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PV Shading Fault Detection and Classification Based on I-V Curve Using Principal Component Analysis: Application to Isolated PV System

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Abstract

Health monitoring and diagnosis of photovoltaic (PV) systems is becoming crucial to maximise the power production, increase the reliability and life service of PV power plants. Operating under faulty conditions, in particular under shading, PV plants have remarkable shape of current-voltage (I-V) characteristics in comparison to reference condition (healthy operation). Based on real electrical measurements (I-V), the present work aims to provide a very simple, robust and low cost Fault Detection and Classification (FDC) method for PV shading faults. At first, we extract the features for different experimental tests under healthy and shading conditions to build the database. The features are then analysed using Principal Component Analysis (PCA). The accuracy of the data classification into the PCA space is evaluated using the confusion matrix as a metric of class separability. The results using experimental data of a 250 Wp PV module are very promising with a successful classification rate higher than 97% with four different configurations. The method is also cost effective as it uses only electrical measurements that are already available. No additional sensors are required.

28 **Keywords:** PV shading faults; I-V curves; Principal Component Analysis; Fault detection;
29 Fault classification

30 **1. Introduction**

31

32 In recent years, photovoltaic (PV) systems have received considerable attention thanks to
33 the development of PV technologies and the growing demand for renewable energy in a wide
34 range of applications (satellites, telecommunication, electric vehicles, homes, agriculture...).

35 Solar PV energy has become the third most important renewable energy after hydro and
36 wind energy with a global installed capacity of 402 GWp by the end of 2017 (REN21, 2018).

37 The efficiency of PV systems is limited to 15–20% (Maghami et al., 2016). In addition, PV
38 modules present an average performance degradation rate of 0.923% per year according to the
39 study of Tabatabaei et al. (2017), which has been evaluated for mono-crystalline silicon (mc-
40 Si) PV systems. More recently, for the same PV technology, Quansah et al. (2018) reported an
41 annual degradation rate of maximum produced power of 1.54%.

42 PV systems are subject to various types of faults. These faults can be related to many
43 factors such as material interactions (corrosion of connectors, yellowing, browning of
44 encapsulation material and discoloration of busbars...) and environment factors such as
45 soiling and shading. Soiling refers to the accumulation of snow, dirt, dust, leaves, pollen, and
46 bird droppings on PV panels (Maghami et al., 2016). Shading may be a result of soiling or
47 occurs due to obstructions caused by trees, buildings or chimneys. Thus, PV cells or modules
48 may be partially or completely shaded during their operation. Shading is one of the most
49 recurrent and damageable faults. In fact, this condition induces important degradation of PV

50 system performances. Partial shading can lead to more than 10-20% of annual reduction in
51 power production in residential applications as shown by Deline et al. (2011). Moreover, the
52 presence of localized shading on PV modules leads to an overheating of the shaded cells
53 despite the presence of bypass diodes. Using the infrared thermography (IRT) many studies
54 prove the presence of hot spot zones on the shaded PV cells (Basri et al., 2015; Tsanakas et
55 al., 2016). Thus, the temperature increase in these zones leads to a thermal power dissipation
56 (Bressan et al., 2016), reduces considerably the PV module lifetime and can damage the
57 shaded cells (Brooks et al., 2015). The detection of such undesirable operating conditions has
58 become mandatory for obvious safety and economic reasons.

59 *a) Existing PV diagnosis approaches in literature*

60 Several PV diagnosis and monitoring studies have been developed. However, the used
61 techniques often require a relatively high cost in equipment or complexity in the diagnosis
62 process development. In general, they are three main approaches used for PV fault diagnosis:
63 image-based, model-based and process history-based also known as data-driven.

64 The common image-based PV diagnosis methods are the ElectroLuminescence (EL) and
65 the IRT imaging under steady state conditions. These methods are becoming increasingly
66 popular, since they offer efficient solution not only for detecting the fault occurrence within a
67 PV plant, but also for isolating accurately the fault. Such optical inspection techniques need
68 appropriate and expensive equipment (thermal camera, silicon charged coupled device (CCD)
69 camera...). EL-based diagnosis method is rather efficient to indicating the existence and the
70 location of contact failures; cell cracks and shunts, inactive PV cells or sub-strings (due to
71 disconnection or shunted bypass diodes) and potential induced degradation (PID) with high
72 accuracy (IEA, 2014). Nevertheless, this technique requires particular test conditions. A

73 camera with high resolution and a high pass filter are required. In addition, electroluminescent
74 inspections must not be done under maximum power point (MPP) conditions; they are
75 performed either in dark environment or after interrupting the PV system's operation. To
76 perform the EL technique, the PV module must be supplied by a DC-current to stimulate
77 radiative recombination in the PV cells (IEA, 2014). Thus, in the case of large PV
78 installations, the experimental setup may become complex, costly and time-consuming. From
79 this point of view, this technique appears more practical for small PV plants. IRT
80 measurements are conducted outdoors and at MPP operation. The majority of faults detected
81 by this method, which are similar to those detected by EL-imaging, have a significant effect
82 on the defective PV module's thermal behaviour; their signature appears as marked and
83 inhomogeneous points in the temperature distribution on the surface of the PV module. IRT-
84 based method is fast, real time and effective to detect and exactly locate the faults thanks to
85 the thermal signature, and without disturbing or interrupting the PV system operation.
86 However, IRT method needs also specific conditions to be performed (sunny cloudless day,
87 high irradiation, low ambient temperature and wind speed, accurate angle of view...) for
88 correct and accurate temperature measurement (IEA, 2014).

89 Model-based approaches generally use an analytical model of the PV system to estimate
90 the parameters, which will be compared to the measured ones obtained from real data. The
91 generated residuals are used as fault features for diagnosis purposes. Recently, some model-
92 based techniques rely on the PV power losses analysis. These modelling methods need
93 knowledge of both irradiance and PV generator temperature to predict the output power of the
94 PV system (Chouder and Silvestre, 2010; Kang et al., 2010). More recently, model-based
95 techniques use the empirical parameters (fill factor (ff), short-circuit current (Isc), open-circuit

96 voltage (V_{oc} ...) that are calculated from the shape of the current-voltage (I-V) curves
97 (Garoudja et al., 2017; Ali et al., 2016; Spataru et al., 2015). The main advantage of these
98 methods is that they have low hardware requirements and are applicable to a wide range of
99 PV systems. If the designed model can capture the main physics of the system, these methods
100 are efficient for shading detection.

101 Data-driven approach is based on data history, collected during operation. Fault features
102 are extracted and analysed for fault diagnosis. Different techniques can be used ranging from
103 signal processing to computational intelligence and machine learning. They do not require any
104 explicit model of the process under monitoring. Among signal processing techniques, time-
105 domain reflectometry (TDR) (Takashima et al., 2008) is used to detect and identify open-
106 circuit faults and spread spectrum time-domain reflectometry (SSTDR) techniques are used to
107 detect catastrophic faults, ground-faults and PV arc faults (Alam et al., 2013; Alam et al,
108 2014). These techniques are costly and require a specific external signal function generator.
109 Moreover, they are not used to detect and identify shading faults. Other techniques extract the
110 fault features from the I-V characteristic of PV module, string or array. Based on the analysis
111 of the first and the second derivatives of I-V curves, Bressan et al. (2016) detect the activation
112 of bypass diodes that indicate the presence of shading fault. This fault is also detected by
113 comparing the I-V curves in normal and shaded operations as studied by El Basri et al.
114 (2015). These methods are simple and effective to detect shading faults, but they are not able
115 to identify and classify the type of shading patterns.

116 Artificial neural network (ANN) and fuzzy classifier are the most used methods for
117 shading fault detection as described in (Dhimish et al., 2017; Spataru et al., 2015). However,

118 these methods suffer from several disadvantages like requiring a large amount of training data
119 for accuracy detection, time-consuming training step and sensitivity to unbalanced weather
120 conditions. In addition, this data is obtained for a specific PV installation. Thus, the rules are
121 strongly tied to the system under study. Another disadvantage of these techniques is that the
122 trained data need to be updated periodically. This is due to the high variability of operating
123 conditions such as the environment variation or solar cells degradation and aging. This means
124 that a trained data in low irradiance and low temperature condition for example, may
125 misclassify the data and generate false alarms for healthy operating conditions if the
126 irradiance and the temperature are higher.

127 However, taking advantage of the PV systems during operation, a huge quantity of data
128 can be collected for analysis. Therefore, data-driven modelling is relevant, and features can be
129 extracted then analysed for fault diagnosis purposes. In the field of features extraction
130 techniques, Principal Component Analysis (PCA) is one of the most common multivariate
131 statistical tools used for data representation and classification (Jolliffe, 2002).

132 PCA has been proved in several studies to be effective and powerful for the diagnosis in
133 different applications and shows good classification performances as in many studies (Harkat
134 et al., 2006; Harmouche et al., 2012; Gharavian et al., 2013; Harmouche et al., 2014; Adouni
135 et al., 2015; Harmouche et al., 2015). This technique is very attractive for applications
136 involving complex systems. To the best of our knowledge, it has not yet been used for PV
137 systems diagnosis in such operating conditions.

138 b) Paper Contribution

139 We propose in this study to investigate the effectiveness of shading fault diagnosis using PCA
140 for the analysis of the features extracted from real I-V curves. The proposed method is applied
141 offline, for the case of a PV module. Based on the obtained results, the PCA's performances
142 for fault detection and classification are discussed.

143 Here are the research contributions:

144

145 - For the first time, an implicit PCA model is developed for PV system fault
146 detection and classification (FDC). This model has several advantages over the
147 reported models in literature, such as simplicity and low training cost. Moreover, this
148 model leads to good and clear data visualization.

149 - Compatibility with the existing PV systems. The FDC method can operate with
150 any connected PV system, thanks to the integration of online I-V tracers for the new
151 existing PV inverter technologies. It takes the advantage of available measurements in
152 such existing systems with no additional hardware.

153 - In addition to its ability to discriminate the healthy data from the faulty ones,
154 the proposed approach shows a good classification capability for the same category of
155 fault
156 (shading). In fact, the different shaded configurations are well classified using the
157 PCA algorithm.

158

159 c) Paper outline

160 The paper is organised as follows; in section 2, preliminary simulation results are presented
161 to verify the ability of using I-V curve and data processing with PCA to separate different
162 faulty conditions. In section 3, a brief description of the experimental setup is done and the
163 experimental tests in healthy and faulty operations are presented. In section 4, the fault
164 detection methodology is described and implemented. The data processing and the
165 evaluation's results are also detailed both in the training and the validation steps. Section 5
166 concludes the paper.

167 **2. Preliminary studies: analysis of the I-V curves for different faults**

168

169 For PV systems, the degradation (or the faulty) modes are reflected differently in the I-
170 V curve, which has a particular shape under shaded condition due to the activation of bypass
171 diodes. In the following, we consider a PV module with the same specifications as the one
172 considered in this paper and a series resistance of 0.3Ω at Standard Test Conditions (STC).
173 To show the effects of some of the PV faults on the I-V curve, we present in Fig.1 the
174 simulation results obtained under healthy conditions, partial shading and degradation of the
175 series resistance. Under shading fault, we consider that the three sub-strings receive non-
176 uniform irradiations. We can observe from Fig.1 that a degradation of the series resistance
177 mainly modifies the I-V curve in the region close to the open circuit voltage V_{oc} (Rodríguez et
178 al. 2015). The same effect can be observed in the case of potential-induced degradation (PID)
179 (Spataru et al. 2015).

180

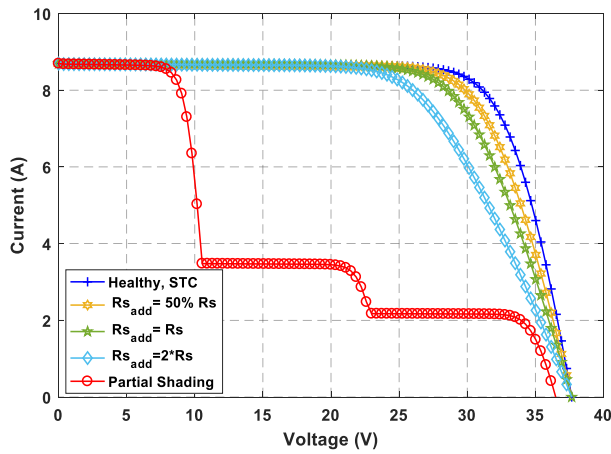


Fig. 1: PV faults' signatures on the I-V curve

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From Fig.2 we can deduce that the projection of the data in the new reference frame spanned by (PC1, PC2) that the partial shading fault could be clearly separated from the degraded series resistance. However to separate the healthy case from the degraded series resistance, additional data processing or/and additional information should be done or included.

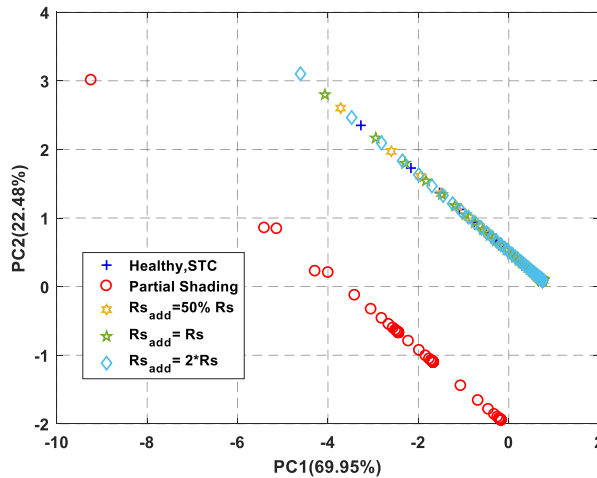


Fig. 2: PCA results in the subspace spanned by PC1 and PC2 for the simulated PV faults

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In the following, we will focus on the shading fault detection with experimental data. Also more details will be provided on the features selected for PCA evaluation.

3. PV system and shading condition

The common models used to reproduce the I-V characteristic of a PV cell are based on the one diode or two diodes equivalent electrical circuit (Askarzadeh and Rezazadeh, 2012). Other models have been developed to offer a better modelling of the physical phenomena in a PV cell (Tossa et al., 2014; Bishop 1988). The classical single diode model is generally used since it is adequate at reproducing the main characteristics of a PV cell. Shading the total or the partial PV system surface is a very serious concern in such systems (Quaschnig and Hanitsch, 1996; Patel and Agarwal, 2008). In order to mitigate the shading effects, PV systems are equipped with bypass diodes. These diodes become operational when the PV cells are reverse biased under shading condition. The activation of these diodes creates a short circuit of the shaded cells, which limits their reverse voltage and thus the dissipated power. In practice, a single bypass diode is usually connected across a group of 18-20 cells.

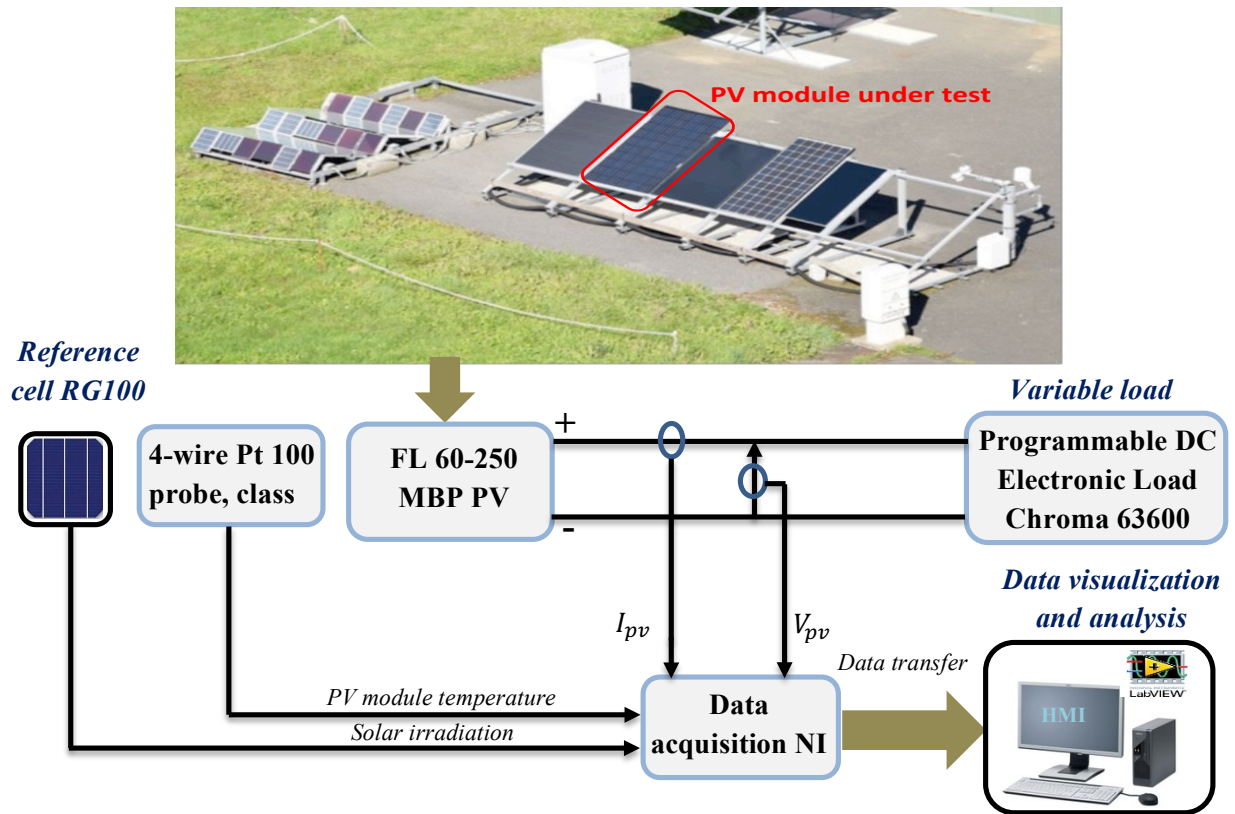
3.1. Experimental set-up description

The evaluation of the proposed fault detection technique is carried out using real data generated from the FL60-250MBP PV module. The main parameters are given in Table 1 under Standard Test Condition (STC) (1000 W/m^2 , $25 \text{ }^\circ\text{C}$). It is composed of 60 mc-Si based PV cells, connected in series and gathered into three sub-strings of 20 PV cells for each one. This module is equipped with three bypass diodes; each one is mounted in anti-parallel to protect a PV sub-string.

In this experiment, the I-V curves are obtained online using a variable load (Programmable DC electronic load Chroma 63600), which provides 101 data from open-circuit voltage to

216 short-circuit current for each I-V curve. Online measuring methods of the I-V characteristic
217 can be also done using other real devices. In fact, their main principle is to apply a variable
218 impedance, which changes from a very large (or small) value to a small (or large) one in order
219 to extract voltages and currents values between open circuit voltage and short circuit current.
220 Many examples of these methods can be found in the literature. Varying the impedance can
221 be created by using resistive load (Van Dyk et al, 2005), charging or discharging a capacitor
222 (Benzagmont et al., 2018; Mahmoud 2006; Muñoz and Lorenzo, 2006; Spertino et al., 2015)
223 or using an electronic switch like MOS transistor (Kuai and Yuvarajin, 2006). The use of one
224 device depends on the PV power and the desired accuracy of measurements. For example, the
225 use of the capacitive load is recommended for measuring in PV installations from 2 up to 50
226 kWp (IEC, 1995). Considering 101 samples in this experiment is enough to sweep the I-V
227 curve of the module under study. A reference cell (RG100 by SOLEMS) is used to measure
228 the solar irradiance captured by the PV module area and a 4-wire Pt100 probe, bonded on the
229 back face of the PV module, is used to measure the temperature.

230 A data acquisition system is installed and a computer is used for supervision and data
231 visualization using LABVIEW®. This experimental setup is installed at the French national
232 observatory SIRTa (Haeffelin et al., 2005). A picture and a diagram describing the
233 instrumentation are displayed in Fig.3.



234

235

Fig. 3: Layout of the experimental setup

236

Table 1

PV module specifications at STC

238

Symbol	Quantity	Value
P_{mpp}	Maximum Power (Wp)	250
I_{mpp}	Current at P_{mpp} (A)	8.21
V_{mpp}	Voltage at P_{mpp} (V)	30.52
I_{sc}	Short-circuit Current (A)	8.64
V_{oc}	Open-circuit voltage (V)	37.67
S	Area of the module (m ²)	1.64

239

240 3.2. Data Acquisition

241

242 Five sets of experimental tests have been conducted to assess the fault detection approach.

243 They have been realised under several operating conditions:

- 244 • One healthy mode
- 245 • Four faulty modes with different shading conditions: for each set, the shading is
- 246 applied by covering the PV cells with a survival blanket.

247 The experimental data is redundant. We have recorded three measurements (A_m , B_m and
248 C_m) of a complete I-V characteristic for each set of healthy and faulty tests. The collected data
249 sets A_m and B_m will be used for the training step while C_m will be used for validation as
250 explained in section 4. Each I-V curve is composed of 101 samples. It is recorded in one
251 minute. 101 samples are enough for our system to sweep a complete I-V characteristic.
252 Generally, the number of samples needed to extract these characteristics is selected according
253 to the size of the PV system and to the mismatching conditions in order to clearly show the
254 deviations and the inflection points on the I-V curve. Despite the short duration between
255 measurements, the irradiation can change significantly. For each I-V curve (Fig.4 and Fig.5),
256 the three cases A_m , B_m and C_m are drawn in blue, red and mustard lines respectively.

257 *3.2.1. Healthy condition*

258

259 Fig.4 illustrates the experimental I-V curve measured three times when the PV module
260 operates in healthy condition and clear condition (more than 800 W/m^2). As the PV module
261 short-circuit current is proportional to the solar irradiation, it produces less current when
262 receiving low irradiation level. We notice that these results are consistent with the datasheet
263 information given under STC (Table 1).

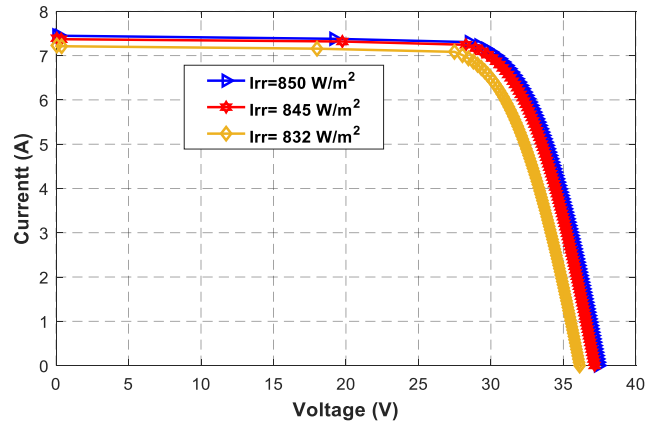
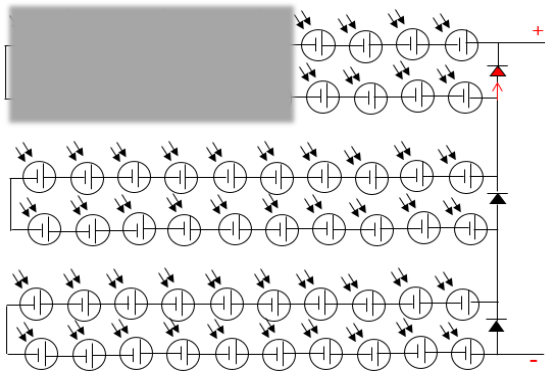


Fig. 4: Experimental I-V curve under healthy (normal) condition

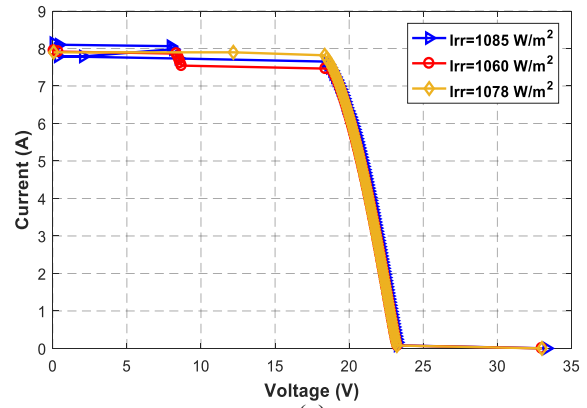
3.2.2. Shading conditions

The four configurations of shading, the active diodes and the I-V characteristics (measured three times for each configuration) are illustrated in Fig.5. In shaded conditions, all the I-V curves show multiple peaks explained by the state of the bypass diodes relative to each type of the applied shading. These peaks prove the efficiency degradation of the PV system under shading since its maximum produced power is reduced. As it is partially shaded, the PV cells of the module under test are under non-uniform irradiation. We note that for each I-V characteristic, the solar irradiation displayed in the legend is the one measured with the reference cell (RG100). The behaviour of the experimental curves differs according to the shading configuration (row level, column level and number of shaded cells) and to the environmental variations (temperature and solar irradiation). Fig.5a shows the first shading configuration; one PV sub-string is partially shaded. The shading of 12 cells leads to the activation of one bypass diode so the deactivation of the faulty sub-string. This is confirmed with the voltage steep variation due to the lost of this sub-string. (Fig.5e). For the rest of the

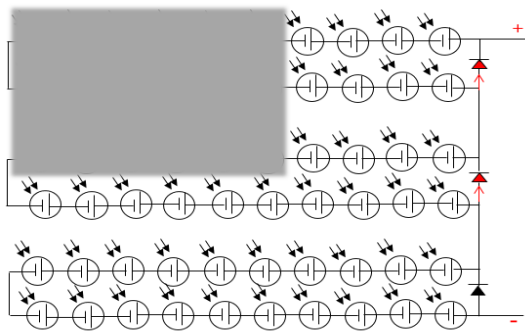
285 configurations, two bypass diodes are activated, as two sub-strings are partially shaded for
 286 each configuration. According to the severity of the shading fault, we have two cases: the
 287 diodes are conducting simultaneously (Fig.5c) and there is one voltage peak (Fig.5g), or they
 288 are activated one after the other (Fig.5b and Fig.5d) and we observe two peaks in the voltage.



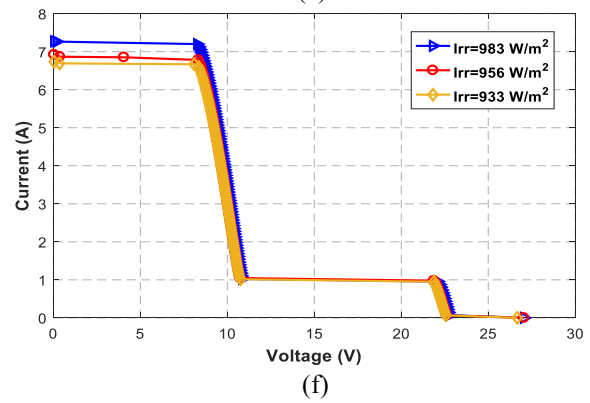
(a)



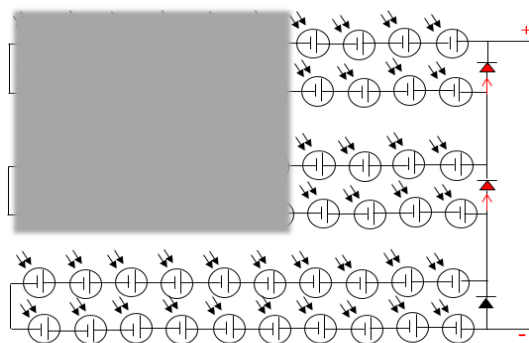
(e)



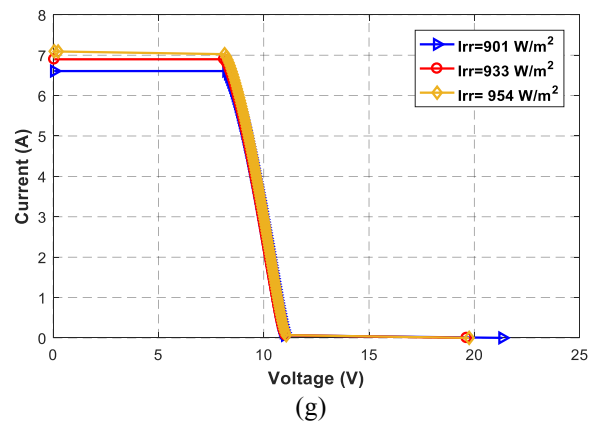
(b)



(f)



(g)



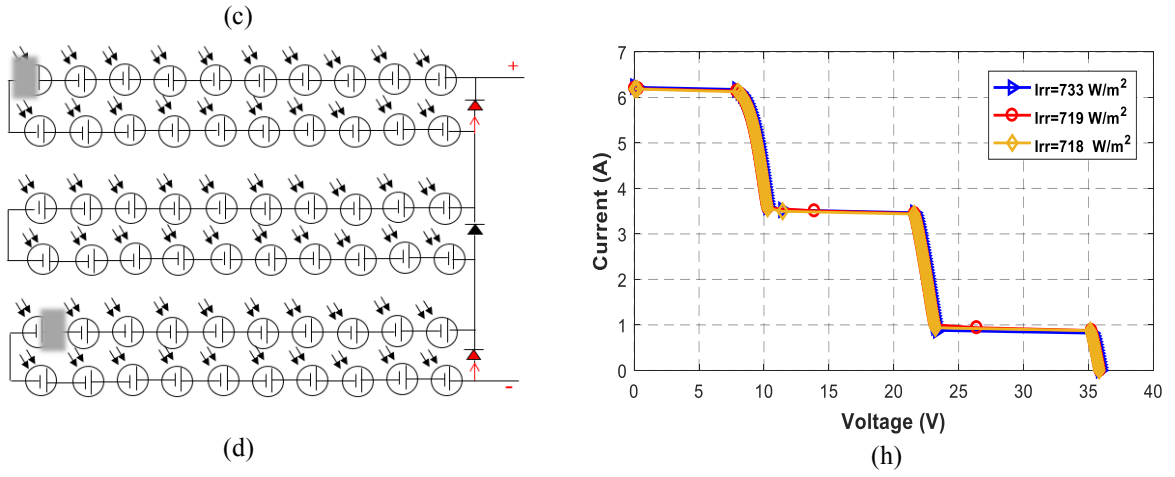


Fig. 5: Shading configurations (a) 1, (b) 2, (c) 3, (d) 4, and experimental I-V curves (e), (f), (g), (h)

3.3. Data reproducibility

For our evaluation, the I-V curve is acquired three times for each experimental test. The main idea behind the data redundancy is to create a database for the diagnosis algorithm. This database will be divided into training data and test data. The experimental tests show that the shading faults strongly modify the shape of the I-V characteristics. Therefore, we investigate in this paper the use of area under the curve (AUC) as a metric to analyse the differences between the redundant data of each experimental test. It is computed based on the PV current and PV voltage. We consider the normalized current with respect to the measured irradiation. An approximation of the AUC is expressed as following:

$$AUC = \sum_i \frac{1}{2} [(v_j - v_{j-1})(i_{norm,j} - i_{norm,j-1})] + i_{norm,j-1}(v_j - v_{j-1}) \quad (1)$$

$$i_{norm} = i \frac{G_{STC}}{G_{mes}} \quad (2)$$

303 where G_{STC} and G_{mes} are respectively the irradiances for STC and the measured one.

304 The standard and relative errors of the AUC computed for each test are given in Table 2.
 305 We can first notice that the highest AUC values are obtained under healthy condition. This is
 306 consistent with the I-V curves. This area mainly varies with reference to the test condition
 307 (healthy or faulty) and to the shading fault type.

308 The replication of the measurements shows very little deviations between the I-V data
 309 obtained for each test, which is consistent with the one-minute measurement process. In fact,
 310 the solar irradiation changes little for a maximum rate of 13 W/m² in healthy case and 25
 311 W/m² for the first faulty configuration, 50 W/m² for the second, 53 W/m² for the third and 15
 312 W/m² for the last one. The maximum relative error accounted for the healthy operation is
 313 4.69% and 2.36% for the faulty one. According to this variability, we assume that the
 314 database is representative of all operating conditions and can be used for evaluating the fault
 315 detection.

316 **Table 2**
 317 Evaluation of area under the curve, the standard and the relative errors for the experimental tests
 318

		Healthy condition	Shading configurations			
			1	2	3	4
Area under the curve	A_m	299.62	153.34	83.06	71.64	157.15
	B_m	296.49	154.26	82.34	72.08	160.87
	C_m	285.56	155.04	82.16	72.10	159.84
Standard error	$\Delta A_m B_m$	3.13	0.92	0.72	0.44	3.72
	$\Delta A_m C_m$	14.06	1.70	0.90	0.46	1.03
	$\Delta B_m C_m$	10.93	0.78	0.18	0.02	2.69

		Healthy condition	Shading configurations			
			1	2	3	4
Relative error (%)	$\Delta A_m B_m / A$	1.04	0.60	0.86	0.61	2.36
	$\Delta A_m C_m / A$	4.69	1.10	1.08	0.64	0.65
	$\Delta B_m C_m / B$	3.82	0.50	0.21	0.02	1.67

319

320

321

4. Shading fault detection

322

The flowchart of the method is displayed in Fig.6. The first step consists in the modelling.

323

The training data represents 67% of the experimental measurements determined for the

324

healthy and all cases of PV shading faults. The second step consists in the data pre-

325

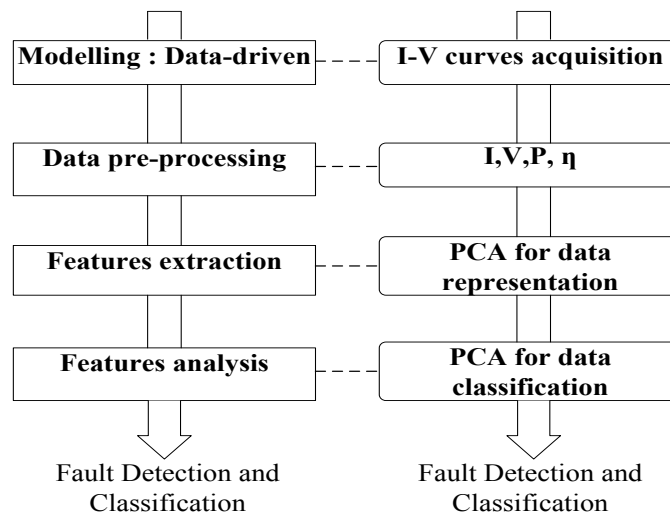
processing. The PV power and efficiency are used as additional information to build the

326

matrix X . Then, the logarithm function is applied to each variable of this database. Finally,

327

the features are extracted and analysed.



328

329

Fig. 6: Flowchart of the FDC algorithm

330

331 When dealing with I-V curves in real environmental conditions, it might be difficult to
332 distinguish healthy operations from faulty ones. Therefore, to ensure reliable fault detection
333 one should find an appropriate workspace in which the data's separability is highlighted.
334 Indeed, PCA is known to be an efficient multivariate statistical tool for this purpose.

335 The PCA is applied to the matrix X to get the principal scores that form the PCA space for
336 data representation and classification.

337 *4.1. Principal Component Analysis formulation*

338 Principal Component Analysis (PCA) is a multivariate statistical technique that seeks in the
339 multidimensional space of system variables the most dominating dimensions to re-express the
340 multivariate database built from a large number of measurements recorded at different times.
341 The new dimensions are uncorrelated so the reduced subspace acts like a denoising filter and
342 keeps the underlying "latent structures" in the data. This new subspace is denoted the principal
343 subspace or the 'representation' subspace. Its complementary subspace into which noises and
344 outliers are rejected is termed the residual subspace. Analytically, PCA searches orthogonal
345 directions, which contain the maximum variance of the projections for the data set points. The
346 PCA task is formulated by a problem of the eigenvector decomposition of the data covariance
347 matrix (Jolliffe, 2002).

348 The data consists of measurements collected at N different sampling times of M variables.
349 The time points represent the observations. PCA uses a linear combination of the original
350 variables to build the new variables while keeping maximum variance information. The first
351

352 principal components, which span the principal subspace, are given by the first l dominant
353 eigenvectors of the data covariance matrix. They are associated to the l highest eigenvalues.
354 The last non-retained eigenvectors ($M - l$) define the residual subspace. In the representation
355 subspace containing the most significant variations, the eigenvectors are denoted loading
356 vectors and the projection of the data on these loading vectors are called principal component
357 scores. These searched directions are called principal components (PCs), each one being
358 characterised by a loading vector and a score component. The percentage of the variance of
359 data contained in each PC is expressed by its corresponding eigenvalue. Each PC is aligned in
360 a direction corresponding to the largest variance of the data, starting with the first PC. Principal
361 components are therefore ordered from the most energised associated to the highest
362 eigenvalue, to the less energised associated to the lowest eigenvalue. Based on stop criteria the
363 principal subspace is spanned with most energised PCs while the residual one is spanned with
364 the remaining PCs. For this purpose, many stopping criteria have been proposed in the
365 literature such as the cumulative percentage of total variance (CPV) (Chiang et al., 2001) and
366 minimizing the Variance of Reconstitution Error (VRE) (Qin et al., 2000). A comparison
367 between 11 methods to determine the number of most energised PCs has been given by Valle
368 et al. (1999). From the data collected in the healthy operating mode of the process, PCA is
369 applied and the loading vectors are used as references to design the model. The scores or their
370 statistical distributions can be also used to design the implicit model. When new data is
371 collected, it is projected in the subspace (principal or/and residual). The deviation from the
372 reference is then measured and analysed to assess the fault occurrence.

373 Let us consider N observations of M process variables gathered into the original data matrix

374 $X_{[N \times M]}$ given by:

375

$$X_{[N \times M]} = [x_1, \dots, x_k, \dots, x_M] \quad (3)$$

376

377 Where $\mathbf{x}_{j(j=1, \dots, N)}$ is the j^{th} variable.

378

379 At first, it consists in centring (zero mean) and reducing (unit variance) the variables for each

380 observation k of $\mathbf{x}_{j(j=1, \dots, N)}$:

$$(x_i)_c(k) = \frac{x_i(k) - \overline{(x_i)}}{(\sigma_i)} \quad (4)$$

381 where $(\mathbf{x}_j)_c$ is the centred and reduced variable, $\overline{(x_j)}$ and (σ_j) are respectively the mean value

382 and the standard deviation of $\mathbf{x}_{j(j=1, \dots, M)}$.

383

384 We can therefore define the new data matrix as:

385

$$(X_c)_{[N \times M]} = [(x_1)_c, \dots, (x_k)_c, \dots, (x_M)_c] \quad (5)$$

386

387 The covariance matrix is then calculated as:

388

$$C = \frac{1}{N-1} X_c^T X_c \quad (6)$$

389

390 The quality of the representation for the collected measurements for fault diagnosis

391 purposes relies on the accuracy of the PCA model. This model depends on the retained PCs to

392 represent the data variability. Let us denote \mathbf{P} the column matrix of loading vectors, which are

393 arranged in the descendent order of their corresponding eigenvalues. The principal component

394 scores are obtained by the projection of the original data centred and reduced on the new space

395 spanned with \mathbf{P} . The matrix $T_{[N \times M]}$ of the principal component scores is defined by:

$$T_{[N \times M]} = (X_c)_{[N \times M]} P_{[M \times M]} = [t_1, \dots, t_k, \dots, t_M] \quad (7)$$

396

397 *4.2. Data pre-processing and features extraction*

398 The selection of the variables is very important to obtain the best representation and
399 discrimination of the data. In order to detect the shading fault, Fadhel et al. (2018) have used
400 the voltage, the current and the power of the PV module as variables. Thanks to PCA, they
401 have successfully distinguished the healthy data from the faulty one. However, using these
402 variables in our case has led to a severe overlapping in the space spanned with the principal
403 scores. This is due to the variation of the irradiance between two measurements for the same
404 operating condition and also to the common levels of voltage between the PV curves obtained
405 under shading faults (Fig.5). In order to have a fault diagnosis, robust to environmental
406 changes and sensitive to fault occurrence, we have:

- 407 ✓ normalised the PV voltage and power with respect to the PV efficiency,
- 408 ✓ used the log function.

409 The selection of these features allows us to use experimental measurements obtained in
410 non-controlled irradiance operating conditions without a huge influence of this environmental
411 parameter.

412 The principal component analysis is finally applied to the training data matrix
413 $X_{[1010 \times 3]} = \log[v/\eta \quad i \quad P/\eta]$ composed of 1010 observations of 3 variables (Fig. 7) where P
414 and η are respectively the power and the efficiency. It consists of 5 sub-matrices of 101*2
415 training observations. The efficiency is computed for each couple of observation (i, v) and is
416 expressed as follows:

$$\eta = \frac{P}{G_{mes} S} 100 \quad (8)$$

417

418 where S is the area of the PV module under test.

419

	v/η	i	P/η
Healthy			
	⋮		
Faulty configurations 1 to 4			
	⋮		

420

Fig. 7: Data set design for PCA analysis

421

422 The data set generated for both healthy and shading conditions during the experimental
 423 tests is composed of 1515 samples. The training step is performed with 1010 samples using
 424 the first two measurements A_m and B_m of each test. The main task of this step consists in the
 425 construction of the PCA model from the learning data set. This implicit model will be used for
 426 validation of the test data set.

427 *4.3. Features analysis in the training step*

428 Table 3 presents the eigenvalues and their relative contributions. The first two PCs retain
 429 99.99% of the information. Projecting the training data into the PCA subspace spanned with
 430 PC1 and PC2, PC2 and PC3, PC1 and PC3 gives the data scatter displayed in Fig.8a, Fig.8b
 431 and Fig.8c respectively. The inclusion of the three principal components in the PCA space
 432 used to project the data gives the 3D representation of Fig.8d. The representation in the
 433 subspace spanned with the first two PCs is able to detect and identify the fault. We can

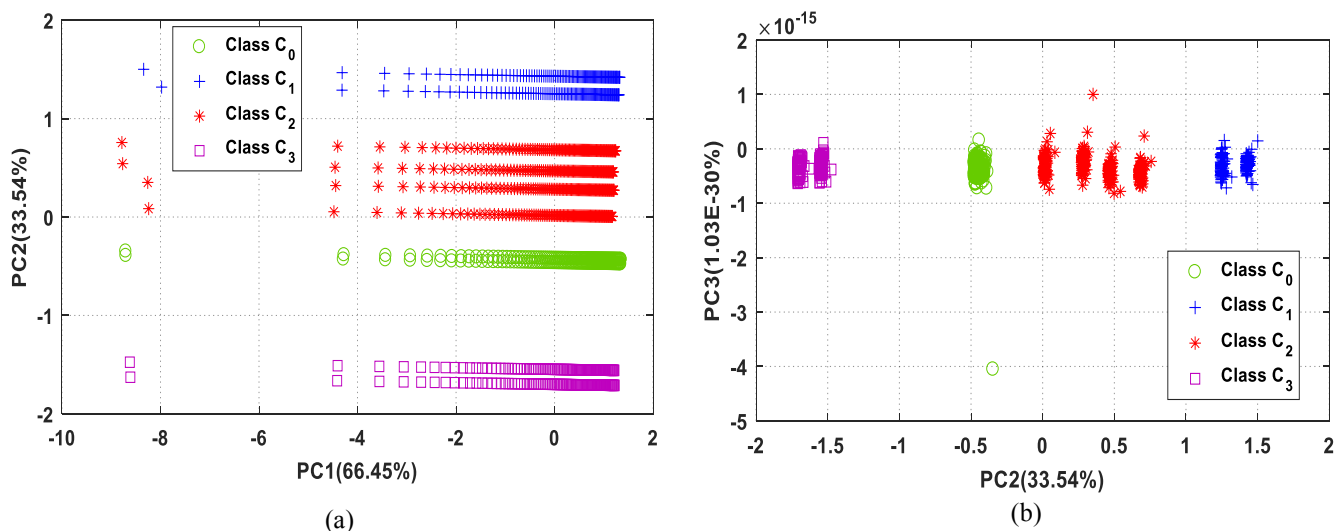
434 observe four classes: one healthy named class C_0 and 3 faulty obtained from 4 faulty
 435 configurations as given in Table 4. Indeed, shading configurations 2 and 3 correspond to the
 436 simultaneous activation of two bypass diodes. The healthy class is well separated from the
 437 faulty classes. Those ones are distinguished with reference to the fault size and location.

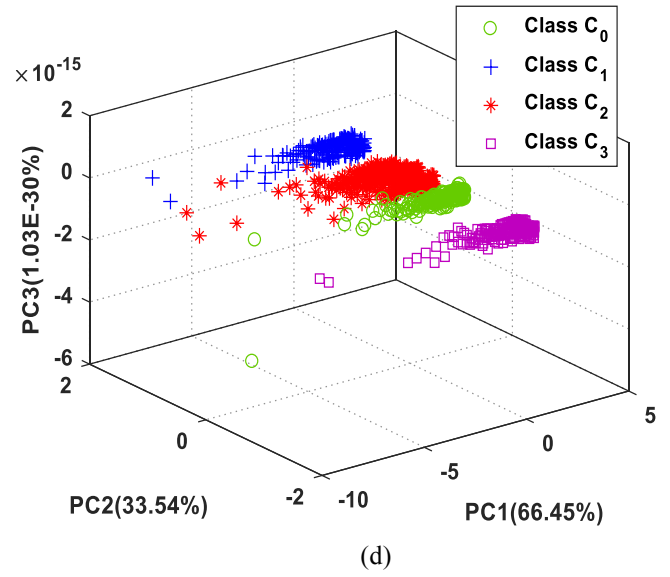
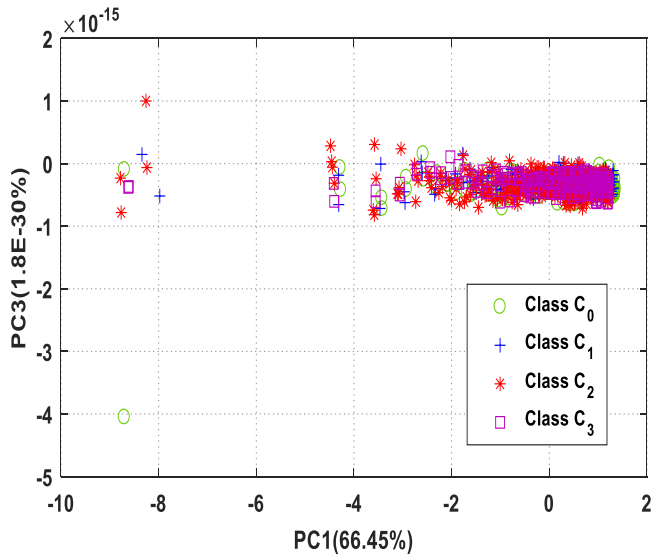
438

439 **Table 3**
 440 Eigenvalues and Percentage of the Principal Component contributions

	Principal components		
	PC1	PC2	PC3
Eigenvalue	1.99	1.006	3.09 E-32
Variance (%)	66.45	33.54	1.03 E-30

441





442 **Fig. 8:** PCA training data set results in the subspace spanned by PC1 and PC2 (a), PC2 and PC3 (b), PC1 and
 443 PC3 (c), and 3D PCA plot

444

445 **Table 4**

446 Classes in the PCA space

Test Condition	Class
Healthy	C ₀
Shading configuration 1	C ₁
Shading configurations 2 and 3	C ₂
Shading configuration 4	C ₃

447

448

449 *4.4. Classification performance in the training step*

450 The results are analysed through the confusion matrix displayed in Table 5. The columns
 451 of this table show the percentage of affectation of the observations of a class *a priori* in a
 452 class *a posteriori*. The error rates of class separability are checked by the one-leave-out cross
 453 validation method. We first compute the coordinates of the gravity centre (considered as the
 454 mean value in our case) of each class *a priori* in the PCA space. Then, the Euclidean distance

455 between these centres and each observation in the training database are evaluated. Finally, an
 456 observation is assigned to a class among the four obtained classes if it is the closest to its
 457 centre of gravity. This table shows that a few errors are found by classifying the
 458 measurements of the training data set. We found that 97.03% of the measurements in healthy
 459 condition have been classified in their a priori class C_0 and only 2.97% misclassification is
 460 found and affected to the faulty class C_2 (corresponding to three misclassified healthy
 461 measurements). We have also found that 100% of the faulty data of shading configuration 4,
 462 represented by faulty class C_3 , are perfectly classified. Based on these good discrimination
 463 results, we can use the implicit model obtained from the training data and PCA for the
 464 analysis of the new observations.

465

466 **Table 5**
 467 Confusion Matrix for training data set classification

Class a priori	Data Assignement a posteriori			
	Healthy Class C_0 (%)	Faulty Class C_1 (%)	Faulty Class C_2 (%)	Faulty Class C_3 (%)
Healthy Class C_0	97.03	0	2.97	0
Faulty Class C_1	0	98.52	1.48	0
Faulty Class C_2	12.62	0	87.38	0
Faulty Class C_3	0	0	0	100

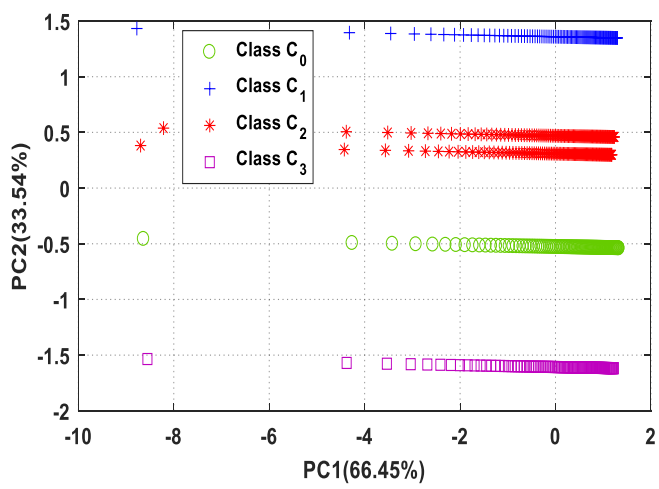
468

469 *4.5. Fault identification performance in the validation step*

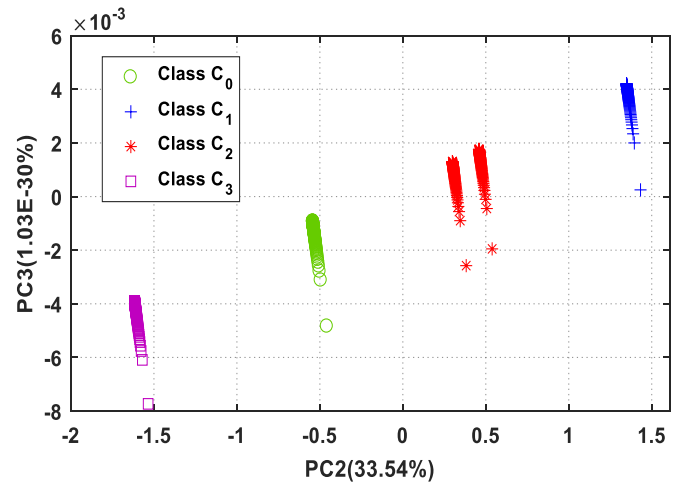
470

471 In order to evaluate the effectiveness of the PCA model for PV system Fault Detection and
 472 Classification, we have used a new data set composed of 505 observations, representing 33%
 473 of the experimental database. The test data set corresponds to the measurements C_m that were
 474 not included in the training data. These measurements are grouped in the test database

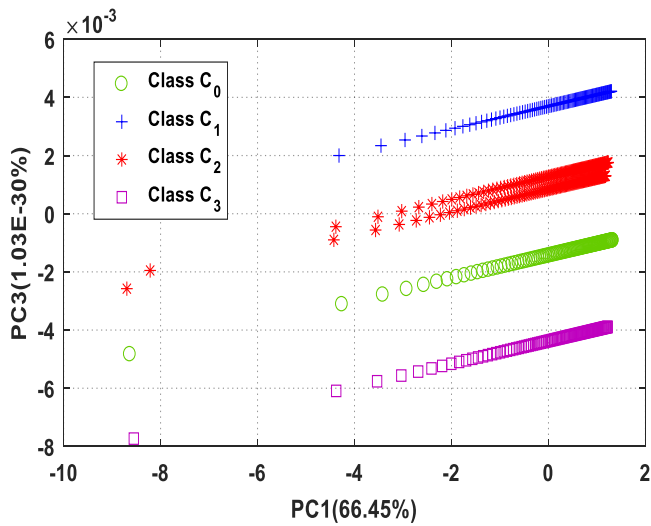
475 according to the three selected representative variables, v/η , i and P/η . Then they are
 476 projected into the PCA space spanned by the eigenvectors determined during the training step
 477 using (7). This projection gives the data classification shown in Fig.9. We can conclude that
 478 all the test observations are well identified and classified in the relevant group. The data
 479 dispersion obtained for the new data in the PCA space is similar to the one obtained with the
 480 training data. The faulty classes are well separated and discriminated from the healthy one.



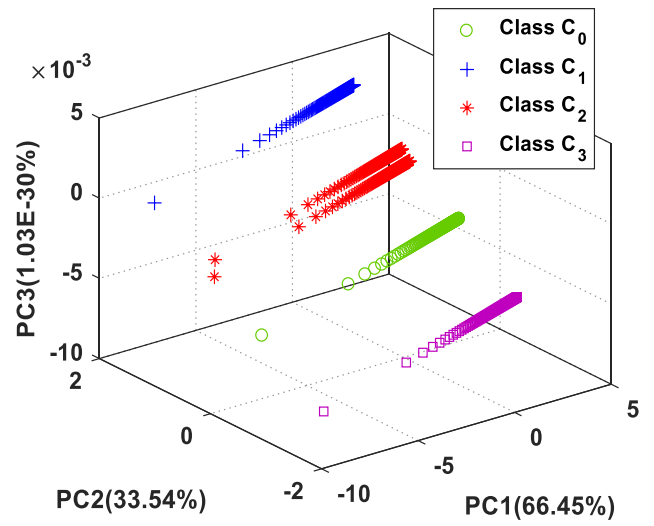
(a)



(b)



(c)



(d)

481

482 **Fig. 9:** PCA results for the test data set in the subspace spanned by PC1 and PC2 (a), PC2 and PC3 (b), PC1 and
 483 PC3 (c) and 3D PCA plot

484

485 With the PCA, we are able to identify successfully the test data in their corresponding
 486 groups. This performance is evaluated through the confusion matrix given in Table 6. We
 487 have succeeded to separate the four *a priori* defined classes with a minimum rate of 97.03%.
 488 Only 4/505 test samples are misclassified in two *a posteriori* groups; 3/101 for healthy class
 489 C₀ and 1/101 for faulty class C₁ representing a classification error of 2.97% and 0.99%
 490 respectively. This confirms that the developed PCA model is very efficient to detect and
 491 identify the fault.

492 **Table 6**
 493 Confusion Matrix for test data set classification

Class a priori	Data Assignment a posteriori			
	Healthy Class C ₀ (%)	Faulty Class C ₁ (%)	Faulty Class C ₂ (%)	Faulty Class C ₃ (%)
Healthy Class C ₀	97.03	0	2.97	0
Faulty Class C ₁	0	99.01	0.99	0
Faulty Class C ₂	12.62	0	100	0
Faulty Class C ₃	0	0	0	100

494

495

496 **5. Conclusion**

497

498 In this study, a data-driven FDC approach is proposed for a PV module shading fault
 499 diagnosis. This method uses the I-V curve of the PV module generated under healthy and
 500 faulty conditions. An experimental setup has allowed the collection of data for five different
 501 operating conditions to build the database. In the pre-processing step the power P has been
 502 added to the original variables v/η and i . Then a normalisation with the efficiency has been

503 done to mitigate the variation of the irradiance and the logarithmic function has been
504 introduced to make the method more sensitive to fault occurrence. Principal Component
505 Analysis has been applied to the training database (66% of the data history). The obtained
506 model has been used for fault detection and classification. In the training step, we have rather
507 good performances with a minimum classification success rate of 87.38% for the 4 classes
508 (one healthy and three faulty). During the validation step (with the remaining 33% of data
509 history), we have obtained successful classification rate with a minimum of 97%.

510 This method does not depend on any particular PV size and only uses available measurements
511 (PV current and voltage) avoiding extra hardware and costs. Furthermore, it is insensitive to
512 the weather conditions changes (sudden variations of solar irradiation and temperature of the
513 PV module). Based on the analysis of real PV data, the study demonstrates the feasibility and
514 effectiveness of the PCA for the diagnosis of PV shading faults.

515

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520

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