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An Automatic Measurement System for the Performance Evaluation of Medium-sized and Large Photovoltaic Plants

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Abstract-
In recent years renewable sources of power are being increasingly exploited to address the challenges of climate change and fossil fuel depletion. Wind power and solar power are two of the few renewable energy sources capable of rapidly satisfying a reasonable proportion of future energy requirements [1].
Acceptance testing of medium-sized and large photovoltaic (PV) plants requires functional tests executed to verify the proper working and energy efficiency. A final certificate ensures the compliance with the technical requirements, as required by Italian *Conto Energia* program. Tests must be conducted according to several technical norms. The paper describes a measurement system, implemented for testing medium-sized PV plants in full compliance with the international standards; moreover, the measurement system can be configured to measure additional parameters, because it is software based. The measurement system has been adopted for the performance evaluation of a 842 kWp PV plant, with satisfactory results.

I. Introduction

The first step in the PV plants testing consists in the checking of: i) electrical continuity and correct connection among the PV modules; ii) correct grounding of voltage dischargers and external conducting parts; iii) insulation of the electrical circuits from the ground, with measured resistance values according to IEC 60364-6:2006-02 "Low voltage electrical installations - Part 6: Verification" [2];; iv) behaviour of the plant in several working conditions, as starting, stopping and mains voltage outage, as required by the standards [3-7].
In CEI 82-25 "Guide for design and installation of photovoltaic (PV) systems connected to MV and LV networks" [3], the experimental characterization of PV plants is required to investigate their performance; to evaluate the overall efficiency, the quantities to be measured are: i) the solar radiation on the panels' surface; ii) the air temperature in the shade; iii) the panels temperature; iv) the DC bus voltage; v) the total DC bus output current in the; vi) the inverter output AC voltage; vii) the invert output AC current; ix) the active power and, x) the electric energy injected to the mains.
The overall accuracy, that is required for the measurement chain including the transducers, must be equal or better than: i) 5% for solar radiation; ii) 1 % for both the air and modules temperature; iii) 2% for voltage, current and power.
Further requirements are defined in IEC 61724:1998-04 " Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis" [4]; in this standard, the features of the data acquisition systems (DAQ) suitable for the PV plants testing are described. A particular attention is given to the simultaneous sampling of the above mentioned quantities, to carry out all the measurements with the required contemporaneity; this is a binding feature for the definitions of the measurment system architecture and in the choice of the DAQ. The presence of voltage and current harmonic distortion, that are introduced by the inverter, involves the adoption of transducers and DAQs with appropriate bandwidth and sampling frequency, respectively.
To draw up a testing report, the measurment of the overall efficiency of the PV plant is required; it can be perfomed in two steps.
The first one concerns the evaluation of the minimum efficiency of the installed PV modules; the conditions that must be satisfied is (1):

$$P_{dc} > 0.85 * P_{nom} * I/I_{stc} \qquad (1)$$

where P_{dc} is the PV generator output power, P_{nom} is the PV generator rated power, I is the solar radiation in [W/m^2] on the PV modules surface, I_{stc} the solar radiation in standard conditions, assumed as 1000 W/m^2.
The second step investigates the perfomance of the DC/AC convertion system; the conditions that must be verified is (2):

$$P_{ac} > 0.9 * P_{dc} \qquad (2)$$

where P_{ac} is the DC/AC convertion system output active power and P_{dc} is the PV generator output power.
The measurment of P_{ac} and P_{dc} must be performed when the solar radiation on the modules surface I is at least 600 W/m^2.
The modules temperature variations can involve appreciable effects on their efficiency; so, if during the measurement of (1) the acquired temperature of the modules is grether than 40 °C, it is accepted a temperature compensation. In these conditions, instead of (1), we can use (3):

$$P_{dc} > (1 - P_{tpv} - 0{,}08) * P_{nom} * I/I_{stc} \qquad (3)$$

where P_{tpv} quantifies the PV generator thermal losses, as reported in its datasheet; all the remaining losses ar tipically assumed as 8%
In the performance evaluation of medium-sized and large PV plants, the geometrical dimensions make it difficult to consider a uniform solar radiation for each installed PV module; moreover, the intensity of the DC and AC currents can reach hundreds of ampere, with the related problems in their transduction [8, 9].
Finally, because of the use of DC/AC power converter, the PV plants can involve some important Power Quality phenomena, in terms of voltage fluctuations, harmonic distortion and transients; their effects can be increased by the MV line lenght, because in many cases the PV plants are located in the countryside and are distant from a primary cabin [10, 11, 12, 13].

II. The measurement system

As reported in Section I, specific requirements are defined by the international standards, in particular for the accuracy of the measurements and for their simultaneous execution.
It is possible to find commercially available measurment kits for the PV plants testing, but, often, their performance are not completely satisfactory. The results of experimental characterizations carried out on the most adopted kits show lacks in the sampling frequency and in the simultaneous acquisition of the signals; the use of multiplexer, or transducers and AD/DC converter with long response times, can reduce the bandwidth of the measurement system, and it introduces a phase displacement between the current and voltage signals, that increases the errors in the efficiency measurement. Starting from these considerations, we decided to develop a measurement system (Fig. 1) to perform all the required tests, in full compliance with the international standards; moreover, the measurement system can be configured to measure additional parameters, because it is software based [14, 15].

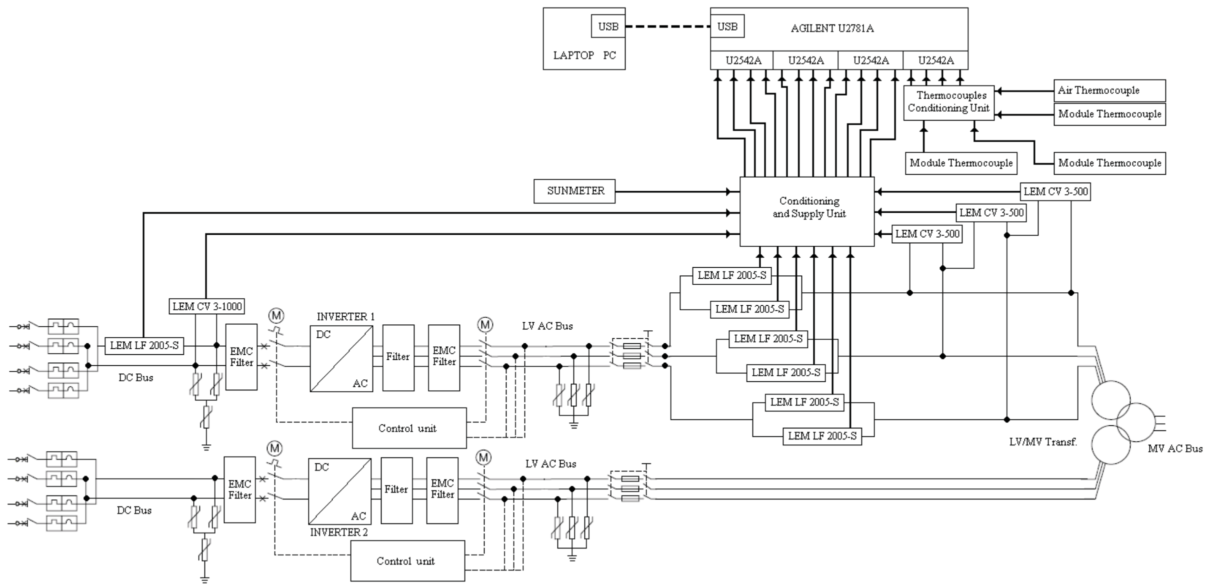

Figure 1. The block diagram of the automatic measurement system.

The core of the measurement system is an Agilent multichannel data acquisition unit, equipped with: i) a chassis Agilent U2781A; ii) 5 boards U2542A DAQ; iii) 5 terminal block and SCSI-II 68-pin connector U2902A.
The system can perform the simultanous sampling of 20 analog channels, with 16 bit resolution, and a sampling frequency up to 500 kSample/s. With the adopted sampling frequency of 20480 Sample/s, time intervals of 200 ms have been acquired, according to IEC 61000-4-7 [16, 17].
The input signals have been transduced with: i) 1 LEM CV 3-1000 for the DC voltage; ii) 1 LEM LF 2005-S for the DC current; ii) 3 LEM CV 3-500 for the AC voltages; iv) 6 LEM LF 2005-S for the AC currents; v) a digital Sunmeter, 0–1250 W/m^2, whit temperature compensation, for the solar radiation; vi) 4 J-type thermocouples with compensation modules, for the air and PV modules temperatures.
We decided to use 2 current transducers in parallel connection on the AC busbars because of their sizes.
The perfomance of the measurment system have been evalueted by means of the Fluke 6100A Power Standard. The obtained accuracies for each measured quantity are: i) ±0,2 % for the DC voltages; ii) ±0,2 % for the AC voltages; iii) ±0,3 % for the DC currents; iv) ±0,3 % for the AC currents; v) ±0,5 % for the DC power; vi) ±0,5 % for the AC power; vi) ±3 % for the solar radiation; vii) ±1 % for the air and modules temperatures; viii) ±2 % for the air humidity. In Fig. 2 the block diagram of the automatic measurement system is depicted.
The software performing the data acquisition, the measurements and the data processing has been developed in the National Instruments LabVIEW environment, and it has been installed on a notebook PC linked to the Agilent system via USB. The software can configure all the parameters required for the tests execution, and it processes the instantaneous power waveforms, the power and efficiency values, attesting if the efficiency test [2] has got a positive result; the measurement of the voltage and current harmonic distortion has been also included.
In detail, the software allows the user to perform the following task: i) input of the reference parameters for testing; ii) input of the rated parameters of the PV plant under test, as reported in the technical documentation; iii) setting of the acquisition parameters, in terms of number of channels to acquire, sampling frequency, buffer sizes, transducers constants; iii) simultaneous acquisition of temperatures, solar radiation, AC and DC voltage and current waveforms; iv) check of the presence of standard conditions for the solar radiation ($I \geq 600$ W/m^2) and the PV modules temperature, to evaluate the efficiency according to (2) or (3); v) processing and visualization of line and phase voltage and current waveforms; vi) processing and visualization of AC and DC instantaneous power waveforms; vi) data processing for the check of conditions in (1), (2) or (3); vii) processing and visualization of the amplitude spectra of the acquired voltage and current waveforms; viii) processing of the current and voltage THD indexes; ix) data storage in NI TDMS format, and automatic visualization of the testing report. A screenshot of the developed software is in Fig. 3.

III. The tested photovoltaic plant: experimental results

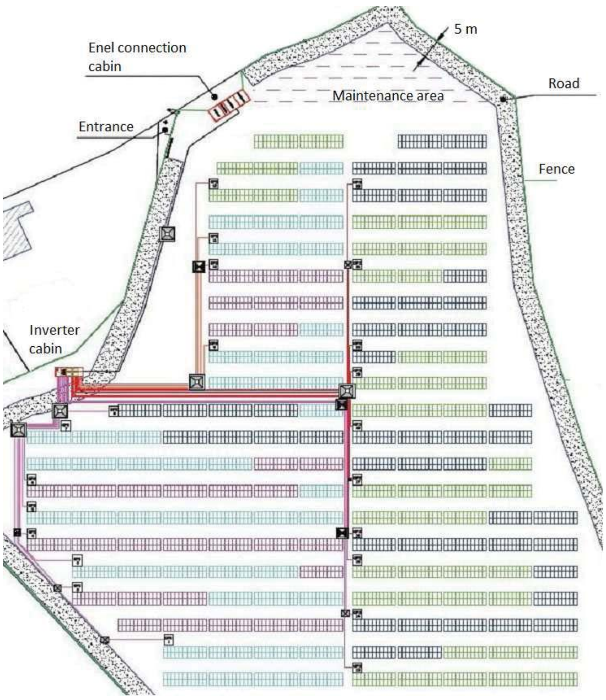

Figure2. PV plant layout.

The automatic testing system we developed has been adopted to test the PV plant that ENERGETICA Italy built near Cupello, a town in the central Italy. 3828 PV polycrystalline silicon modules, produced by ENERGETICA, have beed installed in 2 sub-plant blocks, with a total rated power of 842 kWp. Each sub-plant consists of 87 parallel connected strings, each of them consisting of 22 modules, type E2000/220, rated power of 220 W @ 1000 W/m2 (Fig. 2).
Each subplant is connected to a different inverter, type ABB PVS 800, rated power 500 kW; the inverter cabin is aquipped with other components, as a PLC, EMC filters, measuring current and voltage transformers, current breakers and sectionalising switches.
In Figures 4-6, some experimental results have been reported; they allow the evaluation of the performance of the tested PV plant. The results refer to the efficiency testing of Inverter 1, in the following conditions: i) solar radiation on the modules surface 933 W/m^2; ii) air temperature 30.2 °C; iii) PV modules mean temperature 38.4

°C; iv) air humidity 46%; v) DC voltage 545.4 V; vi) AC current 683.1 A; vii) DC power 372.58 kW. The final results of the testing are shown in Table I.

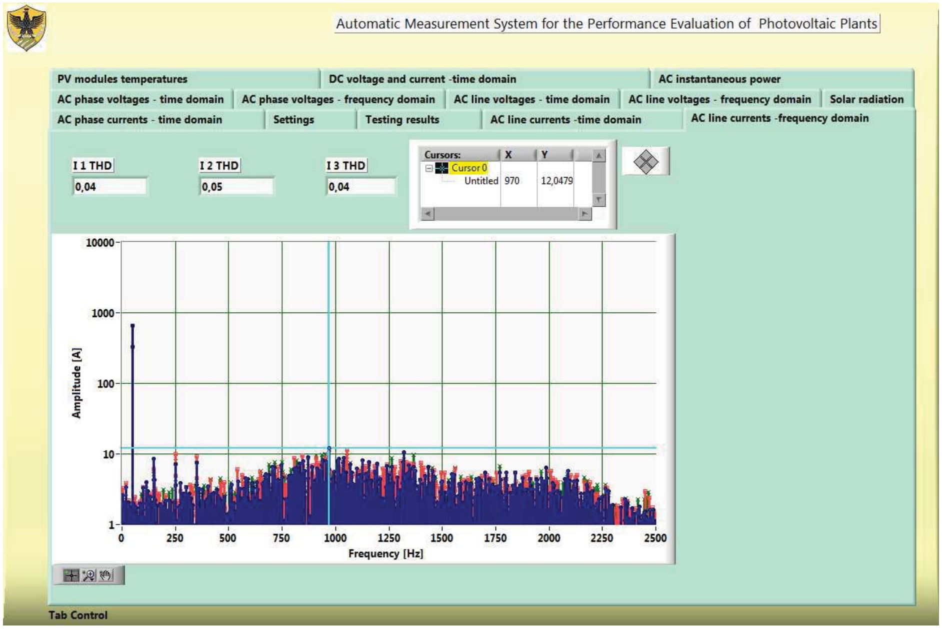

Figure 3. Screenshot of the developed measurement software.

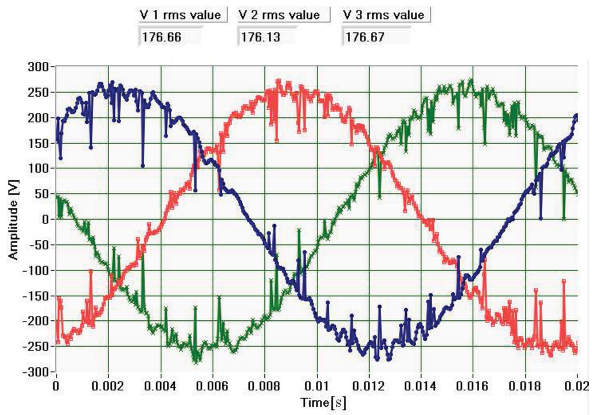

Figure 4. Output voltage waveforms.

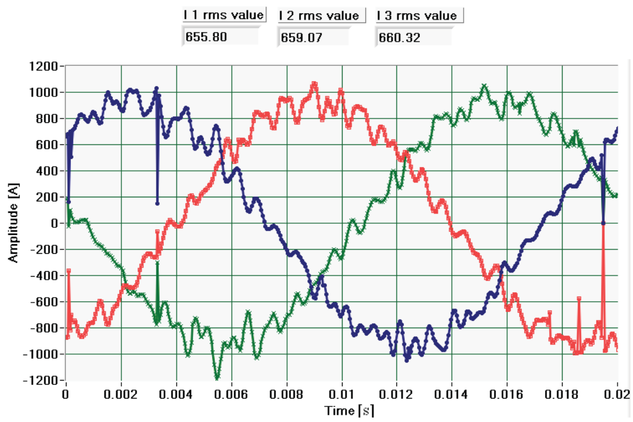

Figure 5. Output current waveforms.

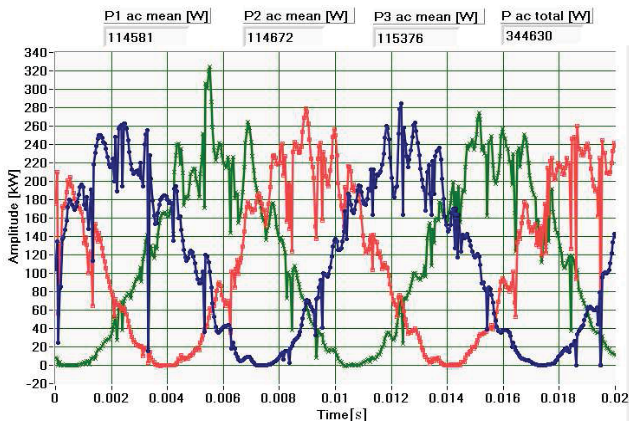

Figure 6. Output instantaneous power waveforms.

Table I. Results of the testing

	Sub-plant #1	**Subplant #2**
Date and time of the test	August 09, 2011; 12:22	August 10, 2011; 11:12
Weather conditions	clear sky	clear sky
Air Temperature [°C]	30	25
Air Humidity %	46	54
PV Modules mean temeperature [°C]	38	37
Solar radiation [W/m^2]	894,81	933,16
DC bus voltage [V]	551,68	545,41
DC bus current [A]	634,36	683,11
DC bus power [W]	349967,68	372573,12
Sub-plant rated power [W]	420640	420640
Reference sular radiation [W/m^2]	1000	1000
AC bus voltages [V_{rms}]	V_1 = 176,15; V_2 = 175,72; V_3 = 176,28	V_1 = 176,66; V_2 = 176,13; V_3 = 176,67
AC bus currents [A_{rms}]	I_1 = 648,55; I_2 = 613,54 A; I_3 = 614,44	I_1 = 655,80; I_2 = 659,07 A; I_3 = 660,32
AC bus active powers [W]	P_1 = 113114,44; P_2 = 106395,84; P_3 = 107313,08	P_1 = 114581,14; P_2 = 114672,37; P_3 = 115376,04
Power Factors	PF_1 = 0,99; PF_2 = 0,99; PF_3 = 0,99	PF_1 = 0,99; PF_2 = 0,98; PF_3 = 0,99
AC bus total active power [W]	326823,36	344629,55
Total apparent power [VA]	330366,84	348594,35
AC conversion efficiency %	93,3	92,5

IV. Conclusions

In this paper, an automatic measurement system for the performance evaluation of medium-sized and large photovoltaic plants has been presented. Although it is possible to find commercially available measurment kits for the PV plants testing, often their performance are not completely satisfactory. The developed system can perform all the required tests, in full compliance with the international standards, as required by Italian *Conto Energia* program; moreover, the measurement system can be configured to measure additional parameters, because it is software based. The automatic testing system we developed has been adopted to test the PV plant that ENERGETICA Italy built near Cupello, a town in the central Italy; the PV plant consists of 3828 PV polycrystalline silicon modules, produced by ENERGETICA installed in 2 sub-plant blocks, with a total rated power of 842 kWp; the obtained results are satisfactory.
A further improvement of the system could be reached by integrating wireless sensor units, to increase the number of measured temperatures on the PV modules [18], and introducing smart power system distributed on the plants [19, 20].

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