STAND ALONE PHOTOVOLTAIC MANAGEMENT SYSTEM FOR ICTs DEVICES

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***Abstract*— This article presents the development of a portable stand-alone photovoltaic system (SAPS) and the mathematical model that allows simulating its behavior and optimizing the design. The purpose of this system is developing an auxiliary source of energy for portable information and communication technologies devices (ICTs). The SAPS was implemented from a 20 Wp foldable photovoltaic generator and a 5200 mAh Ion-Lithium battery bank linked to a netbook from the *Programa Conectar Igualdad* of Argentina (PCI). The model validation was carried out through experimental results obtained by testing a specific application of this type of systems. The results demonstrate an optimization of the equipment fed by the system (netbook), increasing autonomy by 5 hours on a clear day in a month of winter in the city of Corrientes, Argentina. By comparing the theoretical and experimental results it was possible to verify an adequate development of the system for the specific application and the utility of the model as a systems design tool for this type of applications**

Keywords*— Stand Alone Photovoltaic Systems, Equality Connect Program (PCI), Energy backup system, Battery Charging State, Solar Netbook

I. INTRODUCTION

In the last decade, different countries in Latin America (Brazil, Peru, Chile, Uruguay and Argentina) have implemented rural electrification programs with renewable energies for population that are far away from conventional electric power distribution network. Particularly, in Argentina, the national project PERMER (Electrification Program in Rural Markets) [1] contemplates the installation of photovoltaic systems to supply electric power in rural junior and high schools. The supply of electricity through conventional network or autonomous photovoltaic systems allowed, in some of these centers, access to information and communication technologies (ICTs), thus reducing the so-called digital-break.

However, social inclusion programs such as the "Connect Equality Program" (Programa Conetar Igualdad, PCI) [2] have not reached all of these rural schools due to lack of electrical energy. That is, students who attend schools do not have electricity to power their netbooks in the establishment neither at their homes. This situation limits their connectivity, the use of ICTs, etc. preventing fulfilment the objectives set by the program.

Thus, there is a need to extend the use of these technologies in environments where electricity is a strategic asset, using photovoltaic generation and extending the autonomy of electronic devices used in ICTs. In this context, the provision of energy through photovoltaic solar technology is presented as an economic and environmentally appropriate alternative.

The objective of this work is the implementation of a portable photovoltaic energy and storage management system, to serve as backup for the netbooks delivered by the PCI. Additionally develop a mathematical model that allows simulating and optimizing this kind of PV systems.

II. STAND ALONE PHOTOVOLTAIC SYSTEMS (SAPS)

The conversion of solar into electrical energy through photovoltaic modules (PV) has been subject to constant research, developments and has reached a great evolution in recent years. The use of terrestrial photovoltaic technology begins with the installation of autonomous systems either for remote applications or to bring electricity to isolated rural populations. In the last decades the use of systems connected to distribution network has allowed to increase exponentially the installed photovoltaic power shooting up the PV market, reducing costs and increasing conversion efficiency. From this point, the use for isolated applications was expensive. However, nowadays it has been reduced and it is possible to bring new technologies to rural populations, such as ICTs, with the use of PV modules as the main source of energy.

To obtain the desired voltage and current values, electrical interconnection between the photovoltaic modules is done to form the so-called photovoltaic generator. In turn, the latter, due to the intermittence of photovoltaic generation, is associated with storage and control systems, constituting an autonomous photovoltaic system. In this way, accumulation of energy is relevant to maintain the energy supply in cases where generation is insufficient, zero or when there is energy available but is not required. The charges, which represent the demand of energy, can be DC or AC. In the first case the system can supply them directly, since both generation and accumulation are carried out in DC. In the case of the AC, the PV system must have a DC-AC converter.

Another important point to consider is to polarize the photovoltaic generator at his maximum power point to obtain the largest transfer of energy from generator to load / batteries, situation that depends on working conditions. To achieve this goal, an impedance adapter can be installed between the generator and the load / accumulator.

The batteries are the elements responsible for storing the generated energy for its later use. Normally they are arranged in banks of associated cells in series and parallel.

In recent decades there have been significant advances in batteries technologies, seeking to achieve rechargeable elements: smaller, lighter and with higher capacity. The different technologies are characterized by their: energy density (stored load per unit weight of the battery), life cycle (the number of charge / discharge cycles before their disposal), environmental impact, safety, cost, available supply, voltage and current values of charge / discharge [4].

Evaluating the energy density, of the main commercially available batteries technologies, it is observed that the lead-acid battery has a lower energy density than all other technologies (30 Wh / kg), followed closely by nickel cadmium (average 50 Wh / kg), metallic nickel hydride (average 70 Wh / kg), nickel chloride (110 Wh / kg), and the other lithium battery, which has a higher energy density (170 Wh / kg) as well as a high power density.

Lithium is the third lighter element of the Periodic Table, it has a high electrochemical potential and small ionic radius, factors that allow the lithium-ion battery to present high energy density and power [5]. In addition, due to its internal characteristics, it allows fast recharging, high performance in cyclic application, low self-discharge, high recharge efficiency (about 95%) and long service life. These characteristics contribute to increase the use of this technology and large investments in research have leveraged technology improvement with the use of new materials to increase energy density, safety and price reduction [6].

Unlike the lead-acid, nickel-metal-hydride, and nickel-cadmium battery technologies that utilize an aqueous electrolyte, the lithium battery uses an organic electrolyte because metal lithium in contact with gaseous oxygen or moisture undergoes spontaneous combustion, but this electrolyte is stable only in a narrow voltage range (between 2.0 V to 5.0 V) and temperature (up to about 100 ºC).

Therefore, for safe operation of lithium-ion battery, it is essential to have a cell monitor system, whose main function is to control overvoltage, under voltage, temperature, overload and external short circuit.

Regardless of selected battery technology, all SAPS must have a charge controller that is responsible for charge and discharge supervision to maximize their useful life.

The controller cannot directly measure battery state of charge (SoC), its value is determined using algorithms that links Voltage, Current and Temperature values.

In this way, through mathematical models it is possible to estimate the SoC from the cited variables.

A. SAPS Topology

Selected topology is presented in Figure 1. It is composed of 4 (four) elements: PV panel, Batteries, Load and Control. As can be seen, generated energy is leading on a direct current (DC) bus to feed the load or to be accumulated in batteries.

The control system is responsible for managing load energy flow, from the DC bus. This disposition seeks to obtain the maximum autonomy of the load to be fed by an uninterrupted flow of energy.

A second DC / DC converter adapts the voltage and current values present on the DC bus to the values required by the load (netbook).

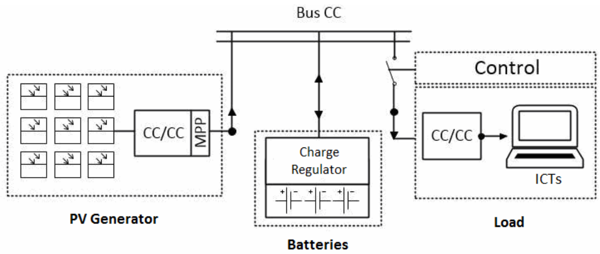


Figure 1: Proposed PV topology.

III. PORTABLE SAPS MATHEMATICAL MODEL

To make a preliminary sizing of the SAPS in question, it was proposed to develop a mathematical model that would allow, from simulation in multiple application scenarios, to approximate the capacity of the battery bank, the PV generator and the control actions required to optimize the operation of whole system.

The goal of this model is to allow a detailed SAPS operation analysis, being able to modify both, components characteristics and operating conditions (regarding demand profiles and weather conditions) in order to achieve the optimal conditions and maximize the autonomy of the electronic equipment that must be fed.

The development and simulation of the mathematical model were carried out in the MATLAB®7.8.1 software that offers, within its programming environment, SIMULINK tool for visual programming.

Each of the stages of the SAPS was modelled through blocks contained in the libraries provided by Simulink (Figure 2).

PV generator: obtained from the ideal diode model, uses irradiance data acquired over a day and cell temperature calculated from the ambient temperature as input parameters. This model provides voltage and current polarization values at maximum power point, as output parameters.

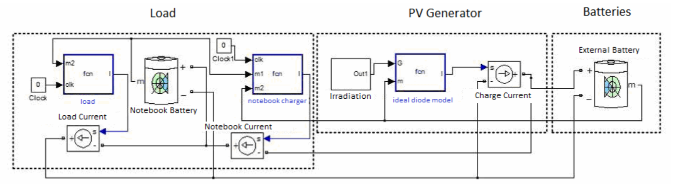


Figure 2: Mathematical model block diagram developed in MATLAB / Simulink.

External batteries: the dynamic battery model presented by Tremblay [7] was used to simulate the operation of lithium-ion batteries. This model allows to know the voltage values at the terminals of the batteries, the voltage on the DC bus, and the discharge current, in addition to the parameters of the battery (nominal voltage, capacity and internal resistance), starting from the initial SoC value.

Load: it was modeled as a constant current source whose value depends mainly on the operating conditions of the electronic device to be powered.

To determine the value of this current, it was necessary to incorporate the internal batteries of the netbook into the model.

Control system: it was implemented as an ON/OFF control whose decision depends exclusively on the SoC of external batteries (and its correlation with the voltage at the terminals of the accumulator). This control was implemented as a decision routine that links parameters of previous mentioned modules.

The following initial conditions were proposed to approximate the results of the modeled system under real operating conditions: Clear day, 11.1 V nominal voltage and 20 % SoC for external batteries; and 10 % SoC for internal batteries.

In other words, the test starts in a condition where the netbook and the external batteries are almost completely discharged. This situation is the most unfavorable for an autonomy analysis. This case has been considered for a preliminary analysis of system behavior.

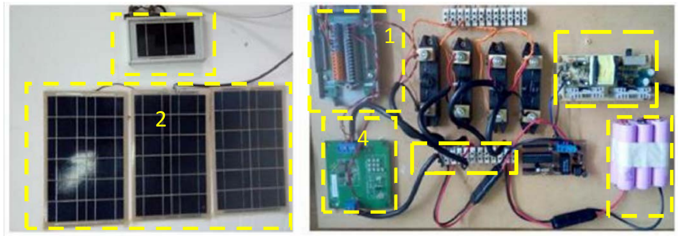
Based on the results obtained in multiple simulations, a preliminary adjustment of the capacity of the photovoltaic generator and the external battery bank was achieved. In this way a relationship of generation / storage necessary for an optimal operation of the SAPS was determined according to the characteristics of associated demand and autonomy requirements raised for the project. With these data an experimental project of the system was carried out in order to validate the mathematical model and to approximate a first functional prototype.

IV. PORTABLE SAPS PROTOTYPE

The layout of experimental prototype built to validate developed mathematical model is presented in Figure 3.

In order to provide ergonomics and portability to the equipment, a 20 Wp folding PV generator was designed from 3 panels of 12 polycrystalline silicon cells each, electrically connected in series (which was manufactured by Solartec SA). The open circuit voltage of the array is 21 V and the short-circuit current is 1.3A.

The battery bank was developed with 6 cells of lithium-polymer of 3.7 V and 2600 mAh. Two arrays of three cells arranged in series were connected in parallel, to achieve the 11.1 V of nominal voltages and 5200 mAh of nominal capacity



(a) (b)

Figure 3: Experimental Setup (a)PV Generator and reference cell (1-Reference cell, 2-Generator) (b) Experimental Prototype (1- Rigol Data Logger, 2- Shunts, 3- CC/CC Netbook, 4-CC/CC MPPT, 5- Bus CC, 6- Control, 7-Bateries)

The charge control of the external battery bank was implemented using a BQ24650 integrated circuit from Texas Instruments. The BQ24650 bases its operation on a synchronous Buck converter [8] and has maximum power point tracking capabilities (by the fixed polarization method) for charging lithium-ion batteries.

To adapt voltage levels between the DC bus and load power input (Netbook), a TL494 based Boost converter [9] was implemented.

On the other hand, an energy flow ON/OFF type control from external battery bank to the load was implemented. The system senses the voltage present at battery terminals to estimate its SoC and allow or prevent load feeding.

An experimental test was developed to determine system operating conditions. The results were compared with values acquired by simulation to validate the mathematical models. Figure 4 shows electrical variables of interest in the system characterization.

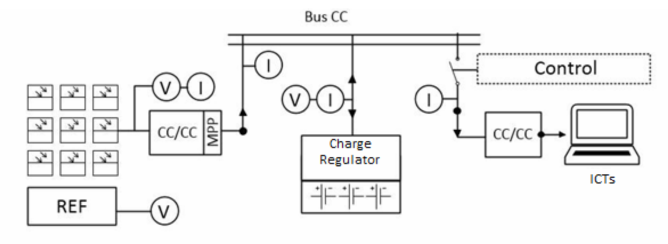


Figure 4: Test current and voltage measuring points of the developed system.

A. Experimental Setup.

The internal batteries voltage and current are inaccessible (internal pack of the netbook), due to constructive issues of the equipment. Fact that leads to the total autonomy of the system is determined by the event log of the operating system of the netbook.

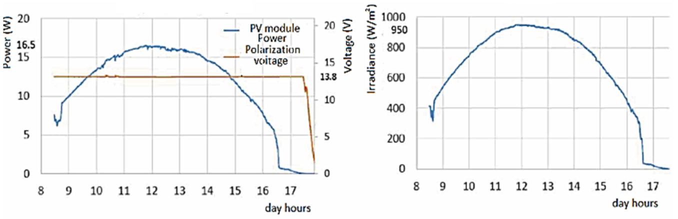
The PV generator was arranged on a flat surface, with the active face facing north and an inclination equal to 30 °. The generator was installed on the building facade of the Physics Department FaCENA UNNE. In the same plane a reference cell was placed to measure values of incident irradiance in the surface of PV generator during the test.

Voltage and current values were acquired and stored at the measurement points showed in Figure 4. A RIGOL DM3606 datalogger was used. The voltage measurements were made directly, while Shunt 0.5 class (5 A /150 mV) resistances were used for current measurements. The measured variables were acquired with a fixed sampling rate equal to 2 S/s.

V. RESULTS

The results acquired through the test of the developed system were compared with the values obtained through a simulation for the same operating conditions.

Figure 5b presents the values of incident irradiance on the plane of the PV generator throughout the test day. Figure 5a shows the power curve injected by PV generator to the battery bank; as well as the polarization voltage values of the photovoltaic generator. In this figure can be observed that the irradiance curve shows an abrupt transition at approximately 8:30 am and at 4:30 pm due to the projection of shadows [10]. On the other hand, it can also be noted that polarization voltage of the PV array remains practically constant throughout the test, this is due to the fact that the tracking method of the maximum power point implemented by the charge controller is fixed polarization at 13.8 V.



a) b)

Figure 5: Curves acquired during system characterization test. (a) PV generator injected Power and Array polarization voltage. (b) Irradiance

The Figure 6 presents a comparison between the current values measured on the battery bank during experimental test and the theoretical results obtained by simulation with developed mathematical model.

Theoretical and experimental results allow observing that the current vs. time curves present three specific operation zones:

In the first zone, comprised between 8 h and 12 h, the initial charge of the batteries occurs without feeding the netbook. That is, all current delivered by PV generator is injected into the battery bank until it reaches to a state of charge equal to 90%. At this moment the control system allows the flow of current from the PV generator and from the external batteries to the netbook (zone 2), fact that is reflected in a change of sign in current profile.

In Zone 2, we appreciate differences between the simulated and measured results. In the initial stage, the current demanded by the equipment presents a stage corresponding to the preload of the internal batteries that the equipment performs before enabling its use. It can be seen that the measured current has fluctuations associated with the demand profile of the netbook. The current fluctuations are composed of a stable type component, which responds to the internal batteries load control, and a higher frequency fluctuation associated with microprocessor consumption. The theoretical results obtained in zone 2 do not present such fluctuations because, due to the lack of data on the charge control of the internal batteries, the power demanded in this period of time has been considered constant.

Around 14:15 h, the state of charge of the external battery bank drops below 20%, causing the control of the system to interrupt the power supply to the netbook (start of zone 3). However, as solar radiation still incident over PV generator surface, the generated energy is used to restart the external battery bank charging process. The netbook continues to operate with its own batteries.

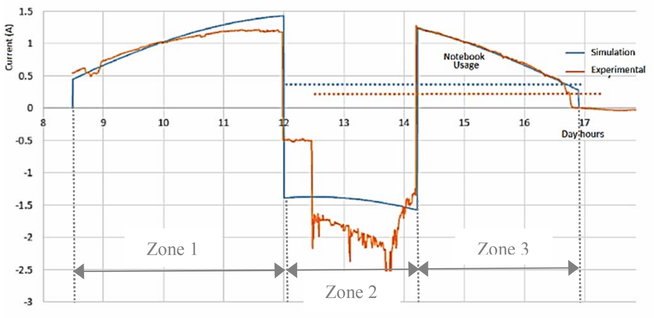


Figure 6: External battery bank current profile. Comparison between experimental and theoretical values.

To determine the overall autonomy it is necessary to know the equipment total useful time, for which the SoC must be evaluated through the values of internal batteries voltage. In simulation results (Figure 7) it is observed that the limit in internal batteries autonomy occurs when they drop below 10% of their SoC. This situation happens around the 16:50 pm granting a total autonomy of 4 hours 50 minutes to the netbook. The test started with a SoC very low for both batteries.

In experimental results, autonomy was calculated based on operative system (OS) events recording. The OS application shows the moment in which the control suspends the netbook due to internal battery discharge. The obtained useful time in this way extends from 12:27 h to 17:10 h, giving an autonomy of 4 hours 43 minutes.

In this way, it is observed that there is a difference between the theoretical and experimental results at the start and at the end of use of the equipment. This is due to the charge control of the internal batteries that prevents the use of the equipment until a minimum charge of its batteries is made.

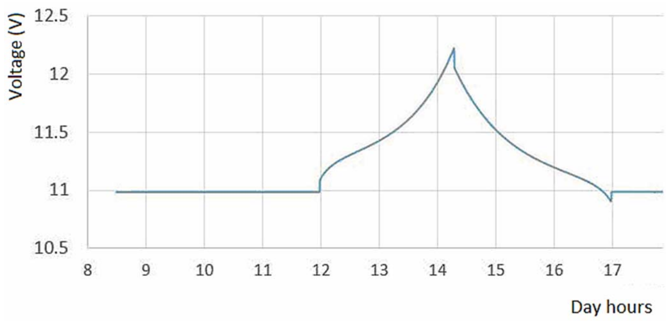


Figure 7: Internal batteries voltage profile

Despite the dynamic differences found, the autonomy determined by simulation compared with measured values are practically the same.

Table 1 presents the results of the energy (Ah) that enters and exits from the battery bank in each zone presented in figure 6. The small differences between theoretical and experimental values correspond to the type of load and irradiance profile specified for the adjustment of the mathematical model. In zones 1 and 3, specifically, this difference is caused by small differences in the measured irradiance values versus the modelled one. In zone 2, the constant consumption that has been used in the model does not include the actions of internal batteries charge control or the fluctuations in the processor demand, fact which produces the observed differences in the equipment consumption. However, in each zone, the results obtained experimentally correspond to the simulations, allowing the model to be validated.

TABLE I. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL VALUES BY ZONES

	Zone 1(Ah)	Zone 2(Ah)	Zone 3(Ah)
Simulation	3.69	3.26	2.15
Experimental Test	3.49	3.35	2.16
Difference (%)	-5.7	2.7	-0.5

VI. CONCLUTIONS

A mathematical model that allows the sizing of autonomous photovoltaic systems to power portable devices was developed. The presented model was verified experimentally and allows optimizing the size of equipment according to energy requirements. An analysis of load flows is carried out through the established control parameters and meteorological conditions to which the system is exposed. The simulation environment used allows a global analysis of the system behavior.

The mathematical model developed was validated through a specific application, experimentally characterized. This application was implemented as an energy backup system for ICTs.

By comparing theoretical and experimental results, the utility of the model as a design tool for this type of systems could be evaluated.

In this way, the results obtained shows that, for the case of the netbooks from the equality connect program; the developed equipment provides autonomy to the equipment. Starting from totally charged batteries, the autonomy of the same extends in approximately 5 (five) hours for a completely clear day.

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