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Calculation of the weighted average efficiency of photovoltaic systems in the Brazilian State of Santa Catarina

Alexandre Kellermann, Renê Alfonso Reiter and Adriano Péres

Department of Electrical and Telecommunications Engineering
Regional University of Blumenau
Rua Sao Paulo, 3250
89030-000 – Blumenau, SC – Brazil
e-mail: alexandre.kellermann@gmail.com, aperes.furb@gmail.com

Abstract. This paper analyses the solar radiation profile of three cities of the Brazilian State of Santa Catarina and shows the calculation of the weighted average efficiency, aiming to allow efficiency maximization designs for the electrical energy processing in photovoltaic systems. By means of data obtained in climatic stations the electrical generation capacity of these stations is shown to optimize the design of power converters. It is shown the results for the cities of Indaial, Itajai and Florianopolis.

Key words

Photovoltaic systems, renewable energy, weighted average efficiency.

1. Introduction

Among renewable sources, solar photovoltaic (PV) energy is one of the most plentiful throughout the Earth's surface and is endless in the human timescale. Therefore, it is one of the most promising alternatives for the composition of a new energy matrix worldwide [1]. It is expected that until 2040 this would be the most important and significant renewable energy source to the world [2], [3].
The conversion of solar energy into electrical energy directly involves sophisticated technologies of semiconductor manufacturing to produce PV cells that meet criteria such as better efficiency, low cost and suitable lifetime [4].
This paper presents the operating principle and basic characteristics of silicon PV cells, since this is the most employed semiconductor in its production. A fundamental aspect for the implementation of PV systems is the knowledge of the characteristics of solar radiation in the location that the system will be installed [5]. In Brazil the atlas of solar irradiation are currently available to assist engineers in the design of PV systems [6]. However, only the appropriate design and specification of modules is not sufficient for the operation of a high performance system. For this reason, this paper aims to investigate the availability and the characteristics of solar irradiation for three cities of the Brazilian State of Santa Catarina: Indaial, Itajai and Florianopolis using the methodology presented by [6].
Santa Catarina is located in the south of Brazil and this area has a subtropical climate with very well defined seasons. This area has a very humidity climate and it interferes in the level of irradiation and in consequence in the level of the possible energy generated by the photovoltaic systems.
By means of the analysis of data sets from solar and weather stations it is presented the calculation of the weighted average efficiency of PV systems using the methodology proposed in [6]. Such data enables the design and implementation of high performance and high efficiency systems, maximizing the potential of the generation system installed, producing more power and enabling more information to the payback time calculation [6].

2. Photovoltaic Panel Model

The knowledge of the physical structure of a photovoltaic module is essential for a better understanding of the behaviour of a system of panels under different operating conditions. The ideal model is not used for its low fidelity by virtue of not considering the eddy current (leakage current and conduction losses). The real model considers these losses being applied in the vast majority of scientific studies with very satisfactory results; both models are illustrated in Fig. 1 [7], [8].

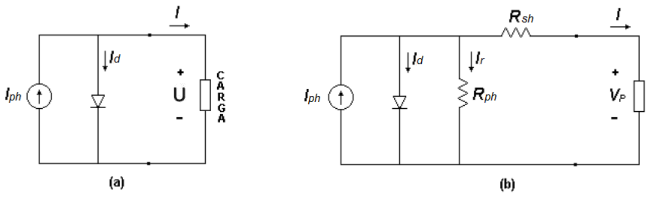

Fig. 1. Equivalent circuit of the solar panel connected to a load: *(a)* the ideal model and *(b)* the real model.

Using the electric equivalent scheme of a PV panel it is possible to associate current or voltage equations to each element in Fig. 1 *(b)*. The output current is given by Equation (1).

$$I = I_{ph} - I_d - I_r \qquad (1)$$

The current I_{ph} is given by the Equation (2) and it varies as a function of solar radiation and temperature.

$$I_{ph} = \left[I_{SC} + J_o\left(T - T_{ref}\right)\right]\frac{S}{S_{ref}} \qquad (2)$$

Where I_{SC} is the panel short-circuit current, J_o is the temperature coefficient, T is the temperature of the PV module, T_{ref} is the reference temperature, S is the solar radiation and S_{ref} is the reference solar radiation.

The diode current, I_d (3), in parallel with the power source features a temperature-dependent non-linear behavior of the panel as well as the state of its operation. This is the main equation associated with the diode. The variable I_o (4) is the reverse saturation current of the diode.

$$\mathbf{I_d} = \mathbf{I_o}\left(\mathbf{e}^{\frac{q.(I.R_{sh+V})}{N_S.n.K.T}} - \mathbf{1}\right) \qquad (3)$$

$$\mathbf{I_o} = \mathbf{I_{D0}}\left(\frac{T}{T_{ref}}\right)\mathbf{e}^{\frac{q.E_g}{n.K}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \qquad (4)$$

Where K is the Boltzmann constant and E_g is the band semiconductor power.

This described model could be used in most applications involving PV cells. However the single exponential model of PV cell is a non-linear transcendental equation with no direct algebraic solution, so its solution requires the use of indirect algebraic methods or computational tools [8].

3. Model Validation

Manufacturers of PV modules provide some important information to design systems based on energy generation from solar PVs. Two curves are very useful to understanding the characteristics of the PV panel: the I-V curve and the P-V curve. The I-V curve shows the maximum panel current (I_{SC}) and open circuit voltage (V_{OC}) as a function of temperature and the P-V curve gives the characteristics of the maximum power generated as a function of the solar irradiation. However the manufacturers do not provide all the data to adjust the mathematical model like: photovoltaic current, resistors value, diode quality factor, reverse saturation current and energy of semiconductor band [7]. Without these values it is impossible to predict reliable experimental results, so it is necessary the use of computational tools to solve the equations of the mathematical model.

The studies made in this paper used the KD245GH Panel (Kyocera) who has the characteristics given in Table I and the missing data were calculated and are given in Table II.

The application of the parameters given in Table II allows to obtain the curves (I-V) in different conditions of temperature and radiation. The results obtained from the single-exponential model are very close to the provided by the supplier's datasheet.

4. Weighted Average Efficiency

In addition to the variation of solar radiation to a particular region another factor that affects the performance of a PV system are the climatic conditions. Within these conditions were created the concepts of inverter efficiency in order to extract the maximum power in addition to assist in sizing the PV assembly.

The IEC 61683:2000 establishes the basic procedures for assessing the performance of power conditioners connected to PV modules. To take into account the characteristic of variability at the point of operation depending on weather conditions and the standard establishes the concept of weighted average (η_W). The IEC 61683 establishes that the converters should be assessed in 5%, 10%, 25%, 50%, 75%, 100% and 120% of the nominal power, being that these benchmarks will also be used in the course of this work.

From the statistical data analysis of weather conditions in central Europe the concept of European weighted average was defined as [5]:

$$\eta_{EU} = 0,03_{\eta 5\%} + 0,06_{\eta 10\%} + 0,13_{\eta 20\%} + 0,10_{\eta 30\%} + 0,48_{\eta 50\%} + 0,20_{\eta 100\%} \qquad (5)$$

In the same manner the California Energy Commission (CEC) created the CEC efficiency to meet the profile of California solar radiation, similar to European efficiency also uses a weighted average of efficiencies in several load conditions of an inverter, represented in Equation (6) [5].

$$\eta_{CEC} = 0,04_{\eta 10\%} + 0,05_{\eta 20\%} + 0,12_{\eta 30\%} + 0,21_{\eta 50\%} + 0,53_{\eta 75\%} + 0,05_{\eta 100\%} \qquad (6)$$

Using this methodology [5] it is developed diferent equations for three cities in the Brazilian state of Santa Catarina. It is very important because the country is very large and present diferent climates between the states and Santa Catarina don't have any studies about the weighted average of efficiency.

The data obtained are from july 2010 to june 2014 adding 48 months with daily records measured every 5 seconds. Considering a hypothetical system formed by a photovoltaic module and an inverter it is possible to analyze the energy production capacity. Fig. 2 presents the classification of the mean values of solar radiation and the portion of energy associated, as well as the frequency that occurs throughout the year.

Table I – KD245GH electrical PV specifications

Characteristics	Value	Unit
Number of Cells	60	-
Maximum power (P_{max})	245	W
Voltage at maximum power (V_{max})	29.8	V
Current at maximum power (I_{max})	8.23	A
Current in short circuit (I_{SC})	8.91	A
Open circuit voltage (V_{OC})	36.9	V
Temperature coefficient of I_{SC}	0.06	%/°C
Temperature coefficient of V_{OC}	-0.36	%/°C
Temperature coefficient power	-0.46	%/°C
Nominal operating temperature	45	°C

Table II – Electrical specifications obtained through calculation

Characteristics	Value	Unit
Saturation current of I_0	8.4294×10^{-7}	A
Diode quality factor (a)	1.12	-
Equivalent series resistance Rs	0.19	Ω
Equivalent parallel resistance Rp	90.562	Ω

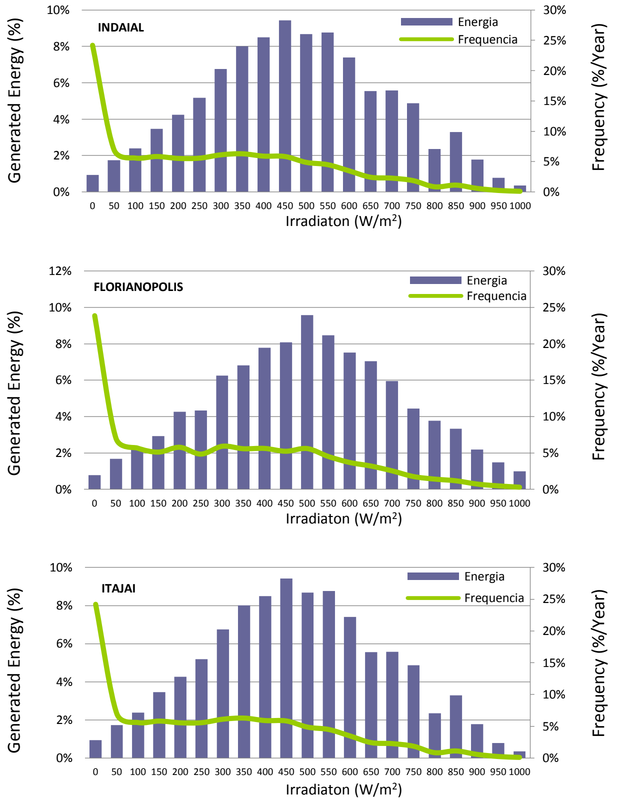

Fig. 2 – Energy available per year for each band of radiation and frequency of occurrence

With these data it is obtained the mean values provided by INMET (National Institute of Meteorology) and the maximum power of the photovoltaic module is determined. These records are divided into seven Classes that match the seven tracks of powers established by IEC 61683. Before the PV system design and the procedure for determining the maximum power output the Fig. 3 presents the results of this classification and frequency of occurrence in each class along the year.

In Table III it is shown the power generated rating for the proposed PV system if it is installed in the city of Indaial and it could be seen that the Class 4 (47%) contribute to the larger share in power generation. From these data it could be obtained the relationship between the average energy and the sum of the system which gives the Equation (7) represents the weighted average to the city of Indaial, Brazil.

$$\boldsymbol{\eta_{IDL} = 0,02_{\eta 5\%} + 0,02_{\eta 10\%} + 0,13_{\eta 25\%} + 0,47_{\eta 50\%} + 0,32_{\eta 75\%} + 0,04_{\eta 100\%}} \quad (7)$$

In Table IV it is shown the power generated rating for the proposed PV system if it is installed in the city of Florianopolis, the Santa Catarina Capital, and it could be seen that the Class 4 (43%) contributes to the larger share in power generation. From these data it could be obtained the relationship between the average energy and the sum of the system which gives the Equation (8) represents the weighted average to the city of Florianopolis, Brazil.

$$\boldsymbol{\eta_{FNS} = 0,02_{\eta 5\%} + 0,02_{\eta 10\%} + 0,12_{\eta 25\%} + 0,43_{\eta 50\%} + 0,35_{\eta 75\%} + 0,05_{\eta 100\%}} \quad (8)$$

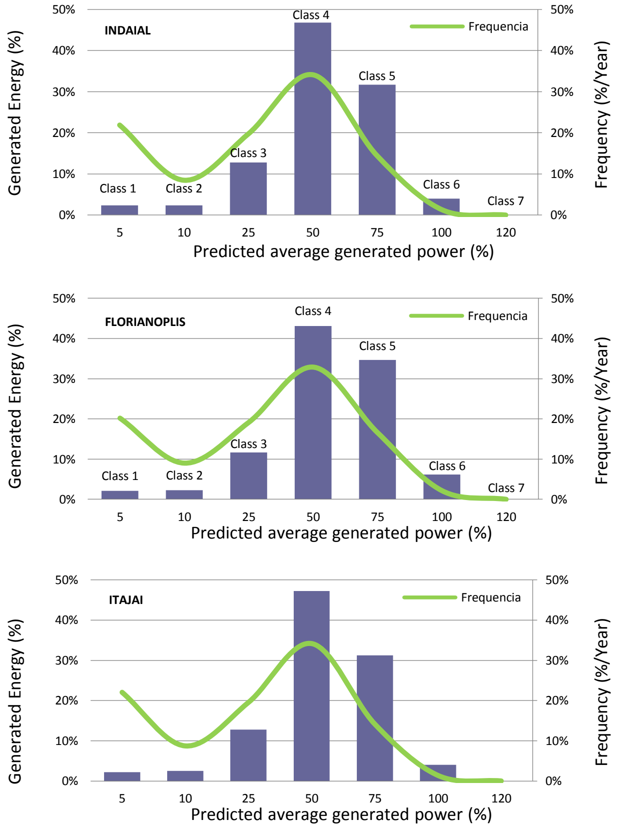

Fig. 3 – Available energy per year as power band established by IEC 61683 for a 245W system in the city of Indaial, Florianopolis and Itajai – Brazil.

Table III – Classification of energy generated annually by a KD245 module in the city of Indaial.

Class	Average Power (W)	Frequency of occurrence (h)	Average Power (kW h)	Weighting
Class 1	12.25	1121	7.9888	0.023505
Class 2	24.5	434	8.1475	0.023972
Class 3	61.25	1011	43.3660	0.127591
Class 4	122.5	1748	159.0210	0.467871
Class 5	183.75	740	107.6693	0.316784
Class 6	245	70	13.6899	0.040278
Class 7	294	0	0.0000	0.000000
Total		5124	339.8825	1.000000

Table IV – Classification of energy generated annually by a KD245 module in the city of Florianopolis.

Class	Average Power (W)	Frequency of occurrence (h)	Average Power (kW h)	Weighting
Class 1	12.25	1022	7.5564	0.021336
Class 2	24.5	456	7.9690	0.022502
Class 3	61.25	969	41.2930	0.116596
Class 4	122.5	1.665	152.7799	0.431394
Class 5	183.75	841	122.7489	0.346597
Class 6	245	110	21.8070	0.061575
Class 7	294	0	0.0000	0.000000
Total		5063	354.1541	1.000000

In the same manner the Table V shows the power generated rating for the proposed PV system. From these data it could be obtained the relationship between the average energy and the sum of the system which gives the Equation (9) represents the weighted average if it is installed in the city of Itajai.

$$\boldsymbol{\eta_{IAI} = 0,02_{\eta 10\%} + 0,02_{\eta 20\%} + 0,13_{\eta 30\%} + 0,47_{\eta 50\%} + 0,32_{\eta 75\%} + 0,04_{\eta 100\%}} \quad (9)$$

Table V – Classification of energy generated annually by a KD245 module in the city of Itajai.

Class	Average Power (W)	Frequency of occurrence (h)	Average Power (kW h)	Weighting
Class 1	12.25	1130	7.3702	0.021839
Class 2	24.5	447	8.3419	0.024719
Class 3	61.25	1.002	43.1114	0.127746
Class 4	122.5	1.751	159.3858	0.472287
Class 5	183.75	724	105.5725	0.312829
Class 6	245	70	13.6950	0.040580
Class 7	294	0	0.0000	0.000000
Total		5124	337.4767	1.000000

5. ECONOMICAL ANALISYS

Table VI shows that the energy output of a photovoltaic module is very similar in the three cities considered.

Table VI – Power Rating generated annual and monthly for KD245 module.

City	Average Power (kW h) - Year	Average Power (kW h) - Month
Indaial	339.88	28.32
Florianopolis	354.15	29.51
Itajai	337.47	28.12

On the basis of this information it is presented a brief economic study for a system installed with 1.9 kWp operating since January 2013.

To set the amount of modules it is used the equation (10) indicating the need of 8 KD245 modules, representing a monthly power of 226,588 kWh (using as reference the energy generated based on solar radiation of Indaial).

$$\mathbf{N} = \frac{Pt}{Pp} \qquad (10)$$

Where:
N is the number of power modules,
Pt is the total nominal power,
Pp is the nominal power of each panel

In Table VII it is presented the general investments needed to implement the system.

Table VI – Project Costs

Item	Cost U$	Lifetime (Years)
Photovoltaic panel	3071	25
Mounting bracket	286	25
Converter	1740	15
Electrical Conduits	53	15
Cables / stretch DC	25	15
Junction box	71	15
Breakers DC	5	15
Terminal strip	10	15
Cable glands	29	15
Ground rod	4	15
Cables / stretch CA	25	15
Circuit Breakers AC	4	15
Meter	1143	15
Electromechanical installation	500	15
Total	**6966**	

Maintenance costs include expenses for preventive maintenance, minor repairs and cleaning of panels annually. The value of total investment in the facility is the current value for install the PV System, already contemplating the freight costs of the converter, photovoltaic panels and meter. This investment at the end of life in 15 years is the cost to the decapitalisation present value, converter and other exchange equipment.

The system generates 226,588 kWh per month and the accumulated in one year is 2719,06 kWh. With this information one can use the equation (11) to calculate the equivalent amount of money saved with the energy generated.

$$\mathbf{U\$(eco) = Eg(year) * T} \qquad (11)$$

Where:
U$ (eco) is the equivalent amount of money saved in one year,
Eg (year) is the PF generated energy injected in the grid and
T is the kWh cost in US$ in Santa Catarina for residences (US$ 0.243 per kWh).

So, the total amount saved results in:

$$\mathbf{U\$(eco) = 2719,06 * 0.243 = U\$\ 662.27}$$

The simple payback period (SPP) measures the time required to recover the investment made, resulting in the relationship between the initial investment in energy efficiency and the savings in one year. It is given by (12).

$$\mathbf{SPP} = \frac{\boldsymbol{investiments\ (U\$)}}{\boldsymbol{saivings\ per\ year\ (U\$)}} \qquad (12)$$

Using (12) the SPP results in:

$$\mathbf{SPP} = \frac{6966}{662.27} = 10.5\ years$$

It is a good return as the service life of the PV array, however, this type of calculation is simplistic and easy to use, but does not consider the time value of money, i.e. the cost of capital. For this, it is used another figure of merit which is the economic payback period discounted (PPD), which considers the value of the capital cost which is the discount rate and the lifetime of the investment, as it is expressed by (13).

$$\mathbf{PPD = n \times CRF(d, n) \times SPP} \qquad (13)$$

Where:
n is the investment lifetime in years,
CRF is the capital recovery factor,
SPP is the simple payback period and
d is the discount rate.

The capital recovery factor (CRF) is used for analysis of energetic alternatives, which calculates the value of a specific investment made in the present with a **d** discount rate in a period of **n** years.

$$\mathbf{CRF(d, n)} = \frac{\boldsymbol{d(1+d)^n}}{\boldsymbol{(1+d)^n - 1}} \qquad (14)$$

As defined by ANEEL (The National Agency of Electrical Energy) the discount rate **d** is 10.85%. The life of the Panel is about 25 years. Using (14) the CRF results in 0.117 and using (13) results in:

$$\mathbf{PPD = 25 \times 0.177 \times 10.5 = 31\ years}$$

When it is considered the cost of the money the investment recovery time becomes higher than the lifetime of the devices used to implement the system. These numbers indicate that it is not viable to invest in photovoltaic systems in the State of Santa Catarina, Brazil with these parameters. Similar numbers could be obtained in other states of Brazil, maybe some states in the north of the country could have best recovery time do to the higher solar irradiation.

Unfortunately the numbers are very dependent of taxes. The electrical energy in Brazil has about 40% of taxes and the country has no incentive program to photovoltaic generation in residences.

6. Conclusion

The characteristics of photovoltaic cells was analysed by means of mathematical modelling using the single-exponential model. With the meteorological data and using the concept of weighted efficiency established by IEC 61683 it was calculated the weighted average efficiency of photovoltaic systems in three cities of the Brazilian State of Santa Catarina: Indaial, Florianopolis and Itajai. These equations serve to make analysis about the potential of solar generation, optimizing the efficiency of photovoltaic generation system allowing the investor to know the payback level and the return time of a possible investment. Nowadays it is not viable economically meaning to generate photovoltaic energy in Brazil do to the excessive taxes in the electrical power system. It is urgent to the Brazilian government to cut taxes to turn viable the massive production of photovoltaic energy by residential customers.

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References

[1] D. Verma, O. Midtgard, and T. O. Satre, “Review of photovoltaic status in a European (EU) perspective”, in Proc. IEEE/PVSC 2011, pp. 3292–3297.
[2] M. A. G. de Brito, L. P. Sampaio, L. G. Junior, and C. A. Canesin, “Research on photovoltaics: review, trends and perspectives”, in Proc. COBEP 2011, pp. 531–537.
[3] W. Li and X. He, “Review of non-isolated high step-up DC/DC converters in photovoltaic grid-connected applications”, IEEE Transactions on Industrial Electronics, 58(4), 1239-1250.
[4] M. R. Patel, Wind and solar power systems: design, analysis, and operation, 2nd ed. Boca Raton, FL: Taylor & Francis, 2006.
[5] F. H. Dupont, C. Rech, and J. R. Pinheiro, “A Methodology to Obtain the Equations for the Calculation of the Weighted Average Efficiency Applied to Photovoltaic Systems”, in Proc. 10th IEEE/IAS Int. Conf. on Ind. Appl., 2012 (pp. 1-8).
[6] E. B. Pereira, F. R. Martins, S. L. de Abreu, and R. Rüther, Brazilian solar energy Atlas (in Portuguese). São José dos Campos: INPE, 2006.
[7] D. Sera, R. Teodorescu, and P. Rodriguez, “PV panel model based on datasheet values”, in IEEE International Symposium on Industrial Electronics, 2007, pp. 2392–2396.
[8] T. P. Gimenes, B. C. Cruz, S. V. G. Oliveira, A. Péres. “Energy processing system for connecting photovoltaic panels to power grid” (in Portuguese), Proc. of SEPOC 2012, pp. 1-9.
[9] O. Lisita Junior. “Photovoltaic systems connected to the network: Case study – 3kWp installed in the parking of USP”, Master Dissertation – USP, São Paulo-SP, 2005.