Recognition of Faulty Modules in a Photovoltaic Array Using Image Processing Techniques

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Abstract:

Visual techniques are very helpful in recognizing the condition of photovoltaic panels which are extensively used for power generation. Being clean source of energy and having zero fuel cost, solar industry has developed in no time. In order to seek maximum power from a photovoltaic, the modules installed in a PV array should be in good health. However, studies show that, direct exposure to sunlight and other faults within a PV array may damage some modules, which in turn may lead to overall efficiency reduction. This research work aims to present a visual technique to recognize faulty module in a PV array by optical image analysis. In addition to imaging techniques, the proposed framework implements mathematical modelling to correctly determine a faulty cell within a PV module. In past, thermal imaging has been used for this purpose but almost negligible work has been done by employing an optimal camera, in this regard, the proposed technique could prove to be a cost effective and efficient alternate solution to the stated problem.

Keywords*—Visual techniques, image recognition, solar panels*

I. Introduction

Photovoltaic systems are very common nowadays for power production. As, solar energy is clean and free, solar power systems are considered perfect for urban installations. Furthermore, the maintenance cost of photovoltaic (PV) systems is almost negligible. All these attributes of solar photovoltaics have made them most popular among renewable energy sources.

In past few years, the demand of solar photovoltaics has been increased. Consequently, some PV modules available in the market are often unhealthy or not in good condition. Sometimes, the manufacturing of PV modules is not up to the mark, as a result PV modules become degraded with time. Environmental factors play a pivotal role towards the performance and health of PV systems. Studies have shown that atmospheric heat and humidity directly affects the health of PV modules [1]. Prolonged exposure of PV modules to heat and humidity may lead to module degradation or discoloration, which is reported as a permanent fault in a PV module. A degraded module calls for the need of a proper cooling mechanism to cope with extreme environmental conditions. It has been reported in literature that every degraded module may cause a 0.8% decrease in efficiency annually [2].

Choi [3] has reported non-linearities or irregularities in the characteristics of degraded PV modules. Phinikarides [4] has presented performance degradation analysis on the basis of PV technology. Moreover, [4] has also listed effects of weathering conditions on PV performance. Also, various degradation rate (R_D) calculating methodologies have been presented in this work, it is shown that the value of R_D varies with methodology Cornaro [5] has presented a case study by discussing a performance analysis of PV modules of various technologies after one year of outdoor exposure in Rome. This work has reported that polycrystalline silicon photovoltaics are more stable as compared to double junction amorphous silicon modules which were prone to degradation in the initial months of installation. However, if the annual performance ratio (PR) is considered, it is almost similar for both technologies. In addition, it is reported in this work that the phenomenon of module degradation is different for PV modules of same models but from different manufacturers.

Various thermographic studies have been done so far in order to diagnose the health of an operational PV module. Also, thermographic analysis is commercially done in PV industries before their installment. Quarter [6] has proposed a light Unmanned Aerial Vehicle (UAV) based thermographic technique in order to monitor and diagnose faulty modules in a PV array. A visual approach has been utilized in this work on the basis of thermal and optical camera together, for the diagnosis of a degraded PV module. The suggested technique is good in fault diagnosis of PV module, but as this technique employs an IR and an optical camera together, this no more remains a cost effective solution to the problem.

Similarly Aghaei [7] has presented another thermography based digital image processing technique to detect a degraded module within a PV array. The author has further employed advanced imaging techniques in the thermal image of a faulty PV array in order to make fault more important and recognizable.

Yinhua Hu [8] has presented a thermography based approach to detect partial shading that is a temporary fault in a PV array. The author has detected the faulty portion of the module on the basis of temperature distribution in the thermal image obtained from an infrared (IR) camera. On the other hand, Karakose [9] has presented an image processing based analysis of moving shadow effects for reconfiguration in PV arrays. The later technique is a cost effective solution as it utilizes an optical camera which is cheaper as compared to a thermal camera. A comparison of prices of thermal and optical cameras have been presented in Table 1.

In recent past, very less or no work has been done on health diagnosis of PV utilizing solely a simple optical camera. In this research work, an optical camera based image processing technique has been presented in order to diagnose health of a PV module. This technique employs a simple Nikon camera in order to capture images of healthy and unhealthy modules of PV array. An algorithm is proposed to detect and recognize unhealthy or faulty cells/ modules in the PV array. The proposed algorithm is tested on an array of size 1x3 (*NsxNp*). The performance of proposed technique is discussed and compared with existing techniques in the last section of the paper.

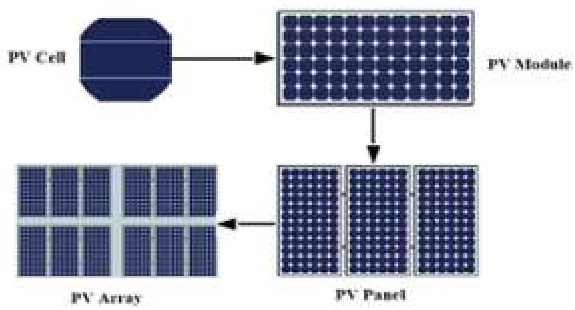

Fig. 1 Cell to array structure of photovoltaic

II. Proposed Image Processing Technique

Existing visual techniques for recognition of faulty or unhealthy module in PV either use thermal camera or they are implemented with thermal and optical camera together. Thus, increasing the complexity and processing time of the overall algorithm. Also, employing a thermal or infrared (IR) camera in addition with an optical camera signifies an exponential rise towards the overall cost of the setup. However, the proposed technique only requires an optical camera (Model: Coolpix L820V1.0) for capturing the images of the PV modules. It is to be noted that the images can be captured from camera of any model with a recommended resolution of 4 mega pixel (MP). The camera resolution of 4 MP has been selected after performing number of experiments with several camera resolution settings, e.g. 640x480 pixels, 2 MP, 4MP, 8 MP, 16 MP etc. During experimentation, it was observed that the resolution of 640x480 pixels, some useful information of the image is gone when it is processed. However, in case of resolution greater than 4MP, it was observed that the processing time of the algorithm is considerably increased, as the algorithm has to scan the pixels of whole image. So, the camera resolution of 4 MP is better in terms of image results and processing time of the algorithm. Later, the images are processed in MATLAB to recognize unhealthy module within a PV array. The algorithm of the proposed technique is shown in Fig.2.

According to the suggested algorithm, the captured image is called in MATLAB and is converted to the inverted image to make the faulty cells more prominent as compared to the rest of healthy cells in a module of the PV array. Later, the image is converted into a binary or black and white image in order to convert faulty cells in black, whereas, the healthy cells of the module are converted into white during this image conversion. It is to be noted that a gray scale image contains values from 0 to 255 whereas, a binary or black and white image contains only two values i.e. 0 for black and 1 for white [10]. So, in the proposed algorithm, pixel level analysis of the binary image is done in order to determine whether a cell/ module is healthy or unhealthy. As, an image is actually a matrix having x and y co-ordinates, so it is imperative to design a mathematical model to correctly conduct cell-wise health analysis of a particular module on the basis of pixel values of the image. In that regard, the proposed algorithm calculates area of each cell within a PV module on the basis of x and y coordinates in the image. After that, number of healthy and unhealthy pixels are determined within a cell of the PV module. Later, this count is compared with the calculated area of the cell. If, the count of unhealthy pixels is greater than 50% of the area of cell, that cell is declared as unhealthy cell, otherwise healthy. A threshold of 50% has been defined on the basis of taking into account the effect of interconnections of cells that also appear in the image of module as black. It is pertinent to note that the author of [9] has performed moving shadow analysis using imaging techniques. In that regard, five image conversions have been done to calculate the percentage of shade, i.e. image erosion, dilation, blurring, canny edge detection and contour drawing operations. These image operations altogether contribute towards increased processing time of the algorithm. Whereas, the proposed algorithm has to go through only two image conversions in order to detect the faulty module. Later, mathematical operations are done in order to exactly determine the location of faulty cell which are described in following section.

TABLE.1. Model-wise price comparison of thermal and optical camera

Optical Camera Model (Sony)	Price in $	Thermal Camera Model	Price in $
LCSEB/B	38	FLIR-E4	980
DSCH300/BM	179.95	FLIR-I40	2800
Alpha a6000	698	63902-0202 NIST	2895
DSC-HX200V	1130.6	PS24	4353.88
A7 Full Frame	1130.6	T200	7500

A. Mathematical Modelling

A PV module consists of number of cells in series and parallel. Further, number of modules in series make a PV string, whereas, number of series strings in parallel make up a PV array. Fig.1 describes the structure of a PV array from cellular to array level. The mathematical model of the problem is described in equations 1-5. *A* represents the area of particular cell that is being scanned by the algorithm at an instant. *I(x, y)* represents the x, y coordinates of a particular pixel of an image that is being processed by the MATLAB code. H represents number of healthy pixels present in the image at cellular level. Similarly, U represents count of unhealthy pixels within a cell. Further, if the count of unhealthy pixels is greater than half of the area of cell, that cell is declared as unhealthy and vice versa.

First of all, area of cell is calculated as;

$$A = (x_2 - x_2) * (y_2 - y_1) \quad (1)$$

If

$$I(x,y) = 1,$$

$$H = H + 1 \quad (2)$$

If

$$I(x,y) = 0,$$

$$U = U + 1 \quad (3)$$

Cell is healthy if;

$$H \geq 0.5A \quad (4)$$

Cell is unhealthy if;

$$U \geq 0.5A \quad (5)$$

B. Extension from module to array

The proposed model can be extended to full PV panel in a way that the algorithm, searches for the unhealthy module in a PV array, once it searches the faulty module/s, the above mentioned model can be utilized to further recognize the fault at cellular level. The mathematical model to detect a faulty module within a PV array is described in equations 6-10.

A_{h1} symbolizes the area of upper half of the module. Similarly, H_{h1} represents the count of healthy pixels in upper half of the module, while U_{h1} represents number of unhealthy pixels in that part.

$$A_{h1} = (x_2 - x_1) * (y_2 - y_1) \quad (6)$$

If

$$I(x,y) = 1,$$

$$H_{h1} = H_{h1} + 1 \quad (7)$$

If;

$$I(x,y) = 0,$$

$$H_{h1} = H_{h1} + 1 \quad (8)$$

First half of module is healthy if;

$$H_{h1} \geq 4 + A_{h1} \quad (9)$$

Here, a multiplying factor of has been taken on the basis of number of cells present in one row of the PV module. In this case, there are four cells in each row of the module.

First half of module is healthy if;

$$U_{h1} \geq 4 + A_{h1} \quad (10)$$

Similarly, the model will check for second half of the same module. The module will be healthy if and only if both halves of the module are recognized as healthy, otherwise the module will be unhealthy even if only one half of it is recognized as unhealthy. This is because, any of the unhealthy part of the module will affect the overall performance of the PV array, thus contributing towards power loss.

III. Experimental Setup

An experimental setup has been established in order to test the performance of proposed algorithm. For this purpose a 1x3 ($N_s x N_p$) monocrystalline PV array, model 7SPM 85 has been utilized. A dataset of images have been obtained from a Nikon camera, model Coolpix L820V1.0 with a resolution of 4 MP.

Experimentation has been done under two weather scenarios in order to test the efficiency of the proposed algorithm. For this purpose, images of the PV array are captured under diffused irradiation conditions in weather scenario 1 [Fig.3]. Moreover, similar dataset of images has been obtained under sunny weather as well [Fig.4]. Later, the algorithm was simulated for both scenarios and the health of PV cells was clearly exhibited as healthy or unhealthy in results of the algorithm in TABLE 3.

TABLE 2: Data sheet of PV model 7SPM 85

Parameters	Value
Cells per module	32
Maximum power (P_{mpp})	86W
Voltage at maximum power (V_{mpp})	16.5V
Current at maximum power (I_{mpp})	5.25 A
Open circuit voltage (V_{oc})	20.2 V
Short circuit current (I_{sc})	6.5 A

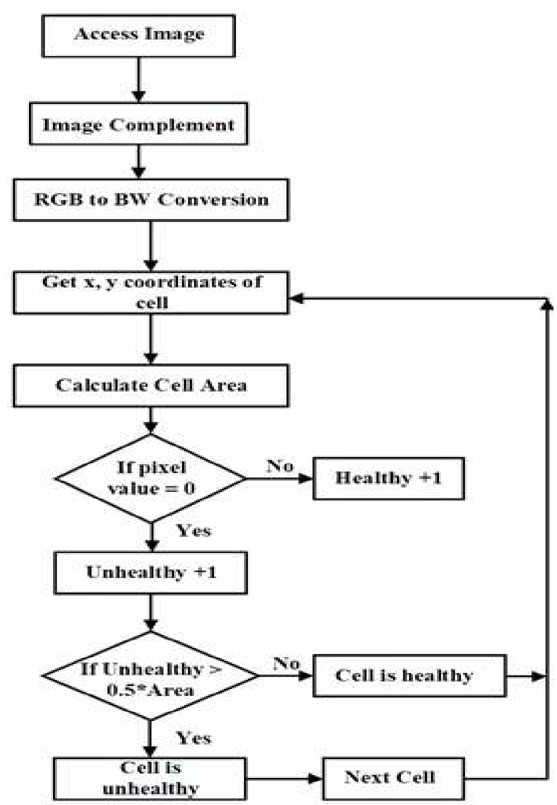

Fig. 2 Flow chart of proposed image processing technique

IV. Simulation Results and Discussion

This section describes the simulation results of the proposed algorithm. In order to prove the effectiveness of the proposed algorithm, the algorithm is run for two weather scenarios.

Weather Scenario 1:

Under this scenario, images were captured under diffused irradiation conditions during sun hours 13:00-14:00. Fig. 3(a) shows the actual image, whereas Fig. 3(b) shows the inverted image and Fig. 3(c) shows the processed image. It can be seen clearly that the processed image is showing the faulty part of the image as black. The algorithm results for this image have been shown in TABLE 3. Cell wise analysis of the module is done in order to precisely recognize faulty cells within a PV module. Next, on the basis of these results, some cooling mechanism of PV modules can be suggested in order to avoid further degradation. As, the degradation can spread to neighboring cells, which may lead to complete degradation of the whole module in the long run. In that regard, it is imperative to design cooling mechanism, so that pre-mature degradation owing to extreme hot weather conditions may be dealt with.

Weather Scenario 2:

Similarly, the images were captured for another weather scenario in order to test the validity and robustness of the proposed algorithm. In this scenario, the weather was sunny and the images were captured during peak sun hours (13:00-14:00). The actual image, inverted image and processed image for weather scenario 2 has been shown in Fig.4 (a), (b), (c) respectively. The simulation results are given in TABLE 3. It can be seen that the algorithm results for this scenario are identical to those in weather scenario 1, while accurately recognizing faulty cells. So, it is verified that the algorithm works well irrespective of the weathering condition.

In past, thermography based visual techniques have been used in order to determine failure within a particular module of a PV array. However, these techniques suffer the challenges of processing time of the algorithm and cost of the camera setup. Moreover, interpretation of IR images is a real challenge owing to weather conditions, reflection and partial shading issues.

On the basis of extent of degradation within a PV module, cooling mechanism for a PV array can be suggested in the future work of this technique. Furthermore, the MPPT of the PV system can be updated according to the health status of the modules that is obtained by the proposed technique.

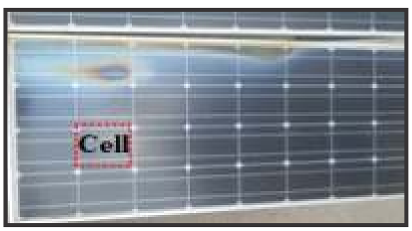

Fig 3. (a) Secenario 1: Actual image of faulty modue

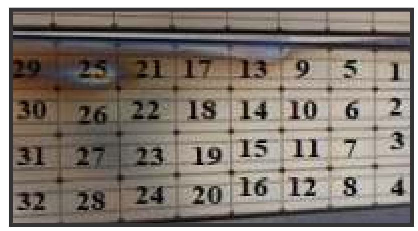

Fig. 3 (b) Inverted image

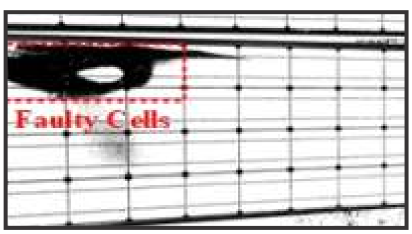

Fig.3 (C) Black and white image

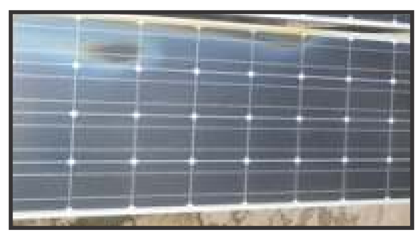

Fig.4.(a) Scenario 2:Actual image of faulty module

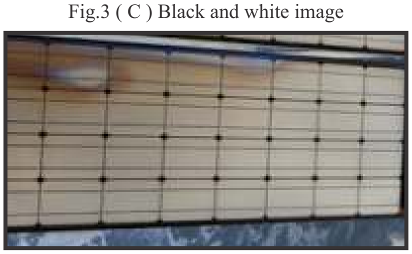

Fig.4.(b) Inverted image

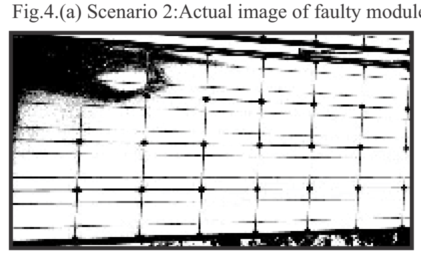

Fig.4 (C) Inverted ismage

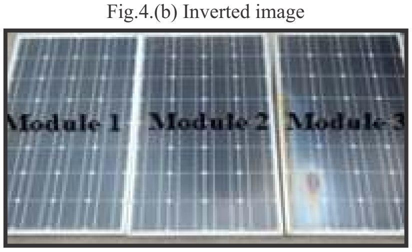

Fig.5. (a) Actual image of ful 1x3 (NsxNp)PV array

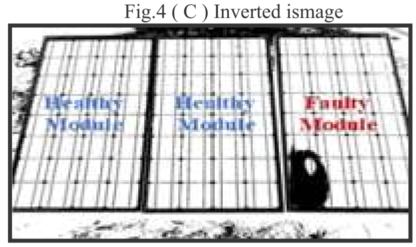

Fig.5.(b) Black & image of full 1x3 (NsxNp) PV arry with faulty module indicated

Fig.5. Actual & black & white image of full 1x3 (NsxNp) PV array

TABLE 3. Simulation results of proposed algorithm under weather scenario 1 & 2

Weather Scenario		Area of Cell (A)	Healthy	Unhealthy	Result on LCD
	1.	44544	43526	1443	cell1 is healthy
	2.	43424	42498	1347	cell2 is healthy
	3.	45312	44338	1403	cell3 is healthy
	4.	46848	45777	1508	cell4 is healthy
	5.	46400	45336	1497	cell5 is healthy
	6.	48000	46951	1490	cell6 is healthy
	7.	50592	49363	1682	cell7 is healthy
	8.	51408	49970	1895	cell8 is healthy
	9.	52704	51520	1645	cell9 is healthy
	10.	52416	51282	1595	cell10 is healthy
	11.	53456	52260	1662	cell11 is healthy
	12.	54912	52863	2522	cell12 is healthy
	13.	54560	53000	2029	cell13 is healthy
	14.	57120	55728	1872	cell14 is healthy
	15.	59136	57610	2015	cell15 is healthy
	16.	60032	58021	2504	cell16 is healthy
	17.	59280	51218	8551	cell17 ishealthy
	18.	60088	58559	2021	cell18 is healthy
Scenario 1	19.	62176	60593	2084	cell19 is healthy
	20.	66368	64189	2696	cell20 is healthy
	21.	67584	28462	39643	cell21 is unhealthy
	22.	68544	66375	2694	cell22 is healthy
	23.	68544	65728	3341	cell23 is healthy
	24.	70656	68232	2957	cell24 is healthy
	25.	72864	20433	52972	cell25 is unhealthy
	26.	72800	55894	17447	cell26 is healthy
	27.	73920	64541	9924	cell27 is healthy
	28.	77380	74119	3819	cell28 is healthy
	29.	81792	9725	72640	cell29 is unhealthy
	30.	81760	74944	7389	cell30 is healthy
	31.	81792	79393	2972	cell31 is healthy
	32.	86336	82817	4108	cell32 is healthy
	1.	23184	22508	983	cell1 is healthy
	2.	24534	23877	973	cell2 is healthy
	3.	25803	25051	1077	cell3 is healthy
	4.	27342	25870	1806	cell4 is healthy
	5.	25578	24944	956	cell5 is healthy
	6.	26352	25798	882	cell6 is healthy
	7.	28224	27441	1123	cell7 is healthy
Scenario 2	8.	28917	27996	1264	cell8 is healthy
	9.	27612	26969	977	cell9 is healthy
	10.	30051	29187	1213	cell10 is healthy
	11.	31005	30294	1066	cell11 is healthy
	12.	31482	30380	1460	cell12 is healthy
	13.	33108	31897	1576	cell13 is healthy
	14.	33345	32130	1582	cell14 is healthy
	15.	34974	33838	1512	cell15 is healthy
	16.	34272	33447	1198	cell16 is healthy
	17.	35685	33927	2137	cell17 is healthy
	18.	40803	39068	2140	cell18 is healthy
	19.	37260	36086	1562	cell19 is healthy
	20.	39528	37929	1999	cell20 is healthy
	21.	38610	13223	25781	cell21 isunhealthy
	22.	39780	38574	1606	cell22 is healthy
	23.	41535	40362	1582	cell23 is healthy
	24.	44019	42268	2172	cell24 is healthy
	25.	41256	13806	27858	cell25 is unhealthy
	26.	46008	40068	6370	cell26 is healthy
	27.	45333	43954	1806	cell27 is healthy
	28.	48438	46505	2375	cell28 is healthy
	29.	46575	83	46925	cell29 is unhealthy
	30.	50616	40026	11041	cell30 is healthy
	31.	51984	49583	2858	cell31 is healthy
	32.	53352	51427	2388	cell32 is healthy

IV. Conclusion

The guaranteed life time of PV module is 20 years but in order to achieve this life time, appropriate maintenance is required as these modules are directly exposed to internal and external stresses. Consequently, effective real time diagnostics and inspection techniques are very essential to prolong lifetime of PV module. Nevertheless, in recent years there has been an increasing growth in monitoring methods for PV systems.

In proposed research, the purpose was to suggest an algorithm of digital image processing technique which was designed in MATLAB environment in order to recognize the health of PV module. For this purpose, images of a 1x3 (*NsxNp*) PV were captured from Nikon Coolpix camera. Proposed technique is cost effective in a way that it employs a simple optical camera to capture images. Moreover, as there are only two image conversions taking place in the algorithm, the processing time of the algorithm is considerably less as compared to existing imaging techniques owing to have four image conversions in their algorithms. The images in suggested technique were processed in MATLAB in order to determine health of the modules in a PV array. Moreover, a particular cell within a module was identified as healthy or unhealthy. The proposed algorithm is tested under two weather conditions i.e. under sunny weather and under diffused irradiation scenario. The results obtained in both scenarios were alike and the faulty cells within a module were clearly recognized as unhealthy in simulation results.

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