Electronic controlled device for the analysis and design of photovoltaic systems

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ABSTRACT

The characterization and design of photovoltaic systems is a difficult issue due to variable atmospheric conditions. Simulators and measurement equipment have been proposed, but most of them do not deal with real atmospheric conditions. This letter proposes an electronic device that first measures the real evolution of the *I-V* characteristic curves of photovoltaic generators and then physically emulates in real time these curves to test photovoltaic inverters. The device consists of a dc-dc converter, a microcontroller and a data storage unit. The two operation modes (emulation and measurement) are digitally driven by the microcontroller. The converter current is controlled by means of a variable-hysteresis control loop whose reference is provided by the microcontroller. In addition, a digital voltage control loop is designed to determine the complete characteristic curves of the photovoltaic generators. A 15kW prototype is designed

and built that can measure three times per second the characteristic curves of up to seven generators and then emulate their electrical behaviour to test photovoltaic inverters. With the proposed device, the optimal configuration and performance of photovoltaic generators, as well as the operation of photovoltaic inverters can be thoroughly analysed under real atmospheric conditions.

INDEX TERMS

Photovoltaic power systems, photovoltaic cell measurements, power electronics

I. INTRODUCTION

Renewable energy systems, particularly photovoltaic systems, are currently experiencing rapid development. Efforts have been made to characterize photovoltaic modules, generators (groups of modules) and inverters [1], [2]. However, the characterization of these systems is quite difficult due to the unpredictable nature of the weather, which creates variable operating conditions.

Various types of laboratory equipment are used to obtain the *I-V* characteristic curves of photovoltaic modules [1]-[3]. Also, real-time simulators have been proposed to test photovoltaic inverters under different operating conditions [4]-[6]. Nevertheless, none of these systems is able to both “save” the real evolution of the *I-V* characteristic curves of photovoltaic generators and “reproduce” them in real time to supply an inverter in a laboratory. A device with these attributes can help to optimize the configuration of these systems in terms of efficiency. By simultaneously measuring the *I-V* characteristic curves of different photovoltaic modules or generators in a given period of time, the evolution of their maximum power points can be known. It is then possible to calculate the maximum energy they could have delivered separately and compare it with the energy that could have been obtained for various configurations such as series/parallel connection, central/string converter, etc. [7]. These configurations can be compared and the optimal one determined from an energetic point of view.

Photovoltaic inverters should be analyzed under realistic operating conditions, including partial shading, dawn, nightfall, etc. These conditions could be recreated at the laboratory with an emulator that could reproduce in real time the previously measured *I-V* characteristic curves. In so doing, there would be no need to make field tests waiting for these particular atmospheric conditions [8]. With this emulator it is also possible to analyse the behaviour of maximum power point tracking (MPPT) techniques. Additionally, the measured characteristic curves of the photovoltaic generators can be used to determine the equivalent characteristic curves of the optimal configuration for these generators. Then, these equivalent curves can be used for laboratory testing of inverters in order to analyze their behaviour under the optimal configuration.

This letter proposes an electronic device with two operation modes, measuring and emulating. The main advantage of the proposed device is its ability to integrate both operation modes. The measuring mode allows the evolution of the photovoltaic characteristic curves of the generators to be measured and stored. The emulating mode allows the testing of any photovoltaic inverter at the laboratory with the stored characteristic curves. Thus, the optimal configuration and performance of photovoltaic modules, as well as the operation of photovoltaic inverters can be thoroughly analysed. A 15kW prototype has been designed and built. A preliminary version of this prototype can be found in [9]. The prototype can simultaneously measure three times per second the characteristic curves of up to 7 different photovoltaic modules or generators and emulate the behaviour of photovoltaic generators up to 500V and 30A. Experimental results focus on the optimization of configurations of photovoltaic modules and generators under particular weather conditions.

II. Description of the Proposed System

The layout of the proposed system is presented in Fig. 1. The figure also includes the practical implementation of the proposed system prototype, details of which will be given in Section IV. The system consists mainly of an electronic converter, a microcontroller and a data storage unit. The converter, described in Section III, contains an inner current control loop for the output current. A measuring board with voltage and current sensors is included with the converter. The microcontroller generates the reference for the current loop and organizes the information from the measuring card in order to store it in the data storage unit. The microcontroller is a digital signal processor (DSP) that is placed in a PC. The data storage unit is basically a database that also runs in the PC. The system can operate in two different modes: measuring and emulating. Both operation modes are driven by the microcontroller.

In the measuring mode, the photovoltaic modules and generators are connected in parallel to the device. A digital voltage control loop is then programmed in the microcontroller to make the photovoltaic generators completely track their *I-V* characteristic curves. This control loop acts as an outer loop that provides the reference for the inner current loop. The common voltage and currents of the modules and generators are continuously measured and corresponding characteristic curves are then stored in the database so they can both be analysed later and used for the emulating mode. In this way, the different configurations that could have been implemented with the measured photovoltaic generators can be analysed in terms of performance, efficiency, maximum available energy, etc. The PC can also be used for real-time monitoring of the *I-V* characteristic curves.

In the emulating mode, the inverter to be tested is connected to the converter and the microcontroller generates the current reference from the desired current/voltage pattern, which is obtained from the previously measured *I-V* characteristic curves. Thus, the device behaves as a real-time emulator of any photovoltaic generator whose electrical behaviour has been measured previously during the measuring mode. The system also incorporates the option of directly programming other characteristic curves on the microcontroller so that performance and efficiency studies of photovoltaic inverters and MPPT algorithms can be reliably and accurately carried out.

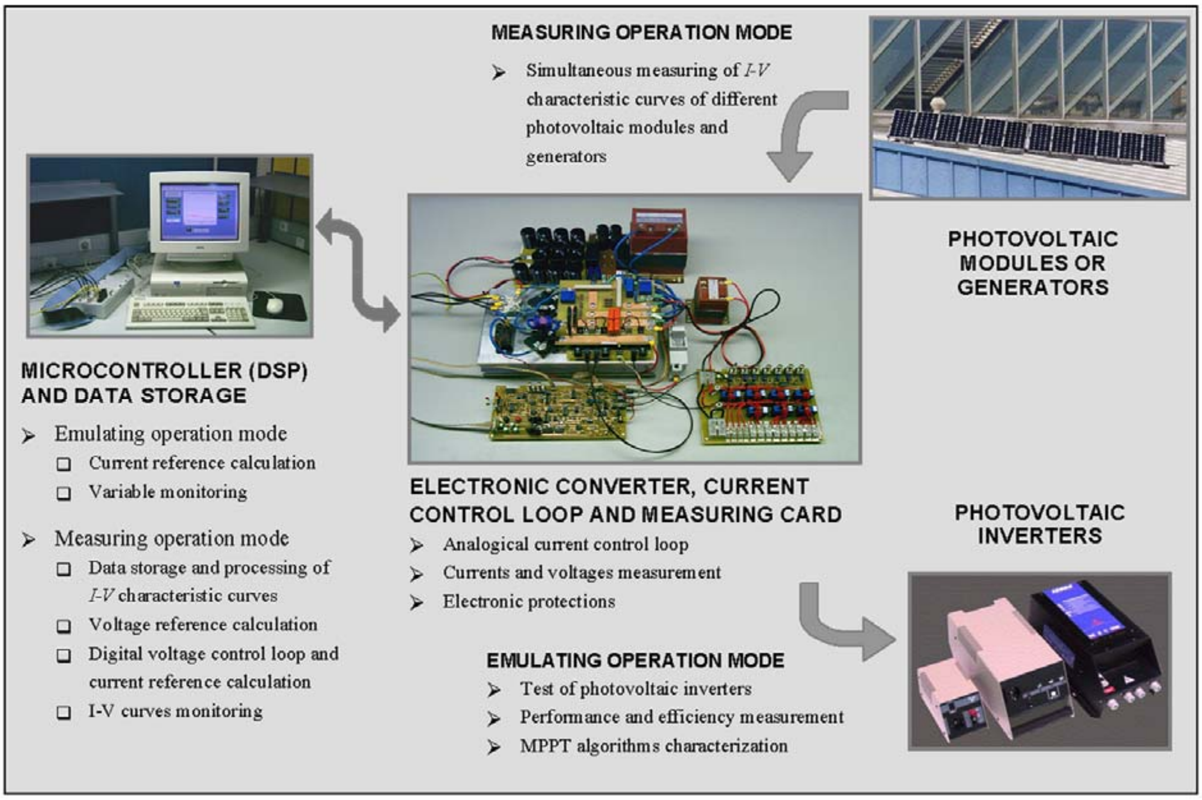

Fig. 1. Proposed measuring/emulating device for the characterization of photovoltaic systems

III. THE ELECTRONIC CONVERTER AND ITS CURRENT AND VOLTAGE CONTROL LOOPS

Fig. 2 shows the scheme of the converter, which consists of a diode bridge, a bi-directional dc-dc converter, an output filter and an energy dissipation circuit. The dc-dc converter is made up of two Insulated Gate Bipolar Transistors (IGBT, T_1 and T_2), two diodes (D_1 and D_2) and an output inductor (L). The output filter, which consists of the capacitors C_{f1} and C_{f2}, the inductor L_f and the resistance R_f, allows short- and open-circuit operation. It is designed to attenuate switching harmonics while damping resonant modes and minimizing losses [10]. The energy dissipation circuit consists of an IGBT (T_3), a free-wheeling diode (D_3) and a dissipation resistance (R), and activates only in the measuring mode.

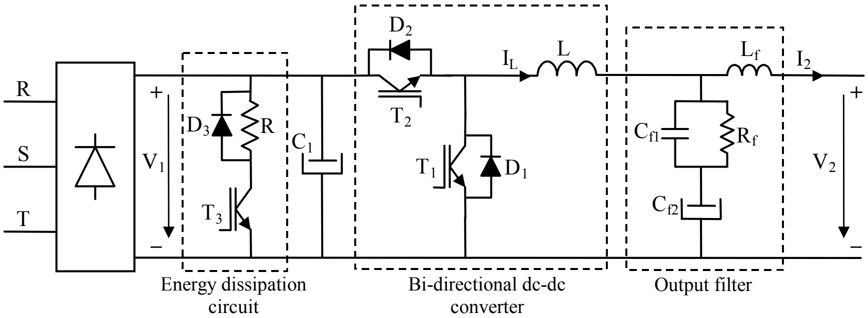

Fig. 2. Scheme of the electronic converter

In the *emulating mode*, the converter works as a buck converter supplied by the rectified ac voltage. In this situation, the energy flows from the ac source to the photovoltaic inverter that is connected at the output of the converter. In order to make the converter emulate the behaviour of a photovoltaic generator, the microcontroller generates the proper current reference for the current control loop from the measurement of the output voltage and the *I-V* characteristic curves stored in the database.

The current I_L through the inductor L is controlled by means of the variable-hysteresis control loop shown in Fig. 3, where D is the duty cycle. This control loop allows the short-circuit operation that is required to both measure and emulate the photovoltaic generators. The output filter hardly affects the dynamics of the current control loop, as it is designed to filter switching harmonics whose frequencies are higher than that of the current loop.

The variable-hysteresis control loop of Fig. 3 achieves constant switching frequency operation by means of tuning the hysteresis width (ΔI) as a function of the duty cycle of switch T_2 (D). The hysteresis width is, in fact, the current ripple. The necessary limitation of this ripple will produce variable-frequency behaviour at low and high duty cycles. The minimum and maximum values for the current ripple, together with the desired value of the constant switching frequency (f_s), define the size of the inductor L, by means of the following well-known expression, where V_2 is the output voltage:

$$\Delta I = V_2 \frac{1-D}{L\, f_s} \tag{1}$$

In the *measuring mode*, the converter works as a boost converter supplied by the photovoltaic modules and generators, which are connected in parallel at the output of the converter. The energy of the generators dissipates in the dissipation circuit. In this mode, the converter makes the photovoltaic modules and generators completely track their *I-V* characteristic curves along the voltage axis. Due to the lower slope, this option achieves more accurate results than tracking the curve along the current axis.

The control loop of Fig. 4 has been designed to control the output voltage of the converter from the open- to the short-circuit condition. This control loop is digitally implemented on the microcontroller and acts as an outer loop for the inductor control loop. The controller is a proportional-integral controller (PI) that includes a feed-forward compensation of the output current I_2 and generates the reference I_{Lref} for the current loop. Given the higher dynamics of the current control loop, it can be considered as a unity transfer function, and then the plant to be controlled consists of the output filter, once the small inductance L_f is neglected. Thanks to the fast dynamics of the proposed system loops, it can emulate in real time the electrical behaviour of photovoltaic generators.

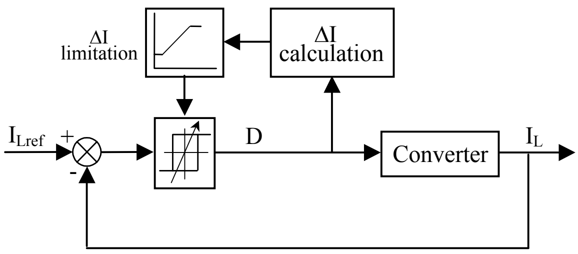

Fig. 3. Variable-hysteresis current control loop

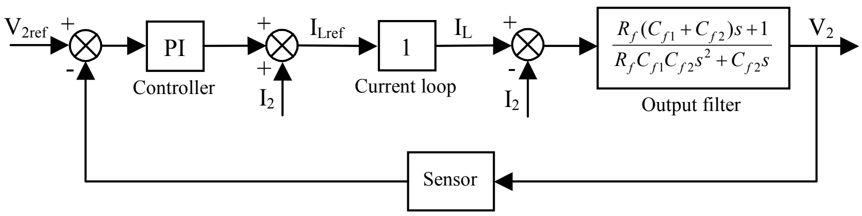

Fig. 4. Voltage outer control loop

IV. EXPERIMENTAL RESULTS

A 15kW prototype has been designed to validate the proposed system. The physical implementation was shown in Fig. 1. The prototype can measure three times per second the characteristic curves of up to seven photovoltaic modules or generators and emulate the electrical behaviour of photovoltaic generators up to

500V and 30A. A SKB 30/08 is used for the diode bridge, a SKM50GB123D for the dc-dc converter and a SKM50GAL123D for the dissipation circuit, all from Semikron. The three-phase ac voltage is 380V. The desired constant switching frequency is 10kHz. L is 4.5mH to limit the ripple to 3A, which appears at a duty cycle D of 0.5. A minimum ripple of 1.22A is set in order to limit the switching frequency during transient conditions to 25kHz. C_1, C_{f1} and C_{f2} are 2.35mF, 110µF and 235µF, respectively, R_f is 3Ω, L_f is 100µH and R is 15Ω. The microcontroller is a dSPACE DS1104 DSP, and a database mySQL is used. The current control loop is implemented on an analog board, together with electronic protections. The output voltage control loop is implemented in the DSP and has a phase margin of 60º and a cut-off frequency of 300Hz. Finally, LEM LA 55-P current and LEM LV 25-P voltage sensors are used in the measuring board.

Fig. 5 presents the experimental results for the variable-hysteresis control loop. The hysteresis width, and thus the current ripple, is modified between the maximum and minimum limits to achieve a constant frequency operation when the output voltage, and thus the duty cycle, increases.

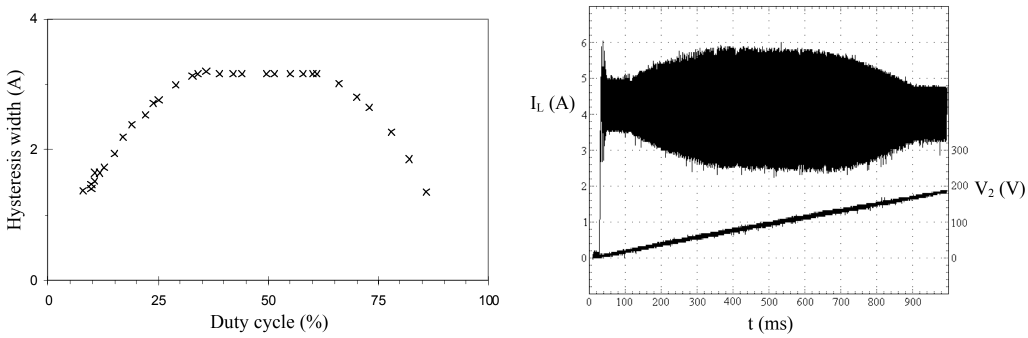

Fig. 5. Experimental results of the variable-hysteresis current control loop

The experimental results shown in Figures 6 to 9 focus on the capability of the proposed device to study and analyse configurations for a photovoltaic system. It consists of six photovoltaic generators mounted together on the same roof. Their *I-V* characteristic curves are continuously measured three times per second during a whole day. Each generator consists of four commercial photovoltaic modules connected in series. The 24 modules are identical. With standard conditions (irradiance of 1000W/m^2, AM1.5G solar spectrum and 25ºC), they have a peak power of 85W, a short-circuit current of 5A, an open-circuit voltage of 22.1V, and current and voltage at maximum power of 4.72A and 18V. That translates to a peak power of 340W, a short-circuit current of 5A, an open-circuit voltage of 88.4V, and a current and voltage at maximum power of 4.72A and 72V for each generator. The total peak power of the generators is 2.04kW.

As an example of the device's measuring capability, Fig. 6, shows the measured curves evolution of one of the generators from 18.5h to 18.85h. This period of the day is quite representative as it coincides with nightfall, a moment in which, due to a nearby building, a progressive shading affects the modules. Another example of the measuring capability of the device is given in Fig. 7. The first graph shows the evolution of the short-circuit currents of the six generators for the whole day, while the second one magnifies an interesting period of time. This period corresponds to the moment in which a cloud passes slowly over the generators. As is shown in the second graph, the curves of the generators progressively suffer a sudden shading as the cloud passes.

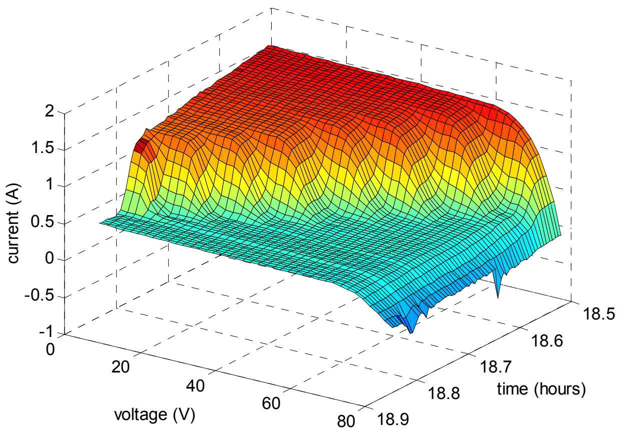

Fig. 6. Measuring results of one of the generators: I-V characteristic curves from 18.5h to 18.85h

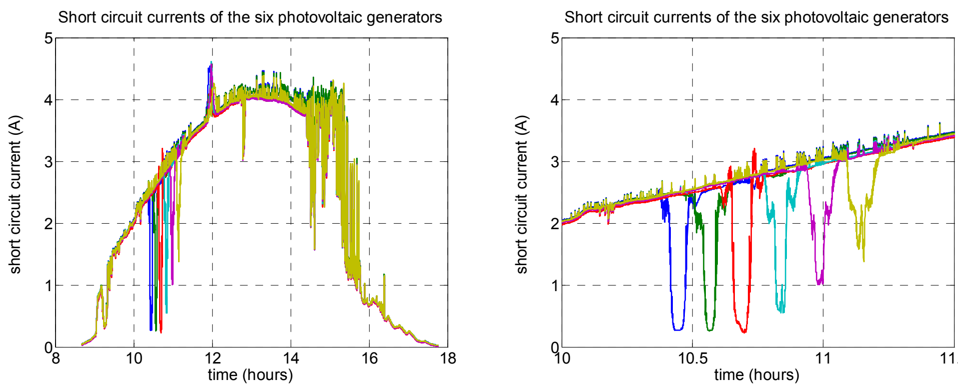

Fig. 7. Short circuit currents evolution of the six generators: whole day (left) and enlarged area (right)

Once the evolution of the curves of the six generators is measured during the whole day, different configurations for the interconnection of the generators can be analysed in order to determine which one of them could have obtained the maximum energy during this day. As a working example, the three configurations of Fig. 8 are analysed. Configuration A consists of two parallel groups of three generators, B consists of three parallel groups of two generators, and C is the same as A but the medium points of both branches are now interconnected. From the measured data, the corresponding characteristic curves of each configuration are calculated for the whole day. Next, the "power efficiency" of each configuration is obtained at each moment as the maximum power of the configuration divided by the sum of the maximum powers of each independent generator. This calculated efficiency shows the performance losses due to the type of configuration. Results are shown in Fig. 9. The power efficiency of the configurations is close to the maximum when the measured curves of the generators are similar, but it decreases when they evolve in a different way, as it happens around 10.5h. At this moment, as it was shown in Fig. 7, a cloud passes slowly over the generators and the characteristic curves exhibit a delayed evolution that is detrimental to the efficiency of the configurations. Finally, the "energy efficiency" can be calculated for the whole day as the maximum energy that each configuration could have delivered divided by the sum of the maximum energies of each independent generator. The efficiency achieved is 97.2% for configuration A, 96.8% for B, and 96.2% for C. Due to the similarity of the photovoltaic modules and their behaviour, the differences in efficiency for the test day are not significant. The configurations should now be analysed for other days and weather conditions, and then an optimal configuration for the six generators could be achieved.

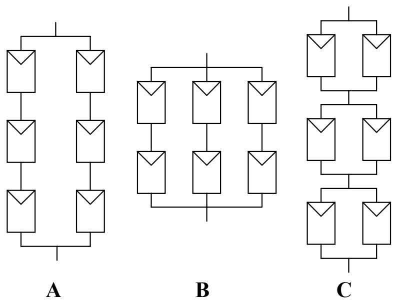

Fig. 8. Analysed configurations for the six photovoltaic generators

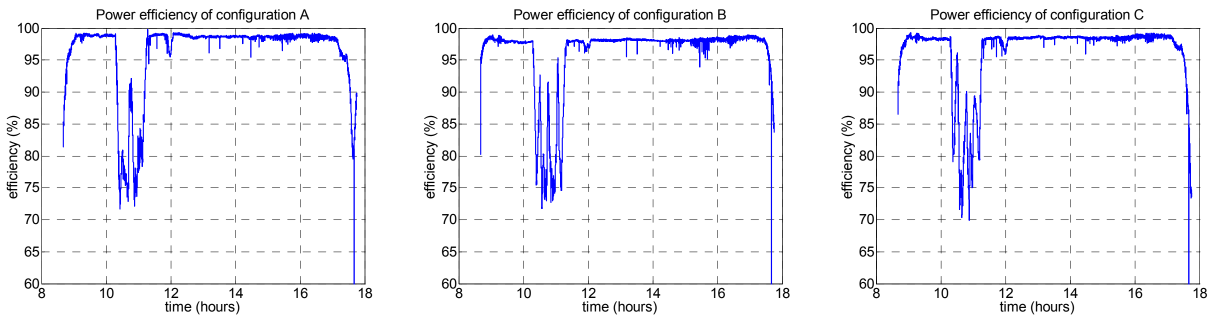

Fig. 9. Power efficiency results for the configurations

V. CONCLUSIONS

A device is proposed in this paper to characterize photovoltaic modules and inverters and optimize their configuration. The system has two operation modes: measuring and emulating. In the first mode, the system systematically measures the evolution of the *I-V* characteristic curves of photovoltaic modules and generators. The stored data can then be used to carry out analyses to optimize configurations of the generators. In the second mode, the system emulates the behaviour of photovoltaic generators with the previously measured curves. Different inverters can then be tested with the same *I-V* characteristic curves. With the proposed device it is possible to analyse aspects such as performance, efficiency, optimal series/parallel configuration, etc., of photovoltaic systems under real atmospheric conditions.

The system consists of a dc-dc converter, a microcontroller and a data storage unit. The dc-dc converter operates as a buck or boost converter, depending on the operation mode of the system. In order to achieve a short-circuit operation, a variable-hysteresis control loop is designed to control the current at the output inductor. The current reference is provided by the microcontroller, which also controls the data storage. In the measuring mode, a digital voltage outer control loop provides the proper current reference to track the complete *I-V* characteristic curves of the modules and generators. In the emulating mode, the current reference is obtained from the stored characteristic curves.

In order to validate the proposed device, a 15kW prototype has been physically implemented. The prototype can measure three times per second the characteristic curves of up to seven different modules or generators, and emulate their behaviour up to 500V and 30A. Experimental results focused on the measuring operation mode show how the proposed device can help to investigate optimal configurations for photovoltaic systems.

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