



HAL
open science

Development of a real-time hot-spot prevention using an emulator of partially shaded PV systems

M. Bressan, A. Gutierrez, L. Gutierrez, Corinne Alonso

► To cite this version:

M. Bressan, A. Gutierrez, L. Gutierrez, Corinne Alonso. Development of a real-time hot-spot prevention using an emulator of partially shaded PV systems. *Renewable Energy*, 2018, *Renewable Energy*, 127, pp.334-343. 10.1016/j.renene.2018.04.045 . hal-01962921

HAL Id: hal-01962921

<https://laas.hal.science/hal-01962921v1>

Submitted on 9 Jan 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Development of a real-time hot-spot prevention using an emulator of partially shaded PV systems

M. BRESSAN³, A. GUTIERREZ³, L. GARCIA GUTIERREZ³, C. ALONSO^{1,2}

¹ CNRS ; LAAS ; 7 Avenue du Colonel Roche, F-31077, TOULOUSE, FRANCE.

² UNIVERSITE DE TOULOUSE ; UPS, INSA ; LAAS ; F-31400, TOULOUSE, FRANCE.

³Department of Electrical and Electronic Engineering, Universidad of the Andes, Bogotá, Colombia

E-mail: m.bressan@uniandes.edu.co, corinne.alonso@laas.fr

Abstract: This work presents an emulation in real-time of the shaded PV systems with a hot-spot prevention. The PV model takes into account the photo-induced current contributions from unshaded and shaded sides thanks to parameters such as the shadow transmittance and the percentage area of the shadows. The use of shadow fault detection in real time is employed avoiding all form of hot-spot formation and PV cells power dissipation. The calculation uses a simple derivative equation able to give the area of detection in function of the PV module voltage. The implementation of the emulator in FPGA takes advantages as a result of their features of adaptability and parallel processing suitable for emulation of complex shading visible on PV systems. The emulation of the proposed PV model and the hot-spot prevention are validated through two experimental tests on PV modules.

Keywords: PV system, partial shading, bypass diode, shading factor, real-time emulation, hot-spot prevention

Nomenclature

δ	Shadow coefficient	I	Cell current
δ_L	Lowest shadow coefficient	I_0	Dark saturation current
δ_n	Calculated shadow coefficient	I_{dv}	Divergence current
τ	Shadow transmittance	I_{ph}	Photogenerated current
a	Constant	I_{ph_i}	Illuminated I_{ph}
a_i	Percentage of illuminated area	I_{ph_s}	Shaded I_{ph}
a_n	Calculated area	I_{ph_T}	Total I_{ph}
a_s	Percentage of shaded area	$I_{ph_{T_i}}$	Completely illuminated I_{ph}
a_{sL}	Lowest percentage of shaded area	$I_{sc_{STC}}$	Short circuit current for STC
k	Boltzmann constant	J	Density current
m	Constant	J_{ph}	Photocurrent density
n	Ideality factor of the diode	J_{ph_i}	Illuminated J_{ph}
q	Magnitude of the electron charge	MSE	Mean Square Error
p_b	Black pixel	R_s	Series resistance
p_w	White pixel	R_{sh}	Shunt resistance
A_c	Cell area	S_f	Shading factor
A_i	Illuminated area	STC	Standard Test Conditions
A_s	Shaded area	T_c	Cell temperature
C_{T_i}	Thermal current coefficient	T_{STC}	Temperature for STC

G_i	Incident irradiance	V	Cell voltage
G_s	Irradiance for shaded area	V_{br}	Avalanche breakdown voltage

18

19 **1. Introduction**

20 The study of PV systems grew significantly in recent years more particularly in urban areas. PV systems can be
 21 affected by several external factors such as shadows. PV arrays in shading conditions not only decrease the
 22 produced energy [1-2] but also increase the risk of structural failures with the apparition of localized hot-spot [3].

23 A monitoring PV system gives accurate information about the behaviour of a PV plant more particularly in
 24 shading conditions. With the measure of the maximum DC power of a PV array, it is easier to perform some fault
 25 detection in real-time seeing the drop of the voltage and the current of the PV systems [4]. The development of
 26 practical fault detection approaches in photovoltaic (PV) systems, intended for online implementation permits to
 27 have a robust system and an important fault detection rate. In the study of Platon [5], the fault detection approach
 28 is based on the comparison between the measured and model prediction results of the ac power production. Chine
 29 [6] presents an automatic fault detection method for grid-connected photovoltaic (GCPV) analyzing the ratio
 30 between DC and AC power to identify some faults. Different types of faults are identified such as a fault in a
 31 photovoltaic module, a fault in a photovoltaic string, a fault in an inverter, and a general fault that may include
 32 partial shading, PV ageing, or MPPT error. The study of Serrano [7] shows a model using data mining techniques
 33 to assess the state of the PV (photovoltaic) generator classifying its state thanks to an algorithm without measuring
 34 ambient conditions. With the result of a 222 kWp CdTe PV case, it is shown that the application of computing
 35 learning algorithms can improved the management and performance of the photovoltaic generators finding faults
 36 during the PV performance. In the study of Silvestre [8], a procedure for automatic supervision, fault detection,
 37 and diagnosis of possible failure sources has been performed to minimize total or partial loss in the productivity
 38 of grid connected PV systems. Other study used a procedure for fault diagnosis in PV systems with distributed
 39 maximum power point tracking at module level—power optimizers (DC/DC) or micro-inverters (DC/AC) [9]. The
 40 work of Madeti [10] presents a new fault detection and diagnosis technique for solar photovoltaic (PV) systems
 41 operating under grid-tied and off-grid modes using local measurements and model predictive.

42 But it is important to minimize the use of DC or AC parameters such as predictive value of a PV systems for the
 43 fault detection in order to avoid the increase the cost and the complexity of the system. The fault detection in real
 44 time takes its advantage minimizing parameters.

45 The second aspect treats the presence of the partial shading which affects drastically the efficiency of the PV
 46 modules such as the presence of hot-spot.

47 A hot-spot refers to the portion of the cell with a higher temperature increase. In the study of Kim [11], it is shown
 48 that the hot-spot phenomena can lead to second breakdown or cell encapsulant damage although the activation of
 49 bypass diodes. An IR camera test proved a temperature increase of localized shaded PV cells in the study of
 50 Bressan [12]. Various simulation and experimental studies have shown the problem of modeling the thermal
 51 behavior of PV cells in hot-spot condition. In the study of Wang [13], five different connection configuration of
 52 PV cells have been studied to compare their performance under partial shading. In the same conditions of partial
 53 shading, a methodology of simulation is proposed optimizing the bypass diodes configuration to prevent hot-spot

54 apparition in PV modules [14]. In the study of Daliento [15], an improved bypass approach based on a power
55 mosfet and a diode has been proposed to reduce the hot-spot temperature in a presence of partial shading. To avoid
56 the permanent damage of the shaded PV cells, the works of Rossi [16] proposed a hysteresis comparator to detect
57 hot-spot apparition and validated in SPICE simulations. There exist other methods able to detect hot-spot, soiling
58 and aging degradation [17-19]. A tool for the evaluation of I-V characteristics and energy yield of PV systems has
59 been performed taking into account the sun position and the shading patterns [20]. This work can be solved through
60 the optimized engines of commercial simulators (Matlab, PSPICE) with very low computation time in comparison
61 to analogous numerical methods.

62 These studies show the importancy to develop real-time simulation methods for complex shaded PV systems and
63 fault detection method to avoid all form of localized hot-spot.

64 PV emulators have been proposed in several studies to reproduce the shaded PV behavior using approaches from
65 analog circuit [21]. The emulator approach is a real challenge to study the high non-linearity and the complexity
66 of PV systems in partial shading. Moreover, the supervision and the real-time fault detection play an important
67 part in this challenge.

68 In this paper, a methodology to emulate in real-time partially shaded PV systems is presented taking into account
69 a shadow transmittance and the percentage of area of the shadow. This work validates the hot-spot detection
70 method that consists to compare I-V curves in normal operation with I-V curves in shaded operation [12]. The main
71 objective of this detection is to accurately identify anomalies and hot-spot formation. The difference of the I-V
72 curves shape permit to dissociate a homogenous shading of a non homogenous. The proposed methodology is
73 implemented in a Field Programmable Gate Array (FPGA). The FPGA use is justified because of the apparition
74 of DC-DC converter with the use of Gallium nitride power transistors which permit to get has greater -high
75 efficiency, high power density and to achieve higher switching frequency [22]. The FPGA is selected as a
76 computational device because of their adaptability and high speed processing features in order to provide a high
77 speed fault detection. The advantage of FPGA implementation is the computation time of the shaded PV model
78 and the hot-spot prevention.

79 The papers is organized as the following, section 2 presents the theoretical model for PV modules in normal and
80 complex shading conditions. Section 3 presents the hot-spot prevention method allowing to separate the non-
81 uniform shadow of a uniform. The simulation and experimentals results are discussed in the last section.

82 **2. PV system and hot-spot condition**

83 Partial shading generates severe mismatch leading to hot-spot apparition. These section introduces this phenomena
84 and the appropriated theoretical model to characterize it accurately.

85 **2.1. Thermal cell dissipation due to shading: theory review**

86 Hot spots are a well-known problem in PV modules and strings that lead to individual cells or portions of a cell t
87 o become reverse-biased and dissipate heat [23]. When a PV cell is covered in a string, the overall current becom
88 es limited by the covered cell increasing its temperature. The affected cells are forced into reverse bias and starts
89 to dissipate power and can lead to its destruction. In the study of Kim [24], most manufacturers do not take into a
90 ccount the reverse breakdown characteristics. A phenomenon called second breakdown can occur that localizes r

91 reverse current flow in a small portion of the cell and can lead to extreme cell temperatures and damage. An IR camera test has been performed to see the PV module behavior in short circuit and in open circuit equipped of bypass diodes in localized shading conditions [12]. A hot-spot area is shown at the level of the covered PV cell increasing its temperature. The current in the PV module sub-string is limited by the shaded PV cell despite the activation of the by-pass diode of the sub string. As a result, it operates under reverse-bias mode, dissipating power in the form of heat. Where a cell dissipates power operating in the reverse bias with various kind of shading illumination, it is shown that the voltage breakdown of the shaded PV cell changes and tends toward 0. This implies the appearance of hot-spot on the PV module.

99 To resume, non-uniform shading has an important impact on PV performances despite the activation of bypass diode. Hot spotting can lead to second breakdown or cell encapsulant damage and permanently degrade the PV panel or leads to safety concerns. Complex shading is difficult to characterize and to interact with power converters with high switching speed [25]. Knowing the shading area and the photoinduced transmittance will permit to understand the PV systems in partially shading conditions. A model is developed considering shadow patterns and it is validated firstly in Matlab. The final part consists to emulate the methodology in real-time to validate hot spot prevention method using FPGA.

106 2.2. Classical solar cell model

107 The photovoltaic effect is the conversion of light into electricity. The classic model of a PV cell is governed by Equation (1) [21]. Equation (1) can be used to acquire I-V curve, which shows the behavior of the current and the voltage of a PV system.

$$I = I_{ph} - I_0 \left[\exp \left(\frac{q(V + I.R_s)}{nkT} \right) - 1 \right] - \frac{V + I.R_s}{R_{sh}} \quad (1)$$

110 Where I_{ph} is the photocurrent (A), I_0 is the dark saturation current (A), n is the ideality factor of the diode (1 to 2), k is the Boltzmann constant ($1.38 \cdot 10^{-23} \text{ J/}^\circ\text{K}$), q is the magnitude of the electron charge ($1.602 \cdot 10^{-19} \text{ C}$), T is the temperature of the cell ($^\circ\text{K}$), R_s is the series resistance, R_{sh} the shunt resistance.

113 However, most of the models in literature do not take into account the effect of the reverse bias. A more precise model is proposed by Bishop [26] which incorporates the avalanche effect as a non-linear multiplication factor that affects the shunt resistance current term, shown below:

$$I = I_{ph} - I_0 \left[\exp \left(\frac{q(V + I.R_s)}{nkT} \right) - 1 \right] - \frac{V + I.R_s}{R_{sh}} - a \frac{V + I.R_s}{R_{sh}} \left(1 - \frac{V + R_s.I}{V_{br}} \right)^{-m} \quad (2)$$

116 Multiplication factor on shunt
117 resistance

118 Where a and m are constant, V_{br} is the avalanche breakdown voltage (V).

119 By studying different PV cells in reverse bias, Bishop has noted a different evolution of the current. The avalanche breakdown in reverse bias represented by a non-linear multiplication factor is shown in red in Equation (2). This factor affects the shunt resistance current term. Negative voltages for solar cells can occur at non-uniform

122 illuminated PV generators, especially during partial shading of PV modules. The breakdown voltages for poly-Si
 123 cells are within the range -12 V to -20 V, whereas for mono-Si cells the breakdown voltages can extend -12V to -
 124 30V [27]. More precisely, when the PV module is partially shaded, the behavior of the I-V curve is different
 125 showing the reverse bias contrary to classic equation. In the study of Kim [24], experimental results have been
 126 performed using the open-circuit technique with a resistive load powered by two 20-cell PV strings with one cell
 127 partially shaded on a clear sunny day. An increase of the temperature of the shaded PV cell is shown thanks to an
 128 IR thermography. This experiment confirms that localized hot spotting is possible despite the activation of the
 129 bypass diode. The shadow properties are complex and difficult to treat. This next section presents the proposed
 130 model that considers shadow properties for describing the behavior of partially shaded PV systems.

131 2.3. Proposed PV model for partially shaded conditions

132 Partially shaded cells have two main shadow features as shown in Fig. 1. The first feature is the shadow geometry
 133 represented by $a_s + a_i = 1$ with a_s , the percentage of shaded area and a_i , the percentage of shaded area. The second
 134 shadow feature is the optical properties represented by the shadow transmittance τ and shading factor S_f . The
 135 shadow transmittance is defined by the relation between the irradiance on the shaded area and the incident
 136 irradiance $\tau = G_s/G_i$ [28]. The shading factor S_f is defined by the shadow opacity where $0 \leq S_f \leq 1$. $S_f = 0$ means
 137 that the available irradiance shines on the PV cell; in contrast, $S_f = 1$ means that all available irradiance is blocked
 138 by the shadow. Thus, $S_f + \tau = 1$. The proposed model is explained more in details in the thesis works of Alonso
 139 Gutierrez between the LAAS-CNRS and the University of The Andes for designing multi-physics complex
 140 systems in embedded hardware [29].



147 **Fig. 1 : Partially shaded PV cell**

148 Fig. 2a shows a 3D
 149 schematic section of a partially shaded PV cell. Electron-hole pairs are generated when photons arrive at the p-n
 150 junction in the illuminated area. As a result, a photogenerated current I_{ph_i} is produced. In contrast, fewer photons
 can arrive at the p-n junction in the shaded area; and thus, a lower photogenerated current I_{ph_s} is produced.

151
152
153

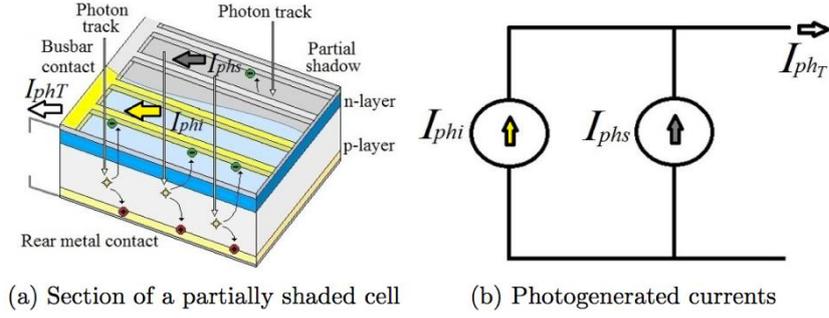


Fig. 2 : Photogenerated currents in partially shaded PV cell

$$I_{ph_T} = I_{phi} + I_{ph_s} \quad (3)$$

154 Using the current density definition $J=I/A$ and the relation $J_{ph_s} = \tau J_{phi}$, the photogenerated current I_{ph_T} becomes
155 :

$$I_{ph_T} = J_{phi} a_i A_c + J_{phi} \tau a_s A_c \quad (4)$$

156

$$I_{ph_T} = J_{phi} A_c (a_i + \tau a_s) \quad (5)$$

157 Given that $S_f + \tau = 1$ and $a_s + a_i = 1$,

$$I_{ph_T} = I_{ph_{Ti}} (1 - a_s S_f) \quad (6)$$

158 And on defining the shadow coefficient δ as :

$$\delta = 1 - a_s S_f \quad (7)$$

159 The obtained photogenerated current is

$$I_{ph_T} = I_{ph_{Ti}} \delta \quad (8)$$

160 Where $I_{ph_{Ti}}$ is the photogenerated current for completely illuminated conditions:

$$I_{ph_{Ti}} = [I_{sc_{STC}} + (C_{Ti}(T_c - T_{STC}))] \frac{G_i}{G_{STC}} \quad (9)$$

161 The Equation (2) becomes :

$$I = I_{ph_{Ti}} \delta - I_0 \left[e^{\left(\frac{q(V+IR_s)}{nkT} \right)} - 1 \right] - \frac{V + IR_s}{R_{sh}} \left[1 + a \left(1 - \frac{V + IR_s}{V_{br}} \right)^{-m} \right] \quad (10)$$

162

163 The solution of the Equation (10) describes the influence of the shadow coefficient δ on the I–V curve and power
 164 production. The following section presents the simulation and the model validation for several experimental
 165 conditions.

166 2.4. Validation of the proposed model with experimental tests

167 The objective of this test is to validate the proposed model under actual shaded conditions. The model is
 168 implemented in Matlab/Simulink©. The experiment comprises two types of shadows projected on the PV modules
 169 shown in Fig. 4. This test uses polycrystalline PV modules TE2200 shown in Table 1.

170 **Table 1: TE2200 PV module specifications**

Variable	Value
Cell type	Mono crystalline
Maximum power rating (P_{max})	250Wp
Open circuit voltage (V_{oc})	37.5V
Short-circuit current (I_{sc})	8.8A
Voltage at maximum power (V_{mp})	30.05V
Current at maximum power (I_{mp})	8.4A
By-pass diodes	3

171 An I–V curve tracer (model MP-160, EKO Instruments, Japan) is used to measure the current–voltage signals. A
 172 digital camera simultaneously records the shadow pattern. In addition, a pyrometer (model SP-Lite, Kipp & Zonen,
 173 Netherland) is used to detect the solar irradiance and a thermographic camera is used to monitor the PV module
 174 temperature. The different steps for the experimental validation of the proposed model consists in measuring and
 175 recording I-V curves, solar irradiance, PV module temperature, and shadow patterns [27]. The analysis of shaded
 176 cells is performed thanks to the image processing methods. The contour selection of the shaded PV cells uses the
 177 histogram distribution. The image conversion to binary image is performed through the Otsu’s method. Finally,
 178 the shaded area is calculated in the following equation :

$$a_s = \frac{\sum p_b}{\sum p_b + \sum p_w} \quad (11)$$

179 where p_b , the black pixels and p_w , the white pixels of the cell area.

180 The next step is to calculate the lowest shadow coefficient δ_L (Equation (12) and the shading factor S_f (Equation
 181 (13). $I_{ph_{Ti}}$ is calculated using the Equation (9), and I_{dv} is measured at the first divergence-current point in the I–
 182 V curve representing the bypass activation shown in Fig. 3.

$$\delta_L = \frac{I_{dv}}{I_{ph_{Ti}}} \quad (12)$$

183

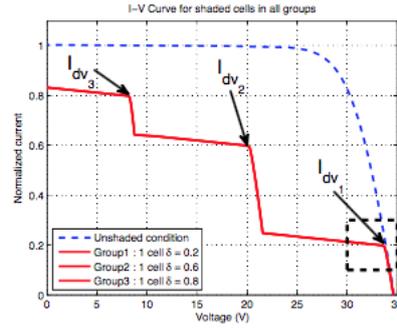


Fig. 3 : Shadow coefficient δ and contribution of partially shaded cells to I-V curve

Fig. 4. (a) and (b) shows an experimental test with shadow test in order to calculate the different parameters presented above. Table 2 summarizes these parameters and values for calculating the shading factor for shadows on the PV modules δ_n are also listed in Tables 3. The experimental and calculated I-V curves for both cases are shown in Fig. 5. Matlab/Simulink © is used in order to evaluate the proposed model with the two cases of experimental tests.

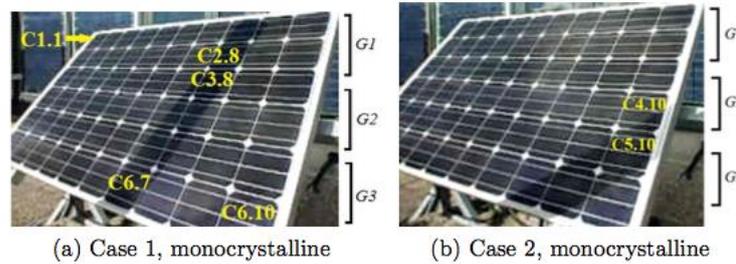


Fig. 4 : Experimental tests for monocrystalline PV module

Table 2 : Shading factor results for PV module TE2200 under test

Type	Monocrystalline	
	Case 1	Case 2
G_i	820W/m ²	910W/m ²
T_c	31°C	31°C
$I_{ph_{Ti}}$	7.07A	7.85A
I_{dv}	2.16A	2.7A
δ_L	0.31	0.34
a_{sL}	0.98	0.91
S_f	0.70	0.72

209
210
211
212
213
214
215
216
217
218
219
220
221

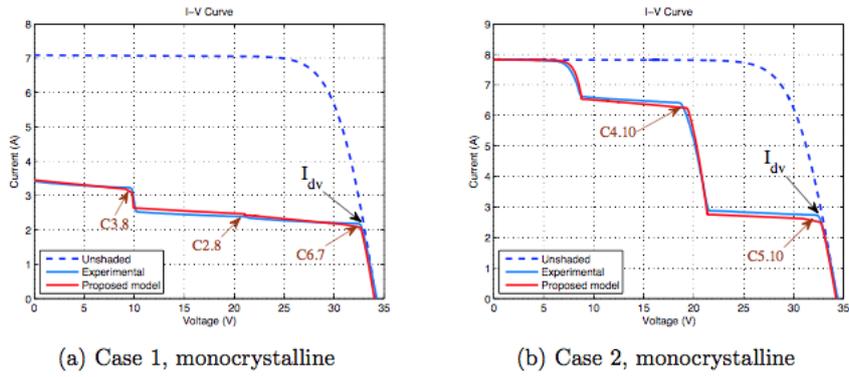


Fig. 5 : I-V curves for two cases tests

Table 3: Shaded area and shadow coefficient for monocrystalline PV module TE2200

Group	Case 1			Case 2		
	Cell	a_s	δ_n	Cell	a_s	δ_n
1	C2.8	0.96	0.33			
2	C3.8	0.80	0.44	C4.10	0.25	0.82
3	C6.7	0.98	0.31	C5.10	0.91	0.34

222
223
224
225

The mean square error (MSE) is used to validate the proposed model with the experiment test. The MSE (Equation (14)) values in Table 4 illustrate the model accuracy. Therefore, the proposed model is suitable for describing the current–voltage behavior of partially shaded PV modules.

$$MSE = \frac{1}{n} \sum_{i=1}^n (e_i)^2 \quad (14)$$

226
227
228
229
230
231
232

The results of the experiments show that the shadow coefficient δ is directly affected by changes in the I–V curve. The PV cell with the lowest value of δ in the PV module causes the lowest divergence-current point in the I–V curve. For instance, the first divergence point in the I–V curve is caused by cell 6.7 of group 3 for Case 1 of the monocrystalline PV module TE2200. In Case 2, the lowest point in the I–V curve is caused by cell C5.10.

Table 4: Model accuracy of the proposed PV model

	Case 1	Case 2
MSE	0.92%	1,07%

233
234
235
236
237
238
9

The proposed partially model shows the importance to develop a hot-spot prevention in order to avoid all temperature increase. The next section presents the two cases of studies with the I-V curves in complex shading conditions. For each case, the evolution of the standard error will be analyzed to extract a general set of interpretation rules which will permit to identify problems of hot-spot. This method shows the area of fault detection that characterizes the presence of a non-uniform shadow on PV array, affecting drastically the PV

239 performance. The method and the implementation process of the proposed model will be explained to show the
 240 importancy to have a faster hot-spot prevention.

241 **3. Hot-spot prevention and shaded PV systems emulator**

242 3.1. Hot-spot prevention method

243 The developed PV emulators should be able to emulate more complicated test cases with appropriate transient
 244 responses as shown above with the both cases. The development of partial shading PV emulators with a fault
 245 detection is proposed regarding power electronic converters for decentralized PV systems and the apparition of
 246 higher switching frequency of transistors. The real-time emulation of complex shaded PV models with fault
 247 detection application can achieve the performance and accuracy requirements. Bypass diodes are used to mitigate
 248 the presence of hot-spot, but it does not prevent hot spotting or the damage it causes. The study of Kim proposed
 249 a string-level hot-spot detection concept that measures changes in the string's small-signal impedance to identify
 250 hot spotting [30]. The Itako's paper [31] presents a development of real time hotspot detection system using scan-
 251 method about the PV solar panel I-V characteristic to distinguish between normal cells and hot-spot cells
 252 depending on the changes of the panel output current in real time. There is a vast collection of hot-spot detection
 253 focused on MPPT applications.

254 The proposed method revisits the idea of using a first derivative calculation to prevent the presence of Hot-spot
 255 validated firstly in simulation [12]. The complete process of implementation is performed in FPGA decreasing the
 256 computation time and responding of the complexity of shaded PV models and its application of hot-spot
 257 prevention. The study of transients and fast response is essentially used with data mining techniques to compare
 258 real-time measurement [7]. The I-V curve acquired during shading conditions is compared to a reference I-V curve
 259 issue to a validated solar model. Their comparison is made through the estimation of the standard error using the
 260 current from the shaded and reference I-V curves, as defined in Equation (15).

$$E(i)_{standard} = \frac{I(i)_{reference} - I(i)_{shaded}}{\max(I(i)_{reference} - I(i)_{shaded})} \quad (15)$$

261 Where $E(i)_{standard}$ is the standard error of the i th I-V curve point, $I(i)_{reference}$ is the current of I-V curve under
 262 reference conditions and $I(i)_{shaded}$ is the current of the I-V curve acquired under shaded conditions. The standard
 263 error is calculated for all of the points composing the I-V curve and its variation in relation to the PV voltage is
 264 used to monitor any changes in the shaded I-V curve as a whole. This derivative is calculated through the Equation
 265 (16).

$$\frac{dE(i)_{standard}}{dV_{module}} = \frac{E(i+1)_{standard} - E(i)_{standard}}{V(i+1)_{module} - V(i)_{module}} \quad (16)$$

266 Where $V(i)_{module}$ is the voltage of the i th I-V curve point.

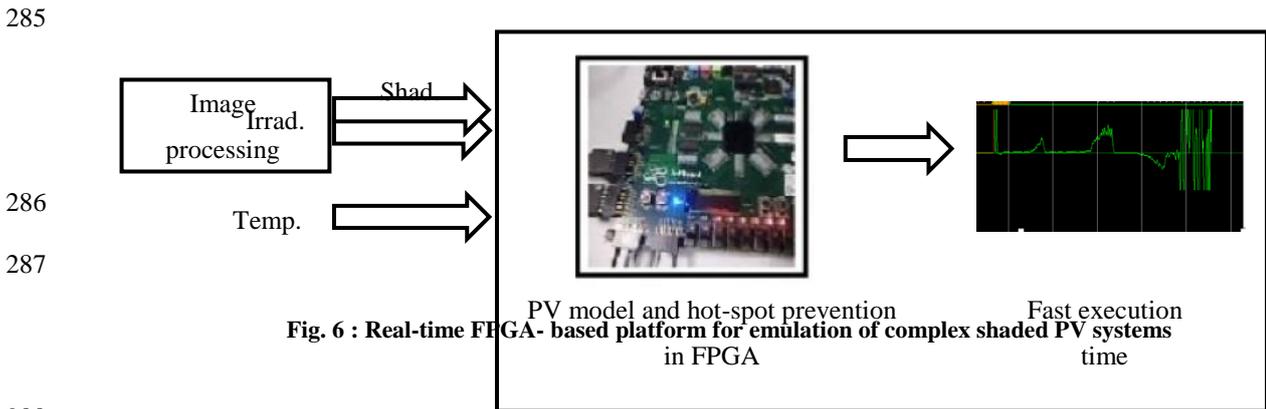
267 The results of the proposed model has been validated with the apparition of positive and negatives peaks which
 268 correspond respectively at the presence of uniform shadow and non-uniform shadow. The positive peak shifts to
 269 lower voltage values as the shadow area becomes wider. The negative peak shifts to voltage values close to the

270 open-circuit voltage for severe cases of non-uniform shading. The case where the positive peak is closed to the
 271 short-circuit current proved a failure of the bypass diode.

272 3.2. Implementation and results

273 Emulation of shaded PV systems and hot-prevention requires powerful processing devices such as FPGAs. The
 274 proposed model and the hot-spot algorithm has been designed using the very high-speed description language
 275 (VHDL) and implemented on Xilinx ZedBoard. Using different parts of the FPGA structure, the functional blocks
 276 of FPGA such as memory and logic resources work in parallel with very high frequency offering high execution
 277 speed. On the first hand, it is necessary to reduce the execution speed consuming less FPGA hardware resources.
 278 On the second hand, insufficient number of bits uses can affect the whole system in precision reduction and
 279 calculation errors.

280 Fig. 6 shows the real-time FPGA-based platform for emulation of complex shaded PV systems. The processing
 281 time to evaluate a point in the I-V curve is $10.5\mu\text{s}$ and approximately 4ms to generate an I-V curve suitable to real-
 282 time applications according to fast computing methods reported in literature. Related works of fast computing
 283 methods for PV modeling such as [32] present a response time of 23mS to compute an unshaded I-V curve or
 284 authors in [33] argue a computing time around $10\mu\text{s}$ to evaluate a complex thermal and electrical PV model.



289

290 The next step of the work is to implement the hot-spot prevention method in the zedboard. Fig. 7 shows the VHDL
 291 flowchart of the presented method of hot-spot prevention. Step 1 consists to calculate the maximum value of the
 292 difference between the reference current and the shaded current. The emulator gives 256 points of I-V curves
 293 measurements as the I-V tracer Mp-160. The execution time of this step is $2.77\mu\text{s}$ which depends on the execution
 294 time of the used FPGA board, in this case 10ns. Step 2 uses the Equation (15) in order to know the normalize error
 295 of the both current. The execution time of this part is $2.53\mu\text{s}$. The different value is stored in the ROM memory in
 296 order to perform the Equation (16) calculation. Step 3 allows to start the hot-spot prevention calculating. The
 297 response time of the hot-spot prevention is approximatively $7.54\mu\text{s}$ as shown in Fig. 8 and Fig. 9. As a result, the
 298 total response time to obtain the I-V curves and to perform the hot-spot prevention is $18\mu\text{s}$.

299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330

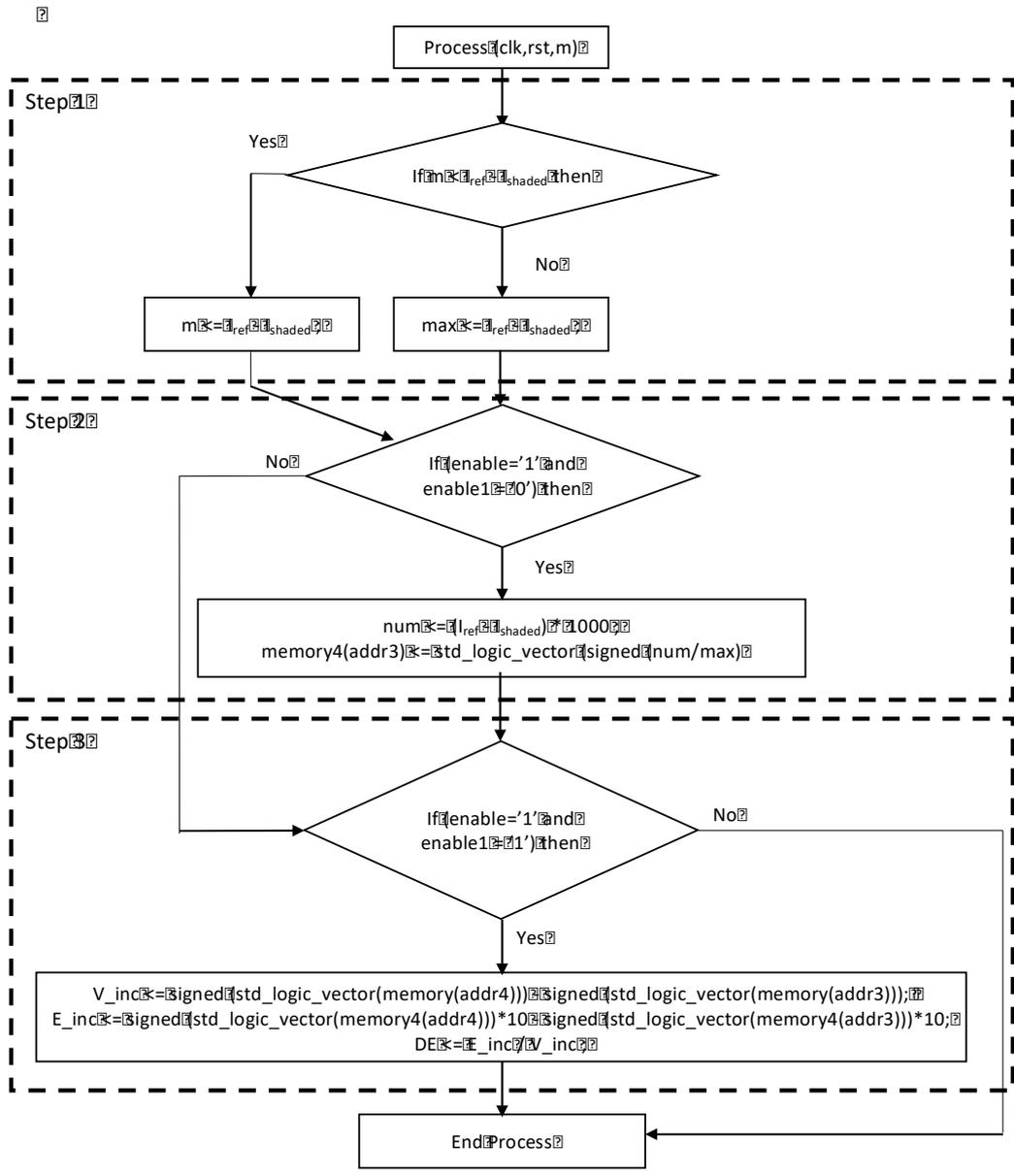


Fig. 7 : VHDL flowchat of the Hot-spot prevention

Fig. 8

and Fig. 9 show the process simulation In VHDL of the hot-spot prevention with the response time for both cases of the study presented in part 2. For Case1, the positive peak can be seen which characterizes the activation of only bypass diode. The negative peak shifts to voltage values close to the open-circuit voltage for severe cases of non-uniform shading. For Case 2, two positive peaks characterize the presence of the activation of two bypass diodes. The amplitude of the positive peak depends on the area of the shadow which can be more important and can accelerate the hot-spot apparition in non-uniform shading cases.

342 shaded area and shading factor with the partial shading behavior. The proposed emulator allows to study the high
343 non-linearity and the complexity of PV systems in partial shading with a hot-spot prevention. The faster total time
344 response of the emulator responds to the demand and to the optimization of power transistors which permit to get
345 greater-high efficiency, high power density and to achieve higher switching frequency. The first perspective work
346 is to investigate the development of a real-time monitoring system able to obtain I-V curves without perturbing
347 PV production in order to connect the FPGA emulator. The second step is to develop the fault detection to avoid
348 the apparitions of hot spot. An active fault tolerant control is one of the fault detection method allowing to detect
349 the positive peak, the area of detection and the part of the non-uniform shadow characterizing the appartition of a
350 hot-spot.

351 **References**

- 352 [1] M.C Alonso-Garcia, J.M Ruiz, F. Chen lo, "Experimental study of mismatch and shading effects in the I-V
353 characteristic of a photovoltaic module", *Solar Energy Materials & Solar Cells* 90, 2006, 329-340.
- 354 [2] A. Woyte, J. Nijs, R. Belmans, "Partial shadowing of photovoltaic arrays with different system configurations:
355 literature review and field test results", *Solar Energy*, Volume 74, Issue 3, March 2003, Pages 217-233.
- 356 [3] Suk Whan Ko, Young Chul Ju, Hye Mi Hwang, Jung Hun So, Young-Seok Jung, Hyung-Jun Song, Hee-eun
357 Song, Soo-Hyun Kim, Gi Hwan Kang, "Electric and thermal characteristics of photovoltaic modules under partial
358 shading and with a damaged bypass diode", In *Energy*, Volume 128, 2017, Pages 232-243.
- 359 [4] P. Guerriero, V. d'Alessandro, L. Petrazzuoli, G. Vallone and S. Daliento, "Effective real-time performance
360 monitoring and diagnostics of individual panels in PV plants," *2013 International Conference on Clean Electrical*
361 *Power (ICCEP)*, Alghero, 2013, pp. 14-19.
- 362 [5] R. Platon, J. Martel, N. Woodruff and T. Y. Chau, "Online Fault Detection in PV Systems," in *IEEE*
363 *Transactions on Sustainable Energy*, vol. 6, no. 4, pp. 1200-1207, Oct. 2015.
- 364 [6] W. Chine, A. Mellit, A. Massi Pavan, S.A. Kalogirou, "Fault detection method for grid-connected photovoltaic
365 plants", *Renewable Energy*, Volume 66, 2014, Pages 99-110.
- 366 [7] L. Serrano-Luján, J. M. Cadenas, J. Faxas-Guzmán, A. Urbina, "Case of study: Photovoltaic faults recognition
367 method based on data mining techniques", *Journal of Renewable and Sustainable Energy*, Volume 8, Issue 4,
368 Pages 043506, 2016.
- 369 [8] Santiago Silvestre, Aissa Chouder, Engin Karatepe, "Automatic fault detection in grid connected PV systems",
370 *Solar Energy*, Volume 94, 2013, Pages 119-127.
- 371 [9] J. Solórzano, M.A. Egado, "Automatic fault diagnosis in PV systems with distributed MPPT", *Energy*
372 *Conversion and Management*, Volume 76, 2013, Pages 925-934
- 373 [10] Siva Ramakrishna Madeti, S.N. Singh, "Online modular level fault detection algorithm for grid-tied and off-
374 grid PV systems", *Solar Energy*, Volume 157, 2017, Pages 349-364
- 375 [11] K. A. Kim and P. T. Krein, "Reexamination of Photovoltaic Hot Spotting to Show Inadequacy of the
376 Bypass Diode," in *IEEE Journal of Photovoltaics*, vol. 5, no. 5, pp. 1435-1441, Sept. 2015.
- 377 [12] M. Bressan, Y. El Basri, A.G. Galeano, C. Alonso, "A shadow fault detection method based on the standard
378 error analysis of I-V curves", In *Renewable Energy*, Volume 99, 2016, Pages 1181-1190.
- 379 [13] Yaw-Juen Wang, Po-Chun Hsu, "An investigation on partial shading of PV modules with different connection
380 configurations of PV cells", In *Energy*, Volume 36, Issue 5, 2011, Pages 3069-3078.

- 381 [14] S. Silvestre, A. Boronat, A. Chouder, "Study of bypass diodes configuration on PV modules", In Applied
382 Energy, Volume 86, Issue 9, 2009, Pages 1632-1640.
- 383 [15] S. Daliento, F. Di Napoli, P. Guerriero, V. d'Alessandro, "A modified bypass circuit for improved hot-spot
384 reliability of solar panels subject to partial shading", In Solar Energy, Volume 134, 2016, Pages 211-218
- 385 [16] D. Rossi, M. Omaña, D. Giaffreda and C. Metra, "Modeling and Detection of Hot-spot in Shaded Photovoltaic
386 Cells," in IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol. 23, no. 6, pp. 1031-1039, June
387 2015.
- 388 [17] Y. Zhao, B. Lehman, R. Ball, J. Mosesian, J. F. de Palma, "Outlier detection rules for fault detection in solar
389 photovoltaic arrays", Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty-Eighth Annual
390 IEEE, 2913 - 2920
- 391 [18] T. Takashima, J. Yamaguchi, K. Otani, K. Kato, and M. Ishida, "Experimental studies of failure detection
392 methods in PV module strings", Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World
393 Conference, Page(s): 2227-2230
- 394 [19] Y. Hirata, S. Noro, T. Aoki, and S. Miyazawa, "Diagnosis Photovoltaic Failure by Simple Function Method
395 to Acquire I-V Curve of Photovoltaic Modules String", Photovoltaic Specialists Conference (PVSC), 2012 38th
396 IEEE, Page(s): 1340-1343
- 397 [20] V. d'Alessandro, F. Di Napoli, P. Guerriero, S. Daliento, "An automated high-granularity tool for a fast
398 evaluation of the yield of PV plants accounting for shading effects", In Renewable Energy, Volume 83, 2015,
399 Pages 294-304
- 400 [21] Tuan Dat Mai, Sven De Breucker, Kris Baert, Johan Driesen, "Reconfigurable emulator for photovoltaic
401 modules under static partial shading conditions", In Solar Energy, Volume 141, 2017, Pages 256-265.
- 402 [22] Z. Pang, X. Ren, J. Xiang, Q. Chen, X. Ruan and W. Chen, "High-frequency DC-DC converter in electric
403 vehicle based on GaN transistors," 2016 IEEE Energy Conversion Congress and Exposition (ECCE),
404 Milwaukee, WI, 2016, pp. 1-7.
- 405 [23] J. W. Bishop, "Microplasma breakdown and hot-spots in silicon solar cells," Solar Cells, vol. 26, no. 4, pp.
406 335-349, 1989.
- 407 [24] K. A. Kim, P.T. Krein, "Photovoltaic hot-spot analysis for cells with various reverse-bias characteristics
408 through electrical and thermal simulation" in *Proc. IEEE Workshop Control Modeling Power Electron.*, Jun. 2013,
409 pp 1-8.
- 410 [25] F. E. Lahouar, M. Hamouda and J. Ben Hadj Slama, "Design and control of a grid-tied three-phase three-level
411 diode clamped single-stage photovoltaic converter," 2015 Tenth International Conference on Ecological Vehicles
412 and Renewable Energies (EVER), Monte Carlo, 2015, pp. 1-7.
- 413 [26] J.W Bishop, "Computer Simulation of the effects of electrical mismatches in photovoltaic cell interconnection
414 circuit", ESTI Project, Commission of the European Communities Joint Research Centre, 1988.
- 415 [27] W. Hermann, W. Wiesner, W. Vaaben, "Hot spot investigations on PV modules-new concepts for a test
416 standard and consequences for module design with respect to bypass diodes", Photovoltaic Specialists Conference,
417 1997., Conference Record of the Twenty-Sixth IEEE, Page(s): 1129-1132.
- 418 [28] S. Guo, T. M. Walsh, A. G. Aberle, and M. Peters, "Analysing partial shading of pv modules by circuit
419 modelling," in 2012 38th IEEE Photovoltaic Specialists Conference, pp. 002957-002960, June 2012.

420 [29] Alonso Galeano. "Study of Photovoltaic System Integration in Microgrids through Real-Time Modeling and
421 Emulation of its Components Using HiLeS". Micro and nanotechnologies/Microelectronics. Université de
422 Toulouse 3 Paul Sabatier, 2017.

423 [30] K. A. Kim, G. S. Seo, B. H. Cho and P. T. Krein, "Photovoltaic Hot-Spot Detection for Solar Panel Substrings
424 Using AC Parameter Characterization," in IEEE Transactions on Power Electronics, vol. 31, no. 2, pp. 1121-1130,
425 Feb. 2016.

426 [31] K. Itako, B. Hossam, T. Kudoh and Q. Huang, "Development of real time hotspot detection system using
427 scan-method for PV generation system," IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics
428 Society, Yokohama, 2015, pp. 001032-001036.

429 [32] A. C. Atoche, J. V. Castillo, J. Ortegón-Aguilar, R. Carrasco-Alvarez, J. Sandoval, and A. Colli-Menchi, "A
430 high-accuracy photovoltaic emulator system using {ARM} processors," Solar Energy, vol. 120, pp. 389 – 398,
431 2015.

432 [33] J.-H. Jung and S. Ahmed, "Real-time simulation model development of single crystalline photovoltaic panels
433 using fast computation methods," Solar Energy, vol. 86, no. 6, pp. 1826 – 1837, 2012.

434

435

436

437