given the prices of different battery models available in the market.

Finally, it is worth mentioning a particular restriction recently proposed in Puerto Rico grid code by PREPA and the public utility AEE. There is an explicit requirement of installing a minimum ESS for both ramp rate control and frequency response. The system must be able to provide 45% of P_N during at least one minute for facing high power ramps, while it also must be able to provide 30% of P_N during ten minutes for frequency response. For the studied 7.2 MW PV plant, the required battery is rated $P_{\text{BAT}} = 3260 \text{ kW}$ (45% P_N) and $C_{\text{BAT}} = 363 \text{ kWh}$ (3 min),

corresponding to a 9C relation, and comparing to the WF model size, it represents a reduction of $k_p = 0.63$ and $k_c = 0.41$, as shown in Figure 3.8 and Table 3.10.

However, as long as the target is to keep the RR compliance above 98.5% along the year, the 45% of P_N requirement proposed by PREPA-AEE could be substituted by a lower requirement. As shown in the graph, 100% annual production is kept until a reduction of $k_p = 0.3$ and $k_c = 0.19$, corresponding to $P_{BAT} = 1519$ kW (21% P_N) and $C_{BAT} = 169$ kWh (1.4 min). That means that in terms of PV plant allowed energy production, the battery size minimum requirement could be further reduced down to this point without increasing penalties due to ramp rate failures. Nevertheless, note that this reduction could be detrimental to the frequency response service, so a simultaneous reduction analysis for this service should be carried out in future works.

Table 3.10: Battery size vs. PV energy production for different commercial C-rates. *C-rate for complying with PREPA-AEE proposed MTR of $P_{BAT} = 45\% P_N$ during 1 min and $P_{BAT} = 30\% P_N$ during 10 min.

E_{GRID} limit	C-rate	Power in kW (% of P_N)	Capacity in kWh (min)
100%	5.9	1493 (20.6)	254 (2.1)
	10	1544 (21.3)	155 (1.3)
	4	1313 (18.1)	328 (2.7)
	2.5	1287 (17.8)	515 (4.3)
	1.8	1287 (17.8)	715 (5.9)
	9*	1519 (21.0)	169 (1.4)
97%	5.9	1081 (14.9)	184 (1.6)
	10	1184 (16.3)	119 (1.0)
	4	1030 (14.2)	258 (2.1)
	2.5	1030 (14.2)	412 (3.4)
	1.8	1030 (14.2)	572 (4.7)
	9*	1158 (16.0)	129 (1.1)

The door for further research in this area is open and providing the statistics of radiation in different climatic zones, the application of this reduction analysis comparing energy production data series from multiple locations is an interesting work to be done.

CHAPTER 4

Reduced size batteries with inverters limitation and oversized PV array

4.1 Reduced battery in combination with PV inverter curtailments

In order to avoid doubling the reference battery capacity $C_{BAT,WF}$, upwards fluctuations can be absorbed by moving the operation point of the PV plant inverters out of the MPP. This is achieved by limiting the output power variations at each inverter locally, as long as they allow it. Therefore, the BESS will be used for supplying the lack of power and energy caused by downwards fluctuations uniquely, requiring as a consequence half of energy capacity compared to the SOC control algorithm explained in section 3.1.1.

The control loop implemented in this strategy is aimed to restore the battery SOC after each downwards fluctuation is over, keeping it fully charged and ready for the next cloud that will cover the PV array. Therefore, the reference value is $SOC = 100\%$. This type of strategies have been widely studied in (de la Parra et al., 2016, 2015; Ina et al., 2004). However, some of these control strategies need additional inputs in order to model the PV plant maximum production at any time. $P_{PV}(t)$ under clear sky conditions is calculated with Linke turbidity factor, T_L , and the measured cell temperature, T_c , at every Δt of the simulation; apart from the location, day and time. In this context, for the particular purpose of our battery size reduction assessment, a new control strategy has been developed, named as *SOC100_PVCurt*, which fulfils the accuracy requirements in a simple way. It accurately mitigates every fluctuation and it minimises the energy loss associated with inverter limitations without the need for additional inputs. The previous strategy that keeps $SOC = 50\%$ will be referenced as *SOC50* along the following sections for comparison purposes.

4.1.1 SOC100_PVCurt control strategy

The simulation implements a SOC control algorithm with a close loop control similar to that of *SOC50* control strategy explained in section 3.1.1. However, as the purpose is to face only downwards fluctuations, the battery must be as charged as possible before the cloud front arrives, so the new reference value is $SOC = 100\%$. Full-size battery power and capacity reference values are again given by the WF model (Table 3.2) but in contrast to *SOC50* strategy, there is no need to double capacity. So the design parameters for absorbing 100% of fluctuations are $P_{BAT,WF}$ and $C_{BAT,WF}$.

The developed control strategy does not need any additional input parameters for reducing PV inverter power curtailments. The general idea is to use part of the excess PV power of the upwards fluctuation for recovering battery SOC to the reference value of $SOC = 100\%$ instead of curtailing inverters power. While SOC is lower than the reference value, all the excess PV power is used for charging the battery. Once the charge process is complete, the algorithm will send a curtailment signal to the PV inverters, so they will be in charge of smoothing the rest of the upwards fluctuation event. The control diagram of *SOC100_PVCurt* strategy is shown in Figure 4.1.

Figure 4.1: *SOC100_PVCurt* control diagram. Upwards fluctuations are absorbed by limiting PV inverters if battery is charged (when $E_{BAT}(t) = E_{BAT,ref}$). Downwards fluctuations are absorbed by discharging the battery.

In this case, the value of the proportional parameter is $K = 15$, in order to both, keep a good balance between speed and system stability and to avoid too high battery power requirements in a SOC recovery process. $E_{BAT,ref}$ is the reference value of the energy stored in the battery, corresponding to full charge and equalling the value of $C_{BAT,WF}$. Eq. (4.1) allows calculating PV inverter power limitation, $P_{PVi,Cu}(t)$, depending on the allowable ramp and on the power required by the battery.

$$P_{PVi,Cu}(t) = P_{GRID}(t) - P_{PV}(t) - P_{BAT}(t) \quad (4.1)$$

The strategy has five main operation modes and the previous equation gets different values in each of them. Eqs. (4.2) - (4.6) define the operation modes:

- a) *Ramp-Down* mode: Battery supports lack of PV power.

$$P_{\text{BAT}}(t) = P_{\text{GRID}}(t) - P_{\text{PV}}(t) \rightarrow P_{\text{PVi,Cu}}(t) = 0 \quad (4.2)$$

- b) *SOC recovery / No ramp* mode: Battery SOC is restored with part of PV power.

$$\left. \begin{aligned} P_{\text{GRID}}(t) &= P_{\text{PV}}(t) - K(E_{\text{BAT,ref}} - E_{\text{BAT}}(t)) \\ P_{\text{BAT}}(t) &= -K(E_{\text{BAT,ref}} - E_{\text{BAT}}(t)) \end{aligned} \right\} \rightarrow P_{\text{PVi,Cu}}(t) = 0 \quad (4.3)$$

- c) *SOC recovery / Ramp-Up* mode: Battery SOC is restored by absorbing upwards ramp.

$$P_{\text{BAT}}(t) = P_{\text{GRID}}(t) - P_{\text{PV}}(t) \rightarrow P_{\text{PVi,Cu}}(t) = 0 \quad (4.4)$$

- d) *Ramp-Up* mode: PV inverters are limited when battery $\text{SOC} = 100\%$.

$$P_{\text{BAT}}(t) = 0 \rightarrow P_{\text{PVi,Cu}}(t) = P_{\text{GRID}}(t) - P_{\text{PV}}(t) \quad (4.5)$$

- a) *Limited Ramp-Up* mode: When the battery size is reduced in terms of power by k_p , the ramp is matched teaming up the battery and inverters power limitation.

$$P_{\text{BAT}}(t) = k_p \cdot P_{\text{BAT,WF}} \rightarrow P_{\text{PVi,Cu}}(t) = P_{\text{GRID}}(t) - P_{\text{PV}}(t) - k_p \cdot P_{\text{BAT,WF}} \quad (4.6)$$

As an illustrative example, Figure 4.2 shows a simulation of Milagro PV plant in operation with a full-size battery rated $C_{\text{BAT}} = C_{\text{BAT,WF}} = 437 \text{ kWh}$ and, later on, Figure 4.3 shows a simulation with a battery power reduction of $k_p = 0.3$. In the first case, the system is operated by the developed strategy, when a cloud front passes over the plant at midday of the day with the worst fluctuation of the year. On the following, the most representative points of Figure 4.2 corresponding to each operation mode are explained:

- *Ramp-Down*: At 12:21 $P_{\text{PV}}(t)$ falls below RR_{LIM} and the battery starts to discharge at $P_{\text{BAT}}(t)$ in order to face the downwards fluctuation and keep $P_{\text{GRID}}(t)$ between limits. Energy stored in the battery, $E_{\text{BAT}}(t)$, decreases accordingly along the event, activating the close loop control of the strategy.
- *SOC recovery / No ramp*: When the fluctuation ends at 12:25, the control uses part of $P_{\text{PV}}(t)$ to recharge the battery.
- *SOC recovery / Ramp-Up*: At 12:30, in order to always match the prescribed RR_{LIM} , the battery is charged but smoothing the internal demand requested by the feedback loop.
- *Ramp-Up*: At 12:53, an upwards fluctuation starts when $E_{\text{BAT}}(t)$ is completely recovered ($\text{SOC}=100\%$), so PV inverter limitation is activated. Then, a small downwards fluctuation discharges the battery to $E_{\text{BAT}}(t) = 424.5 \text{ kWh}$. When the cloud is gone at 12:57, a strong upwards fluctuation starts and the strategy faces the first part of the fluctuation by charging the battery to $E_{\text{BAT,ref}}$. When the value is achieved, the system automatically enters in PV inverter curtailment mode, facing the rest of the

upwards fluctuation this way. Therefore, the control strategy is able to change automatically between SOC recovery and PV inverter curtailment modes without affecting to the system stability and keeping the RR_{LIM} imposed to $P_{GRID}(t)$.

As a result, when PV excess power of the first part of an upwards fluctuation is used for recovering the SOC of the battery, part of the energy losses caused by the inverter limitation are saved.

Figure 4.2: *SOC100_PVCurt* control strategy in operation. A battery rated $C_{BAT} = 437$ kWh is discharged during downwards fluctuation and after the event, battery SOC is recovered to the reference value. If battery is fully charged, PV inverter curtailment is activated. Inside an upwards fluctuation, SOC recovery / PV curtailment functions can be alternated if $SOC = 100\%$ is achieved in the middle of the event.

With the previous example, four of the five operation modes of *SOC100_PVCurt* are explained. In order to explain the *Limited Ramp-Up* mode, a simulation of the plant operation with a reduced battery is going to be performed. In particular, it is reduced by a factor of $k_p = 0.3$, resulting a limited battery power of $P_{BAT} = k_p \cdot P_{BAT,WF} = \pm 1545$ kW. Figure 4.3 shows the operation of this mode.

The battery is at full charge at the instant taken as reference ($t = 0$). At around $t = 5$ min, a downwards fluctuation starts, requiring power from the battery. At $t = 7$ min, it can be seen that the limited power of the battery $P_{BAT}(t)$ makes to fail the required ramp rate during some instants, so all the scans from $t = 7$ min to $t = 9$ min will be considered as non-compliant in the RRC assessment. At around $t = 10$ min, an upwards fluctuation starts, which is absorbed by the battery without problems until $t = 13$ min. At this instant, $P_{PV}(t)$ increases in a high magnitude and the limited power of the battery cannot afford it, so *Limited Ramp-Up* mode is started to match the ramp and to avoid penalties as follows: From this instant till the battery gets completely charged, at $t = 15$ min, the inverter power limitation $P_{PVi,Cu}(t)$ gives support to the battery in order to smooth the upwards ramp of $P_{GRID}(t)$ appropriately. When the battery is at full-charge again, only the inverters power limitation is in charge of matching the rest of the ramp. This way, every non-compliance that could occur during upwards fluctuations is avoided and, even with a limited battery, the inverter curtailment losses are reduced as much as possible.

Figure 4.3: *SOC100_PVCurt* control strategy in operation with reduced battery. If the required power for smoothing a downwards ramp is higher than the reduced battery power (± 1545 kW), the fluctuation cannot be fully mitigated and the ramp is not fulfilled. In upwards ramps, power absorbed by the reduced battery is complemented by limiting inverters power, so the ramp is fulfilled.

4.1.2 Energy losses caused by PV inverters curtailments

The practice of using inverters for absorbing fluctuations involves some energy loss, because when PV inverters are curtailed, not all of the available PV energy is fed into the grid. In order to evaluate the importance of such PV production losses, two approaches are going to be used; the relative approach and the absolute approach.

4.1.2.1 Inverter losses characterisation: the relative approach.

The so-called relative approach consists in applying the method explained in section 3.1.1 that was used to calculate battery power and capacity requirements. This way the importance of individual inverter limitation events is characterised. Five iterative simulations are performed obtaining the respective curtailed inverter power and energy series ($P_{PVi,Cu}$ and $E_{PVi,Cu}$ respectively) for full RRC, simulating with *RR* values of 5, 7.5, 10, 20 and 30%/min and considering $\Delta t = 2$ s. If we split into bins of a histogram the resulting data of curtailed inverter power or energy series, we can define certain power or energy intervals, obtaining as a result the graphs of Figure 4.4. For the whole series, any $P_{PVi,Cu}$ and $E_{PVi,Cu}$ of any upwards fluctuation event lies in between one of those intervals, considering them as normalised to the maximum event of the year, $P_{PVi,Cu,MAX}$ and $E_{PVi,Cu,MAX}$. Looking for presentation clarity, the histograms consider only the range higher than a threshold $u = 0.1\%$.

Figure 4.4: PV inverters limitation losses histograms, in terms of curtailed power (a) and energy (b), normalised to the maximum limitation requirement of the studied year. The simulations are performed for $RR = 5, 7.5, 10, 20$ and $30\%/min$ and for $\Delta t = 2$ s.

It can be seen that the occurrence of inverter curtailments follows a distribution similar to the histograms of Figure 3.4. This makes sense as they are correlated with the occurrence of upwards fluctuations in the same way as the battery charge events are in *SOC50* strategy, so the behaviour must be analogous. However, in the power histogram, the curves of different RR_{LIM} are slightly more dispersed between them than in the case of the histograms of *SOC50* strategy. The stricter the RR_{LIM} , the more frequent are higher power curtailments. This is derived from the operation of *SOC100_PVCurt* strategy. When the battery is recharging in *SOC recovery / Ramp-Up* mode explained in Eq. (4.4), at the middle of the ramp the battery gets completely charged and the inverter curtailment must be launched at high $P_{PVi,Cu}(t)$ power. This is clearly seen in Figure 4.2 at 12:57. In this upwards fluctuation event, the first part, which has low power requirement, is absorbed by the battery ($P_{BAT}(t) < 0$). But later, in the time of the event when more power is demanded for absorbing the fluctuation, the inverter is absorbing it ($P_{PVi,Cu}(t) \ll 0$). As a consequence, the stricter the RR_{LIM} , the flatter the allowable ramp and therefore the higher the power curtailment demanded to the inverters.

4.1.2.2 Inverter losses quantification; the absolute approach

In the global view, the total energy loss is quantified as the total PV production loss caused by inverter curtailments along a full year operation period of the plant. In the case of *SOC100_PVCurt* strategy, the energy curtailed by the inverters is much lower than the total energy managed by the battery in upwards fluctuations under *SOC50* strategy. Table 4.1 shows total losses associated with inverter curtailment in function of the total available yearly PV energy. The results are calculated from the simulations carried out with RR_{LIM} of 5, 7.5, 10, 20 and $30\%P_N/min$ explained above plus an extra simulation for a RR_{LIM} of $2\%P_N/min$. This strict requirement is proposed in (CRE, 2012) and it is included here for comparison purposes, because the studies carried out in (de la Parra et al., 2016, 2015) were also based on this regulation.

Table 4.1: Annual energy loss associated with inverter limitation in upwards fluctuations, for different RR and $\Delta t = 2$ s and operating under $SOC100_PVCurt$ strategy.

RR_{LIM} in $\%P_N/\text{min}$	$E_{PVi,Cu}$ in MWh	$E_{PVi,Cu}/E_{PV}$ in %
2	509.2	3.27
5	214.2	1.37
7.5	131.3	0.84
10	89.1	0.57
20	27.9	0.18
30	11.2	0.07

As expected, the total inverter losses are very low, especially for less restrictive ramp rate limitations. This makes sense, as in the cases with steeper ramps an important part of the upwards fluctuations can be absorbed by the battery after it is discharged in a downwards fluctuation and also their energy requirements are much lower.

For strict ramp rates, the losses are higher, but still, they are very low. In order to evaluate the effectiveness of the new $SOC100_PVCurt$ strategy, inverter losses are going to be compared with the state of the art strategies studied in (de la Parra et al., 2016) for a RR_{LIM} of 2%/min. Although those simulations were carried out for a larger PV plant, the losses were normalised to the production, so the results of our simulations are comparable to them. In the cited study, it is stated that with a basic strategy the loss associated with inverters limitation is more than 9%, while an advanced strategy reduces it to 2.33%. In the case of $SOC100_PVCurt$ strategy developed in our work, the results of Table 4.1 for $RR_{LIM} = 2\%/\text{min}$ show an intermediate loss of 3.27%. Given the simplicity of the strategy, it is a good result.

4.1.3 Methodology to reduce battery requirements

The steps to implement the battery size reduction assessment will be the same ones as those described in section 3.2.1, but adapting the simulation process according to $SOC100_PVCurt$ control strategy. Full-size battery power and capacity reference values are given by the WF model (Table 3.2) and corresponding to $P_{BAT,WF}$ and $C_{BAT,WF}$ respectively.

Upwards fluctuations are going to be considered fully covered by PV inverters, which means that the PV plant will operate at full ramp rate compliance during these events. We will consider that the inverters can modify their MPP fast and accurate enough within the required Δt to smooth down output PV power. However, for downwards fluctuations, the ramp rate compliance assessment will be carried out for each battery k_p and k_c combination.

The practical implementation procedure explained in section 3.2.1 is easily adapted to the new strategy by introducing two modifications. Now, in Eq. (3.24) only positive values of $P_{BAT}(t)$ are evaluated, corresponding to downwards fluctuations. Analogously, in (3.26) only positive values are evaluated, corresponding to discharged battery energy $E_{BAT}(t)$.

It must be noted that when the battery operates in SOC recovery mode, although the reduction factor k_p will not affect to the RRC assessment, it will affect to the recharging operation. The recovery speed will be slower, which will increase the total operating time of the battery.

4.1.4 Results and discussions

In order to compare the behaviour of reduced batteries operated by *SOC100_PVCurt* strategy with the case of *SOC50* strategy, the same simulations carried out in section 3.2.2, applied to the case of Puerto Rico, have been performed implementing the new strategy.

As a first comparison between both strategies, the scenario where battery power is reduced to 10% of $P_{BAT,WF}$ is going to be analysed ($k_p = 0.1$, $k_c = 1$). Figure 4.5 shows in the same graph the results obtained from two simulations. The first case (with the lines drawn in blue for every graph) shows the evolution of relevant parameters along every week of the year if the plant is operated under *SOC100_PVCurt* strategy. The second case (with lines drawn in red) show the same parameters if the plant is operated under *SOC50* strategy.

Figure 4.5a and b show the ramp rate compliance and the associated PV power curtailment factor evolution along the year for each strategy. Derived from these parameters, Figure 4.5c and d show the corresponding evolution of weekly energy production loss, with respect to maximum energy production of the PV plant obtained with full-power battery. It must be pointed out that, owing to the energy losses associated with inverters power limitation, the maximum production achievable with *SOC100_PVCurt* is slightly lower than the maximum production achievable with *SOC50* strategy. However, the response of *SOC100_PVCurt* against battery size reduction is much better. The results show that, for the same battery power reduction factor of $k_p = 0.1$, *SOC100_PVCurt* strategy achieves a better RRC along the year, falling into less curtailment penalties, which increase the PV energy production with respect to *SOC50* strategy.

Figure 4.5: Yearly simulation of the PV plant operated by *SOC100_PVCurt* strategy, with a reduced battery ($k_p = 0.1$, $k_c = 1$) and comparing with the results of *SOC50* strategy. Weekly ramp rate compliance oscillates around RRC_{min} (a), generating fewer curtailments than *SOC50* along the year (b). Weekly energy loss with respect to full-power battery is low and total production is closer to the maximum achievable value (c and d).

Figure 4.6 and Figure 4.7 extend the simulation exercise to different power and capacity battery sizes. Figure 4.6 shows, for every k_p and k_c combination, the annual PV energy loss with respect to the one obtained with full-size battery, rated $P_{BAT,WF} = 5148$ kW and $C_{BAT,WF} = 437$ kWh. The most relevant result obtained from this graph is that for every k_p and k_c combination the energy loss is lower than when implementing *SOC50* control strategy. Given that the battery is used only for supporting downwards fluctuations, the result makes sense.

Figure 4.6: Annual energy loss with respect to full-size battery case, in function of power and capacity reduction factors k_p and k_c , implementing the *SOC100_PVCurt* control strategy.

Moreover, there is no energy loss beyond 15% $P_{BAT,WF}$ - 10% $C_{BAT,WF}$ combination, placed in the corner of the graph. Note that the values are lower than in *SOC50* case. Reducing below

those limits, the losses increase exponentially, with even a higher degree than in *SOC50* case. So, when reducing the power or capacity from one point, the non-compliances increase dramatically. The losses are limited to around 34% of the maximum generation in the no battery case, which is the scenario where only upwards fluctuations are absorbed by PV inverter curtailment.

Figure 4.7 shows the combinations of reduction of power and capacity of the battery that leads to a set of yearly PV plant production limits, as well as the C-rates, all explained in 3.2.2. Under *SOC100_PVCurt* strategy, the reference C-rate is doubled as the design capacity, $C_{\text{BAT,WF}}$, is half of the capacity required under *SOC50* strategy. The full-size battery for 100% RRC is rated 11.8C, sized $P_{\text{BAT,WF}} = 5148 \text{ kW}$ (71.1% P_N) and $C_{\text{BAT,WF}} = 437 \text{ kWh}$ (3.6 min); and the corresponding reference C-rate line is drawn in dash-dot. Please, note that 100% limit here means the yearly production of the PV plant operated under *SOC100_PVCurt* strategy and without falling into penalties, i.e. operating along the year always above $RRC_{\text{min}}=98.5\%$. This value equals the yearly production of the same plant operated under *SOC50* strategy but subtracting the energy loss associated with the inverters power limitations. In the present case, the annual loss is 0.57% of the total production, displayed in Table 4.1 for a $RR_{\text{LIM}} = 10\%/min$; so the 100% production limit of *SOC100_PVCurt* equals the 99.43% of the production of *SOC50*.

The main difference of the results shown with respect to previous case is that as the new reference C-rate is higher, the commercial battery C-rate lines used in this study will lie below the reference dash-dot line of 11.8C. That means that a PV plant operated by *SOC100_PVCurt* strategy requires a battery with higher power density than in *SOC50* strategy case, being less determinant the energy capacity. This fact becomes evident by taking a look to the way the production limit lines are placed in the graph. Limits are more separated along k_p axis than along k_c axis. In other words, the reduction of battery power has more effect in PV production loss than the reduction of battery capacity.

Figure 4.7: Different annual production percentage limits with respect to maximum achievable one, depending on k_p and k_c combinations and implementing *SOC100_PVCurt* strategy. Dotted lines represent k_p and k_c combinations that keep C-rates of commercial batteries, being them in reference to WF model battery C-rate (11.8C) in dash-dot line. 9C is also included following PREPA-AEE minimum battery requirement.

Table 4.2 describes the most significant points of Figure 4.7 corresponding with different C-rate batteries available in the market (Saft, 2016; Samsung SDI, 2016), regarding 100% and 97% annual PV generation targets. For comparison purposes, the points with equivalent energy production limits obtained with *SOC50* simulations are included. As explained before, 100% of production under *SOC100_PVCurt* is equivalent to the limit of 99.43% under *SOC50*. Following the same analogy, 97% of the production under *SOC100_PVCurt* is equivalent to the limit of 96.45% under *SOC50*.

Table 4.2: Battery size vs. PV energy production for different commercial C-rates, comparing results between *SOC100_PVCurt* and *SOC50* strategy. *C-rate for complying with PREPA-AEE proposed MTR of $P_{BAT} = 45\% P_N$ during 1 min and $P_{BAT} = 30\% P_N$ during 10 min.

E_{GRID} limit	C- rate	SOC100_PVCurt		SOC50		Saving	
		Power in kW (% of P_N)	Capacity in kWh (min)	Power in kW (% of P_N)	Capacity in kWh (min)	Power (%)	Capacity (%)
100% (99.43% SOC50)	11.8/5.9	747 (10.3)	64 (0.5)	1261 (17.4)	214 (1.8)	41	70
	10	747 (10.3)	75 (0.6)	1313 (18.1)	132 (1.1)	43	43
	9*	747 (10.3)	83 (0.7)	1287 (17.8)	143 (1.2)	42	42
	4	747 (10.3)	187 (1.6)	1236 (17.1)	309 (2.6)	40	39
	2.5	747 (10.3)	299 (2.5)	1236 (17.1)	495 (4.1)	40	40
	1.8	747 (10.3)	415 (3.5)	1236 (17.1)	687 (5.7)	40	40
97% (96.45% SOC50)	11.8/5.9	515 (7.1)	44 (0.4)	1030 (14.2)	175 (1.5)	50	75
	10	515 (7.1)	52 (0.4)	1159 (16.0)	116 (1.0)	56	55
	9*	515 (7.1)	58 (0.5)	1133 (15.7)	126 (1.1)	55	54
	4	515 (7.1)	129 (1.1)	1004 (13.9)	251 (2.1)	49	49
	2.5	515 (7.1)	206 (1.7)	1004 (13.9)	402 (3.3)	49	49
	1.8	515 (7.1)	286 (2.4)	1004 (13.9)	558 (4.6)	49	49

First conclusion is that with *SOC100_PVCurt*, both battery power and capacity requirements are much lower, reducing around 40-50% both parameters. It must be noted that in the case of reference C-rate, the especially high save in capacity is due to changing from 5.9C to 11.8C, as the full-size design capacity in *SOC100_PVCurt* is half of the design capacity of *SOC50*.

In the particular case of *SOC100_PVCurt*, the required battery power to achieve each PV production limit is constant for every C-rate, so the lower the C-rate of the commercial battery used is, the higher the capacity requirement will be. This fact can be seen as a battery technology limitation.

With regards to PREPA-AEE restriction, as long as the target is to keep the RR compliance above 98.5% along the year, the 45% of P_N requirement proposed by PREPA-AEE could be substituted by an even lower requirement using *SOC100_PVCurt* strategy. As shown in the graph, 100% annual production is kept until a reduction of $k_p = 0.15$ and $k_c = 0.19$, corresponding to $P_{BAT} = 747$ kW (10.3% P_N) and $C_{BAT} = 83$ kWh (0.7 min). As also explained at the end of section 3.2.2, please note that this reduction could be detrimental to the frequency response service, being necessary the corresponding further analysis of this issue.

It must be pointed out that if the battery size is highly reduced, it will be no more able to absorb part of upwards fluctuations, having to increase proportionally the inverter power limitations and therefore the associated losses. In order to evaluate this fact, Figure 4.8 shows for every k_p and k_c combination of the simulations the energy loss associated with inverter limitations.

Figure 4.8: Energy loss associated with inverters limitation when absorbing upwards fluctuations, calculated for each battery k_p and k_c combination and implementing *SOC100_PVCurt* strategy.

The results are given normalised to the annual available PV energy $E_{PV,Cu}$. In the flat area of high k_p and k_c values, the inverter limitation losses are around the 0.57% indicated in Table 4.1 for $RR_{LIM} = 10\%/min$. When either battery power is reduced to less than 25% of $P_{BAT,WF}$ or capacity is reduced to less than 15% of $C_{BAT,WF}$, an important part of upwards fluctuations cannot be absorbed any more by recovering the SOC of the battery, so inverter limitation must be activated more frequently increasing the losses up to 0.64%.

As explained in section 3.2.1, $P_{PV,w}$ parameter is curtailed along the year depending on the weekly ramp rate compliance RRC_w , so for every combination of k_p and k_c , the available curtailed PV energy, is different. If k_p is reduced below 15% or k_c below 5%, the battery cannot absorb most of the downwards fluctuations, RRC_w falls drastically and the penalties reduce $E_{PV,Cu}$. By reducing the available PV power, the occurrence of upwards fluctuations and the associated inverter limitation losses are decreased again, following the dynamics explained in Figure 3.5a-b. This fact shapes the characteristic “crater-form” of the graph. However, given the huge PV plant production losses explained in Figure 4.6, extremely low values of k_p and k_c are not recommendable. As a reference, it is recommended to use only the inner part of the “crater” for evaluating the behaviour of inverter losses depending on battery size reduction.

4.2 Oversized PV array and inverter operation in saturation

As common practice, a good design criteria for properly matching inverters and PV array nominal power is to keep the inverter-to-array ratio¹, named as DR_{INV} , between values of $0.7 < DR_{INV} < 1.5$. Some inverter manufacturers even limit this margin to $0.85 < DR_{INV}$ in order to assure that they will operate at relative low power (Lorenzo, 2014). However, given current PV module prices, oversizing the PV array with respect to the inverter output power

¹ Some authors prefer the term array-to-inverter ratio, which is just the inverse.

range is a practice that is becoming popular. This way, DC PV power output increases for an identical solar irradiance and the inverter frequently operates in saturation. At first glance, it seems that enhancing saturation losses on purpose makes no sense, but this way more total energy and in a less variable way is generated for the same nameplate power capacity, overcoming other losses of DC side of the system and increasing the equivalent hours of a PV plant.

Moreover, if the saturation reduced PV power fluctuations, the technique could have some other advantages. Due to current high battery investment costs, it could be profitable to oversize PV array if the fluctuations were reduced and as a consequence a battery with lower power and energy capacity requirements was needed to comply with a prescribed RR_{LIM} . In other words, it could be more desirable to increment PV array size rather than battery power or capacity. An oversized PV array mitigates part of the fluctuations in the following two ways:

- When the size of the PV array is larger, high frequency fluctuations are mitigated by the low-pass filter smoothing effect intrinsic to enlarging the area of the PV array, as explained in section 2.1. For more information, the reader is addressed among others to (Hoff and Perez, 2010; Lave et al., 2012; Marcos et al., 2011a, 2011b).
- In central hours of a clear day, when PV array output power $P_{PV,DC}(t)$ is close to its peak power $P_{PV,p}$, the inverter will saturate as DC power exceeds its rated capacity. When a cloud partially covers the array, a DC power fluctuation will occur, but at inverter level the fluctuation will only start when $P_{PV,DC}(t)$ falls below its maximum input power. In other words, the fluctuation will be curtailed.

Figure 4.9 shows for a highly fluctuating day, the real output PV power of the Milagro PV plant $P_{PV}(t)$, and a simulation of the output power of the same plant but oversizing its PV array, named as $P'_{PV}(t)$. It must be noted that to cover the illustrative needs of this example, a simple oversizing factor $k_{os} = 1.3$ has been applied.

Figure 4.9: Output PV power at the PCC of Milagro PV plant, $P_{PV}(t)$, and simulation of the output power in a case with an oversized PV array installed in the same plant, $P'_{PV}(t)$, in a highly fluctuating day. In (b) a zoomed short period of (a) can be seen, where saturated output power smooths part of the fluctuations.

The zoomed area of Figure 4.9b shows that some high frequency fluctuations and some low magnitude fluctuations of the original non-oversized plant production data, $P_{PV}(t)$, are mitigated when operating in inverter saturation, resulting in a smoother output power $P'_{PV}(t)$.

In this section this effect is going to be studied in order to quantify the potential of its use for the reduction of battery requirements in RR control and implementing *SOC100_PVCurt* strategy. It appears that small high frequency fluctuations are easily smoothed down, but it must be investigated what happens with strong magnitude and long lasting fluctuations. The aim will be to show the smoothing effect of an oversized PV array, combining this technique with the battery size reduction assessment. The comparative study is going to be carried out for a $RR_{LIM} = 10 \text{ \%/min}$ scenario.

4.2.1 Emulation of an oversized PV plant by means of artificial data series

The deep study of the PV array oversizing technique requires accurate data of an oversized PV plant, which would allow us to compare the latter with the original configuration of Milagro PV plant. Output power data of a plant with an oversized array must include not only the effect of an oversizing parameter which scales-up the peak power of the PV array, but also the low pass filter effect due to its larger area. Hence, the simple method of multiplying the real power dataset of the Milagro PV plant by an oversizing factor, explained in the illustrative example of Figure 4.9, is not enough.

In order to include the low pass filter phenomenon in the battery size reduction method, two different artificial and comparable PV plants are going to be emulated. Both plants have a nameplate power capacity of $P_N = 7.2 \text{ MW}$ but one of them has its PV array oversized by a factor $k_{os} = 1.5$ respect to the other. Emulation of the original Milagro PV plant will be named as *Plant A* and its configuration is identical to the one described in section 2.2.1, being its inverter-to-PV array power ratio $DR_{INV} = 0.8$. Emulation of the oversized Milagro PV plant will be named as *Plant B* and the inverter-to-PV array power ratio resulting from the oversizing process is $DR_{INV} = 0.53$. Figure 4.10 describes the emulation of both plants.

The comparison must be as fair as possible and because of that, both data sources must be originated in the same way. As we do not have available measured data series for an oversized PV plant, both *Plant A* and *Plant B* power series are going to be created artificially by means of the technique developed in (Marcos et al., 2011b). This method creates the output power of a PV plant using as input the signal of the irradiance measured on the PV generator plane. It filters out high frequency components of the irradiance as a low-pass filter does, where the cut-off frequency depends on the surface area of the PV array.

For emulating *Plant A*, starting from an irradiance data series measured on-site in Milagro PV plant, the power data series of the plant is built. This data series is obtained as the output of the model, being S the real area of 52 ha and considering a K gain of 0.91, which is reasonable taking into account the degradation of the plant. For *Plant B*, we will consider a PV array area of $S'=78 \text{ ha}$, which results from incrementing the original plant area proportionally by the oversizing factor k_{os} , while a K gain value of 0.91 is also used. Figure 4.11 describes the construction of the artificial power data series of both plants by means of the low-pass filter model technique.

Figure 4.10: Emulation of two PV plants with artificial PV power data series. *Plant A* emulates original configuration of Milagro PV plant. *Plant B* emulates the oversizing of PV array by a factor of $k_{os} = 1.5$ and its inverter operates in saturation. Both plants have the same nameplate power $P_N = P'_N = 7.2$ MW.

Figure 4.11: Low-pass filter transfer functions of *Plant A* and *Plant B*. The irradiance signal input is smoothed according to the cut-off frequency of each modelled plant, dependent of the square root of each area, obtaining as output the respective power signal.

Figure 4.12a shows, for a strong fluctuation, the input and output parameters of the previous model in the domain of time; normalised value of the irradiance incident on the inclined plane $G_{45^\circ, \alpha}(t)$, and normalised output PV power of *Plant A* and *Plant B*, $P_{PV}(t)$ and $P'_{PV}(t)$ respectively. It can be seen that both PV plants act as low-pass filters of the irradiance signal, being stronger the filtering effect of the large PV array. Figure 4.12b shows the absolute values for a whole day and Figure 4.12c is a zoomed detailed of b. It can be seen that by saturating the inverters of *Plant B*, a good part of small fluctuations are curtailed.

Figure 4.12: Incident irradiance at inclined plane $G(45^\circ, \alpha)$ at Milagro PV plant location and output PV power of *Plant A* and *Plant B* w/o inverter saturation; normalised values in a time lapse of a fluctuation (a) and absolute values in a day, including zoomed lapse (b-c). The smoothing effect of the oversized PV array is observed in $P'_{PV}(t)$ power curve. Including the inverter saturation of *Plant B*, part of DC side fluctuations is curtailed (c).

4.2.2 Battery size in an oversized PV plant: The Oversized WF model

When a PV array is oversized with respect to its inverters nameplate power, the instant output power $P'_{PV}(t)$ is limited to that value, but the fluctuations follow a shape characterised by the new PV array power $P'_{PV,DC}(t)$. For example, a downwards $P'_{PV,DC}(t)$ power fluctuation curve at the array following the WF model, is translated to a downwards $P'_{PV}(t)$ output power fluctuation curve starting at the saturation limit but following the shape of the first curve. Therefore, in order to size correctly the battery for absorbing every possible fluctuation, an *Oversized Worst Fluctuation* model is proposed, which takes into account the saturation point. In our emulation, this point is the nameplate power P'_N and its ratio respect to the maximum DC power $P'_{PV,DC,MAX}$ observed at the output of the oversized array is k_{os}^{-1} . Figure 4.13 shows the classic model and the update for implementing it in an oversized PV plant.

Figure 4.13: (a) Worst Fluctuation model, defined in (Marcos et al., 2014b), where a downwards fluctuation at the array is outputted. (b) Oversized Worst Fluctuation model, where the fluctuation starts at the saturation point P'_N .

As explained in section 3.1.2, the equations that rule the classic model are the following:

$$P_{PV,WF}(t) = A e^{\left(-\frac{t}{\tau}\right)} + y_0 \quad (4.7)$$

$$P_{GRID,WF}(t) = A - r_{\max} t + y_0 \quad (4.8)$$

$$P_{BAT,WF}(t) = P_{PV,WF}(t) - P_{GRID,WF}(t) \quad (4.9)$$

The initial value or amplitude of the decay is set to $A = 90$ and the offset to $y_0 = 10$, modelling the transition from operating at 100% of P_N under clear sky conditions to 10% of P_N under diffuse irradiance, effect of the cloud coverage. $r_{\max}$ is the maximum allowed ramp in (%/s).

But in the oversized case, the amplitude of the $P_{PV,WF}(t)$ exponential decay function and the initial value and the slope of the ramp $P_{GRID,WF}(t)$ imposed in a non-oversized plant, are adjusted to obtain the new power fluctuation curve $P_{PV,WFOs}(t)$ and the new output ramp $P_{GRID,WFOs}(t)$. The updated model takes into account that from the inverter point of view, the fluctuation starts at $P'_N = k_{os}^{-1} \cdot P'_{PV,DC,MAX}$, being $k_{os}^{-1} = 0.67$ in our case. Therefore, the new parameters are $A' = (100 \cdot k_{os}^{-1}) - 10$ and $r'_{\max} = k_{os}^{-1} \cdot r_{\max}$.

Besides, a typical exponential decay function has a fast decaying behaviour during the first instants. After a certain time span set by the time constant defined as τ , it falls slower. In WF model, this value depends on the shortest dimension of the PV plant, l , in the following way.

$$\tau = 0.042 \cdot l - 0.5 \quad (4.10)$$

If we kept the original time constant as design criteria for the saturated fluctuation, we would disregard the fast decaying property of the beginning. In fast fluctuations which are not as strong as the worst case but that they occur during periods where the array is producing below P'_N , the fast decay will also reach inverter output level, so a battery sized for a slower decay would not be able to absorb it. Therefore, the *Oversized WF* model has a different time constant

which is set as a reduction of the original τ (calculated using the l of the oversized array) by the time that the non-saturated curve lasts arriving from full-power to k_{os}^{-1} , named as t_k and defined in Figure 4.13a. The time constant is defined in the following Eq. (4.11).

$$\tau' = \tau - t_k \quad (4.11)$$

In this case, this means that t_k is the time span between 100% $P'_{PV,p}$ to 67% $P'_{PV,p}$ and it has a value of $t_k = 16.9$ s. We can define the *Oversized WF* model applying the adjustments to the original model, as defined in the following equations:

$$P_{PV,WFOs}(t) = A' e^{\left(-\frac{t}{\tau'}\right)} + 10 \quad (4.12)$$

$$P_{GRID,WFOs}(t) = A' - r'_{max} t + 10 \quad (4.13)$$

$$P_{BAT,WFOs}(t) = P_{PV,WFOs}(t) - P_{GRID,WFOs}(t) \quad (4.14)$$

where the instant values are calculated multiplying the nameplate capacity P_N and oversizing factor k_{os} by the Eqs. (4.12) - (4.14). The battery power for absorbing the fluctuation is given by $P_{BAT,WFOs}(t)$ and the instant value of this function along the fluctuation is given by Eq. (4.15).

$$P_{BAT,WFOs}(t) = \frac{k_{os} \cdot P_N}{100} \left[A' \left(1 - e^{-t/\tau'} \right) - r'_{max} t \right] \quad (4.15)$$

Obtaining the maximum of that function, the maximum battery power requirement is calculated:

$$P_{BAT,WFOs} = \frac{k_{os} \cdot P_N}{100} \left[A' - \tau' r'_{max} \left(1 + \ln \left| \frac{A'}{\tau' r'_{max}} \right| \right) \right] \quad (4.16)$$

where $P_{BAT,WFOs}$ is defined in (kW), r'_{max} in (%/s) and τ' in (s). In order to calculate the required energy capacity to face the fluctuation, Eq. (4.15) must be integrated along the time span that lasts from the beginning of the oversized worst fluctuation to the instant when the ramp reaches $0.1P'_{PV,DC,MAX}$, defined as $T'_R = A'/r'_{max}$.

$$C_{BAT,WFOs} = \int_0^{T'_R} P_{BAT,WFOs}(t) dt = \frac{A' \cdot k_{os} \cdot P_N}{100 \cdot 3600} \left[\frac{A'}{2 \cdot r'_{max}} - \tau' \right] \quad (4.17)$$

where $C_{BAT,WFOs}$ is given in (kWh). In oversized PV plants, the design criteria of battery requirements for absorbing 100% of the fluctuations will be the values given by the *Oversized WF* model, $P_{BAT,WFOs}$ and $C_{BAT,WFOs}$.

Let us focus now on the case of *Plant A* of previous section, with a nameplate capacity of 7.2 MW and with the shorter dimension of its PV array being $l = 700$ m. According to the classic WF model it would require a battery rating $P_{\text{BAT,WF}} = 5148$ kW (71,1%) and $C_{\text{BAT,WF}} = 437$ kWh (3,6 min). Oversizing the PV array of that plant as per the emulation explained before to obtain *Plant B*, the required battery according to the *Oversized WF* model would be $P_{\text{BAT,WFos}} = 5182$ kW (71,54%) and $C_{\text{BAT,WFos}} = 408$ kWh (3,4 min).

4.2.3 Battery size reduction assessment for the emulated PV plants

In order to analyse the behaviour of reduced batteries operated by *SOC100_PVCurt* strategy in an oversized PV plant, the same simulation process carried out in sections 3.2.2 and 4.1.4 has been performed for the new plants. With the emulated plants as scenarios, two parallel extensive simulation rounds of battery size reduction assessment are carried out for every k_p and k_c combination. The simulation round corresponding to *Plant A* uses the artificial series of $P_{\text{PV}}(t)$ as input and the design battery size considered as starting point is modelled according to the classic WF model; being $P_{\text{BAT,WF}} = 5148$ kW and $C_{\text{BAT,WF,os}} = 437$ kWh. The simulation round corresponding to *Plant B* uses the series of $P'_{\text{PV}}(t)$ and the design battery size is modelled according to the *Oversized WF* model; being $P_{\text{BAT,WF}} = 5182$ kW and $C_{\text{BAT,WF,os}} = 408$ kWh. In Figure 4.14a the annual energy loss with respect to full-size battery corresponding to the simulation rounds of each plant are displayed.

Figure 4.14: Annual energy loss with respect to full-size battery case, in function of k_p and k_c , comparing *Plant A* (7.2 MW) and *Plant B* (7.2 MW / PV array oversized); (b) is a detail of the corner section of (a). An oversized PV plant has more losses for the same battery reduction rate than a non-oversized plant.

Figure 4.14b is a zoom detail of the corner area of Figure 4.14a. It can be seen that the energy loss of the oversized *Plant B* starts to increase with a higher battery size than in *Plant A*; especially in power, 5% higher. This fact means that the ramp rate failures are higher when reducing a battery in an oversized PV plant than doing it in a non-oversized plant. Moreover, in the no battery case there are more losses, which means that *Plant B* falls into more total penalties.

Figure 4.15a and Figure 4.15b show the production limits & C-rates graph for *Plant A* and *Plant B* respectively, where each reference C-rate corresponds to the design battery size of each plant.

Figure 4.15: Different annual production percentage limits with respect to maximum achievable one, depending on k_p and k_c combinations for non-oversized *Plant A* (a) and oversized *Plant B* (b). Penalties caused by battery reduction affect more to an oversized PV plant, having less battery size reduction potential.

The main difference of the results shown is that the production limits are more separated in the oversized plant than in the non-oversized one. In both cases, limits are more separated along k_p axis than along k_c axis, so the reduction of battery power has more effect in PV production loss than the reduction of battery capacity. However, *Plant B* is more sensitive to battery power reductions than *Plant A*, but it is also much more sensitive to battery capacity reductions. While *Plant A* only suffers from losses due to capacity reduction at very low values, in *Plant B* capacity reductions below 10% increase the losses. Hence, some kind of energy demanding fluctuation events must affect more to the oversized plant than to the non-oversized one.

In order to assess the battery size reduction potentials resulting from the simulations of both plants in a fair way, we are going to compare the yearly energy production obtained in *Plant A* with the production obtained in *Plant B* if the same battery was installed. Three scenarios with three battery sizes are compared for a complete analysis. Table 4.3 shows the three scenarios, obtaining different productions in each plant (E_{GRID}) depending on the battery size used.

In first scenario, the battery size used as a reference is the most reduced one that allows *Plant A* to operate along the year without falling into penalties, producing the maximum possible energy during the year. The set of power and capacity combinations of the battery that affords such production lies on the 100% limit line of Figure 4.15a. For this exercise, the nominal C-rate battery and the commercial 10C battery are selected. Nominal C-rate is 11.8C in *Plant A* and 12.7C in *Plant B*, so, the reference nominal battery is rated $P_{\text{BAT},11.8\text{C}} = 721 \text{ kW}$ and $C_{\text{BAT},11.8\text{C}} = 61 \text{ kWh}$ (57 in 12.7C). In the case of the 10C battery, the reference power requirement value of the nominal C-rate is considered, so it is rated $P_{\text{BAT},10\text{C}} = 721 \text{ kW}$ and $C_{\text{BAT},10\text{C}} = 72 \text{ kWh}$.

The second and third scenarios use battery sizes that allow 95% and 90% of the maximum production respectively. The latter is small enough because the penalties derived from battery size reduction cause 10% of PV production loss of *Plant A*, so in this exercise it does not make sense to assess any battery reduced below this limit.

Table 4.3: PV energy production obtained in *Plant A* and *Plant B* with different battery sizes of a nominal C-rate battery and 10C commercial battery. The reference battery size is the one that allows *Plant A* to achieve 100% of PV production without falling into penalties, rated 721 kW / 61 kWh - 11.8C.

Scenario	C-rate	Power in kW (% of P_N)	Capacity in kWh (min)	Plant A		Plant B		ΔE_{GRID} %
				E_{GRID} in MWh	%MAX $E_{\text{GRID A}}$	E_{GRID} in MWh	%MAX $E_{\text{GRID B}}$	
1	11.8/12.7	721 (10.0)	61/57 (0.5)	14 930	100%	18 784	98.3%	25.81
	10	721 (10.0)	72 (0.6)					
2	11.8/12.7	335 (4.6)	29/27 (0.3)	14 183	95%	17 427	91.2%	22.87
	10	335 (4.6)	34 (0.3)					
3	11.8/12.7	216 (3.0)	19/17 (0.2)	13 437	90%	16 529	86.5%	23.01
	10	216 (3.0)	22 (0.2)					

On the one hand, analysing the PV production it can be seen that in all three scenarios, for the same battery, *Plant B* produces more than *Plant A*. For instance, with the battery of scenario 1, *Plant B* produces yearly 25% more than *Plant A*. But this is achieved by oversizing the PV array by a factor of 1.5, which means that the number of PV modules is increased by 50%. In this sense, this table can be seen as a tool to evaluate if the 50% of increase in the investment costs of the PV array is compensated along the life of the project with the 25% of increase in the yearly PV production.

On the other hand, assessing the battery size reduction against PV production, it can be seen that, with the oversizing technique of *Plant B*, the battery can be significantly reduced without losing production. For instance, a 10C battery can be reduced by a 70%, from a size of $P_{\text{BAT},10\text{C}} = 721$ kW and $C_{\text{BAT},10\text{C}} = 72$ kWh (scenario 1, which allows *Plant A* producing 14.9 GWh) to a size of $P_{\text{BAT},10\text{C}} = 216$ kW and $C_{\text{BAT},10\text{C}} = 22$ kWh (scenario 3, which allows *Plant B* producing 16.5 GWh) not only without losing PV production, but also increasing it by 10.7%. Therefore, project developers can use this tool to evaluate if, at the expense of increasing 50% the number of PV modules, the project could improve its feasibility by saving costs thanks to 70% less battery requirements and thanks to increasing yearly PV production by 10.7%.

However, it is interesting to see that, respect to its own production, the oversized plant falls into more penalties than non-oversized one. In scenario 1, while *Plant A* produces its 100% (no penalties), *Plant B* produces its 98.3% achievable energy (penalties cause a total loss of 1.7% of the production). That means that along the year, the plant operates several weeks below the $RRC_{\text{min}}=98.5\%$ because of the reduced size of its battery, which is derived in penalties. This fact confirms the impressions obtained when we analysed Figure 4.14b and it is clear that an oversized plant is more sensitive to the battery size reduction in terms of penalties. In order to find out this phenomenon, an exhaustive analysis of the fluctuations events of an oversized plant is carried out in the next section.

4.2.4 Fluctuations events characterisation in an oversized PV plant

The deep study of fluctuations events of an oversized PV plant is done by characterising battery power and energy events and inverter limitation events occurred in each type of fluctuations. Following the methodology explained in section 3.1.1, the histogram of battery and inverter

responses for absorbing 100% of downwards and upwards fluctuations are shown in Figure 4.16, for either *Plant A* and *Plant B*. As in previous cases, the power and energy series of the simulations are normalised and placed in between different intervals. This time, in order to see their intrinsic behaviour, battery events are normalised to the largest event of the year instead of WF or WF_{os} design values. Regarding the battery, the references are $P_{BAT,MAX}$ and $E_{BAT,MAX}$, while in the inverter limitation case, the reference is the maximum limitation $P_{PVi,Cu,MAX}$.

Battery power discharge events are distributed as described in Figure 4.16a in each of the plants. As seen, low power fluctuations have less frequency in the oversized *Plant B* than in *Plant A*. This is consistent with the high frequency components attenuation effect provided by a larger PV array, but also with the low power fluctuations curtailment entailed by the saturation of the inverters when $P_{PV,DC}(t)$ is higher than P'_N .

However, in *Plant B* power demands around 0.2 - 0.5 of $P_{BAT,MAX}$ are amplified with respect to *Plant A*. This amplification makes *Plant B* more sensitive to battery power requirements reduction because when it is reduced, the amplified demands cannot be covered and the ramp rate failures explained in previous section occur. Figure 4.16b shows both the amplification of medium power events and the attenuation of low power events mentioned before.

Figure 4.16: Histograms of battery power (a) and energy (c) managed during downwards fluctuations and histogram of inverters power limitations during upwards fluctuations (e); for *Plant A* and *Plant B*. In an oversized plant, low power and energy downwards fluctuations are smoothed by the oversizing technique, while medium size events are amplified (b and d). Upwards fluctuations remain quite similar to the non-oversized plant (f).

In the case of battery discharge energy events shown in Figure 4.16c and d, the difference with respect to *Plant A* occurs mainly in very low energy demanding events.

Regarding the upwards fluctuations, the behaviour of inverter power limitations scarcely vary from *Plant A* to *Plant B*, which is shown in Figure 4.16e. For simplicity reasons, the histogram of limited energy events is omitted, but the variation is similar.

In order to justify the phenomenon shown in Figure 4.16b, the graphs displayed in Figure 4.17 illustrate the effects described above in the time domain, showing three hours of operation of *Plant A* and *Plant B* before midday of a highly fluctuating day. First of all, it is interesting to point out how the battery power signal of *Plant B* is attenuated filtering out the high frequency noise. Second, the amplification of some medium-size power events takes place at t_1 and at t_2 . The first event requires a maximum battery power value of $P_{BAT}(t_1) = 2331$ kW in *Plant A* and it is amplified to $P'_{BAT}(t_1) = 2853$ kW in *Plant B*. The second one is amplified from $P_{BAT}(t_2) = 1367$ kW to $P'_{BAT}(t_2) = 1767$ kW. As the array is oversized, the PV power fall of these events is amplified by the oversizing factor while the allowed RR_{LIM} is the same, so the required battery power is higher. Finally, it can be seen that inverter limitations occurred during upwards fluctuations practically remain equal for both plants; barely one event disappears and the form factor of the rest changes a bit due to the steeper ramp-up occurred in $P'_{PV}(t)$ curve of the oversized *Plant B*.

Finally, it is worth pointing out a consequence of this behaviour. With an oversized PV array, low power fluctuations are mitigated and the high frequency noise of the battery operation signal is reduced, just as a low-pass filter does. This fact leads to a reduction of the total battery operating time, which is a good notice since the degradation associated with the number of cycles will decrease. Taking into account only downwards fluctuations of the whole year, the battery in *Plant B* is used 6% less time than in *Plant A*. Besides, taking into account both discharge and SOC recharge events, the battery in *Plant B* is used 10% less time than in *Plant A*. Regarding the degradation caused by the time of use, it can be an important save.

Figure 4.17: Battery and inverter limitations in operation around midday on a highly fluctuating day, in *Plant A* (a) and in oversized *Plant B* (b). High frequency components of battery power operation are smoothed by means of the oversizing technique. However, some medium-size components are amplified like discharges at t_1 and at t_2 . Some low power inverter limitations are also smoothed out.

4.2.5 Conclusion

As a conclusion of the battery size reduction assessment method developed in this thesis, all three techniques developed in previous sections are going to be compared. In this comparison, the techniques are enumerated as follows: *Technique 1* is the size reduction assessment of a battery operated under *SOC50* strategy, developed in section 3.2. *Technique 2* is the size reduction assessment of a battery operated under *SOC100_PVCurt* strategy which also limits PV inverters, developed in section 4.1. *Technique 3* is the size reduction assessment combining *SOC100_PVCurt* strategy and PV array oversizing technique, developed in the present section. To be as fair as possible, all three techniques are simulated in a PV plant emulated using artificial data series, as it was done in section 4.2.1.

The exercise is the same as the one shown in Table 4.3, but including the *Technique 1*. The selected battery is the 10C configuration, also explained in that table. This way, the comparison of the alternatives and the improvement process must be considered as sequential implementations, as follows: First, the *Technique 1* is implemented to the previously explained

Plant A, then *Technique 2* and finally *Technique 3*. Table 4.4 shows the results of the three alternatives. As in that case, two approaches are used for the analysis: first, evaluating the PV production of each alternative for a same battery size; second, evaluating the effect of reducing a battery from one alternative to the next.

Table 4.4: PV energy production obtained in an emulation of the Milagro PV plant (7.2 MW) with different sizes of a 10C commercial battery and implementing the three techniques developed in this work: *Technique 1* (*Plant A* under SOC50), *Technique 2* (*Plant A* under SOC100_PVCurt) and *Technique 3* (oversized *Plant B* under SOC100_PVCurt). The reference battery size is the one that allows *Plant A* to achieve 100% of PV production without falling into penalties. %MAX E_{GRID} is the percentage of the maximum achievable production at each plant.

P_{BAT} in kW (% of P_N)	C_{BAT} in kWh (min)	Technique 1		Technique 2		Technique 3		ΔE_{GRID} 1→2 %	ΔE_{GRID} 2→3 %
		E_{GRID} in MWh	%MAX E_{GRID} A	E_{GRID} in MWh	%MAX E_{GRID} A	E_{GRID} in MWh	%MAX E_{GRID} B		
721 (10.0)	72 (0.6)	13 628	90.8%	14 930	100%	18 784	98.3%	9.6	25.8
335 (4.6)	34 (0.3)	11 407	76%	14 183	95%	17 427	91.2%	24.3	22.9
216 (3.0)	22 (0.2)	10 281	68.5%	13 437	90%	16 529	86.5%	30.7	23.0

Following the first approach, it can be seen that for the same battery size, each new technique improves the PV production of the previous one. Comparing *SOC50* and *SOC100_PVCurt*, in spite of the losses associated with the inverter limitations, the latter has a higher battery size reduction potential; which allows for an increase in yearly PV production with the same battery size.

Regarding the behaviours of *Technique 2* and *Technique 3*, in this chapter we have seen that despite *Plant A* and *Plant B* have the same nameplate power; the oversized one tolerates a less intense battery size reduction for achieving maximum production limit. That means that it needs a larger battery for complying with the minimum $RRC_{min} = 98.5\%$ and to avoid penalties. However, it has been demonstrated that the total produced energy using the same battery size is more, which leads to the question of finding a trade-off between yearly PV production increase and the increase of investment costs derived from oversizing the PV array.

Following the second approach and focusing on the battery size reduction against PV production, the comparison between the three techniques should be seen as follows. The battery required to reach the PV production target of scenario 1 with the basic *Technique 1* is rated $P_{BAT} = 721$ kW and $C_{BAT} = 72$ kWh, resulting in a PV production of 13.6 GWh. However, if *SOC100_PVCurt* strategy is implemented (*Technique 2*) and the battery is reduced by 53% down to $P_{BAT} = 335$ kW and $C_{BAT} = 34$ kWh, PV production would even increase by 4% to 14.2 GWh. If then the oversizing technique is implemented (*Technique 3*) and the battery is reduced by an extra 35% down to $P_{BAT} = 216$ kW and $C_{BAT} = 22$ kWh, the production would increase by 16% to 16.5 GWh.

These results are interesting for PV plant projects developers and for battery manufacturers. The battery requirements in an oversized PV plant changes radically from the classic PV plants, so this study should be taken into account to find the optimal *battery size-PV array-inverter power* ratios.

CHAPTER 5

Experimental validation of reduced size battery control strategies

5.1 From virtual scenario to the lab

In the previous chapters, the relation between PV power ramp rate limitation and battery storage requirements has been deeply studied in a statistical way. The results were used for creating a method that effectively assesses the potential of reducing the battery size of PV plants that operate under different control strategies in a scenario affected by strict grid codes.

In this chapter, the implementation of such strategies in a real PV+BESS system is shown, together with the results of the tests to validate them.

The scenario of application continues being the regulation proposed by (PREPA, 2012), so the ramp rate limitation value, power data monitoring frequency and scan differential method used for evaluating RRC of the PV plant are the main guides that control strategies implementation must follow. However, some features will be improved for complying with more restrictive eventual regulations, in order to prepare the path for developing flexible control systems which are easily adaptable to different grid codes.

The new concept of battery size reduction developed in this thesis must be efficiently implemented, in order to operate limited batteries between safe operation limits and minimising the non-compliant events in which the required ramp rate limitation cannot be guaranteed. In order to achieve all the objectives, an advanced controller has been designed.

The system must be accurate and fast enough for managing every device in time to absorb the fluctuations as required. Apart from the RR control tasks, the controller must handle accurately instrumentation equipment, communications between devices and the energy flow along the system within the time constraints imposed by the grid code. Although it is going to be designed and tested in a laboratory, its operation must be prepared for real use in utility-scale PV plants.

In this work, two strategies are going to be validated, *SOC50* and *SOC100_PVCurt*; whose algorithms have been introduced in sections 3.1.1 and 4.1.1, and are detailed in this chapter.

5.2 Implementation of ramp rate control strategies

5.2.1 SOC50 control strategy

The control algorithm of this strategy continuously recovers battery SOC to its reference point, which is set as half-charge. If the recovery process is made with enough speed, consecutive fluctuations can be considered as independent and the energy requirements of discharge and charge events can be considered independently. Therefore, the algorithm tries to restore the battery to $SOC = 50\%$ before the start of every new fluctuation.

In RR control tasks, the battery will operate up to a maximum rated $P_{BAT,WF}$ in each fluctuation event, but the capacity reserved at the beginning of each type of fluctuation (downwards or upwards) will be $C_{BAT,WF}$; i.e. half of the nominal capacity for each type ($C_{BAT} = 2 \cdot C_{BAT,WF}$). The values are given by the WF model (Table 3.2).

SOC50 control strategy was firstly explained in section 3.1.1. Its control diagram was also introduced in Figure 3.2, but it is repeated in Figure 5.1 for clarity reasons and the reference point of the battery energy is adapted according to the WF model.

Figure 5.1: *SOC50* control diagram. The output of the RR limiter is controlled by a feedback loop SOC controller, in order to recover the SOC of the battery to its reference point after each fluctuation.

In this case, the value of the proportional parameter is set to $K = 10$, in order to both, keep a good balance between speed and system stability; and to avoid too high battery power requirements in a SOC recovery process. $E_{BAT,ref}$ is the reference value of the energy stored in the battery, corresponding to $SOC = 50\%$ and equalling the value of $C_{BAT,WF}$. Eq. (5.1) is the main equation that performs RR control tasks and at the same time sets the battery power for recovering its SOC.

$$P_{BAT}(t) = P_{GRID}(t) - P_{PV}(t) \quad (5.1)$$

The strategy has four main operation modes (apart from standby mode) and previous equation gets different values in each of them. Table 5.1 defines the operation modes and shows the values assigned to the battery power in each of them.

Table 5.1: Operation modes of *SOC50* control strategy. Values taken by the battery power and its sign are shown, involving a discharge (D) or charge (C) of the battery. *Grid injection is limited to PV plant nameplate power, which limits maximum battery discharge power.

State	Operation mode	$P_{BAT}(t)$	Sign
S0	Battery OFF - Equilibrium	0	--
S1	Ramp-Down / Excess-SOC recovery	$P_{GRID}(t) - P_{PV}(t)$	> 0 (D)
S2	Ramp-Up / Lack-SOC recovery	$P_{GRID}(t) - P_{PV}(t)$	< 0 (C)
S3	Excess-SOC recovery*	$-K \cdot [E_{BAT,ref} - E_{BAT}(t)]^*$	> 0 (D)*
S4	Lack-SOC recovery	$-K \cdot [E_{BAT,ref} - E_{BAT}(t)]$	< 0 (C)

The functions of each mode are the following:

- S0: Battery in standby, in absence of fluctuations and charged at its reference $E_{BAT,ref}$.
- S1: Battery discharges supporting lack of PV power, reducing SOC.
- S2: Battery charges excess PV power, increasing SOC.
- S3: If $SOC > 50\%$, it is restored discharging excess energy in absence of fluctuations.
- S4: If $SOC < 50\%$, it is restored charging part of PV power in absence of fluctuations.

Note that the injection to the grid is limited by the nameplate power of the PV plant, as per Eq. (5.2), so in *Excess-SOC recovery* mode the battery power is limited by Eq. (5.3):

$$P_{GRID}(t) = \min \left[P_{PV}(t) - K \cdot (E_{BAT,ref} - E_{BAT}(t)), P_N \right] \quad (5.2)$$

$$P_{BAT}(t) = \min \left[-K \cdot (E_{BAT,ref} - E_{BAT}(t)), P_N - P_{PV}(t) \right] \quad (5.3)$$

In order to illustrate the evolution of an operation under *SOC50* strategy, the diagram of Figure 5.2 shows the Finite-State Machine (FSM) of the algorithm which governs the transitions between each mode. Each operation mode of Table 5.1 is associated with a state and the FSM changes from one mode to another in response to the external inputs or transitions explained in the diagram. The process starts and stops at S0 equilibrium state.

Figure 5.2: Finite-State Machine (FSM) of *SOC50* control strategy. The algorithm changes from one mode to another depending on the inputs related to the SOC of the battery and the direction of the fluctuation at each execution instant. Each state is defined in Table 5.1.

The implementation of *SOC50* control algorithm in the I&C equipment of the laboratory is done by adapting the controller output. As shown in Figure 5.1, the output of the ideal RR control algorithm for simulated systems is the battery power. The ideal case supposes that the battery reacts immediately to the set-point and with a perfect response. But real BESS systems have internal losses and the response has an error with respect to the set point.

To shape the real behaviour, the output variable of the practical implementation of the RR controller is the set point of BESS output power, $P_{ESS,set}(t)$. Besides, SOC control loop restores the energy of the BESS at battery level, so the set point of the RR controller is adjusted by additional feedback elements to identify the functional relationship between the output variable and the feedback signal. $P_{ESS,set}(t)$ is multiplied by the instant efficiency of the converter, $\eta_{CNV}(t)$, and the battery round-trip efficiency, η_{BAT} , obtaining the battery discharge/charge power $P_{BAT,set}(t)$. Integrating it, the set-point battery energy $E_{BAT,set}(t)$ is obtained.

Finally, $P_{ESS,set}(t)$ is passed to the input/output server (I/O) of the I&C system in order to send it to the BESS converter by means of the communication system. The adapted diagram is now shown in Figure 5.3.

Figure 5.3: Practical implementation of *SOC50* control algorithm in the I&C system of the laboratory. Output of the controller is the BESS power set-point, sent via I/O server to the I&C infrastructure of the laboratory, where BESS converter acts accordingly

Now, the value of the proportional parameter is $K = 45$, which improves SOC recovery speed in the real BESS and keeps system stability. $E_{\text{BAT,ref}}$ is the reference value of the energy stored in the battery, corresponding to $\text{SOC} = 50\%$ and equalling the value of $C_{\text{BAT,WF}}$ but scaled as explained in section 2.3.3. Adapting the ideal Eq. (5.1), we obtain the main equation that performs RR control tasks and at the same time sets the battery power for recovering its SOC.

$$P_{\text{BAT,set}}(t) = \eta_{\text{CNV}}(t) \cdot \eta_{\text{BAT}} \cdot (P_{\text{GRID}}(t) - P_{\text{PV}}(t)) \quad (5.4)$$

5.2.2 SOC100_PVCurt control strategy

The SOC control algorithm of this strategy has a close loop control diagram similar to that of *SOC50*. However, as the purpose is to face only downwards fluctuations, the battery must be as charged as possible before the cloud front arrives, so the new reference value is $\text{SOC} = 100\%$. Battery power and capacity reference values are again given by the WF model (Table 3.2) but in contrast to *SOC50* strategy, there is no need to double capacity. So the design parameters are $P_{\text{BAT,WF}}$ and $C_{\text{BAT,WF}}$.

SOC100_PVCurt control strategy was firstly explained in section 4.1.1. Its control diagram was also introduced in Figure 4.1 but it is repeated in Figure 5.4 for clarity reasons.

Figure 5.4: *SOC100_PVCurt* control diagram. Upwards fluctuations are absorbed by limiting PV inverters if battery is charged (when $E_{BAT}(t) = E_{BAT,ref}$). Downwards fluctuations are absorbed by discharging the battery.

In this case, the value of the proportional parameter is set to $K = 15$, in order to both, keep a good balance between speed and system stability; and to avoid too high battery power requirements in a SOC recovery process. $E_{BAT,ref}$ is the reference value of the energy stored in the battery, corresponding to full charge and equalling the value of $C_{BAT,WF}$. Eq. (5.5) allows calculating PV inverter power limitation, $P_{PVi,Cu}(t)$, depending on the allowable ramp and on the power required by the battery.

$$P_{PVi,Cu}(t) = P_{GRID}(t) - P_{PV}(t) - P_{BAT}(t) \quad (5.5)$$

The strategy has five main operation modes (apart from standby mode) and the previous equation gets different values in each of them. Table 5.2 defines the operation modes and shows the values assigned to the battery power and PV inverters power limitation in each of them:

Table 5.2: Operation modes of *SOC100_PVCurt* control strategy. Values taken by the battery power and its sign are shown, involving a discharge (D) or charge (C) of the battery.

State	Operation mode	$P_{BAT}(t)$	Sign	$P_{PVi,Cu}(t)$
S0	Battery OFF - Equilibrium	0	--	0
S1	Ramp-Down	$P_{GRID}(t) - P_{PV}(t)$	> 0 (D)	0
S2	SOC recovery / No ramp	$-K[E_{BAT,ref} - E_{BAT}(t)]$	< 0 (C)	0
S3	SOC recovery / Ramp-Up	$P_{GRID}(t) - P_{PV}(t)$	< 0 (C)	0
S4	Ramp-Up	0	--	$P_{GRID}(t) - P_{PV}(t)$
S5	Limited Ramp-Up	$k_p \cdot P_{BAT,WF}$	< 0 (C)	$P_{GRID}(t) - P_{PV}(t) - k_p \cdot P_{BAT,WF}$

The functions of each mode are the following:

- S0: Battery in standby, in absence of fluctuations and charged at its reference $E_{BAT,ref}$.
- S1: Battery discharges supporting lack of PV power.
- S2: SOC recovery with part of PV power, in absence of fluctuations.
- S3: SOC recovery by absorbing upwards ramp.

- S4: $SOC = 100\%$; so PV inverters are limited.
- S5: SOC recovery, but with battery power limited by k_p .

In order to illustrate the evolution of an operation under *SOC100_PVCurt* strategy, the diagram of Figure 5.5 shows the FSM of the algorithm which governs the transitions between each mode. Each operation mode of Table 5.2 is associated with a state and the FSM changes from one mode to another in response to the external inputs or transitions explained in the diagram. The process starts and stops at S0 equilibrium state.

Figure 5.5: Finite-State Machine (FSM) of *SOC100_PVCurt* control strategy. The algorithm changes from one mode to another not only depending on the inputs related to the SOC of the battery and the direction of the fluctuation, but also checking if the battery power is limited. Each state is defined in Table 5.2.

The implementation of *SOC100_PVCurt* control algorithm in I&C equipment is also done by adapting the controller outputs to the operated plant characteristics. The first output of the practical implementation of the RR controller is the BESS output power set-point, $P_{ESS,set}(t)$. As before, for SOC control purposes this parameter is adjusted by the converter and the battery efficiencies, obtaining the battery power.

The second output of the RR controller is the PV inverters power limitation set-point $P_{PVi,Cu}(t)$. Given that this parameter is a command to a simulated PV plant, its implementation is identical

to the ideal model. The energy losses caused by inverter curtailments are monitored by a variable, integrating $P_{PVi,Cu}(t)$ along the operation period.

Both set points are passed to the I/O server of the I&C system in order to send $P_{ESS,set}(t)$ to the BESS converter via communication system and to simulate the PV plant inverters curtailment with $P_{PVi,Cu}(t)$ value. The adapted diagram is shown in Figure 5.6.

Figure 5.6: Practical implementation of *SOC100_PVCurt* control algorithm in the I&C system of the laboratory. Output set points of $P_{ESS,set}(t)$ and $P_{PVi,Cu}(t)$ are sent via I/O server to the I&C infrastructure, where BESS converter and virtual PV inverter act accordingly.

The value of the proportional parameter is also $K = 45$ and $E_{BAT,ref}$ reference value now corresponds to $SOC = 100\%$, equalling the value of $C_{BAT,WF}$ scaled as explained in section 2.3.3. Again, Eq. (5.4) sets the battery power for recovering its SOC. But now, in order to perform RR control tasks both Eq. (5.4) and Eq. (5.6) are needed, depending on the operation mode of the strategy.

$$P_{PVi,Cu}(t) = P_{GRID}(t) - P_{PV}(t) - P_{ESS,set}(t) \quad (5.6)$$

5.2.3 Battery use in SOC50 and SOC100_PVCurt strategies

In chapter 4 the battery size reduction assessment potentials of the two strategies were compared. However, the time of use of the battery in each of the cases was not evaluated. In this section, both strategies are going to be compared focusing on the operation of the battery and in its use. This exercise will also be useful to illustrate the behaviour of the strategies along a representative period in a graphical way.

Both strategies are implemented in Matlab® in order to create a simulation environment that describes the behaviour of BESS system coupled to Milagro PV plant. Using as input the dataset explained in section 2.2, a comparison between both strategies operation during week 22 has been carried out. The second day of the week includes the worst fluctuation of the year, so the selected period is considered as representative for the whole year for evaluating the accuracy of the RR control. The battery is sized with the values of Table 3.2 for $RR_{LIM} = 10\%P_N/\text{min}$.

Figure 5.7a and b show respectively the evolution of relevant power and energy parameters running the simulations under *SOC50* and *SOC100_PVCurt* strategies. In order to compare the strategies in a quantitative way, Table 5.3 shows the values of some relevant operation and energy parameters resulted from the simulations.

Figure 5.7: Simulation of PV+BESS system performing RR control, implementing *SOC50* (a) and *SOC100_PVCurt* (b) control strategies and using as input Milagro PV plant output power data series. ($RR_{LIM} = 10\%P_N/\text{min}$ and $\Delta t = 2$ s).

Table 5.3: Comparison between *SOC50* and *SOC100_PVCurt* control strategies. Results of a simulated operation during the week containing the worst fluctuation of the year.

Control strategy	OF	OF_c	OF_d	$OF_{PVi,Cu}$	$E_{BAT,max} / E_{BAT,min}$ (kWh)	ΔE_{BAT} (kWh)	E_{GRID} (MWh)	$E_{PVi,Cu}$ (MWh, %)
<i>SOC50</i>	0.272	0.146	0.126	--	590/100	490	400.3	--
<i>SOC100_PVCurt</i>	0.185	0.129	0.056	0.034	437/100	237	398.6	-1.7, -0.4

Battery operating factors were defined previously in Table 3.5, while PV inverter limitation operating factor, $OF_{PVi,Cu}$, is calculated as the total time that inverters power is limited with respect to total time that PV plant is generating. Table 5.3 also contains the upper and lower limits of the energy stored in the battery during the simulated week, as well as the energy produced by the plant and the losses caused by the inverter power limitations.

The battery operates more frequently under *SOC50* control strategy, with a total operating factor of 0.27, taking into account both discharge and charge events. After supporting downwards or upwards fluctuations, the SOC controller operates in order to bring back the stored energy to $E_{BAT,ref}$. This fact increases drastically the operating time of the battery with respect to *SOC100_PVCurt* strategy, which only recharges the battery after supporting downwards fluctuations. The same happens with the total battery capacity used, ΔE_{BAT} . However, due to the losses associated with PV inverter limitations during upwards fluctuations, *SOC100_PVCurt* produces 0.4% less energy, being neglectable though.

Extending the simulation period to the whole year, we obtain the final results collected in Table 5.4, which in relative terms are quite similar to the results for the week shown above.

Table 5.4: Comparison between *SOC50* and *SOC100_PVCurt* control strategies. Results of a simulated operation during the whole year of the dataset.

Control strategy	OF	OF_c	OF_d	$OF_{PVi,Cu}$	$E_{BAT,max} / E_{BAT,min}$ (kWh)	ΔE_{BAT} (kWh)	E_{GRID} (MWh)	$E_{PVi,Cu}$ (MWh, %)
<i>SOC50</i>	0.254	0.133	0.121	--	682/100	582	15 588	--
<i>SOC100_PVCurt</i>	0.176	0.12	0.056	0.035	437/100	237	15 497	-90, -0.6

5.3 Controller

The controller is the physical device that commands the PV+BESS system according to the strategies described in the previous section. The NI-PXIe explained in section 2.3.1. implements the controller and, apart from the RR control tasks, it must fulfil other functions to operate the BESS accurately. Therefore, the structure of the controller is divided in different functional blocks, implementing in each of them a specific part of the control algorithm that governs the PV+BESS system. Figure 5.8 shows a diagram of the different blocks implemented in the controller.

The first block is the RR control, which consists of the implementation of the strategies explained in previous section. It receives as inputs the instant PV power value and the feedback control signal requiring power to restore the SOC of the battery.

Figure 5.8: Functional block diagram of the controller. RR control, EMS and SOC control blocks configure the control algorithm that operates the BESS reacting to the behaviour of the emulated PV plant. The I&C infrastructure of the laboratory is configured following the hardware-in-the loop concept, in order to implement control strategies that can be tested running real and virtual systems.

The next important block is the energy management system (EMS). Accurate instrumentation equipment measures voltage, current and power at every point of the system with the required precision. Simultaneously, an EMS is needed to monitor the energy flow at every point of the BESS, in order to perform an accurate energy balance along the complete test system. But collected power and energy data must be used inside the control algorithm in order to evaluate the availability of the BESS for absorbing fluctuations and to watch out the limitations of power, capacity and operation limits at every instant of the operation. Therefore, an accurate EMS is coupled to the control algorithm, which updates the control variables according to the real-time values of the parameters measured by the instrumentation. This EMS forms the second functional block of the controller and it receives the inputs of the RR control block and the I/O server.

Last but not least, the implementation of the SOC control loop explained in previous section forms the third functional block. It recovers the energy stored in the battery to its reference point and for that, this block needs to know the state of the BESS which is monitored by the EMS block. Depending on the energy value given by the latter, the SOC control requests the required power to recover the battery energy but being careful of matching the RR_{LIM} . Hence, SOC control block is implemented in the controller and coupled to the output of EMS block and to the input of RR control block.

During its execution, the controller receives inputs of real and simulated values. The EMS supplies real time parameters measured at every point of the hardware BESS, but the controller also uses the power data series of the Milagro PV plant in order to emulate the real-time output of a PV power plant. Also, the controller sends $P_{ESS,set}(t)$ and $P_{PVi,Cu}(t)$ commands to hardware and to simulated systems respectively. Hence, we say that the controller acts in *hardware-in-the loop* mode (HIL). This technique is used in the development of real-time controllers that need to manage the behaviour of systems or plants that are not physically in the test bench. In our case, the BESS and I&C equipment are the real hardware of the HIL system.

On the contrary, the simulation of the PV plant, formed by its power data series and the PV inverter power limitation values, is the virtual part of the HIL system. Figure 5.8 explains this configuration and the role of each functional block explained above in the layout of the controller. Therefore, the power fed into the grid, $P_{\text{GRID}}(t)$, is necessarily a simulated value, which is calculated as the sum of simulated (S) and measured (M) values of the parameters shown in Eq. (5.7).

$$P_{\text{GRID}}^{\text{S}}(t) = P_{\text{PV}}^{\text{S}}(t) + P_{\text{ESS}}^{\text{M}}(t) + P_{\text{PVi,Cu}}^{\text{S}}(t) \quad (5.7)$$

5.3.1 Energy management system

The EMS measures the energy managed at each level of the BESS, either at AC side or at DC side of the converter, $E_{\text{ESS}}(t)$ and $E_{\text{ESS,DC}}(t)$ respectively. Also, it must estimate the effective energy stored in the battery, understood as the exact available energy to be discharged under a downwards fluctuation and named as $E_{\text{BAT}}(t)$. The instant active power measured at every point ($P_{\text{ESS}}(t)$ and $P_{\text{ESS,DC}}(t)$) is integrated in order to have a real time value of the energy flow and to know the effective SOC for facing a charge/discharge process with precision. Figure 5.9 shows the diagram of the EMS and its communication system for updating the control variables involved in SOC control with measured values. Figure 5.10 shows the implementation of the EMS in LabVIEW.

Figure 5.9: Diagram of the energy management system (EMS) used for monitoring real time values of BESS. The measured parameters are used for updating the values of control variables, in order to perform an accurate SOC control and keep BESS in optimum conditions for performing ramp rate control tasks.

Figure 5.10: LabVIEW implementation of the EMS. Energy balance at every point of the BESS is monitored by the system in real time, counting total energy and also energy of single fluctuation events. Main goal of EMS is to calculate the effective SOC of the battery for maximising fluctuations mitigation. Energy loss associated with inverter limitations (*SOC100_PVCurt* strategy) is also monitored by EMS.

In order to explain the integration of EMS and the rest of the blocks of the controller under the HIL environment, a combined controller-BESS-plant diagram has been built, shown in Figure 5.11.

Figure 5.11: Integration of EMS with RR control and SOC control blocks of the controller that runs the HIL environment, valid for either *SOC50* or *SOC100_PVCurt*. Set point value of the ESS power is updated with the real value of ESS DC power in order to control battery SOC with accuracy.

The full process is the following: Against an eventual fluctuation of PV plant output power $P_{PV}(t)$, the ramp rate control unit determines the required ramp to be held in $P_{GRID}(t)$ and accordingly, the set points of $P_{ESS,set}(t)$ and $P_{PVi,Cu}(t)$ are outputted. The communication system of the controller sends $P_{ESS,set}(t)$ from the I/O server to the converter of the BESS unit and after the correspondent reaction time, real value of the BESS output power, named as $P_{ESS}(t)$, is stabilised (AC side of converter) and monitored back to the controller together with the DC power value $P_{ESS,DC}(t)$. Then, the controller must evaluate the updated battery SOC derived from supplying the power required to face the ramp. This is done in three steps.

a) Estimation of SOC variation caused by $P_{ESS,set}(t)$

First, the SOC controller needs to estimate the energy that will be charged/discharged in the battery due to current set point $P_{ESS,set}(t)$, so it takes into account the instant converter efficiency and the battery round-trip efficiency, $\eta_{CNV}(t)$ and η_{BAT} . Converter instant efficiency is calculated with the power values measured by the wattmeters installed in AC and DC side of the converter, so the EMS provides the controller with these measurement data. Battery round-trip efficiency is considered constant for the power range of the test bench and it is characterised by means of the tests explained in section 2.3.2. Multiplying $P_{ESS,set}(t)$ by the efficiencies, the battery power $P_{BAT,set}(t)$ is estimated and integrating it along the execution step, the energy that will be charged/discharged in the battery during the present step is obtained, $E_{BAT,set}(t)$.

b) Monitoring of battery energy

Second, the SOC controller needs to know the energy charged/discharged in the battery along all the operation time previous to the current execution step. There is a difference between the power set point value and the real value achieved at every execution step, so the controller must receive feedback of measurement data in order to perform the SOC control loop with updated values. This way, the EMS counts the energy flow by measuring and integrating the BESS power at DC level, $P_{ESS,DC}(t)$. At the time of monitoring the measured energy flow, round-trip efficiency of the battery must be applied just once, only to charge and not to discharge. This is justified following the definition of round-trip efficiency:

$$\eta_{BAT} = \frac{E_{BAT}^D}{E_{BAT}^C} \rightarrow E_{BAT}^D = E_{BAT}^C \cdot \eta_{BAT} \quad (5.8)$$

Hence, implementing the following equations in the EMS, energy stored in the battery until $t-1$ is accurately estimated with measured data.

$$\text{Charge:} \quad E_{BAT}(t-1) = \int_0^{t-1} \eta_{BAT} \cdot P_{ESS,DC}(t) dt < 0 \quad (5.9)$$

$$\text{Discharge:} \quad E_{BAT}(t-1) = \int_0^{t-1} P_{ESS,DC}(t) dt > 0 \quad (5.10)$$

By adding the energy monitored by the EMS for previous steps of execution $E_{BAT}(t-1)$ and the estimated set point energy input provided by the current step $E_{BAT,set}(t)$, the total energy stored in the battery at the end of the present step is calculated. Comparing it with the reference

$E_{\text{BAT,ref}}$. SOC controller calculates the error and the feedback required to restore the real SOC to its reference. This error is amplified by the proportional constant of $K = 45$. This will be the resulting feedback value to be rested from the available PV power and used for restoring the SOC. The feedback must be limited by the corresponding k_p factor if we use a reduced-power battery.

c) Definition of reference energy value based on effective capacity

Given the converter and battery losses, two different capacities are defined along the BESS. From the point of view of RR control, the energy capacity of the ESS, named as C_{ESS} , is the total energy that could be supplied by the BESS to face a downwards fluctuation or the total energy that could be absorbed in the BESS in an upwards fluctuation. Therefore, it can be seen as the total discharge/charge energy available at its output and it is considered as the effective capacity of the BESS.

However, in order to overcome the internal losses caused by the converter, the effective BESS capacity must be oversized, obtaining the capacity of the battery and named as C_{BAT} . Eq. (5.11) shows the oversizing criteria, where η_{CNV} is set as an average converter efficiency. This value depends on the power at which operates the ESS, but RR control operation requires a widespread range of ESS power, varying from null to maximum power. Hence, the value obtained in section 2.3.2 must be corrected by a more conservative value, so an average efficiency of 0.9 is set as convenient.

$$C_{\text{BAT}} = \frac{C_{\text{ESS}}}{\eta_{\text{CNV}}} \quad (5.11)$$

Note that this is the useful battery capacity and it is the value that will handle the EMS in the test-bench. However, according to the tests carried out in section 2.3.2, this value would correspond with the useful 70% of the total battery capacity to be installed. In order to operate a real utility-scale BESS between the safety limits explained in those tests, it should be oversized accordingly.

Once the battery capacity is defined, the SOC of the battery is calculated using the following relation:

$$\text{SOC}_{\text{BAT}} = 100 \cdot \frac{E_{\text{BAT}}(t)}{C_{\text{BAT}}} \quad (5.12)$$

where $E_{\text{BAT}}(t)$ is the energy stored in the battery, calculated in previous step b). SOC controller must regulate previous equation to its reference point. The reference value must take into account the converter efficiency, so, as the design capacity of the BESS was calculated with the WF model, the reference equals that value oversized by the efficiency:

$$E_{\text{BAT,ref}} = \frac{C_{\text{BAT,WF}}}{\eta_{\text{CNV}}} \quad (5.13)$$

5.3.2 SOC control

The function of this block is to recover the battery to its reference SOC, calculating the power at which the battery must operate to recover its charge. First it calculates the error signal as the difference between the reference value $E_{\text{BAT,ref}}$ and the feedback signal $E_{\text{BAT}}(t)$. Second, the error is applied to the proportional controller in order to obtain the control output signal.

5.3.2.1 SOC recovery mode execution

In the practical implementation of the SOC control, the feedback loop is conditioned by a minimum value in order to avoid inefficient operation of the BESS at the last part of SOC recovery. A tolerance of $\pm 120 / K$ (kWh) is set to the control error and when this value is reached, the SOC recovery process will be concluded. Otherwise, values of the controlled variable $P_{\text{ESS}}(t)$ would be very low and as a consequence the efficiency of the converter would decay dramatically. As a result, the effective power for charging the battery, $P_{\text{ESS,DC}}(t)$, would be practically null.

This phenomenon is explained in Figure 5.12. It shows the response of BESS to a downwards fluctuation, followed by corresponding SOC recovery process. After the battery is discharged between $t = 77\text{s}$ and $t = 161\text{s}$, the system enters in SOC recovery mode. The energy stored in the battery $E_{\text{BAT}}(t)$ raises relatively quickly till around $t = 300\text{s}$. However, during the last three minutes the charge power $P_{\text{ESS}}(t)$ is low, resulting in low values of converter instant efficiency $\eta_{\text{CNV}}(t)$, shown in the graph at the bottom. With this scenario, the effective power that charges the battery $P_{\text{ESS,DC}}(t)$ is very low; so, in order to avoid an inefficient long recovery process it is interrupted. Hence, the energy of the battery at this point is full-charge minus the tolerance $E_{\text{BAT,stop}} = 120 / K$.

Figure 5.12: SOC recovery process close to $E_{\text{BAT,ref}} = 437$ kWh value. SOC error is limited with a tolerance, setting a minimum feedback loop value at which SOC recovery mode stops. Converter efficiency falls at low powers and the effective recharge DC power would be so low that a full-recharge would enlarge an inefficient process.

Besides, in order to avoid oscillating ON-OFF operations, a hysteresis region is defined for launching and stopping the SOC recovery process. Figure 5.13 defines the region for either *SOC50* or *SOC100_PVCurt* implementation.

Figure 5.13: Hysteresis for launching SOC recovery process. Battery is discharged (charged) under a fluctuation. Afterwards, it is allowed to be recharged (discharged) to its reference point only if a threshold error $E_{BAT,th}$ has been discharged (charged) from the reference point. The recovery process stops at $E_{BAT,stop}$. By definition of hysteresis, the limits must keep $|E_{BAT,th}| > |E_{BAT,stop}|$.

5.3.2.2 About the selection of K in SOC control

When SOC control loop is enabled, the energy stored in the battery is brought to its reference point by charging the lack or discharging the excess (discharge only in *SOC50*) of energy. The proportional constant K of the feedback loop decides the speed of the recovery process, allowing the BESS converter operating at more or less power depending on that value. The faster the process, the sooner the system will be ready for a new fluctuation. However, the magnitude of K has some implications in the practical implementation of the SOC control.

On the one hand, the proportional controller has implications when operating reduced power batteries. If they are operated with an elevated value of K , the power limit is reached more frequently. The consequences are different if the system operates under *SOC50* or *SOC100_PVCurt*.

On the other hand, high values of K can reduce battery durability. If between consecutive fluctuations the SOC controller acts sharply to recharge lack or to discharge the excess of energy, battery power curve along the operation will be noisy and with peaks, the number of cycles will be elevated and the associated degradation will increase.

Let us consider the following scenario in order to understand the effects of K . Figure 5.14 shows the results of different laboratory tests; a period of the system operation under a fluctuating event and different values of K in each. Figure 5.14a is the response of the BESS and the resulting power fed into the grid under a strong PV power downwards fluctuation, followed by the SOC recovery process; the last part has been zoomed out in Figure 5.14b.

(a)

(b)

Figure 5.14: Implications of controller parameter K in the SOC recovery process. Six tests with different values of K are carried out, obtaining six combinations of BESS power and injected grid power. With top K values, battery is charged (a-b) and discharged (c) at higher power, faster but completing more number of cycles. If a reduced power battery is controlled with a high K controller, its limit is frequently reached (b).

It can be seen the operation of the system responding to the worst fluctuation of the simulated PV scenario, implementing 6 different values of K in the SOC control loop: 75, 60, 45, 30, 15 and 6. The first part of the operation is a pure RR control in a *Ramp-Down* mode (1). When the downwards fluctuation ends, the system enters in *SOC recovery* mode (2), using all available PV power for recharging the battery. During these two modes, the system acts identically with the 6 controllers. But in the last part of operation, when PV power starts increasing again in an

upwards fluctuation, each controller acts in a different way (3). It is a mixed mode, performing ramp-up tasks but recovering SOC by recharging the lack of energy of the battery. It can be seen that the higher the K value, the higher the recharge power of the BESS. When PV power is higher than the required BESS power, the system feeds power to the grid in a ramp-up shape.

Under *SOC100_PVCurt* strategy and reduced power battery, an elevated K value will frequently enter the system in *Limited Ramp-Up* mode, explained in section 4.1.1. The battery limitation is supported by inverter curtailment, so there is no major problem to comply with an upwards ramp like the one shown on Figure 5.14b. However, in this case a high K value would imply more losses associated to inverter limitations.

But in *SOC50* strategy, the ramp of interval 3 cannot be fulfilled if the system operates with high values of K . For instance, if the battery power was reduced by a factor $k_p = 0.5$, values of more than 30 would imply non-compliances (NC) in RRC assessment. If the battery was reduced by $k_p = 0.3$, the non-compliant scans would be even more (for every K value and during more instants). As an extreme case, with a value of $K = 75$, all scans from $t = 1540$ s to $t = 1765$ s, almost 4 minutes, would be non-compliant for power.

Hence, an appropriate value of K is needed to quickly restore the battery to the desired SOC after each fluctuation, but avoiding the described problems. A good practice would be to set variable values of K depending on the operation mode and on the k_p factor.

5.3.3 Real time control architecture optimisation

In real-time (RT) applications, response time of a task is defined as the time elapsed between its dispatch to the time when it finishes its job. This time is very short and the RT controller is able to fulfil every programmed task of the RR control algorithm with the required accuracy before the prescribed time constraint of the execution step T_s , defined as deadline.

However, the reaction time of the equipment under control creates some problems to the control algorithm implemented in the RT controller. This parameter is the time elapsed from the instant when a given actuator receives a command, to the instant when its output is changed as required. If a particular task allocated in the control schedule requires an input of measured BESS output power for deciding an action, a slow reaction time in the latter will affect to the decision quality of the first one. If for example, due to the reaction time the task waiting for a $P_{ESS}(t)$ data receives an obsolete value which corresponds to the previous time-step of execution ($t-1$), the output of the task will be erroneous. Therefore, it is necessary to detect the bottleneck of the whole system in order to act accordingly in other components to optimise it as a whole.

In the test bench of the laboratory, the bottleneck is the power electronics of BESS converter. Depending on the magnitude difference between the instant power of the converter, $P_{ESS}(t)$, and the set value we wish to obtain for the next time-step, $P_{ESS,set}(t + 1)$, the reaction time can oscillate between 0.5 - 2 seconds; the higher the power gradient, the longer the reaction time of the power electronics. Given this restriction, the bottleneck must be sorted out at control algorithm level, scheduling the tasks and managing efficiently strategical delay times to avoid data acquisition errors caused during the reaction time of the converter.

When the length of the execution step T_s is long enough to complete every control task and additionally to wait for the reaction time of the converter without reaching the deadline, the problem can be solved adding a controlled delay named as τ_d . It is inserted in the control schedule between the instant t when the set point $P_{ESS,set}(t)$ is sent to the I/O server and the instant when the reaction is completed, allowing to measure $P_{ESS}(t + \tau_d)$. The duration of τ_d must be balanced so that the following expression is fulfilled.

$$\tau_d \ll T_s \rightarrow P_{ESS}(t + \tau_d) = P_{ESS,set}(t) \quad (5.14)$$

As a good design value, $\tau_d = T_s/2$ guarantees enough time for assuring a considerable reaction time of the converter and leaves enough time yet for completing other tasks before the deadline. This way, the delay must be added to the response time of all the tasks scheduled in the control algorithm. Figure 5.15 shows the result of operating RR controller under a downwards fluctuation with this technique for an execution step of $T_s = 2$ s and two scenarios; with and without using a reaction time delay.

Figure 5.15: Effect of BESS converter reaction time at high-power gradients and use of a controlled delay for optimising control accuracy ($T_s = 2$ s). Real power ramp $P_{GRID}(t)$ matches better the set value $P_{GRID,set}(t)$ when a delay of $\tau_d = T_s/2$ is inserted in the control loop to wait until converter reaction is stabilised. Values of $T_s \geq 2$ s allow to insert into the execution step a delay that offsets the long reaction time of the BESS converter.

In the scenario without delay of Figure 5.15a, the output of the system is measured immediately after sending the command $P_{ESS,set}(t)$ and the data logger does not register the correct measured BESS output power. Therefore, an erroneous measured $P_{ESS}(t)$ is logged, the power fed into the grid is erroneous and the prescribed ramp is not fulfilled. To prevent this, in the second scenario a delay has been inserted in the control loop between the task that sends the set-point and the task that reads the measured BESS output power. As it can be seen in Figure 5.15b the system now is stabilised around the required parameters.

Given the long reaction time of the converter, this technique solves completely the problem if $T_s \geq 2$ s. If for example $T_s = 2$ s, a delay of $\tau_d = 1$ s is appropriate. This technique is accurate

enough to be used in regulations like the one proposed by PREPA and APER for Puerto Rico (PREPA, 2012). Since the data-logging frequency required in that proposal is $\Delta t = 2$ s, the system would fulfil the control requirements easily as it has been shown in Figure 5.15b.

But for lower Δt values, the minimum delay of 1 s cannot be included inside the control schedule, because it would be longer than the deadline. In this case, a shorter delay must be inserted in order to guarantee the deadline of every execution loop. However this is not always feasible. It must be noted that gradients of more than 200 W/s require the longest reaction times of the converter of our lab. However, the gradients of a real-scale system would be multiplied by the scale factor (i.e. 200 kW/s), so the converter of the utility-scale BESS should be prepared for short reaction times to face these large power gradients.

In order to insert the appropriate delay in the correct point of the control schedule, LabVIEW can assure that a command of a scheduled sequence is executed at a particular instant in the period of the loop. Figure 5.16 describes how the sequence of different commands is scheduled inside a timed loop which is executed with a period of T_s .

Figure 5.16: Scheduled control sequence executed in a timed loop, performing at every execution step different tasks of the algorithm following a timed sequence. Grid power and battery energy values are saved from one cycle to the next.

First the control algorithm calculates the required BESS power for facing a ramp and sends the set value $P_{ESS,set}(t)$ to the I/O server of the controller; second, the communication system transmits the data; third, converter receives it and acts accordingly; fourth, after its reaction

time, it achieves to operate at the correct power; fifth, the measured output power is registered for other control tasks and monitoring/data-logging functions.

In order to calculate the time elapsed from the first step to the fourth, a response monitoring system is included in the test bench. By means of time-testers, we make sure that each command is executed at a precise instant inside the period and, using controlled delays, we give enough time to other associated functions to do their job before continuing with the execution of subsequent tasks. Next to the step where $P_{\text{ESS,set}}(t)$ is sent, different delays are inserted in the frames subsequent to the RR control algorithm. After each delay, the responses of the converter are measured and the error with respect to the set value is calculated. Eqs. (5.15) - (5.16) show different delay alternatives that are studied, being all of them a fraction of the execution period T_s . The parameter ε_i is the error of the converter response after each delay alternative.

$$\tau_{d1} = 0 ; \tau_{d2} = 0.5T_s ; \tau_{d3} = 0.83T_s ; \tau_{d4} = 0.93T_s \quad (5.15)$$

$$\tau_{di} \mid i = 1:4 \rightarrow \varepsilon_i = P_{\text{ESS}}(t + \tau_{di}) - P_{\text{ESS,set}}(t) \quad (5.16)$$

Figure 5.17 shows an operation of the system for a span of 200 seconds, and the response of BESS after each of the delays explained above. RR control strategy calculates the required $P_{\text{ESS,set}}(t)$ values in order to absorb the shown downwards fluctuation and it is sent to the converter at $t = 44$ ms. Depending on the delay implemented in the control schedule, the response of the ESS is acquired at four different instants, reading different values. As seen, the longer the delay, the more accurate is the response given by the converter.

Figure 5.17: Measured BESS power $P_{\text{ESS}}(t)$ vs. set-point $P_{\text{ESS,set}}(t)$ with different delays implemented in the control schedule, with an exigent $\Delta t = 1$ s. The high BESS power gradient lapse is zoomed out and displayed on the right side. Due to the reaction time of the converter, a longer delay improves control response accuracy.

Despite τ_{d4} solves the problem with the highest accuracy; it is quite dangerous to include such a high delay. After $P_{ESS}(t)$ data is obtained, the control algorithm has to complete other tasks prior to the deadline of the execution step and using τ_{d4} the remaining time is too short. The delay which involves the lowest error of Eq. (5.16) and at the same time assures the execution of the rest of command sequence before the deadline is the optimum delay. Therefore, a delay of $\tau_d = 0.83T_s$ has been included in the control system, as a trade-off between accuracy of measured BESS power data and appropriate control timing.

5.4 RRC of reduced batteries

5.4.1 Emulation of reduced batteries

The control system of the test-bench has input-fields to specify the utility-scale BESS design power and capacity requirements, i.e. $P_{BAT,WF}$ and $C_{BAT,WF}$, as well as the k_p and k_c size reduction parameters with which we want to carry out the test. As explained in section 2.3.3 the physical battery of the laboratory is the base for the emulation of the utility-scale battery.

Reduced test-battery requirements P_{ESS} and C_{ESS} are calculated applying k_p and k_c reduction factors to the scaled design parameters of the test-battery. The following example illustrates the equivalence. A utility-scale design BESS power of $P_{ESS,WF} = 5148$ kW is scaled to a test-BESS design power of $P_{ESS,WF} = 5.148$ kW. For testing a battery reduced by $k_p = 0.3$, the test power requirement would be $P_{ESS} = 1.545$ kW and it emulates a utility-scale system of $P_{ESS} = 1545$ kW. Regarding the capacity, the utility-scale design BESS capacity of $C_{ESS,WF} = 437$ kWh is scaled to a test-BESS design capacity of $C_{ESS,WF} = 437$ Wh. For testing a battery reduced by $k_c = 0.3$, the test capacity would be $C_{ESS} = 139$ Wh and it emulates a utility-scale system of $C_{ESS} = 139$ kWh.

The practical implementation of battery power and capacity limitations is carried out by means of two functions. On the one hand, the system implements a function that calculates if in each execution step the BESS is commanded to operate in a power higher than the limited P_{ESS} . On the other hand, another function calculates if in an execution step the limited energy capacity is going to be surpassed, either discharging more energy than C_{ESS} or charging beyond that value.

Both power and capacity limit functions are represented as blocks that are added to the control diagram shown in Figure 5.11, obtaining the updated Figure 5.18. As shown in the figure, the power limit function is represented as a k_p *limiter* block that is inserted at the output of the RR control unit, limiting the output set-point $P_{ESS,set}(t)$. The block must be inserted in the output of the feedback SOC controller too, because the manipulated control variable needs to be calculated complying with the reduced battery power constraint. The capacity limit function is represented as a k_c *limiter* block that is inserted in series with the k_p limiter block, limiting the output set-point $P_{ESS,set}(t)$ in terms of the prospective energy that could charge to/discharge from the battery. Figure 5.18 represents the control diagram of the complete hardware-in-the-loop system. The size reduction limiter blocks affect the inputs and outputs of the SOC feedback controller and of the EMS.

Figure 5.18: Complete HIL control system, including RR control, SOC control, EMS and plant. Reduced battery control requirements are also included, inserting k_p and k_c limiters for operating with reduced battery requirements.

Both blocks also handle two flags in order to evaluate the ramp rate compliance of the PV+ESS system. If in a particular execution step either power or capacity limitation is activated, a flag is raised for the scan corresponding to that step. Later, a process that supervises the RRC of the plant will decide if the scan is non-compliant analysing the following additional criteria:

- K_p limiter and NC_P scan determination

Power limitation is evaluated implementing Eq. (3.24) in the limiter block. When the k_p limiter is activated, $P_{ESS,set}(t)$ is coerced to the limited range $\pm P_{ESS}$ and raises a flag to notify the system its operation in limited battery power mode. If in addition to this flag, the system manages a downwards fluctuation under $SOC100_PVCurt$ strategy, or any direction fluctuation under $SOC50$, the limiter notifies the RRC assessment supervisor process that the present scan must be marked as NC_P . As explained before, the non-compliance is avoided in upwards fluctuations if the system is supported by PV inverter limitations.

- K_c limiter and NC_C scan determination

Capacity limitation is evaluated implementing appropriately Eq. (3.26) in the limiter block; evaluating against the corresponding capacity value of either $SOC50$ or $SOC100_PVCurt$ strategy. When the k_c limiter is activated, the block raises a flag to notify the system its operation in limited battery capacity mode. It also calculates the difference between the current stored energy $E_{BAT}(t)$ and the limited battery capacity C_{BAT} ; and it obtains the power (limiting again $P_{ESS,set}(t)$) at which the system is allowed to operate during the next execution step to avoid surpassing full-charge/discharge. From the next execution to the end of the event, the

BESS is switched to standby mode, keeping $P_{\text{ESS,set}}(t) = 0$ kW, maintaining the flag raised and notifying the RRC assessment supervisor process that all the scans must be marked as NC_C .

5.4.2 RRC assessment

When every control and communication task commanded by the controller is performed, a supervisor process checks the results of the algorithm in order to evaluate the ramp rate compliance of the PV+BESS plant at the end of each execution step. This process is named as *RRC assessment* process and evaluates if the plants fulfils the technical requirements imposed by the grid code where the plant operates. In this case, the process implements the compliance assessment methodology explained in 3.2.1 for the Puerto Rico grid code, but it can be easily customised for performing supervisory tasks attending to other RR_{LIM} or Δt requirements.

In a real utility-scale PV plant the system would carry out the RRC assessment by comparing the output grid power measured data of two consecutive execution steps with a duration of T_s . If the variation between them is higher than the maximum allowed one during the step, ΔP_{RR} , it is registered in a non-compliances counter variable. This scan differential assessment is done by logging one scan every 2 s.

But the test-bench of the laboratory is a scaled system and the precision errors are also multiplied by a factor of x1000. This way, a common precision error at the converter output power of ± 30 W/s (0.6%) is interpreted as an error of ± 30 kW/s at the emulated utility-scale converter output. In the PV plant of Milagro, where a RR_{LIM} of 10 % P_N /min means that every two seconds the output power must vary less than 24.14 kW, the scaled-up precision error is higher than that value and it prevents us for assessing correctly the RRC. Because of that, an alternative technique is used for assessing the ramp rate compliance of the emulated plant: Every time the supervisor process receives a notification of NC_P and/or NC_C from the limiter blocks, the non-compliances counter NC is incremented. Simultaneously, while PV plant injects power to the grid, total generating scans are counted and finally, implementing Eq. (3.28), the instant ramp rate compliance is calculated and registered. Exactly in the last scan of the week, the RRC value indicated by the supervisor process is assigned to the whole past week and a corresponding PV power curtailment is set as a penalty to the operation of the following week.

5.5 Test and validation of reduced size battery control strategies

In order to check if the reduced batteries control system works properly, some tests are carried out in the laboratory. On the one hand, the behaviour of the control system must be checked in detail, evaluating if every operation mode of the implemented strategies and the control response in each of them is adequate. On the other hand, a representative period of operation will be useful to know if the final goal of the control system, i.e., the RR control of the PV+BESS plant, is achieved accurately and as expected for a certain combination of power and capacity reductions.

5.5.1 Evaluation of the controller accuracy

The control system operation is validated checking carefully if each operation mode of either *SOC50* or *SOC100_PVCurt* implementations works appropriately. Besides, the response of the controller in each of the modes is also analysed. The most relevant parameter to observe is the PV plant output power fed into the grid $P_{\text{GRID}}(t)$: It must follow the ramps imposed by the RR control unit output set-point, named as $P_{\text{GRID,set}}(t)$. This assessment will prove that the developed controller is suitable for strict grid codes.

The next parameter to evaluate is BESS output power $P_{\text{ESS}}(t)$, checking its response against the required set-point $P_{\text{ESS,set}}(t)$. This assessment will prove that the developed controller has been improved in order to overcome the long reaction time of the converter. If the result is accurate enough, the controller is prepared for working with utility-scale BESS converters, which are supposed to be more precise and adequate for highly demanding applications.

5.5.1.1 Validation of controller operation modes

For this validation, a short time lapse of operation is going to be analysed in order to illustrate graphically each operation mode. The test is performed using a battery configuration following the WF model of Table 3.2, but reduced by the factors $k_p = 0.3$ and $k_p = 0.3$. Figure 5.19 shows grid, BESS and PV inverters limitation power, as well as the energy of the battery; all of them measured during an operation of the system using as input the PV power data of Milagro PV plant. The test is elapsed 1400 seconds and has two variants. The one shown in Figure 5.19a is a test which implements the *SOC50* control strategy, while the other shown in Figure 5.19b implements the *SOC100_PVCurt* strategy. Table 5.5 explains the name of the operation mode running during each interval and marked at the graphs, as well as if each interval contains non-compliant scans. Mixed operation modes combining RR control and SOC recovery are also indicated.

Figure 5.19: Validation of operation modes of *SOC50* (a) and *SOC100_PVCurt* (b) control implementation. Two laboratory test operations are shown to compare the behaviour of the system under each strategy. The arrows indicate non-compliant scans.

Table 5.5: Control system operation modes at each period of the validation test under *SOC50* and *SOC100_PVCurt* strategy. Ramp rate compliance status is included, marking periods which contain non-compliant scans. *Transition between two operation modes during a single period.

Period	Operation Mode			
	SOC50	RRC	SOC100_PVCurt	RRC
1	Ramp-Up (pure)		Ramp-Up	
2	Ramp-Down (SOC rec.)		Ramp-Down	
3	Ramp-Up (SOC rec.)	NC_P	Limited Ramp-Up (SOC rec.) / Ramp-Up*	
4	Excess-SOC recovery		BESS OFF	
5	Ramp-Down (SOC rec.)	NC_P	Ramp-Down	NC_P
6	Lack-SOC recovery		SOC recovery (No ramp)	

As it can be seen, each operation mode designed in sections 5.2.1 and 5.2.2 for the simulation environment is correctly implemented in the controller. The BESS completes its required RR control tasks and the SOC control is successful to bring the energy stored in the battery to the respective reference point at reasonable speed.

The emulation of reduced sized batteries also works appropriately. Under *SOC50*, the upwards fluctuation occurred during interval 3 is too strong and there are two instants where the battery power is not enough to support the prescribed RR_{LIM} , BESS charge power limits at $P_{ESS} = -0.3 P_{ESS,WF}$. During interval 5, a strong downwards fluctuation causes the same problem, this time while battery is discharging. All these instants are marked as non-compliant by the RRC assessment process. Under *SOC100_PVCurt*, during the event of interval 3, the inverter limitations successfully support the BESS and they team up fulfilling the required grid power ramp. Hence, only the failure of interval 5 is marked as *NC*.

5.5.1.2 Validation of control response

Regarding the control response of the relevant parameters, it can be seen in Figure 5.19a and b that both $P_{GRID}(t)$ and $P_{ESS}(t)$ match their respective set-points appropriately. $P_{GRID}(t)$ only fails its set-point when the limited battery power prevents it from matching the required ramp.

But comparing deeply the set-points with the reached values at every execution step, there are some differences. Although the RT control architecture has been optimised by means of controlled delays, there are still some errors due to the long BESS converter reaction time and the short execution deadline of $T_s = 1$ s. Table 5.6 shows the mean errors between $P_{GRID,set}(t)$ and $P_{GRID}(t)$, named as ε_{GRID} and between $P_{ESS,set}(t)$ and $P_{ESS}(t)$, named as ε_{ESS} . Note that ε_{GRID} is calculated in two ways. First way takes into account every $P_{GRID}(t)$ scan along the whole time lapse of the test, which gives the idea of the mean error. Second way only takes into account scans when BESS is operating. Like this, the direct effect of the converter reaction time is more evident.

Table 5.6: Errors between set-point values and reached values of grid feed-in power and BESS power. Grid power error is calculated for the total operation period and also focusing only on instants when battery is operating.

Error	SOC50	SOC100_PVCurt
$\varepsilon_{\text{GRID}}$	1.38 %	0.55 %
$\varepsilon_{\text{GRID}}(P_{\text{ESS}}(t) \neq 0)$	1.41 %	1.35 %
$\varepsilon_{\text{ESS}}(P_{\text{ESS}}(t) \neq 0)$	4.51 %	4.32 %

First conclusion is that the errors are acceptable. $\varepsilon_{\text{GRID}}$ is low enough to affirm that the controller is suitable for using it in strict ramp-rate regulations. It is especially low for *SOC100_PVCurt* strategy. The reason is that although the error on $P_{\text{GRID}}(t)$ caused by the converter reaction time is the same in both strategies, with *SOC100_PVCurt* there are no reduced battery power limitations in upwards fluctuations, so this strategy boosts control response of $P_{\text{GRID}}(t)$. Nevertheless it can be seen that $\varepsilon_{\text{GRID}}$ error calculated for instants when BESS is operating and ε_{ESS} are similar for both strategies. The $\varepsilon_{\text{GRID}}$ is lower than ε_{ESS} because the absolute magnitude of $P_{\text{GRID}}(t)$ is bigger than $P_{\text{ESS}}(t)$; but they are always proportional for both strategies, as the origin of the error is the converter of the BESS.

However, converter structures with faster reaction times would be desirable for real-scale PV plants.

5.5.2 Improvements to increase RRC

When limited power or capacity batteries are operated, it is anticipated that part of the scans will not comply with the RR limitation and it is assumed that they will cause some penalties. The ramp can be failed owing to either lack of battery power or lack of battery capacity, or both. But once the non-compliance happens, the system can operate efficiently and optimise its limited resources for fulfilling back the ramp during less restrictive incoming scans.

Let us consider the following scenario. Under a strong downwards fluctuation which demands high battery power and energy, a battery reduced in both power and capacity will not be able to fulfil the required ramp owing to both reductions. The battery will do its best and support with its limited power part of the PV power decay. However that scans will be marked as NC_p anyway, so this operation just wastes energy that could be used later in a smaller ramp, affordable in terms of power as long as there is enough energy stored yet. Therefore, in order to optimise its resources for further medium-size fluctuations, the control system must put the BESS in standby during too large events that surely are out of range of the reduced battery.

Figure 5.20 shows the operation of the system with reduced battery under the strongest fluctuation of the PV power simulated data input, where two scenarios are analysed. The graphs on the left show the response of two different reduced BESS; the first one, called scenario 1, is a low-power battery with a combination of $k_p = 0.4$ and $k_c = 0.1$ (top-left) while the second one, scenario 2, is a medium-power combination of $k_p = 0.6$ and $k_c = 0.1$ (bottom-left). As seen, both configurations fail the strong ramp along a similar amount of scans.

Scenario 1 starts the NC period at $t = 30$ s. The system is non-compliant in power, NC_p , until $t = 100$ s. At this point, the battery is out of charge and it is stopped, being the system non-

compliant in capacity, NC_C , till the end of the fluctuation at $t = 456$ s. Total non-compliant time during the whole event is 426 s. Scenario 2 starts the NC period 5 s later thanks to its higher power and it is NC_P until $t = 77$ s. Due to the same reason, the battery is discharged earlier, so the system is NC_C till the end of the fluctuation. Total non-compliant time during the event is 421 s.

Now, RRC of both scenarios are enhanced by implementing an energy-save function that sends the BESS to standby when the system assumes that the battery has too low power for facing the ramp. The results are shown on the right side graphs of Figure 5.20.

Enhanced scenario 1 starts its NC_P period at $t = 30$ s, but as the BESS is in standby, no power is supplied and it saves energy until the ramp power requirement is affordable. At $t = 308$ s, the system can fulfil the ramp again and the non-compliance period is over, facing the rest of the fluctuation. With this technique, total non-compliant time has been reduced to 278 s, 34.7% less than before. Scenario 2 starts its NC_P period at $t = 35$ s and at $t = 250$ s the system can fulfil the ramp again, facing the ramp again earlier than scenario 1 thanks to the higher power of the battery. However, because of that high power it is discharged at $t = 285$ s, so the system is NC_C until the end of the event. In this case, total-non compliant time is reduced to 361 s, 14.25% less than basic scenario 2.

Figure 5.20: Operation of two reduced BESS under a strong fluctuation, without (top-left and bottom-left) and with (top-right and bottom-right) RRC improvement technique. If it is assumed that the required RR_{LIM} cannot be fulfilled, the system would better switch the BESS to standby in order to save energy for facing a less restrictive power requirement with enough energy.

The result is interesting. It turns out that this technique enhances much more the RRC of batteries with highly reduced power, rather than less reduced ones. This makes sense, since the key of the improvement-technique is to save energy, so when the batteries with lower power are switched on again after their NC_p period, they operate at lower power and they discharge less energy. This leads to thinking that, even with batteries with higher power, the controller should wait until the last part of the fluctuation to save more energy and to start BESS again at lower power. However, this would be useful in cases with a long fluctuation and a strong PV power decay. If the power started to recover earlier, like for example at $t = 300$ s, the low-power battery of scenario 1 could not reduce its NC period, unlike the high-power one of scenario 2. Anyway, we can confirm that the developed technique improves the RRC of batteries with every grade of power reduction operating under high-energy demanding fluctuations.

Despite it is clear that in the particular case of scenario 1 the period of NC is reduced more, given that such a long fluctuation rarely occurs, the technique used in scenario 2 is considered as the best method for general application. Hence, the controller will stop the BESS until the instant when the required power equals the limited battery power; supporting the ramp from that instant till it is discharged.

5.5.3 Comparison between simulation and experimental tests

For each developed control strategy, several laboratory tests have been carried out in order to check the differences between the simulated environment and the real operation of the system in a representative period. Week 22 contains the worst fluctuation, so the tests are performed using as input PV data of that week. The batteries used in the tests are reduced batteries, in order to check the performance of the system under non-compliances. Besides, for a fair comparison the K parameter of the SOC controller is set as 45 in both simulated and real environment.

In order to compare simulations and experimental values, two tests of one week duration have been performed in the laboratory; one implementing $SOC50$ strategy and the other one implementing $SOC100_PVCurt$ strategy. At the same time, two simulations implementing each strategy have been done for the same week. As an illustrative comparison, Figure 5.21 shows the test of one week of operation of Milagro PV plant coupled to a BESS and running $SOC100_PVCurt$ strategy. For sake of simplicity the graph of $SOC50$ test is omitted. The battery is sized according to the WF model of Table 3.2, but reduced by the factors $k_p = 0.3$ and $k_c = 0.3$. It is rated $P_{BAT} = 1545$ kW and $C_{BAT} = 131$ kWh. Figure 5.21a corresponds to the simulated operation, while Figure 5.21b shows the laboratory test.

(a)

(b)

Figure 5.21: Validation of the control system during a representative period. Simulation (a) and laboratory test (b) of one week operation of Milagro PV plant with a BESS sized according to the WF model but reduced by the factors $k_p = 0.3$ and $k_c = 0.3$, implementing *SOC100_PVCurt* strategy.

Table 5.7 shows the most relevant parameters for comparing the behaviour of the real system with the simulation under each strategy. It contains relevant data of both tests, including ramp rate compliance with the reduced battery, the operating factors of the BESS and the PV inverter limitations, battery capacity usage, energy flown through the battery and total produced energy.

Table 5.7: Comparison between simulation and laboratory test operation of the PV+BESS system.

Parameter	SOC50 (sim)	SOC50 (test)	SOC100_PVCurt (sim)	SOC100_PVCurt (test)
C_{BAT} (kWh)	262.2	291.3	131.1	145.6
RRC (%)	98.9	98.9	99.5	99.5
OF	0.215	0.153	0.137	0.112
OF_c	0.108	0.091	0.082	0.071
OF_d	0.107	0.062	0.055	0.041
$OF_{PVi,Cu}$	--	--	0.048	0.057
$E_{BAT,max}/E_{BAT,min}$ (kWh)	241/0	239.6/0	131.1/0	145.6/0
ΔE_{BAT} (kWh, % C_{BAT})	241 (92)	239.6 (82)	131.1 (100)	145.6 (100)
$\sum E_{BAT}^D$ (kWh, % E_{GRID})	2007.6 (0.5)	3469.8 (0.87)	1098.3 (0.3)	2248.0 (0.57)
$\sum E_{BAT}^C$ (kWh, % E_{GRID})	2007.6 (0.5)	3642.3 (0.91)	1098.3 (0.3)	2360.1 (0.6)
η_{BAT} (%)	--	95.26	--	95.25
E_{GRID} (MWh)	400.5	398.36	398.32	396.09
$E_{PVi,Cu}$ (MWh; %)	--	--	-2.3; -0.58	-2.52; -0.63

The differences between each strategy were already explained in section 5.2.3, so here only the differences between simulated and real environment are explained.

Regarding the comparisons between simulations and tests, please note that, in the tests, the battery capacity is oversized respect to the effective capacity of the BESS, as explained in Eq. (5.11). Main difference of the results is the value of the produced energy, which is slightly lower in the real system. This makes sense as the real BESS has internal losses while the simulation does not take into account any loss. These losses become evident if we take a look to the total energy flow through the battery in the tests of each strategy. Total charged energy $\sum E_{BAT}^C$ and total discharged energy $\sum E_{BAT}^D$ are much higher in the experimental test of each strategy than in the simulation. This is caused by the converter losses (look at Figure 5.12 as a reminder). Besides, note that $\sum E_{BAT}^D$ of each strategy is lower than the respective $\sum E_{BAT}^C$. This is due to the internal losses of the battery, modelled by the round-trip efficiency.

Finally, it must be noted that the operating factors of the battery in the test cases are lower than in the simulations. This is caused by the improvement of SOC recovery process explained in section 5.3.2. Introducing the hysteresis of Figure 5.13, the process is more efficient and the battery is in standby if the recovery power set-point is low, whereas in the simulation there is no hysteresis and the battery operates more often.

CHAPTER 6

Conclusions and future research lines

The electricity system is evolving towards a decentralised grid in which the traditionally vital issue of ensuring system stability and power quality will be even more important. TSOs and DSOs will continue serving the classic methods for balancing the system in order to keep the frequency between limits, but new techniques will have to be implemented in order to integrate the great increase of PV power share in the future electricity mix. In this scenario, energy storage systems will play a key role and their use must be optimised in order to avoid hindering the competitiveness of PV power. This thesis contributes to a smart use of ESS with tools and techniques to reduce the storage requirements for PV power ramp rate control.

6.1 Relation between battery size and ramp rate limitation

Chapter 3 has assessed a method for effectively reducing the size of the battery, in terms of power and energy capacity, below the design value given by the worst fluctuation (WF) model. It has been carried out addressing the impact of size reduction by taking into consideration, both, the fluctuation occurrence and the penalties in case of non-compliance of the prescribed ramp-rate limitation.

The simulations carried out for a 7.2 MW PV plant allow for deriving the relation between ramp rate compliance and battery size reduction. A model has been developed for describing the probability of occurrence of fluctuations that could not be absorbed by a certain reduced battery. It consists of an exponential decay function adjusted by battery operating factors. In the case of power, it models the probability of occurrence of an instant with a battery discharge power requirement higher than a given reduced battery specified by the user. In the case of energy, for a given reduced capacity specified by the user, it gives information about how likely it is not to have enough capacity for absorbing the complete fluctuation event, once immersed in it. The model accurately analyses the yearly ramp rate compliance and it shows that, given the low occurrence of fluctuations with high power or energy requirement, the battery can be considerably reduced from its size for full ramp rate compliance. With a battery rating only 20%

of the full-power indicated by the WF model, the probability that the PV plant fails the prescribed $RR_{LIM} = 10\%/min$ is 0.2%, while if the power is reduced to 10%, it only increases to 1%. In terms of energy requirements, the probability is even lower, having a probability of failure of 0.1% with a battery capacity reduced up to the 10% of the nominal one. This fact also makes evident that the battery required for ramp rate control must have a high power/energy ratio.

Once the potential for reducing the storage requirements has been confirmed, the concept has been implemented in a specific scenario. Hence, the impact of the penalties caused by battery size reduction in the requirements particularly proposed in Puerto Rico grid code has been analysed. In this scenario, the yearly simulations implemented a basic control algorithm that recovers the SOC of the battery to 50% before the start of every new fluctuation, *SOC50*. Taking into consideration weekly ramp rate compliance and the derived penalties in terms of PV power curtailments, the study has presented tools that evaluate the produced energy with different combinations of battery power and capacity reductions according to different commercial C-rates.

In this case, for an optimal reduction of the worst fluctuation model battery sized $P_{BAT,WF} = 5148$ kW (71.1% P_N) and $2 \cdot C_{BAT,WF} = 874$ kWh (7.2 min), 100% annual PV plant production is kept until $P_{BAT} = 1493$ kW (20.6% P_N) and $C_{BAT} = 254$ kWh (2.1 min). That means that for Puerto Rico particular case, the battery could be reduced to the 30% of the WF model size without losing PV generation. It is worth underlining that this battery reduction would not have a significant negative impact on the Puerto Rico system considering the low occurrence of the worst fluctuations.

6.2 RR control with reduced batteries in combination with other techniques

However, the battery size required for PV power ramp rate control application can be further reduced if upwards fluctuations are mitigated by moving the operation of PV inverters out of their MPP. For this, in chapter 4 a novel control strategy has been developed starting from similar state-of-art strategies. The proposed strategy, named as *SOC100_PVCurt*, fulfils the ramp rate control requirements combining effectively the operation of the battery and PV inverters power limitation. By recovering the SOC of the battery during upwards fluctuations, less PV inverter limitations are necessary and the associated energy loss is considerably reduced comparing to basic inverters limitation strategies. For $RR = 10\%/min$, this strategy allows for reducing the power and capacity requirements an extra 40% and 70% respectively with respect to the basic *SOC50* strategy, at the expense of a neglectable PV production loss of 0.57% due to inverters power limitation.

In the second part of chapter 4, an interesting technique has been studied for reducing the high-frequency fluctuations of the PV plant by oversizing its PV array, and, consequently, for checking if it is useful for reducing storage requirements even more. The results show an interesting effect when applying the size reduction assessment to a plant with its PV array oversized by 1.5. Although the low frequency fluctuations and the associated battery discharge power events are attenuated up to 5%, medium power events are amplified; which implies that, when the battery power is progressively reduced, the oversized plant falls into ramp rate failures

with a lower battery reduction degree than a non-oversized one. However, comparing to the PV production of a non-oversized plant, it can be seen that, with the oversizing technique the battery can be significantly reduced without losing production. For instance, a battery that allows a non-oversized plant reaching its maximum PV production without falling into penalties can be reduced by a 70% if the PV array is oversized, not only without losing PV production, but also increasing it by 10.7%. Therefore, project developers can use this tool to evaluate if, at the expense of increasing 50% the number of PV modules, the project could improve its feasibility by saving costs thanks to 70% less battery requirements and thanks to increasing yearly PV production by 10.7%. Last but not least, it must be noted that this practice implies several non-compliances that leads the oversized PV plant to considerable penalties, so the TSO must allow this issue to implement the technique.

6.3 Experimental validation of control strategies

With all the lessons learned from the theoretical studies, the reduced size battery control strategies have been implemented in a laboratory, addressing the accuracy and control response required for implementing the method in a utility-scale PV plant. The implementation of ideal strategies in the controller of a real application involves adapting the control variables to the BESS used in the laboratory. The BESS has been characterised in order to obtain its operation limits and round-trip efficiency, expressed as a combination of the efficiency of the battery and the converter in full charge-discharge cycles. This value has been used to model the losses and to improve the SOC recovery process of the controller. The controller combines its ramp rate control tasks with an efficient energy management system and an optimised SOC controller to operate the PV+BESS system identically as it would be done in a utility-scale PV plant. In this context, the operation has been adapted and improved for performing ramp rate control tasks with reduced size batteries. Given the fluctuations monitoring requirements, fast time-response of the controller is indispensable, so the control response has been optimised in order to overcome some limitations of the BESS converter.

Finally, the control system has been validated by means of several tests. The accuracy of the controller has been checked and it can be considered as an appropriate system to be implemented in a utility-scale PV plant. Besides, the differences between the implementations of *SOC50* and *SOC100_PVCurt* strategies have been confirmed in a full week test.

6.4 Future research lines

In future works, further size reduction feasibility could be assessed with the developed tools. It has been shown that, by using the results of the battery size reduction against the production decrease, it could be interesting to carry out further techno-economic analysis, evaluating the battery costs saving and the incomes losses caused by curtailed generated energy. For instance, it could make sense to lose part of the production if as a counterpart the resulting battery is smaller, but this is achieved with a deep cost-benefit analysis. In the particular case of the combination of battery size reduction with inverter limitations and PV array oversizing

technique, multiple decision factors arise, so a careful study should be carried out to obtain the optimal solution.

This work addressed exclusively the storage requirements for PV plants ramp rate control, but in some grid codes, this requirement is usually combined with other services that the storage systems must provide. Particularly, a common practice is to use a battery for providing frequency control services when the TSO asks for it. As explained along the thesis, in the particular case of Puerto Rico, a recent requirement proposed by PREPA together with the public utility specifies that the system must be able to provide 45% of P_N during at least one minute for facing high power ramps, while it also must be able to provide 30% of P_N during ten minutes for frequency response. Therefore, an interesting research work to be done is the battery size reduction assessment taking into account the power and energy reserved for supplying frequency control. The size reduction could be detrimental to the frequency response service, so a simultaneous reduction analysis for this service should be carried out in future works.

In line with this, the study could be extended to a combination of multiple applications identified in section 1.3.2, such as virtual inertia, voltage control or faults ride-through.

Following the research trends detected in the state of the art, another interesting research line is to apply the size reduction assessment to centralised ESS that smooth the fluctuations of a PV fleet. The combination of geographically aggregation of PV plants used for smoothing power fluctuations and the analysis carried out in this thesis would be an interesting work.

Focusing on ESS technology, the developed size reduction method should be applied to different types of storage. When reducing the storage requirements, the depth of discharge and level of use of power and energy highly increases, which in some storage technologies could imply certain problems such as cycling degradation. Besides, the strategies addressed in this study imply another effect. While the first one keeps the battery at $SOC = 50\%$ most of the time, the second one does it at full-charge. This issue has other impacts such as calendar ageing. If the battery is kept in standby during a long time, the *SOC100_PVCurt* strategy would imply a higher calendar ageing, given that most of the time the SOC is 100%. Therefore, a deep study of size reduction assessment and the implementation of different control strategies regarding the impact on the life cycle of different storage technologies is also an interesting research line.

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