

Control Strategies and Real Time Operation of Storage Systems Integrated with MV Photovoltaic Plants

S. Barsali, R. Giglioli, M. Giuntoli,
G. Lutzemberger, D. Poli

DESTEC, University of Pisa





Presentation outline

- ❑ Introduction
- ❑ The control architecture
- ❑ The system under study
- ❑ Experimental tests
- ❑ Conclusions



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1. Introduction

Background

- ❑ In the last years, electricity grids moved towards the increasing share of renewable sources.
- ❑ One of the most important characteristics is the possibility of controlling the various sources and loads connected to the grid, to improve the overall efficiency.
- ❑ A major role can be played by usage of energy storage systems, able to provide several services for the producer or for the grid.
- ❑ Services can be divided in **power services**, in which power exchanges are in the order of minutes, and **energy services**, in the order of hours.
- ❑ This paper shows with a systematic approach the services that a storage system can provide to the power system when installed in parallel with a renewable plant (RES).



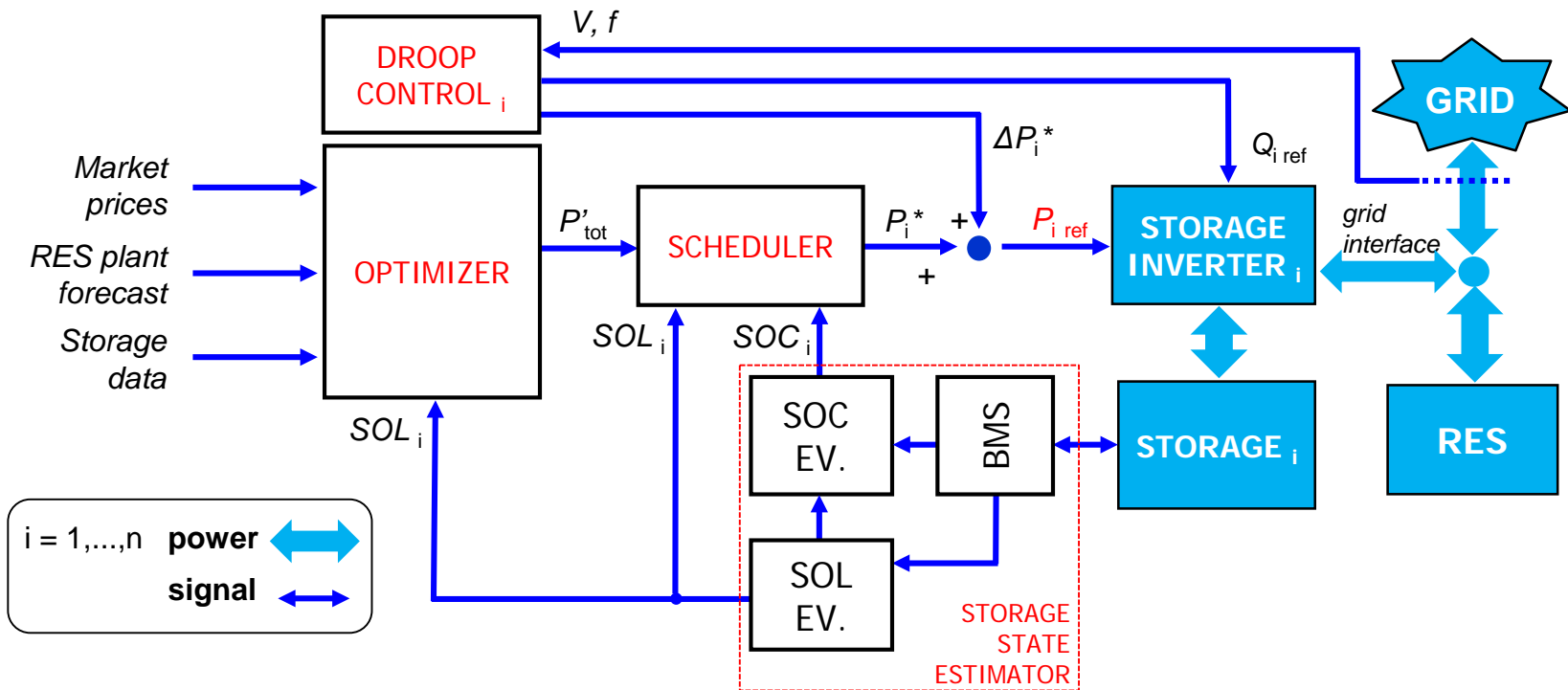
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- The system under study
- Experimental tests
- Conclusions

2. The control architecture

General scheme (1/3)

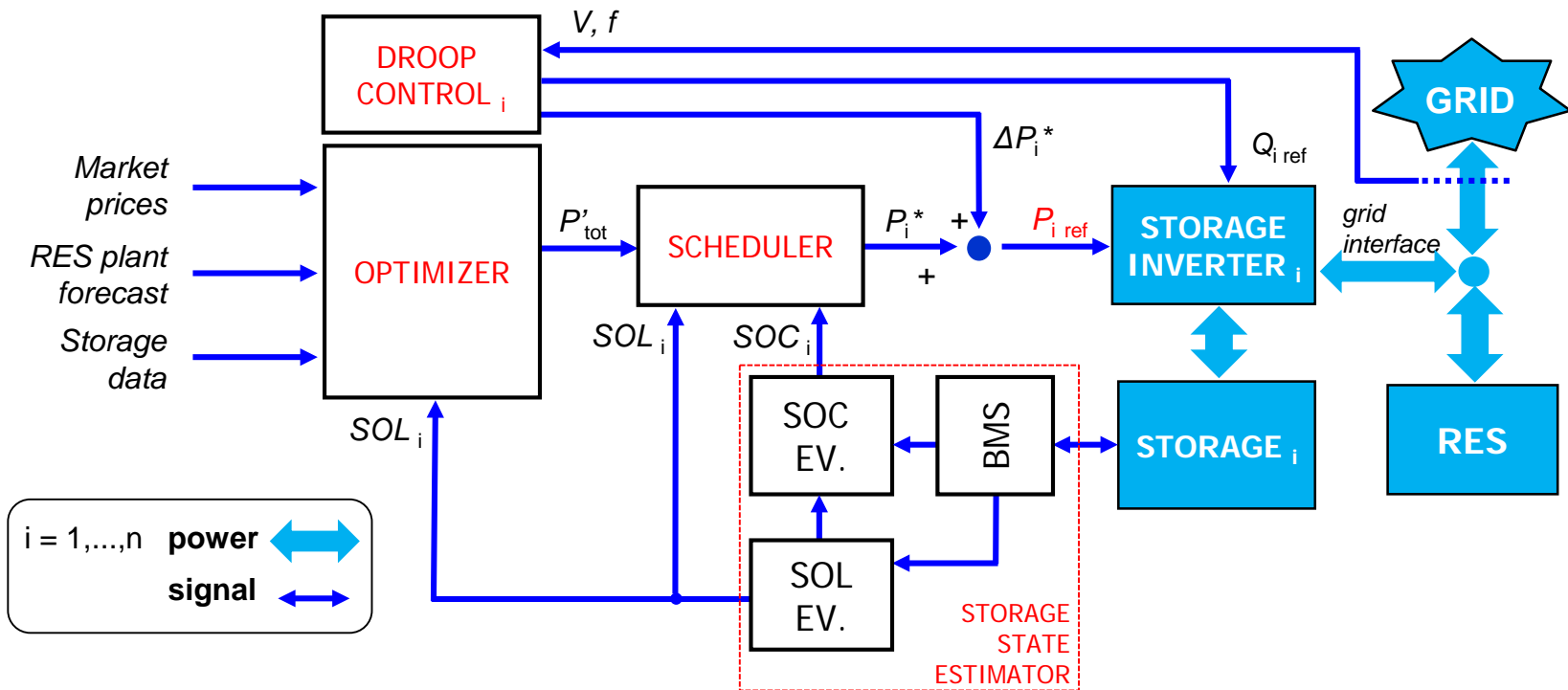
- ❑ The aim of the proposed architecture is to provide a general strategy for the **Storage**, in order to control power exchange between **Renewable Energy Source (RES)** and the **Grid**.
- ❑ The storage system can be composed by different branches in parallel, each one formed by cells in series. Indeed, branches can be controlled independently.



2. The control architecture

General scheme (2/3)

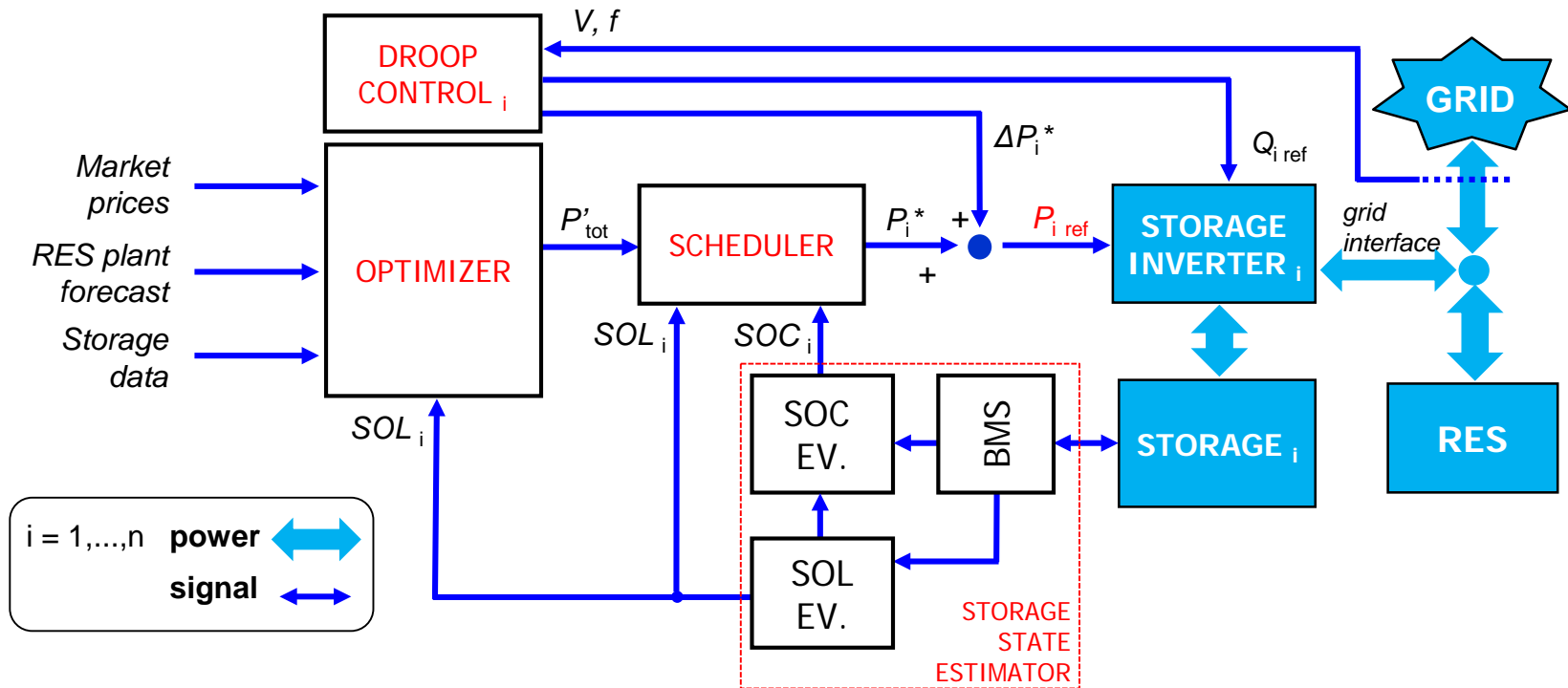
- ❑ Different control functions have been implemented:
The **optimizer**, the **scheduler**, the **droop controls**, the **storage state estimator**.
- ❑ Main output is constituted is constituted by the reference power $P_{i\text{ref}}$ of each storage inverter.



2. The control architecture

General scheme (3/3)

- ❑ The **optimizer** evaluates P'_{tot} at each quarter of hour of the following day, starting from market prices, forecast about RES and storage data.
- ❑ The **scheduler** divides P'_{tot} in different separated P_i^* , from SOC_i and SOL_i of each branch provided by the **storage state estimator**.
- ❑ An active power correction ΔP_i^* and a reactive power reference $Q_{i\ ref}$ is provided by the **droop controls**.





2. The control architecture

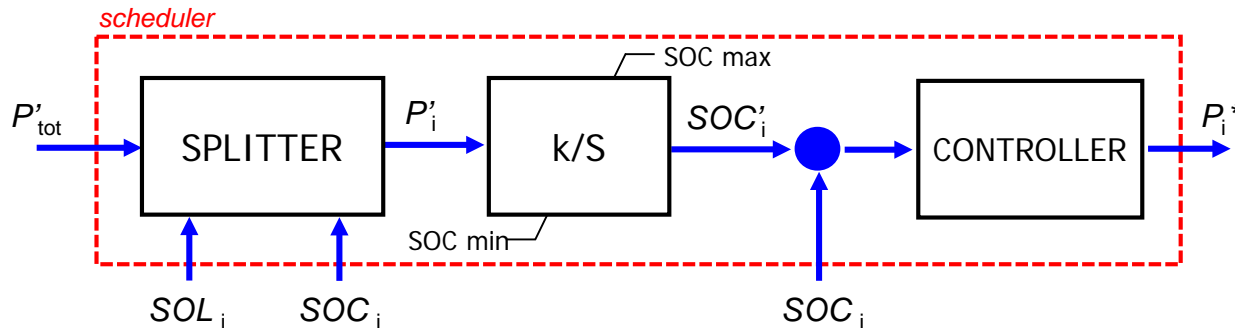
Optimizer

- ❑ The optimizer was originally conceived to optimize the day-ahead thermal and electric scheduling of a Large scale VPP plant.
- ❑ The original algorithm has as an input the expected power pattern of the electrical and thermal load, and the expected power profile of RES.
- ❑ With time steps of 15 minutes, the daily optimal operation of the energy storage systems and dispatchable generation is evaluated, to meet the load and maximize the VPP net daily profit.
- ❑ Algorithm takes into account costs for electricity and fuel, subsidies for RES, etc. Constraints are capabilities of generators, storage systems, public and distribution lines.
- ❑ With respect to the original model, the algorithm has been adapted to plants composed by PV source, its small house loads and an energy storage system.

2. The control architecture

Scheduler (1/2)

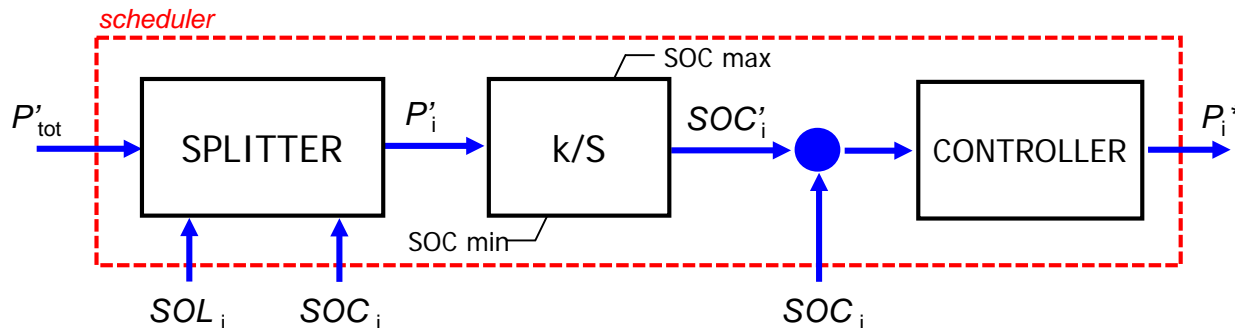
- Starting from the P'_{tot} and from actual SOC_i and SOL_i of each one of the storage branches, the *splitter* shares the global amount of the needed power in different set-points P'_i for each storage inverter.
- If SOC_i and SOL_i are the same between the branches, the splitter simply shares in equal parts the global evaluated power. Otherwise, it defines different set-points.



2. The control architecture

Scheduler (2/2)

- ❑ Each P'_i is then converted in a continuous SOC'_i reference profile. This can be done from the knowledge of voltage and current.
- ❑ Finally, in order to make each storage branch effectively follow its desired SOC trend, each set-point SOC'_i is compared with the present estimated SOC_i .
- ❑ The resulting error is elaborated by a controller that sends the proper reference power values P_i^* to each storage inverter.





2. The control architecture

Storage State Estimator - BMS

- ❑ It is physically integrated into the battery pack: **BMS** monitors temperature, voltage and current within each storage branch, giving alarms to avoid damages.
- ❑ As time passes, the inner charge of cells placed in series gets uneven, mainly due to differences in self-discharge processes, so cell voltages tend to differ from each other.
- ❑ All this results in a progressive reduction of the available capacity of the battery pack, whose performance can be restored to its original level only through a process of equalisation.
- ❑ This latter can be performed: **passively**, by discharging the most charged cell on resistors, or **actively**, where the most charged cell supplies energy to the least charged one.

- ❑ SOC can be continuously evaluated through the numerical integration of the current exiting from each storage branch: this process implies an accumulation of errors from different sources (i.e. sensor, numerical integration, ...).

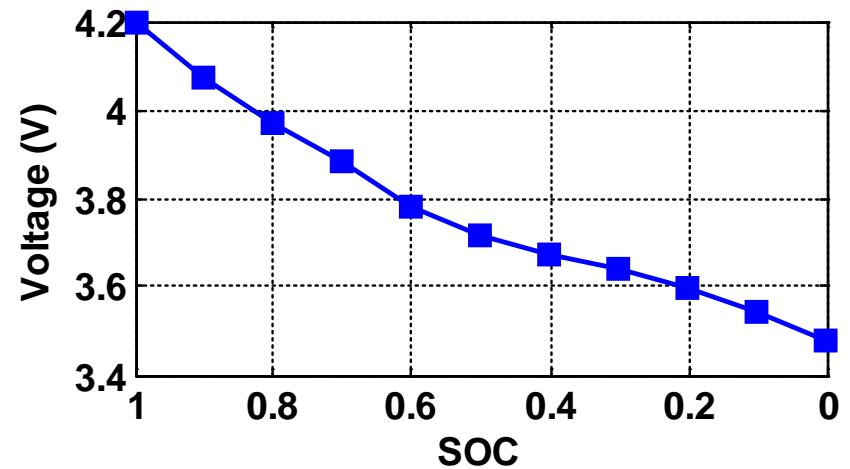
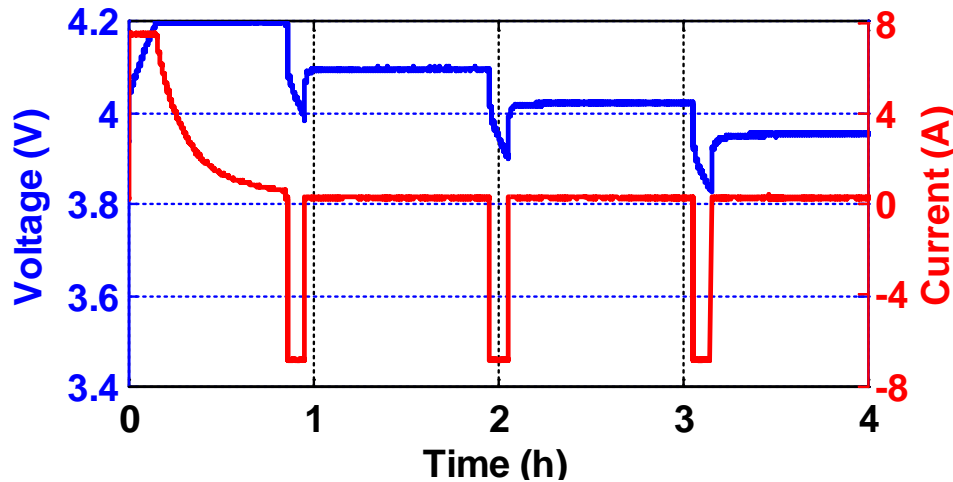
$$Q_{ext} = \int i_{ext}(t)dt \quad SOC = 1 - \frac{Q_{ext}}{C_{min}}$$

- ❑ Q_{ext} is the charge extracted starting from a known state of full charge.
- ❑ C_{min} is the lowest nominal capacity among the cells.
- ❑ The presence of capacity inequalities may occur in case of substitution of elements with new ones, installed in series with the others already aged.
- ❑ An error compensation can be applied through the use of the correlation between SOC and the *corresponding rest voltage*.

2. The control architecture

Storage State Estimator – SOC evaluation (2/3)

- ❑ One single cell is here taken as reference to show the correlation.
- ❑ The cell is first charged, then subject to partial discharge phases (plot on left).
- ❑ At the end of pause (as example 3600 s) after each partial discharge, voltage is independent on the previous battery current.
- ❑ From the current drawn at each step and the measure of the *corresponding rest voltage*, the correlation shown in figure can be derived for the cell (plot on right).





2. The control architecture

Storage State Estimator – SOC evaluation (3/3)

- ❑ During plant operation SOC_i are continuously evaluated by integrating current (see definition).
- ❑ At each plant stop a correction to SOC is applied using the OCV-SOC correlation curve.
- ❑ The curve is obtainable starting from the single cell characteristic, by multiplying voltages for the number of elements in series.

Main requirements:

- ❑ The cell considered for OCV-SOC characterisation must be of the same type of the cell used inside the plant.
 - ❑ The behaviour in terms of OCV-SOC characteristic must be homogeneous between cells.
 - ❑ Cell voltages inside each branch must be perfectly equalised.
 - ❑ The time of non operation of the plant must be sufficient to stabilise the voltage.
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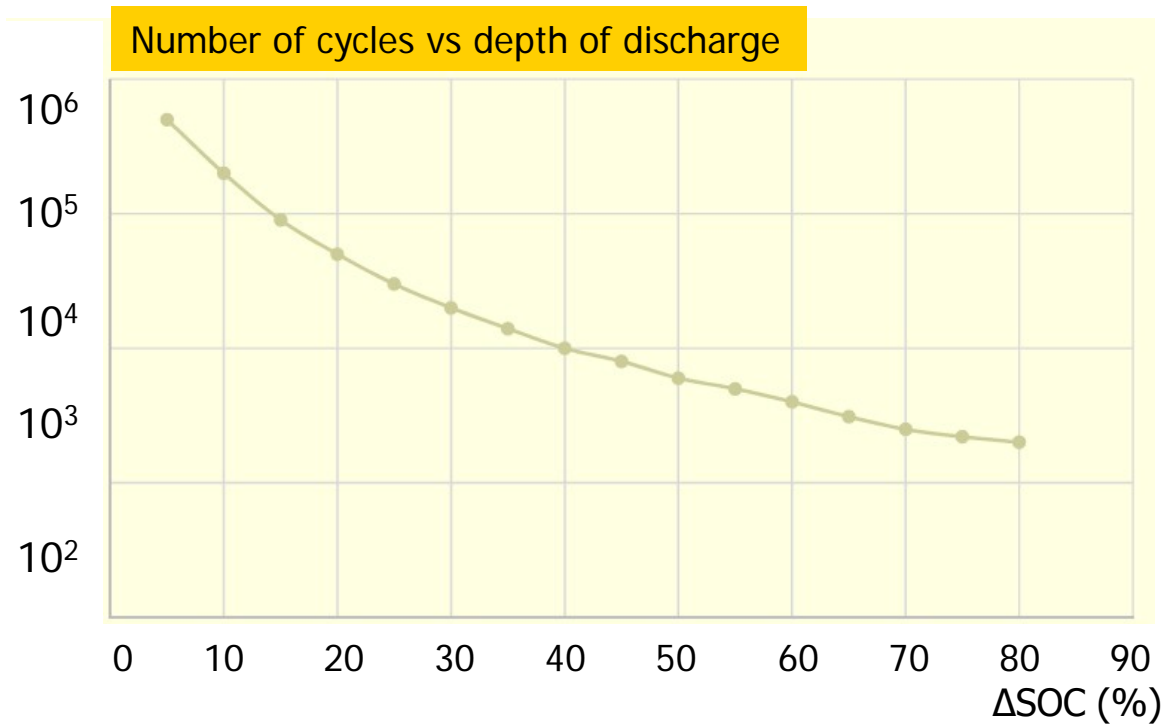


2. The control architecture

Storage State Estimator – SOL evaluation (1/2)

- ❑ SOL evaluates the aging process due continuous cycling of each storage branch.
 - ❑ Different values depending on the considered technology.
 - ❑ Deep charge-discharge cycles, i.e. SOC variations in the order of tens of percent, executed at low current rates and high durations.
 - ❑ This kind of stress strongly influences the storage life (i.e. 1000-3000 cycles @ 100-80% DOD for the considered cell).
 - ❑ Shallow charge-discharge cycles, i.e. SOC variations in the order of a few percent, for short durations.
 - ❑ Storage life corresponding to such micro-cycles can be estimated in several hundreds of thousands.

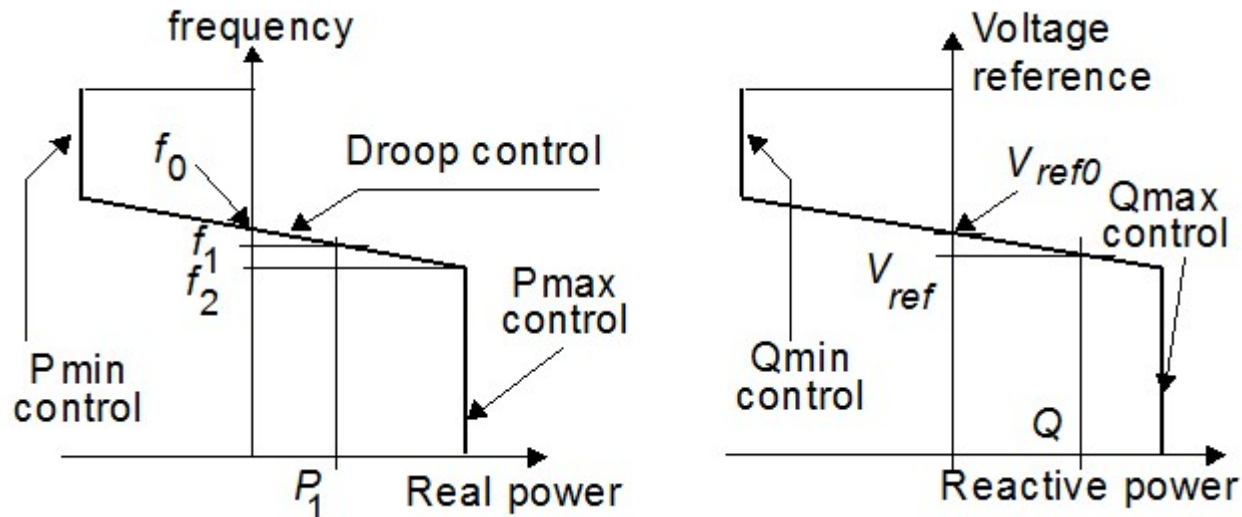
- ❑ Aging process can be at a first level correlated to the effect of the deep charge-discharge cycles, neglecting the shallow ones.
- ❑ Much more accurate techniques can be considered, by definition of cell mathematical models experimentally validated.



2. The control architecture

Droop Control

- ❑ In each storage inverter a real power/frequency and reactive power/voltage droop control was implemented.
- ❑ The values of f_0 and V_{ref0} define the frequency and voltage values for which the inverter should exchange null real and reactive power.
- ❑ As the grid frequency and voltage change, the inverter will modify the real and reactive power managed by the storage inverter, according to the droop linear characteristic.





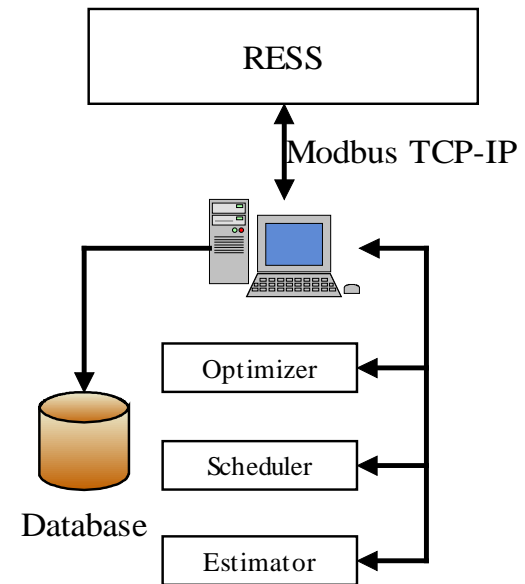
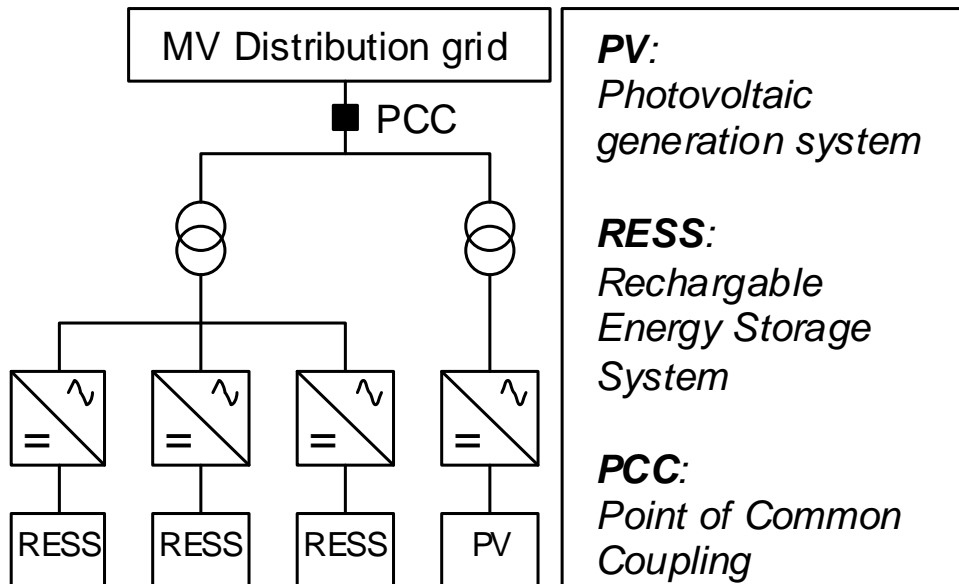
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3. The system under study

General characteristics (1/3)

- ❑ The plant under study is composed by three rechargeable energy storage systems (RESSs) connected in parallel to a MV photovoltaic plant (PV).
- ❑ A software program was developed to perform the functions of the *optimizer*, the *scheduler* and the *SOC-SOL evaluators*, together with data exchange protocol (Modbus TCP-IP).





3. The system under study

General characteristics (2/3)

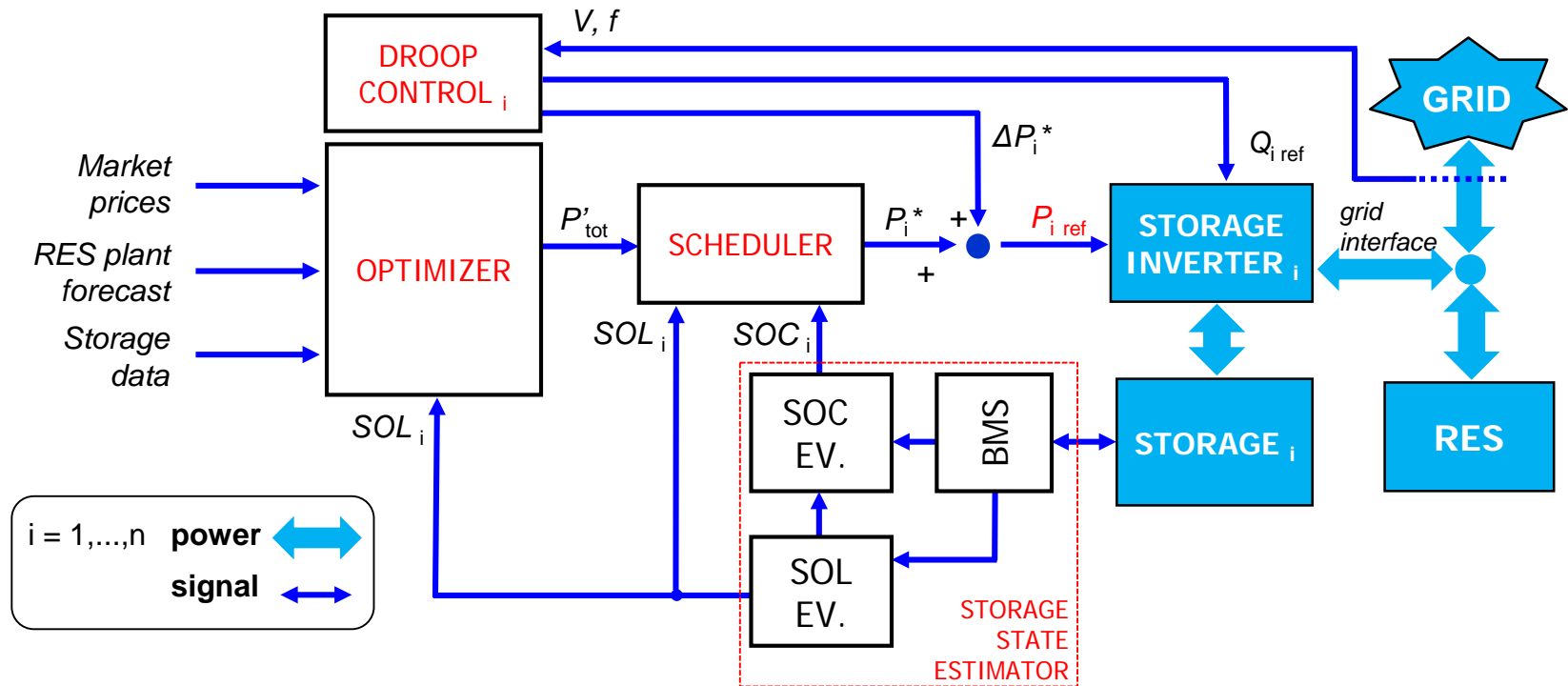
- ❑ Storage is placed in parallel to a 3.7 MW photovoltaic plant.
- ❑ The converter is composed by three 350-kVA modules.
- ❑ The lithium-ion batteries are able to provide around 900 kW for 8 seconds and 650 kW in steady state. Other main characteristics in table.

Number of strings	3	Nominal cell capacity (Ah)	70
Number of modules per string	18	Nominal module energy (kWh)	3.1
Number of cells per module	12	Nominal string energy (kWh)	55.9
Nominal module voltage (V)	44	Nominal battery pack energy (kWh)	168
Nominal string voltage (V)	799		

3. The system under study

General characteristics (3/3)

- ❑ The control architecture already presented has been implemented.
- ❑ The power set-points of the three storage inverters are defined in order to optimize the timing of the injection of the PV generation into the MV grid.





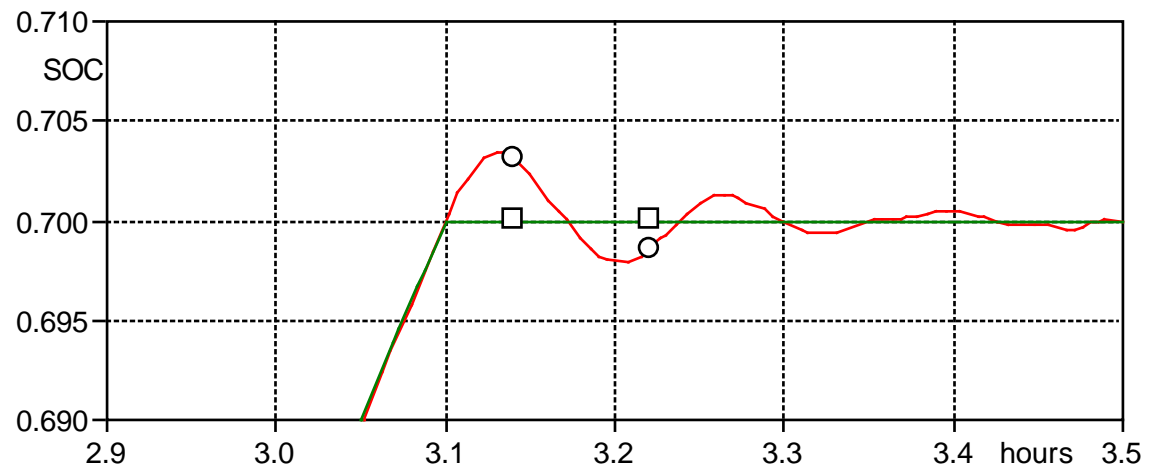
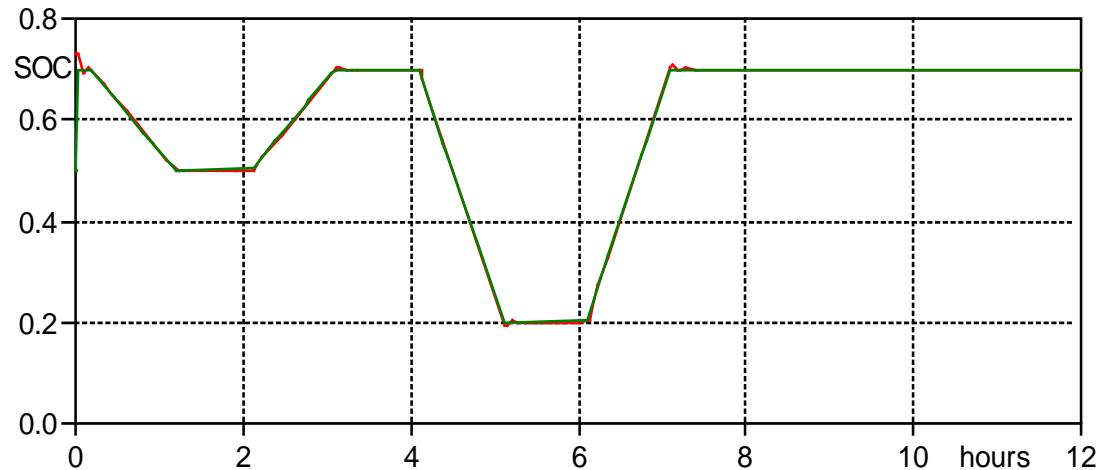
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4. Experimental tests

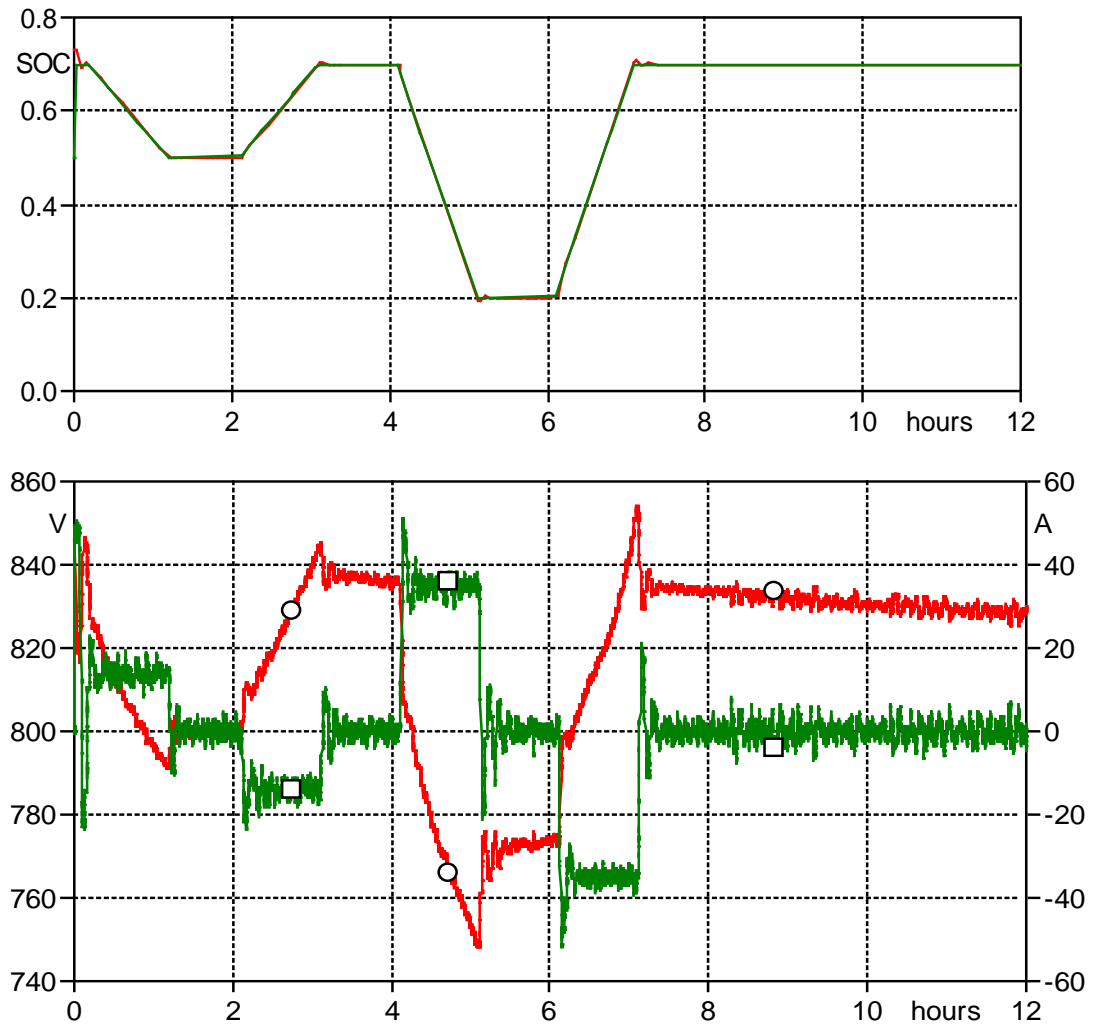
SOC vs time (1/2)

- ❑ Example of SOC profile deriving from the *optimizer*, applied to one single inverter.
- ❑ SOC of each branch limited between 0.2 and 0.7.
- ❑ Plots show desired (green) and actual (red) SOC evaluated by SOC evaluator.



4. Experimental tests SOC vs time (2/2)

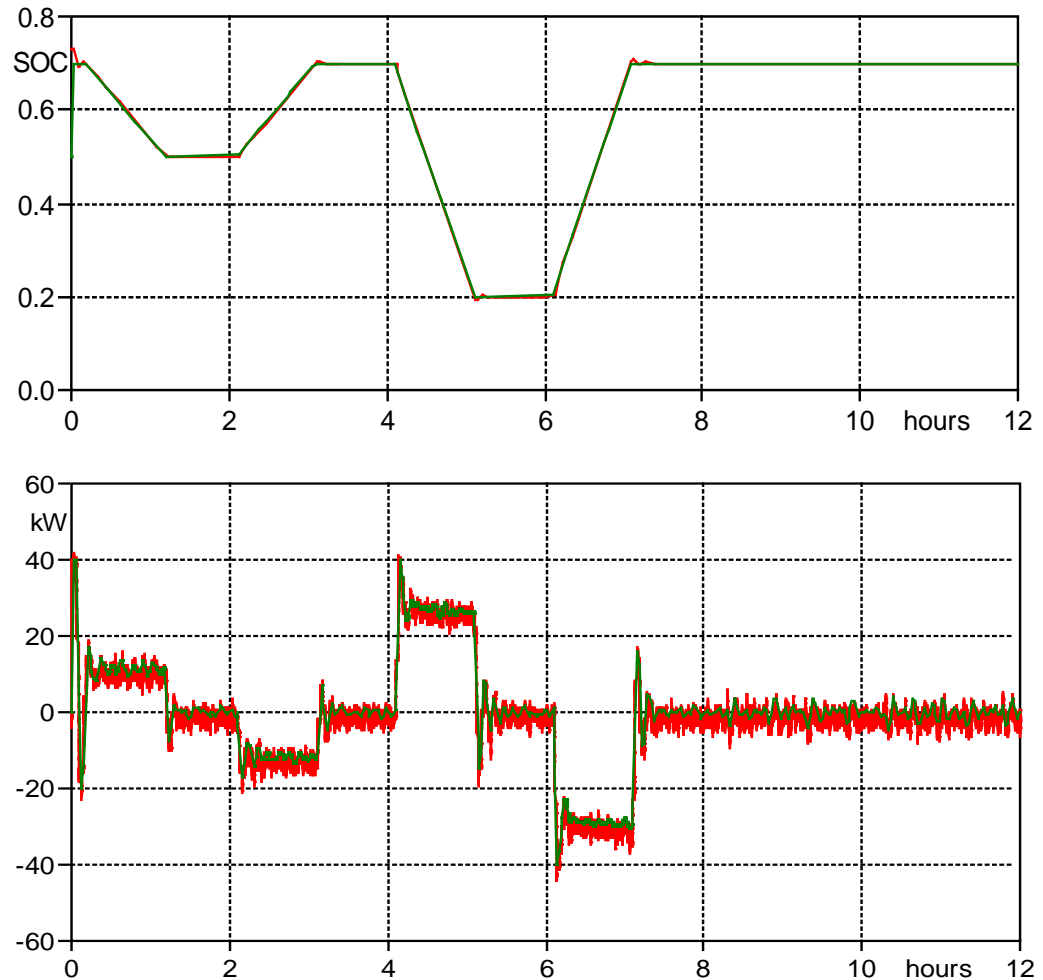
- Voltage (red) and current (green) of a string of modules corresponding to the SOC profile deriving from the optimizer.



4. Experimental tests

Inverter power output (1/2)

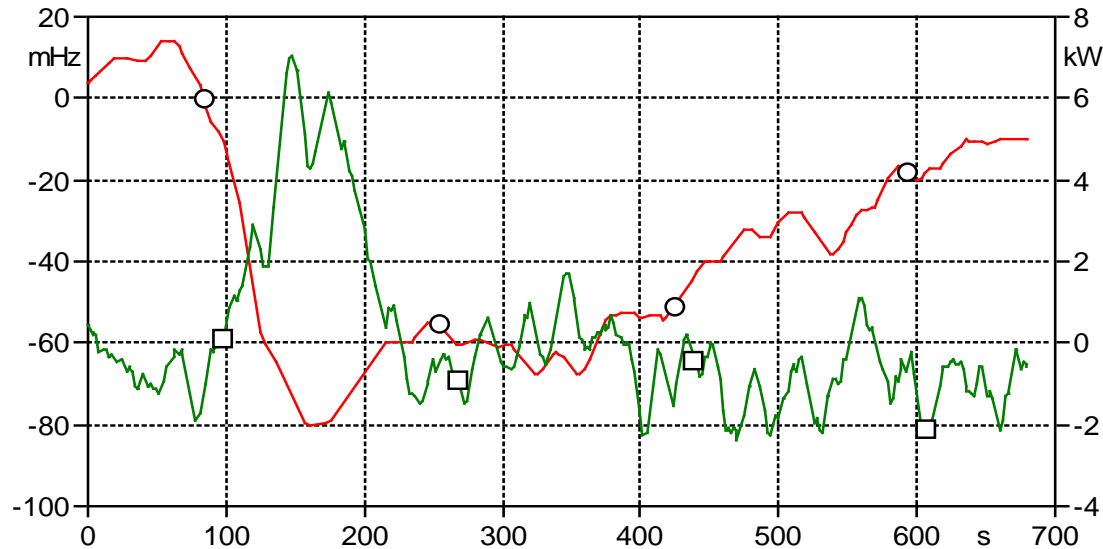
- ❑ Inverter power output corresponding to the SOC profile deriving from the *optimizer*.
- ❑ On the time scale of hours, the inverter output power clearly follows its set-point.



4. Experimental tests

Inverter power output (2/2)

- ❑ Fast power fluctuations depend on the controller parameters and on the effect of the droop control.
- ❑ Plot shows the inverter power output (green) and the frequency difference from 50 Hz (red) on a time scale of seconds.
- ❑ Due to a decrease in grid frequency, a power injection of about 7 kW was delivered by the storage inverter.
- ❑ The fluctuations of active power depend on the accuracy of the instruments used for voltage and current measurements.





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This paper has shown:

- ❑ The formulation and practical implementation of a novel control architecture on an energy storage system, thus enhancing the control of the power flows between the RES and the grid.
- ❑ The development of a storage state estimator, able to perform monitoring actions, the voltage equalisation of cells, as well as SOC and SOL evaluations, during typical operating conditions.
- ❑ The design of a control architecture able to cope with possible differences among the storage elements.
- ❑ Further developments are presently under study, with the aim to maintain the proposed architecture also with much more differences among the branches of the storage system.



Thank you for your attention



1. Introduction

Background (1/2)

- ❑ In the last years, electricity grids moved towards the increasing share of renewable sources.
- ❑ One of the most important characteristics is the possibility of controlling the various sources and loads connected to the grid, to improve the overall efficiency.
- ❑ A major role can be played by usage of energy storage systems, able to provide several services for the producer or for the grid.
- ❑ Services can be divided in **power services**, in which power exchanges are in the order of minutes, and **energy services**, in the order of hours.



1. Introduction

Background (2/2)

❑ Power Service – Security

Significant benefits can be achieved in terms of:
Peak shaving, Net congestion resolution, Islanding, Ramp.

❑ Power Service – Power Quality

Power Quality can be significantly increased by reducing short-term interruption, participating to frequency regulation, etc.

❑ Energy Service – Load levelling

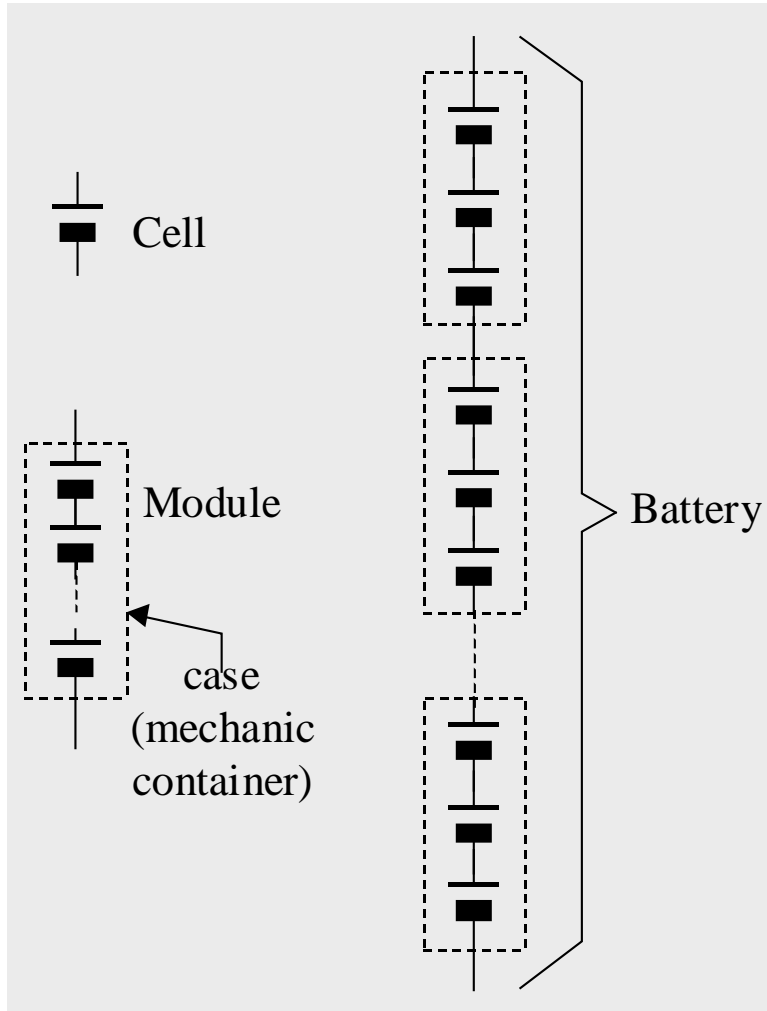
Significant benefits can be achieved charging it during off-peak hours and discharging it during peak hours.

❑ Energy Service – Efficiency

Changes in load profile can modify the operating point of the power system, increasing efficiency of generating units.

❑ This paper shows with a systematic approach the services that a storage system can provide to the power system when installed in parallel with a renewable plant (RES).

Storage State Estimator – BMS (1/2)



- ❑ Usually batteries are composed by several cells in series.
- ❑ Cells are grouped into modules.
- ❑ Since the current is the same for all cell in series, in principle SOC should never unbalance. **But cells have also self-discharge.**
- ❑ **Non-homogeneity in self-discharge and other minor phenomena cause, sooner or later the SOC's to unbalance.**
- ❑ Charging of a battery is to be stopped whenever the most charged cell is full; discharge whenever the less charged is empty.
- ❑ **As far as unbalance proceeds, the usable charge gest lower and lower. So equalisation is strictly needed.**



2. The control architecture

Storage State Estimator – BMS (2/2)

Battery monitoring system

- ❑ monitor temperature (above 60°C typically shut-down mandatory).
- ❑ monitor SOC (excessive charge and discharge can damage the cell).
- ❑ monitor current.

Battery Management

- ❑ As time passes the inner SOC of cells in series gets uneven (mainly due to differences in self-discharge). A good BMS stops charging when the most charged cell is full and stops discharging when the least charged cell is empty.
- ❑ It is a reversible process: cell equalisation can restore the original pack capacity.

❑ Passive balancing

Made with resistors. Low capital cost, losses during life.

❑ Active balancing

Here the most charged supply energy towards the least charged.
