Comprehensive Study, Simulation and Analysis of the Fault effects on the Performance of Different Photovoltaic Array Configurations

Faiza Belhachat and Cherif Larbes

Abstract−Photovoltaic (PV) system fault analysis is crucial for improving the safety and efficiency of PV systems. Faults not only degrade performance but also negatively impact system longevity. Power output can be significantly affected by configuration, PV technology, partial shading (PS), and other operating conditions. Therefore, an accurate fault analysis requires studying the impact of faults on the performance of different photovoltaic array configurations (PVACs). The article conducts a detailed study and analysis of faults such as partial shading, bypass diode, open circuit, short circuit, line-to-ground, line-to-line, and degradation. To analyze the combined effecton different configurations,the case of multiple faults occurring simultaneously, with varying irradiance is also considered. The PVACs examined include Series (S), Series-Parallel (SP), Total-Cross-Tied (TCT), Honey-Comb (HC) and Bridge-Linked (BL). A 6x4 PV array was modeled and simulated under various scenarios to assess their impact on the performance of different PVACs and to determine the most suitable configuration for maximizing power output under these conditions. The obtained simulation results are compared and discussed. It has beenfound that using appropriate PVAC can minimize the impact of faults. The results show the superiority of S and SP PVACs, which provide the best performance in most fault scenarios. Furthermore, the TCT PVAC is no longer suitable in the case of a fault, unlike in the case of partial shading, where it outperforms the other PVACs in several situations.

Key words− Fault, photovoltaic, configuration, performance, effect.

I. INTRODUCTION

In recent years, the number of photovoltaic (PV) solar power plants has steadily increased worldwide. In fact, PV power generation systemsoffer undeniable advantages, including long life, low aging effects, low maintenance, low operating costs and robustness. However, various types of failures can occur in PV systems requiring testing and performance measurements of PV modules during maintenance work. Additionally, these failuressignificantly reduce the power generated by the PV array, which inevitably leads to a reduction in theefficiency and performance of the entire system. All system components whether modules, DC circuits or inverters can be a source of interference. The main faults of PV modules that can significantly affect the efficiency of power generation include cell failure, dirt, broken glass, delaminationand discoloration, hot spots and bypass diode failure [1-5]. The shading fault is a common fault that can occur in PV systems.In fact, changing the connections of the modules within a PV array using S, SP, HC, BL and TCT connections is one of the methods to lessen the effects of partial shading (PS) [6]. Experimental investigations on different PV array configurations (PVACs) have shown that the TCT configuration has the lowest mismatch loss in the case of PS compared to the other PVACs [6]. Shading is a special case of the mismatch defect as it reduces the amount of sunlight reaching the cells, leading to a reduction in power generation across the array. However, other faults can appear in a configuration even inthe presence of PS affectingthe PVACsperformance [7-9].
As a result, it is necessary to study and analyze these defects and their impact on the behavior of the different PVACs in order to identify the most resilient configurations that perform best under faulty conditions. While the performance of the different PVACs under partial shading has been widely studied in the literature [6], the impact of various faults on the efficacy of the existing configurations has not been thoroughlyinvestigated in previous works, a gap that this study aims to address.Thus, studying theseimpactsis essential for analyzing the performance of each configuration and selecting the onemost suitable to ensure optimal performance in the case of faults. This paper provides a comparative analysis and evaluation of faults such as partial shading, bypass diode failure, open circuit, short circuit, line to ground, line to line and degradation across various configurations including S, SP, BL, HCand TCT.The effect of multiple faults is also examined. A comparison of the performance results shows that selecting the appropriate configuration under faulty conditions can improve the system's efficiency. The study was conducted using an array of 24 PV modules organized in six rows and four columns, modeled in Simulink. The main contributions of this paper are:

- An increase in energy production is accomplished by using the appropriate PVAC for various fault scenarios.

- Five configurations have been tested including S, SP, TCT, HC and BL in order to choose the most appropriate depending on the fault encountered.

- Various faults such as partial shading, bypass diode failure, open circuit, short circuit, line to ground, line to line and degradationwere considered in this study.

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- The case of multiple failuresinPVarray interconnections was also examined.

-It has been demonstrated that the S and SP PVACs are the most appropriate in the case of faults and that the performance of the TCT PVACs has been severely degraded under these fault conditions.

- Assessing the impact of each configuration, which allows for the systematic selection of the most resilient configuration to failures, minimizing losses.

The paper is organized as follows: Section 2 presents the model of the PV module. In Section 3, the modeling and simulation of different PVACs are presented. Section 4, describes the different faults that can occur on PV modules. Section 5 presents the study, analysis and simulation of the impact of faults on different PVACs. The results obtained under faulty conditions are discussed in Section 6. The conclusion is provided in Section 7.

II. PV MODULE MODELING

To simulate the functioning of a solar PV cell, it is necessary to establish its electronic model. Solar PV modules consist of several solar cells connected in series. A PV array can be created by combining multiple solar panels. In this section, a one-diode solar cell model for simulatingPV arrays with dimensions N_sx$N_p$is described. The equivalent electrical circuit of the model based on a single diode is depicted in Fig.1.

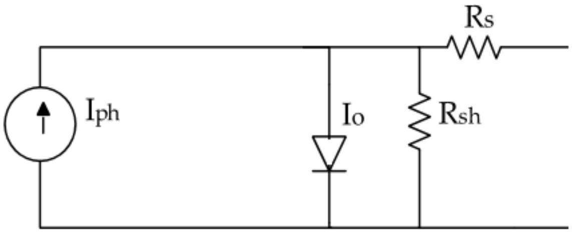

Fig.1: Equivalent circuit of PV solar cell.

A PV panel consists of N_p and N_s solar cells arranged in parallel and series, respectively. The resulting PV module current is shown in equation (1):

$$I = N_p\left(I_{pv} - I_0\left[\exp\left(\frac{V + I_{pv}R_s}{V_t N_s} - 1\right)\right]\right) - \left(\frac{V + I_{pv}R_s}{V_t N_s} - 1\right) \qquad (1)$$

Where I_0 is the reverse saturation current, R_s is the series resistance and R_p is the parallel resistance, whereas V_t represents the thermal voltage at any temperature given by:

$$V_t = \frac{N_s K T}{q} \qquad (2)$$

K is the Boltzmann constant equal to 1.3805 x 10-23, *q* is the electron’s charge constant of 1.9x10^{-19} C and *T* is the temperature at STC. A single 150W PV module is used to simulate a 6x4 PV array using Matlab/Simulink for different configurations. Table 1 contains the specifications of the PV module under consideration. The model parameters used are shown in Table 2.

Table.1
Technical details of the CA Solar MS-150M PV module.

Characteristics	**Value**
Maximum Power (W)	149.89
Cells per module (N_{cell})	72
Open circuit voltage V_{oc} (V)	43.2
Short-circuit current I_{sc} (A)	4.87
Voltage at maximum power point V_{mp}(V)	34.4
Current at maximum power point I_{mp} (A)	4.36
Temperature coefficient of V_{oc} (%/deg.C)	-0.39718
Temperature coefficient of I_{sc} (%/deg.C)	0.060411

Table.2
Model parameters for the CA Solar MS-150M PV module

Model parameters	**Value**
Light-generated current I_L (A)	4.8982
Diode saturation current I_0 (A)	5.5248e^{-10}
Diode ideality factor	1.0227
Shunt resistance Rsh (ohms)	131.2651
Series resistance R_s (ohms)	0.75917

Fig. 2 shows the I-V and P-V characteristics of the CA Solar MS-150M PV module.

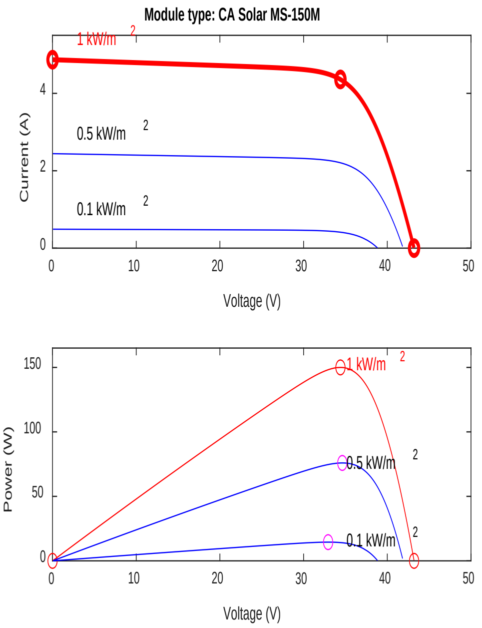

Fig.2:I-V and P-V characteristics of the CA Solar MS-150M PV module.

III. MODELING AND SIMULATION OF PV ARRAY CONFIGURATIONS (PVACS)

The PVAC refers to the way in which the PV modules are connected inside the array. Many connectivity topologies for PV modules are suggested in the literature, including S, SP, TCT, HC and BL connections. The S and SP topologies are the basic arrangements for connecting PV modules. The PV array's voltage can be raised thanks to the modules' series coupling. In the P connection, the total current is the sum of all the currents. The SP connection is the most popular connection type, which is made by connecting the PV modules in series to form a string or branch (to achieve the necessary voltage required). These strings are connected in parallel to increase the total output current. In the TCT configuration, the modules are first connected in parallel to form parallel connection groups; these will then be connected in series. Therefore, the PV modules are fully connected in this type of coupling. The HC and BL topologies reduce the number of connections between modules of adjacent strings by about half, compared to the topology TCT, which considerably reduces the quantity and time of wiring from the PV array.

Fig 3 depictsillustrative schemefor the different PVACs that are intended for the analysis of the impact of faults on PV arrays, including S, SP, TCT, BL and HCinterconnections.Fig 4 shows the Simulink model of TCT PVAC.

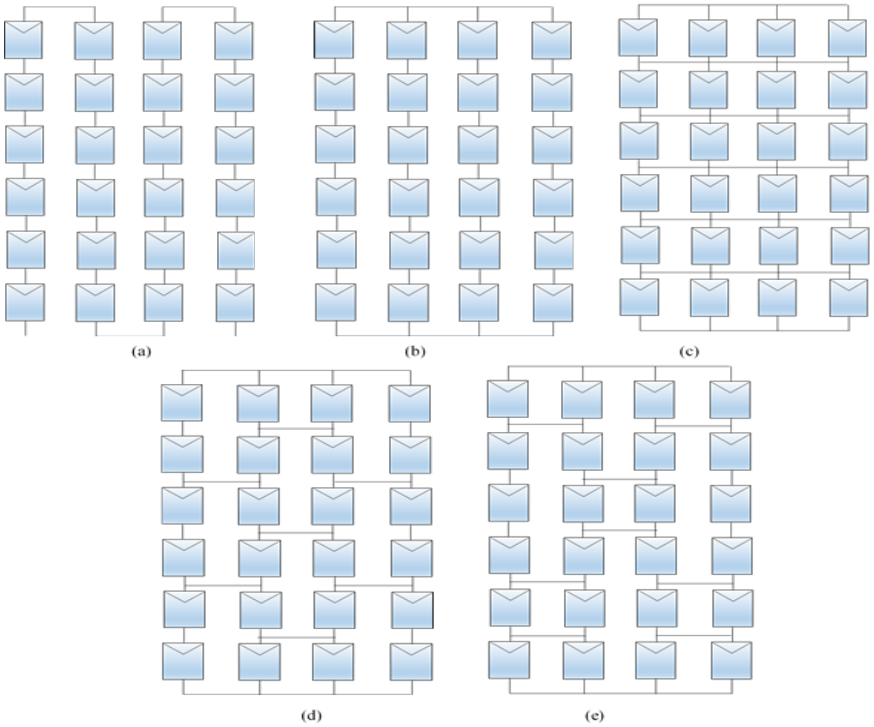

Fig.3: Different PVACs: (a) S. (b) SP. (c) TCT. (d) BL. (e) HC.

Fig.4: A modeling of a 6x4 TCT PVAC.

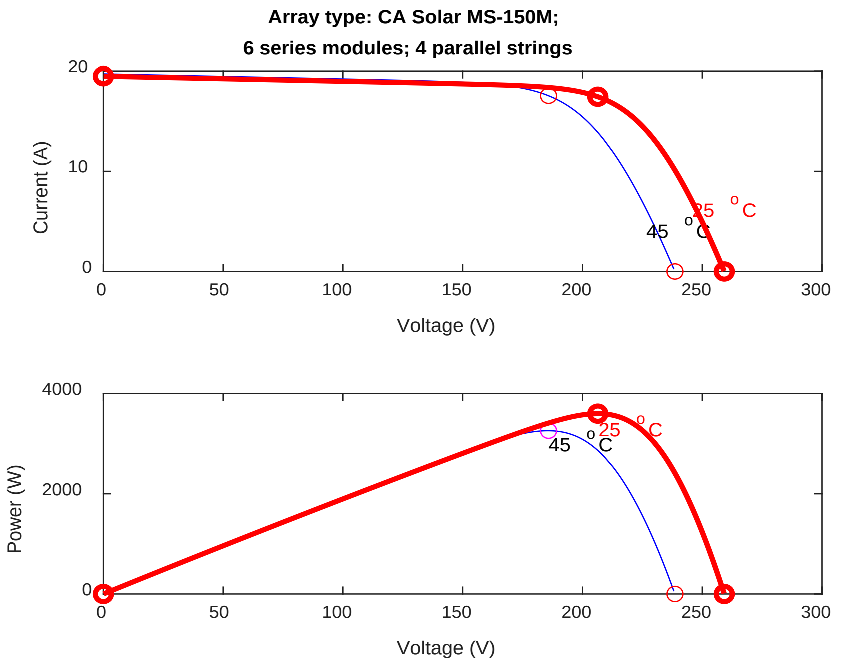

Fig.5: P-V and I-V characteristics of the TCT PVAC under uniform conditions.

Fig.5shows the P-V and I-V characteristics of the TCT configuration under uniform conditions. All PVACs exhibit the same characteristics under these operating conditions. Table 3 presents the maximum power, voltage and current for different PVACsunder standard test conditions (STC).

Table. 3
Power, voltage and current of different PVACs.

Configuration	**S**	**SP**	**TCT**	**HC**	**BL**
Power (W)	3600	3600	3600	3600	3600
Voltage (V)	827	206.1	206.1	206.1	206.1
Current (A)	4.353	17.47	17.47	17.47	17.47

IV. CONSIDERED FAULTS

In this section, we provide a brief description of the faults considered in this study.

A. Partial shading

Shading happens when a solar panel part is blocked by an object such as a tree or building, hence reducing the light quantity received by the solar cells. Because most of the cells are in series, if a part of the panel becomes shaded, then the whole module produces less power. This may also lead to hot spots that damage the cells over time [10].

B. Bypass diode failure

The fault of the bypass diode occurs when the bypass diode in a solar module fails to function correctly. Normally, the working principle of bypass diodes is to protect the panels: they shield against partial shading or cell failure. With a faulty or shaded cell, a bypass diode provides an alternate path for current so that it can bypass the affected cell, preventing damage to the entire panel. A bypass diode fault removes this protection, leading to significant energy losses, hot spots, and potential damage to the solar cells or even the cover panel, which reduces the overall efficiency of the PV system [10].

C. Open circuit

An open circuit happens when there is a break in the circuit, thus current flow cannot take place. It can result from poor connections, disconnected cable, or defective solar module. The inability of the system to produce power is primarily because there is no way the current will flow between the panels and the inverter. Power loss is hence total [10].

D. Short circuit

A short circuit occurs when there is a direct connection between two conductors, causing excessive current to flow uncontrolled.The occurrence could be from poor wiring, physical damages to the solar cells, or internally damaged components. Therefore, a short circuit results in extra current that may flow and damage components, perhaps even damage the section of the panel irreversibly or even reduce its efficiency, which can be a fire hazard [10].

E. Degradation fault

A degradation fault in a photovoltaic module refers to the gradual decline in the panel’s performance over time. As a result, the module is no longer able to produce power at its original capacity. This can be caused by several factors, which, over time, lead to a loss in efficiency [10].

F. Line-to-line fault

A line-to-line fault occurs when there is a short-circuit connection between two live conductors of a system. In this case, abnormal high current flows between the two lines but does not circulate to perform useful work. This could damage cables, circuit breakers, or inverters. Such faults can lead to power production shutdowns in a PV system and increase the risk of fire or equipment overheating, thus compromising safety and system performance [10].

G. Line-to-Ground Fault

A line-to-ground fault occurs when an energized conductor comes into contact with the ground or an earthed metallic surface. The risks involved include energy loss, equipment malfunction, and danger to life from electric shock due to leakage current to the earth. In the PV system, this fault can cause disturbances that require the intervention of protective devices, such as circuit breakers, to prevent further damage [10].

V. STUDY, ANALYSIS AND SIMULATION OF THE IMPACT OF FAULTS ON DIFFERENT PVACS

In this section, several types of faults are analyzed and simulated, including faults with and without PS, as well as other cases of combined faults.For this reason, a PV array with 6x4 modules is simulated, consisting of six rows and four strings. Fig.6 shows an example of some faults considered in this paper for the 6 X4 SP PV array.

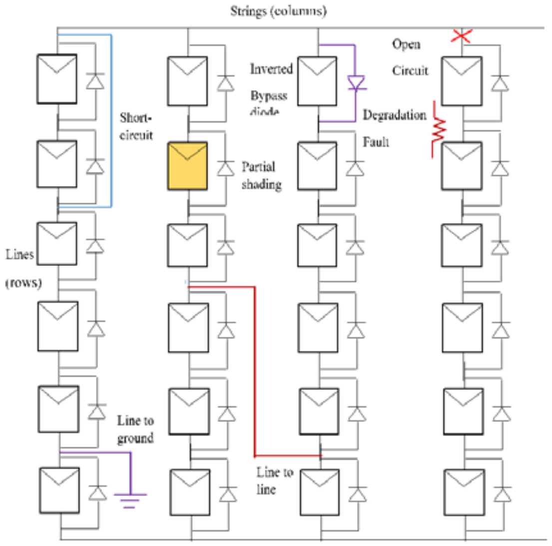

Fig.6: Example of some defects considered in the 6 X4 SP PV array

Different failure cases will be tested to evaluate their impact on each PVAC in order to determine which configuration is the most appropriate and resilient in these failure situations. To do this, we considered two cases: the case of a single fault and the case of multiple faults. The faults considered for performance analysis are bypass diode failure, short-circuit, ground faults, line- to-line, degradation and partial shading. All fault scenarios are examined and the obtained results are compared in terms of the maximum power point and relative power losses (ΔP_L (%)).

A.Partial shading fault (PS)

Table 4 shows the scenario of the PS fault.The comparison of the performance of the different PVACs in the caseof a PS fault is shown in Table 5. In this fault scenario, the S PVAC is the best configuration as it offers the highest performance and is followed by the TCT PVAC. For a better evaluation of various faults, different scenarios are tested with and without the presence of PS in the following sections.

B. Diode bypass fault

B.1. Diode bypass fault without PS

The bypass diode faults without PS consideration are summarized in Table6. The comparison of the performance of the different PVACs in the case of bypass diode failure without PS is shown in Table 7.

- In the case of a disconnected bypass diode under uniform operating conditions, there is no change, and it is obvious that all the PVACs have the same power value.
- In the case of a short-circuited or reversed bypass diode without PS, the S PVAC provides the highest value of power, followed by the SP PVAC and therefore the S configuration has the lowest power loss compared to all PVACs.

Table.4
Scenario of a PS fault.

Assignation	**Fault description**
F-PS	The last three modules of the third string are shaded at 300 W/m^2+ the last three modules of the fourth string are also shaded at 300 W/m^2

Table.5
PVACs performance in case of a PS fault.

PSfault	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-PS	**2391**	**33.5833**	1778	50.6111	1835	49.0277	1818	49.5	1823	49.3611

Table.6
Scenario of a diode bypass fault without PS.

Assignation	**Fault description**
F-DBP-D$_1$	The first bypass diode is disconnected from the first string
F-DBP-D$_2$	The first four bypass diodes are disconnected from the first string
F-DBP-SC$_1$	The first bypass diode is short-circuited in the first string
F-DBP-SC$_2$	The first four bypass diodes are short-circuited in the first string
F-DBP-I$_1$	The first bypass diode is inverted in the first string
F-DBP-I$_2$	The first four bypass diodes are inverted in the first string

Table.7
PVACs performance in case of a diode bypass fault without PS.

Diode bypass Fault	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-DBP-D$_1$	**3600**	-	**3600**	-	**3600**	-	**3600**	-	**3600**	-
F-DBP-D$_2$	**3600**	-	**3600**	-	**3600**	-	**3600**	-	**3600**	-
F-DBP-C$_1$	**3436**	4.5555	3224	10.4444	2856	20.6666	2942	18.2777	3018	16.1666
F-DBP-C$_2$	**3277**	8.9722	821.8	77.1722	569.3	84.1861	663.1	81.5805	637.4	82.2944
F-DBP-I$_1$	**3440**	4.4444	3237	10.0833	2875	20.1388	2960	17.7777	3035	15.6944
F-DBP-I$_2$	**2866**	20.3888	868.8	75.8666	612.7	82.9805	708.4	80.3222	682.2	81.05

B.2. Diode bypass fault with PS

Table 8 shows the bypass diode fault scenariosunderpartially shaded conditions.The comparison of the performance of the different PVACs in the case of bypass diode failure with PS is shown in Table 9.

- For the shading scenario F-PS$_1$, the S configuration exhibits the best performance, whereas in the second scenario (F-PS$_2$), the TCT PVAC provides the highest performance. So, it depends on the shading pattern, its intensity and its location.
- For the same shading scenarios in the presence of a fault in the bypass diode, the following can be observed:
- For the fault of a disconnected bypass diode, in the scenarios F-PS-DBP-D$_1$, F-PS-DBP-D$_2$, F-PS-DBP-D$_3$ and F-PS-DBP-D$_4$, the PVAC that provides the greatest power and the lowest relative loss is the TCT configuration followed by the HC PVAC.
- For the fault of a short-circuited bypass diode, in the scenarios F-PS-DBP-SC$_1$, F-PS-DBP-SC$_2$ and F-PS-DBP-SC$_3$, the PVAC that provides the greatest power and the lowest relative loss is the S configuration.
- For the fault of a shorted bypass diode, in the F-PS-DBP-SC$_4$ scenario, the PVAC that provides the greatest power and the lowest relative loss is the SP configuration.
- For the fault of an inverted bypass diode, in the F-PS-DBP-I$_1$ scenario, the PVAC that provides the greatest power and the lowest relative loss is the BL PVAC.
- For the fault of an inverted bypass diode, in the scenarios F-PS-DBP-I$_2$ and F-PS-DBP-I$_3$, the configuration that provides the greatest power and the lowest relative loss is the S PVAC
- For the fault of an inverted bypass diode, in the F-PS-DBP-I$_4$ scenario, the PVAC that provides the greatest power and the lowest relative loss is the HC PVAC.

Table.8
Scenario of a diode bypass fault with PS.

Assignation	**Fault description**
F-PS1	The first module of the first string is partially shaded at 400 W/m^2
F-PS2	The 6 modules of the first string are shaded at 400 W/m^2
F-PS-DBP-D$_1$	The first module of the first string is shaded at 400 W/m^{2}with its bypass diode disconnected
F-PS-DBP-D$_2$	The 6 modules of the first string are shaded at 400 W/m^2 with their diodes disconnected
F-PS-DBP-SC$_1$	The first module of the first string is shaded at 400 W/m^{2}with its bypass diode short-circuited
F-PS-DBP-SC$_2$	The 6 modules of the first string are shaded at 400 W/m^{2}with their bypass diodes short-circuited
F-PS-DBP-I$_1$	The first module of the first string is shaded at 400 W/m^2 with its reversed bypass diode
F-PS-DBP-I$_2$	The 6 modules of the first bypass diode string are shaded at 400 W/m^2 with their bypass diodes inverted
F-PS-DBP-SC$_3$	The first three modules of the first string are shaded at 400 W/m^{2}with their bypass diodes short-circuited, and the last three modules of the same string are shaded at 400 W/m^2 without fault in their bypass diodes
F-PS-DBP-SC$_4$	The first three modules of the first string are shaded at 400 W/m^2 with their bypass diodes shorted-circuited, and the last three modules of the same string are unshaded and faultless in their bypass diodes (without bypass faults and without shading in the three last modules)
F-PS-DBP-D$_3$	The first three modules of the first string are shaded at 400 W/m^{2}with their bypass diodes disconnected, and the last three modules of the same string are shaded at 400 W/m^2 without fault in their bypass diodes
F-PS-DBP-D$_4$	The first three modules of the first string are shaded at 400 W/m^2 with their bypass diodes disconnected, and the last three modules of the same string are unshaded and faultless in their bypass diodes (without bypass faults and without shading in the three last modules)
F-PS-DBP-I$_3$	The first three modules of the first string are shaded at 400 with their bypass inverted, and the last three modules of the same string are shaded at 400 W/m^2 without fault in their bypass diodes
F-PS-DBP-I$_4$	The first three modules of the first string are shaded at 400 W/m^{2}with their bypass diodes inverted, and the last three modules of the same string are unshaded and faultless in their bypass diodes (without bypass faults and without shading in the three last modules)

Table.9
PVACs performance in case of a diode bypass fault with PS.

Faults	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-PS1	**3432**	4.6666	3211	10.8055	3121	13.3055	3059	15.0277	3012	16.3333
F-PS2	1672	53.5555	2936	18.4444	**3121**	13.3055	3059	15.0277	3012	16.3333
F-PS-DBP-D$_1$	694.7	80.7027	688.1	80.8861	**697.8**	80.6166	694.1	80.7194	688.1	80.8861
F-PS-DBP-D$_2$	694.7	80.7027	688.1	80.8861	**697.8**	80.6166	694.1	80.7194	688.1	80.8861
F-PS-DBP-SC$_1$	**3436**	4.5555	3224	10.4444	2856	20.6666	2942	18.2777	3018	16.33
F-PS-DBP-SC$_2$	**684.1**	80.9972	0	100	0	100	0	100	0	100
F-PS-DBP-I$_1$	1672	53.5555	2936	18.4444	2874	20.1666	2960	17.7777	**3012**	16.3333
F-PS-DBP-I$_2$	**684.7**	80.9805	1.989	99.9447	1.991	99.9446	1.998	99.9445	1.989	99.9447
F-PS-DBP-SC$_3$	**688.3**	80.8805	678.7	81.1472	653	81.8611	675.1	81.2472	666.5	81.4861
F-PS-DBP-SC$_4$	694.2	80.7166	**1053**	70.75	979.4	72.7944	1035	71.25	1024	71.555
F-PS-DBP-D$_3$	693.2	80.7444	688.1	80.8861	**697.8**	80.6166	694.1	80.7194	688.1	80.8861
F-PS-DBP-D$_4$	698.8	80.5888	701.8	80.5555	**1218**	66.1666	993.8	72.3944	717.3	80.075
F-PS-DBP-I$_3$	**688.5**	80.875	679.6	81.1222	655.9	81.7805	676.2	81.2166	668.6	81.4277
F-PS-DBP-I$_4$	694.5	80.7083	701.8	80.5055	969.7	73.0638	**989.6**	72.5111	717.3	80.075

C. Short-circuit fault with and without PS

Complex partial shading scenario which is illustrated in Table 10 is used to evaluate short-circuit fault under complex PS conditions.Table11 shows the short-circuit fault with and without PS.

The comparison of the performance of the different PVACs in the case of short-circuits failure with and without PS is shown in Table 12:

- In all the scenarios of short-circuited modules with PS, the S PVAC presents the best performance in terms of power and losses (i.e. the highest power and the lowest loss) and it is followed by the SP PVAC which comes in second position.
- In this default scenario, the S PVAC is the best configuration as it offers the highest performance in terms of maximum power and losses, followed by the SP PVAC.

Table.10

Complex PS scenario.

	String 1	String 2	String 3	String 4
Row 1	1000 W/m^2	1000 W/m^2	500 W/m^2	1000 W/m^2
Row 2	300 W/m^2	1000 W/m^2	600 W/m^2	1000 W/m^2
Row 3	400 W/m^2	300 W/m^2	1000 W/m^2	1000 W/m^2
Row 4	1000 W/m^2	200 W/m^2	800 W/m^2	200 W/m^2
Row 5	600 W/m^2	500 W/m^2	1000 W/m^2	1000 W/m^2
Row 6	200 W/m^2	200 W/m^2	1000 W/m^2	400 W/m^2

Table.11

Scenario of a short-circuit fault with and without PS.

Assignation	**Fault description**
F-SC1	The first module of the first string is short-circuited but without shading
F-PS-SC1	The first module of the 1st string is short-circuited without shade and the 1st module of the last string is shaded at 400 W/m^2 but without fault in the bypass diode
F-SC2	The first four modules of the last string are short-circuited
F-PS-SC2	The first four modules of the last string are short-circuited and shaded at 200 W/m^2, 300 W/m^2, 400 and W/m^2 500 W/m^{2}respectively
F-PS-SC3	The first four modules of the last string are short-circuited and shaded at 200 W/m^2, 300 W/m^2, 400 and W/m^2 500 W/m^{2}respectively + The first four modules of the third string are shaded at 200 W/m^2, 300 W/m^2, 400 W/m^{2}and 500 W/m^2 respectively
F-PS-SC4	The first four modules of the last string are short-circuited without shading + The first four modules of the third string are shaded at 200 W/m^2, 300 W/m^2, 400 W/m^{2}and 500 W/m^2 respectively
F-CPS-WSC	Shading scenario of table10 without short-circuit fault.
F-CPS-SC	Shading scenario of table10 + The first four modules of the last string are short-circuited

Table.12

PVACs performance in cases of a short-circuit fault with and without PS.

SC Faults	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-SC1	**3436**	4.5555	3224	10.4444	2856	20.6666	2942	18.2777	3018	16.1666
F-PS-SC1	**3248**	9.7777	3038	15.6111	2856	20.6666	2847	20.9166	2894	19.6111
F-SC2	**2847**	20.9166	821.8	77.1722	573.7	84.0638	663.1	81.5805	637.4	82.2944
F-PS-SC2	**2847**	20.9166	821.8	77.1722	573.7	84.0638	663.1	81.5805	637.4	82.2944
F-PS-SC3	**1973**	45.1944	758.1	78.9416	573.7	84.0638	662.6	81.5944	637.1	82.3027
F-PS-SC4	**1973**	45.1944	758.1	78.9416	573.7	84.0638	662.6	81.5944	637.1	82.3027
F-CPS-WSC	1452	59.6666	1551	56.9166	1716	52.3333	1707	52.5833	**1731**	51.9166
F-CPS-SC	**1085**	69.8611	690.3	80.825	508.5	85.875	535.1	85.1361	527.9	85.3361

D. Degradation fault

D.1. Degradation faults without PS

Table 13 shows the degradation fault. The comparison of the performance of the different PVACs in the case of degradation failure is shown in Table 14.

D.2. Degradation faults with partial shading

In this fault scenario, the S configuration is the most efficient PVAC as it offers the highest performance, followed by the SP configuration.

Table 15 shows the degradation faults with partial shading. The comparison of the performance of the different PVACs in the case of a degradation fault with PS is shown in Table 16.

E. Ground faults

Table 17 shows the ground fault. The comparison of the performance of the different PVACs in the case of a ground fault is shown in Table 18.

Table.13

Scenario of a degradation fault without PS.

Assignation	**Fault description**
F-DEG-1	This fault is represented by a resistance of 2 ohms between the first and second modules of the first string
F-DEG-2	This fault is represented by a resistance of 2 ohms between the first and second modules of the first string and a resistance of 6 ohms between the second and third modules of the second string

Table.14

PVACs performance in case of a degradation fault without PS.

Degradation fault	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-DEG-1	**3561**	1.0833	3555	1.25	3531	1.9166	3538	1.7222	3545	1.5277
F-DEG-2	**3441**	4.4166	3403	5.4722	3350	6.9444	3375	6.25	3353	6.8611

Table.15

Scenario of a degradation fault with PS.

Assignation	**Fault description**
F-DEG-PS1	Degradation fault in the first string (resistance of 2 ohms between the first and second modules) + the first two modules of the first string are shaded at 500 W/m^2 and 500 W/m^2 respectively
F-DEG-PS2	Degradation fault in the first string (2 ohms between the first and second modules) + the first string is not shaded + the first two modules of the second string are shaded at 500 W/m^{2}and 500 W/m^2 respectively
F-DEG-PS3	Degradation fault in the first string (2 ohms between the first and the second module) + The first two modules of the first string and also the second first modules of the second string are shaded at 500 W/m^2 and 500 W/m^2
F-WDEG-PS	The first two modules of the first string and also the second first modules of the second string are shaded at 500 W/m^{2}and 500W/m^2 respectively without defect of degradation

Table.16

PVACs performance in case of a degradation fault with PS.

Degradation fault	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-DEG-PS1	**3200**	11.1111	3051	15.25	3165	12.0833	3073	14.6388	3137	12.8611
F-DEG-PS2	**3200**	11.1111	3030	15.8333	3148	12.5555	3110	13.6111	3127	13.1388
F-DEG-PS3	**2785**	22.6388	2362	34.3888	2445	32.0833	2420	32.7777	2402	33.2777
F-WDEG-PS	**2829**	21.4166	2365	34.3055	2447	32.0277	2423	32.6944	2405	33.1944

Table.17

Scenario of a ground fault.

Assignation	**Fault description**
F-GRD-1	This fault is located between the first and the second module of the first string and also between the second and the third module of the second string

Table18.

PVACs performance in case of a ground fault.

Ground faults	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-GRD-1	2634	26.8333	**3237**	10.0833	2856	20.6666	2986	17.0555	3018	16.1666

F. Line to line fault

Table19 shows the line-to-line fault.The comparison of the performance of the different PVACs in the case of a line-to-line fault is shown in Table 20.

In this fault scenario, the SP PVAC is the best configuration because it offers the highest power and is followed by the BL PVAC.

G. Open circuit fault

F-OPC:The fifth module of the third string is disconnected.
The series configuration is poorly suited to this type of fault, the TCT and HC PVACs provide the highest powers with lower losses

H. Multiple faults

Table 21 shows the cases of multiple faults.The comparison of the performance of the different PVACs in the case of multiple faultsis shown in Table 22.

- In the case of multiple faults (scenario F-MLP$_1$, F-MLP$_2$ and F-MLP$_3$), we notice that it is the SP PVAC which presents the best performance.

- In the case of multiple faults (scenario F-MLP$_4$ and F-MLP$_5$), we notice that it is the configuration S that presents the best performance.

Table.19

Scenario of a line-to-line fault.

Assignation	**Fault description**
F-LL-1	In this fault, the wire is connected between the first and second modules of the first string and also between the second and third modules of the second string

Table.20

PVACs performance in case of a line-to-line fault.

Line to line fault	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-LL-1	2634	26.8333	**3237**	10.0833	2856	20.6666	2986	17.0555	**3018**	16.1666

Table.21

Scenario of multiple faults.

Assignation	**Fault description**
F-MLP1	The last three modules of the third string are shaded at 300 W/m^2. The last three modules of the fourth string are shaded at 300 W/m^2 + the first three modules of the third string are shorted and the first three modules of the fourth string are shorted
F-MLP2	The last three modules of the 3rd string are shaded at 300 W/m^2 and the last three modules also of the fourth string are shaded at 300 W/m^2 + the first three modules of the third string and the first three modules of the fourth string are short-circuited + line to ground fault in the first string between the first and second modules and in the second string between the 2nd and third modules)
F-MLP3	The last three modules of the 3rd string are shaded at 300 W/m^2 and the last three modules also of the fourth string are shaded at 300 W/m^2 + the first three modules of the third string and the first three modules of the fourth string are short-circuited + a resistance of 6 ohms between the first and second modules of the first string
F-MLP4	The last three modules of the 3rd string are shaded at (100 W/m^2,200 W/m^{2}and 300 W/m^2) respectively and the last three modules of the fourth string are shaded at (400 W/m^2,500 W/m^{2}and 600 W/m^2) respectively + short circuit in the first three modules of the third and fourth string + a resistor of 6ohms between the 1st and 2nd modules of the first string
F-MLP5	The first four modules of the last string are short-circuited without shadowing + The first four modules of the third string are shadowing at 200 W/m^2, 300 W/m^2, 400 W/m^{2}and 500 W/m^{2}respectively + degradation fault (represented by an ohm resistance of 6 in the last string between 5th and 6th modules)

Table.22

PVACs performance in cases of multiple faults.

Combined faults	S		SP		TCT		HC		BL	
	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)	P(W)	ΔP_L (%)
F-MLP1	1186	67.0555	**1223**	66.0277	1039	71.1388	1087	69.8055	1086	69.8333
F-MLP2	430.3	88.0422	**1223**	66.0277	1039	71.1388	1087	69.8055	1086	69.8333
F-MLP3	1121	68.8611	**1221**	66.0833	1039	71.1388	1087	69.8055	1086	69.8333
F-MLP4	**1279**	64.4722	1233	65.75	1077	70.0833	1092	69.6666	1094	69.6111
F-MLP5	**1955**	45.6944	987.4	72.5722	560.8	84.4222	671.9	81.3361	638.8	82.2555

VI. RESULTS AND DISCUSSION

In this study, a thorough comparative analysis of faults and their impact on the efficiency of various PV interconnection schemes, including S, SP, HC, BL, and TCT are presented.

- The TCT and HC PVACs can improve power generation in open circuit faults. Thus, in the presence of PS and without any other faults, the TCTconnection is considered the most optimal PVAC and shows the best performance.
- In case of fault, the S PVAC presents the best performance and the SP PVAC comes in second in terms of performance. Except for a few certain situations where the results change.
- The TCT PVAC which presented the best performance in the majority of cases of shading, suffered from serious performance degradation.
- Under multiple faults, SP and S PVACs outperform other interconnections, but the SPPVAC is the most adequate.
- The performance of some PVACs under faulty conditions with the presence of PS may change in some situations compared to faults without PS.
- The performance of the various PVACs varies depending on the scenario used, i.e. the power generated varies depending on the location of the fault, the type of fault, whether the fault occurs with PS, or without PS.

VII. CONCLUSION

This paper provides a comprehensive examination of the impact of faults on the performance of various PVACs such as S, SP, HC, BL and TCT.

The performance of each PVACwas assessed under typical fault conditions such as partial shading, open-circuit, degradation, short circuit, bypass diode failure, line to line and line to ground.A case of multiple faults in a PV array under uniform irradiance and PS is also investigated to evaluate their impact on the various PV interconnections considered.The different PVACs have been tested and analyzed under several fault scenarios in order to identify the most resilient PVACunder fault conditions, allowing for improvements in system performance by optimizing the power of the appropriatePVAC.

This study helps in selecting the PVACthat is the least sensitive to the various faults, thereby improving power generation.

In future work, we recommend practical verification of these PVACs under fault conditions and the investigation of additional fault types.

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