Hindawi Publishing Corporation
International Journal of Photoenergy
Volume 2008, Article ID 356261, 7 pages
doi:10.1155/2008/356261

Research Article

RMS Current of a Photovoltaic Generator in Grid-Connected PV Systems: Definition and Application

P. J. Pérez, G. Almonacid, J. Aguilera, and J. de la Casa

IDEA Group, Department of Electronic Engineering, University of Jaén, 23071 Jaén, Spain

Correspondence should be addressed to P. J. Pérez, pjperez@ujaen.es

Received 18 September 2007; Accepted 19 February 2008

Recommended by Ugo Mazzucato

This paper includes a definition of a new and original concept in the photovoltaic field, *RMS current* of a photovoltaic generator for grid-connected systems. The *RMS current* is very useful for calculating energy losses in cables used in a PV generator. As well, a *current factor* has been defined in order to simplify *RMS current* calculation. This factor provides an immediate (quick and easy) calculation method for the *RMS current* that does not depend on the case particular conditions (orientation, location, etc.). *RMS current* and *current factor* values have been calculated for different locations and modules.

1. INTRODUCTION

The *RMS current* of a photovoltaic generator of a grid-connected photovoltaic system (GCPVS) is a new concept that allows an easy calculation of certain matters related to photovoltaic systems, like the energy losses in photovoltaic generator cables. This new concept implies a new approach of photovoltaic systems engineering, an approach that allows the use of new photovoltaic system design methods, more similar to those used in other engineering fields.

The current generated by a photovoltaic cell, module, or generator depends on its technological and/or inherent characteristics and on the temperature and radiation exposure. Such a dependence on radiation and temperature implies a remarkable random character in the yearly current, which means that it can be studied as a stochastic process. However, in necessary calculations for the design and evaluation of photovoltaic systems, experts can use the radiation and temperature data of typical meteorological year [1], as they are very close to the real values of the system. Therefore, we can *state that a photovoltaic cell, the module, or the generator current in GCPVS is periodical, and the period is one year*.

Considering all these facts, we can define a cell *RMS current* $[I_{\mathrm{RMS},C}]$ by the expression (1) where $i_{m,C}(t)$ is the instant current of the cell maximum power point and T is one year:

$$I_{\mathrm{RMS},C} = \sqrt{\frac{1}{T}\int_T i_{m,C}(t)^2 dt}. \tag{1}$$

A module *RMS current* $[I_{\mathrm{RMS},M}]$ can be defined in the same way that in the case of a cell, but using the module instant current in the maximum power point $[i(t)_{m,M}]$:

$$I_{\mathrm{RMS},M} = \sqrt{\frac{1}{T}\int_T i(t)_{m,M}^2 dt}. \tag{2}$$

If we suppose all the parallel cell branches of the module provide the same current, the module *RMS current* will be the cell *RMS current* multiplied by the amount of parallel cells $[N_{\mathrm{PC}}]$ in the module:

$$I_{\mathrm{RMS},M} = \sqrt{\frac{1}{T}\int_T \left[i(t)_{m,C}N_{\mathrm{PC}}\right]^2 dt} = I_{\mathrm{RMS},C}N_{\mathrm{PC}}. \tag{3}$$

Likewise, supposing all the modules are identical and show the same tilt, we could define the generator *RMS current* as the module *RMS current* multiplied by the number of parallel modules (N_{PM}) in the generator:

$$I_{\mathrm{RMS},G} = I_{\mathrm{RMS},M} \cdot N_{\mathrm{PM}}. \tag{4}$$

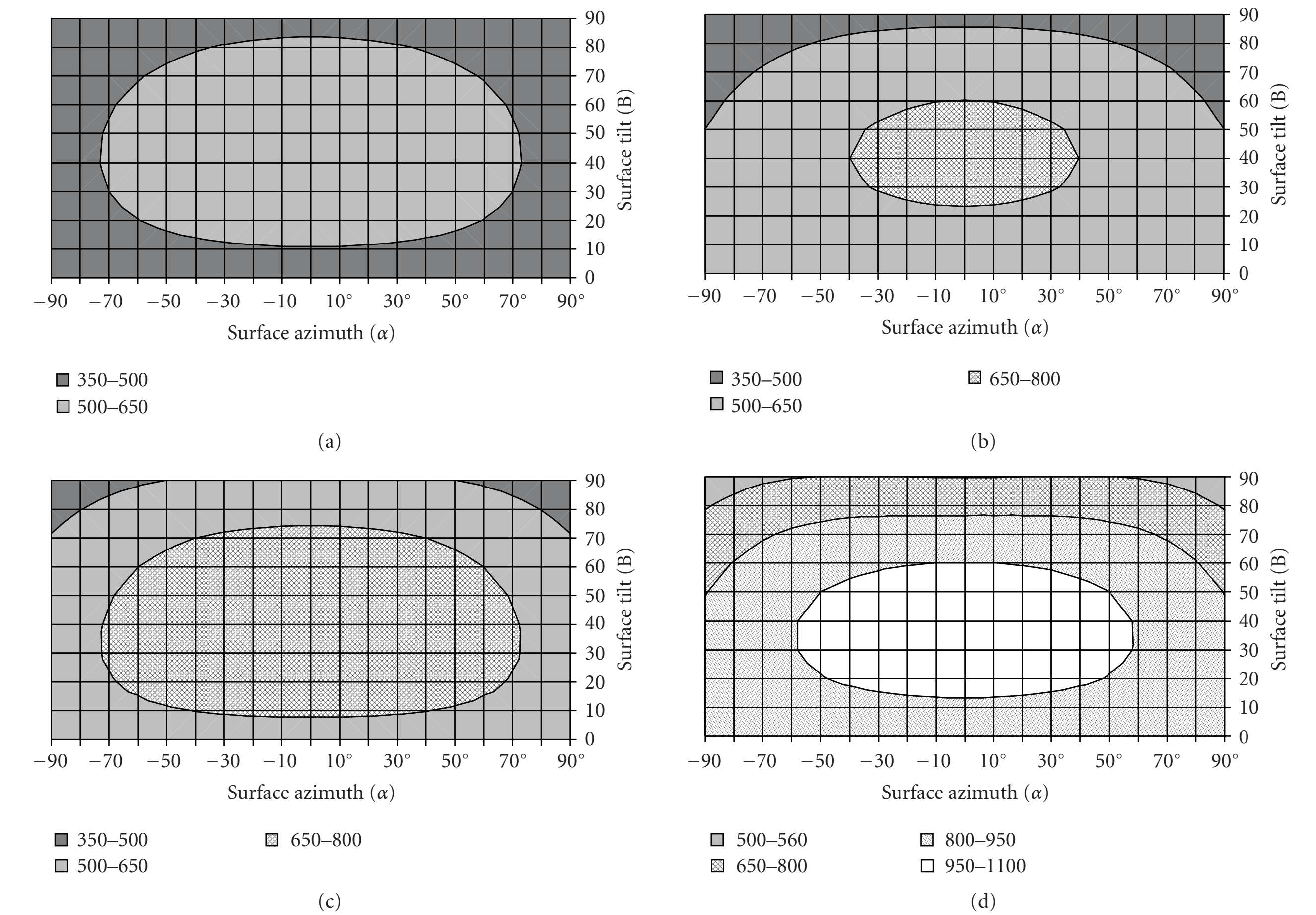


Figure 1: Cell RMS current (mA) for different orientations and European locations. (a) Bergen-Norway, (b) Bonn-Germany, (c) Paris-France, (d) Madrid-Spain.

2. METHODS

The calculation procedure of the RMS current is the following one.

Initially, the value of the cell current at the maximum power point for ten minute intervals [2] is calculated from the following values: daily mean monthly irradiation and temperature, and cell parameters measured at standard test conditions. The applied model is based on the following procedure.

(1) Calculation of the direct and diffuse daily mean monthly irradiation through those expressions proposed by Liu and Jordan [3] and correlations obtained by Page [4].
(2) Irradiance calculation from daily irradiation according to the method proposed by Whillier [5].
(3) Calculation of irradiances within generator following the model proposed by Perez et al. [6] for the diffuse component considering the transmittance losses due to Fresnel reflection losses, dirt and low irradiance levels.
(4) Calculation of the ambient air temperature, supposing it can be modelled according to two half-waves of two cosine functions [7].
(5) Calculation of short-circuit current; fill factor and current at cell maximum power point [8].

Taking current values at cell maximum power point as starting point, the cell *RMS current* in GCPVS can be calculated through the following approximation:

$$I_{\mathrm{RMS},C} \approx \sqrt{\frac{1}{365}\sum_{i=1}^{12}\left(dm_i\sum_{j=1}^{144} I_{M,C\,j}^2 \cdot \Delta t\right)}, \qquad (5)$$

where $\Delta t = 1/144$ (this value equals the ten-minute interval measured in days), dm_i (number of days for each month) and $I_{M,C}$ are the value of $i_{m,c}(t)$ at the medium point of the ten-minute interval expressed in Amps.

3. RESULTS AND DISCUSSION

3.1. RMS current of a cell different locations and orientations

This paragraph includes those values obtained through the previously described calculation method for the *RMS current* of a photovoltaic cell, located in different European locations and with several cell orientations. For that purpose, four European locations have been chosen: *Bergen (Norway),*

Table 1: Cell RMS current mean values, standard deviation, and coefficient of variation.

	Spain	France	Germany	Norway
Latitude	40°	49°	51°	60°
$\bar{I}_{\text{RMS}}$ (mA)	**860**	**633**	**560**	**497**
σ_I (mA)	113	82	73	64
CV_I (%)	**13.2**	**12.9**	**13.1**	**12.8**

Table 2: Cell current factor mean ($\overline{F}_I$), standard deviation (σ_F), and coefficient of variation (CV_F).

	Spain	France	Germany	Norway
Latitud	40°	49°	51°	60°
$\overline{F}_I$	**1.58**	**1.58**	**1.59**	**1.63**
σ_F	0.044	0.037	0.036	0.040
CV_F (%)	**2.8**	**2.3**	**2.3**	**2.4**

Bonn (Germany), Paris (France), and Madrid (Spain), located in northern, central, and southern Europe, respectively. Main reasons for this choice are the availability of the radiation and temperature data and the aim of studying the behaviour of the *RMS current* in several European latitudes.

The studied cell shows the following values at standard test conditions (Cell temperature = 25°C, Air Mass = 1.5, Irradiance = 1000 W/m25)

(i) Short-circuit current (I_{SC}) = 3.26 A.
(ii) Open-circuit voltage (V_{OC}) = 0.6 V.
(iii) Maximum power point current (I_M) = 3.05 A.
(iv) Maximum power point voltage (V_M) = 0.48 V.
(v) Maximum power point (P_M) = 1.46 W.
(vi) Normal operating cell temperature (NOCT) = 47°C.

Daily mean monthly maximum, minimum temperature, and irradiation values of studied locations match the last ten years mean values provided by the Langley Nasa Research Center (http://eosweb.larc.nasa.gov/see).

RMS current values ($I_{\text{RMS},C}$) for cell orientations between 90° East and 90° West, and cell tilts between 0° and 90°, in 10° steps, have been calculated and a total of 190 values have been obtained for each location. *RMS current* values obtained for studied locations have been represented in Figure 1.

Table 1 shows the mean value [$\bar{I}_{\text{RMS}}$] of the 190 *RMS current* values obtained for each studied location, standard deviation [σ_I], and coefficient of variation [CV_I]:

$$\bar{I}_{\text{RMS}} = \frac{\sum_{K=1}^{190} I_{\text{RMS},C,K}}{190},$$

$$\sigma_I = \sqrt{\frac{\sum_{K=1}^{190}\left[I_{\text{RMS},C,K} - \bar{I}_{\text{RMS}}\right]^2}{190}}, \tag{6}$$

$$\text{CV}_I = \frac{\sigma_I}{\bar{I}_{\text{RMS}}}.$$

Obviously, values obtained show that *RMS current* values depend largely on cell orientation and latitude. This dependency is very similar to the case of irradiation. This way, the *RMS current* in the south of Europe is 70% greater than in the North and values dispersion due to cell orientation is really high, with standard deviations until 113 mA and coefficients of variation of 13%.

3.2. Definition of current factor

Previous values show that *RMS current* values are strongly dependent on different factors. This characteristic makes difficult its application in quick methods for designing or analysing photovoltaic systems operation, as the calculation procedure is long and tedious and it should be made for each location, orientation, and module type.

To facilitate *RMS current* calculation and encourage its use within photovoltaic field, a new parameter has been introduced, the so-called *current factor*. This factor allows an easy and simple calculation method for the *RMS current* and offers a great advantage: it can be applied to a wide range of orientations, latitudes, and temperatures. In this sense, it allows a simple and direct calculation for virtually all the interest cases related to grid-connected PV systems.

The *current factor* [F_I] of a photovoltaic cell is defined as the ratio between its *RMS current* and the yearly mean daily irradiation at cell surface, both parameters normalised to the standard conditions values;

$$F_I = \frac{I_{\text{RMS}}/I_{M,\text{stc}}}{H_{\text{da}}(\alpha,\beta)/H_R}. \tag{7}$$

If irradiance remained 1000 W/m^2 in a constant and continuous way during the whole year, (which we call at standard test conditions), *RMS current* value would match current value at maximum power point and the yearly mean daily radiation would be 24 kWh/m^2. Thus, *current factor* is defined as the ratio between cell *RMS current* [I_{RMS}], divided by current at maximum power point at standard test conditions [$I_{M,\text{stc}}$], and the yearly mean daily irradiation at cell surface [$H_{\text{da}}(\alpha,\beta)$], divided by reference yearly mean daily irradiation [H_R = 24 kWh/m^2], this way, a dimensionless and standardised (equivalent to the unit at standard test conditions) factor is obtained.

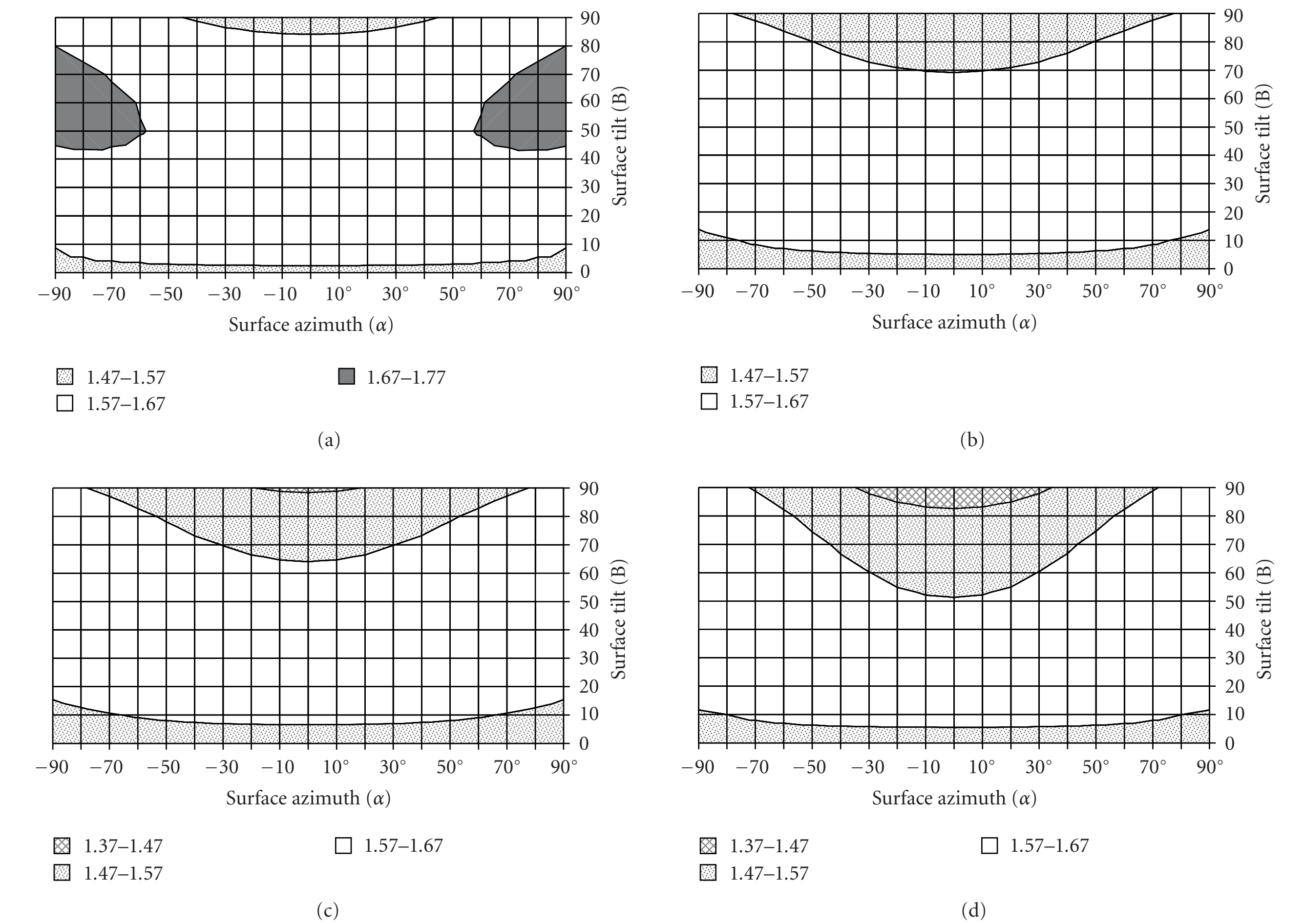


Figure 2: Current factor for different orientations and European locations. (a) Bergen-Norway, (b) Bonn-Germany, (c) Paris-France, (d) Madrid-Spain.

If we considered all parallel cell strings of a module and all parallel module strings of a generator to provide the same current, the *current factor* value would be the same for the cell, the module, and the generator.

3.3. Current factor for different locations and orientations

Within this section, the *current factor* value is calculated for a photovoltaic cell placed in different European locations, differently positioned, and with different cell orientations. Studied locations and cell are the same rather than those studied in the previous section.

Figure 2 represents those values obtained for *current factor* and Table 2 shows most remarkable values.

Considering those values obtained for *current factor* (F_I), we can remark the following.

(a) *Current Factor* mean values range between 1.58 for the case of Spain and 1.63 for Norway, increasing according to latitude. Although *RMS current* values in southern Europe are up to 70% higher than in northern Europe, *current factor* value is lower in the South, but only 3% lower than in North.

(b) Dispersion of values due to cell orientation is low, with standard deviations around 0.04 and coefficients of variation under 3%.

From the above data, we can conclude that *current factor* values are very homogeneous for the whole Europe and much less dependent on cell tilt and orientation than in *RMS current* case. We can observe a wide area with very homogeneous values in central orientations and tilts, that is, from 70° East to 70° West, and tilts from 0° to 70°.

Another interesting matter is that *current factor* mean values are very similar to the values obtained for this factor for those orientations maximising the annual irradiation received by the cell, as shown in the Table 3.

3.4. Current factor for different photovoltaic modules

With the aim of providing *RMS current* values for other locations and cell types as well as checking the low dependency of *current factor* with respect to location and module type, this section includes values obtained through

Table 3: Current factor mean value for different European locations and value for orientation maximising the annual irradiation received by the cell.

	Spain	Italy	Germany	Norway
Latitude	40°	42°	51°	60°
$\overline{F}_I$	1.58	1.58	1.59	1.63
F_I for maximum $H_{da}(\alpha, \beta)$	1.58	1.58	1.60	1.62

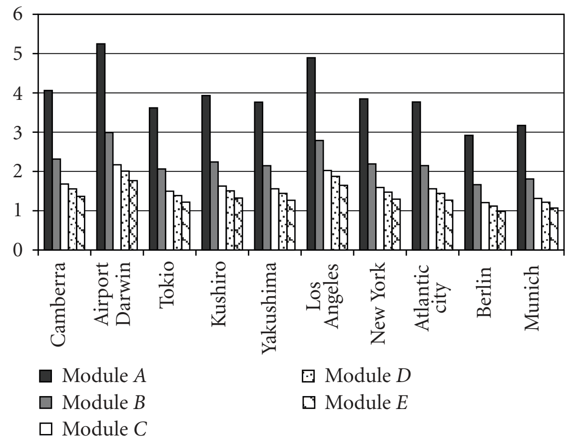


Figure 3: RMS current values ($\overline{I}_{RMS}$) in Ampere, for different types of modules located in different cities.

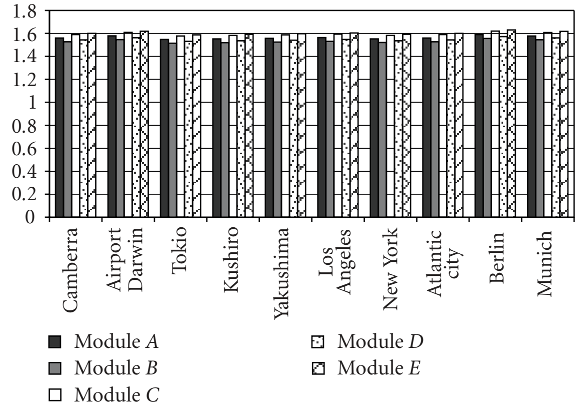


Figure 4: Current factor average values ($\overline{F}_I$) for different types of modules located in different cities.

the previously described calculation method for the *current factor* of different types of photovoltaic modules situated in different locations.

For that purpose, ten locations have been chosen: Camberra (AUS), Airport Darwin (AUS), Tokio (JAP), Yakushima (JAP), Kushiro (JAP), Los Angeles (USA); New York (USA); Atlantic City (USA); Munich (GER); and Berlin (GER). The main reason for this choice is studying the behaviour of *RMS current* in those countries with the highest PV power installed until 2004.

The calculated values correspond to five types of photovoltaic modules available in market with different characteristics. Mainly, they show different short-circuit current and different manufacturing techniques (monocrystalline and multicrystalline silicon). Table 4 includes values of modules main electrical parameters, whose data are provided by manufacturers in modules specification sheets at standard test conditions.

Figure 3 shows the dependency of *RMS current* values with respect to the location and the module type. Figure 4 shows that mean value obtained for *current factor* is very similar in all those different modules and locations that have been studied.

3.5. Values obtained for RMS current and current factor in real system

Within this apart, *RMS current* and *current factor* values calculated from the theoretical model applied in this paper are compared to those values obtained from monitored values in *UNIVER Project* [8] System 1 and the "*Pérgola Fotovoltaica*" [9].

The *UNIVER Project* (THERMIE Program: SE/00383/95/ES/UK) is made up of four grid-connected PV systems and a total power of around 200 kWp at standard test conditions. System 1 is located at University of Jaén Campus parking and shows 38° West orientation and a 7° tilt. The generator real power is 62 kWp at standard test conditions, which means a generator real current at maximum power point of 135 A.

The "*Pérgola Fotovoltaica*" is a 2 kWp grid-connected PV system integrated at terrace of University of Jaén Escuela Politécnica Superior. The generator is made up of 23 photovoltaic modules Isofotón I-88 with a 15.45 A current at maximum power point. This generator is divided into four series-connected subgenerators; three of which are made up of 6 series-connected modules; meanwhile the fourth one only has five modules. Subgenerators orientations are 6°, 21°, 36°, and 51° East, respectively, and all of them show the same tilt, 15°. However, in order to simplify the analysis of *RMS current*, we are supposing that all the modules show a 30° East orientation and the generator current at maximum power point at standard test conditions is 15.45 A.

To compare *RMS current* and *current factor* values calculated by the theoretical model to those values obtained from monitored data, the following procedure has been followed.

(1) Calculating (theoretical) *RMS current* and (theoretical) *current factor* values by the theoretical model applied in previous sections, from irradiation monthly mean daily values obtained from irradiance monitored data.

Table 4: Parameters at standard test conditions of different modules.

Module	Type	N_{SC} (*)	N_{PC} (**)	I_M	V_M	P_M
A	c-Si	12	6	18.3	5.8	106
B	m-Si	36	1	7.10	16.9	120
C	c-Si	72	1	4.95	35.4	175
D	c-Si	36	1	4.72	18.0	85
E	m-Si	54	1	4.00	25.1	100

(*) Number of cells in series (N_{SC}).
(**) Number of cells in parallel (N_{PC}).

Table 5: Theoretical and measured values of irradiation, RMS current and current factor for "Pérgola Fotovoltaica" and UNIVER Project System 1.

		Theoretical values		Measured values	
	Hda(α,β)	$I_{RMS}(A)$	F_I	$I_{RMS}(A)$	F_I
UNIVER Project	5.19	46.1	1.58	45.8	1.57
Pérgola FV	5.66	5.79	1.59	5.75	1.58

(2) Calculating (real) *RMS current* from instant current monitored values in studied systems generators.
(3) Calculating (real) *current factor* value from irradiation yearly mean daily value obtained from monitored data and (real) *RMS current* value.

Table 5 includes both theoretical and real *RMS current* and *current factor* values corresponding to "*Pérgola Fotovoltaica*" during 1997 and 1998, and to *UNIVER Project* system 1 during 2000 and 2001. These data show how real values for *current factor* match theoretical ones, with these ones being slightly lower than real values.

3.6. Approximate calculation procedure of the RMS current

From (7), we can demonstrate that the *RMS current* of a cell, module, or generator in GCPVS equals the product obtained by multiplying the *current factor* by the current at maximum power point at standard test conditions and by yearly mean daily radiation divided by the reference radiation [H_R = 24 kWh/m^2]:

$$I_{\mathrm{RMS}} = F_I I_{M,\mathrm{stc}} \frac{H_{\mathrm{da}}(\alpha,\beta)}{H_R}. \quad (8)$$

Starting from the previous data, we can consider that value of the *current factor* that will be more usual in a typical GCPVS is 1.59. Thus, we obtain a new equation that provides, on the one hand, an immediate (quick and easy) calculation of *RMS current* and, on the other hand, an approximate value (small error) of *RMS current* which can be useful in the field of engineering,

$$I_{\mathrm{RMS}}[A] \approx 0.066\, I_{M,\mathrm{stc}}[A]\, H_{\mathrm{da}}[\mathrm{kWh/m^2}]. \quad (9)$$

3.7. RMS current application

One of the *RMS current* applications is the calculation of the power or energy losses taking place in generator cables of a GCPVS. The dissipated mean power equals the value obtained by multiplying the cables resistance by the square value of generator *RMS current*:

$$P = \frac{1}{T}\int_T R\cdot i(t)^2 dt = R\frac{1}{T}\int_T i(t)^2 dt = R\cdot I_{\mathrm{RMS}}^2. \quad (10)$$

From this point, we can easily estimate the yearly energy losses in generator cables:

$$E[\mathrm{Wh}] = 365\,[\mathrm{day}]\,24[\mathrm{h/day}]\,R[\Omega]\,I_{\mathrm{RMS}}^2[A^2]. \quad (11)$$

Cables resistance is defined as the product obtained by multiplying material resistivity and length divided into cross-sectional area. In the case of copper conductors, the following value is obtained:

$$R[\Omega] = \frac{1}{56}\frac{L[\mathrm{m}]}{S[\mathrm{mm^2}]}. \quad (12)$$

When operating with both previous equations, the following expression (13) is obtained for the yearly energy losses in generator cables. This expression shows how energy losses in generator cables are in direct proportion to cable length and *RMS current* as well as in inverse proportion to the cross-section area:

$$E[\mathrm{Wh}] = 156.43\frac{L[\mathrm{m}]}{S[\mathrm{mm^2}]}I_{\mathrm{RMS}}^2[A^2]. \quad (13)$$

If we use the approximate calculation (9) of the *RMS current*, we get an immediate approximation of the energy losses in generator cables in a typical GCPVS:

$$E[\mathrm{Wh}] \approx 0.68\frac{L}{S}I_{M,\mathrm{stc}}^2 H_{\mathrm{da}}^2(\alpha,\beta). \quad (14)$$

The energy lost in a generator with different cross-sections and currents will be obtained by adding up the energy losses in different cables, considering for each cable, its length, its cross-sections, and its RMS current. This is the case of a generator made up of several parallel branches using low cross-section cables for connecting modules and larger cross-section cables for connecting the generator to the inverter.

4. CONCLUSIONS

The *RMS current* of a photovoltaic generator is a new concept that allows an easy calculation of certain matters related to photovoltaic systems, as the energy losses in photovoltaic generator cables. The *RMS current* value is very dependent on the used cell type and the radiation, so its value has to be calculated for each generator, as it changes according to the module type, orientation, and location.

The *current factor* solves out to a great extent the strong *RMS current* dependency with respect to orientation and location. And, therefore, the *current factor* allows a simple, easy, and quick calculation of the *RMS current* of a cell, module, or generator

REFERENCES

[1] I. J. Hall, R. R. Prairie, H. E. Anderson, and E. C. Boes, "Generation of Typical Meteorological Years for 26 SOLMET Stations," SAND78-1601. Alburquerque NM: Sandia National Laboratories, 1978.

[2] G. Blesser and D. Muro, "Guidelines for Assessment of Photovoltaic Plants," Document A. Photovoltaic System Monitoring. Report EUR 16338 EN, 1995.

[3] B. Y. H. Liu and R. C. Jordan, "The interrelationship and characteristic distribution of direct, diffuse and total solar radiation," *Solar Energy*, vol. 4, no. 3, pp. 1–19, 1960.

[4] J. K. Page, "The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40°N-40°S," in *Proceedings of the Annual Conference of the American Solar Energy Society*, Denver, Colo, USA, August 1979.

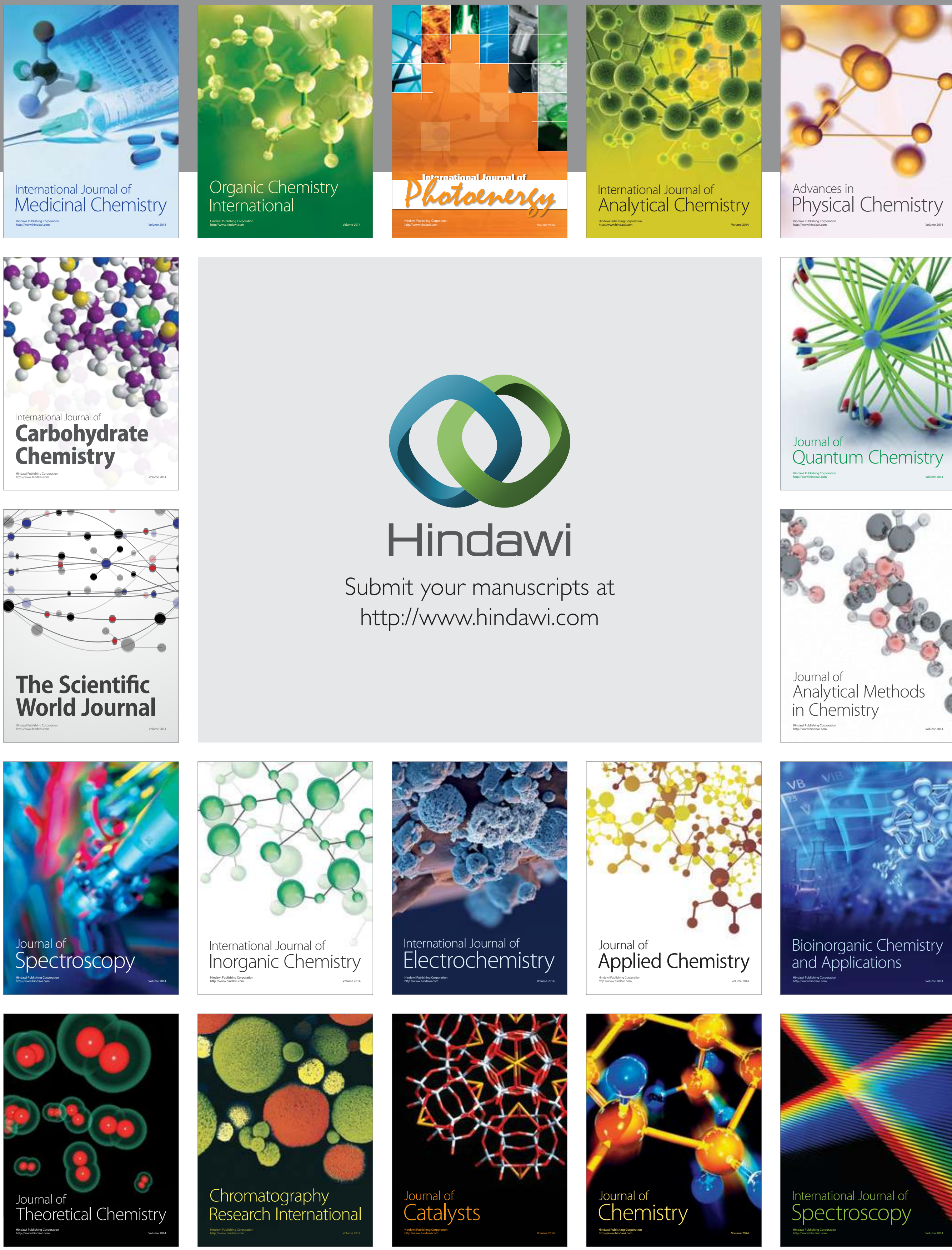
[5] A. Whillier, "The determination of hourly values of total solar radiation from daily summations," *Theoretical and Applied Climatology B*, vol. 7, no. 2, pp. 197–204, 1956.

[6] R. Perez, R. Seals, P. Ineichen, R. Stewart, and D. Menicucci, "A new simplified version of the perez diffuse irradiance model for tilted surfaces," *Solar Energy*, vol. 39, no. 3, pp. 221–231, 1987.

[7] M. A. Green, *Solar Cells: Operating Principles, Technology, and System Applications*, Prentice-Hall, Englewood Cliffs, NJ, USA, 1982.

[8] P. J. Pérez, J. Aguilar, G. Almonacid, and P. G. Vidal, "UNIVER PROJECT. A 200 kwp photovoltaic generator at Jaén University campus. First experience and operational results," in *Proceedings of the 17th European Photovoltaic Solar Energy Conference and Exhibition*, Munich, Germany, October 2001.

[9] G. Nofuentes and G. Almonacid, "The "PV Pergola project": lessons learned and results of two-year monitoring," in *Proceedings of the 16th European Photovoltaic Solar Energy Conference and Exhibition*, Glasgow, UK, May 2000.


International Journal of Medicinal Chemistry
Organic Chemistry International
International Journal of Photoenergy
International Journal of Analytical Chemistry
Advances in Physical Chemistry
International Journal of Carbohydrate Chemistry
Hindawi
Submit your manuscripts at
http://www.hindawi.com
Journal of Quantum Chemistry
The Scientific World Journal
Journal of Analytical Methods in Chemistry
Journal of Spectroscopy
International Journal of Inorganic Chemistry
International Journal of Electrochemistry
Journal of Applied Chemistry
Bioinorganic Chemistry and Applications
Journal of Theoretical Chemistry
Chromatography Research International
Journal of Catalysts
Journal of Chemistry
International Journal of Spectroscopy