Experimental evaluation of an analytic method for sizing standalone PV systems

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EXPERIMENTAL EVALUATION OF AN ANALYTIC METHOD FOR SIZING STAND-ALONE PV SYSTEMS

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ABSTRACT: The performance of a stand-alone PV system depends on the behavior of each component and on the solar radiation, size of PV-array and storage capacity. Therefore, the correct sizing plays an important role on the reliability of the stand-alone PV systems. The purpose of this paper is to present the experimental evaluation of an analytic method for sizing stand-alone systems in Brazil. The task of sizing a PV system consists of finding the PV-array area and the battery capacity that fit in well with the energy demanded and the behavior of solar radiation for a specific loss of load probability (LLP). The analytic method consists of calculating the slope of the modules and the isoreliability curves as a function of the latitude and clearness indexes. These curves can be obtained from two parameters, denominated *a* and *b*. Method A consists of finding the parameters *a* and *b* as a function of the latitude and in method B these parameters are obtained as a function of the latitude and clearness indexes. A stand-alone system was sized for Porto Alegre-RS-Brazil by using method B for a daily energy demand of 296 Wh/day and LLP=10^{-2}. As result, we found that system is formed by two modules of 50 W, two lead-acid batteries, C_{20} = 150 A.h, 12 V and the charge controller. The load is composed by four fluorescent lamps of 20 W. Measurements of the PV-array and batteries voltage shows that the performance of the PV system is the expected.
Keywords: Stand-alone PV system, Sizing

1 INTRODUCTION

Rural electrification programs have been launched in Brazil in the last decade [1], [2]. In these programs, the percentage of use of PV technology is increasing because consumers live in remote rural areas and the incidence of high amount of solar radiation in Brazil. Projects were successful carried out, but results not as good as expected were found. In order to improve larger scale application of PV systems in Brazil, specialists of the university, federal government, utility and industry are working together to develop purposes and actions.

The performance of a stand-alone PV system depends on the behavior of each component and on the solar radiation, size of PV-array and storage capacity [3-6]. Thus, the first approach to optimize a stand-alone PV system is to carry out an adequate sizing. This paper describes an analytic method and the analysis of experimental data obtained from a PV-system sized by the method.

2 ANALYTIC METHOD

2.1 PV-array and storage capacity

The electric energy provided by the PV system relies on the natural behavior of local solar radiation. Consequently, the system is related to a loss of load probability (LLP), defined as the ratio of energy deficit to energy demand.

The PV-array capacity C_A [7], [8] and the storage capacity C_S are defined related to average daily energy demand L:

$$C_A = \frac{\eta A G_{dm}}{L} \tag{1}$$

and

$$C_S = \frac{C}{L} \tag{2}$$

where, A is the PV-array area, η is the PV-array efficiency, G_{dm} is annual average daily irradiation on a horizontal surface and C is maximum energy that can be taken out of the batteries.

For specified location and LLP, the couples C_A-C_S allow us to obtain the isoreliability curve. Thus, the PV system can be sized starting from this curve and additionally considering the economic analysis.

The storage capacity represents how many days the battery can supply the demand, without any energy from the PV-array. For instance, if C_S = 5, this means that the batteries have stored energy for five cloudy days.

PV array capacity is defined as a function of annual average daily irradiation on a horizontal surface in order to make easier the task of sizing the PV system. However, the isoreliability curve is obtained considering the daily irradiation on PV-array during 10 years.

2.2 Proposed analytic method

The task of sizing a PV system consists of finding the slope of the modules as well as the PV-array area and the battery capacity that fit in well with the energy demand and the behavior of solar radiation for a specific loss of load probability. Some analytic methods were developed [9]-[10]. The proposed analytic method allows us to obtain the isoreliability curves for LLP=10^{-1} and LLP=10^{-2} for a stand-alone PV system in Brazil. To develop the method, a constant daily load during whole year was taking into account [11], [12]. The input data are latitude and clearness indexes. The slope of the module can be determined following a similar procedure.

The isoreliability curves are given by [13], [14]:

$$\ln(C_A + 1) = a[\ln(C_S)]^{-b} \tag{3}$$

Parameters *a* and *b* are calculated by a set of equations, presented in Table I, where ϕ is the absolute of latitude and Kt_{inv} is the daily average clearness index related to June, the month corresponding to the winter solstice.

Table I: Equations to estimate parameters *a* and *b*, for LLP=10^{-1} and LLP=10^{-2} as well as for both developed methods. These parameters can be used to size stand-alone PV systems in Brazil.

LLP	Met	Equations
10^{-1}	A	$\phi \le 20° \Rightarrow a = -2.5690x10^{-3}\phi + 7.6620x10^{-1}$
		$\phi > 20° \Rightarrow a = -7.7868x10^{-3}\phi + 1.4406x10^{-4}\phi^2 + 8.1540x10^{-1}$
		$\phi \le 20° \Rightarrow b = -2.9121x10^{-3}\phi + 9.2957x10^{-5}\phi^2 + 3.0472x10^{-2}$
		$\phi > 20° \Rightarrow b = 2.0441x10^{-3}\phi - 3.4187x10^{-2}$
	B	$\phi \le 20° \Rightarrow b = -8.4906x10^{-1}Kt_{min} + 7.6827x10^{-1}Kt_{min}^2 + 2.3670x10^{-1}$
		$\phi > 20° \Rightarrow b = -1.5558Kt_{inv} + 1.3128Kt_{inv}^2 + 4.6659x10^{-1}$
10^{-2}	A	$\phi \le 20° \Rightarrow a = -7.5410x10^{-3}\phi + 1.3774x10^{-4}\phi^2 + 9.4780x10^{-1}$
		$\phi > 20° \Rightarrow a = +9.8285x10^{-3}\phi + 6.5120x10^{-1}$
		$\phi \le 20° \Rightarrow b = 1.7241x10^{-4}\phi + 1.2220x10^{-1}$
		$\phi > 20° \Rightarrow b = 4.2578x10^{-2}\phi - 6.5387x10^{-4}\phi^2 - 4.6940x10^{-1}$
	B	$\phi \le 20° \Rightarrow a = -7.541x10^{-3}\phi + 1.3774x10^{-4}\phi^2 + 4.8608Kt_{med} - 5.2816Kt_{med}^2 - 1.4730x10^{-1}$
		$\boldsymbol{\phi > 20° \Rightarrow a = +9.8285x10^{-3}\phi - 7.2092Kt_{inv} + 6.5197Kt_{inv}^2 + 2.6190}$
		$\phi \le 20° \Rightarrow b = 3.6277Kt_{med} - 4.1920Kt_{med}^2 - 6.2630x10^{-1}$
		$\boldsymbol{\phi > 20° \Rightarrow b = -5.7709Kt_{inv} + 4.6904Kt_{inv}^2 + 1.8933}$

Two methods can be used. Method A consists of finding the parameters *a* and *b* as a function of the latitude and in method B these parameters are obtained as a function of the latitude and clearness indexes.

The slope of the modules can also be calculated by a set of equations. Both methods are present in Table II. For LLP=10^{-1}, method B was not developed because method A presents very good results.

Table II: Equations to obtain the slope of the modules (β) for LLP=10^{-1} and LLP=10^{-2} as well as for both developed methods.

LLP	Met.	Equations
10^{-1}	A	$\phi \le 7° \Rightarrow \beta = 10°$
		$\phi > 7° \Rightarrow \beta = 1.860 + 1.081\phi$
10^{-2}	A	$\phi < 5° \Rightarrow \beta = 10°$
		$5° \le \phi \le 20° \Rightarrow \beta = 9.067 + 5.865x10^{-1}\phi$
		$\phi > 20° \Rightarrow \beta = 5.166 - 2.882x10^{-1}\phi + 5.666x10^{-2}\phi^2$
	B	$\phi < 5° \Rightarrow \beta = 10°$
		$5° \le \phi \le 20° \Rightarrow \beta = 38.924 + 5.865x10^{-1}\phi - 54.416Kt_{inv}$
		$\boldsymbol{\phi > 20° \Rightarrow \beta = 18.021 - 2.882x10^{-1}\phi + 5.666x10^{-2}\phi^2 - 25.261Kt_{inv}}$

3 SIZING THE STAND-ALONE PV SYSTEM

A PV-system at Porto Alegre (ϕ = - 30°) was designed by using method B for a daily energy demand of 296 Wh/day and LLP=10^{-2}. The equations marked up in both tables were used. Taking into account the latitude and Kt_{inv} for Porto Alegre, we obtained a = 0.97096 and b = 0.22359. Then, Eq. 3 was used and for C_S = 7 the PV-array capacity estimated is of 1.309. From Eq. 1, η = 11% and G_{dm} = 4457 Wh/m^2 the PV-array area is found equal to 0.87 m^2, corresponding to two modules of 50 W.

A structure support was designed to install both modules, as illustrated in Fig. 1. The energy loss and the inaccuracy of the method were considered equal to 10%. The battery capacity for the selected PV-array capacity is 1813 Wh/day. Two lead-acid batteries, C_{20} = 150 A.h, 12 V, were assembled to the power system and the maximum depth of discharge of 60% is controlled by the charge controller. Maximum electrical current supported by controller is 10 A. The cut-off voltage is of 11 V and voltage of reconnection is 12.5 V. High threshold voltage to protect the battery against overcharge is 14.2 V and the reconnection is implemented when voltage reaches 13.4 V.

The load is composed of four fluorescent lamps of 20 W and they turn on and turn off by a timer system, as shown in Fig. 2.

Figure 1: Modules installed on the structure support.

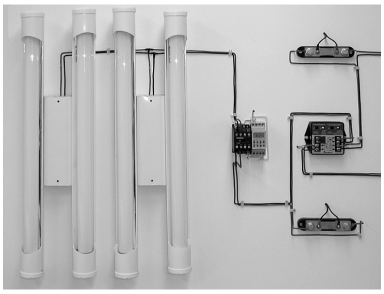

Figure 2: Fluorescent lamps, charge controller, shunts and timer system.

4 EXPERIMENTAL RESULTS

The system was installed and a data acquisition system was developed in order to monitor and record experimental data. It is composed of a microcomputer, a GPIB interface and a 20-channels multiplexer plugged into a 6½ digital multimeter. Fig. 3 illustrates the data acquisition system. Battery array voltage, current from modules, current through lamps, ambient temperature and irradiance have been measured and the data have been saved each two minutes interval. The electrical currents are measured using a shunt for current up to 50 A. The current through lamps will be used to calculate the LLP of the system.

Figure 3: Data acquisition system.

Fig. 4 presents the output power of the PV system and the power consumed by load during a clear day in autumn. We observed that energy produced by modules is 20% less than expected and the ratio of daily energy produced by PV-array to the energy demanded by the constant load is 1.8. Monthly average daily electrical energy supplied by PV system is illustrated in Fig. 5. The values varies of 207 Wh/day (June) to 275 Wh/day (January and December).

In Fig. 6 the evolution of the battery array voltage is shown, for the same day of autumn. We note that batteries voltage falls down when energy is requested by the load. The monthly average daily voltage is given in Fig. 7. We observe that in winter voltage is 12.2 V, 4 % lower than in summer. Consequently, we conclude that the performance of the stand-alone PV system is the expected. To carry out an extended analysis, long time measurements are needed.

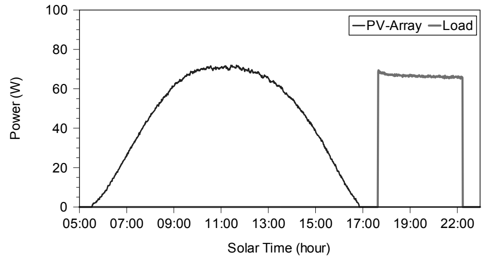

Figure 4: Output power of the PV system and power consumed by load at a clear day.

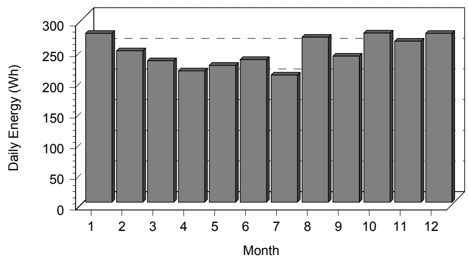

Figure 5: Monthly average daily electrical energy supplied by PV system.

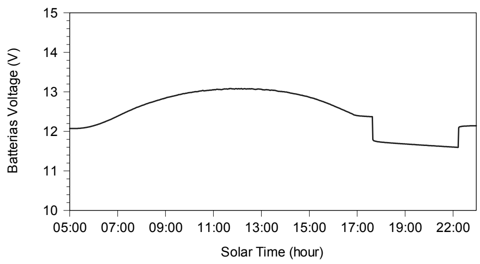

Figure 6: Evolution of the battery array voltage at a clear day.

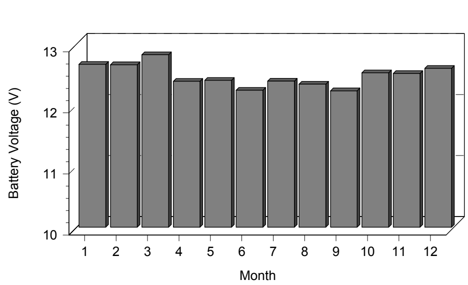

Figure 7: Monthly average daily battery array voltage.

5 CONCLUSIONS

The stand-alone PV system was sized by the new analytic method. The power system was installed and monitored in order to analyze the proposed method. The experimental data shows that PV system supplies the energy demand as required.

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