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Power conditioning units in grid-connected photovoltaic systems: A comparison with different technologies and wide range of power ratings

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Abstract

Nowadays, the electronic converter which connects the photovoltaic array (PV) with the utility grid is subject to multiple requirements in terms of energy efficiency, power quality and grid stability. The paper focuses on a comparison among grid-connected Power Conditioning Units (PCUs) with different sizes, technologies and PV system architectures. In particular, the comparison includes the following items: single-phase and three-phase systems; with low-frequency or high-frequency transformers and transformerless version; with MOSFETs and IGBTs transistors. The comparison, based on experimental tests in which the signals of voltage, current and power are sampled at fast rate and with low uncertainty, is performed thanks to the normalisation of the input/output powers with respect to the power ratings. A set of meaningful parameters permits to characterise the behaviour of the PCUs which are studied both in field operation and in laboratory with known and constant test conditions. Regarding the PV systems in field operation, five plants have been analysed with PCUs from 230 kW down to 3 kW. The PCUs under study in laboratory include 1-kW inverter, one string-inverter with multi-MPPT, one per string, and two module integrated inverters. The experimental results demonstrate that the different PCUs mostly have similar performance, although the single-phase PCUs exhibit lower DC–AC efficiency at partial load, whereas a three-phase PCU shows lower MPPT efficiency, when defects in the solar cells generate multiple maximum power points in the current–voltage curve of the PV array.

Keywords: Experimental methods; Photovoltaic systems; Grid-connected Power Conditioning Units; Performance analysis

1. Introduction

The grid connection of a photovoltaic (PV) generator can occur specially by an electronic converter which interfaces the best possible the Direct Current (DC) side and the Alternating Current (AC) side of the PV system. This device, usually named inverter, becomes the crucial component for successful operation of a grid-tied PV system. Thus, it is more specifically called Power Conditioning Unit (PCU). Not only the DC–AC conversion is required to the PCU, but also the optimum utilisation of the PV generator, i.e., the Maximum Power Point Tracking (MPPT) Femia et al., 2013, the adjustment of the active and reactive powers in order to hold the power factor at the desired value (Hassaine et al., 2009) and finally the grid-interface protection against the network perturbations (Ruz et al., 2011; Kjaer et al., 2005).

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Currently, after the massive penetration of intermittent renewable sources as PV and wind power systems, other tasks are required to the PCUs. In particular, these issues can be mentioned: the supply of reactive power (capacitive or inductive, regardless the sign), when the grid voltage is outside selected thresholds; the progressive reduction of active power, if the frequency exceeds a given limit; the delayed and gradual ramp-up to preserve the grid stability; the fault ride through function in the event of a voltage dip (Spertino et al., 2012; Chicco et al., 2006).

Regarding the architecture of power conversion (as voltage source), the PV systems can have either a *centralised* inverter for the array of PV modules or as many inverters as the PV strings (*string* inverters for a certain number of series connected modules) or the modules are (module integrated inverters also known as *AC modules*). Moreover, in case of multiple inverters, it is possible to perform a "*master–slave*" operation with one master and several slaves which are switched on (or off) by the master, according to the irradiance and thus power increment (or decrement) Spertino et al., 2012. In such a way, each inverter works at nearly full load with maximum efficiency.

Which is the optimum solution is a difficult topic, because at least two viewpoints must be considered:

- the viewpoint of the electric machine, called variable-frequency converter, with the typical configuration in single-phase or in three-phase mode;
- the viewpoint of the PV generator as an array of PV modules.

From the viewpoint of the electric machine, usually controlled by Pulse Width Modulation (PWM), the three-phase DC–AC converter has only six electronic switches (two per leg), whereas the single-phase converter has at least four switches (H-bridge) and so twelve switches are needed for a three-phase grid connection. In this regard, there are many inverter structures derived from either the H-bridge topology or the Neutral Point Clamped (NPC) topology Teodorescu et al., 2011; Patrao et al., 2011; Oleschuk et al., 2010. These examples can be introduced: the H5 inverter (https://www.s, xxxx); HERIC inverter (http://www.su, xxxx); REFU inverter (http://europe, xxxx); Ingeteam inverter (http://www.in, xxxx); Conergy inverter (http://www.co, xxxx). The recent situation of the inverter market is well summarised in PV-Magazine (xxxx), where some of these structures are included, showing their competitiveness.

From the previous notes it is clear that the DC–AC efficiency is better for the three-phase solution, even if the single-phase inverter is the only solution up to 6 kW in Italy. Moreover, since the ripple voltage at the DC side is as a result of the double-frequency ripple in the instantaneous power (single-phase) at the AC side, the three-phase system minimises this DC ripple in balanced conditions with consequent saving and life extension for the bus capacitor.

Usually a DC–DC converter (step-up, step-down, push–pull, etc. (Taghvaee et al., 2013; Adinolfi et al., 2009; Graditi et al., 2014, 2011a,b, 2010), integrated into the PCU, permits to the designer a wide range of MPP voltage, so as to easily decide the number of series connected modules per string. In the three-phase configuration, the steady-state operation, after the search algorithm of the MPPT, is obtained with *longer time duration*, because the rates $\Delta v/\Delta t$ and $\Delta i/\Delta t$ are slower, being higher inner inductances and capacitances.

On the other hand, from the viewpoint of the PV generator, the single-phase solution permits: to reduce the mismatch of the *I–V* characteristics (or to minimise in case of AC module), because of manufacturing tolerances, defects and partial shading; to avoid the blocking diodes in case of string inverter; to improve the availability with respect to the durations of maintenance, failure and repair, since the other two inverters can continue to work.

Furthermore, the PV-system point of view, which is a direct consequence of the previous two items, has to be not neglected because the DC enclosure (with PV-array circuit combiner, ground-fault protection) and AC enclosure (with grid-interface breaker) influence the cost and the correct operation of the PV plants. It is possible to stress that the single-phase configuration with string-inverters allows to avoid the DC enclosure, while the three-phase configuration permits to simplify the AC enclosure (Chen et al., 2013; Spertino and Corona, 2013).

In order to assess accurately the PCU behaviour, a measuring procedure was set up by using calibrated instruments which have the proper traceability to the national standards in Italy from INRIM institute (http://www.in, xxxx). The paper focus is on the experimental results from PCUs with different technologies and wide range of power ratings; the tests have been carried out both in laboratory and in field operation for a detailed comparison, in terms of energy efficiency and power quality towards the utility grid. The following sections deal with: the identification of PCU parameters; the measuring circuits for detection of PCU parameters; the experimental results of PCU in field operation; the experimental results of PCU in laboratory; the concluding remarks.

2. Identification of PCU parameters

A practical concept to compare the behaviour of different PCUs is to consider the devices as black boxes, in which it is possible to measure input and output signals in terms of instantaneous voltage, current and power. Thus, the performance of all the tested PCUs was characterised by the following parameters which highlight the overall energy efficiency, the power quality towards the grid and the loading on reactive components at DC side (e.g., film, ceramic and electrolytic capacitors).

The presented study was conducted for a wide range of active powers normalised by the power ratings P_{ACr}, where the active component (kW) is used instead of the apparent power, as a result of the conventional practice of unitary power factor (International Electrotechnical Commission,