International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 16, No. 3, September 2025, pp. 1949~1961
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v16.i3.pp1949-1961

Evaluating shading effects on photovoltaic modules: Mathematical modeling with ideal, single, and double diodes

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Article Info

Article history:

Received Oct 17, 2024
Revised Mar 30, 2025
Accepted May 25, 2025

Keywords:

Double diodes
Efficiency ratio
Fill factor
Ideal diode
Mismatch power loss
Partial shading
Single diode

ABSTRACT

Among the issues that solar systems face is partial shadowing that can be caused by many factors, such as trees, buildings, or clouds. A shaded module will produce less energy, which reduces the power supplied by a solar system based on PV panels. The purpose of this study is to model and simulate photovoltaic modules based on an ideal single and double diode. After that, we will simulate five configurations formed by nine photovoltaic solar panels: series (S), parallel (P), series-parallel (SP), bridge-link (BL), and total-cross-tied (TCT) under uniform and non-uniform cases (center, diagonal, and frame). These five PV solar configurations are compared in terms of short circuit currents (ISC), open circuit voltages (VOC), peak powers (PMP), the voltage and current values corresponding to maximum power (VMP, IMP), mismatch power loss (MPL), fill factor (FF), efficiency ratio (ER), and overall maximum power (OMP). The six PV configurations are simulated, considering the parameters of the STM6-40/36 PV module.

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1. INTRODUCTION

Solar energy is among the most widely used renewable energy sources in the world and particularly in Morocco. Utilizing renewable energy sources, such as solar and wind power, which primarily focus on decreasing greenhouse gas emissions, is crucial for moving towards sustainable energy solutions [1]. One of the advantages of PV systems is that they require minimal maintenance for producing electrical energy [2]. The solar photovoltaic systems are sensitive to many factors, including solar irradiance, temperature, and aging [3], [4]. Looking towards, the research [5] analyzes the effect of temperature and dust on solar energy production in Morocco. It also evaluates the quality of groundwater used for maintaining photovoltaic panels. The findings reveal a 20% reduction in energy production at 45 °C, although the water is generally suitable. The output of photovoltaic panels is significantly affected by dust, which reduces efficiency and power generation as its accumulation increases. The study [6] analyzes the impact of dust on PV panel performance and proposes an effective cleaning system that not only removes dust but also helps maintain lower temperatures on the panels. Clouds, trees, poles, buildings, and other objects can shade some cells or modules in a PV array during partial shading conditions [7].

Due to the shading effect, the efficiency of photovoltaic systems decreases; several solutions have been proposed to overcome this problem, such as the topology of the photovoltaic network and maximum power point techniques (MPPT) [8]-[10]. The PV system architecture is one of the most effective solutions to significantly reduce power losses due to the shading effect [11]-[14]. Jha [15] discusses a generalized modeling of photovoltaic modules and array configurations under partial shading, using manufacturer data to simulate and analyze their performance with MATLAB. In the literature [16], the focus is on modeling and assessing the performance of different photovoltaic (PV) array configurations under various partial shading conditions (PSC) to improve efficiency and reduce mismatch losses. The study examines configurations such as series (S), parallel (P), series-parallel (SP), total-cross-tied (TCT), bridge-linked (BL), and honey-comb (HC) using a 6×4 PV array and the bishop model for detailed simulation. The findings demonstrate that the TCT configuration typically yields the best performance across most shading scenarios, providing valuable guidance for selecting optimal PV array setups. Kareem *et al.* [17] address the challenge of improving photovoltaic (PV) system efficiency by introducing a modified series-parallel (MSP) configuration and comparing it with four other setups: SP, TCT, BL, and HC. Using a 3×3 solar array, the study simulates various partial shading conditions in MATLAB/Simulink. The results indicate that MSP performs best under both even and uneven row shading, while TCT excels in vertical uneven shading, and both TCT and MSP are effective for diagonal shading. Pendem and Mikkili [18] tackle the issue of enhancing energy efficiency in photovoltaic (PV) systems impacted by partial shading conditions (PSC), which result in power mismatches between modules. They model and simulate the performance of several 5×5 PV array configurations, S, SP, BL, and HC, across various shading scenarios. The evaluation includes key performance metrics such as global maximum power point (GMPP), mismatch losses, and efficiency, using KYOCERA-KC200GT PV modules in MATLAB/Simulink. Using a 3×3 PV array based on a single diode, the authors analyzed the performance of S, P, SP, TCT, and BL configurations in shading situations. The best performance was achieved with the TCT configuration [19].

Despite previous studies, they did not compare the shading effect on three types of photovoltaic cell modeling: modeling based on an ideal diode, modeling based on a single diode, and modeling based on two diodes. This comparative analysis is essential as each model behaves differently under varying shading conditions. Understanding these differences can lead to better optimization of photovoltaic systems, enhancing their overall efficiency and performance. By evaluating the shading impact across these models, we can identify the most effective approach for real-world applications. In this paper, we investigate the effect of shading on PV cells using three different models: the first based on a lossless ideal diode, the second based on a single diode with resistors, and the third based on two diodes with resistors.

2. METHOD

This section describes the method used to evaluate the effect of shading on solar panels. This study assesses the impact of shading by modeling a 3×3 photovoltaic array based on three types of photovoltaic cells: an ideal single diode, a single diode with resistors, and double diodes. Figure 1 illustrates the simulation model of the 3x3 photovoltaic array in MATLAB/Simulink. Simulations are conducted under uniform isolation and three shading scenarios (center, diagonal, and frame) to analyze their effects.

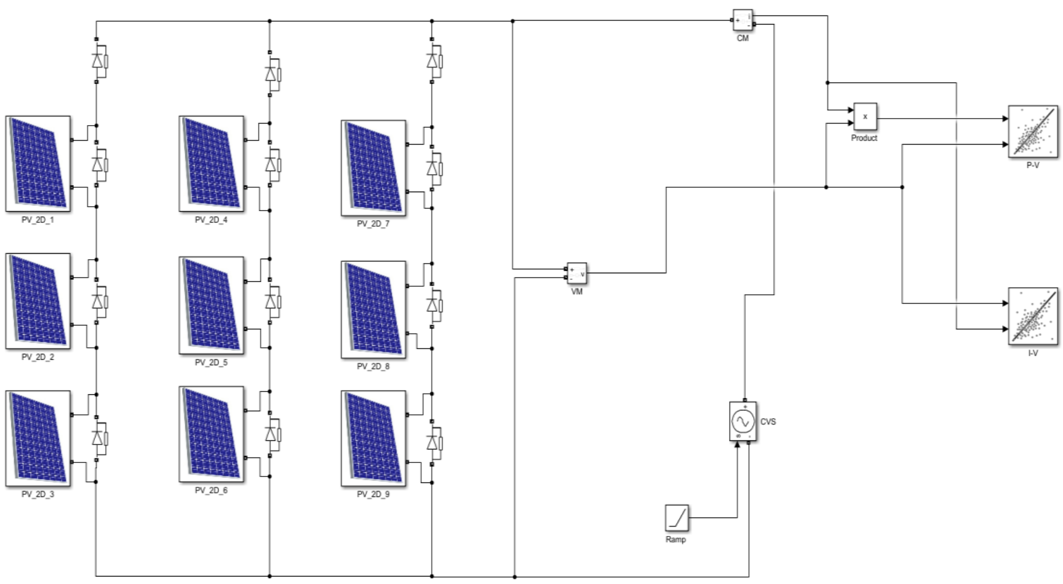


Figure 1. PV array 3×3 simulation in MATLAB/Simulink

Five panel configurations, S, P, SP, TCT, and BL, are examined to determine which performs best under shading. Key metrics, including short-circuit current (ISC), open-circuit voltage (VOC), peak power (PMP), mismatch power loss (MPL), fill factor (FF), efficiency ratio (ER), and overall maximum power (OMP), are analyzed using the STM6-40/36 module. The findings provide valuable insights for improving solar energy production and optimizing system design. The photovoltaic module parameters used in this article are based on the work cited in [20]. Table 1 provides all the necessary parameters of STM6-40/36.

Table 1. STM6-40 PV module specification

Parameters	Ideal single diode	Single diode	Double diode
Voltage at maximum power (V_{mp})	18 V	18 V	18 V
Current at maximum power (I_{mp})	2.23 A	2.23 A	2.23 A
Open circuit voltage (V_{oc})	21.6 V	21.6 V	21.6 V
Rated power (W)	40 W	40 W	40 W
Short circuit current (I_{sc})	2.36 A	2.36 A	2.36 A
Total number of cells in series (N_S)	36	36	36
Total number of cells in parallel (N_P)	1	1	1
Ideality factor of the diode (n)	1.5328	1.5328	n_1= 1.5818 n_2= 1.5445
Shunt resistance (Rsh)	-	15.855 Ω	597.29 Ω
Series resistance (Rs)	-	2.9309 mΩ	11.01 mΩ

3. MATHEMATICAL EQUIVALENT MODELING OF PV MODULE

The literature suggests several equivalent models for PV cells [21], [22]. In this work, we have studied three equivalent models: the ideal diode (ID), the single diode (SD), and the double diode (DD) model. Figure 2 shows the three models studied in this paper: the ideal diode model Figure 2(a), the single-diode model Figure 2(b), and the double-diode model Figure 2(c).

3.1. Ideal-diode PV module

In order to study the electrical behavior of a photovoltaic cell in the face of numerous phenomena such as shading, the cell can be modelled by a simplified model based on a single photogenerated current I_{ph_Cell} and one diode. The equivalent model of this cell is presented in Figure 2(a). The current produced by a PV cell I_{ph_Cell} is as (1).

$$I_{ph\_Cell} = \frac{I_r}{I_{r0}}\left[I_{SC} - K_i(T_r - T)\right] \tag{1}$$

The output current of the PV cell is as (2).

$$I_{PV\_Cell} = I_{ph\_Cell} - I_0\left[exp\left(\frac{qV_{PV\_Cell}}{T.n.k}\right) - 1\right] \tag{2}$$

PV cell saturation current is described by (3).

$$I_0 = \frac{I_{sc}}{(exp(\frac{V_{oc}.q}{k.n.TN_S}) - 1)}.\left[\frac{T}{T_r}\right]^3 exp(-\frac{qE_{g0}}{nk}\left(\frac{1}{T_r} - \frac{1}{T}\right)) \tag{3}$$

The PV module equivalent circuit based on an ideal diode cell is shown in Figure 3(a). The current output of this PV is as (4).

$$I_{PV} = N_p.I_{ph\_Cell} - N_p.I_0\left[exp(\frac{q.V_{PV}}{N_S.n.k.T}) - 1\right] \tag{4}$$

Where: I_{ph_Cell} : photogenerated current of PV cell, I_{sh} : current through parallel resistor, R_{sh} : parallel resistor, R_s : series resistor, V_{PV_Cell} : output voltage of PV cell, I_{PV_Cell} : output current of PV cell, I_{sc} : short circuit current, I_r : solar irradiation of PV cell, I_{r0} : reference solar irradiation (I_{r0} = 1000 W/m^2), I_{rs}: reverse saturation current of diode, I_0: saturation current of PV cell, K_i: coefficient of cell current (Ki = 0.002), T: PV cell temperature, T_r: PV cell reference temperature (T_r = 298 K), n: quality factor the diode, E_{g0}: gap energy (E_{g0}= 1.1 eV), k : constant of Boltzmann ($k = 1.3805 \times 10^{-23}$ J/K), N_s: number of cells in series, N_p: number of cells in parallel.

3.2. Single diode PV module

PV cells with a single diode equivalent model have a current source I_{ph_Cell}, an antiparallel diode (D), series resistance (R_s), and a parallel shunt resistance (R_{sh}). Figure 2(b) illustrates this equivalent model of a PV cell. PV module equivalent circuit shown in Figure 3(b). The current output of the PV module in this case is as (5).

$$I_{PV} = N_p.I_{ph\_Cell} - I_{sh} - N_p.I_0\left[exp(\frac{q(N_S.I_{PV}.R_S+N_p.V_{PV})}{N_S.N_p.n.k.T}) - 1\right] \quad (5)$$

The shunt resistor current I_{sh} is defined by (6).

$$I_{sh} = \frac{R_S.I_{PV\_Cell}+V_{PV\_Cell}}{R_{sh}} \quad (6)$$

Partial shading causes reverse bias in shaded modules, increasing heat and risking damage [23]. To address this challenge, we will use anti-return semiconductor diodes with anti-parallel diode protection for each module. MATLAB/Simulink model of the photovoltaic panel is presented in Figure 4, which is based on one diode cell.

3.3. Double diodes PV module

The double diode model provides a more precise and detailed representation of the behavior of solar cells compared to the single diode model. Figure 2(c) shows the equivalent circuit representation of this PV cell. In the case of an equivalent model with two diodes, the current supplied by the PV module is as (7).

$$I = N_p.I_{ph} - I_{sh} - N_p.I_{01}\left[exp\left(\frac{q(N_S.I.R_S+N_p.V)}{N_S.N_p.n_1.k.T}\right) - 1\right] - N_p.I_{02}\left[exp\left(\frac{q(N_S.I.R_S+N_p.V)}{N_S.N_p.n_2.k.T}\right) - 1\right] \quad (7)$$

The expression of the two saturation currents I_{01} and I_{02} is expressed as (8).

$$I_{01} = I_{rs1}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{qE_{g0}}{n_1k}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right], \quad I_{02} = I_{rs2}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{qE_{g0}}{n_2k}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \quad (8)$$

(a)

(b)

(c)

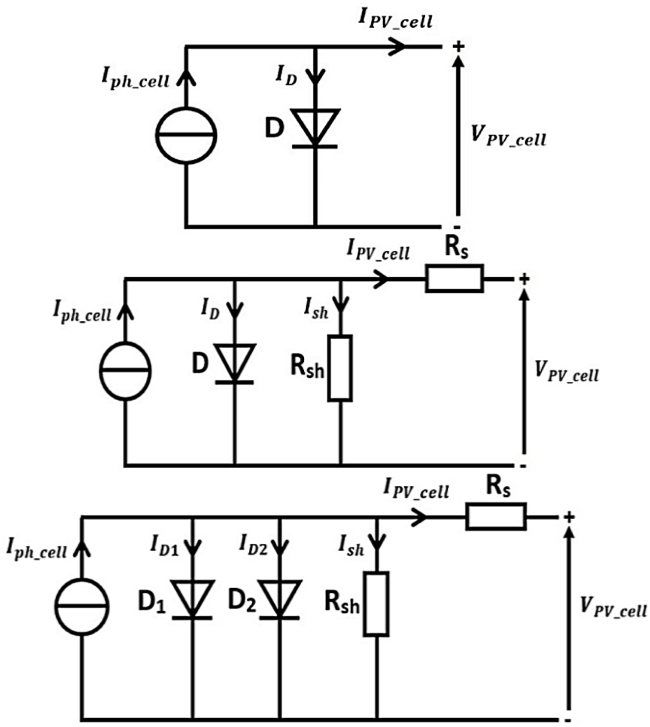


Figure 2. Equivalent circuit: (a) ideal diode model, (b) single diode model, and (c) double diode model

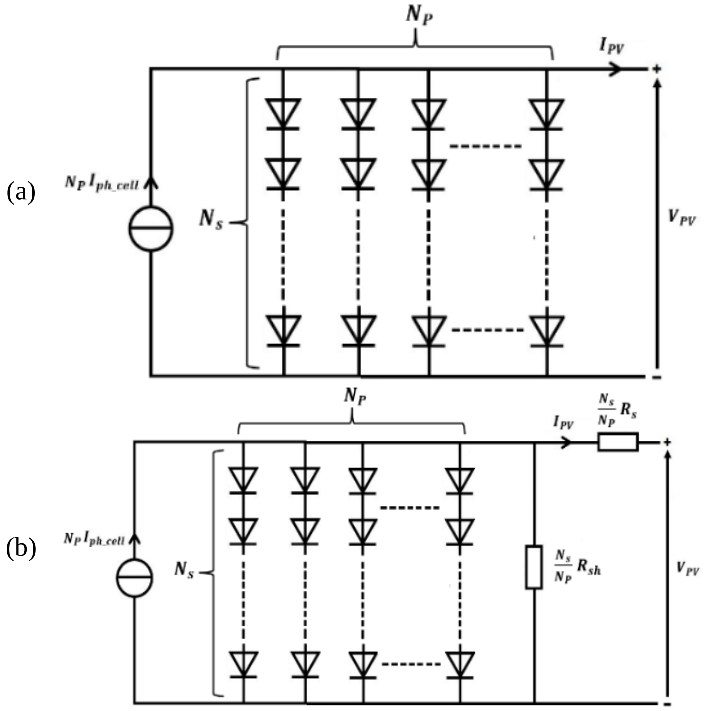


Figure 3. PV module equivalent circuit based: (a) on an ideal diode cell and (b) on a single diode cell

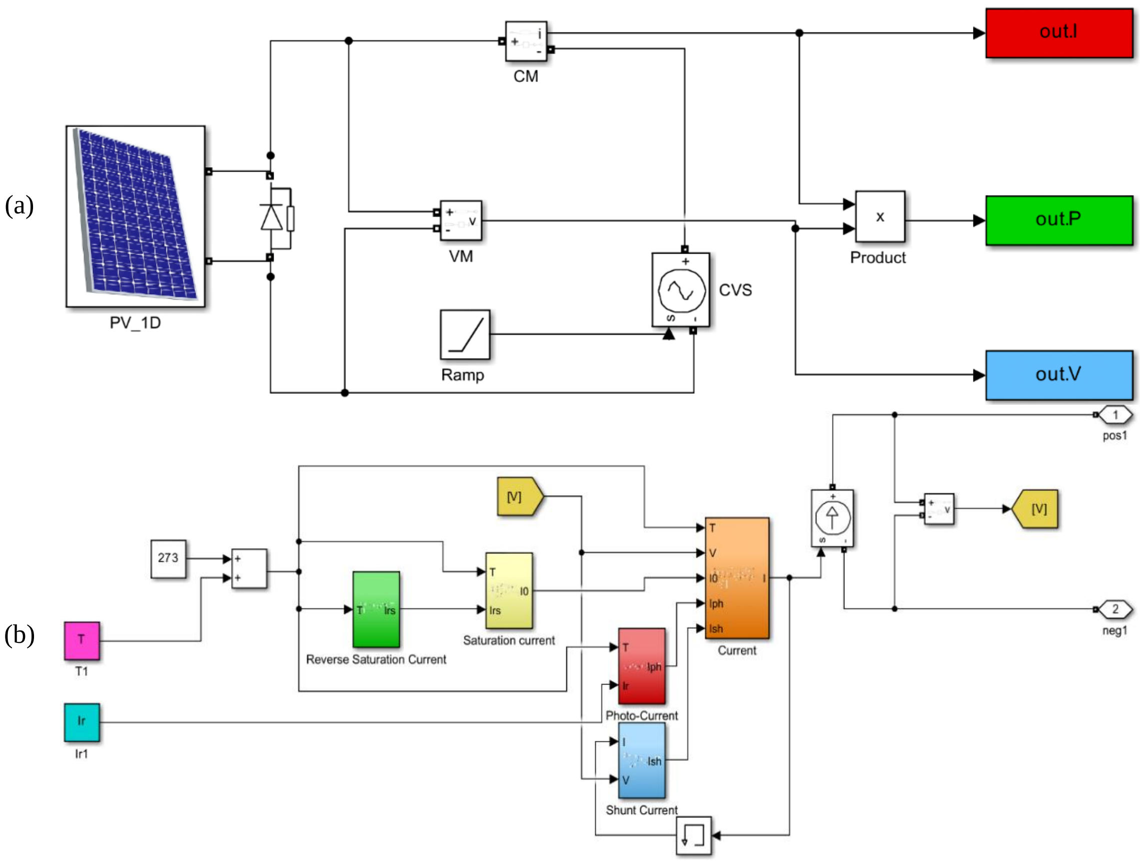


Figure 4. MATLAB/Simulink model of the photovoltaic panel: (a) implementation of the photovoltaic system as a subsystem including voltage, current, and power measurements using MATLAB/Simulink; and (b) detailed view of the solar panel model based on a single-diode equivalent circuit

4. MODELING AND SIMULATION OF PV ARRAYS

In this section, we have created four photovoltaic array configurations in MATLAB/Simulink based on an ideal diode (ID), single diode (SD), and double diode (DD) PV cell. These configurations are subjected to four types of irradiations: uniform and non-uniform. The best configuration among the four is chosen by comparing several criteria.

4.1. PV array configuration 3×3

In the present work, fifteen PV array types are modelled and studied in MATLAB/Simulink; each array consists of nine photovoltaic panels. Three electrical panel models are used: ID, SD, and DD. Four PV field configurations are evaluated: series field (S), parallel field (P), series-parallel field (SP), bridge-link field (BL), and total-cross-tied field (TCT).

- Series configuration (S): The output current of the photovoltaic array in this configuration is equal to the current passing through each PV module [24], [25]. The nine volts from each module add up to the output voltage. This configuration is shown in Figure 5(a).
- Parallel configuration (P): Nine PV modules would be linked in parallel in this configuration. One PV module's voltage is equal to the output voltage, and the total of the nine currents passing through each module is equal to the output current [26]. In Figure 5(b), this configuration is displayed.
- Series-parallel configuration (SP): The total output voltage and current of a PV module are equal to the sum of the voltage and current of the three modules [24], [25]. This PV array is shown in Figure 5(c).
- Bridge-link configuration (BL): The combination of four modules in a rectifier bridge gives this configuration [24], [25]. This configuration is given in Figure 5(d).
- Total-cross-tied configuration (TCT): The connections are established between all nine PV modules as shown in Figure 5(e) [24], [25].

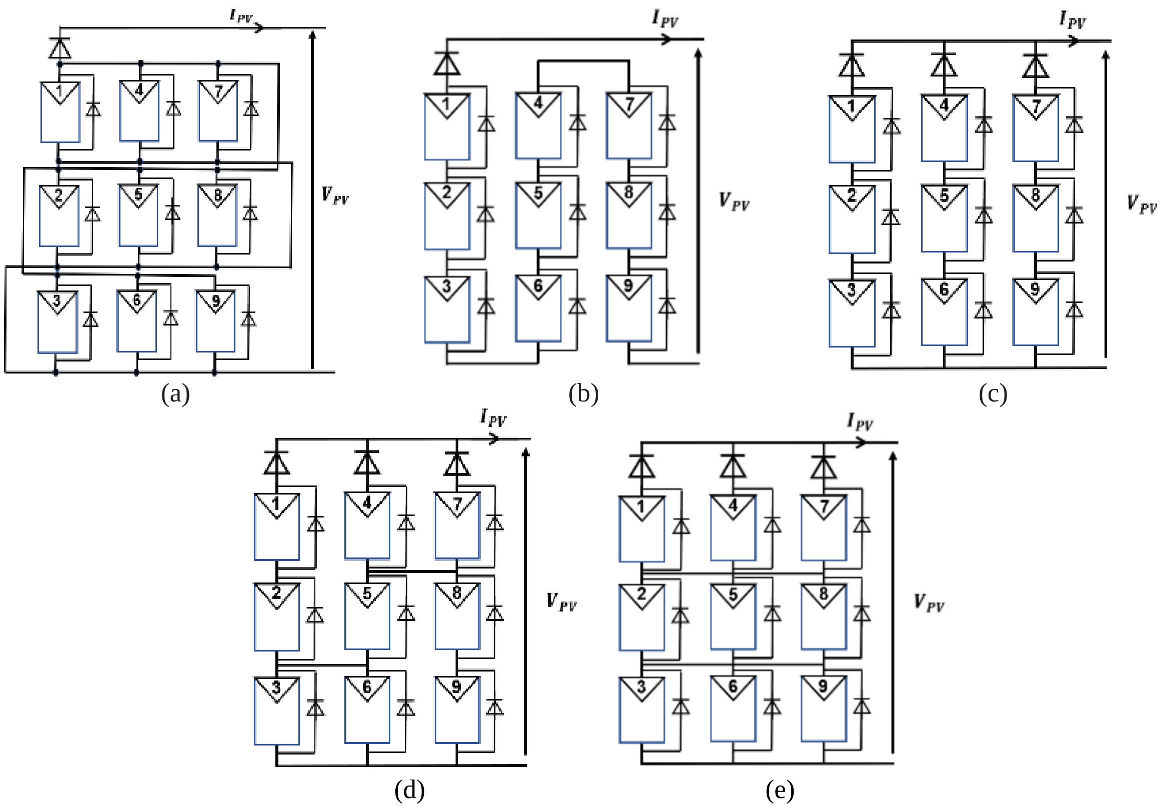


Figure 5. PV configuration: (a) parallel, (b) series, (c) series-parallel, (d) bridge-link, and (e) total-cross-tied

4.2. Shading model configurations

The five PV configurations (S, P, SP, BL, TCT) are being tested and simulated under partial shading effect. Four cases will be simulated and analyzed to analyze the shading effect. The following figure shows the uniform case and three partial shading scenarios.

- Uniform condition (case 1): All modules have an insolation of 1000 W/m^2. Figure 6(a) illustrates this case.
- Center shading condition (case 2): PV5 in the center is subjected to 200 W/m^2. There is also an isolation of 1000 W/m^2 on the other modules. This case is shown in Figure 6(b).
- Diagonal shading condition (case 3): A PV1 module has an insolation of 200 W/m^2, a PV5 module has an insolation of 400 W/m^2 and a PV9 module has an insolation of 600 W/m^2. A 1000 W/m^2 insulation is provided by the other modules. Figure 6(c) depicts this case.
- Frame shading condition (case 4): PV1, PV4 and PV9 receives 200 W/m^2 of solar insolation, PV6 receives 400 W/m^2, PV2 and PV8 receives 600 W/m^2, a PV3 and PV7 receives 800 W/m^2. PV5 module has solar insolation of 1000 W/m^2. Figure 6(d) gives this case.

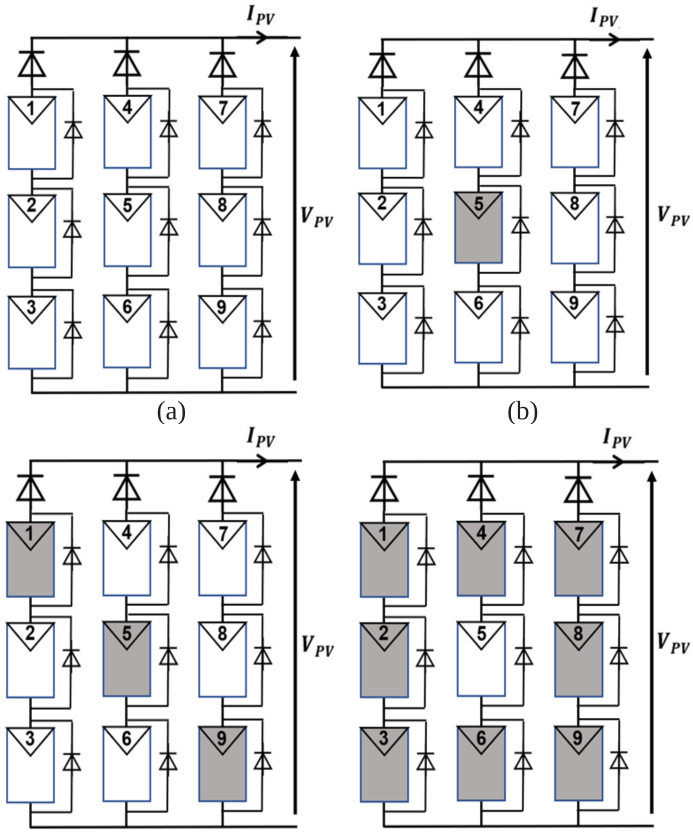


Figure 6. Shading model configurations: (a) uniform case, (b) center, (c) diagonal, and (d) frame shading case

5. RESULTS AND DISCUSSION

Examining the performance of the following PV array topologies: S, P, SP, BL, and TCT under a range of partial shading scenarios, including frame, diagonal, uniform, and center shading, is the aim of this section. To do this, we will use MATLAB/Simulink to simulate the five configurations (S, P, SP, BL, and TCT) and assess the impact of partial shade in four shading scenarios. The evaluation of the effect of partial shading (four cases) on photovoltaic modules based on an ideal diode (ID), single diode (SD) and double diodes (DD) is conducted by plotting the current and power curves simulated on MATLAB/Simulink, and contrasting the values of: short circuit currents (ISC), open circuit voltages (VOC), peak powers (PMP), mismatch power loss (MPL), fill factor (FF), efficiency ratio (ER) and overall maximum power (OMP). Peak power PMP refers to the maximum amount of energy generated by a PV array. This value indicates the efficiency and capacity of the PV system to produce energy. In the following expression, mismatch power loss (MPL) is expressed as a percentage:

$$MPL = \frac{P_{MP\_i0} - P_{MP\_ij}}{P_{MP\_i0}} . 100 \tag{9}$$

The efficiency ratio (ER) is defined by (10).

$$ER = \frac{P_{MP\_ij}}{P_{MP\_i0}}.100 \quad (10)$$

Overall maximum power (OMP) is given by (11).

$$OMP = \frac{P_{MP\_ij}}{P_{MP}}.100 \quad (11)$$

P_{MP_i0} is the maximum power provided by configuration S($i=0$), P($i=1$), SP($i=2$), BL($i=3$) or TCT($i=4$) under uniform condition. P_{MP_ij} represents the maximum power generated by the configuration S($i=0$), P($i=1$), SP($i=2$), BL($i=3$), TCT($i=4$) in the scenario: Uniform ($j=0$), Center ($j=1$), Diagonal ($j=2$) and Frame ($j=3$). P_{MP} is the maximum power among the four configurations tested in the same shading.

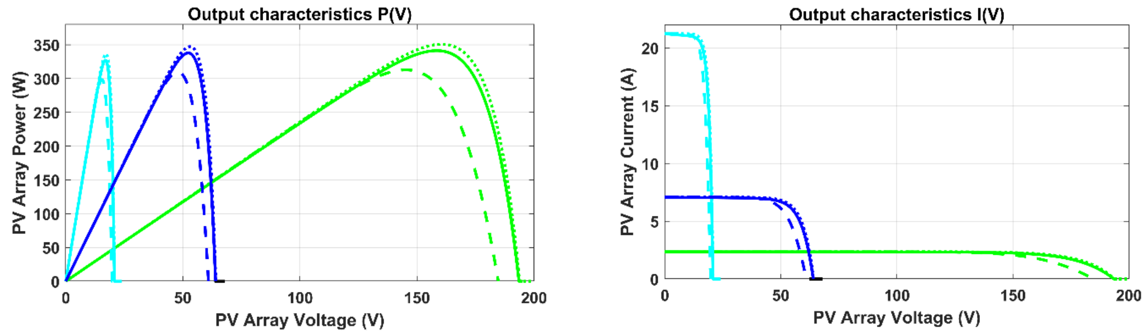
Fill factor (FF) is calculated as the quotient of the maximum output power ($V_{MP}\times I_{MP}$) and the product of open circuit voltage and short circuit current ($V_{oc}\times I_{sc}$). Fill Factor is expressed in (12) as a percentage:

$$FF(\%) = \frac{V_{MP}.I_{MP}}{V_{oc}.I_{sc}}.100 \quad (12)$$

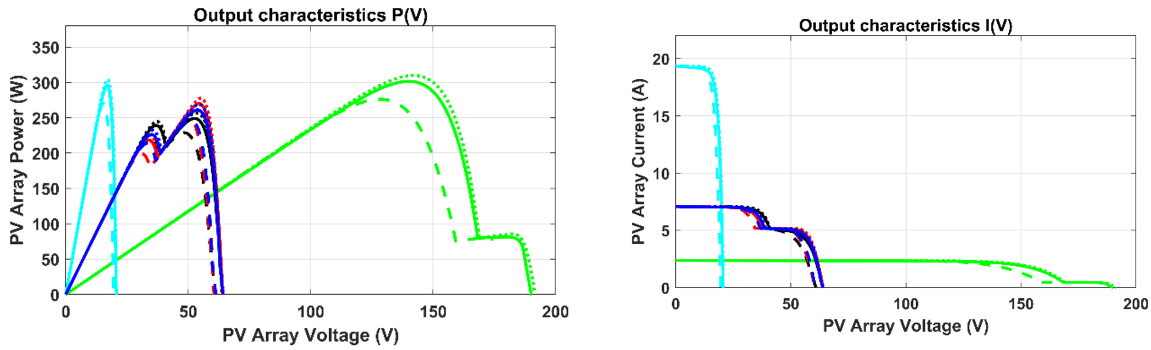
V_{MP} and I_{MP} are respectively the voltage and current corresponding to the maximum power.

Based on the simulation results in Figures 7 and 8, it can be observed that the two-diode model provides higher short-circuit voltages than those provided by the single-diode model. Subsequently, we have detailed each shading case and its effect on each model.

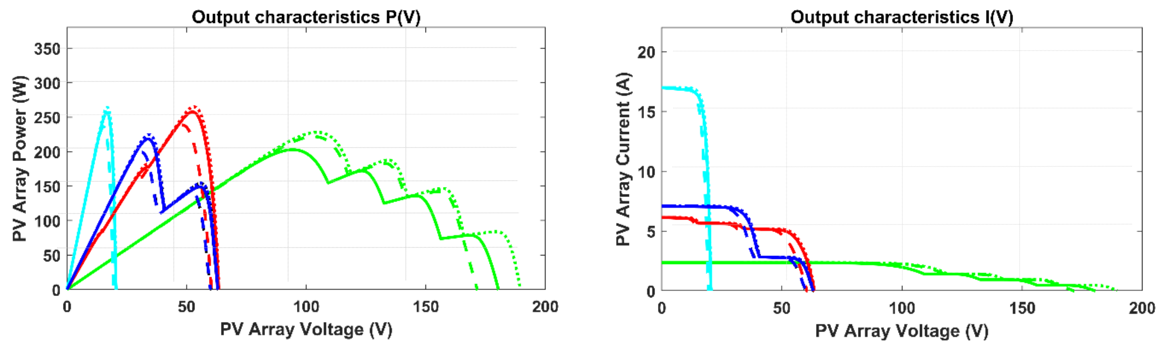
- Uniform condition (case 1): Under these irradiation conditions, 1000 W/m², there are no multiple maxima power points; the four PV array configurations present a single maximum power point. The efficiency ratio is the same for all configurations and equals 100%. The fill factor for all PV network configurations has a good value, ranging between 71% and 76%. The best value of peak powers is provided by the series configuration based on an ideal diode, with this power being 350 W. Figures 7(a) and 8(a) provide detailed information on the various parameters evaluated. The SP, BL, and TCT configurations have almost identical short circuit current I_{SC} values, but there is a slight difference in V_{OC}, especially in the two-diode configuration. The overall maximum power is high, equaling 100% in the case of the series configuration with an ideal diode. The mismatch power loss has a very good value 0% for all array configurations. However, the S and P configurations, based on an ideal diode, with one or two diodes, generate voltages and currents that differ significantly from those of the other configurations.
- Center shading condition (case 2): According to Figures 7(b) and 8(b), during the center isolation, there are multiple maxima power points. The curve in Figure 7(b) shows two maximum power points provided by structures S, SP, BL, and TCT, but the parallel P configuration provides a single maximum power point. Parallel configuration based on double diodes (P DD) has the lowest Mismatch Power Loss, 10%, but very little open circuit voltage is generated. The best value of fill factor is given by the Parallel configuration based on the ideal diode (P ID) 76%. P ID, P SD, and P DD yield a good value of the efficiency ratio. The disadvantage of parallel configuration is that it yields a minimal open circuit voltage (V_{OC}). S ID configuration offers the best value of overall maximum power and the highest global peak power value. The SP, BL, and TCT configurations have nearly identical short circuit currents I_{SC} values of 7.08 A, but there is a small difference in open circuit voltages.
- Diagonal shading condition (case 3): Under this shading condition, Figure 8(c) shows that the file factor represents a favorable value 78% while the voltage produced is minimal in the P ID, P SD, and P DD configurations. Total-cross-tied and parallel are among the best configurations in this shading scenario due to the Mismatch Power Loss factor's good value of around 20%. TCT ID and P ID produce favorable results for overall maximum power and peak power: 100% and 264 W, respectively. The Parallel configuration provides significantly favorable results for the efficiency ratio 78%. Figure 7(c) presents that configurations S ID and S SD have four maximum power points, one of which is a global point with a value of 220 W for S ID and 202 W for S SD. Configuration S DD offers three maximum power points, including two local maxima. Configurations BL ID, BL SD, and BL DD provide two maximum power points each. The configurations P and TCT, based on the three models ID, SD, and DD, produce a single maximum power point.
- Frame shading condition (case 4): During this insolation, the photovoltaic array, made up of nine modules, is affected by shading effects on most of them, with the notable exception of the central module, which captures the total irradiance of 1000 W/m^2. Parallel configuration produces the lowest mismatch power loss around 46%. P ID gives a best fill factor FF=76%, but minimal voltage. The parallel configuration based on one diode provides good values for Fill Factor equal to FF=76%, for efficiency ratio equal to ER=76%, for overall maximum power equal to 12%, and for peak power equal to 180 W, but this configuration P ID offers a minimal open circuit voltage. Figures 7(d) and 8(d) show in detail the comparison between the twelve configurations subjected to frame shading condition.



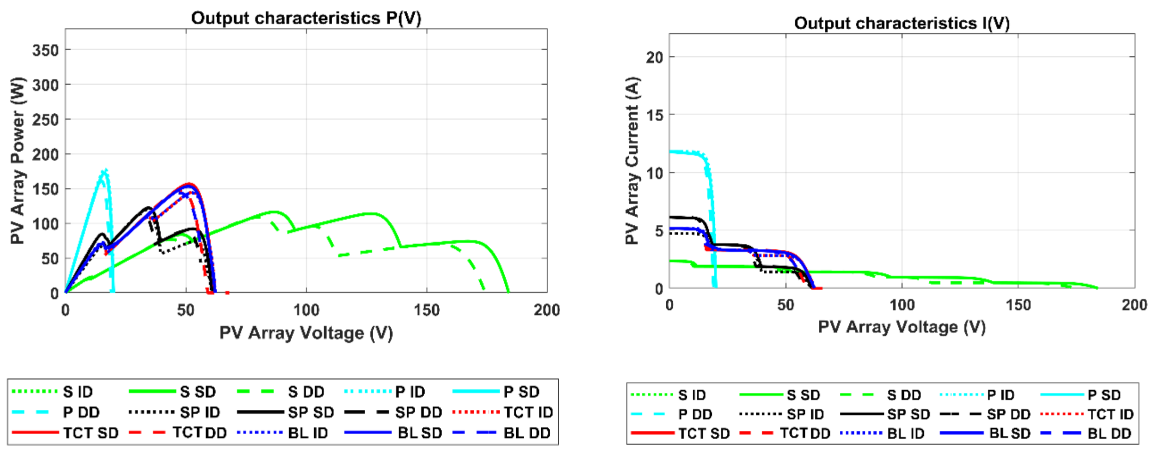
(a)



(b)



(c)



(d)

Figure 7. P(V) and I(V) of series (S), parallel (P), series-parallel (SP), bridge-link (BL), total-cross-tied (TCT) based on an ideal diode (ID), single (SD), and double-diode (DD) under partial shading: (a) uniform, (b) center, (c) diagonal, and (d) frame

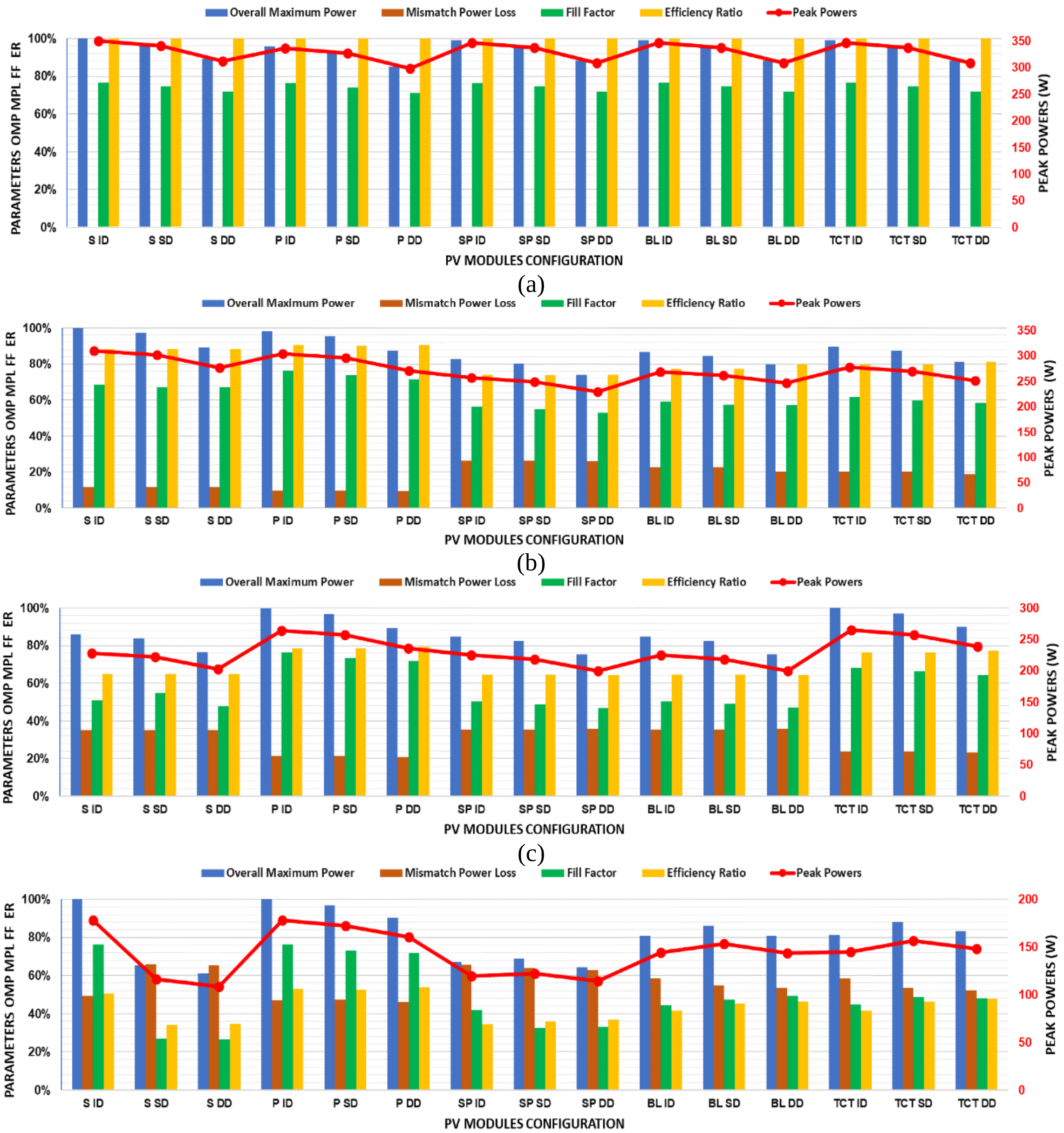


Figure 8. Mismatch power loss (MPL), fill factor (FF), efficiency ratio (ER), and overall maximum power (OMP) of five PV array configurations: S, P, SP, BL, TCT, based on an ideal (ID), single diode (SD), and double diode (DD) under uniform and non-uniform irradiation: (a) uniform, (b) center, (c) diagonal, and (d) frame

6. CONCLUSION

In this study, five array configurations were examined: S, P, SP, BL, and TCT, under uniform and three partial shading scenarios: center, diagonal, and frame. The first step of our work was to develop in MATLAB/Simulink a mathematical cell model based on three different models: the ideal diode, the one-diode model with a resistor and the two-diode model. Next, we created, tested, simulated, and analyzed the fifteen 3x3 PV configurations under four different scenarios. To evaluate the effect of shading on photovoltaic modules, we compare several performance metrics. From the results obtained, in the absence of shading, the SP configuration is among the best configurations that yield good evaluation parameter values, specifically the SP ID configuration. The TCT configuration provides values that are nearly identical to those of the SP configuration; however, it requires more cables. In our case, the TCT configuration requires 14 connection cables between the 9 PV solar, while the SP configuration requires only 10 cables to connect the 9 panels. Therefore, the TCT configuration incurs a cost that is 40% higher than that of the SP configuration.

The configuration P is the optimal configuration in the presence of shading, but this type of configuration does not provide a high short-circuit voltage. Configuration TCT, more specifically configuration TCT ID, comes after configuration P, which provides good values for indicator metrics, but a high implementation cost.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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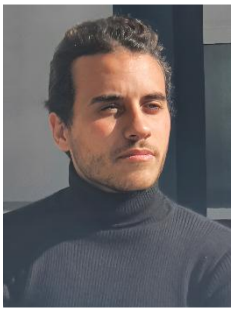

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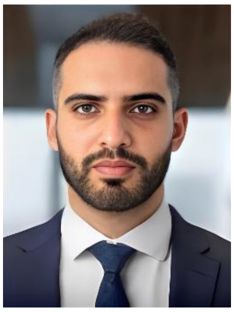

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