

System-on-Chip for Real-Time Satellite Photovoltaic Curves Telemetry

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Abstract—This paper presents a *System-on-Chip* design for real-time satellites photovoltaic curves telemetry. In these applications, the limitation of memory and communication bandwidth makes quite difficult to store and to transmit the whole characteristic current-voltage (I - V) curve of any solar section in real-time. The proposed solution is based on the real-time calculation of the equivalent single-diode model of the solar section. The single-diode model fits accurately the behavior of any solar panel, so once the parameters are calculated, saved, and transmitted, at any working conditions, that specific curve could be later reproduced. The system is based on a *LEON3* 32-bit microprocessor core implemented in a *Field Programmable Gate Array*. The *LEON* microprocessors were originally designed by the *European Space Agency, Paris, France*, to be used in space projects where high reliability is required. In addition, in order to design the system as simple and reliable as possible, from all the methods available in the literature to extract the five parameters of the equivalent model, the *Oblique Asymptote Method* has been chosen for its simplicity and precision. Finally, some experimental results are presented to demonstrate the accuracy of the final system.

Index Terms—*LEON* microprocessor, oblique asymptote (OA) method, photovoltaic energy, single-diode model, system-on-chip.

I. INTRODUCTION

IN AEROSPACE applications, solar arrays are constantly monitored to compare the prelaunch predicted characteristics with on-orbit real ones and to monitor the degradation of the solar cells over the operational life of the satellite. These data are crucial to know the real behavior as well as for the design of future mission's solar arrays. In the literature, some examples

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of space missions solar array monitoring can be found: Mars Express and Venus Express [1], MITA mission [2], SPOT family and Envisat [3], PROBA-2 [4], Proteus multimission [5], Smart-1 Spacecraft [6], and Mars Orbiter Mission [7]. In some cases, like on Mars Express, this telemetry was crucial to find anomalies during the mission and to implement corrective methods. Nevertheless, solar array electrical telemetry is limited to the measurement of only one point, the current injected at the main bus voltage [7]. Although this is a valuable information, and it is used to estimate the solar cells degradation, this information is not enough to exactly know how the solar cells have been effected by the space environment during the mission lifetime.

A more complete way to monitor the performance of the solar array is to measure the whole current-voltage (I - V) curve of a solar cell. This curve provides much more information than the single point measurement does (short circuit current, open circuit (OC) voltage, maximum power point (MPP), parasitic series and shunt resistances, fill factor). However, the spacecraft memory and communication bandwidth limitations complicate the storage or transmission of the whole I - V curve in real-time and this technique has been only used in the *International Space Station* as an experiment to compare in-flight and preflight measurements of three junction and four junction inverted metamorphic solar cells [8].

In this paper, a solution to measure the full I - V curve of a pilot cell in a satellite is presented. The method is based in measuring the whole I - V curve of the pilot cell using as a load a transistor working in linear region [8] and reducing the data to be transmitted, modeling, in real-time, the photovoltaic cell using the well-known single-diode model.

The next sections of the paper are structured as follows. In Section II, the single-diode model and some algorithms used to calculate its parameters are briefly explained. In Section III, the theory of the *Oblique Asymptote (OA)* method is presented. Section IV presents the implementation of the *OA* method in the *LEON 3* processor and analog circuit used to sweep the curve and to acquire the data. In Section V, experimental results are presented and finally, Section VI summarizes and concludes the study.

II. SOLAR CELL SINGLE-DIODE MODEL

This model is based on the equivalent electrical circuit of a solar cell depicted in Fig. 1, and at a given working conditions,

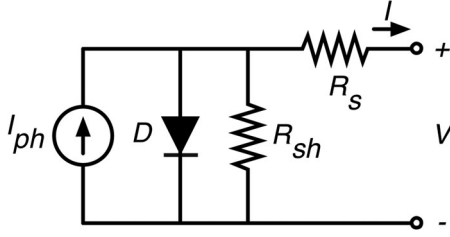


Fig. 1. Single-diode model equivalent electrical circuit.

has a current-voltage dependence given as

$$I = I_{ph} - I_{sat} \left(e^{\frac{V+IR_s}{nV_T}} - 1 \right) - \frac{V + IR_s}{R_{sh}}. \quad (1)$$

The curve generated by this model fits the real I - V characteristic of most of the photovoltaic sources with high level of accuracy [9]–[12]. As can be seen, the model equation depends on five parameters: the photocurrent, I_{ph} , the diode saturation current, I_{sat} , the diode ideality factor multiplied by the thermal voltage, nV_T , the series resistance, R_s , and the shunt resistance, R_{sh} . If these five parameters are calculated for any particular working conditions, i.e., any irradiance, temperature, and ageing conditions, then, only saving or transmitting these five data, the whole I - V curve can be precisely reconstructed using (1).

Many algorithms are proposed in the literature to calculate the parameters of this model. The exact methods [13] try to solve the model numerically, but usually require extensive computation resources and accurate initial guesses to obtain a valid solution using iterative methods. The analytical methods [14]–[19] simplify the extraction of the parameters considering some approximations in the original equation. Nevertheless, these methods also have the drawback that they usually require some information of the I - V curve which can entail some difficulties to be accurately measured in practice [15]. The curve-fitting methods [20]–[23] consist on finding (by solving an optimization problem) the best theoretical curve which fits the real one. The main problem of these fitting techniques is that they require lot of computation and they need strongly initial data seeds near the solution so they can converge. There are also methods that use the nonelementary *Lambert W* function to extract the parameters [24]–[26]. However, the *Lambert W* function it is defined implicitly and, therefore, at least the numerical methods needed to obtain the solutions that provide the *Lambert W* function are also needed to obtain the parameters of the model. There are also solutions with simplified models of three and four parameters [15], [27], [28] that obtain explicitly the corresponding parameters just by using information near the *MPP* of the photovoltaic module. Nevertheless, these models are only valid for some specific working conditions and its accuracy is quite low.

In the authors' opinion, in regard to all the methods mentioned above, a very interesting method for satellite real-time applications with the limited computations resources is the *OA Method* [19]. This method is comparable in precision with the widely used analytical five-point method [9] but with the advantage that the calculations involved in its resolution is simpler than the other. Also, this method only needs to know the short circuit current point (I_{sc}), the slope of the I - V curve at the short circuit point (I'_{sc}) and three different points of the curve to calculate the model parameters. Besides, this method does not need any preset parameter so any change in the photovoltaic module characteristics will be correctly modeled.

III. OA METHOD

For applying the *OA* method (1) is rewritten in a more simplified way (2), which depends on five new parameters,

$$I = A - B (C^V D^I - 1) - EV \quad (2)$$

where

$$A = I_{ph} \frac{R_{sh}}{R_{sh} + R_s}, B = I_{sat} \frac{R_{sh}}{R_{sh} + R_s}, C = e^{\frac{1}{nV_T}}, \quad (3)$$

$$D = e^{\frac{R_s}{nV_T}}, E = \frac{1}{R_{sh} + R_s}.$$

If the new parameters A , B , C , D , and E are obtained, then the original parameters can be also determined by

$$I_{ph} = A \frac{\ln(C)}{\ln(C) - E \ln(D)}, I_{sat} = B \frac{\ln(C)}{\ln(C) - E \ln(D)},$$

$$nV_T = \frac{1}{\ln(C)}, R_s = \frac{\ln(D)}{\ln(C)}, R_{sh} = \left(\frac{1}{E} - \frac{\ln(D)}{\ln(C)} \right). \quad (4)$$

The key elements needed in order to apply this method are: the short circuit current point (I_{sc}), the slope of the I - V curve at the short circuit point (I'_{sc}), and three different points of the curve (I_1, V_1), (I_2, V_2), and (I_3, V_3).

The method is based on considering the approximation $A + B = I_{sc}$ and $E = -I'_{sc}$. In other words, the line $I = I_{sc} + I'_{sc}V$ is assumed to be the *OA* of the single-diode model equation. The other parameters are obtained explicitly as follows: Eq. (5) as shown at the bottom of the page;

$$C = \exp \left(\frac{f(V_2, I_2) - f(V_3, I_3) - (I_2 - I_3) \ln(D)}{V_2 - V_3} \right) \quad (6)$$

$$B = \exp(f(V_1, I_1) - V_1 \ln(C) - I_1 \ln(D)) \quad (7)$$

$$A = I_{sc} - B \quad (8)$$

$$E = -I'_{sc} \quad (9)$$

where

$$f(V, I) = \ln(I_{sc} + I'_{sc}V - I). \quad (10)$$

As can be seen, the calculation needed in this method is quite simple, so it can be easily implemented in a microprocessor.

$$D = \exp \left(\frac{(f(V_1, I_1) - f(V_2, I_2))(V_2 - V_3) - (f(V_2, I_2) - f(V_3, I_3))(V_1 - V_2)}{(I_1 - I_2)(V_2 - V_3) - (I_2 - I_3)(V_1 - V_2)} \right) \quad (5)$$

IV. IMPLEMENTATION OF THE OA METHOD USING LEON3 SYSTEM ON CHIP

For photovoltaic real-time control and monitoring systems, microprocessors, *digital signal processors*, and *field programmable gate arrays (FPGAs)* have been widely used due to their versatility, speed, and processing capability [29]–[32]. Nevertheless, in aerospace application only qualified electronics components can be used so a simple microcontroller cannot be used. The *LEON* family microprocessors were designed by the *European Space Agency* to be used in Space Projects, where high reliability is a main requirement. The *LEON3* processor is a synthesizable *Very High Speed Integrated Circuit Hardware Description Language (VHDL)* model of a 32-bits processor compliant with the *SPARC V8* architecture, highly configurable, and suitable for *System-on-Chip (SoC)* implementation. This microprocessor is distributed as a part of the *Gaisler Research library (GRLIB)* IP open-source library designed by *Aeroflex Gaisler*. *GRLIB* is a library of *VHDL* source codes of industrial property cores for designing a complete *SoC* around the *LEON3* core. Besides, the *LEON3* processor has a fault tolerant version, called *LEON3-FT*, suitable for space environment and multi-processor design (up to 4 CPUs). This version is proposed for critical space applications and it is designed for operation under harsh space environment, including the functionality to detect and correct *single event upset* errors. *Aeroflex* offers the *LEON3-FT* microprocessors in single-chip radiation-tolerant *ASIC* and radiation-tolerant *FPGA* technology.

As the main goal of this paper is not to test the radiation-tolerant functionality of the system, but the capability to be implemented in a *LEON3* microprocessor. The *OA* method has been implemented in a *SoC* based on a *LEON3* 32-bit microprocessor core implemented in a commercial *FPGA (Xilinx Spartan 3 AN)*. Nevertheless, the *SoC* proposed can be implemented without any modifications in a *LEON3-FT* microprocessor version.

The *SoC* have been synthesized, placed, and routed using *Xilinx ISE 14.7* software. The microprocessor requires two independent *serial peripheral interface* controllers to communicate with the *analog-to-digital converter (ADC)* and *digital-to-analog converter (DAC)*. The *ADC* is used to read the current and voltage sensors connected to the pilot cell. The *DAC* is used to generate the reference voltage to change the pilot cell working point. The *ADC* used is a *LTC1407-A* from *Linear Technology* with 14-bits unsigned resolution with two 1.5 Msps simultaneously sampled differential inputs. The *DAC* is a *LTC2624* from *Linear Technology* with 12-bits unsigned resolution. The whole sweep of the *I-V* curve has to be slow (about 15 s), so the voltage and the current have been stabilized before the measurements. So as the sample rate and the *DAC* update rate are not key points in this application, the sample rate used in the *ADC* is 600 ksp/s and the *DAC* is updated at 6-Hz frequency. The final *SoC* designed is shown in Fig. 2 with the *LEON3* core and the different IPs used.

The proposed *SoC* based on the *LEON3* processor requires: an area of 10329 LookUp Tables (LUTs) (87% available LUTs), one embedded multiplier for arithmetic approximations, and

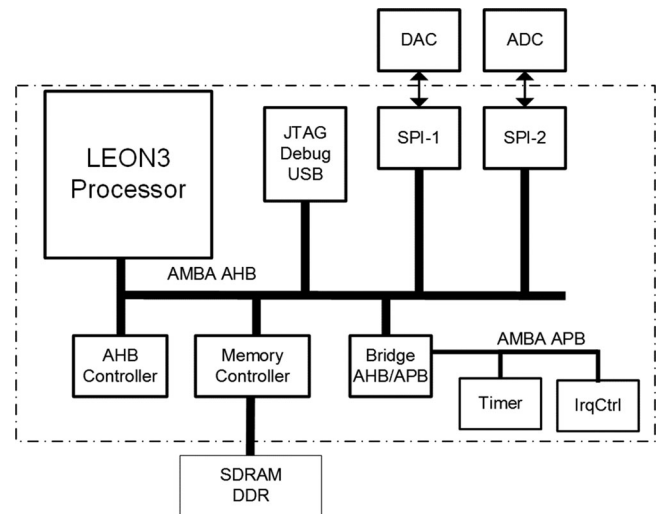


Fig. 2. SoC used to implement the OA method.

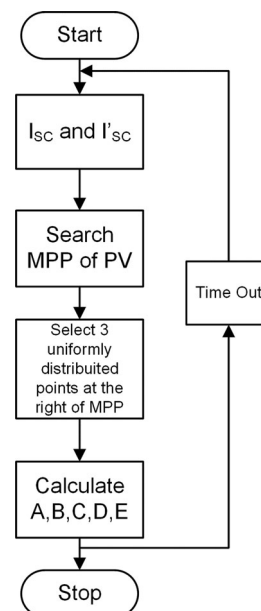


Fig. 3. Flowchart of OA method implementation.

eight embedded memories for cache memory. The maximum working frequency is 50 MHz. In this application, only integer hardware has been synthesized because the *FPGA* logic and memory utilization increases when a *floating point unit* is added. The performance obtained is about at 28 *dhystone millions of instructions per second* at 50-MHz system clock frequency, enough for this application. The *OA* method has been programmed using C language and compiled with *Bare-C* cross-compiler. *GRMON2* software has been used for debugging; it communicates with the *LEON debug support unit* and allows us nonintrusive debugging of the complete system. The software application has been compiled using an *msoft-float* option to use the software floating point libraries because this *SoC* does not include a hardware support for floating point.

Fig. 3 shows a flowchart of the implemented program. The algorithm starts obtaining the short circuit point of the *I-V* curve

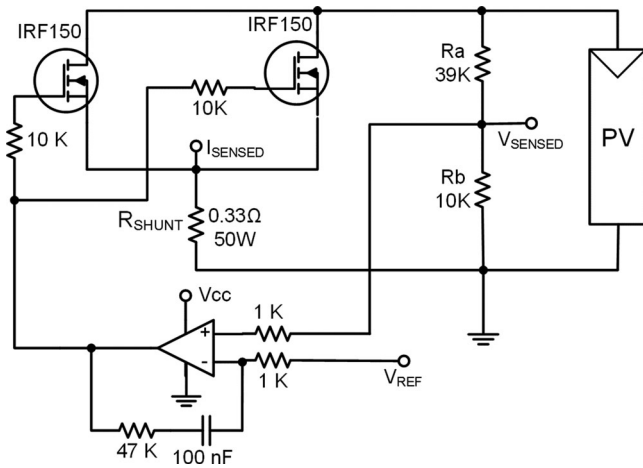


Fig. 4. Electronic load used to control de the solar panel.

(0, I_{sc}) by setting the output reference voltage to zero and reading the current value from the *ADC*. After obtaining (I_{sc}), the slope of the I - V curve near the short circuit point (I'_{sc}) is calculated increasing, slightly, step by step the output reference voltage and reading the corresponding current values. Using 50 measured points and applying linear regression the slope of I - V curve is obtained. To minimize the computational resources *least squares estimation* is used. The next step is to measure three points of the I - V curve with a voltage higher than the *MPP*. For this purpose, first, the *MPP* point and the *OC* point are obtained increasing the output reference voltage in steps and sensing the current and voltage each step. After obtaining the *MPP* and the *OC*, three uniformly distributed points (V_1, I_1), (V_2, I_2), and (V_3, I_3) are chosen. Using these values and applying (3)–(10) the characteristic parameters of the pilot cell are obtained. The algorithm is executed every 60 s to obtain the *PV* parameters in different conditions. Profiling the code by using *GRMON2*, only need 0.239 s to obtain the *PV* parameters and only the 25% of this time is needed to calculate A, B, C, D, E parameters. This 60 s time-out and the number of measurements can be adjusted depending on the mission requirements.

The final system is composed of three blocks.

- 1) *LEON3* microprocessor that executes the *OA* method to obtain the characteristic values of *PV* from the sensed values.
- 2) Electronic load to set the *PV* output voltage to a value defined by *LEON3 SoC*.
- 3) Acquisition Interface: It is used to obtain the values of voltage and current from a pilot cell and to adapt their levels to values suitable to be acquired by the digital system.

Although a dc - dc converter could be used to regulate the *PV* voltage, it has been discarded because they are bulky and heavy because of the use of inductors. For aerospace applications, an electronic load suits better [8]. As can be shown in Fig. 4, the electronic load used is based on two parallel power MOSFET transistors working in their linear region. A simple voltage feedback loop is also implemented to adjust the gate voltage to assure a voltage regulation mode. The pilot cell working voltage (V_{PV})

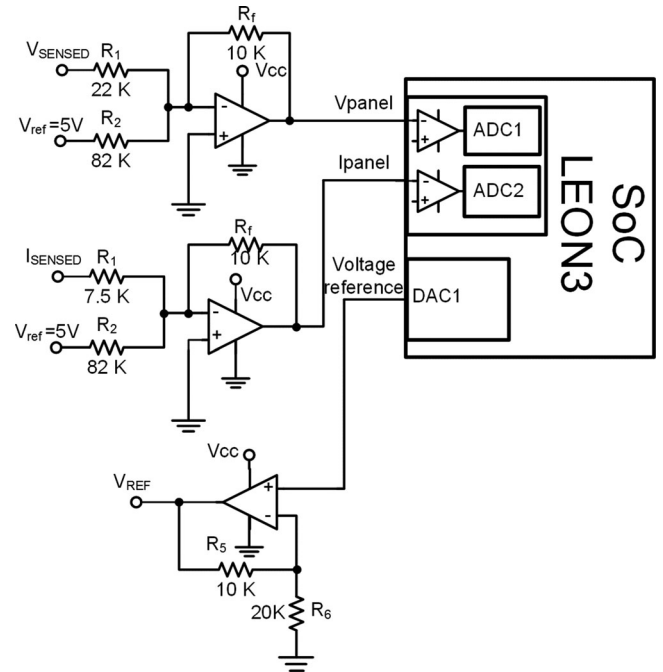


Fig. 5. Auxiliary circuit to measure voltage and current from PV panel.

TABLE I
ELECTRICAL PARAMETERS OF PV MODULE BP-380

Typical Electrical Characteristics	Quantity
Maximum Power (P_{max})	80 W
Voltage at Pmax (V_{mp})	17.6 V
Current at Pmax (I_{mp})	4.55 A
Short Circuit Current (I_{sc})	4.8 A
OC Voltage (V_{oc})	22.1 V
Warranted minimum power	76 W

is set by the *LEON3* through the voltage reference (V_{REF}). Fig. 5 shows the *LEON3* microprocessor with the auxiliary acquisition needed to adapt all the voltages to the *ADC* and *DAC*. The voltage and current values sensed from the *PV* cell are adapted using two inverting adders.

V. EXPERIMENTAL SETUP AND RESULTS

The system described in the previous sections has been used to estimate, in real-time, the parameters of a solar panel *BP-380* from *BP SOLAR* (Table I shows its electrical characteristics). In order to demonstrate the correct operation of the whole system, four different curves have been measured and their parameters extracted in real time. Next, the measured curves and the theoretically curves generated from the extracted model parameters were represented in *MATLAB* to compare them.

In Figs. 6 and 7, it is depicted four I - V and P - V measured curves (at different hours with different irradiance levels), and the generated curves from the model calculated parameters. In Table II, it is shown the parameters extracted for each curve and the *root mean square error (RMSE)* between the real curve and the theoretical one. *RMSE* has been calculated as

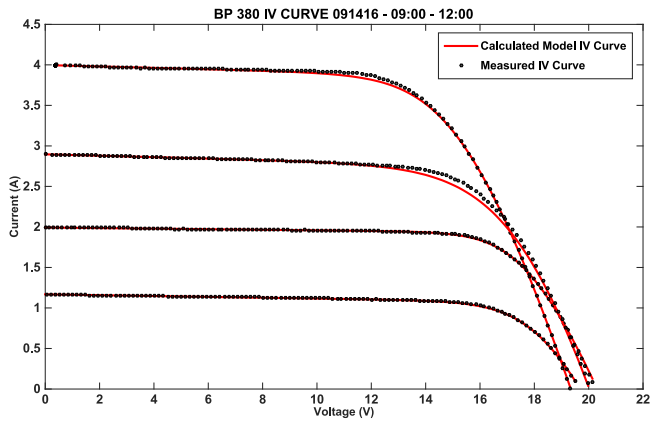


Fig. 6. Measured I - V curves versus calculated model I - V curves.

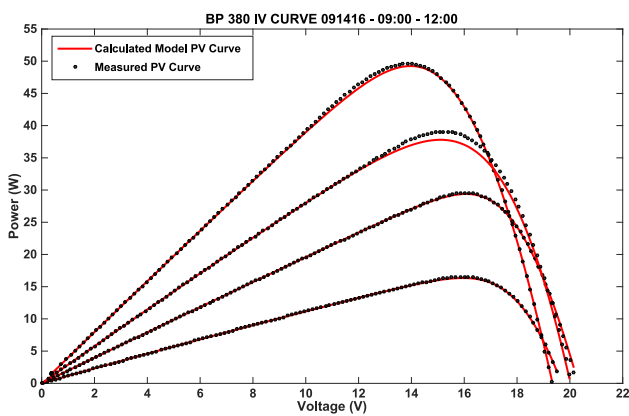


Fig. 7. Measured P - V curves versus calculated model P - V curves.

TABLE II
BP-380 FOUR CURVES PARAMETERS AND RMSE

I_{ph} (A)	I_{sat} (A)	nVT (JC)	R_s (Ω)	R_{sh} (Ω)	RMSE
4.0224	2.5330E-07	1.1695	0.732	115.995	4.4855E-3
3.0099	6.4701E-07	1.3138	0.633	69.745	5.1069E-2
1.9988	1.6632E-10	0.8767	0.943	290.092	7.2976E-3
1.1734	1.9384E-09	0.9155	0.916	192.695	4.4855E-3

indicated in [33] using (11) where N is the total number of points of the measured curve, $i_{real}(n)$ are the measured currents and $i_{model}(n)$ are the calculated currents using the model parameters,

$$RMSE = \sqrt{\frac{\sum_{i=1}^N |i_{real}(n) - i_{model}(n)|^2}{N}}. \quad (11)$$

As can be seen, the accuracy of the system is acceptable, the $RMSE$ is below 1% in three of the four curves modeled (5.1% in the other one).

Although the accuracy of the system is not very high, the curves generated from the five parameters extracted in real time from the solar panel are quite similar to the original ones.

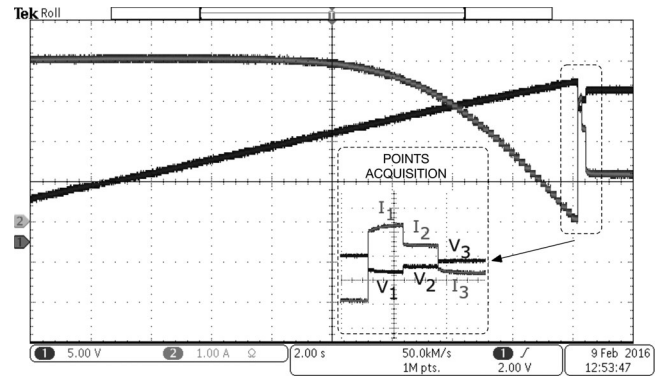


Fig. 8. Parameter extraction oscilloscope screenshot. Channel 1 – Black: Voltage 5 V/div. Channel 2 – Grey: Current 1 A/div.

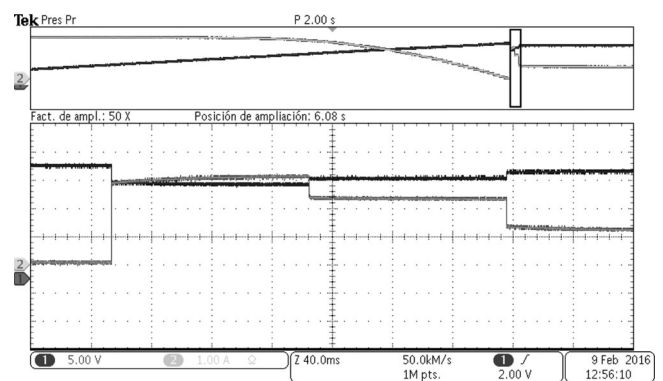


Fig. 9. Parameter extraction oscilloscope screenshot Points extraction detail. Channel 1 – Black: Voltage 5 V/div. Channel 2 – Grey: Current 1 A/div.

It is worth remembering that the system's final application is photovoltaic curves telemetry, so the accuracy presented is acceptable. As can be seen in Figs. 6 and 7, these curves provide much more information than the single point measurement does.

In Fig. 8, it is shown an oscilloscope screenshot showing the electrical behavior of the system during the parameter extraction process. First of all, a whole curve sweep is done to calculate the short circuit current and the slope near this point. After that, the three points needed by the OA algorithm are measured and the model parameters extracted. In Fig. 9, it is shown that the points acquisition detailed oscilloscope screenshot, as can be seen the times have been adjusted, so the measurements can be properly done.

Once the correct behavior of the system has been demonstrated. The system has been programmed to acquire a curve and to extract its parameters every 3 min (from 13:00 to 14:00). The results of this test are shown in Table III, where the extracted parameters are listed, and in Fig. 10 where the theoretical curves generated with these parameters are depicted. As mentioned before, the curve can be reconstructed later only saving the five parameters every 3 min. This is an example how the final system is intended to work.

TABLE III
BP-380 ONE HOUR MODEL PARAMETERS

Hour	I_{ph} (A)	I_{sat} (A)	nVT (JC)	R_s (Ω)	R_{sh} (Ω)
13:00	3.833	1.109E-06	1.330	0.621	411.240
13:03	3.802	7.783E-07	1.302	0.644	406.688
13:06	3.756	8.135E-07	1.305	0.639	432.824
13:09	3.694	1.218E-06	1.351	0.607	462.785
13:12	3.636	7.336E-07	1.309	0.631	458.506
13:15	3.556	5.611E-07	1.295	0.632	476.695
13:18	3.510	1.503E-06	1.385	0.573	555.910
13:21	3.443	6.518E-07	1.317	0.609	548.238
13:24	3.403	6.385E-07	1.316	0.610	412.613
13:27	3.334	1.023E-06	1.362	0.563	607.709
13:30	3.277	4.045E-07	1.286	0.620	473.089
13:33	3.212	3.288E-07	1.276	0.623	366.350
13:36	3.133	3.081E-07	1.277	0.619	419.902
13:39	3.083	1.834E-07	1.240	0.629	328.969
13:42	3.010	3.384E-07	1.289	0.583	320.857
13:45	2.934	1.639E-07	1.243	0.615	327.254
13:48	2.867	2.286E-07	1.264	0.592	267.361
13:51	2.792	7.882E-08	1.188	0.648	265.168
13:54	2.709	6.178E-08	1.178	0.649	246.447
13:57	2.641	6.476E-08	1.178	0.642	240.147
14:00	2.573	4.623E-08	1.160	0.640	208.609

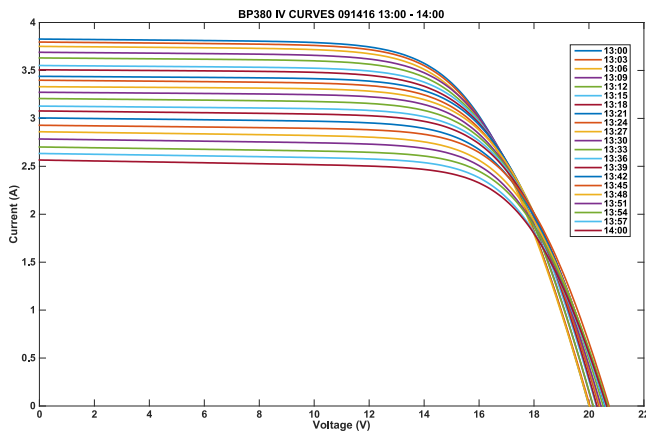


Fig. 10. BP-380 1-h reconstructed curves.

VI. CONCLUSION

This paper presents the implementation of an SoC to extract in real time the five parameters of the equivalent single-diode model of a photovoltaic module. The system is based on a LEON3 microprocessor implemented in an FPGA. It has been demonstrated that this microprocessor can execute the OA method for extracting the parameters in real time accurately. Once the five parameters have been calculated, only saving these data, the whole I - V curve can be later entirely reproduced.

The main application of this system is spacecraft telemetry, where the limitations of memory and communication bandwidth complicate the storage or transmission of the whole I - V curve in real-time. The proposed system allows us for having the telemetry of the whole I - V curve transmitting only five parameters instead of a whole set of points.

Finally, experimental results have been presented showing an acceptable accuracy and the correct operation of the final system.

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