Experimental Implementation of an Electronic Load for Global Maximum Power Point Tracking

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***Abstract*— This work deals with the partial shading effect in the power curve of a PV solar array. Using a semiconductor device – MOSFET or IGBT – as electronic load added to a buck converter, it is possible to scan the power curve of a photovoltaic string and therefore empirically determine its optimum voltage, even in presence of partial shading. The aim of this paper is to give experimental details regarding the laboratory implementation of a proof-of-concept prototype meant to detect the Global Maximum Power Point. Three cases are presented that consider the partial shading effect of a PV string, with disturbances of different sizes and shapes. In the last part a novel exciting signal is presented, which allows to reduce the scanning time of the power curve. The experimental results illustrate the performance of the implemented circuit.**

Keywords— Global Maximum Power Point, MPPT, Partial Shading.

I. Introduction

The increasingly growing utilization of Photo-Voltaic (PV) energy is mainly due to the costs diminution of the PV modules and the power converters. On the other hand, latest governmental policies encourage the production of clean energy, which considerably contributes to the use of PV sources [1]. In this scenario, the increasing concern for clean and sustainable energy, impulses initiatives that promote the use of renewable energy sources integrated to electrical grids. Actually, in the global context, solar photovoltaic plants have registered record capacity additions in the last years [2].

Generally, PV systems can be classified into On-Grid and Off-Grid, with an installed capacity of 99% and 1%, respectively. These data confirm the major tendency of injecting the PV energy to the electricity grid. Nevertheless, there are still several problems regarding these PV systems, which pose important challenges in order to increase the capacity factor and to improve the power quality of the current power plants [3].

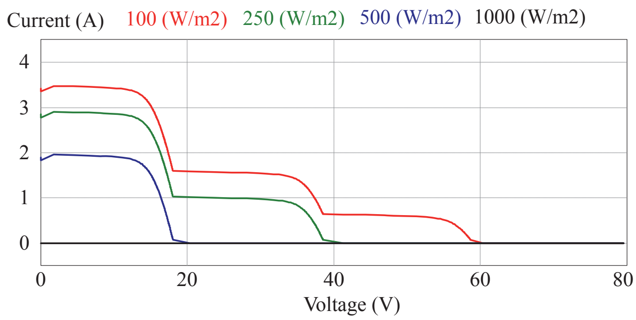

Fig. 1 By-pass diode current, with different solar radiation.

One of the major issues related with the capacity factor is the partial shading effect, since it produces a distortion in the characteristic Power-Voltage curve of the PV modules [4]. This is because the PV panels are constructed with by-pass diodes, which are connected in parallel to the PV cells, aimed to avoid a hot spot in the shadowed modules. In fact, when the PV module is under the partial shading effect, the current flows through the by-pass diodes as shown in Fig. 1, where a string of 4 PV modules is considered. It is observed that the diodes currents generate a mismatch in the PV string, leading to an uncharacteristic power curve.

Fig. 2 illustrates the partial shading effect in a PV string. Actually, Fig. 2 (a) shows the series connection of three

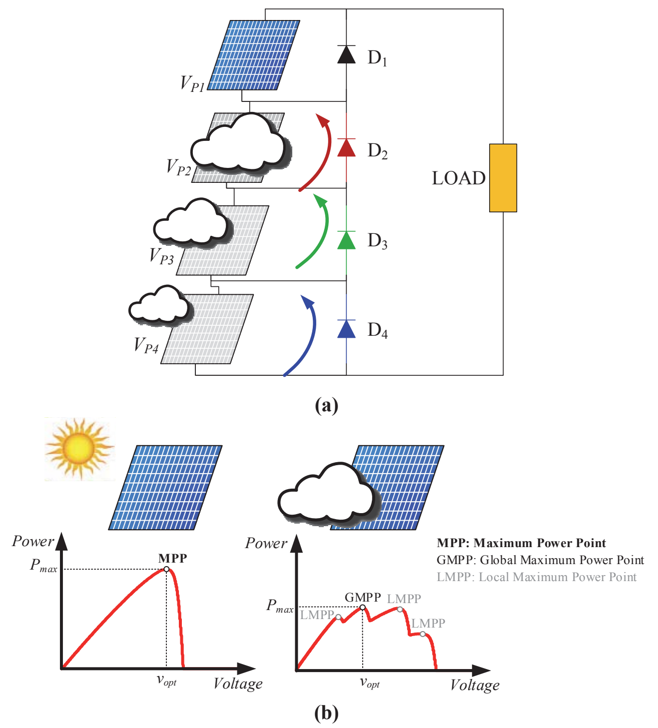

Fig. 2 Partial shading effect in a PV string
(a) Conduction of the by-pass diode, **(b)** Power-Voltage curves of a solar array.

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modules, where the middle one is shadowed. Clearly, the parallel diode D_2 by-passes [5] the affected cell and the solar string delivers the power from the remaining two bright panels. Due to these by-pass diodes, partial shading causes a distortion in the power curve, which can produce multiple local optimum points, as depicted in Fig. 2 (b).

In such condition, where local and global optimums exist in the power-voltage curve of the solar array, classical Maximum Power Point Tracking (MPPT) methods, such as Perturb and Observe (P&O) and Incremental Conductance [6][7] are not capable to determine whether the maximum point is the actual global optimum. Therefore, the voltage that maximizes the power is not ensured if the solar array does not work in the right operating point.

This work presents the implementation details of a modified buck converter, where an electronic load stage is included in order to scan the power curve of a PV array. This part is aimed to obtain the Global Maximum Power Point (GMPP) [8] in order to maximize the photovoltaic power extracted from the PV modules. Moreover, further improvement is proposed in the exciting waveform of the electronic load in order to accelerate the power sweep, as will be explained in Section V.

II. Experimental Driver Circuit for Tests

The Integrated Circuit (IC) 555 and some discrete components are used to generate a saw-tooth wave, as shown in the schematic of Fig. 3. This triangular output is connected to the MOSFET gate, which acts as an electronic load to the solar array. Then, the MOSFET device will operate in its three operating regions: saturation, linear and cut-off [9][10].

The scanning results are presented in Fig. 4, which illustrates the load sweep for a 50 Wp solar module. The scan starts with the open circuit voltage V_{oc} – where the PV current is zero – and finishs in short circuit, when the current reaches its maximum value, I_{sc}. The waveforms shown in Fig. 4 also include the power

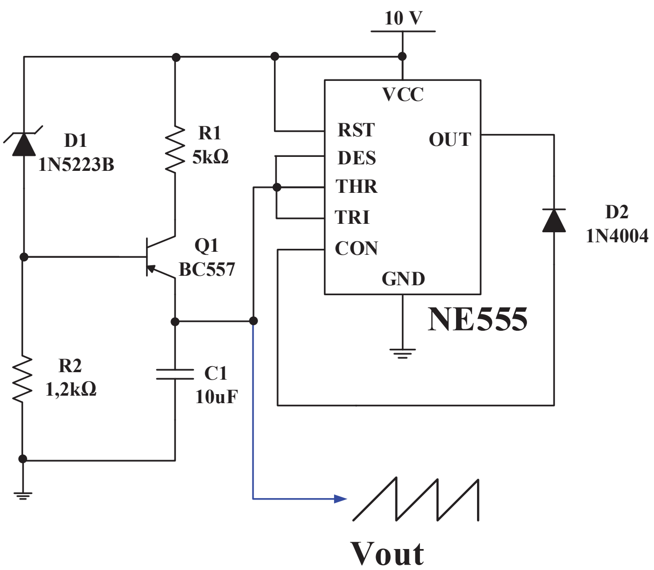

Fig. 3 Circuit schematic for triangular waveform generation.

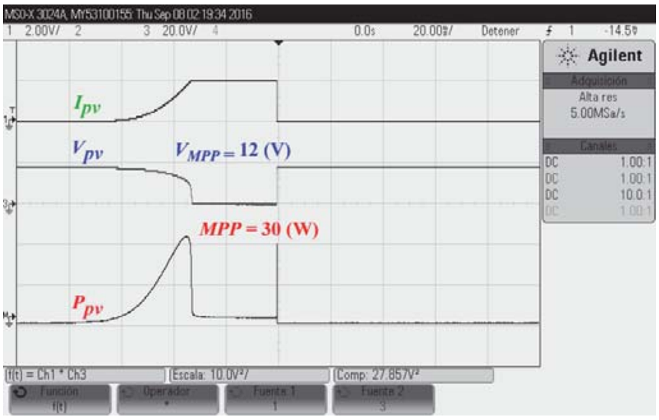

Fig. 4 Experimental scan process of a 50 Wp module.

of the module, which was internally computed in the oscilloscope. As can be seen in the results of Fig. 4, the obtained power curve shows a typical response of a non-shaded panel, as there is only one maximum equal to 30 W, which is obtained with a voltage of V_{mpp} = 12 V. Although the nominal power of the solar module is 50 Wp, the maximum power is only 30 W due to the reduced radiation conditions available during the test. As can be seen from the x-axis scale of 20 ms/div, the time taken by this preliminar scan process is less than 60 ms, which can be considerably acelerated, as will be explained in the forthcoming sections.

At this point, it is important to highlight that software-based methods are an alternative to the presented approach [11][12]; nevertheless, hardware solutions achieve faster responses reaching the GMPP, have low complexity and are easy to implement [13]. In fact, as shown in Fig. 4, the scan process can be performed in a few milliseconds (depending on the analog-to-digital conversion and the processing time of the microcontroller), which is negligible compared with the dynamic of the partial shading sources such as clouds, birds, trees, etc.

III. Global Maximum Power Point Algorithm

In order to perform the electronic load sweep and therefore to obtain the power curve of the PV array, a simple buck converter was implemented as a proof-of-concept prototype, integrating a MOSFET device, which gate is driven by the circuit of Fig. 3.

The main goal of the laboratory set-up is to achieve the joint operation of the curve scanning and a digital PI controller for the buck converter, in order to operate in the GMPP. The schematic of the modified buck converter is shown in Fig. 5, where the value of the main components are depicted. Classic design criteria can be used to select the converter components, as detailed in [14].

As depicted in Fig. 5, a diode (Ds) is connected between the MOSFET (electronic load) and the buck converter, which is used to disconnect the PV array during the scanning time. The complete operation of the topology, is described in the following.

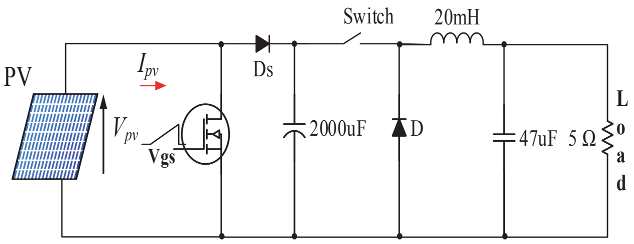

Fig. 5 Modified buck converter for scanning the PV power curve.

The proposed algorithm to operate the PV panels in their GMPP is sequential, starting with the power curve scan, following with the determination of the GMPP and finishing with the voltage control of the buck converter that allows the maximization of the power extracted from the PV panels. Each stage of the implemented algorithm is depicted in the forthcoming subsections.

A. Power Curve Scan

A triangular exciting waveform is applied to the MOSFET (or IGBT) gate. Then, the voltage V_{pv} and current I_{pv} are obtained for the whole sweep made with the circuit of Fig. 3. The scan velocity must be selected according with the speed of the Analog-to-Digital conversion in order to obtain a representative number of point of the power curve. In fact, taking advantage of the high speed state-of-the-art microcontrollers, the exciting waveform of the scan circuit can be optimized.

B. GMPP Selection

This part of the algorithm consists in the iterative comparison of the maximum power as deeply explained in [15] and shown in Fig. 6. The voltage and current are acquired with the ADC and the instant power is calculated, if this value is higher than the stored maximum power, the optimal conditions are saved. This is iteratively repeated in order to trace the whole curve.

C. PI Control

A digital PI controller is implemented, which reference is the optimal voltage found in the previous stage V_{gmpp}. The output of the PI controller varies the duty cycle of a PWM signal of 10 kHz that finally controls the buck converter. The implemented control is shown in Fig. 7.

It is possible to observe in Fig. 7, that the error has a negative gain. This can be explained considering that the system output is the PV voltage V_{pv}, which is the input of the buck converter. Then, as the duty cycle increases, the input voltage of the buck converter decreases, when the output voltage is fixed, e.g. when the converter is connected to a battery. Therefore, the gain of the PI controller must be negative in order to achieve the expected results with negative feedback.

IV. Experimental Results

Three different tests were performed on a low-power laboratory prototype in order to evaluate the performance of the whole GMPP algorithm presented in this work. These tests were executed under ambient conditions with variable radiation. Another important issue to mention regarding the tests, is that

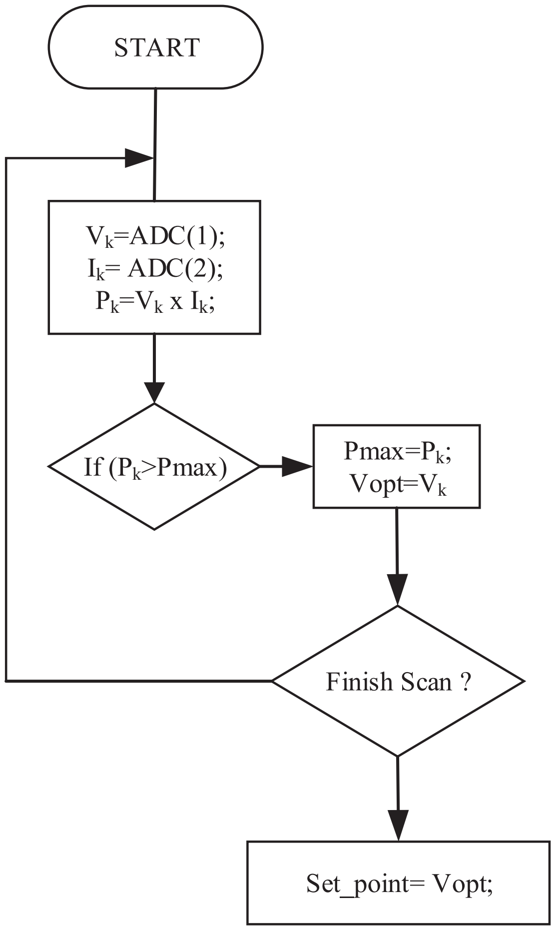

Fig. 6 GMPP Algorithm.

they were performed during early spring, which implies low radiation.

A. Case 1

A 50 Wp PV array is exposed to sun light (without shadow) and the characteristic curves are plotted in Fig. 8. The algorithm determines the operating point that maximizes the power. This value is sent to the control stage that is in charge to track the reference.

As shown in Fig. 8, the algorithm successfully track the optimal voltage once the load sweep is over. As the PV array is evenly illuminated, there is only one optimum. In this case, the maximum power reaches the 22.5 W, which is obtained considering that the voltage in the Maximum Power Point (MPP) is V_{mpp} = 12 V.

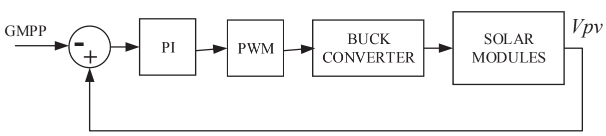

Fig. 7 Implemented Control Block.

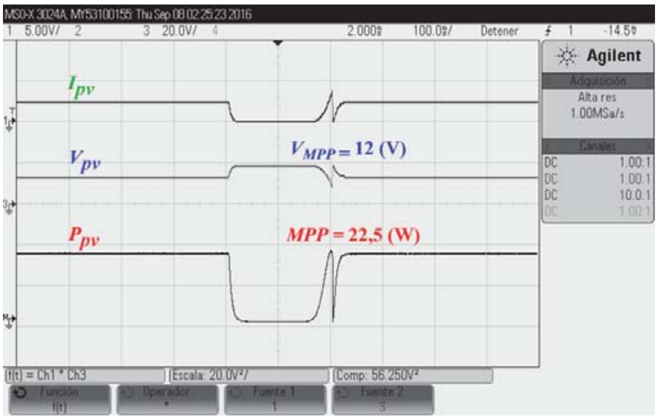

Fig. 8 50Wp PV array without shadow, case 1.

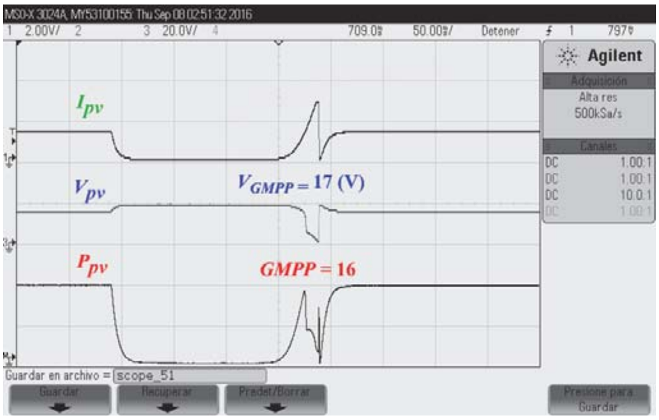

Fig. 9 50Wp PV array with partial shading, case 2.

B. Case 2

A small shadow is applied to the PV array, which distorts the power curve. As can be seen in Fig. 9, a small local optimum is produced due to the operation of the bypass diodes. This local optimum is quite different from the GMPP. Without the load sweep, it could be possible that typical MPPT algorithms may be trapped in this local optimum, leading to a considerable reduction of power.

In this case, the GMMP is located at V_{mpp} = 17 V, achieving a PV power of 16 W. On the other hand, the local optimum is obtained in V_{pv} = 6 V, with a power of 9 W. These mismatch could lead to a 44% of potential power losses, if traditional MPPT algorithms are used, as depicted in TABLE I, where a summary of the eventual losses due to false maximums is presented.

Also, it is possible to observe from Fig. 9 that the modified buck converter determines the global point that maximizes the power and then, the reference is followed by the controller.

C. Case 3

This case is similar to the previous one; however, the GMPP power is 8.25W and in the local optimum, the power is 6 W, giving a difference between the global and local optimums of 2.25 W. Regarding the operating voltages the global optimum is achieved at V_{mpp} = 11V and the local optimum at V_{pv} = 5V. Therefore, a wrong MPPT will imply a power loss of 28 %, as shown in TABLE I. The waveforms obtained in the laboratory prototype with the load sweep are shown in Fig. 10, where the voltage, current and power of the PV module are illustrated.

TABLE I LOCAL AND GLOBAL OPTIMUMS FOR CASES 2 & 3

	Voltage (V)	Power (W)	Power Losses (%)
Case 2	17	16	0 %
	6	9	44 %
Case 3	11	8.25	0%
	5	6	28%

V. NEW OPTIMIZED EXCITING WAVEFORM

Taking advantage of the fast response of the state-of-the-art MOSFET (or IGBT) devices used to scan the power curve of a PV source, it is possible to optimize the saw-tooth exciting waveform presented in Fig. 3. In fact, the speed of the power scan can be performed quite faster than software and capacitive methods, such as the one presented in [16], which has a considerable slower dynamic response because it performs the full charge of a capacitor and then its discharge must be done through the load resistor.

The proposed signal consist in a modified saw-tooth waveform, which is designed to perform the scanning process in 2 ms. The shape of the proposed exciting waveform improves the activation voltage of the MOSFET, considering the nonlinear behavior of this semiconductor device. The proposed exciting waveform is shown in Fig. 11, where it can be seen that the modified saw-tooth wave starts from 3 V approximately. This value is selected equal to the MOSFET threshold, where the device starts to conduct. Therefore, the PV module goes from the open circuit voltage to the short circuit condition. The final value of the exciting waveform is equal to 5V, where the semiconductor device is fully settled in its saturation region, and therefore the short circuit current of the PV panels is achieved.

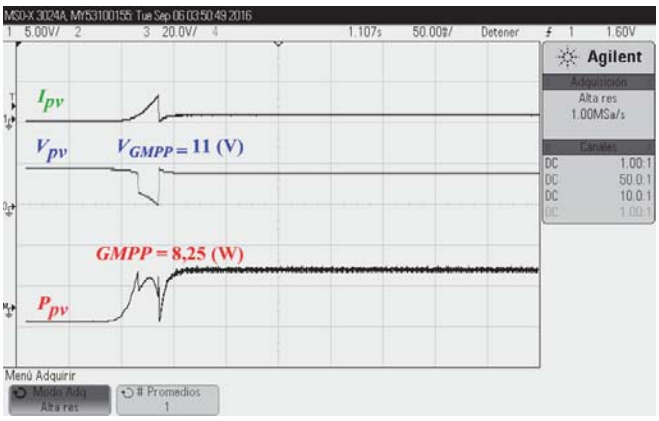

Fig. 10 50Wp PV array with partial shading, case 3.

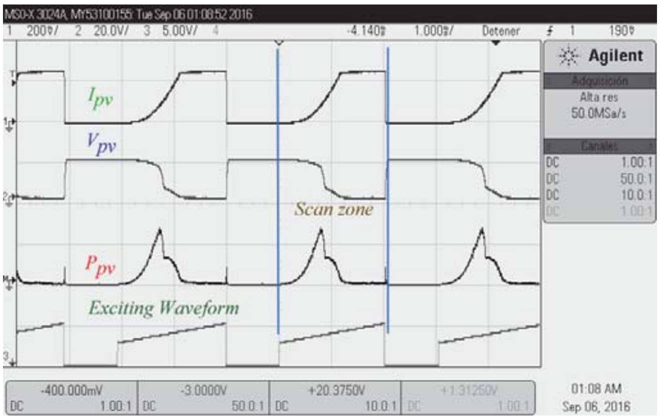

Fig. 11 Scan PV power with a modified exciting waveform.

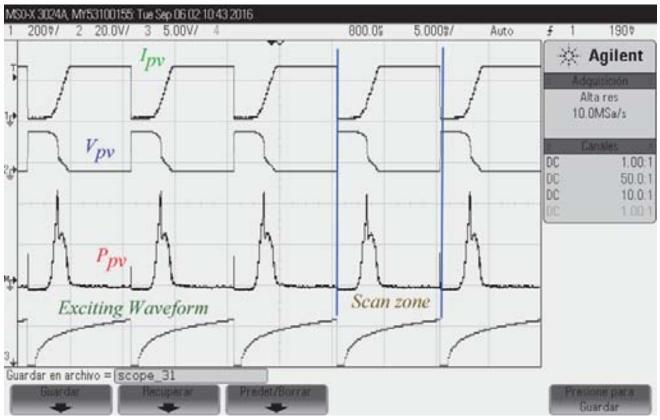

Fig. 12 Scan PV power with a logarithmic exciting waveform.

A possible variation of the presented waveform is shown in Fig. 12, where a logarithmic signal is applied to the MOSFET gate. The advantage of this variant lies in the fastest scan process with a simple mathematical operation. In fact, just changing the exciting waveform of Fig. 11, by applying the logarithmic function, the scan process is reduced to less than 1 ms, as can be appreciated in Fig. 12.

Both signals are generated using the 8-bit digital-to-analog converter DAC0808 [17], which is connected to a voltage follower to avoid unwanted distortions. The schematic of the proposed circuit is presented in Fig. 13, where some details were omitted for the sake of simplicity.

It is worth mentioning that the energy during the scan process is majorly dissipated in the semiconductor device and only a small amount is burned in the internal series and shunt resistors of the PV module. Taking this fact into consideration, the maximum allowable PV power is 100W, because the semiconductor device used as electronic load has a dissipation power of 150 W at 25°C. In fact, it was empirically corroborated that lower rated power semiconductors reached operating temperatures beyond their allowable limits. In this sense, all tests presented in this work were performed with a 50 Wp PV panel, with an open circuit voltage of 22V and a short circuit current of 3.2 A.

In order to handle a higher amount of power, it is possible to connect several IGBT in series and/or parallel, so the voltage and/or current of the PV module can be divided into several semiconductor devices.

In this work, the semiconductor devices used for the power scan are the IRFP048N MOSFET [18] and the G4PC40U IGBT [19]. In both cases the behavior of the power scan process is the same.

The image shown in Fig. 14 that illustrates the circuit for the power scan, which implements the schematic of Fig. 13. The digital inputs for the D/A converter used to generate the modified exciting waveform were provided for the TMS320F28335 DSP board. For the electronic load, the G4PC40U IGBT was used, which includes a small heat sink to avoid over-temperatures due to energy dissipation, as shown in Fig. 14.

VI. Conclusions

This work is focused on the implementation details and the experimental results of an electronic load for obtaining the GMPP in PV arrays under the partial shading effect. The experimental set-up was built in order to illustrate the distortion of the power curve when a shadow covers part of the solar array. In fact, three cases were presented, where important power losses could be produced if no proper GMPP searching is performed. A simple laboratory prototype demonstrates the feasibility of integrating the electronic load with a buck converter. Also, with a simple modification on the exciting waveform, a considerable reduction of the scan time is achieved, which is desirable in order to avoid interfering with the normal operation of the converter, considering that it must be disconnected to perform the power scan. Finally, it is important to highlight that the scan speed is limited by the computing capabilities of the microprocessor device and the dynamic response of the PV modules.

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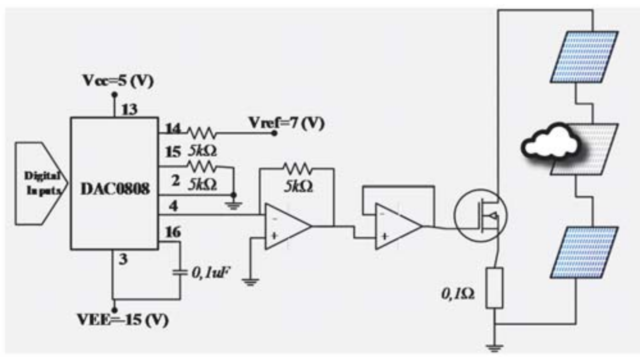

Fig. 13 Circuit diagram for the generation of the exciting signal.

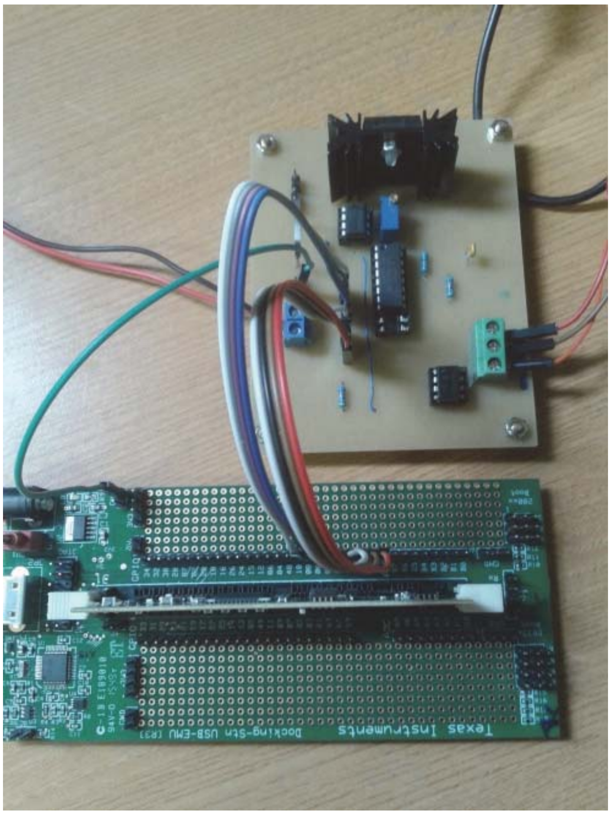

Fig. 14 Prototype for the PV scan.

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