DIPARTIMENTO DI
INGEGNERIA ELETTRICA ELETTRONICA E INFORMATICA

Dottorato di ricerca in Ingegneria dei Sistemi, Energetica, Informatica e delle Telecomunicazioni

Borsa di studio ENEL Green Power

Caratterizzazione e massimizzazione dell'efficienza di impianti di produzione di energia elettrica da fonti rinnovabili tramite l'utilizzo di elettronica di potenza distribuita

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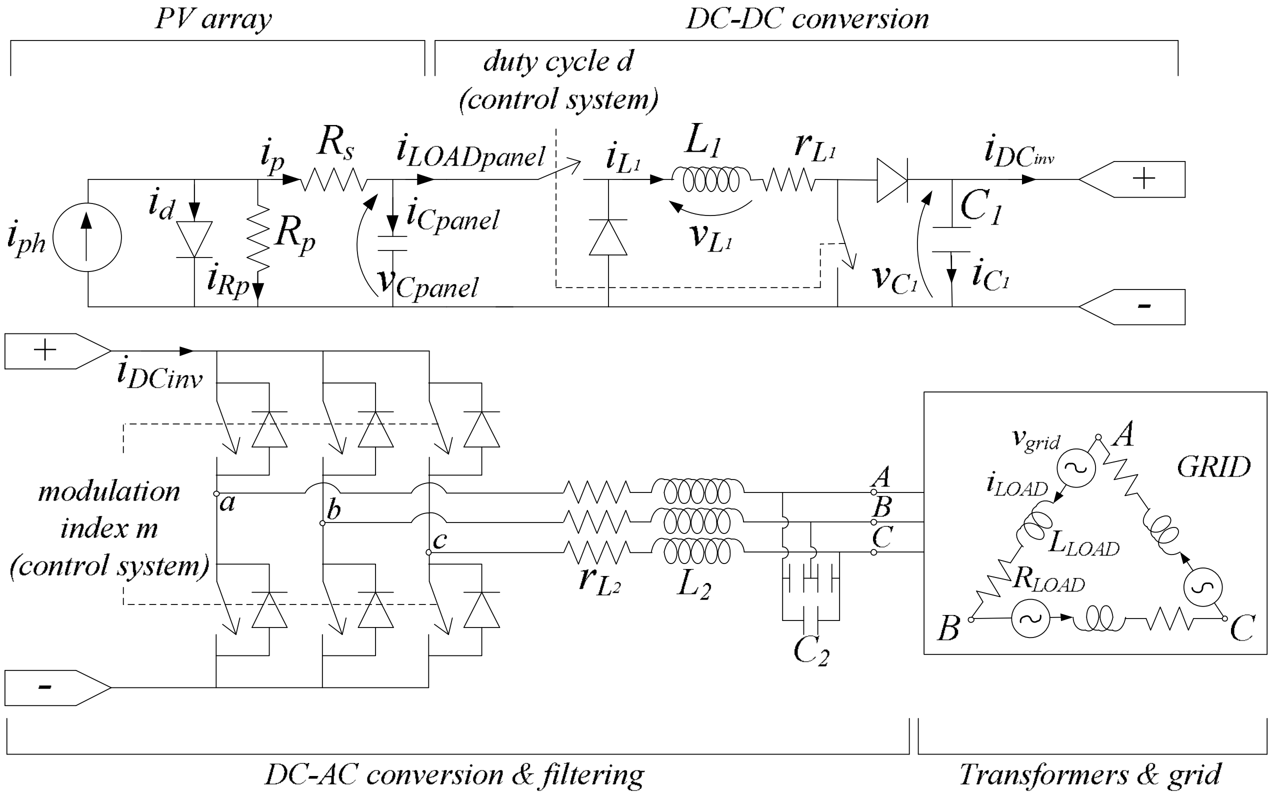
Academic Year 2018-2019 **Tutor: Prof. Giuseppe Scarcella**

OVERVIEW

- The installation of **distributed converters** and of **distributed electrochemical storage systems** in large PV fields is a very topical subject.
- Unfortunately, the **evaluation of performance** in comparison to standard configurations (central inverters) as well as the **energy management of the battery packs** in utility-scale PV fields are **difficult tasks** for several reasons, for example:
  - Large number of partial unavailabilities
  - Monitoring systems issues leading to missing or wrong data
  - Large number of time-varying parameters depending on seasonality, degradation rates, power derating in case of high temperatures, etc.
- A **proper modeling approach** can **overcome this kind of issues** allowing the assessment of a suitable energy management strategy

MODELING APPROACH FOR LARGE PV PLANTS

- Development of a **novel behavioral model based on a modified state-space average method** devoted to large PV plants with multiple conversion stages DC/DC and DC/AC getting a good **trade-off between accuracy and complexity**



Block diagram of a generic grid-connected PV system with multi-stage conversion system.
State-space representation for each component. All the components are mixed into a single state-space average model.
The DC-bus current plays a key role linking the "DC side" with the "AC side".

MODELING APPROACH FOR LARGE PV PLANTS

$$\dot{x} = \overline{A}x + \overline{B}u$$
$$y = \overline{C}x + \overline{D}u$$

Average state-space representation of the PV plant (d is the DC/DC converter duty cycle)

$$\overline{A} = A_{ON}\,d + A_{OFF}\,(1-d)$$
$$\overline{B} = B_{ON}\,d + B_{OFF}\,(1-d)$$

$$x = \begin{bmatrix} v_{C_{panel}} \\ i_{L_1} \\ v_{C_1} \\ x_1 \\ \ldots \\ \ldots \\ x_{18} \end{bmatrix}$$

State variables includes x_i symmetrical components of the AC side electric quantities.

Inputs are related to irradiance, module temperature and grid voltage.

$$u = \begin{bmatrix} i_{ph} \\ i_d \\ V_{grid} \end{bmatrix}$$

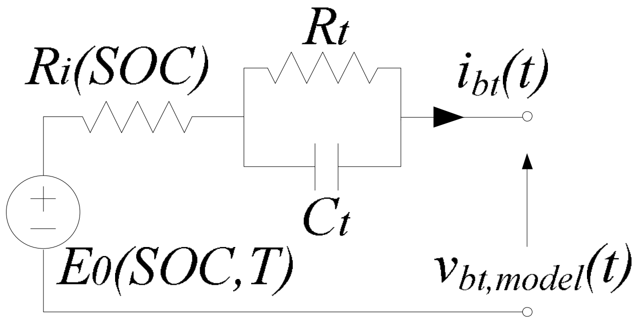
$$y = \begin{bmatrix} x_1 \\ \ldots \\ \ldots \\ x_{12} \end{bmatrix}$$

$$i_{DCinv} = \langle i_{DCinv} \rangle_0 = \frac{\sqrt{3}m}{2}\Big[x_1 \cos\left(\varphi_a - \frac{\pi}{6}\right) - x_2 \sin\left(\varphi_a - \frac{\pi}{6}\right) + x_3 \cos\left(\varphi_b - \frac{\pi}{6}\right) - x_4 \sin\left(\varphi_b - \frac{\pi}{6}\right) + x_5 \cos\left(\varphi_c - \frac{\pi}{6}\right) - x_6 \sin\left(\varphi_c - \frac{\pi}{6}\right)\Big]$$

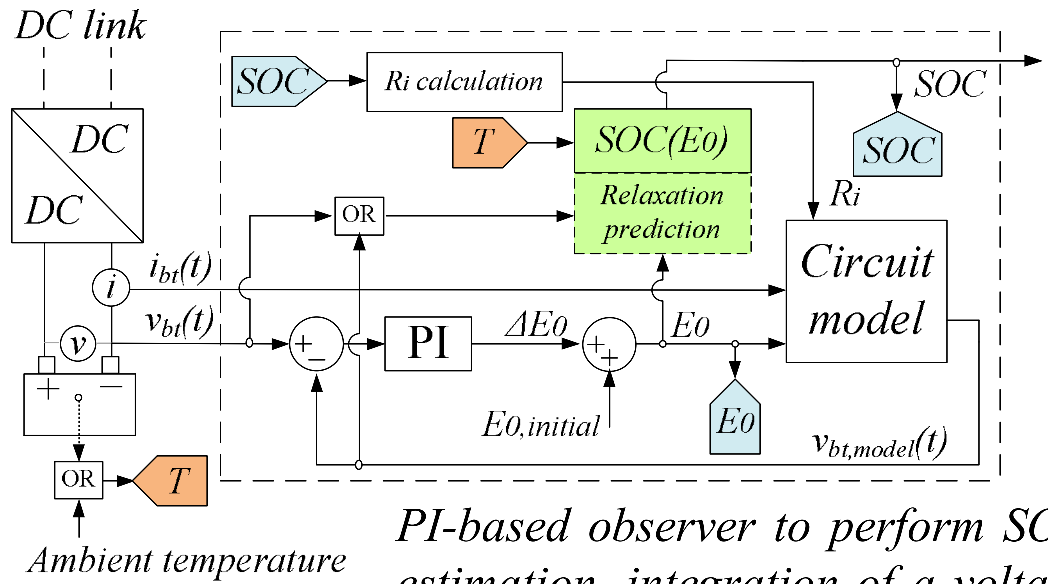
Introduction of a straightforward approach to calculate the DC-link current from the direct-sequence components of AC currents

MODELING APPROACH FOR BATTERIES

- Development of a **real-time model-based algorithm** for the **estimation of *SOC* (State of Charge), *SOH* (State of Health), *PC* (Power Capability) and *EC* (Energy Capability)**



Equivalent circuit model belonging to the Thevenin tipology



PI-based observer to perform SOC estimation, integration of a voltage relaxation prediction function

The ***PC*** represents the **power that the battery pack can continuously manage** for a given **time horizon *Δt*** without overcoming the fixed *SOC* thresholds. The product between *PC* and *Δt* represents an estimation of the ***EC***. Such parameters are crucial to properly size the battery packs being part of a distributed storage system in a large PV plant.

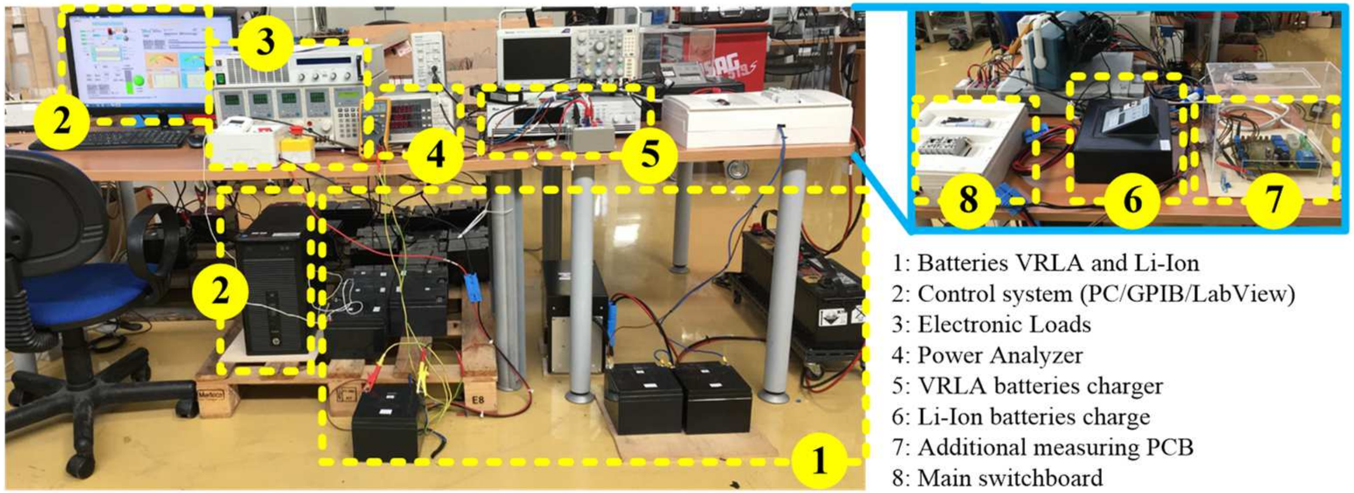
VALIDATION TESTS

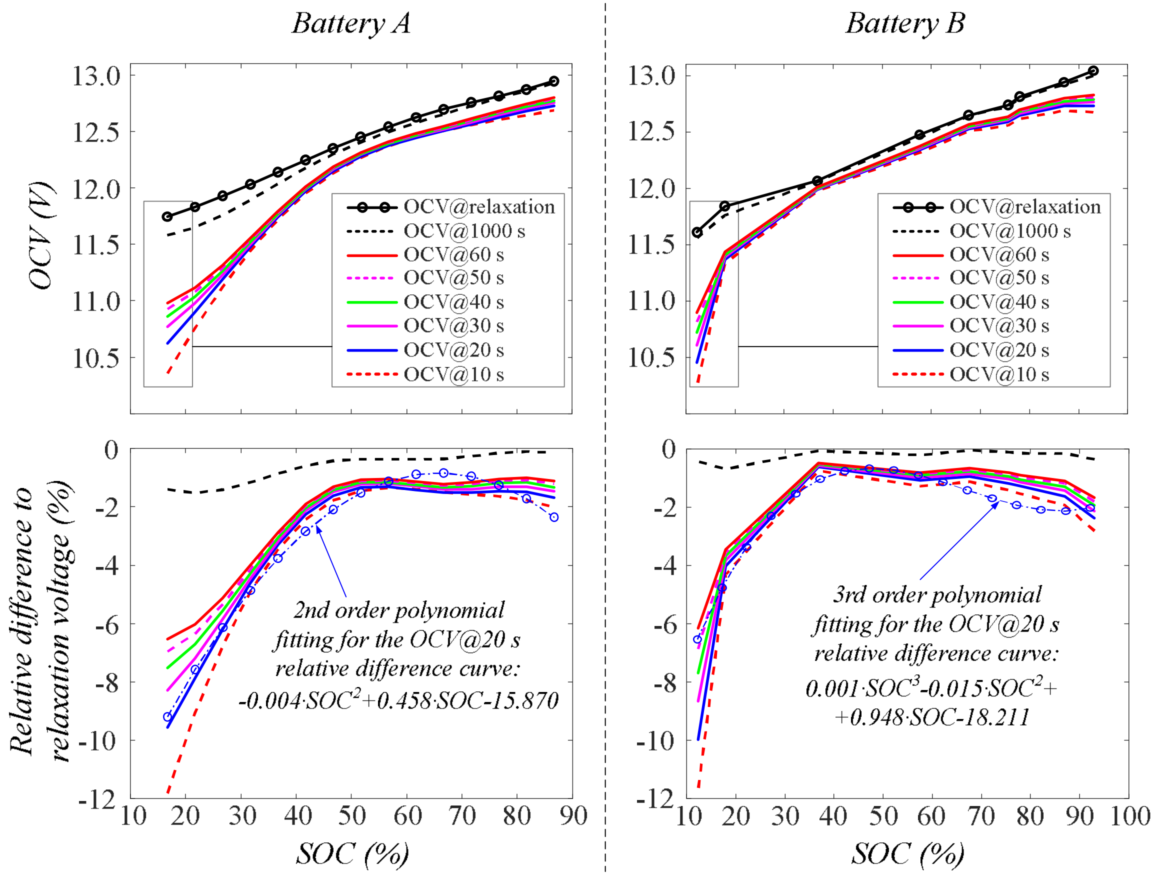
- **Validation of the described models** has been carried out under different criteria by exploiting **data coming from some existing ENEL Green Power PV plants** (in Brazil and in Central Italy) as well as through laboratory tests.
- About the **behavioral model of PV plants**, its **accuracy** can be assessed as the relative difference between the **measured power curve** (provided by **dataloggers** mounted in operating PV plants) and the power curve provided by the model. Referring to the energy produced on a daily basis, we experienced an **average relative error about 3.5 %** that is satisfactory with respect to the typical precision of meters and sensors in large PV plants. At the same time, the integrated state-space average model of the PV field model ensures **significant benefits in terms of computational time**

$$\varepsilon_{\%} = \frac{E_{model} - E_{measured}}{E_{measured}} 100$$

Daily energy relative error calculation

VALIDATION TESTS



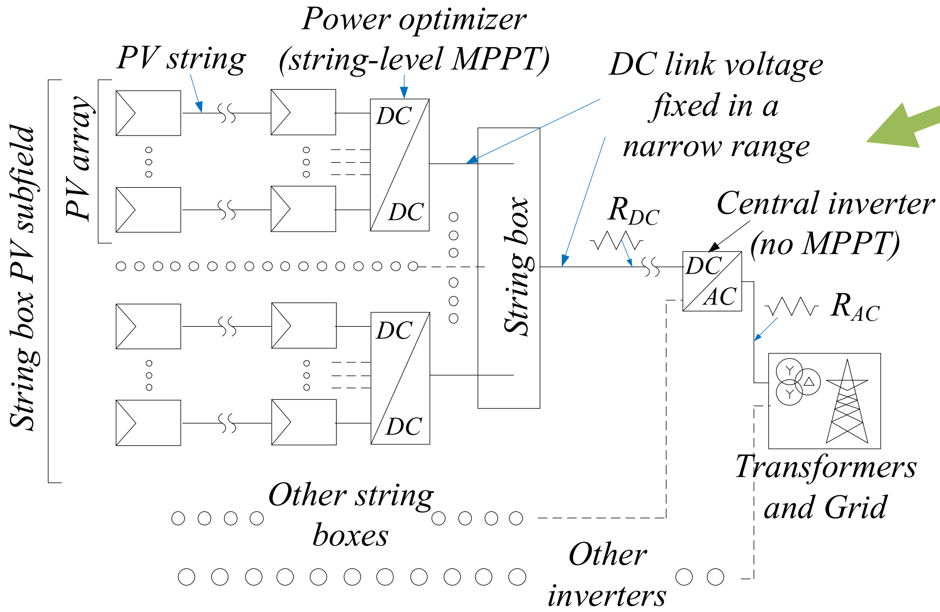


The validation process of the battery estimation algorithm has been carried out performing some tests on the experimental bench shown in the picture.

Open circuit voltage (OCV) at different time intervals after the discharge shows a typical trend with respect to the relaxation voltage and to the actual SOC. This trend can be approximated with a low order polynomial function and easily implemented in look-up tables.

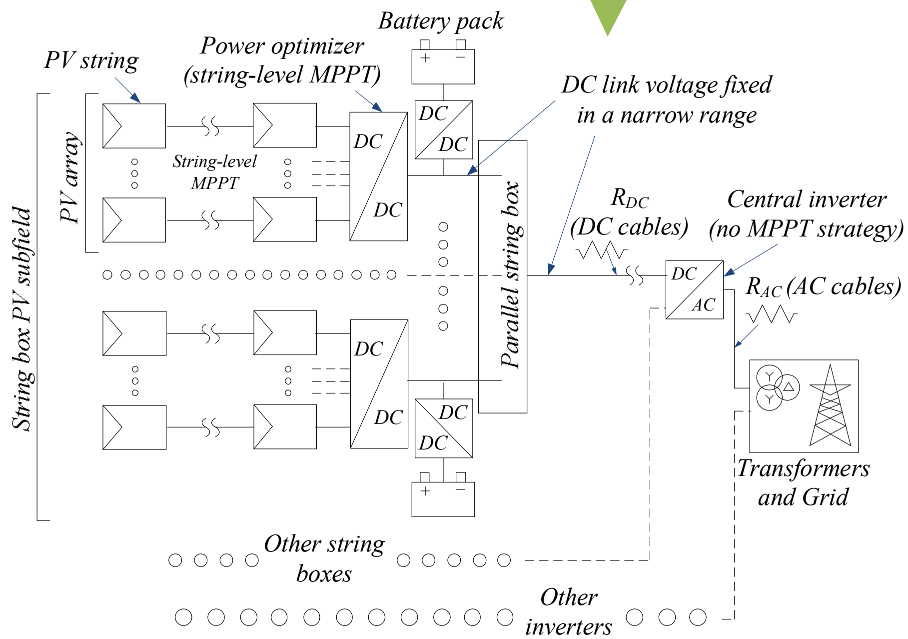
A CASE STUDY:
2 MW PV PLANT IN CENTRAL ITALY

- 500 kW PV experimental subfield with string optimizers



Actual configuration of the experimental subfield

Hypothesis: adding a distributed storage system

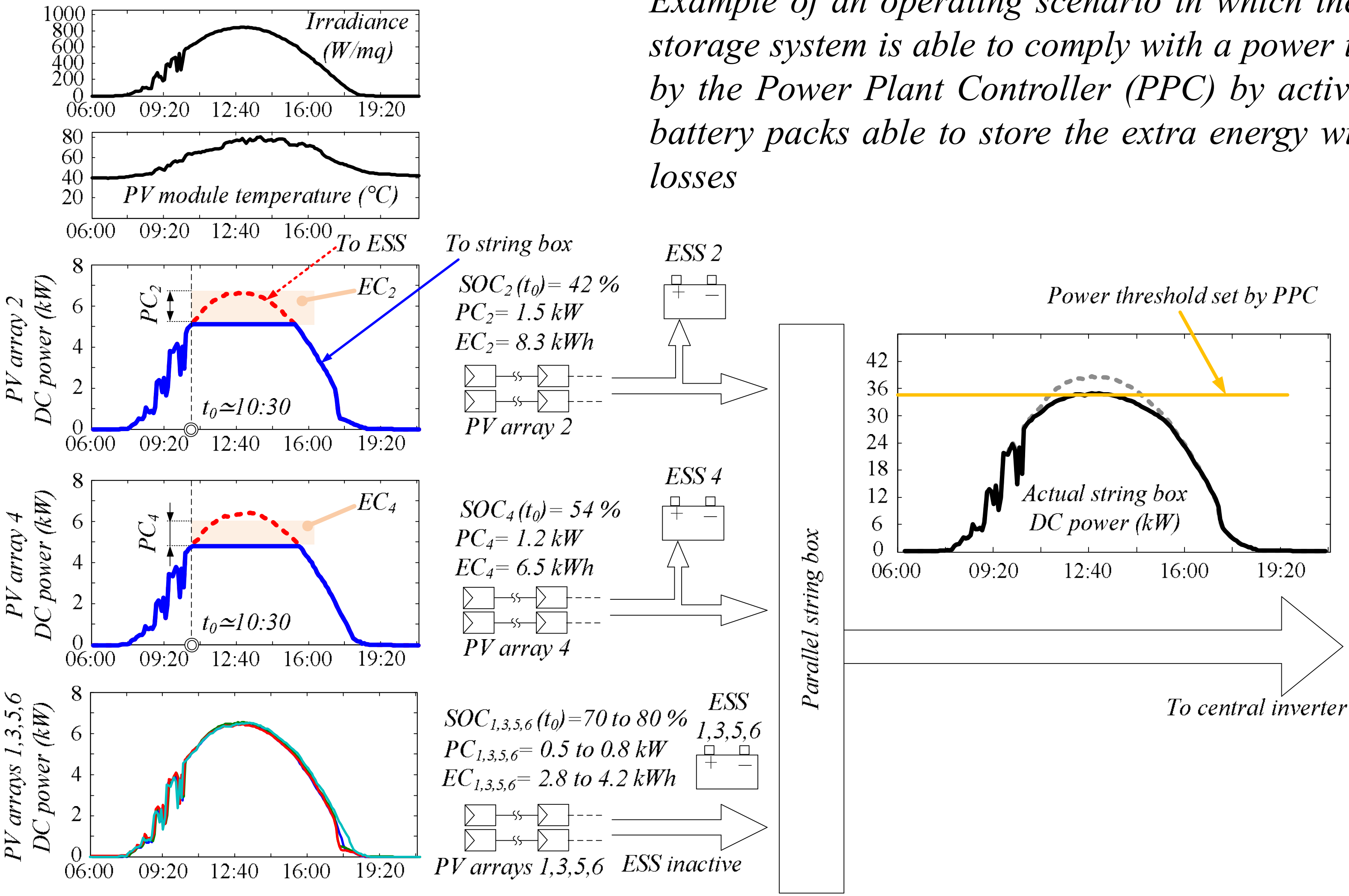


Pictures of the PV plant and of the optimizers

A CASE STUDY:
2 MW PV PLANT IN CENTRAL ITALY

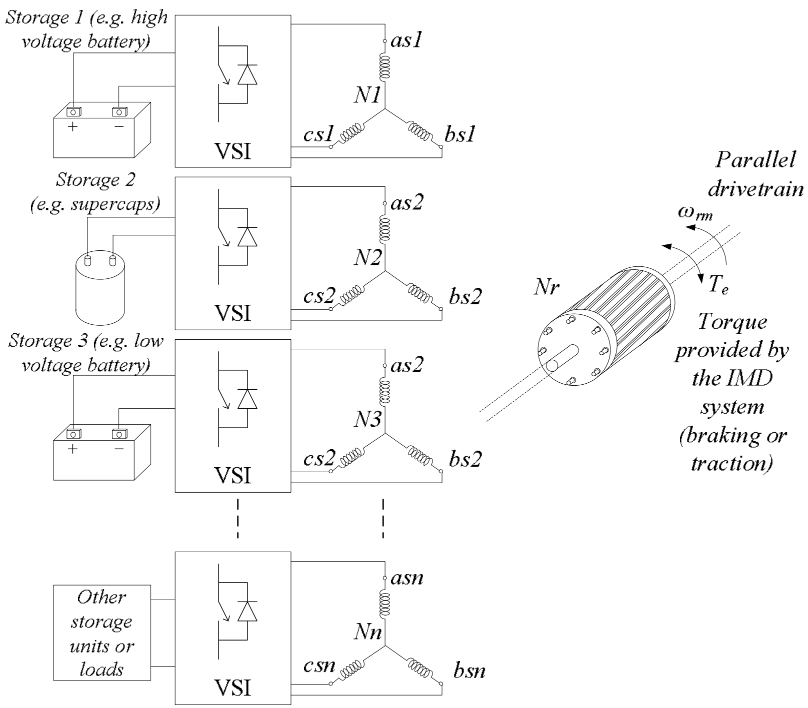
- 500 kW PV experimental subfield with string optimizers. Example of an operating scenario

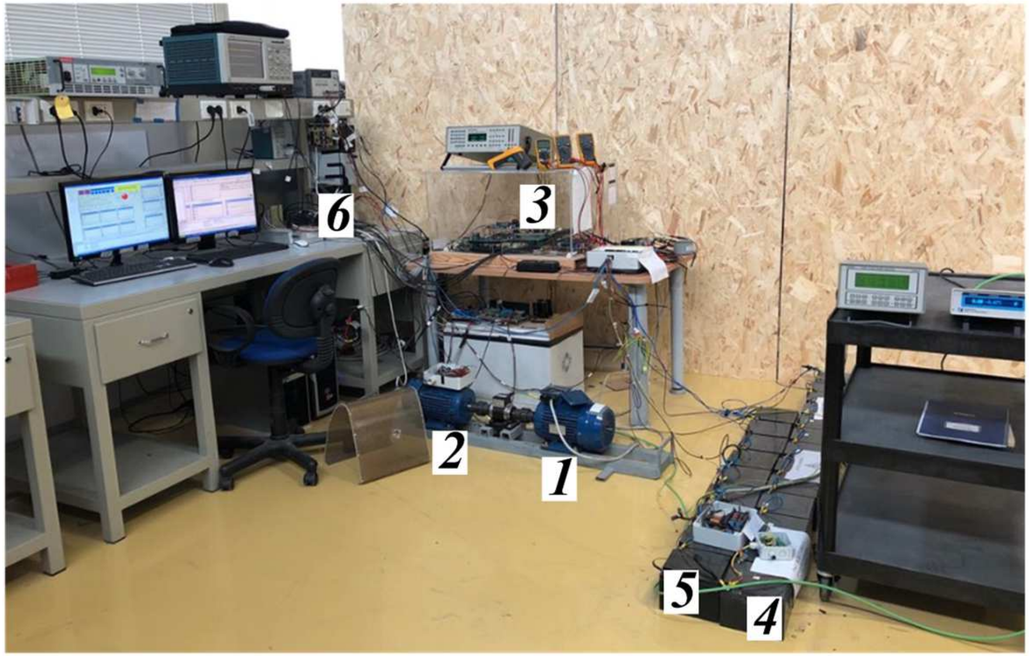
Example of an operating scenario in which the distributed storage system is able to comply with a power threshold set by the Power Plant Controller (PPC) by activating only 2 battery packs able to store the extra energy with minimum losses



OTHER RESEARCH ACTIVITIES DURING THE ACADEMIC YEAR

- **<u>Automotive</u>: Integrated Multi-Drives Topology devoted to Hybrid Electric Vehicles**





1. *Induction machine emulating the HEV drivetrain*
2. *Multi-winding induction machine*
3. *Power converters VSIs (switching frequency 30 kHz, dead time 1 us)*
4. *Storage unit 1: 13 x 12V 27Ah VRLA battery pack*
5. *Storage unit 2: 9 x 12V 27Ah VRLA battery pack*
6. *Control and monitoring system DSPACE DS1104*

RESEARCH ACTIVITIES DURING THE ACADEMIC YEAR

❑ Papers / Conferences:

- G. Nobile, M. Cacciato, G. Scarcella, G. Scelba, “Losses Minimization Control for an Integrated Multi-Drives Topology devoted to Hybrid Electric Vehicles”, published in IEEE Transactions on Industrial Electronics
- G. Nobile, M. Cacciato, G. Scarcella, G. Scelba, A. G. F. Di Stefano, G. Leotta, P. M. Pugliatti, F. Bizzarri “Performance assessment of utility-scale PV plants exploiting a novel integrated state-space average modelling approach”, submitted for publication in Taylor & Francis EPE Journal
- G. Nobile, M. Cacciato, G. Scarcella, G. Scelba, E. Vasta, A. G. F. Di Stefano, G. Leotta, P. M. Pugliatti, F. Bizzarri “Distributed converters in large PV plants: performance analysis supported by behavioral models”, in proceedings of the IEEE ELECTRIMACS 2019 Conference, Salerno (Italy), 21-23 May 2019
- G. Nobile, M. Cacciato, G. Scarcella, G. Scelba, E. Vasta, L. Tornello, A. G. F. Di Stefano, G. Leotta, P. M. Pugliatti, F. Bizzarri “A novel model-based approach for the energy management of distributed storage systems in utility-scale PV fields”, in proceedings of the IEEE EPE 2019 Conference, Genova (Italy), 3-5 Sep 2019

❑ PhD Schools / Workshops:

- 20-24 May 2019, Gaeta (Italy), PhD School: European PhD School on 'Power Electronics, Electrical Machines, Energy Control and Power Systems
- 7 March 2019, ENEL Green Power Innovation Hub Catania, ENEL Green Power-UK Consulate Meeting: PhD Research Activity Oral Presentation
- 21 March 2019, ENEL Green Power Innovation Hub Catania, UNICT-ENEL Green Power Meeting & Workshop: PhD Research Activity Oral Presentation