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

OVERVIEW

- The **evaluation of performance** obtained by using **string inverters or optimizers instead of central inverters** in utility-scale PV fields is a **difficult task** due to several reasons, for example:
  - Large number of partial unavailabilities
  - Monitoring systems issues leading to missing or wrong data
  - Operating constraints: thresholds in active power imposed by Power Plant Controller (PPC), reactive power control, etc.
  - Large number of time-varying parameters depending on seasonality, degradation rates, power derating in case of high temperatures, etc.
- A **proper modeling approach** could **overcome this kind of issues**. For sake of example, in case of missing data for a specific time period, a model could provide the theoretical energy produced by the PV plant for the same time period.

A CASE STUDY – 300 MW PV PLANT IN NOVA OLINDA, BRAZIL
4 MW EXPERIMENTAL SUBFIELD WITH CENTRAL AND STRING INVERTERS

In the 2 MW **subfield having central converters** there are **two inverters whose rated power is 1025 kVA**, fan cooled, mounted into an electric cabin. In the 2 MW **subfield with string inverters each converter has a rated power of 60 kVA** but can reach 66 kW in case of unity power factor and ambient temperature below 30° C. String converters, mounted in the field without using cabinets and without fan cooling, are grouped in a separate cabin close to the transformers using AC parallel switchboards named QPCA.

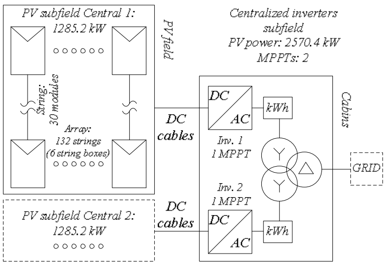


Fig. 1: Power system configuration of the 2 MW subfield with central inverters

PV modules	
P (W)	315
V_{oc} (V)	46.2
I_{sc} (A)	9.01
V_{mpp} (V)	37.2
I_{mpp} (V)	8.48
NOCT (°C)	45±2
P/Temp (%/°C)	-0.40
V_{oc}/Temp (%/°C)	-0.30
I_{sc}/Temp (%/°C)	+0.06
Number of cells	72
Central Inverters	
Rated AC power (kVA)	1025
AC output (V, Hz)	400±10%, 50/60
MPPT input DC voltage range (V)	675-1320
Maximum Efficiency (%)	98.9
MPPTs per power converter	1
String Inverters	
Rated AC power (kVA)	60 (up to 66)
AC output (V, Hz)	800, 50/60
MPPT input DC voltage range (V)	600-1450
Maximum Efficiency (%)	99.0
MPPTs per power converter	4

Table I: Main technical data

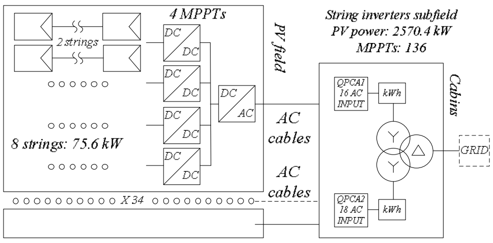


Fig. 2: Power system configuration of the 2 MW subfield with string inverters

UTILITY SCALE PV FIELDS WITH MULTI-STAGE POWER CONVERTERS: MODELLING APPROACH

The **model of a utility-scale PV plant** shown in Fig. 3 is **general-purpose**, in fact it can be used to simulate the central inverters subfield as well as the string inverters subfield or part of them (strings, string boxes, etc.) with minimal modifications.

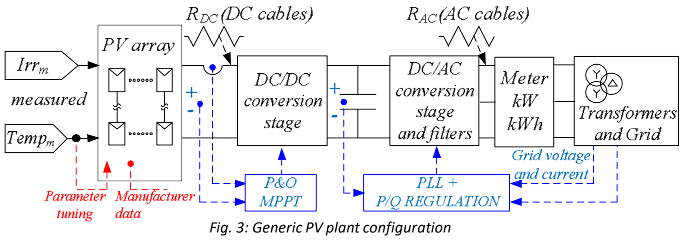


Fig. 3: Generic PV plant configuration

MULTI-STAGE CONVERSION SYSTEM MODELING

The **main novelty** is related to the creation of a complete model in which each component of the PV field is included by using its **state-space representation**. Such representation gives the opportunity to get simple identification processes. At the same time, all the conversion components are mixed into a single state-space average model. In other words, the PV plant becomes a **single state-space system** whose inputs are irradiance and cell temperature and whose output are the electric quantities to be known. An **innovative approach** has been developed to **integrate models of the power conversion stages** represented in Fig. 4 by means of an analytical formulation exploited to calculate the average value of the **DC-link current as a function of the AC current symmetrical components**.

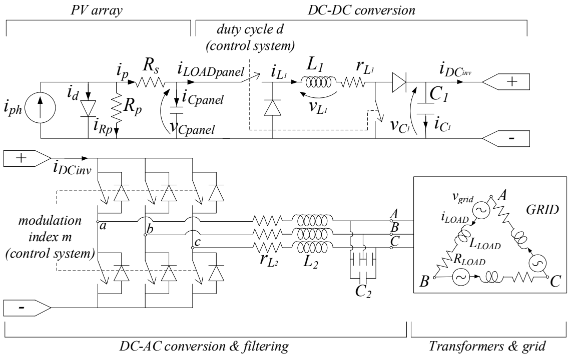


Fig. 4: Block diagram of a PV system with multi-stage conversion system

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

$$x = \begin{bmatrix} v_{C_{panel}} \\ i_{L_1} \\ v_{C_1} \\ x_1 \\ \dots \\ \dots \\ x_{18} \end{bmatrix} \quad u = \begin{bmatrix} i_{ph} \\ i_d \\ V_{grid} \end{bmatrix} \quad y = \begin{bmatrix} x_1 \\ \dots \\ \dots \\ x_{12} \end{bmatrix}$$

x_i = symmetrical components

$$i_{ab} = 2x_1 \cos\omega t - 2x_2 \sin\omega t$$
$$i_{bc} = 2x_3 \cos\omega t - 2x_4 \sin\omega t$$
$$i_{ca} = 2x_5 \cos\omega t - 2x_6 \sin\omega t$$
$$v_{AB} = 2x_7 \cos\omega t - 2x_8 \sin\omega t$$
$$v_{BC} = 2x_9 \cos\omega t - 2x_{10} \sin\omega t$$
$$v_{CA} = 2x_{11} \cos\omega t - 2x_{12} \sin\omega t$$
$$i_{LOAD_{AB}} = 2x_{13} \cos\omega t - 2x_{14} \sin\omega t$$
$$i_{LOAD_{BC}} = 2x_{15} \cos\omega t - 2x_{16} \sin\omega t$$
$$i_{LOAD_{CA}} = 2x_{17} \cos\omega t - 2x_{18} \sin\omega t$$

State-space averaging modeling approach

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

$\overline{C}$ *identity matrix*

$\overline{D}$ *null*

The elements of these matrices are listed in the full paper

MODEL VALIDATION

For sake of example, in Fig. 5 the power measured at the meter of the string inverters subsection QPCA 1 is compared to the power curve obtained in simulation for the same subfield in a sunny day during which a power limitation occurs due to the inverter internal maximum power threshold. **Thanks to the novel model, it can be estimated the theoretical extra-energy with a good accuracy.**

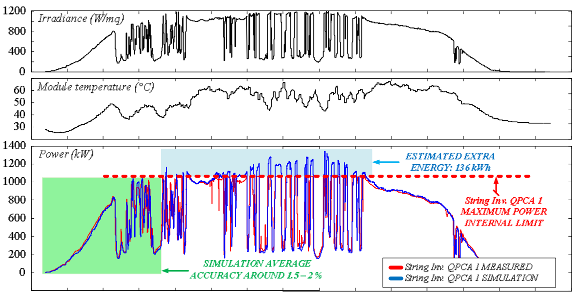
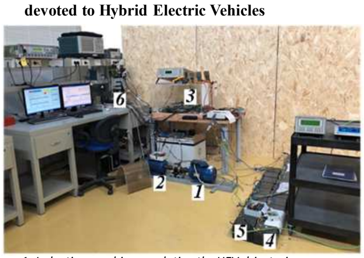


Fig. 5. Simulation vs measured data of string inverters subsection QPCA 1 during a sunny day

Elaboration of data acquired by the monitoring system in the real PV plant, supported by the developed model, shows that **string inverters ensure a gain in terms of produced energy** around 2-3%. Anyway, the accurate assessment of such gain requires data for a larger time period in order to detect the variations due to seasonality. Also the identification of causes leading to mismatch phenomenon compensated by string inverters requires further investigations.

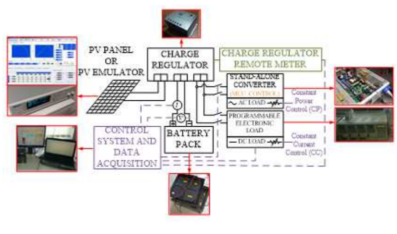
OTHER RESEARCH ACTIVITIES DURING THE ACADEMIC YEAR

- **Automotive**: 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)
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

- **Energy Storage**: Performance Assessment of Equivalent-Circuit Models for Electrochemical Energy Storage Systems. Development of real-time model-based State of Charge and State of Health estimation methods.



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2. G. Nobile, M. Cacciato, G. Scarcella, G. Scelba "Performance Assessment of Equivalent-Circuit Models for Electrochemical Energy Storage Systems", in Proc. 43th Annual Conference of the IEEE Industrial Electronics Society (IECON 2017)
3. G. Nobile, M. Cacciato, G. Scarcella, G. Scelba "Multi-criteria experimental comparison of batteries circuital models for automotive applications", 2018 Communications – Scientific Letters of the University of Zilina
4. G. Nobile, M. Cacciato, G. Scarcella, G. Scelba, L. Salvo "Performance Assessment of a novel Integrated Multi- Drives Topology for Automotive Applications", in Proc. 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM) (oral presentation)
5. G. Nobile, M. Cacciato, G. Scarcella, G. Scelba, A. G. F. Di Stefano, G. Leotta, P. M. Pugliatti, F. Bizzarri "Comparison between central and string inverters performance for the utility-scale PV plant in Nova Olinda Brazil", in Proc. 2018 35th European PV Solar Energy Conference and Exhibition (EU PVSEC)
6. G. Nobile, M. Cacciato, G. Scarcella, G. Scelba, "Losses Minimization Control for an Integrated Multi-Drives Topology devoted to Hybrid Electric Vehicles", accepted for publication in IEEE Transactions on Industrial Electronics