ANALYTIC METHOD FOR SIZING STAND-ALONE PV SYSTEMS IN BRAZIL

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ABSTRACT: Good performance of a stand-alone system is related to correct sizing. The purpose of this paper is to present 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 demand and the behaviour of solar radiation for a specific loss of load probability (LLP). To achieve this goal, a computer program was developed to simulate a stand-alone system with constant demand during the year. The system was simulated during ten years in order to find the slope of the modules that leads to the lowest PV-array cost for LLP=10^{-1} and LLP=10^{-2}. The procedure was then applied to obtain the isoreliability curves, i.e. the PV-array capacity as a function of the storage capacity, for both LLPs. This approach was carried out for 144 Brazilian cities. Equations were fitted to the values of slope of the modules found for each place as a function of the latitude and clearness indexes. The isoreliability curves can be obtained if two parameters, denominated *a* and *b*, are estimated. Two methods are presented. The method A consists of finding the parameters *a* and *b* as a function of the latitude and in the method B these parameters are obtained as a function of the latitude and clearness indexes. In this way, a stand-alone system can be more easily sized in Brazil, starting from a set of equations. The proposed analytic methods were applied to size a stand-alone system in Torres (latitude = - 29.3º). For LLP=10^{-2}, the difference between the simulated and estimated values is lower than 10% and 6% when method A and method B are used, respectively.
Keywords: Stand-Alone PV System; Sizing.

1 INTRODUCTON

Good performance of a stand-alone PV system is related to the correct sizing. However, for many places irradiation data does not exist to design the system and it is usually sized intuitively. Consequently, many problems may appear for users. For instance, if the system is oversized it becomes expensive and if it is undersized, the produced energy is not as expected.

The methods based on the simulation of the system for a large period are a good approach for sizing the system. However, in many times this kind of computer program is not available and, on the other hand, it is not easy to use. Due to these facts, some analytic methods were developed [1]-[4]. The purpose of this paper is to present 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 demand and the behaviour of solar radiation for a specific loss of load probability (LLP).

2 SIMULATION OF A STAND-ALONE PV SYSTEM

2.1 Estimation of Daily Irradiation

In this simulation, the input data includes: slope of the module β, loss of load probability, storage capacity, PV-array efficiency and monthly average daily irradiation on a horizontal surface.

A sequence of daily clearness indexes is generated by the Aguiar's Method [5] and by using the monthly average daily irradiation on a horizontal surface. Following this, the daily irradiation is split into its beam and diffuse components on a horizontal surface [6]. Starting from the daily total and diffuse irradiation, the hourly irradiation data on a horizontal surface are estimated, using the method proposed by Collares-Pereira and the ratio of hourly diffuse to daily diffuse irradiation is obtained from Liu-Jordan model [6], [7]. The hourly diffuse irradiation on a tilted surface is calculated using the Perez's model [8]. Hourly solar irradiation data is used because the methods to estimate the hourly diffuse irradiation on PV-array is more accurate. Then, the daily irradiation is obtained starting from the hourly values.

2.2 Performance of Stand-Alone PV Systems

The electric energy provided by the PV system relies on the natural behaviour of local solar radiation. Consequently, the system is related to a loss of load probability (LLP) [1]-[4], [9],[10] defined as the ratio of energy deficit to energy demand.

The PV-array capacity C_A [1], [2] and the storage capacity C_S [2] are defined related to average daily energy demand L:

$$C_A = \frac{\eta A G_{dm}}{L} \qquad (1)$$

and

$$C_S = \frac{C}{L} \qquad (2)$$

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

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.

In order to calculate LLP, the daily state of charge (SOC) of the batteries is simulated for each day, during ten years. The state of charge is the ratio of available to nominal capacity of batteries. At the end of day **i,** SOC is obtained by doing a balance of energy consumed by users and supplied by PV-array, as follows:

$$SOC(i) = \min\left[SOC(i-1) + \frac{C_A G_d(\beta)}{C_S G_{dm}}\eta_{Bc} - \frac{1}{C_S};1\right] \quad (3)$$

η_{Bc} = charge efficiency of the batteries and
$G_d(\beta)$ = total daily irradiation on PV-array.

In these equations, we assume that all energy produced by the PV-array passes through batteries and a constant daily load during whole year [3], [11], [12]. If SOC is greater than 1, it's assumed to equal 1. On the other hand, if a lack of energy occurs, then SOC is negative. This means that the available energy is lower than that demanded by users. Then, the deficit of energy is:

$$E_D(i) = |SOC(i)|C_S \quad (4)$$

and SOC(i) is reduced to zero. This procedure is carried out for every N days and LLP is given by:

$$LLP = \frac{\sum_{i=1}^{N} E_D(i)}{N} \quad (5)$$

Using this procedure, LLP is obtained as a function of C_A and C_S. However, we need to calculate C_A for a determined LLP and C_S. An interactive method is used to achieve this goal.

The optimisation of the slope of the modules consists of finding the value that leads to the lowest cost of PV-array. Bearing this in mind, the cost of PV-array is normalised to the daily energy demand:

$$P_N = \frac{P}{L} = \frac{C_A}{\eta G_{dm}} P_{mod} \quad (6)$$

where P_{mod} is the price per square meter of the modules.

The system is simulated for a ten years period and the LLP is obtained from the analysis of the state of charge of the batteries and an initial value of C_A. An interactive method is used to calculate C_A for a determined LLP and C_S.

3 PROPOSED ANALYTIC METHOD

The computer program was carried out for 144 Brazilian cities, illustrated in the Figure 1. The system was simulated for a ten years period in order to find the slope of the modules (β) that leads to the lowest PV-array cost for LLP=10^{-1} and LLP=10^{-2}. The lowest slope was limited to 10^o, because for low latitudes its optimum value is smaller than 10^o. Then, the procedure was applied to obtain the isoreliability curves, i.e., the PV-array capacity as a function of the storage capacity, for both LLPs. A isoreliability curve are illustrated in Figure 2.

The isoreliability curves can be fitted by the following equation [2]:

$$C_A = aC_S^{-b} \quad (7)$$

where *a* e *b* are parameters which depend on the LLP and location. However, analyzing the results we concluded that Equation 7 can be modified by:

$$\ln(C_A + 1) = a[\ln(C_S)]^{-b} \quad (8)$$

The parameters *a* and *b* were calculated for the 144 locations and a set of equations was found to estimate both parameters as well as the slope of the modules. Two methods are presented. The method A consists of finding the parameters *a* and *b* as a function of the latitude and in the method B these parameters are obtained as a function of the latitude and clearness indexes.

Figure 1: Distribution of the 144 Brazilian cities selected to simulate the stand-alone PV system.

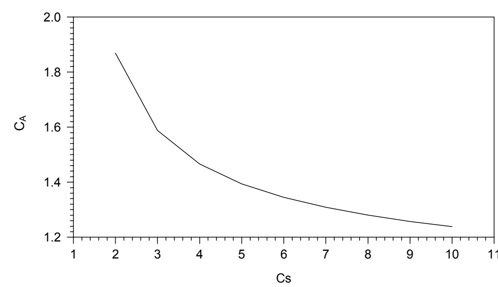


Figure 2: The isoreliability curves for a stand-alone system at Porto Alegre ($\phi = -30^o$) and for LLP=10^{-2}.

4 RESULTS AND DISCUSSION

We verified that the optimum slope of the modules increases as a function of the latitude (ϕ), but the behaviour is not linear and depends on the LLP. Then, equations to estimate β as a function of latitude were found, in order to define the method A, for both LLPs. The results are 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.

The comparison of estimated (V_{Est}) to simulated (V_{Sim}) values is carried out by the average deviation, defined as follows:

$$D_{Aver} = \frac{\sum_{i=1}^{n}\left|\frac{V_{Est} - V_{Sim}}{V_{Sim}}\right|}{n} 100\% \quad (9)$$

For method A and LLP=10^{-1}, D_{Aver} = 4.5%. In this case, the value of the average deviation is low, then it is not necessary to develop method B. However, for LLP=10^{-2}, the average deviation, for method A, is equal to 24.6% and 8.4% for latitudes lower than 20^o and higher than 20^o, respectively. When method B is used this values became equal to 15.9% and 7.9%, for latitudes lower than 20^o and higher than 20^o, respectively. From an analysis of the influence of the difference between the estimated and simulated values of β, we concluded that variation of 10º results in an increase cost of the PV-array of 3%.

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

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

Figure 3 compares the simulated values of the slope of the modules with that estimated by method A and method B. We observe that for LLP=10^{-1}, method A fits in well to simulated data. Similarly, method B yields better fits to low latitudes.

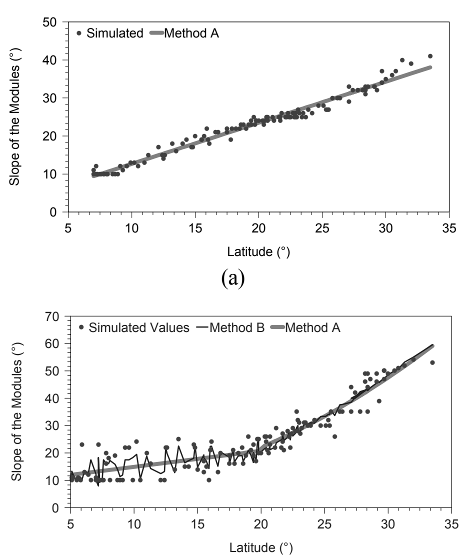


Figure 3: Simulated slope of the modules and values estimated by method A and method B for (a) LLP=10^{-1} and (b) LLP=10^{-2}.

Table II: Equations to estimate parameters *a* and *b*, for LLP=10^{-1} and LLP=10^{-2} as well as for both developed method. These parameters can be used to size stand-alone 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	$\phi \le 20° \Rightarrow a = -7.541x10^{-3}\phi + 1.3774x10^{-4}\phi^2 + 4.8608Kt_{med} - 5.2816Kt_{med}^2 - 1.4730x10^{-1}$
		$\phi > 20° \Rightarrow a = +9.8285x10^{-3}\phi - 7.2092Kt_{inv} + 6.5197Kt_{inv}^2 + 2.6190$
		$\phi \le 20° \Rightarrow b = 3.6277Kt_{med} - 4.1920Kt_{med}^2 - 6.2630x10^{-1}$
		$\phi > 20° \Rightarrow b = -5.7709Kt_{inv} + 4.6904Kt_{inv}^2 + 1.8933$

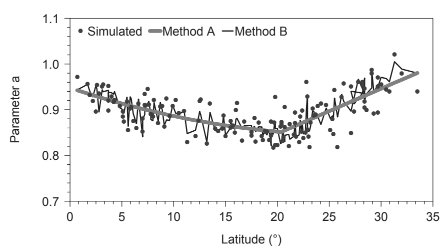
From Equation 8 and the isoreliability curves determined for each location, the *a* and *b* parameters were calculated. Then, a set of equations was obtained to estimate these parameters for both LLPs and methods. The results are summarized in Table II, where Kt_{min} is the daily average clearness index related to the month that presents the lowest irradiation data.

The analysis of average deviation demonstrates that parameter *a* presents good result and the values of D_{Aver} are lower than 3.3%. For high LLP and method A, the average deviation is of 0.5% and, then, method B is not necessary. From Equation 8, we verify that this parameter influences strongly the value of C_A, meanwhile, the parameter *b* affects the shape of the curve. The average deviation of the parameter *b* is high, as shows Table III.

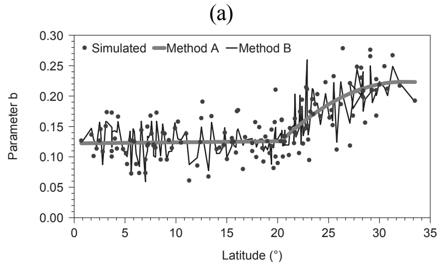
The results obtained with method A and method B as well as the simulated values of parameters *a* and *b* for LLP=10^{-2} are presented in Figure 4. We observe that better results were obtained with method B.

Table III: Average deviation (D_{Aver}) of the parameter *a* and *b* estimated by using method A and method B as well as for LLP=10^{-1} and LLP=10^{-2}.

LLP	Met.	Parameter		D_{Aver} (%)
10^{-1}	A	a	$\phi \leq 20^o$	0.5
			$\phi > 20^o$	0.8
		b	$\phi \leq 20^o$	68
			$\phi > 20^o$	53
	B	b	$\phi \leq 20^o$	38
			$\phi > 20^o$	30
10^{-2}	A	a	$\phi \leq 20^o$	2.4
			$\phi > 20^o$	3.3
		b	$\phi \leq 20^o$	20
			$\phi > 20^o$	17
	B	a	$\phi \leq 20^o$	1.6
			$\phi > 20^o$	2.5
		b	$\phi \leq 20^o$	13
			$\phi > 20^o$	12



(a)



(b)

Figure 4: Simulated and estimated values of the (a) parameter *a* and (b) parameter *b*, using both proposed methods and for LLP=10^{-2}.

5 CONCLUSIONS

The method B presents the better results, but if irradiation data does not exist, the method A can be used with only a slightly decreasing of accuracy. Both proposed analytic methods were applied to size a stand-alone system in Torres (ϕ = -29.3°). This location was selected because the results presented the highest difference between the simulated and estimated values. For LLP=10^{-2}, this difference is lower than 10% and 6% when method A and method B are used, respectively.

In summary, two analytic methods for sizing stand-alone systems in Brazil were developed and analysed. Such methods can easily be used by PV system designer in order to obtain cost effective systems.

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