Assessing MPPT techniques on hot-spotted and partially-shaded photovoltaic modules: Comprehensive review based on experimental data

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***Abstract*—Hot-spotting is a reliability problem influencing photovoltaic (PV) modules, where a mismatched solar cell/cells heat up significantly and reduce the output power of the affected PV module. Therefore, in this paper, a succinct comparison of seven different state-of-the-art MPPT techniques are demonstrated, doing useful comparisons with respect to amount of power extracted, hence calculate their tracking accuracy. The MPPT techniques have been embedded into a commercial off-the-shelf MPPT unit, accordingly running different experiments on multiple hot-spotted PV modules. Furthermore, the comparison includes real-time long-term data measurements over several days and months of validation. Evidently, it was found that both fast changing MPPT (FC-MPPT) and the modified beta (M-Beta) techniques are best to use with PV modules affected by hot-spotted solar cells as well as during partial shading conditions, on average, their tracking accuracy ranging from 92% to 94%. Ultimately, the minimum tracking accuracy is below 93% obtained for direct PWM voltage controller (D-PWM-VC) MPPT technique.**

***Index Terms*—Photovoltaic; Hot-Spots; MPPT; GMPP; Power Mitigation; Thermal Imaging; Tracking Accuracy.**

I. INTRODUCTION

HOT-SPOTTING is a reliability problem in Photovoltaic (PV) modules, this phenomena is well-identified when a mismatched solar cells' heat up significantly and reduce the PV module output power [1]. PV hot-spots occur when a cell, or group of cells activates at reverse-bias, dissipating power instead of delivering it, and consequently operating at anomalous temperature levels [2] and [3]. The PV hot-spots are also the main cause of accelerated ageing, and sometimes irreversible damage of entire PV panels [4].

There are a number of other reliability issues affecting PV modules such as PV module disconnection [5], faults associated with maximum power point tracking (MPPT) units [6] and [7], PV micro cracks [8], and fluctuations in the wind speed and humidity variations [9]. All of these factors affect the PV module output power performance, thus decrease its annual energy production. However, this article addresses the impact of hot-spotting in PV modules.

PV Hot-spot easily can be detected using IR inspection, which has become a common practice in current PV application as presented in [10]. However, the impact of hot-spot on the operation and performance of PV modules have been not often addressed, which helps us to explain why there is lake of accepted approaches which deals with hot-spotting as well as specific criterion referring to the acceptance or rejection of affected PV module in commercial frameworks.

In the past and still a present practice, hot-spotting effect is usually mitigated by the adoption of bypass diodes which are parallelized with the PV modules, with the target to limit the maximum reverse voltage across the hot-spotted or shaded solar cells, therefore to increase the overall short circuit current and the open circuit voltage [11] – [13]. However, this method of mitigating hot-spots are not encountered the favor, since it requires additional cost and can be even detrimental in terms of power dissipation caused by additional bypass diodes as discussed by Manganiello *et al.* [14].

Most recently, distributive MPPT method suggested by Coppola *et al.* [15] and Olalla *et al.* [16] are a conventional method to mitigate hot-spot in PV modules, with an approximate reduction up to 20 °C for small and medium hot-spotting areas. On the other hand, Kim & Krein [17] show the "inadequateness" of the standard bypass diodes, the insertion of a series-connected switch are suited to interrupt the current flow during bypass activation process. However, this solution requires a quite complex electronic board design that needs devised power supply and appropriate control logic for activating the hot spot protection device.

In 2018, two hot-spot mitigation techniques developed by Dhimish *et al.* [18]. Both techniques consists of several MOSFETs connected to the PV module in order to switch ON/OFF the hot-spotted PV solar string. The proposed technique is fairly reliable, but it does not contain any modelling or statistical analysis for the overall impact of PV hot-spots on the output power performance.

On the other hand, under hot-spotting scenarios, the characteristics of the PV modules show multiple local maximum power points (LMPPs), and a unique global

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maximum power point (GMPP). Many conventional MPPT methods, such as Perturb and Observe (P&O) [19], Incremental Conductance (INC) [20], and Beta method [21] are enable to distinguish the GMPP from the LMPPs. Consequently, both the generated power and the system reliability are significantly affected. As detailed by the real data in [22], the measured power loss due to the wrong tracking of operating point at LMPPs instead of GMPP is high up to 60~70%.

To address this reliability issue in the MPPT methods, several hardware-based methods have been industrialized, including bypass diodes method [11], reconfiguration of PV modules [23], and the distributed MPPT units [15]. Without adding additional hardware components, many software based GMPPT approaches have been extensively proposed. Since tracking GMPP can be considered as an optimization problem, many artificial intelligent (AI) methods have been suggested, such as particle swarm optimization [24], fuzzy logic inference system [25], MPPT genetic algorithm [26], artificial neural network (ANN) [27], artificial bee colony [28], and the grey wolf optimization [29]. These AI approaches are effective for most shading patterns with high accuracy, but not capable of enhancing the hot-spotted solar panels output power. Also, the implementation of these AI methods are challenging to use since some parameters have to be wisely tuned and therefore the users must have certain professional knowledge on them.

Some researchers [30] and [31] proposed a new algorithms by modifying the conventional MPPT techniques in order to attain better performance by assuming that all PV output power peaks, including LMPPs and the GMPP, approximately locate at the multiple of 0.8 of the open circuit voltage (V_{oc}). However, their tracking accuracy for hot-spotted PV modules could optimally reach up to 90% of the expected GMPP. On the other hand, hill climbing is one other of the most common method to track the GMPP [32] – [35]. This method is so similar to P&O and the difference is in the parameter which the perturbation process is applied to the duty cycle of the converter, and the power measured gain factor. In this technique if the different in the measured power is less than zero, means that the direction is incorrect, hence the perturbation should be applied in reverse direction. Therefore, to attain the GMPP of the desired PV system.

Furthermore, a hybrid evolutionary algorithm called the DEPST technique was implemented using a combination of the differential evolutionary (DE) algorithm and particle swarm optimization (PSO), to detect the maximum power point under partial shading conditions [36]. The tracking accuracy of this technique is always above 98%. In addition, an improved differential evolution-based MPTT algorithm using SEPIC DC/DC converter is proposed in [37] and [38]. Results of this technique shows that the MPPT algorithm has the capability to track the GMPP within 2s with an accuracy of 99%, and respond to load variation within 0.1s.

One of the most important factor in choosing a proper MPPT method mainly lies within three specifications:

1) **Performance:** tracking speed and accuracy.
2) **Control:** including voltage and current sensors, complexity of the control system, parameter tuning or perturbation, partial shading detections.
3) **Circuit and Economic Benefits:** analog or digital circuit interface unit, applications such as PV standalone or gird-based PV integration, and the cost of the entire MPPT systems.

An up-to-date review of recent advanced MPPT techniques [39] – [45] are listed in Table I including the comparison of the performance, control, and circuit and economic benefits. All MPPT techniques have a parameter tuning, in other words, there is perturbation process required to adjust the algorithm, hence to track the GMPP during partial shading conditions. Algorithm proposed by [39] – [42] archives high tracking accuracy ranging from 99% and above. While, the static conductance-based MPPT technique [44] as well as the direct PWM voltage controller MPPT technique [45] has a fairly lower tacking accuracy; always below 98.5%.

As noticed in Table I, all MPPT techniques require the values of the current and voltage of the PV system. And all techniques has an analog output interface.

Table I Comparison of different up-to-date (2018) MPPT methods

Method	Performance		Control				Circuit and Economic		
	Tracking Speed	Tracking Accuracy	Sensors	Complexity	Parameter Tuning	Partial Shading	Analog or Digital	Application	Cost
Fast Changing MPPT [39]	Fast	High	V & I	Medium	Yes	Yes	Analog	SA & Grid	Medium
Linear Extrapolation-Based MPPT [40]	Fast	High	V & I	Low	Yes	Yes	Analog	SA	Medium
Modified Beta [41]	Fast	High	V & I	High	Yes	Yes	Analog	SA & Grid	Medium
I-V Curve MPPT [42]	Medium	High	V & I	Low	Yes	Yes	Analog	SA	Low
Enhanced Adaptive Perturb and Observe [43]	Fast	High	V & I	High	Yes	Yes	Analog and Digital	SA	Medium
Static Conductance-Based MPPT [44]	Medium	Medium	V & I	High	Yes	Yes	Analog	SA	High
Direct PWM Voltage Controller [45]	Medium	Medium	V & I	High	Yes	Yes	Analog and Digital	SA & Grid	Low

Where V = Voltage sensor, I = Current sensor, SA = PV standalone system, Grid = PV Grid Connection;

As an industrial point-of-view, the cost of the MPPT unit plays viral role in the selection criterion. So tradeoff between efficiency and cost is necessary to get desired goal. Two parameters which have the most effect on cost of a method are sensors and microcontrollers. Curve fitting and look-up table MPPT technique [42] do not require a high computational micro-controllers as well as the director PWM voltage controllers MPPT technique [45], therefore, these methods are classified as an inexpensive. On the other hand, the static conductance-based MPPT technique [44] requires high computational micro-controllers as well as a multi-layer controller system integration; makes the algorithm highly expensive in its nature. Almost all of the numerical methods are medium in terms of the cost [39 - 41] and [43], because they should do a large number of calculations to achieve MPP so they need high computation microcontrollers, but not necessary to include expensive sensors or actuators.

As a generic remark, there are a limited number of MPPT methods ultimately attempt to optimize the output power of hot-spotted PV modules with respect to effectively tracking the GMPP, but not the LMPPs. In addition, there are a limited evaluation of MPPT methods on hot-spotted PV modules, since most adapted approaches were evaluated and assessed only during partial shading conditions affecting PV modules, but not using hot-spotting scenarios. Hence, the main motivation of this work include the following:

- Study and analyse the impact of hot-spots on the performance and characteristics of PV modules using commercial off the shelf MPPT units.
- Compare and evaluate the tracking accuracy of seven up-to-date [39] - [45] MPPT techniques using various hot-spotted PV modules under real-time long-term environmental conditions, but not their oscillation, speed of tracking, GMPPT vs. LMPPS, and the transient response, since these parameters extensively have been discussed in the original articles.
- Last, evaluating the MPPT techniques based on their tracking accuracy, ultimately propose the best MPPT method to use with hot-spotted PV modules and partial shading scenarios.

In this article, the term "partial shading" corresponds to all factors that might affect the examined PV modules such as moving clouds, flying birds, dust, and rain. On the other hand, hot-spotting is a phenomenon where a mismatched solar cell/cells heat up significantly and reduce the output power of the affected PV module. Nevertheless, does not necessary means partial shading (even though no shade affecting the PV module, the hot-spot remains consistent).

II. Methodology

A. Examined PV Modules

In this work, the evaluation for hot-spotted PV modules were analysed based on two different PV systems. First system shown in Fig. 1(a) comprises 10 polycrystalline silicon PV modules, whereas second PV system shown in Fig. 1(b) contains 220 roof-mounted polycrystalline silicon PV modules. The PV modules electrical characteristics at standard test conditions (STC) where the irradiance (*G*) is equal to 1000 W/m^2 and the PV module temperature (*T*) is equal to 25 °C, as follows:

- Maximum power point (P_{mpp}): 220.2 W_p
- Voltage at maximum power point (V_{mpp}): 28.7 V
- Current at maximum power point (I_{mpp}): 7.67 A
- Open circuit voltage (V_{oc}): 36.7 V
- Short circuit current (I_{sc}): 8.18 A

Before representing the impact of the hot-spotting on the output power performance of the PV modules, and to ensure that the output loss in the power is caused by hot-potting phenomenon, not other factors such as partial shading, dust, or cracks; a thermal imaging camera FLIR i5 was used to inspect all examined PV modules. Example of the output thermal image is shown in Fig. 1(c). The thermal image camera has the following specifications:

- Thermal image quality: 100 x 100 pixels
- Field of view: 21° (H) x 21° (V)
- Thermal sensitivity: 21.18°

After the inspection is determined, the output power generated by the hot-spotted PV modules will be monitored and traced using an MPPT unit, and therefore compare the results with theoretical predictions, hence to estimate the tracking accuracy (η). This step is critical because it allows to rank the best MPPT algorithm that achieves the maximum tacking accuracy.

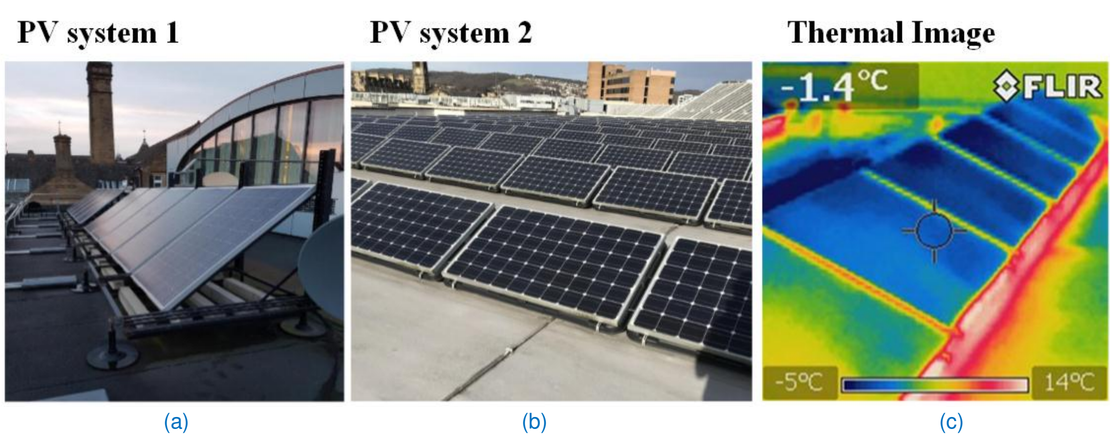

Fig. 1. Examined PV systems. (a) PV system 1, (b) PV system 2, (c) Example of thermal image captured for PV systems 2

B. Impact of Hot-spotted PV modules on commercial MPPT tracking accuracy – background for current MPPT problem

In order to study the impact of hot-spotted PV modules on a commercial MPPT tracking accuracy. One of the common used commercial MPPT unit (Flexmax 80 MPPT) available in PV industry market was examined. The MPPT unit tracking accuracy under partial shading conditions is always greater than 98.5%, as noted in the datasheet. The tracking accuracy (η) is calculated using (1).

$$\eta = \frac{P_{hot-spotted\ PV\ module}}{P_{healthy\ PV\ module}} \times 100 \qquad (1)$$

where $P_{hot-spotted\ PV\ module}$ and $P_{healthy\ PV\ module}$ are the output power of the hot-spotted PV module and healthy PV module, respectively.

Fig. 2(b) shows the real and thermal image for two adjacent PV modules, where the first PV module is healthy (does not contain any hot-spots), and the second has two hot-spotted solar cells. Both PV modules were connected to an MPPT unit, in order to examine the MPPT tracking accuracy under real-time long-term data measurements using same environmental conditions. The output power for both PV modules are shown in Figs. 2(c) and 2(d). Evidently, the MPPT unit connected to the healthy PV module had an average tracking accuracy of 98.7% throughout the day. There is drop in the tracking accuracy for the second MPPT unit connected to the hot-spotted PV module, η = 96.2%.

It is understood that hot-spotting in PV modules reduce the amount of generated power of the affected PV modules, but, compared to partial shading conditions, MPPT units (such as tested Flexmax 80 MPPT shown in Fig. 2(b)) fails to extract maximum output power of hot-spotted PV modules. Main reason behind this is that MPPT technique does not consider the drop in the V_{oc} and I_{sc}, but untimely tries to track the global maximum power point (GMPP) of PV modules not the local maximum power points (LMPPs) as shown in Fig. 2(a). Another reason that hot-spotted PV modules strongly depends on the environmental parameters such as strong wind speed (eventually cools down PV surface and reduce hot-spotting impact [40]), humidity variations and the ambient temperature [16], therefore, with such environmental conditions, the MPPT tracking accuracy might differ meaningfully.

Based upon previous discussion, in the next sections, a comparison between seven different MPPT techniques, recently suggested in 2018 will be evaluated on hot-spotted PV modules, but not only on partial shading conditions as this information is briefly discussed in the original articles. In addition, these MPPT techniques will be ranked based on their tracking accuracy using numerous real-time long-term environmental conditions, but not their transient response, this information is briefly discussed in the original articles.

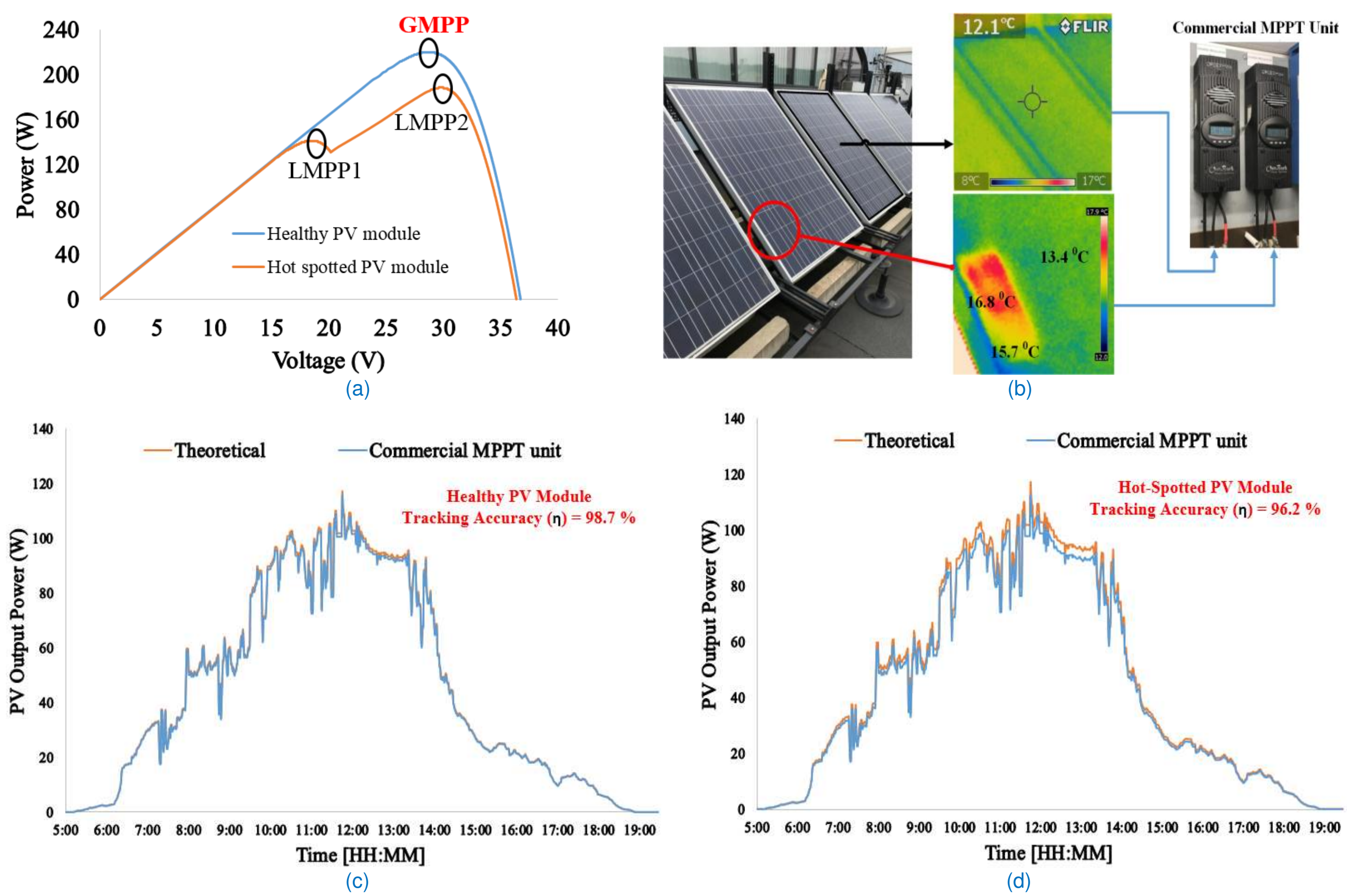

Fig. 2. Hot-spotted PV module inspection. (a) Global and local maximum power points, (b) Healthy PV module and hot-potted PV module inspection using thermal imaging, (c) Output power of healthy PV module, average MPPT tracking accuracy is 98.7%, (d) Output power of the hot-spotted PV module, average MPPT tracking accuracy is 96.2%

III. Considered MPPT Techniques

Seven different MPPT techniques are assessed using the analysis of their tracking accuracy on different hot-spotted PV modules. The evaluated MPPT techniques are summarized as follows:

1) **Fast Changing MPPT (FC-MPPT)** [39]: main idea of this MPPT is to remove random number in the voltage calculation equation of the conventional cuckoo search method as shown in Fig. 3. Therefore, it maintains fast and reliability tracking for GMPP during the change in the uniform and non-uniform irradiance levels, its tracking accuracy is always higher than 99.8%.

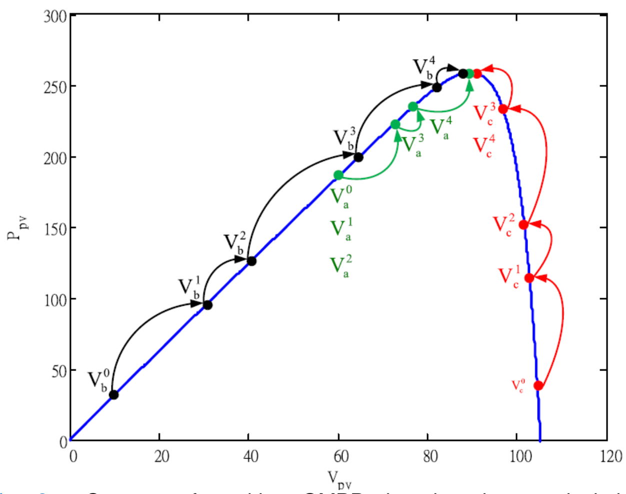

Fig. 3. Concept of tracking GMPP though voltage calculation described in [32]

2) **Linear Extrapolation-Based MPPT (LEB-MPTT)** [40]: this method involves only three sampling periods to reach GMPP under any dynamic conditions. Its main advantages including, simplicity of analysis, fixed minimal convergence time, ease of implementation since it does not require the open circuit voltage, and its tracking accuracy is always above 99.6%.

3) **Modified Beta (M-Beta)** [41]: this technique relies on modifying the MPPT algorithm using β parameter, henceforth it will not overlook at the GMPP and LMPPs during partial shading conditions. The novelty of this technique that it has the capability of detecting the occurrence of partial shading conditions without the need of any additional threshold or periodical interruption, but only β value which is determined by (2), where I_{String} refers to the current of the PV modules, V_{eq} is the equivalent voltage, and c is the diode constant. The MPPT tracking accuracy is always greater than 99.5%. Whereas β value is limited between two thresholds β_{min} *and* B_{max}.

$$\beta = \ln \frac{I_{String}}{V_{eq}} - c \times V_{eq} \qquad (2)$$

4) **I-V Curve MPPT (I-V-MPPT)** [42]: this techniques approximate the current-voltage (I-V) curve for particular sub-region of partially shaded PV modules, subsequently estimates the upper limits for the array power in these sub-regions. Fig. 4 shows the estimation of an I-V curve at (V_k, I_k) value. Ultimately, the tracking accuracy is always greater than 99.5%.

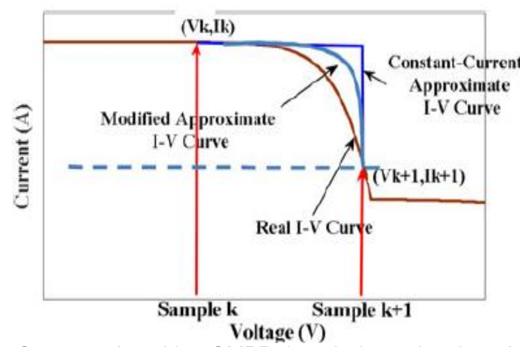

Fig. 4. Concept of tracking GMPP though the estimation of the I-V curve characteristics [35]

5) **Enhanced Adaptive Perturb and Observe (EA-P&O)** [43]: this MPPT technique mitigate the limitations of the conventional P&O using the analysis of state oscillation, diverged tracking direction, and the tracking for optimal GMPP. The technique is able to diminish the power loss during partials shading conditions, whistle its tracking accuracy is maintained over 99.3%.

6) **Static Conductance-Based MPPT (SCB-MPPT)** [44]: the novelty of this MPPT technique lies in the fact that a power versus static conductance curve of the PV module is used to accurately track the GMPP, with reference the measured solar irradiance (G). The MPPT requires four tuning parameters taking into account the maximum derivative of the power with respect to the PV conductance. Overall MPPT tracking accuracy is always greater than 98.5%.

7) **Direct PWM Voltage Controller (D-PWM-VC)** [45]: in this MPPT method, a direct PWM controller based on single gain (K) is used to directly estimate the duty cycle (D). The working principle of the proposed PWM controller is shown in Fig. 5. Simultaneously, its mathematical operation contains an integral controller. In practice, this MPPT is complex to implement, and its optimum tracking accuracy is equal to 98%.

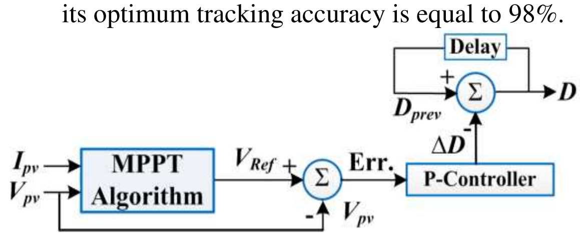

Fig. 5. Proposed D-modulation control scheme [38]

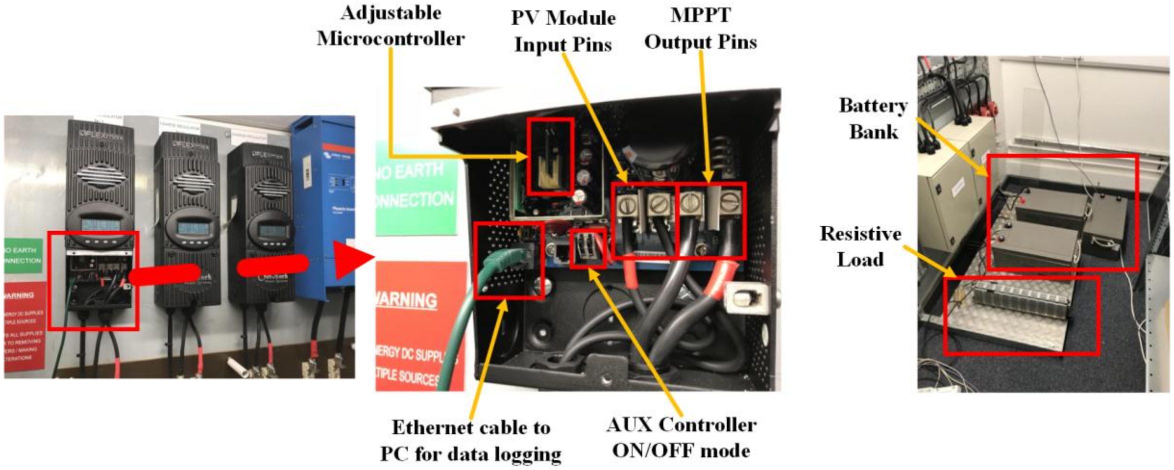

Fig. 6. Internal configuration of the MPPT unit, battery bank, and the resistive load (16 Ω)

IV. Evaluation of MPPT Techniques

In order to evaluate the optimum MPPT technique to use with hot-spotted PV modules, and as noticed earlier in section III, all selected MPPT technique have tracking accuracy of at least 98%. Hence, in this section, all MPPT techniques will be compared and ranked based on their tracking accuracy. In order to modify the experimented MPPT unit with the required MPPT technique, the internal adjustable microcontroller and AUX controller switch was configured. The data is monitored and logged using a PC through an Ethernet cable. A battery bank and resistive load (16 Ω) was also used. The internal assembly of the MPPT unit and the load are shown in Fig. 6.

A. Examine healthy PV module during normal operational conditions

Before evaluating the MPPT techniques on a hot-spotted PV modules, it is worth to monitor their tracking accuracy on a healthy PV module (examined PV module is shown in Fig. 7) throughout long-term data dimensions; roughly over one complete day of operation. The MPPT unit was modified with the configuration of the examined MPPT technique, each MPPT is experimented over full day of operation, while their output power vs. theoretical output power predictions are shown in Fig. 8. The ambient temperature during all days is between 14~14.8 °C.

Remarkably and as expected, the optimum MPPT technique is the FC-MPPT tested over the first day, its average tracking accuracy reaches 99.73%. Second best MPPT technique is LEB-MPPT with 99.66% tracking accuracy. Finally, the minimum tracking accuracy (98.32%) is obtained using the D-PWM-VC. The D-PWM-VC had the lowest tracking accuracy because it has two main drawbacks:

1) The controller gain (K) strongly depends on load value, and since in this work a pure resistive load of 16 Ω was used. Therefore, the gain must be calculated again in every applied partial shading conditions, in which the algorithm lacks to support.

2) The estimation of the current at maximum power point (I_{mpp}) depends on the calculations of the voltage reference (V_{ref}), this reference voltage is roughly estimated and therefore must be considered in almost all partial shading scenarios.

To sum up, this sub-section demonstrated the overall MPPT techniques and their tracking accuracy using a duration of full day, while running the examined MPPT algorithms during normal operational conditions; no partial shading is applied. It is worth remembering that the MPPT techniques transient response, oscillation, and speed of tracking are briefly discussed in the articles [39] – [45].

Fig. 7. Examined Healthy PV module – no existence of hot-spots, dust, cracks, or soiling

B. MPPT techniques performance using hot-spotted PV module

In this section, the performance of the MPPT techniques will be compared according to their tracking accuracy using a PV module affected by two hot-spotted solar cells. The PV module real and thermal image are shown in Fig. 9. The hot spotted cells temperature have an increase of 9.8 °C and 9.4 °C compared to adjacent healthy solar cells. Similar to previous section, the hot-spotted PV module is connected to the MPPT unit running different MPPT technique over a period of full day. Therefore, it is possible to calculate the average tracking accuracy for each examined MPPT algorithm, consequently discover the ideal technique.

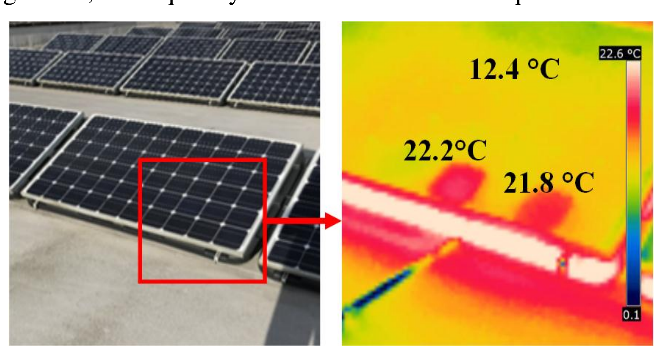

Fig. 9. Examined PV module affected by two hot-spotted solar cells

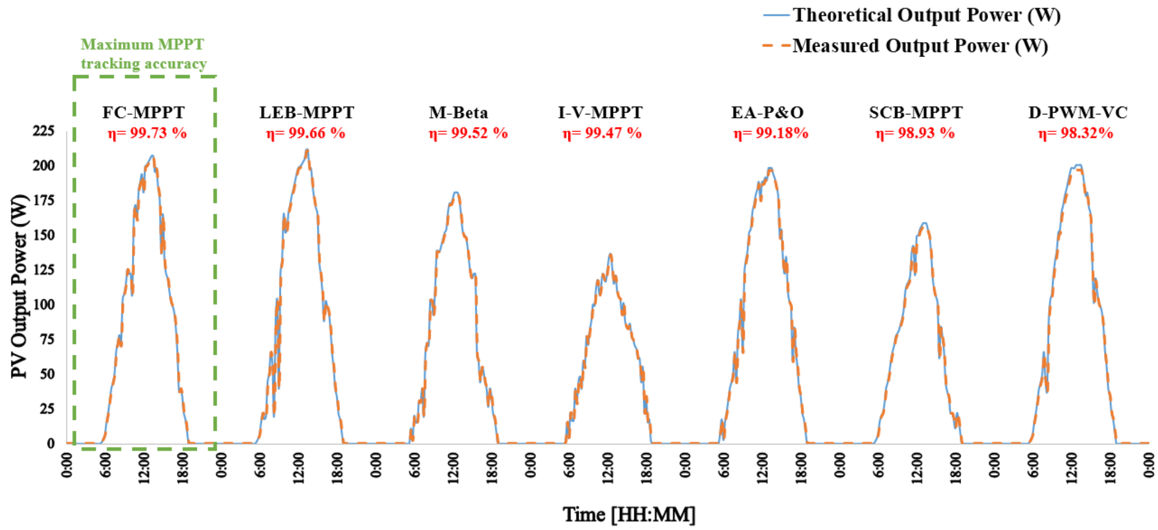

Fig. 8. MPPT Techniques output tracking accuracy using healthy PV module under normal and partial shading scenarios

The output results of the power vs. theoretical power predictions are shown in Fig. 10. Here, it is evident that all day scenarios had almost identical solar irradiance profile, where there is rapid change and fast transient in the solar irradiance affecting the hot-spotted PV module. The ambient temperature in all considered days ranging from 16~17 °C.

M-Beta technique achieved the maximum tracking accuracy (97.32%). As presented in section III, this technique relies on β value, determined by (2). Fig. 11 shows a typical P-V curve determined for the hot-spotted solar module. Regions 1 to 3 (n=1, n=2, and n=3) presents the tacking profile for β value to localize and operate the PV module at the GMPP. In region 1, β value is out of the range (less than β_{min}). Therefore, starting from the region 2, there is a slight increase in β value which fluctuates between the ranges of β_{min} to β_{max}. Hence, in the last region, n = 3, it tracks the GMPP using suitable β value (practically β = -18, calculated using (2), labeled as "8").

Therefore, M-Beta MPPT technique had the best performance due to its optimum localization method for the GMPP, even though the PV module is affected by a hot-spotted solar cells. Interestingly, the FC-MPPT technique is ranked the 3rd, whistle it was ranked the first in the previous section (refer to Fig. 8). This technique fails to attain high tracking accuracy for the hot-spotted PV module since it depends on measuring the voltage levels for all P-V curves, while for hot-spotted PV modules, the output voltage and current characteristics, principally the drop in the V_{oc} and I_{sc} is unexpected, and it fluctuates differently compared to partial shading conditions. Thereafter, the FC-MPPT, I-V-MPPT, and the D-PWM-VC had low tracking accuracy. On the other hand, the LEB-MPPT method had on average a tracking accuracy of 97.11%. This technique had the second best MPPT tracking accuracy because it has the capability of determining the V_{oc} and I_{sc} for the hot-spotted PV module using a linear outline calculations for the P-V GMPP profile.

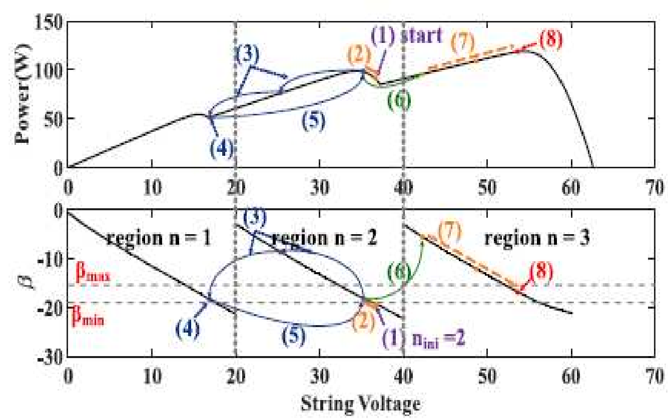

Fig. 11. Localizing and tracking GMPP using M-Beta MPPT technique

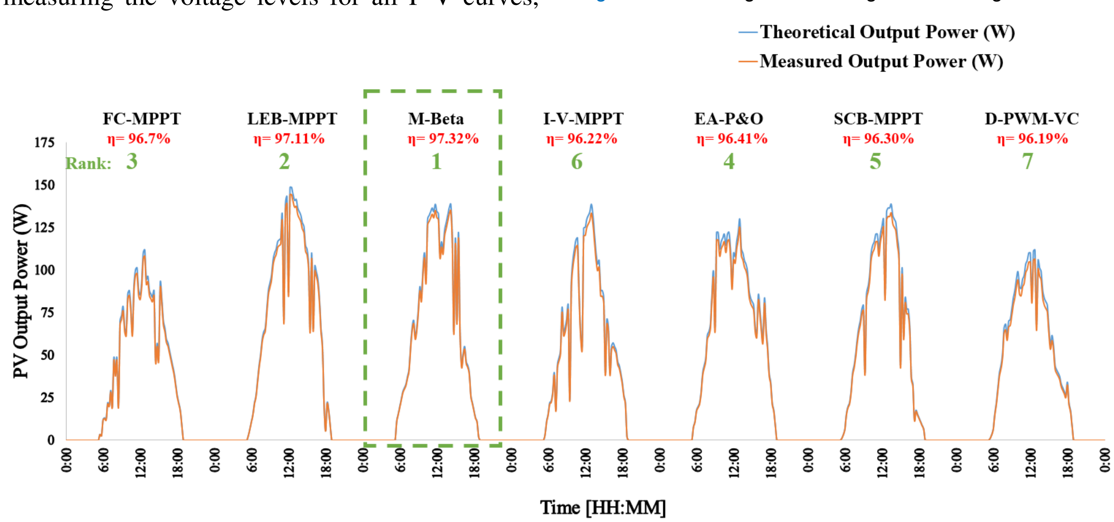

Fig. 10. MPPT Techniques output tracking accuracy using PV module affected by two hot-spotted solar cells

C. MPPT techniques performance using PV module affected by multiple (>5) hot-spotted solar cells

In this section, the MPPT techniques are evaluated using a PV module affected by several (>5) hot-spotted solar cells. Fig. 12(a) shows real and thermal image of the examined PV module. Furthermore, Fig. 12(b) illustrates the P-V curve of the examined PV module under STC. It was found that the power loss due to the existence of hot spots is equal to 31.6 W.

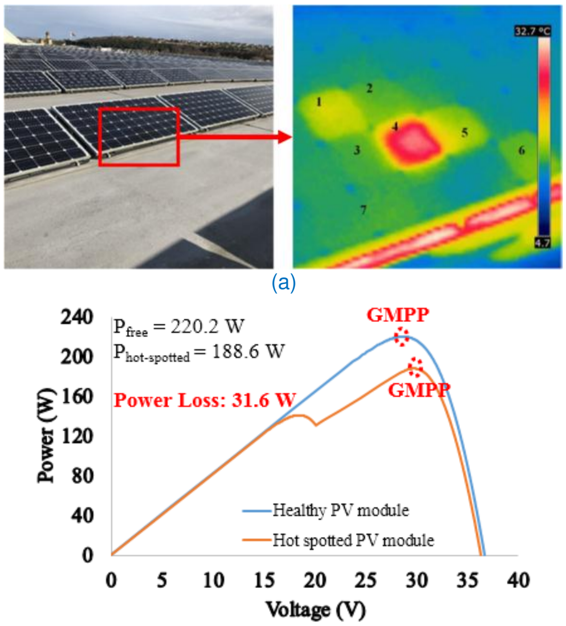

Fig. 12. (a) Examined PV module affected by >5 hot-spotted solar cells, (b) P-V curve characteristics under STC

The output power performance and the MPPT tracking accuracy for the entire tested techniques are shown in Fig. 13. The M-Beta MPPT had the dominant tracking accuracy (92.92%), while the D-PWM-VC stall the last (90.51%). In fact, all MPPT techniques could not accurately track the optimum GMPP of the hot-spotted PV module (i.e. above 97%) due to the existence of the hot-spots in the examined PV module. The hot-spots impacts the entire performance of the PV module. The PV module main electrical characteristics such as V_{oc}, I_{sc}, V_{mpp} and I_{mpp} are affected and successively changed from their theoretical origins.

D. MPPT techniques performance using PV module affected by hot-spotted solar cells and permanent shade

Another interesting result to discuss, is whether the considered MPPT techniques are capable of tracking accurately the GMPP of a PV module affected by hot-spotted solar cells as well as a permanent shade. Fig. 14 shows the examined PV module affected by two hot-spotted solar cells and a permanent shade.

The output power and tracking accuracy for all MPPT techniques are shown in Fig. 15. Comparatively, the FC-MPPT and M-Beat techniques had nearly same tracking accuracy centrally located at 93.60% to 93.62%. Same result obtained for I-V-MPPT, EA-P&O, and SCB-MPPT, all had equivalent tracking accuracy with an average at intervals of 92.88% to 92.92%. As expected, the D-PWM-VC had lowest tracking accuracy about 92.32%.

Evidently, this section verifies that both FC-MPPT and M-Beta techniques are optimum to use with PV modules affected by hot-spotted solar cells and a permanent shade. However, M-Beta practically had the best tracking accuracy (on average greater than 98%) for all investigated hot-spotted PV modules. The second best MPPT method, certainly lies within the FC-MPPT and LED-MPPT techniques, depending on number of hot-spotted solar cells in the PV module as well as partial shading conditions. Whereas, the minimum tracking accuracy is obtained using D-PWM-VC technique for all considered scenarios.

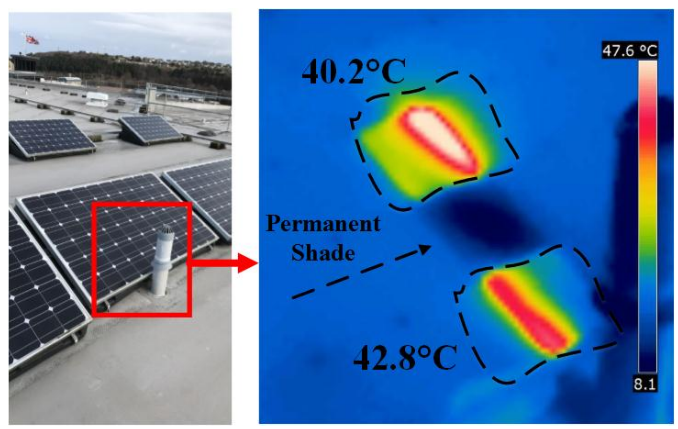

Fig. 14. Examined PV module affected by two hot-spotted solar cells and permanent shade

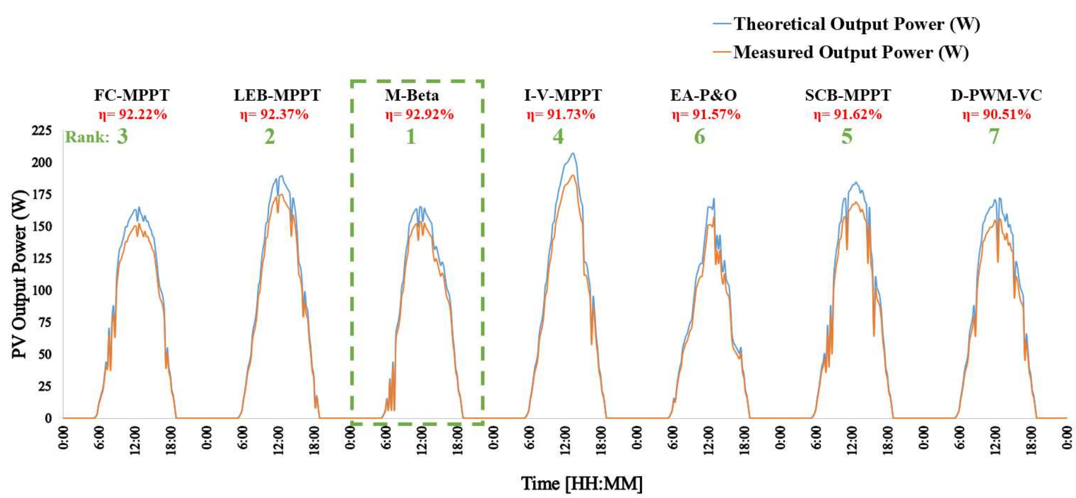

Fig. 13. MPPT Techniques output tracking accuracy using PV module affected by several (>5) hot-spotted solar cells

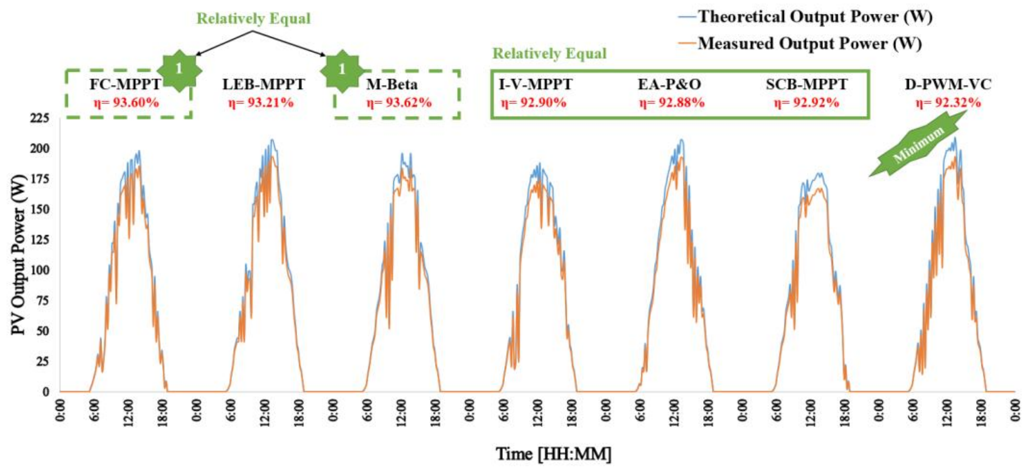

Fig. 15. MPPT Techniques output tracking accuracy using PV module affected by two hot-spotted solar cells and permanent shade

Main outcomes of data presented in this section, includes following remarks:

1) The fast changing MPPT (FC-MPPT) technique is optimum to use with PV modules affected only by partial shading scenarios; on average its tracking accuracy is equal to 99.73%.
2) For hot-spotted PV modules, the optimum MPPT technique is the modified beta (M-Beta), with overall tracking accuracy from 92.92% to 97.32%.
3) For PV modules affected by hot-spotted solar cells and partial shading scenarios. Experimentally, it was found that both FC-MPPT and M-Beta had almost identical tracking accuracy.
4) I-V-MPPT, EA-P&O, and SCB-MPPT techniques almost generates same extent of power during all experimental validation.
5) The minimum tracking accuracy is obtained using D-PWM-VC technique for all considered scenarios due to its controller gain and voltage reference threshold limitations.

V. Performance Ratio Analysis

Performance ratio (PR) is a widely used metric for comparing relative performance of PV installations whose design, technology, capacity, and location differ [46] - [48]. The PR is calculated using (3).

$$PR = \frac{\eta_{measured}}{\eta_{theoretical}} \times 100 = \frac{\frac{E}{G}}{\eta_{theoretical}} \times 100 \qquad (3)$$

where $\eta_{measured}$ and $\eta_{theoretical}$ are the actual measured efficiency and theoretical output efficiency of the examined PV installations, E is the output energy of the PV system (kWh), and G is the solar irradiance incident in the plant of the PV array (kWh).

In order to compare and evaluate the examined MPPT techniques using the analysis of the PR ratio, the examination of a PV sub-system comprising seven PV modules, all affected by two hot-spotted solar cells has been conducted for a duration of six months; April to September 2018. The configuration for the conducted experiment including PV modules and the MPPT units are shown in Fig. 16.

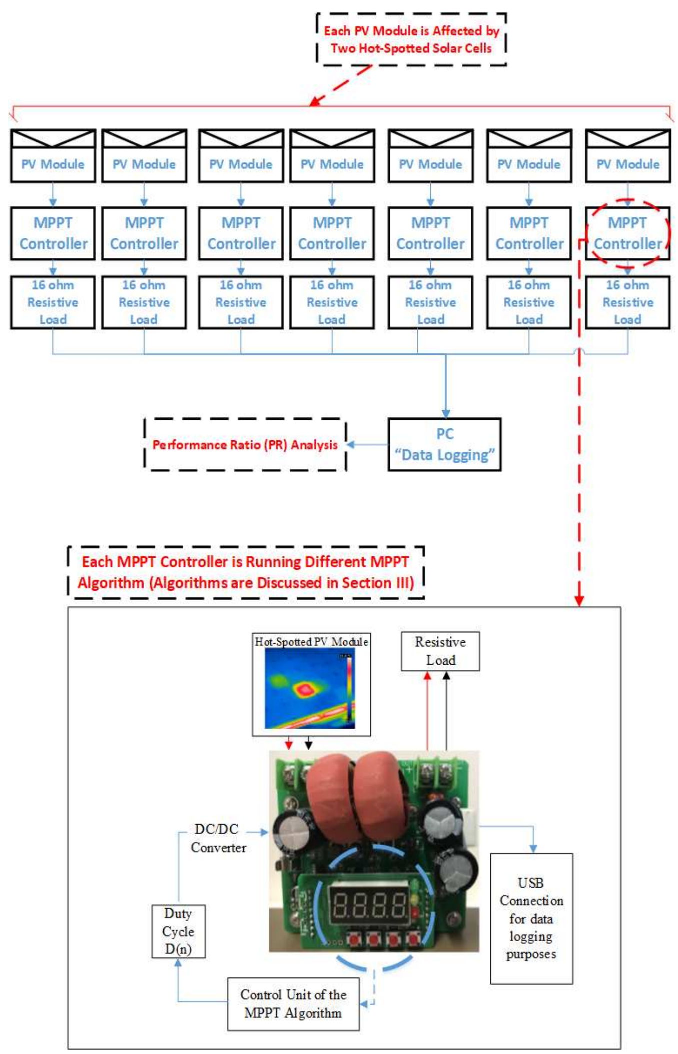

Fig. 16. Performance ratio (PR) analysis for all examined MPPT algorithms using experimental evaluation of seven different PV modules affected by the same type of hot-spotting; this experiment last for 6 months; starting from March to August 2018

The PV modules are connected to a MPPT controller running different MPPT algorithm, the MPPT controller shown in Fig. 16 has an adjustable control unit to modify the microcontroller using any MPPT algorithm, and the MPPT unit has a USB link to the PC for data logging purposes. A pure resistive load (16 Ω) is used with all PV modules. Data analysis of the PR ratio is captured and analysed over the studied period. It is worth noting that all PV modules were affected by same environmental conditions, including solar irradiance, ambient temperature, humidity and wind speed.

Daily PR is captured for all PV modules over a period of six months, resulting a total of 184 samples. The data is processed using Minitab software and concisely compared. Since the measured data of all MPPT algorithms does not follow a normal (or Gaussian) distribution, because environmental conditions such as wind, rain, dust, and partial-shading will skew the distribution and accuracy of the MPPT units, resulting a low PR ranges. Therefore, the distribution of the PR ratio is better explained with a Weibull distribution, which often arises when the range of variations of a population/samples are physically limited to one extremist value; in this case, it is the MPPT algorithms output power tracking accuracy.

According to the results shown in Fig. 17(a), the PR ratio over the considered period of the experiment is equal to 97.33%, 97.03% and 96.76% for the MPPT algorithms M-Beta, FC-MPPT and the LEB-MPPT, respectively. It is evident that the maximum PR is observed for the PV module connected to the MPPT unit running M-Beta technique, whereas the second optimum technique is FC-MPPT. Subsequently, Fig. 17(b) shows that all other examined MPPT techniques achieve a PR ratio less than 96.5%, whereas the minimum PR ratio is observed for the PV module connection to the D-PWM-VC MPPT algorithm. A summary for the PR ratio of all examined MPPT algorithms are presented in Fig. 17(c); maximum to minimum.

As a result, the analysis of the PR ratio over a period of six months confirms that the M-Beta and FC-MPPT MPPT methods have the highest overall tracking accuracy. This result also confirms the appropriateness of the conducted experiments in previous sections; where similar outcomes were acknowledged.

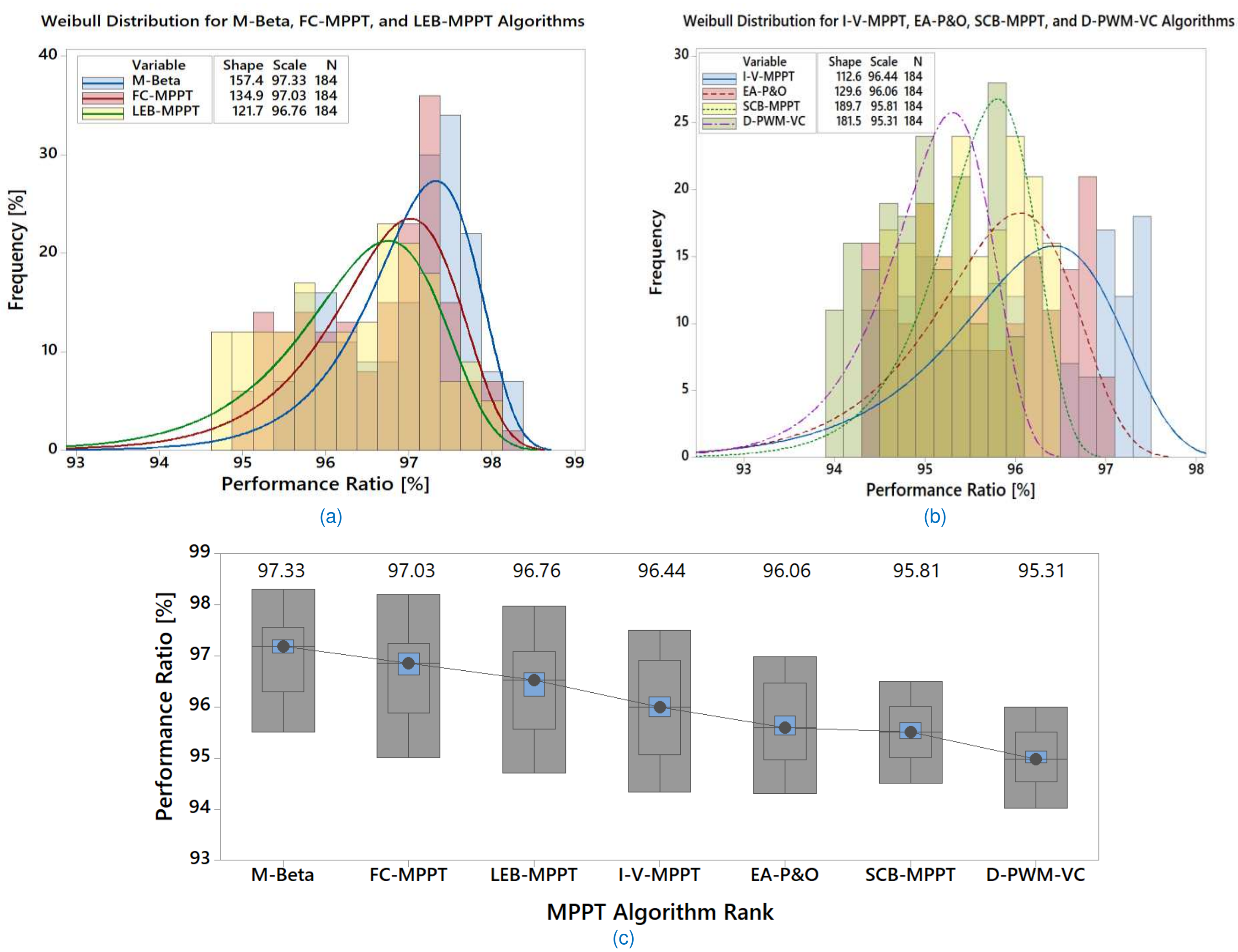

Fig. 17. Distribution of the daily integrated performance ratio (PR) for all MPPT algorithms. (a) PR for M-Beta, FC-MPPT, and LEB-MPPT algorithms, (b) PR for I-V-MPPT, EA-P&O, SCB-MPPT, and D-PWM-VC algorithms, (c) Comparison of the obtained PR for all MPPT algorithms

VI. Discussion and Future Recommendations

In this work, seven up-to-date MPPT algorithms have been discussed and their tracking accuracy are compared. The novel contribution of this study includes the analysis and the assessment of the examined PV MPPT algorithms not only using PV modules affected by partial shading conditions, but also PV modules affected by various types of hot-spots.

Nowadays, there are hundreds of existing PV MPPT algorithms, eventually their tracking accuracy always been compared during partial shading conditions. However, few previous algorithms have been tested under hot-spotting scenarios affecting PV modules.

Noting that each of the examined techniques has its own advantages and disadvantages concerning the tracking accuracy, tracking speed, cost, and their implementation complexity. The selection of the examined PV MPPT algorithms are taken into account following criterion:

- The algorithm is either implemented using an advanced mathematical approach, or it is an advancement of a conventional method such as the I-V or P-V curve identification procedure.
- The algorithm is not implemented using machine learning techniques, such as fuzzy inference system or artificial neural networks, since the hot-spotting phenomenon significantly will affect the main electrical parameters of the PV modules, hence, the machine learning algorithms are fairly inefficient in identifying the loss in some PV parameters such as the V_{oc} and I_{sc}.

In this study, the examined MPPT algorithms were evaluated using various case studies including:

- PV modules affected by partial shading conditions.
- PV module affected by two hot-spots.
- PV modules affected by >5 hot-spots.
- PV module affected by two hot-spots and permanent shade.

Results show that the M-Beta and FC-MPPT methods proposed by [41] and [39], respectively, had the optimum tracking accuracy and maximum output power compared to all other tested algorithms. It was noticed that both methods rely on the analysis of the voltage at maximum power point, and subsequently classify the identification region which the MPPT algorithm has to operate; typically tracks the GMPP.

Additional long-term experiment has been conducted to evaluate the effectiveness of the examined MPPT algorithms. This experiment includes the examination of a PV sub-system comprising seven PV modules, all affected by two hot-spotted solar cells. The evaluation for the MPPT has been carried out using the analysis of the performance ratio. The main outcomes of this experiment are:

- All examined PV modules have PR ratio above 95%.
- The best mean average PR ratio is observed for M-Beta method at 97.33%, whereas the minimum is equal to 95.31% for D-PWM-VC MPPT method.

There are two key recommendations following the outcomes of this article on the basis of enhancing the efficiency of the PV MPPT algorithms, these are being summarized as follows:

- The analysis of the accuracy for any given MPPT algorithm must be evaluated under **(i)** partial shading conditions, **(ii)** PV modules affected by different hot-spots, since hot-spotting phenomenon has been raised in the last 10 years as one of the major as well as common defects in PV modules [49], and **(iii)** MPPT algorithms must be analysed on PV modules affected by different weather conditions including real-time long-term data verification over a duration of several days/months.
- PV research community and solar energy industry have to start to investigate the impact of PV hot-spotting on the accuracy of current MPPT units available in the market. Because so far, MPPT are only tested under partial shading conditions.

VII. Conclusion

Considering the drawbacks and limited number of MPPT techniques adopted to enhance hot-spotted PV modules output power, and since the characteristics of hot-spotted PV modules are different than partial shading scenarios. Therefore, in this paper, a succinct comparison of seven different state-of-the-art MPPT techniques are discussed, with respect to amount of power extracted and their tracking accuracy.

The MPPT techniques have been embed into a commercial off the shelf MPPT unit, subsequently running various experimental verification on a number of hot-spotted PV modules. Furthermore, the comparison between all selected MPPT techniques includes a real-time long-term data measurement over several days/months of validation.

References

[1] X. Wu, M. Bliss, A. Sinha, T. R. Betts, R. Gupta and R. Gottschalg, "Accelerated Spatially Resolved Electrical Simulation of Photovoltaic Devices Using Photovoltaic-Oriented Nodal Analysis," in IEEE Transactions on Electron Devices, vol. 62, no. 5, pp. 1390-1398, May 2015, doi: 10.1109/TED.2015.2409058.

[2] M. Dhimish, V. Holmes, P. Mather, and M. Sibley, " Novel hot spot mitigation technique to enhance photovoltaic solar panels output power performance," in Solar Energy Materials and Solar Cells, vol. 179, pp. 72-79, June 2018, doi: 10.1016/j.solmat.2018.02.019.

[3] F. G. Della Corte, G. De Martino, F. Pezzimenti, G. Adinolfi and G. Graditi, "Numerical Simulation Study of a Low Breakdown Voltage 4H-SiC MOSFET for Photovoltaic Module-Level Applications," in IEEE Transactions on Electron Devices, vol. 65, no. 8, pp. 3352-3360, Aug. 2018, doi: 10.1109/TED.2018.2848664.

[4] M. Simon, and E. L. Meyer, "Detection and analysis of hot-spot formation in solar cells," in Solar Energy Materials and Solar Cells, vol. 94, no. 2, pp. 106-113, 2010, doi: 10.1016/j.solmat.2009.09.016.

[5] E. Moon, D. Blaauw and J. D. Phillips, "Subcutaneous Photovoltaic Infrared Energy Harvesting for Bio-implantable Devices," in IEEE Transactions on Electron Devices, vol. 64, no. 5, pp. 2432-2437, May 2017, doi: 10.1109/TED.2017.2681694.

[6] T. K. Soon and S. Mekhilef, "A Fast-Converging MPPT Technique for Photovoltaic System Under Fast-Varying Solar Irradiation and Load Resistance," in IEEE Transactions on Industrial Informatics, vol. 11, no. 1, pp. 176-186, Feb. 2015, doi: 10.1109/TII.2014.2378231.

[7] Z. Yi and A. H. Etemadi, "Fault Detection for Photovoltaic Systems Based on Multi-Resolution Signal Decomposition and Fuzzy Inference Systems," in IEEE Transactions on Smart Grid, vol. 8, no. 3, pp. 1274-1283, May 2017, doi: 10.1109/TSG.2016.2587244.

[8] M. Dhimish, V. Holmes, P. Mather, C. Aissa and M. Sibley, "Development of 3D graph-based model to examine photovoltaic micro cracks," in Journal of Science: Advanced Materials and Devices, vol. 3, no. 3, pp. 380-388, 2018, doi: 10.1016/j.jsamd.2018.07.004.

[9] J. Wong, "Perturbation Theory for Solar Cell Efficiency II—Delineating Series Resistance," in IEEE Transactions on Electron Devices, vol. 60, no. 3, pp. 917-922, March 2013, doi: 10.1109/TED.2012.2236334.

[10] M. Abdelhamid, R. Singh and M. Omar, "Review of Microcrack Detection Techniques for Silicon Solar Cells," in IEEE Journal of Photovoltaics, vol. 4, no. 1, pp. 514-524, Jan. 2014, doi: 10.1109/JPHOTOV.2013.2285622.

[11] S. Lien, Y. Lin, Y. Cho and D. Wuu, "Performance of Flexible Photovoltaic Modules Encapsulated by Silicon Oxide/Organic Silicon Stacked Layers," in IEEE Transactions on Electron Devices, vol. 63, no. 4, pp. 1615-1620, April 2016, doi: 10.1109/TED.2016.2535343.

[12] A. S. Teran et al., "Energy Harvesting for GaAs Photovoltaics Under Low-Flux Indoor Lighting Conditions," in IEEE Transactions on Electron Devices, vol. 63, no. 7, pp. 2820-2825, July 2016, doi: 10.1109/TED.2016.2569079.

[13] M. Dhimish, V. Holmes, B. Mehrdadi, M. Dales, and P. Mather, “PV output power enhancement using two mitigation techniques for hot spots and partially shaded solar cells,” in Electric Power Systems Research, vol. 158, pp. 15-25, 2018, doi: 10.1016/j.epsr.2018.01.002.

[14] P. Manganiello, M. Balato and M. Vitelli, "A Survey on Mismatching and Aging of PV Modules: The Closed Loop," in IEEE Transactions on Industrial Electronics, vol. 62, no. 11, pp. 7276-7286, Nov. 2015, doi: 10.1109/TIE.2015.2418731.

[15] M. Coppola, S. Daliento, P. Guerriero, D. Lauria and E. Napoli, "On the design and the control of a coupled-inductors boost dc-ac converter for an individual PV panel," International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion, Sorrento, 2012, pp. 1154-1159, doi: 10.1109/SPEEDAM.2012.6264548.

[16] C. Olalla, Md. Hasan, C. Deline, and D. Maksimovic, “Mitigation of Hot-Spots in Photovoltaic Systems Using Distributed Power Electronics,” in Energies, vol. 11, no. 4, pp. 726, 2018, doi: 10.3390/en11040726.

[17] K. A. Kim and P. T. Krein, "Reexamination of Photovoltaic Hot Spotting to Show Inadequacy of the Bypass Diode," in IEEE Journal of Photovoltaics, vol. 5, no. 5, pp. 1435-1441, Sept. 2015, doi: 10.1109/JPHOTOV.2015.2444091.

[18] M. Dhimish, V. Holmes, B. Mehrdadi, M. Dales, and P. Mather, "Output-Power Enhancement for Hot Spotted Polycrystalline Photovoltaic Solar Cells," in IEEE Transactions on Device and Materials Reliability, vol. 18, no. 1, pp. 37-45, March 2018, doi: 10.1109/TDMR.2017.2780224.

[19] S. K. Kollimalla and M. K. Mishra, "A Novel Adaptive P&O MPPT Algorithm Considering Sudden Changes in the Irradiance," in IEEE Transactions on Energy Conversion, vol. 29, no. 3, pp. 602-610, Sept. 2014, doi: 10.1109/TEC.2014.2320930.

[20] G. C. Hsieh, H. I. Hsieh, C. Y. Tsai and C. H. Wang, "Photovoltaic Power-Increment-Aided Incremental-Conductance MPPT With Two-Phased Tracking," in IEEE Transactions on Power Electronics, vol. 28, no. 6, pp. 2895-2911, June 2013, doi: 10.1109/TPEL.2012.2227279.

[21] M. A. G. de Brito, L. Galotto, L. P. Sampaio, G. d. A. e Melo and C. A. Canesin, "Evaluation of the Main MPPT Techniques for Photovoltaic Applications," in IEEE Transactions on Industrial Electronics, vol. 60, no. 3, pp. 1156-1167, March 2013, doi: 10.1109/TIE.2012.2198036.

[22] G. Petrone, G. Spagnuolo, R. Teodorescu, M. Veerachary and M. Vitelli, "Reliability Issues in Photovoltaic Power Processing Systems," in IEEE Transactions on Industrial Electronics, vol. 55, no. 7, pp. 2569-2580, July 2008, doi: 10.1109/TIE.2008.924016.

[23] H. S. Sahu and S. K. Nayak, "Extraction of Maximum Power From a PV Array Under Nonuniform Irradiation Conditions," in IEEE Transactions on Electron Devices, vol. 63, no. 12, pp. 4825-4831, Dec. 2016, doi: 10.1109/TED.2016.2616580.

[24] R. B. A. Koad, A. F. Zobaa and A. El-Shahat, "A Novel MPPT Algorithm Based on Particle Swarm Optimization for Photovoltaic Systems," in IEEE Transactions on Sustainable Energy, vol. 8, no. 2, pp. 468-476, April 2017, doi: 10.1109/TSTE.2016.2606421.

[25] S. Tang, Y. Sun, Y. Chen, Y. Zhao, Y. Yang and W. Szeto, "An Enhanced MPPT Method Combining Fractional-Order and Fuzzy Logic Control," in IEEE Journal of Photovoltaics, vol. 7, no. 2, pp. 640-650, March 2017, doi: 10.1109/JPHOTOV.2017.2649600.

[26] K. Sundareswaran, V. Vigneshkumar and S. Palani, "Development of a hybrid genetic algorithm/perturb and observe algorithm for maximum power point tracking in photovoltaic systems under non-uniform insolation," in IET Renewable Power Generation, vol. 9, no. 7, pp. 757-765, 9 2015, doi: 10.1049/iet-rpg.2014.0333.

[27] L. M. Elobaid, A. K. Abdelsalam and E. E. Zakzouk, "Artificial neural network-based photovoltaic maximum power point tracking techniques: a survey," in IET Renewable Power Generation, vol. 9, no. 8, pp. 1043-1063, 11 2015, doi: 10.1049/iet-rpg.2014.0359.

[28] J. Ahmed and Z. Salam, "An Enhanced Adaptive P&O MPPT for Fast and Efficient Tracking Under Varying Environmental Conditions," in IEEE Transactions on Sustainable Energy, vol. 9, no. 3, pp. 1487-1496, July 2018, doi: 10.1109/TSTE.2018.2791968.

[29] S. Mohanty, B. Subudhi and P. K. Ray, "A Grey Wolf-Assisted Perturb & Observe MPPT Algorithm for a PV System," in IEEE Transactions on Energy Conversion, vol. 32, no. 1, pp. 340-347, March 2017, doi: 10.1109/TEC.2016.2633722.

[30] Y. Wang, Y. Li and X. Ruan, "High-Accuracy and Fast-Speed MPPT Methods for PV String Under Partially Shaded Conditions," in IEEE Transactions on Industrial Electronics, vol. 63, no. 1, pp. 235-245, Jan. 2016, doi: 10.1109/TIE.2015.2465897.

[31] K. S. Tey and S. Mekhilef, "Modified Incremental Conductance Algorithm for Photovoltaic System Under Partial Shading Conditions and Load Variation," in IEEE Transactions on Industrial Electronics, vol. 61, no. 10, pp. 5384-5392, Oct. 2014, doi: 10.1109/TIE.2014.2304921.

[32] M. Seyedmahmoudian, B. Horan, T. K. Soon, R. Rahmani, A. M. T. Oo, A, S. Mekhilef, and A. Stojcevski, "State of the art artificial intelligence-based MPPT techniques for mitigating partial shading effects on PV systems–A review," in Renewable and Sustainable Energy Reviews, vol. 64, pp. 435-455, Oct. 2016, doi: 10.1016/j.rser.2016.06.053.

[33] W. Zhu, L. Shang, P. Li and H. Guo, "Modified hill climbing MPPT algorithm with reduced steady-state oscillation and improved tracking efficiency," in The Journal of Engineering, vol. 2018, no. 17, pp. 1878-1883, 11 2018, doi: 10.1049/joe.2018.8337.

[34] H. A. Sher, K. E. Addoweesh and K. Al-Haddad, "An Efficient and Cost-Effective Hybrid MPPT Method for a Photovoltaic Flyback Microinverter," in IEEE Transactions on Sustainable Energy, vol. 9, no. 3, pp. 1137-1144, July 2018, doi: 10.1109/TSTE.2017.2771439.

[35] J. S. Goud, K. R., B. Singh and S. Kumar, "Maximum power point tracking technique using artificial bee colony and hill climbing algorithms during mismatch insolation conditions on PV array," in IET Renewable Power Generation, vol. 12, no. 16, pp. 1915-1922, 10 12 2018, doi: 10.1049/iet-rpg.2018.5116.

[36] M. Seyedmahmoudian et al., "Simulation and Hardware Implementation of New Maximum Power Point Tracking Technique for Partially Shaded PV System Using Hybrid DEPSO Method," in IEEE Transactions on Sustainable Energy, vol. 6, no. 3, pp. 850-862, July 2015, doi: 10.1109/TSTE.2015.2413359.

[37] K. S. Tey, S. Mekhilef, M. Seyedmahmoudian, B. Horan, A. T. Oo and A. Stojcevski, "Improved Differential Evolution-Based MPPT Algorithm Using SEPIC for PV Systems Under Partial Shading Conditions and Load Variation," in IEEE Transactions on Industrial Informatics, vol. 14, no. 10, pp. 4322-4333, Oct. 2018, doi: 10.1109/TII.2018.2793210.

[38] A. Shahdadi, A. Khajeh and S. M. Barakati, "A new slip surface sliding mode controller to implement MPPT method in photovoltaic system," 2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC), Tehran, 2018, pp. 212-217, doi: 10.1109/PEDSTC.2018.8343798.

[39] B. Peng, K. Ho and Y. Liu, "A Novel and Fast MPPT Method Suitable for Both Fast Changing and Partially Shaded Conditions," in IEEE Transactions on Industrial Electronics, vol. 65, no. 4, pp. 3240-3251, April 2018, doi: 10.1109/TIE.2017.2736484.

[40] B. B, K. R. A.G., S. I. G and N. Chilakapati, "A Linear Extrapolation Based MPPT Algorithm for Thermoelectric Generators under Dynamically Varying Temperature Conditions," in IEEE Transactions on Energy Conversion, 2018, doi: 10.1109/TEC.2018.2830796.

[41] X. Li, H. Wen, Y. Hu, L. Jiang and W. Xiao, "Modified Beta Algorithm for GMPPT and Partial Shading Detection in Photovoltaic Systems," in IEEE Transactions on Power Electronics, vol. 33, no. 3, pp. 2172-2186, March 2018, doi: 10.1109/TPEL.2017.2697459.

[42] M. A. Ghasemi, A. Ramyar and H. Iman-Eini, "MPPT Method for PV Systems Under Partially Shaded Conditions by Approximating I–V Curve," in IEEE Transactions on Industrial Electronics, vol. 65, no. 5, pp. 3966-3975, May 2018, doi: 10.1109/TIE.2017.2764840.

[43] J. Ahmed and Z. Salam, "An Enhanced Adaptive P&O MPPT for Fast and Efficient Tracking Under Varying Environmental Conditions," in IEEE Transactions on Sustainable Energy, vol. 9, no. 3, pp. 1487-1496, July 2018, doi: 10.1109/TSTE.2018.2791968.

[44] O. Lopez Santos et al., "Analysis, Design and Implementation of a Static Conductance-Based MPPT Method," in IEEE Transactions on Power Electronics, 2018, doi: 10.1109/TPEL.2018.2835814.

[45] A. F. Murtaza, M. Chiaberge, F. Spertino, J. Ahmad and A. Ciocia, "A Direct PWM Voltage Controller of MPPT & Sizing of DC Loads for Photovoltaic System," in IEEE Transactions on Energy Conversion, 2018, doi: 10.1109/TEC.2018.2823382.

[46] M. Dhimish, V. Holmes, P. Mather and M. Sibley, " Preliminary assessment of the solar resource in the United Kingdom," in Clean Energy, vol. 2, no. 2, pp. 112-125, Oct. 2018, doi: 10.1093/ce/zky017.

[47] J. A. Ruiz-Arias, E. F. Fernández, Á. Linares-Rodríguez and F. Almonacid, "Analysis of the Spatiotemporal Characteristics of High Concentrator Photovoltaics Energy Yield and Performance Ratio," in IEEE Journal of Photovoltaics, vol. 7, no. 1, pp. 359-366, Jan. 2017, doi: 10.1109/JPHOTOV.2016.2623089.

[48] M. Schweiger, W. Herrmann, A. Gerber and U. Rau, "Understanding the energy yield of photovoltaic modules in different climates by linear performance loss analysis of the module performance ratio," in IET Renewable Power Generation, vol. 11, no. 5, pp. 558-565, 12 4 2017, doi: 10.1049/iet-rpg.2016.0682.

[49] M. Dhimish, P. Mather and V. Holmes, "Evaluating Power Loss and Performance Ratio of Hot-Spotted Photovoltaic Modules," in IEEE Transactions on Electron Devices, vol. 65, no. 12, pp. 5419-5427, Dec. 2018, doi: 10.1109/TED.2018.2877806.

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