Received November 3, 2019, accepted November 27, 2019, date of publication November 29, 2019,
date of current version December 12, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2956916

Comprehensive Study of Partially Shaded PV Modules With Overlapping Diodes

ZAID ALQAISI, (Student Member, IEEE), AND YOUSEF MAHMOUD, (Senior Member, IEEE)
Department of Electrical and Computer Engineering, Worcester Polytechnic Institute, Worcester, MA 01609, USA

Corresponding author: Zaid Alqaisi (zaalqaisi@wpi.edu)

ABSTRACT Bypass diodes are usually connected in PV modules to reduce the impact of partial shading. There are two configurations of the bypass diodes used in commercially available PV modules: non-overlapping bypass diodes, in which each diode is separately connected to a unique group of series PV cells, and overlapping bypass diodes, in which the diodes are connected to mutual PV cells. Because almost all PV studies are based on non-overlapping configuration, the effects of the diodes are well understood. On the other hand, a complete analysis for the effects of the overlapped bypass diodes on the performance of the PV module has not been yet systematically disclosed. Moreover, there is still no available mathematical formulation to model such PV modules without the use of circuit simulations. This paper first derives a mathematical modeling approach to simulate overlapped PV modules and then provides a comprehensive study and analysis for the effect of overlapped bypass diodes on the electrical response of PV module under a wide variety of possible shading levels to fully understand their effects and impact. Moreover, it reveals their effects on partial shading power losses, and on the hot spot formation, which both have not yet been investigated in the literature of overlapped PV modules. Their possible negative effects on the efficiency of micro inverters are also illustrated. The results are validated both using Matlab Simulink and experimentally.

INDEX TERMS Bypass diode, modeling, simulation, hot-spot, overlapping, partial shading, photovoltaic, power losses.

I. INTRODUCTION

Due to its cleanliness and sustainability, the exploitation of solar energy in the world via solar photovoltaic PV systems has been escalating over past years [1]–[3]. The output electric power of PV systems is highly affected by the surrounding environmental conditions mainly represented by solar irradiance and temperature.

In addition to the environmental conditions, the performance of PV systems depends highly on its shading scenario in case of shading existence in PV systems. Under this situation, PV systems are divided into two categories: homogeneous PV systems in which all PV units in a PV system receive the same levels of irradiance and temperature, and non-homogeneous PV systems in which PV units in a PV system work on dissimilar irradiances or temperatures. Homogeneous PV systems exhibit a convex power-voltage (*P*-*V*) characteristic curve in its output where one power peak is formed which can provide the maximum power of a PV system, known as the maximum power point MPP. On the other hand, non-homogeneous PV systems, power curve with multiple power peaks MPPs, only one of them is the global power peak GMPP at which true maximum power is produced [4]. Usually, partial shading occurs when a part of a PV system is shaded (by moving clouds, bird droppings, adjacent PV modules, or other obstructions …etc.) while the rest of the system is fully illuminated and is considered a major cause of power losses in PV systems [5].

Two sources of power losses exist during partial shading: mismatch power losses and misleading power losses [6]–[8]. Moreover, the shaded cells develop negative voltages dissipating some power which leads to hotspots and consequent PV cells failure [9], [10]. These power losses can be reduced either through passive or active techniques [11]. The most commonly used method commercially is connecting bypass diodes antiparallel with series-connected cells [12]. These diodes are used to mitigate some losses by providing an alternative path to the current flow when a cell or group of cells connected in series are shaded. On the other hand, bypass diodes complicate the extraction of maximum available power in PV modules as they cause multiple power peaks to appear in the output power curve which requires advanced

The associate editor coordinating the review of this manuscript and approving it for publication was Firuz Zare.

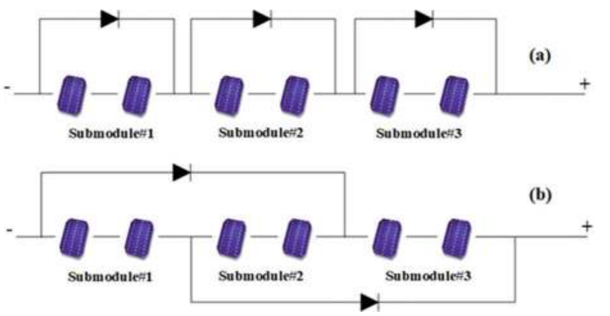

FIGURE 1. The used configurations of diodes in commercial PV modules: (a) non-overlapped diodes configuration and (b) overlapped diodes configuration.

maximum power point tracking algorithms to correctly converge to the GMPP and escape a local peak trap [13]–[16].

Two typical bypass diode configurations exist in commercially available PV modules, namely non-overlapping and overlapping configurations as demonstrated in Fig. 1 [12].

Most commercial PV modules are manufactured with non-overlapped bypass didoes configuration as reported in [17]. Although PV modules with overlapping configurations are less common in PV industry, the analysis of such system is essential to provide PV designers and engineers with models and tools to deal with such systems when needed.

The effect of bypass diodes, in the non-overlapped configuration, on the behavior and characteristics of partially shaded PV modules have been thoroughly examined in many studies [12], [18]–[24]. Although they lead to the appearance of multiple power peaks in the PV output power curve and form misleading power losses, they contribute to the reduction in mismatch power losses. A quantifications for these effects are comprehensively reported in many investigations such as in [12], [18]–[24]. However, few studies considered the overlapped bypass diodes configuration [12], [17], [24].

A comparison for the electrical characteristic curves of two PV modules have the same number of bypass diodes with different configurations are carried out in [12], [17]. Both studies concluded that the overlapped bypass diodes configuration has the same effect on the characteristics of PV modules as that of the non-overlapped bypass diodes when the non-overlapped cells are shaded. However, they also noticed that the short circuit current of the PV module with overlapping increases, in case of the overlapped cells are shaded, which could exceed the rated short circuit current of the PV module.

The authors in [24] reported that power losses in PV modules with overlapped bypass diodes is higher and can be as less as to one-third of its peak power. A discretized model for PV module with overlapping bypass diodes is reported in [25]. It confirmed previous results and showed that partial shading causes higher power reduction in overlapping configuration even for small shaded area.

In [26], the authors deeply discussed the overcurrent occurrence in PV module with overlapping. Consequently, this observation was scrutinized further in [27] and new recommendations to change the wiring and protection standards of PV system have been discussed.

Although some studies investigated the effect of bypass diodes in overlapped configuration [12], [17], [24], [26] as summarized above, a comprehensive analysis for the effects of overlapped bypass diodes on the power losses and characteristic curves have not been yet systematically disclosed [28]. Furthermore, the hot spots development in PV modules with overlapped bypass diodes has not been yet considered although a vast number of papers address its formation and impact on the performance of PV module in the non-overlapped configuration [10], [29], [30].

This manuscript meets the gap in the literature and conducts a comprehensive investigation to study the effects of overlaps didoes configuration on the development of output characteristics curves under all possible shading scenarios. It develops a model for overlapped configuration by using Lambert *W* function and quantifies the partial shading power losses occurring under this configuration comparing it to that of the non-overlapped configuration. Moreover, it includes the effects on the hot spot formation in both configurations comparatively. Finally, the negative impact of PV module with overlapping on the micro-inverter efficiency has been investigated in this study.

This paper is organized as follows: Section II provides an overview of the bypass diodes configurations and presents a PV modeling approach suitable for bypass diodes overlapped configuration. Section III compares the electrical characteristics of PV module with different bypass diodes arrangements under all possible shading scenarios. The partial shading power loss in term of mismatch and misleading power losses on both configurations are investigated in section IV. Next, Section V analyses the impact on the hotspot's formation. Section VI investigates the impact of the bypass diodes configurations on the micro-inverter efficiency. Finally, Section VII validates the results of the study experimentally.

II. PV MODULES WITH OVERLAPPING BYPASS DIODES

A. PV MODEL OVERVIEW

A variety of PV models are reported in the literature [31]–[35], where the single diode and double diodes PV models are typically used. The single diode PV model has been most regularly used because it provides a balance between accuracy and computational effort while the double diode model is used when high accuracy is needed on the expense of computational time.

This paper adopts the single diode model consisting of a photon current source, diode, shunt, and series resistances. The used model accounts for the module behavior in the negative diode breakdown operation [19], [36]–[38]. The relationship between the output current I and the terminal voltage V in the single diode model for a PV module is expressed as [36]:

$$I = I_{ph} - I_s \times (e^{\frac{V+I\times R_s}{a}} - 1) - \frac{V + I \times R_s}{R_{sh}} - b \times (V + I \times R_s) \times \left(1 - \frac{V + I \times R_s}{V_{br}}\right)^{-m} \quad (1)$$

where the parameters I_{ph}, I_s, R_s, R_{sh}, are the photon current, diode reverse saturation current, the series resistance, and the shunt resistance, respectively. The parameter a is equal to N_sKTA/q, where N_s, K, T, A, q are the number of series connected cells in the module, Boltzmann constant, the PV module temperature, the ideality factor of the diode, and electron charge,respectively. The coefficients b, V_{br}, m are related to negative voltage operation of the PV cell material.

To reduce the computational complexity and convergence issues related to the transcendental form of (1), equation (1) is reformulated and expressed in the explicit form $V = f(I)$ using the Lambert W function [39]:

$$V_{cell} = \begin{cases} R_{sh} \cdot (I_{ph} + I_s) - (R_{sh} + R_s) \\ \cdot I - a \cdot Lambert(W) & I \leq I_{ph} \\ V_{br} - I \cdot R_s - S_{R\min} & I > I_{ph} \end{cases} \quad (2)$$

where W refers to the Lambert function, which it represents the solutions y of the equation $y \times e^y = x$ for any complex number x, and S_{Rmin} to the minimum real root of the following equations [39]:

$$W = \frac{R_{sh} \cdot I_s}{a} e^{\left(\frac{R_{sh}\cdot(I_{ph}+I_s-I)}{a}\right)} \quad (3)$$

$$\frac{1}{R_{sh}} \cdot S^4 + \left(I_{ph} - I - \frac{V_{br}}{R_{sh}}\right) \cdot S^3 + bV_{br}^3 \cdot S - b \cdot V_{br}^4 = 0 \quad (4)$$

B. MODES OF OPERATIONS

A PV module with overlapping bypass diodes has four possible modes of operations, as illustrated in Fig. 2. The first one occurs when both bypassed diodes are in the reverse biased mode because all the three submodules carry the same current as shown in Fig. 2(a).

The second mode of operation happens when the first bypass diode is forward biased and the other one is reverse biased as shown in Fig. 2(b). In this case, the first and second submodules carry the same current while the third submodule's current is the summation of the other submodules' current and the current in the bypassed diode. In this case, the output power is only produced by the third submodule.

The third mode occurs when the first bypass diode is reverse biased, and the second bypass diode is forward biased as illustrated in Fig. 2(c). In this case, the second and third submodules carry the same current, while the first submodule's current is the summation of the other submodules' current and the current in the bypassed diode. In this case, the output power is only produced by the first submodule.

The final case occurs when both bypass diodes are forward biased, as illustrated in Fig. 2(d). In this case, each

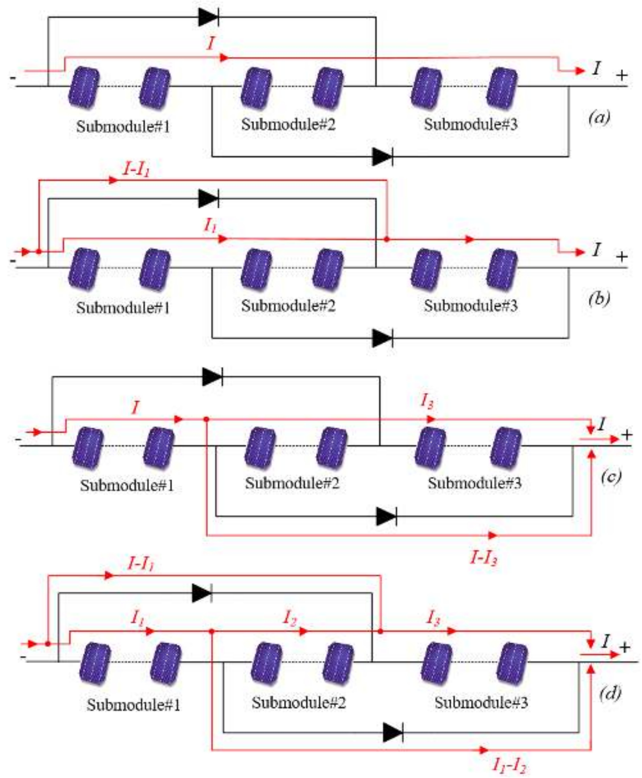

FIGURE 2. The operation modes of PV module with overlapping bypass diodes.

submodule could operate at a dissimilar current as none of the bypassed diodes are in the reverse mode. This situation occurs when the second submodule has the minimum photon current among other submodules in a PV module. It also could occur in case that the string current is larger than the photon currents of the first submodule and the third submodule. Under such situation, the output current of the PV module is equal to the sum of third submodule output current and the difference between the current of the first and second submodules. Furthermore, the voltage of the first and third submodules (V_1 and V_3) are equal to the negative voltage of the second submodule (V_2) assuming that the diode voltage V_d is zero.

C. PROPOSED MODEL

This section proposes a mathematical formulation, utilizing the Lambert function, to derive equations modeling PV modules with overlapping diodes. Although Lambert function was utilized extensively in previous works to model PV systems with non-overlapping bypass diodes, there is still no study in the literature presenting a mathematical model of partially shaded PV modules with overlapping bypass diodes based on the Lambert function. It is important to mention that there is a discretized model that has an excellent accuracy for PV modules with overlapping diodes, developed in [25], however, it requires some computational effort by extracting piecewise functions for each nonlinear elements such as PV cell and diode. Therefore, the goal of the model proposed in

TABLE 1. A summary for the states of bypass diodes.

Photon Currents of the PV module	Bypass Diode State $Z_{(2j-1)}$	$Z_{(2j)}$
$I \leq (I_{ph\text{-}min})_j$	1	1
$I > (I_{ph1})_j$ & $(I_{ph1})_j \leq (I_{ph2})_j$ & $I \leq (I_{ph3})_j$	0	1
$I > (I_{ph3})_j$ & $(I_{ph3})_j \leq (I_{ph2})_j$ & $I \leq (I_{ph1})_j$	1	0
$I > (I_{ph2})_j$ & $(I_{ph2})_j < (I_{ph1})_j$ & $I \leq (I_{ph3})_j$	0	0
$I > (I_{ph2})_j$ & $(I_{ph2})_j < (I_{ph3})_j$ & $I \leq (I_{ph1})_j$	0	0
$I > (I_{ph1})_j$ & $I > (I_{ph3})_j$	0	0

this paper is to allow simple modeling for PV modules with overlapping diode. A PV cell can operate in the first, second, and fourth quadrants of its *I-V* curve. In the first and fourth quadrants, the cell voltage is positive but the current of the PV cell in the fourth quadrant is negative. Whereas, in the second quadrant of the *I-V* curve the PV cell has negative voltage and positive current.

Based on the four possible modes of operation of the PV module with overlapping diodes, the string voltage is expressed as the following:

$$\begin{aligned} V_{string} &= \sum_{j=1}^{n_{ps}} [\, (Z_{(2j-1)} \cdot Z_{2j} \cdot \sum_{i=1}^{n_s} V_{cell-i}(I) + Z_{2j} \cdot (1 - Z_{(2j-1)}) \\ &\quad \cdot \sum_{i=\frac{2}{3}n_s+1}^{n_s} V_{cell-i}(I_3) \\ &\quad + Z_{(2j-1)} \cdot (1 - Z_{2j}) \cdot \sum_{i=1}^{\frac{n_s}{3}} V_{cell-i}(I_1) - (1 - Z_{(2j-1)} \cdot Z_{2j}) \cdot V_d \\ &\quad + (1 - (Z_{(2j-1)} + Z_{2j}) \cdot 0.5^{(Z_{(2j-1)} Z_{(2j)})}) \cdot \sum_{i=\frac{2}{3}n_s+1}^{n_s} V_{cell-i}\,(I_3)] \end{aligned} \tag{5}$$

where n_{ps} is the number of series PV modules, n_s is the number of series PV cells in each submodule, and $Z_{(2j-1)}$ and Z_{2j} are integers modeling the effect of a bypass diodes within a PV module *j*. An integer is equal to one when the bypass diode is reversed biased; otherwise it is equal to zero.

Each PV cell voltage in the overlapping configuration can be calculated, using (2), as the following:

$$V_{cell} = \begin{cases} R_{sh} \cdot (I_{ph} + I_s) - (R_{sh} + R_s) \\ \cdot I_k - a \cdot Lambert(W) & I_k \leq I_{ph} \\ V_{br} - I_k \cdot R_s - S_{R\min} & I_k > I_{ph} \end{cases} \tag{6}$$

where I_k is the current of k^{th} submodule and I_{ph} is the photon current of a cell which located in the k^{th} submodule.

A summery for the states of bypass diodes is presented in Table 1. The current *I* is the string current, $(I_{ph-min})_j$ is the photon current of the submodule receiving minimum irradiance in a PV module *j*, and $(I_{ph1})_j$, $(I_{ph2})_j$, and $(I_{ph3})_j$ are the minimum photon currents of the first, second, and third submodules of the PV module *j*.

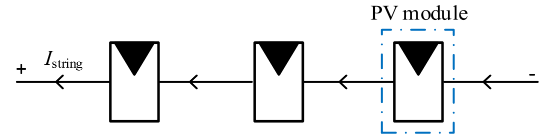

FIGURE 3. A PV string under study.

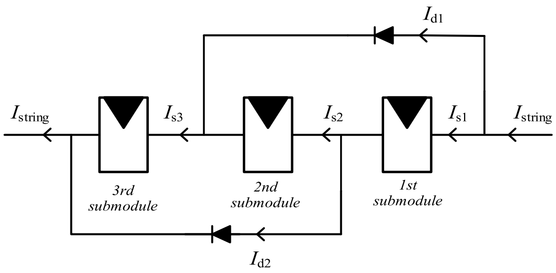

FIGURE 4. A PV module with overlapping bypass diodes.

D. VERFICATION OF THE PROPOSED MODEL

This section verifies the proposed model formulations by comparing the operating currents and voltages of a partially shaded PV module with overlapping diodes in a PV string system using the proposed approach and compared to those resulting from MATLAB Simulink. A string consisting of three PV modules with overlapping diodes is used for this comparison as shown in Fig. 3. The PV module understudy, as illustrated in Fig. 4, has four possible modes of operations while the other series PV modules are considered fully sunny. The PV module chosen for this study is "YL-165" and has the following characteristics: $V_{oc} = 29$ V, $I_{sc} = 7.9$ A, $V_{mp} = 23$ V, and $I_{mp} = 7.2$ A.

The first mode of operation occurs when the PV module receives uniform irradiance or when the string current is less than the minimum photon current in the first PV module. In this case, the first term in (5) is activated for the PV module. This case (at 1 kW/m^2 for the PV module and 7.2 A for the string current) was simulated using the proposed approach and compared to that of the Simulink. The results are summarized in Table 2.

The second and third modes of operations occur when one bypass diode of the first PV module in this illustration is activated. To verify the accuracy of the proposed approach in this case, suppose the photon currents of the first submodule are (3.96A, and 5.55A), while the photon currents of the second and third submodules are (7.9 A). The other two PV modules are fully sunny and the operating string current is (7.2 A). The submodule's currents and voltages of the first PV module and the string current and voltage are shown in Table 3. The first submodule has a negative voltage which means it operates in the second quadrant of its *I-V* curve. By using (5) the voltage of the first PV module is equal to the summation of the voltage of the third submodule and the forwarded biased

TABLE 2. The currents & voltages of the submodules of the PV module and PV string at the first mode of operation.

	Current (A)		Voltage (V)	
	Proposed Model	Simulink Model	Proposed Model	Simulink Model
First submodule	7.2	7.2	7.66	7.662
Second submodule	7.2	7.2	7.66	7.662
Third submodule	7.2	7.2	7.66	7.662
String	7.2	7.2	68.91	68.96

TABLE 3. The currents & voltages of the submodules of the PV module and PV string at the second mode of operation.

	Current (A)		Voltage (V)	
	Proposed Model	Simulink Model	Proposed Model	Simulink Model
First submodule	4.80	4.77	-9.23	-9.25
Second submodule	4.80	4.77	8.73	8.75
Third submodule	7.2	7.2	7.66	7.662
String	7.2	7.2	53.12	53.14

TABLE 4. The currents & voltages of the submodules of the PV module and PV string at the fourth mode of operation (1st scenario).

	Current (A)		Voltage (V)	
	Proposed Model	Simulink Model	Proposed Model	Simulink Model
First submodule	4.27	4.26	8.57	8.58
Second submodule	2.45	2.42	-9.07	-9.08
Third submodule	5.38	5.36	8.57	8.58
String	7.2	7.2	54.03	54.06

diode voltage. It can be noticed that the proposed approach shows high accuracy in this case.

The fourth mode of operation occurs when the two bypass diodes of the first PV module, in this example, are forward biased. Let the photon current of the first submodule is (6.34 A), the photon currents of the second submodule are (1.59 A, and 4.75A), and the photon current of the third submodule is (7.9 A). The other two PV modules are fully sunny and the operating string current is (7.2A).

The submodule's currents and voltages of the first PV module and the string current and voltage in the first scenario of this case are listed in Table 4. The second submodule has a negative voltage, which means it operates in the second quadrant of its *I-V* curve. By using (5) the voltage of the first PV module is equal to the summation of the voltage of the third submodule and the forwarded biased diode voltage. It can be noticed that the proposed approach displays high accuracy in this case.

TABLE 5. The currents & voltages of the submodules of the PV module and PV string at the fourth mode of operation (2nd scenario).

	Current (A)		Voltage (V)	
	Proposed Model	Simulink Model	Proposed Model	Simulink Model
First submodule	1.72	1.69	-10.09	-10.11
Second submodule	-0.62	-0.68	9.59	9.61
Third submodule	4.86	4.83	-10.09	-10.11
String	7.2	7.2	35.37	35.36

The second scenario of the fourth mode of operation happens when the string current is larger than the photon currents of the first and the third submodules. In this scenario, the shaded PV module has a negative voltage when the second submodule operates in the first or the fourth quadrant of its *I-V* curve, otherwise the PV module has positive voltage. To illustrate this, suppose the photon currents of the first submodule are (0.79A, and 3.17A), the photon currents of the second submodule are (4.75A, and 6.34A), and the third submodule's photon currents are (3.96A, and 5.55A). The other two PV modules are sunny and the operating string current is (7.2A). The submodule's current and voltage of the first PV module and the string current and voltage are listed in Table 5. The first and third submodules have negative voltages, which means they operate in the second quadrant of their *I-V* curve, and the second submodule operates in the fourth quadrant of its *I-V* curve. By using (5) the voltage of the first PV module is equal to the summation of the voltage of the third submodule and the forwarded biased diode voltage. In this case, the voltage of the first PV module is negative. It can be noticed that the proposed approach shows high accuracy in this case.

III. CHARACTERIZATION OF PV MODULES WITH OVERLAPPING BYPASSED DIODES

In this section, the developed generalized model presented above is utilized to investigate the dynamic behavior of PV module with overlapping diodes and to compare it with the well-known non-overlapping bypass diodes to reveal the impact of overlapping configuration on the electrical characteristics of PV module.

A. CASE I: THE NON-OVERLAPPING SUBMODULE IS SHADED

This case refers to the second and third modes of operation as discussed before. The submodule is shaded with different shading levels (30%, 50% and 90% of shading) while the other two submodules are kept at full illuminations. At each

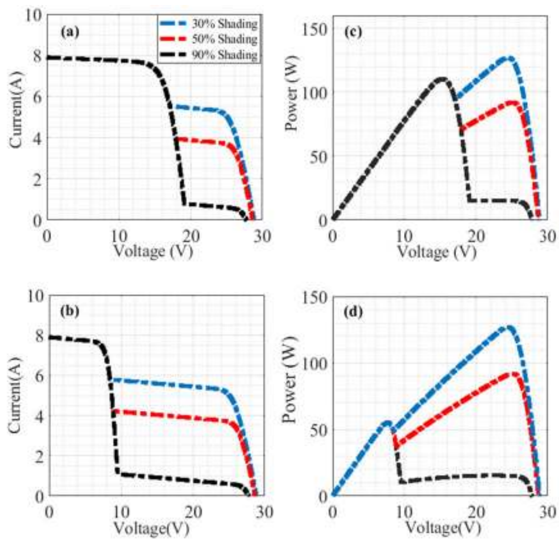

FIGURE 5. Electrical characteristics of PV module under different shading patterns of case I: (a) I-V curves of PV module with no-overlapping, (b) I-V curves of PV module with overlapping, (c) P-V curves of PV module with no-overlapping, and (d) P-V curves of PV module with overlapping.

situation, the *I-V* and *P-V* curves are recorded. The electrical characteristics of both configurations are depicted in Fig. 5.

As noted, the overlapping configuration moves the voltages to the left when the bypass diode conducts current. Moreover, the maximum powers in both configurations are very similar at the low level of shading. However, the power generated in overlapping bypass diodes is reduced at higher levels of shading in comparison to the non-overlapping configuration.

B. CASE II: THE OVERLAPPING SUBMODULE IS SHADED

In this test, the second submodule of the PV module with overlapping is shaded whereas the other submodules are kept at full irradiance.

The electrical characteristics of PV module with non-overlapped bypass didoes are the same as in the case I as was shown in Fig. 5(a) and Fig. 5(c) because the exact location has no significant impact on the electrical response of the PV module with non-overlapping diodes. However, the PV module with an overlapping configuration has different electrical characteristics as plotted in Fig. 6. As seen, the PV module with overlapped bypass diodes has short circuit current higher than the rated short circuit current of the PV module at different shading levels. This result was reported in [12], [17]. The maximum output power of this configuration is still equal or lower than the case of the PV module with non-overlapped bypass diodes. This study reveals that the PV module with overlapping bypass diodes generates higher local power when both bypass diodes are forward biased, and this generated power rises with an increment of shading level. This occurs because the second submodule acts as a load for the PV module with overlapping diodes.

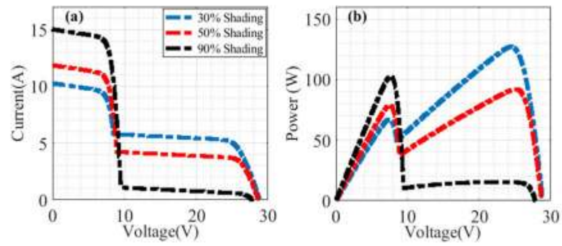

FIGURE 6. Electrical characteristics of PV module with overlapped bypass diodes under different shading patterns of case II: (a) I-V curves and (b) P-V curves.

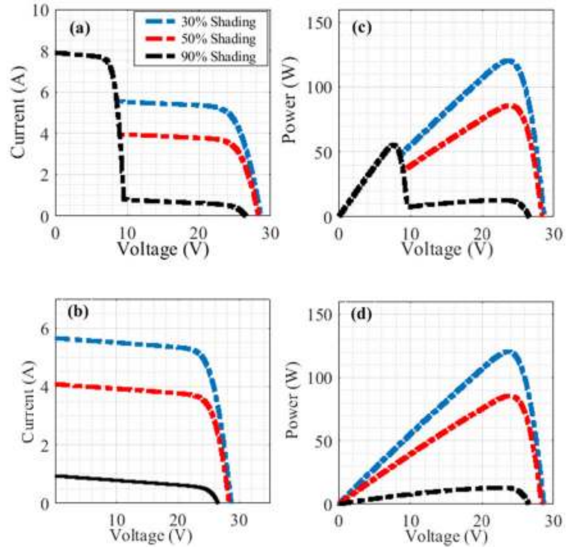

FIGURE 7. Electrical characteristics of PV module under different shading patterns of case III: (a) I-V curves of PV module with no-overlapping, (b) I-V curves of PV module with overlapping, (c) P-V curves of PV module with no-overlapping, and (d) P-V curves of PV module with overlapping.

C. CASE III: THE OVERLAPPING SUBMODULE IS SUNNY

In this case, the first and third submodules are shaded in the PV module with overlapping bypass diodes configurations. The submodules are shaded with different shading levels (30%, 50% and 90% of shading) while the middle submodule is kept at full irradiance. At each situation, the *I-V* and *P-V* curves are recorded. The electrical characteristics of PV module with overlapping, in this case, are compared to the electrical characteristics of the PV module with non-overlapping diodes at the same shading scenarios to illustrate the impact of the overlapping bypass diodes configuration on the electrical characteristics of PV module.

Fig. 7 illustrates the electrical characteristics of PV module in this case. Although there is partial shading on the non-overlapping submodules, there is one peak in the *P-V* curve. This occurs because the first and third submodules force the middle submodule to operate at their current. It is worth to mention that the totally shaded PV modules with overlapping in PV string behave as a load for the string, whereas, in case of PV modules with non-overlapping the consumed power is limited by the bypass diodes.

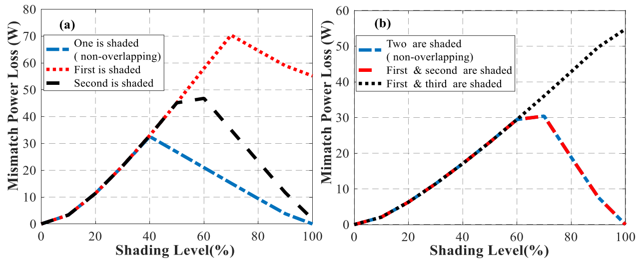

FIGURE 8. Mismatch loss of PV module with different bypass diodes configurations: (a) one submodule is shaded, and (b) two submodules are shaded.

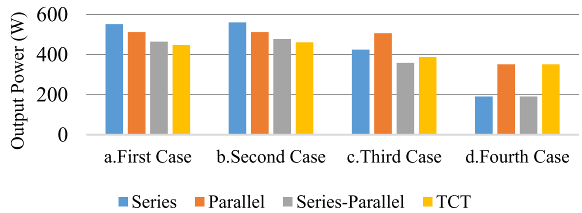

FIGURE 9. Output power of different electrical configurations of PV modules with overlapping diodes: (a) one non-overlapped submodule is shaded, (b) one overlapped submodule is shaded, (c) one PV module is shaded, and (d) Two PV modules are shaded.

IV. POWER LOSSES QUANTIFICATION

As mentioned in literature, partial shading causes two types of power loss. The first one is mismatch power loss, which occurs because series connected cells receive dissimilar levels of irradiance [6] . The second one is due to the appearance of MPPs, known as misleading power loss [6].

In this section, a quantification of power losses in the PV module with overlapping is conducted. Moreover, the power losses in the PV module with overlapping bypass diodes are compared to these in the PV module with non-overlapping to expose the impact of overlapping bypass diodes on power losses at different shading scenarios.

The exact location of shaded submodule has no significant impact on the electrical characteristics of PV modules with non-overlapping, whereas, the situation is different in case of PV modules with overlapping bypass diodes.

A. MISMATCH POWER LOSSES QUANTIFICATION

Although mismatch power loss is quantified in literature for non-overlapped PV modules, there is still no available investigation on the mismatch power losses occurring in overlapped PV modules. First, the mismatch power loss of PV module with overlapping diode is examined and compared with the non-overlapping module. Then, an analysis of different electrical configurations of partially shaded PV modules with overlapping diode are investigated in this section.

The mismatch power loss of a PV module with overlapping is investigated in terms of various shading levels and the number of shaded submodules. The shading level changed from 0% to 100% for each case of shading scenario. The first shading scenario refers to shading one submodule while the second shading scenario refers to shading two submodules. Then the mismatch power losses of the PV module with overlapping diodes are compared to the mismatch power losses of the PV module with non-overlapping diodes to reveal the impact of the overlapping bypass diodes configuration on the power losses. The resulted mismatch power losses in both shading scenarios are quantified in Fig. 8 for both configurations.

As seen, the mismatch power loss is affected by the exact location of the shaded part in the PV module with overlapping diodes. The PV module with overlapping has less mismatch power loss when the second submodule is shaded at shading level 50% or more. On the other hand, the PV module with non-overlapping bypass diodes has significantly less mismatch power loss in comparison to the case with overlapping bypass diodes at shading level more than 40%.

In the second shading scenario when two submodules are shaded, both configurations have the same mismatch power loss shading level lower than 60%. However, the mismatch power loss of PV module with overlapping when the first and third submodules are shaded is higher at shading level more than 60% because the unshaded submodule has the same current of the shaded submodules.

The electrical configuration of the PV modules, such as series, parallel, series- parallel, and TCT configurations, affects the output power of the partially shaded PV modules.

Different electrical configurations of partially shade PV modules with overlapping are examined in terms of various shading scenarios to assess the performance of each configuration.

A system consists of four PV modules with overlapping diodes with different electrical configurations is analyzed under four shading scenarios. The first case refers to shading one non-overlapped submodule, the second one refers to shading one overlapped submodule, the third case refers to shading one PV module and the fourth case refers to shading two PV modules. In this case, the shaded two PV modules in series-parallel and TCT configuration, are located in different strings. The shaded unit receives 100 W/m^2 while the unshaded units receives 1000 W/m^2. Fig. 9 illustrates the output power of partially shade modules with different electrical arrangements. It can be noticed that series configuration has the highest output power when one submodule is shaded, whereas, the parallel configuration is the best in terms of the output power when one or more PV modules are shaded. The TCT configuration in the fourth case has the same output power as the parallel one because the two shaded PV modules are diagonal, otherwise it has the same output power as the other configurations. Fig. 10 conducts a mismatch power loss comparison among different electrical configurations of PV system with overlapping diodes. It can be seen that when one PV module is shaded or two PV modules are shaded, the parallel configuration is the optimal structure.

B. MISEADING POWER LOSSES QUANTIFICATION

The misleading power losses of a PV module with overlapping diodes is investigated in terms of various shading levels

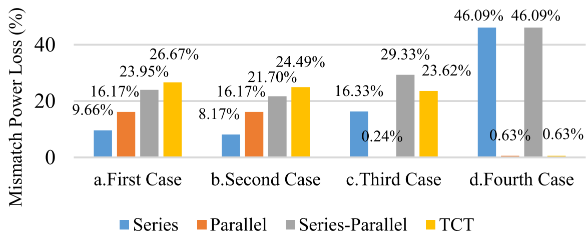

FIGURE 10. Mismatch power loss of partially shaded PV systems with overlapping didoes: (a) one non-overlapped submodule is shaded, (b) one overlapped submodule is shaded, (c) one PV module is shaded, and (d) Two PV modules are shaded.

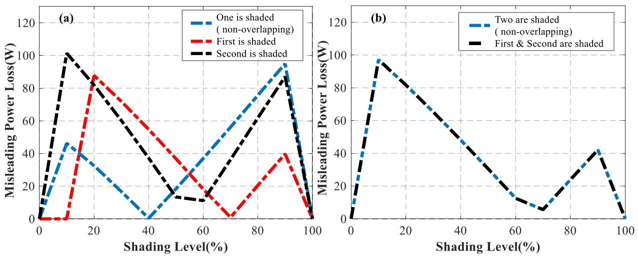

FIGURE 11. Misleading power loss of PV module with different bypass diodes configurations: (a) one submodule is shaded, (b) two submodules are shaded.

and the number of shaded submodules. The shading level changed from 0% to 100% for each case of shading scenario described in the previous subsection. The misleading power loss is depicted in Fig. 11. As noticed, the misleading loss is affected by the location of the shaded part of the PV module with overlapping bypass diodes. The misleading power loss of PV module with overlapping, in case of the second submodule is shaded, is less than that when the first (or third) submodule is shaded at shading level between 20% and 60%. While the PV module has the same GMPPs in both cases, the LPPs are higher when the second submodule is shaded. Moreover, the misleading power loss is less when the first (or third) submodule is shaded at high shading level because smaller GMPP has resulted. The misleading loss has a similar shape in both configurations.

In case of the first (or third) and second submodules are shaded, PV module with overlapping has similar misleading power loss as in the PV module with non-overlapping. Finally, it is important to mention that PV modules with overlapping has no misleading power loss when the first and third submodules are shaded.

V. HOT SPOTS FORMATION

PV hot spots occur when a cell or group of cells are partially or completely shaded, dissipating power instead of generating it and consequently operating at higher temperature [10]. Hot spots affect the performance of PV modules even if the temperature of the shaded cells is less than bearable cell temperature limit. Moreover, hot spots can cause damage to PV panel if the temperature of shaded cells exceeds the maximum acceptable limit. The amount of power dissipated in a reverse-biased PV cell depends on the bypass diodes configurations as the power dissipation through a shaded submodule is limited by a bypass diode.

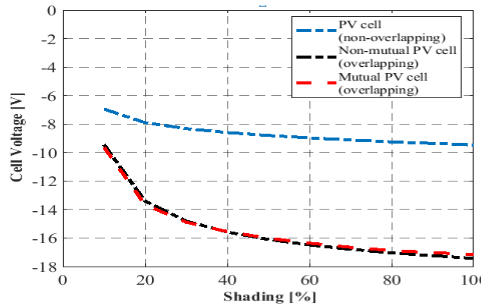

FIGURE 12. The negative voltage of the shade cell in the PV module.

The authors in [10], discuss the hot spot formation of partially shaded PV string with non-overlapping bypass diodes. It was shown that the bypass diodes are inadequate to protect the panel against hot spot formation. However, there is no study in the literature conducts the hot spot formation of PV modules with overlapping bypass diodes.

This section presents an examination of hot spots formation of one shaded cell of PV module with overlapping bypass diodes and comparing it to the hot spot formation in the case with non-overlapping bypass diodes. A PV module consists of 48 cells, 16 cells per submodule, with different bypass diodes configuration, is utilized to investigate the hot spot formations. The nominal fully illuminated power per cell is 3.45 W with local maximum power at 0.48V and 7.2 A.

To study the hot spot of a shaded PV cell, the second quadrant of its *I-V* curve must be taken into consideration. The negative voltage of the shaded cell in a bypassed substring is equal to the summation of the voltages of the healthy cells and the forward biased voltage. By using equations (3), (4), and (6), the negative voltage of one shaded cell in subpanel of a PV module with different bypass diodes configurations are estimated as depicted in Fig. 12. As noticed, the shaded cell in PV module with overlapping has higher negative voltage. Moreover, in both configurations the negative voltage of the shade cell increases with shading level.

Fig. 13 compares the power dissipation through the shaded cell in both configurations with different shading levels. It can be noticed that the shaded cell of a PV module with overlapping bypass diode dissipates more power. Moreover, the mutual PV cell in the overlapping configuration dissipates less power than of the non-mutual PV cell in the same configuration as shading level more than 40%.

The maximum power dissipation through the non-mutual PV cell for the overlapping configuration is 110.4 W, while, the mutual PV cell dissipates 111.1 W. However, the maximum power dissipation in the non-overlapping configuration is 55 W.

VI. IMPACT ON MICRO-INVERTER

Commercial micro-inverters have voltage range at which the maximum power can be extracted. At some shading pattern, the MPP is located outside the MPPT voltage range of

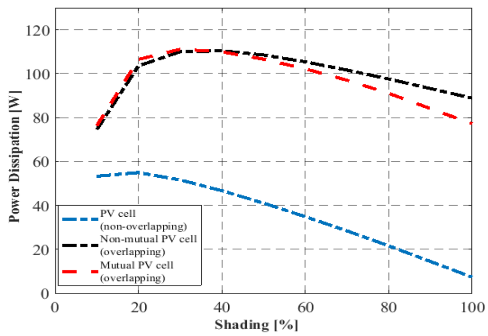

FIGURE 13. Power dissipation through a shaded cell of submodule with different bypass diodes configurations.

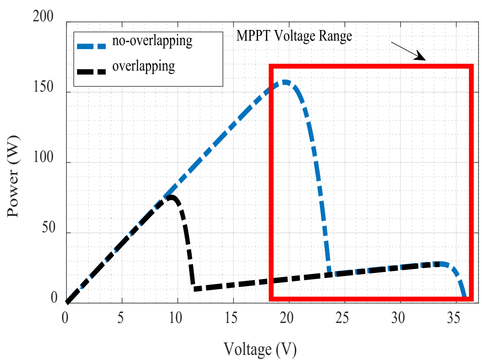

FIGURE 14. Performance of micro-inverter with different bypass diodes.

micro-inverter leading to more power losses as the inverter is unable to operate at the MPP. It is worth mentioning that the bypass diodes configuration in a PV module has a significant effect on the ability of the micro inverter to extract the available MPP. In this study, the Solar -Bridge P250LV-230-AU is used to explain the impact of the bypass diodes configurations on the micro-inverter efficiency. Fig.14 demonstrates the impact of bypass diodes configuration on the power extracted from the commercial inverter. The figure shows the power curves for two identical PV modules operating at the same shading pattern. However, one PV module is connected through overlapping configuration while the other is connected via non- overlapping configuration. The figure also shows the micro inverter window (represented by the red rectangle) which shows the allowable voltage range of the inverter. As seen, while the inverter can extract the GMPP power of the non-overlapping PV module as its voltage exists inside the allowable inverter window, the inverter is unable to operate at the GMPP power of the overlapping PV module. Therefore, the inverter will be forced to operate at a local MPP instead of the true maximum power losing a significant amount of power (63.4% power loss in this case).

VII. EXPERIMENTAL VERIFICATIONS

A commercial PV module (ALT200-24P) that is consisting of 72 series- connected solar cells is used in this experimental setup as shown in Fig. 15. The PV module is connected to three bypass didoes in a non-overlapping

FIGURE 15. Test PV module.

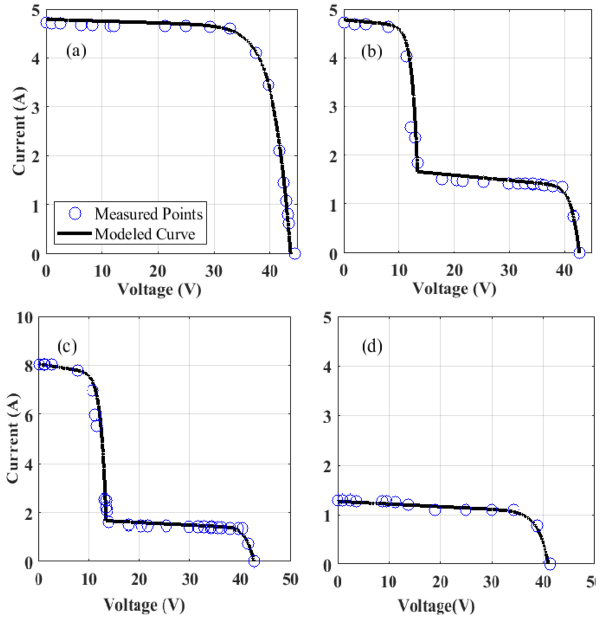

FIGURE 16. Modeled and measured I-V curves of the PV module with overlapping under different shading patterns: (a) without shading (b) the first submodule was shaded, (c) the second submodule was shaded, and (d) the first and third submodule were shaded.

configuration. In order to study the electrical characteristics of PV module with overlapping bypass diodes, the module is reconfigured into overlapping configuration using two of the bypass diodes. To validate the developed model and results in this study, the PV module is tested experimentally under outdoor conditions where the irradiance was approximately 800 W/m^2. The *I-V* curves of the PV module were measured using variable resistor. The PV module was tested for various shading scenarios. First, it was tested under fully illuminated conditions then intentional shading was created. The shading included the first submodule, the second submodule, separately. Finally, a shading for combinations of first and third submodules was created, covering all the possible shading scenarios. The resulted measured *I-V* curves are depicted in Fig. 16 with the modeled *I-V* curves. As noticed, both modeled and measured curves highly match.

VIII. CONCLUSION

The paper proposes a new mathematical formulation to model the overlapped PV modules, replacing the existing modeling method that relies on heavy circuit simulation. The paper then utilizes the developed model to conduct a comprehensive investigation for the effect of overlapped diodes on the PV module performance under partial shading in terms of electrical characteristics, power losses quantification, hot spot formulation and the effect on inverter operation. The outcomes of the study are compared also to PV modules with non-overlapping PV modules to disclose their impact more easily.

The conducted study shows that the available maximum power in overlapped PV module cannot exceed that of the non-overlapped PV module for the same shading scenario, indicating the superiority of the non-overlapping PV modules as opposed to the recommendations of some manufacturers.

The investigation also reveals that the performance of overlapped PV modules is sensitive to which submodule is shaded unlike PV modules with non-overlapping PV modules where their performance is unaffected by which submodule is shaded as long as the shading is identical. The PV module with overlapping diodes has a single power peak under different partial shading conditions when the first and third submodules are shaded.

The study also investigated, for the first time, the effect of overlapping diodes on the well-known partial shading power losses; both misleading and mismatch power losses. It was shown that the power losses of the PV module with overlapping bypass diodes affected by the shaded part.

It was exposed that the shaded PV cell of PV module with overlapping bypass diodes dissipated power more than the shaded cell of PV module with non-overlapping at the same shading level. Therefore, the failure possibility of PV panel with overlapping bypass diodes is higher.

Finally, the paper examines the impact of bypass diodes configuration on the micro-inverter performance. The micro-inverter could become unable to track the global maximum power peak in PV module with overlapping when one submodule is shaded, leading to more power loss.

REFERENCES

[1] J. Shi, W.-J. Lee, Y. Liu, Y. Yang, and P. Wang, "Forecasting power output of photovoltaic systems based on weather classification and support vector machines," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Oct. 2011, pp. 1–6.

[2] A. Elrayyah, Y. Sozer, and M. E. Elbuluk, "Modeling and control design of microgrid-connected PV-based sources," *IEEE J. Emerg. Select. Topics Power Electron.*, vol. 2, no. 4, pp. 907–919, Dec. 2014.

[3] B. Subudhi and R. Pradhan, "A comparative study on maximum power point tracking techniques for photovoltaic power systems," *IEEE Trans. Sustain. Energy*, vol. 4, no. 1, pp. 89–98, Jan. 2013.

[4] A. Mäki and S. Valkealahti, "Effect of photovoltaic generator components on the number of MPPs under partial shading conditions," *IEEE Trans. Energy Convers.*, vol. 28, no. 4, pp. 1008–1017, Dec. 2013.

[5] L. Gao, R. A. Dougal, S. Liu, and A. P. Iotova, "Parallel-connected solar PV system to address partial and rapidly fluctuating shadow conditions," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1548–1556, May 2009.

[6] H. Patel and V. Agarwal, "Maximum power point tracking scheme for PV systems operating under partially shaded conditions," *IEEE Trans. Ind. Electron.*, vol. 55, no. 4, pp. 1689–1698, Apr. 2008.

[7] C. Wang, K. Zhang, J. Xiong, Y. Xue, and W. Liu, "A coordinated compensation strategy for module mismatch of CHB-PV systems based on improved LS-PWM and reactive power injection," *IEEE Trans. Ind. Electron.*, vol. 66, no. 4, pp. 2825–2836, Apr. 2019.

[8] X. Qing, H. Sun, X. Feng, and C. Y. Chung, "Submodule-based modeling and simulation of a series-parallel photovoltaic array under mismatch conditions," *IEEE J. Photovolt.*, vol. 7, no. 6, pp. 1731–1739, Nov. 2017.

[9] A. Kovach and J. Schmid, "Determination of energy output losses due to shading of building-integrated photovoltaic arrays using a raytracing technique," *Sol. Energy*, vol. 57, no. 2, pp. 117–124, Aug. 1996.

[10] K. A. Kim and P. T. Krein, "Reexamination of photovoltaic hot spotting to show inadequacy of the bypass diode," *IEEE J. Photovolt.*, vol. 5, no. 5, pp. 1435–1441, Sep. 2015.

[11] Y. Mahmoud and E. F. El-Saadany, "Enhanced reconfiguration method for reducing mismatch losses in PV systems," *IEEE J. Photovolt.*, vol. 7, no. 6, pp. 1746–1754, Nov. 2017.

[12] S. Silvestre, A. Boronat, and A. Chouder, "Study of bypass diodes configuration on PV modules," *Appl. Energy*, vol. 86, no. 9, pp. 1632–1640, Sep. 2009.

[13] S. Selvakumar, M. Madhusmita, C. Koodalsamy, S. P. Simon, and Y. R. Sood, "High-speed maximum power point tracking module for PV systems," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1119–1129, Feb. 2019.

[14] A. M. S. Furtado, F. Bradaschia, M. C. Cavalcanti, and L. R. Limongi, "A reduced voltage range global maximum power point tracking algorithm for photovoltaic systems under partial shading conditions," *IEEE Trans. Ind. Electron.*, vol. 65, no. 4, pp. 3252–3262, Apr. 2018.

[15] M. Balato, L. Costanzo, P. Marino, G. Rubino, L. Rubino, and M. Vitelli, "Modified TEODI MPPT technique: Theoretical analysis and experimental validation in uniform and mismatching conditions," *IEEE J. Photovolt.*, vol. 7, no. 2, pp. 604–613, Mar. 2017.

[16] S. Tang, Y. Sun, Y. Chen, Y. Zhao, Y. Yang, and W. Szeto, "An enhanced MPPT method combining fractional-order and fuzzy logic control," *IEEE J. Photovolt.*, vol. 7, no. 2, pp. 640–650, Mar. 2017.

[17] M. C. Alonso-García, J. M. Ruiz, and F. Chenlo, "Experimental study of mismatch and shading effects in the I–V characteristic of a photovoltaic module," *Sol. Energy Mater. Sol. Cells*, vol. 90, no. 3, pp. 329–340, Feb. 2006.

[18] M. C. Alonso-García, J. M. Ruiz, and W. Herrmann, "Computer simulation of shading effects in photovoltaic arrays," *Renew. Energy*, vol. 31, no. 12, pp. 1986–1993, Oct. 2006.

[19] J. W. Bishop, "Computer simulation of the effects of electrical mismatches in photovoltaic cell interconnection circuits," *Sol. Cells*, vol. 25, no. 1, pp. 73–89, Oct. 1988.

[20] C. Deline, A. Dobos, S. Janzou, J. Meydbray, and M. Donovan, "A simplified model of uniform shading in large photovoltaic arrays," *Sol. Energy*, vol. 96, pp. 274–282, Oct. 2013.

[21] E. Karatepe, M. Boztepe, and M. Çolak, "Development of a suitable model for characterizing photovoltaic arrays with shaded solar cells," *Sol. Energy*, vol. 81, no. 8, pp. 977–992, Aug. 2007.

[22] G. Petrone and C. A. Ramos-Paja, "Modeling of photovoltaic fields in mismatched conditions for energy yield evaluations," *Electr. Power Syst. Res.*, vol. 81, no. 4, pp. 1003–1013, Apr. 2011.

[23] A. Woyte, J. Nijs, and R. Belmans, "Partial shadowing of photovoltaic arrays with different system configurations: Literature review and field test results," *Sol. Energy*, vol. 74, no. 3, pp. 217–233, Mar. 2003.

[24] E. Díaz-Dorado, A. Suárez-García, C. Carrillo, and J. Cidrás, "Influence of the shadows in photovoltaic systems with different configurations of bypass diodes," in *Proc. SPEEDAM*, Jun. 2010, pp. 134–139.

[25] E. Díaz-Dorado, J. Cidrás, and C. Carrillo, "Discretized model for partially shaded PV arrays composed of PV panels with overlapping bypass diodes," *Sol. Energy*, vol. 157, pp. 103–115, Nov. 2017.

[26] H. Ziar, M. Nouri, B. Asaei, and S. Farhangi, "Analysis of overcurrent occurrence in photovoltaic modules with overlapped by-pass diodes at partial shading," *IEEE J. Photovolt.*, vol. 4, no. 2, pp. 713–721, Mar. 2014.

[27] H. Ziar, S. Farhangi, and B. Asaei, "Modification to wiring and protection standards of photovoltaic systems," *IEEE J. Photovolt.*, vol. 4, no. 6, pp. 1603–1609, Nov. 2014.

[28] B. B. Pannebakker, A. C. de Waal, and W. G. J. H. M. van Sark, "Photovoltaics in the shade: One bypass diode per solar cell revisited," *Prog. Photovolt., Res. Appl.*, vol. 25, no. 10, pp. 836–849, Oct. 2017.

[29] D. Rossi, M. Omaña, D. Giaffreda, and C. Metra, "Modeling and detection of Hotspot in shaded photovoltaic cells," *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 23, no. 6, pp. 1031–1039, Jun. 2015.

[30] T. Ghanbari, "Permanent partial shading detection for protection of photovoltaic panels against hot spotting," *IET Renew. Power Gener.*, vol. 11, no. 1, pp. 123–131, Nov. 2017.

[31] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, May 2009.

[32] K. Ishaque, Z. Salam, and H. Taheri, "Simple, fast and accurate two-diode model for photovoltaic modules," *Sol. Energy Mater. Sol. Cells*, vol. 95, no. 2, pp. 586–594, Feb. 2011.

[33] S. A. Mahmoud, M. M. Alsari, E. I. Reda, and R. M. Alhammadi, "MATLAB modeling and simulation of photovoltaic modules," in *Proc. IEEE 55th Int. Midwest Symp. Circuits Syst. (MWSCAS)*, Aug. 2012, pp. 786–789.

[34] Y. Mahmoud, W. Xiao, and H. H. Zeineldin, "A simple approach to modeling and simulation of photovoltaic modules," *IEEE Trans. Sustain. Energy*, vol. 3, no. 1, pp. 185–186, Jan. 2012.

[35] S. Kumar, H. S. Sahu, and S. K. Nayak, "Estimation of MPP of a double diode model PV module from explicit I–V characteristic," *IEEE Trans. Ind. Electron.*, vol. 66, no. 9, pp. 7032–7042, Sep. 2019.

[36] G. N. Psarros, E. I. Batzelis, and S. A. Papathanassiou, "Partial shading analysis of multistring PV arrays and derivation of simplified MPP expressions," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 499–508, Apr. 2015.

[37] G. Liu, S. K. Nguang, and A. Partridge, "A general modeling method for I–V characteristics of geometrically and electrically configured photovoltaic arrays," *Energy Convers. Manage.*, vol. 52, no. 12, pp. 3439–3445, Nov./Dec. 2011.

[38] H. Kawamura, K. Naka, N. Yonekura, S. Yamanaka, H. Kawamura, H. Ohno, and K. Naito, "Simulation of I–V characteristics of a PV module with shaded PV cells," *Sol. Energy Mater. Sol. Cells*, vol. 75, nos. 3–4, pp. 613–621, Feb. 2003.

[39] E. I. Batzelis, I. A. Routsolias, and S. A. Papathanassiou, "An explicit PV string model based on the Lambert *W* function and simplified MPP expressions for operation under partial shading," *IEEE Trans. Sustain. Energy*, vol. 5, no. 1, pp. 301–312, Jan. 2014.

ZAID ALQAISI received the B.Sc. degree in electrical engineering from the Jordan University of Science and Technology, Irbid, Jordan, in 2012, and the M.Sc. degree in environmental and renewable engineering from German Jordanian University, Amman, Jordan, in 2015. He is currently pursuing the Ph.D. degree in electrical engineering with the Worcester Polytechnic Institute, Worcester, MA, USA. His research interests include photovoltaic modeling, power electronic converters, and power system stability and control.

YOUSEF MAHMOUD (SM'17) received the B.Sc. degree in electrical power engineering from Albalqa'a Applied University, Amman, Jordan, in 2009, the M.Sc. degree in electrical power engineering from the Masdar Institute of Science and Technology, Abu Dhabi, UAE, in 2012, and the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2016. He is currently an Assistant Professor with the Worcester Polytechnic Institute, Worcester, MA, USA. His research interests mainly include control and operation of grid-connected photovoltaic power systems and their power electronic converters, including PV modeling, maximum power point tracking, and partial shading impact.