Design and Implementation of a Curve Characterizer for PV Panels using a Cuk Converter

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***Abstract*—This paper presents the development of a portable curve characterizer for PV panels. The developed system allows to obtain the power-voltage (P-V) and current-voltage (I-V) curves, where measured variables are transferred to a computer using serial communication. To acquire all the current and voltage values of the PV module selected, a DC-DC Cuk converter is used as a resistance emulator. Adjusting its duty cycle, the equivalent resistance seen by the PV module is modified, obtaining all the current and voltage values provided by the PV panel. Finally, the implemented prototype is presented, as well as the verification of the curve characterizer, through computer simulations and experimental results.**

***Index Terms*—Curve characterizer, PV panels, I-V and P-V curves, DC-DC Cuk converter.**

I. Introduction

It is estimated that 79.5% of energy consumed in the world in the year 2016 was derived from the use of fossil fuels, they are non-renewable sources and their use for power generation is highly damaging to the environment. If there is no significant reduction of CO_2 emissions by human activities, there will be irreversible impacts on natural and human systems [1].

Faced with these facts government actions have emerged around the world to encourage the use of renewable energy. By the end of the year 2015, it is estimated that 146 countries had policies to stimulate the use of renewable energy, be they at national, state or provincial level and 173 nations had established goals for the use of renewable energy [2]. Regarding the generation of electricity from renewable sources, photovoltaic solar energy has been gaining prominence in the world market, accounting for about 55% of the renewable energy capacity newly installed in the world in 2017, corresponding to an increase of 99 GW of installed capacity compared to the previous year [1].

For design, installation and maintenance of a PV system, it is necessary to know the characteristic facings of the PV panels that contain it. The main characteristics of PV panels are the curves that relate the power and the current with its generated voltage, being known respectively P-V and I-V curves. Some parameters in these curves are usually provided by the manufacturers, but the values are obtained under certain environmental conditions, called Standard Test Conditions (STC), and this condition is rarely achieved outside the laboratory environment. Thus, only with experimental measurements can it be possible to know precisely the real parameters of a PV panel. However, equipment for this purpose, currently available in the market, has high prices, which makes them less accessible [3].

There are several methods for obtaining the characteristic curves of a PV panel. Among them, the most important are six main methods used for this purpose, they are: through a variable resistor, through a capacitive charge, through an electronic charge, through a bipolar power amplifier, through a four-quadrant power supply and using a dc-dc converter [4]. In first method using a variable resistor, voltage and current values are obtained by successive measurements of these values after manual variations of rheostat resistance, which will be connected to output terminals of the PV panel [5]. The second method is based on the biasing of a PV panel by a large capacitor; which is charged as this module moves from short-circuit to open-circuit [6]. The third method uses a transistor as a load. A resistance between the drain and the source is modulated through the gate-source voltage, and consequently the current flow supplied by the PV panel [7]. The fourth method consists in use of a simple circuit using a bipolar amplifier. This method allows the current and voltage on PV panel to be reversed and therefore I-V curves of this panel can be plotted [4]. In the fifth method a four-quadrant power supply is used. This can be used as an adjustable load for other power supplies or other equipment, such as a PV panel, with the primary interest of obtaining the I-V curve in the first quadrant [8]. The latter method is based on the ability of DC-DC converters to emulate a variable resistor. This property is applied to obtain I-V curves of PV panels [9].

The study developed by Durán et al. [4] demonstrates that

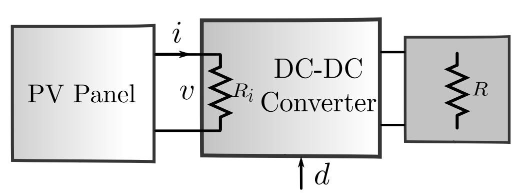

Fig. 1. DC-DC converter characterization method.

the last method has the best performance at relatively low cost. Given the above information, this work aims to expose the design, simulation and development of a curve characterizer using a DC-DC converter, designed to trace the characteristic curves of low power PV panels, as shown in Fig. 1.

The paper is organized as follows: The next section describes the characterization method selected and the algorithm developed used in this work. Section III shows an application of this method to characterize the I-V and P-V curves of a PV panel through a DC-DC converter. Finally, simulation and experimental results are given in section IV.

II. DC-DC Converters as Resistance Emulator

DC-DC converters are widely used in photovoltaic systems as a connection between the solar modules and the power grid, allowing system stability and Maximum Power Point Tracking (MPPT). The three basic topologies of these converters are *buck* (lowering the output voltage), *boost* (increasing the output voltage), and *buck-boost* (maintain the output voltage) and the relationship of transformation can be electronically controlled by changing the duty-cycle (d) in the range [0,1], in continuous (CCM) and discontinuous (DCM) conduction modes. Nowadays, buck-boost derived configurations has been used more frequently to characterize the I-V curves of PV panels [9].

Buck-boost derived configurations that provide the same conversion ratio are: Zeta, Cuk and SEPIC. In Zeta topology, the input current is always discontinuous producing high input ripple and significant noise problems. Cuk and SEPIC converters exhibit non-pulsating input current and therefore, the sweep of the I-V curve is performed more efficiently. Thus, these topologies are better suited to accomplish this task. Both topologies have very similar characteristics, but for the Cuk converter the polarity of output voltage is opposite input [10]. In addition, all buck-boost DC-DC converters behave like direct current transformers with the ability to step-up or step-down the input voltage. Therefore, just as the alternating current transformer, the DC-DC converters are capable to modify the equivalent resistance changing the conversion ratio. Thus, this work uses Cuk converter as a resistance emulator to obtain the I-V and P-V curves of the PV module, since it is capable to behave as a step-up or step-down transformer with non-pulsating current [11].

A. Cuk Converter

The Cuk converter is an inverting converter that has an output voltage that is either greater than or less than the input voltage. It is essentially a boost converter followed by a buck converter with a capacitor to couple the energy. This converter comprises two inductors (L_1 and L_2), two capacitors (C_1 and C_2), a load (R), a switch (Q) and a diode (D_1), as shown in Fig. 2.

The converter operation mode is divided into two modes, conduction and non-conduction modes. The conduction mode starts when the switch Q conducts. The current through the inductor L_1 increases and the voltage of the capacitor C_1 reverses the diode D and turns it off. C_1 discharges its energy to the circuit formed by C_2, L_2 and R. In non-conduction mode, the switch Q is turned off and the capacitor C_1 is charged from the input voltage (V_{in}) and the energy stored in the inductor L_2 is transferred to the load resistor (R).

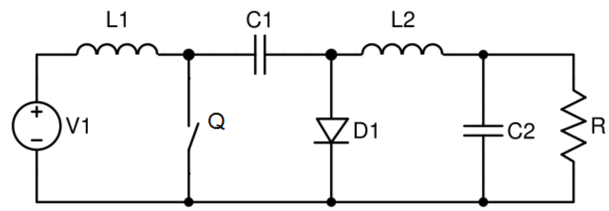

Fig. 2. DC-DC Cuk converter schematic.

The parameters of the passive components to operate in CCM, L_1, C_1 and L_2 are given by the following equations [11]:

$$L_1 = \frac{V_{mpp} D}{f \Delta i_{in} I_{mpp}}; \tag{1}$$

$$C_1 = \frac{I_{mpp}(1-D)}{f \Delta v_{C_1}}; \tag{2}$$

$$L_2 = \frac{G(D) V_{mpp} D}{f \Delta i_{out}}; \tag{3}$$

Where, V_{mpp} and I_{mpp} are the voltage-current pair at maximum power point, Δi and Δv are current and voltage variations, f is switching frequency, $G(D)$ is the static gain and D is the duty-cycle. The C_2 component is not crucial to this application and can be omitted from design [11]. However, it was decided not to remove it from the project and use the same equation used for component C_1 calculation. $G(D)$ and D values are obtained from the following equations:

$$G(D) = \sqrt{\frac{I_{mpp}}{V_{mpp}} R}; \tag{4}$$

$$D = \frac{G(D)}{1 + G(D)}. \tag{5}$$

Where, R is the value of the load resistance of Cuk converter. For obtain this value, it is necessary to calculate the equivalent inductance (L_{eq}) between L_1 and L_2 and its given by the following inequality [9]:

$$R < 2 f L_{eq}. \tag{6}$$

Also, for a better operation of Cuk converter it is necessary to project a capacitor at the input of the converter, to filter the input current ripple, smoothing the PV terminal voltage. For this was used a equation [11],

$$C_{in} = \frac{4 \Delta i_{in}}{\pi^3 f \Delta v_{Cin}}. \tag{7}$$

III. Characterization Method

The method selected is based on the fact that the equivalent resistance seen by the photovoltaic module varies as a function of the resistance of the load allocated to the output of the converter and its operating duty-cycle, as depicted in Fig 3. The equivalent resistance seen by the panel is modified by varying the duty-cycle. So for each duty-cycle a distinct equivalent resistance is seen by th PV panel and consequently a voltage and current pair occur at its terminals [9].

For this method, a Cuk converter is used to sweep the I-V and P-V curves by varying the duty-cycle between 0% and 100%. Thus, the curve characterizer operates as follows: the DC-DC converter emulates different resistive values by varying the duty-ratio. The output voltage and current of the PV module are measured and send to the microcontroller. Then, the data is sent to the computer to plot the I-V and PV curves.

A. Duty-Cycle Sweep Algorithm

This work uses an algorithm whose function is to vary the duty-ratio gradually and collect the corrensponding current and voltage variations at the PV panels terminals. For this, an approach of Duty-Cycle Sweep (DCS) of Pulse Width Modulated (PMW) strategy based on microcontroller was used. In our case, the duty-cycle is increased from 0% to 100% [12].

Then, this algorithm starts initializing the PWM module of a microcontroller. First, the PWM duty-cycle (D) is varied using the ratio between activation time (T_{ON}) and total period (T), once D = T_{ON} / T. Then, T_{ON} be incremented from 0 to T, thus varying the value of D from 0 to 1. The resistance seen by the panel (R_i) is a function of D and varies in CCM according to:

$$R_i = \frac{R(1-D)^2}{D^2}; \tag{8}$$

where R is the load resistance of the Cuk converter. After each variation of D, the voltage and current pair are measured and stored to characterize the panel. When D reaches one, the sweep algorithm ends. The algorithm is represented by the flowchart shown in Fig. 4.

IV. Results

In this work, the solar module Singfo SFM-020 is used as reference. Its electrical parameters at STC are presented in Table I. Using equations that relate output current and output voltage of a PV panel [14], several I-V and P-V curves were simulated varying irradiation and temperature, to be used as reference. Therefore, using equations from Section II, f = 62.5 kHz (the maximum PWM frequency achieved by the microcontroller), different values of D (0 < D < 1) and 10% for all current and voltage variations, the component values of the converter were obtained as shown in the Table II.

To carry out the measurement, a set-up was built with PV panel, two halogen reflectors and a thermometer were placed, as shown in Fig. 5. This set-up was developed to emulate abrupt variations in weather conditions, mainly irradiation and temperature. Then, these measured values are used by the curve characterizer to plot different I-V and P-V curves of the selected PV panel.

Then, from the values of Table II, the prototype of the Cuk converter was implemented, as shown in Fig. 6. As was mentioned in previous chapters, it was decided to use simple and low cost components, mainly the microcontroller

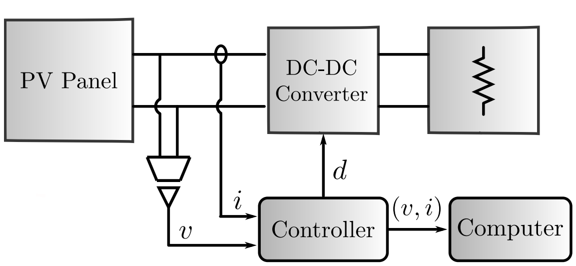

Fig. 3. Proposed characterization method.

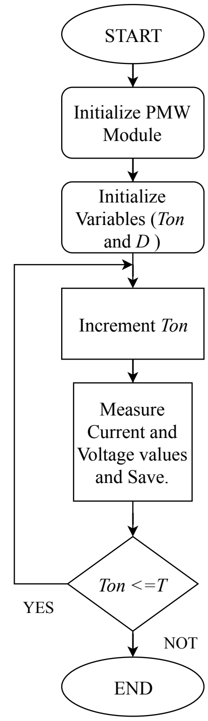

Fig. 4. Flowchart of a DCS algorithm used.

TABLE I
Electrical parameters of selected PV panel.

Maximum power (Pmax)	20 W
Voltage at Pmax (Vmpp)	17.2 V
Current at Pmax (Impp)	1.17 A
Open Circuit Voltage (Voc)	21.5 V
Short Circuit Current (Isc)	1.35 A
Isc Temperature Coefficient (T_{CI})	45 mA/ °C
Voc Temperature Coefficient (T_{CV})	- 35 mV/ °C

TABLE II
ELECTRICAL VALUES OF THE COMPONENTS USED FOR CUK CONVERTER.

Input Capacitor (C_{in})	220 μF
Input Inductor (L_1)	3.03 mH
Accumulator Capacitor (C_1)	470 μF
Output Inductor (L_2)	2.62 mH
Output Capacitor (C_2)	2.2 μF
Load Resistor (R)	2 Ω
Output Capacitor (C_2)	2.2 μF
Switch (Q)	IRF530N
Diode (D)	UF5406

ATMEGA328P, into Arduino Nano open-source electronics platform. Other components, such as inductors, were conceived in our laboratory with our own materials. All this because our main objective was always to develop a portable prototype for use in laboratory practices.

Also, the I-V and PV curves are displayed using a software developed in Matlab R2016a. This software uses the data measured by the microcontroller and it plots the I-V and P-V curves of the PV module, for a specified irradiation and temperature. An image of this software, displaying an I-V and P-V curves, is shown in Fig. 7.

A. Curve Characterizer Verification

To verify the proposed curve characterizer, two tests were developed: the first one uses half of power of halogen reflectors and the second one uses the maximum power of them. The irradiation-temperature pair was found for both tests using an Minipa MT-405 Digital Thermometer and Davis 6450 Solar Radiation Sensor. For the first test was obtained T_1 = 28°C and G_1 = 285 W/m^2, and for the second test T_2 = 42°C and G_2 = 545 W/m^2.

Then, using these values, the corresponding I-V and P-V curves are obtained using the methodology of Ortiz-Rivera and Peng [14]. These curves are compared with those obtained from the proposed curve characterizer, demonstrating the effectiveness of our prototype, since there is a satisfactory error between the experimental values with the theoretical values. In Fig. 8 and Fig. 9, the I-V and P-V simulated and experimental curves of the first test are compared. The comparison of simulated and experimental I-V and P-V curves for the second test are illustrated in Fig. 10 and Fig. 11. Therefore, it can be said that the curve characterizer, for these case studies, operates satisfactorily.

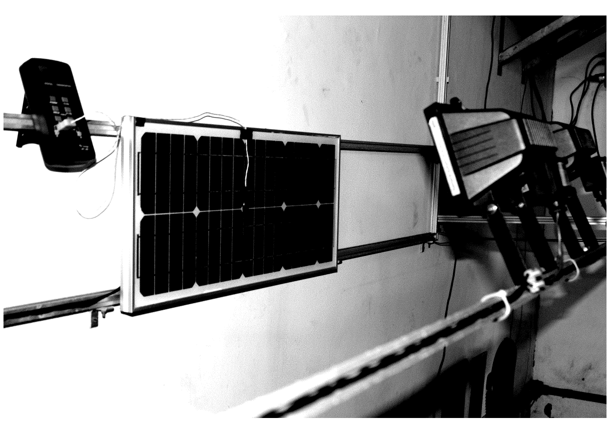

Fig. 5. Set-up developed whit the PV panel.

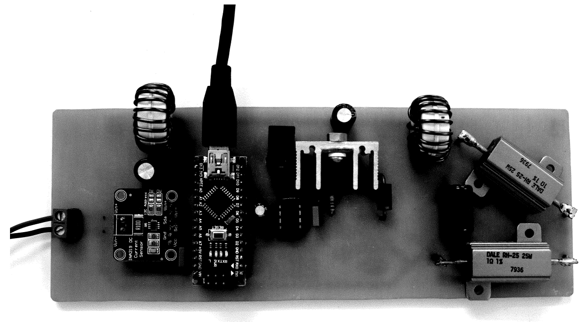

Fig. 6. DC-DC Cuk converter prototype.

V. CONCLUSIONS

This paper presents the design and implementation of a portable curve characterizer based on a DC-DC Cuk converter. The developed system allows obtaining the P-V and I-V curves, where measured variables are transferred to a computer using serial communication. It was checked a Cuk converter property of acting as a resistance emulator, using DCS in fixed switching frequency PMW algorithm. Finally, the implemented prototype was presented, as well as the verification of the curve characterizer, through computer simulations and experimental results. This results demonstrate the effectiveness of the curve characterizer plotting the I-V and P-V curves model under different weather conditions.

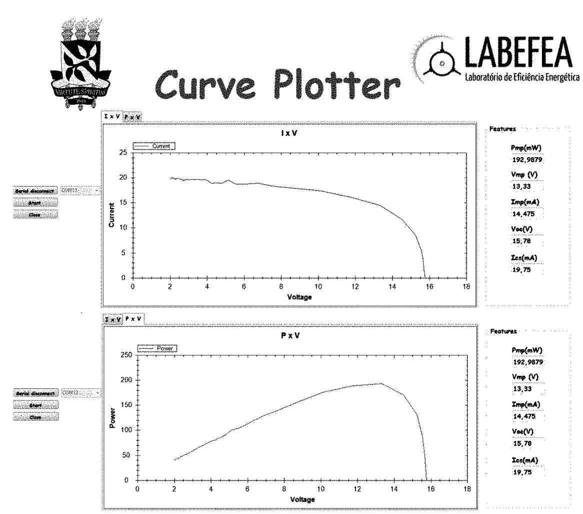

Fig. 7. Software developed in testing phase.

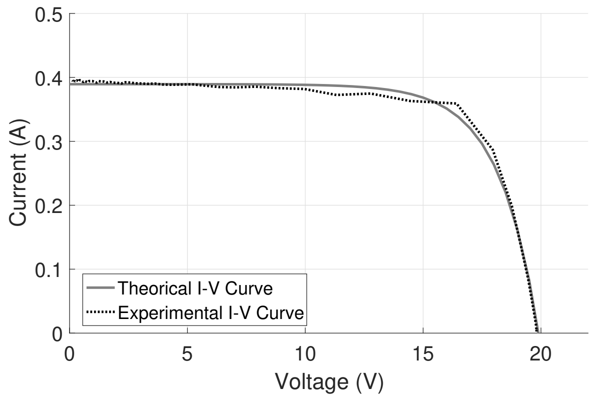

Fig. 8. I-V curves traced at T_1 = 28°C and G_1 = 285 W/m^2.

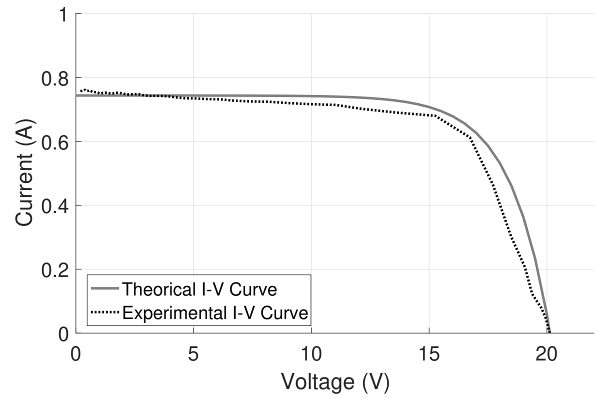

Fig. 10. I-V curves traced at T_1 = 42°C and G_1 = 545 W/m^2.

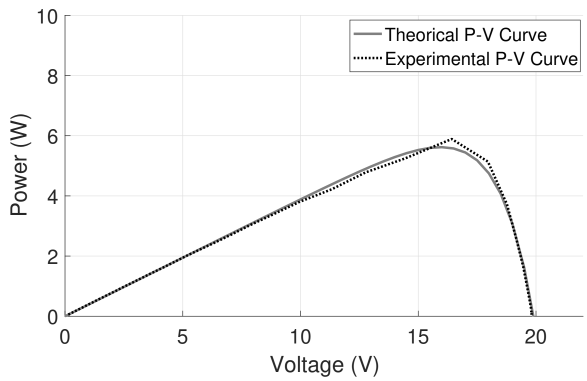

Fig. 9. P-V curves traced at T_1 = 28°C and G_1 = 285 W/m^2.

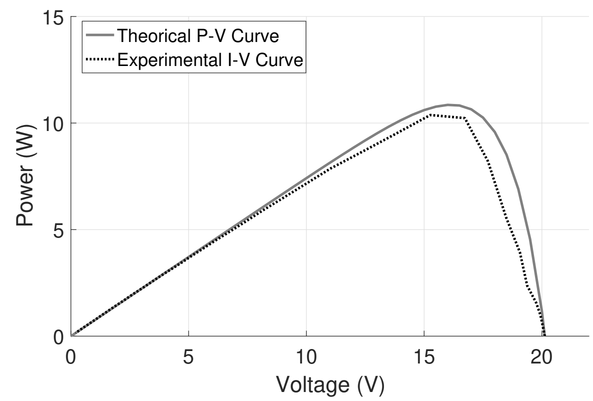

Fig. 11. P-V curves traced at T_1 = 42°C and G_1 = 545 W/m^2.

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REFERENCES

[1] REN21. Renewables 2018: Global Status Report. Renewable Energy Policy Network for the 21st Century. 2018.

[2] REN21. Renewables 2016: Global Status Report. Renewable Energy Policy Network for the 21st Century. 2016.

[3] E. Durán, J. Galán, M. Sidrach-de-Cardona, and J.M. Andújar, "A new Application of the Buck-Boost-Derived Converters to obtain the I-V curve of PV Modules", in Proc. of the 38th IEEE PESC, pp. 413-417, Jun. 2007.

[4] E. Durán, M. Piliougine, M. Sidrach-de-Cardona, et al., "Different methods to obtain the IxV curve of PV modules: A review", in Photovoltaic Specialists Conference, pp. 1-6, 2008.

[5] M. M. Mahmoud, "Transient analysis of a PV power generator charging a capacitor for measurement of the I–V characteristics", Renewable Energy, Volume 31, Issue 13, Pages 2198-2206, 2006.

[6] J. Muñoz, E. Lorenzo, "Capacitive load based on IGBTs for on-site characterization of PV arrays", Solar Energy, Volume 80, Issue 11, Pages 1489-1497, 2006.

[7] N. Forero, J. Hernández, G. Gordillo, "Development of a monitoring system for a PV solar plant", Energy Conversion and Management, Volume 47, Issues 15–16, Pages 2329-2336, 2006.

[8] J. Fernández-Reche, I. Cañadas, M. Sánchez, J. Ballestrín, L. Yebra, R. Monterreal, J. Rodríguez, G. García, M. Alonso, F. Chenlo, "PSA Solar furnace: A facility for testing PV cells under concentrated solar radiation", Solar Energy Materials and Solar Cells, Volume 90, Issue 15, Pages 2480-2488, 2006.

[9] E. Durán, J. M. Andújar, J. M. Enrique, and J. M. Pérez-Oria, "Determination of PV Generator I-V/P-V Characteristic Curves Using a DC-DC Converter Controlled by a Virtual Instrument," International Journal of Photoenergy, vol. 2012, Article ID 843185, 13 pages, 2012.

[10] M. Khodabandeh, E. Afshari and M. Amirabadi, "A Family of Cuk-, Zeta-, and SEPIC-based Soft-Switching DC-DC Converters", in IEEE Transactions on Power Electronics, Jan. 2019.

[11] T. A. Pereira, W. M. dos Santos, D. C. Martins, R. F. Coelho, "Caracterizador elétrico de módulos fotovoltaicos utilizando o conversor CC-CC Ćuk", in Revista Eletrônica de Potência (SOBRAEP), v. 22, n. 2, p. 139-147, jun. 2017.

[12] E. Durán, J. Galán, M. Sidrach-de-Cardona, M. B. Ferrera and J. M. Andujar, "A new application of Duty Cycle Sweep based on microcontroller to obtain the I-V characteristic curve of photovoltaic modules," 2008 IEEE International Conference on Industrial Technology, Chengdu, 2008, pp. 1-6.

[13] SINGFO SOLAR ENERGY SCI. & TECH. CO., LTD. www.singsolar.com/data/attachments/dsh.522-068.1.pdf.

[14] E. I. Ortiz-Rivera and F. Z. Peng, "Analytical model for a photovoltaic module using the electrical characteristics provided by the manufacturer data sheet," in IEEE 36th Power Electronics Specialists Conference, pp. 2087–2091. June 2005.