Bond Graph Model for Fault Detection of Partial Shaded PV Array Considering Different Module Connection Schemes and Effects of Bypass Diodes

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ABSTRACT

Fault detection in solar photovoltaic (PV) arrays is a fundamental task to protect PV modules from damage and to eliminate risks of safety hazards. In this work, we show a new methodology for automatic supervision and fault detection of PV Systems, based mainly on optimal placement of sensors. This supposes the possibility to build a dynamic model of the system by using the bond graph tool, and the existence of a degradation model in order to predict its future health state. The choice of bond graph is motivated by the fact that it is well suited for modeling physical systems where several types of energies are involved. Fault behavior of PV arrays is highly related to the fault location, fault impedance, irradiance level, and use of blocking diodes. In this work, PV array is connected using series parallel (SP) and Total Cross Tied (TCT) configurations including sensors to measure voltage and currents. The simulation results show the importance of the approach applied for the detection and diagnosis of fault in PV system. These results have been contrasted with real measured data from a measurement campaign plant carried on electrical engineering laboratory of Grenoble using various interconnection schemes are presented.

I. Introduction

Sustainability and development of new energy resources are one of the important issues globally. It is due to the rise in world oil prices, the protocol that each country is encouraged to increase alternative sources of energy and the demand of ever-increasing energy needs [1].

The electric energy consumption is one of the most essential parts of life which is continuously increasing [1]. The increasing of consumption cannot be stopped completely, so the generation of electrical energy is increased depend on value of consumption [2]. As another solution, the total consumption can be reduced by increasing the efficiency of systems. Furthermore, the renewable energy should be used to meet demand of electric energy [3].

Some experiences have been carried out trying to introduce remote monitoring and fault detection in PV systems [4] - [5]. These experiences use climate data from satellites observation. From these data, and with the complete information of the PV system design, is possible the calculation of the expected system's energy yield. Finally, the fault analysis is based in the comparison of predicted yields with the real measured ones in the monitoring process. The calculated system's energy yields have not the same accuracy than yields calculated from real monitored data; values of RMSE about 10 % have been reported for irradiance estimated using these methods [6]. Other authors have developed new simulation tools for the diagnostic and fault detection of PV systems. Most of these approaches are not based on the use standard software tools and are just been focused in the detection of determinates incidences [7]. Although the real-time simulation technique of the PV system has been developed in [8], it is still difficult to analyze the features of the PV system within the same atmosphere condition. Moreover, these techniques utilize an expensive solar simulator and their flexibilities are limited due to the construction of hardware. Numerous researchers have been trying to developed equate simulation model by the simulation platforms for instance SPICE [9], SABER [10], and EMTP [11]. However, the combination of the PV system with varied series and parallel topology by using these simulation models cannot reveal the characteristics of the PV system. The simulated time is also an obstacle with these software platforms. Although the rate of calculation can be speeded up with the traditional mathematic model [12], the electrical behavior of the PV system still cannot be shown significantly. Furthermore, there are some simulation models being constructed with Neural Networks [13], Fuzzy [14] and Neural Fuzzy [15] algorithms for improving the simulated performance of the PV system, but an accurate model and expansibility of the PV system is still difficult to achieve.

Non ideal conditions refer to some specific situations where solar cells reach their limits and cannot provide specified power. The problem, which is referred to in some literatures as non optimal conditions or unbalanced generations has drawn recent attention [16] - [17]. Common non ideal conditions include partial shading, low solar radiation, dust collection, and photovoltaic ageing.

Generally, it is preferable to build a solar array using all the same panels and to keep them away from any shading. However, it is not easy to avoid shading in residential installations because of the change in sunlight direction throughout the day. Furthermore, obstacles, such as trees, birds, and other constructions, etc., can cause partial shading. Studies [18] have revealed that min or shading can cause a major reduction in solar power output of the photovoltaic array. Prior experiments have been conducted investigating the effect of shade on various PV systems, many of which were cited in a comprehensive literature review by Woyte et al. [19] Other recent works include simulations of partially shaded PV cells [20] - [21] experimental results of different maximum power point tracking algorithms under shaded conditions [22] and the effect of shade on PV system performance [23] - [24].

II. Bond Graph Modeling

A bond graph is a labeled and directed graphical representation of a physical system. The basis of bond graph modeling is power/energy flow in a system. As energy or power flow is the underlying principle for bond graph modeling, there is seam less integration across multiple domains. As a consequence, different domains (such as electrical, thermal.) can be represented in a unified way. The power or the energy flow is represented by a half arrow, which is called the power bond or the energy bond [25] - [26]. One of the advantages of bond graph method is that models of various systems belonging to different engineering domains can be expressed using a set of only nine elements: inertial elements (I), capacitive elements (C), resistive elements (R), effort sources (Se) and flow sources (Sf), transformer elements (TF), gyrator elements (GY), 0–junctions (J0) and1–junctions (J1). I, C and R elements are passive elements because they convert the supplied energy into stored or dissipated energy. Se and Sf elements are active elements because they supply power to the system and TF, GY, 0 and 1 are junction elements that serve to connect I, C, R, Se and Sf, and constitute the junction structure of the bond graph model.

From the FDI point of view, the causal properties of bond graph models are used to determine the origin of a fault. In the BG diagnosis, it is important to have a bond graph model that includes all the parameters that are related to the faults under analysis.

III. Modeling of PV Panel

Photovoltaic panels are more still widespread source of electricity. For the purposes of computer simulations, it is useful to have an accurate model [27].

Many papers on the topic of modeling of the PV panels were published. Many, however, deal only with the basic photovoltaic cells [28] - [29] - [30]. The course of i = f (v) cell characteristic is usually approximated by Shockley's equation. This equation is able to model the ideal cell behavior sufficiently.

III.1. Photovoltaic Generator Model

The solar cell is basically a p-n junction diode, and its traditional equivalent circuit may express itself similar to what is shown in fig.1.

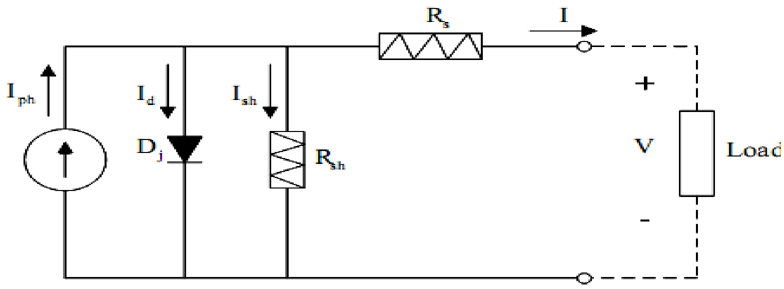


Figure 2. Solar-cell equivalent circuit

According to the physical property of p-n semiconductor, the V-I characteristics of PV module could be expressed as equation (1) [31] - [32].

$$I(1+R_s / R_{sh}) = -n_p I_{sat}\left[exp\left\{\left(\frac{q}{AkT}\right)\left(\frac{V}{n_s}+IR_s\right)\right\}-1\right]+n_p I_{ph}-\frac{(V-n_s)}{R_{sh}} \qquad (1)$$

In addition, the module reverses saturation current Isat shown in equation (2) is varied with temperature T.

$$I_{sat} = I_{rr}\left(\frac{T}{T_r}\right)^3 exp\left\{\left(\frac{qE_{gap}}{kA}\right)\left(\frac{1}{T_r}-\frac{1}{T}\right)\right\} \qquad (2)$$

The I_{ph} expressed in equation (3) represents the photocurrent proportionally produced to the level of cell surface temperature and radiation.

$$I_{ph} = \{I_{sso} + k_i(T - T_r)\}\frac{S_i}{100} \qquad (3)$$

For the bond graph representation, the PV generator is then modeled by a flow source Sf = I_{ph} in parallel with two resistors R_{diode} and R_{sh}, the whole followed by a serial resistance R_s. The diode element is labeled R_{diode}, it produces a non-linear current that is essentially exponential in nature:

$$J_{Rd} = J_s\left[exp\left(\frac{qV}{kT}\right)-1\right]. \qquad (4)$$

The regular diode is non-linear resistor, as its constitutive equation relates voltage across and current through the diode to each other, an effort flow relationship in bond graph terminology.

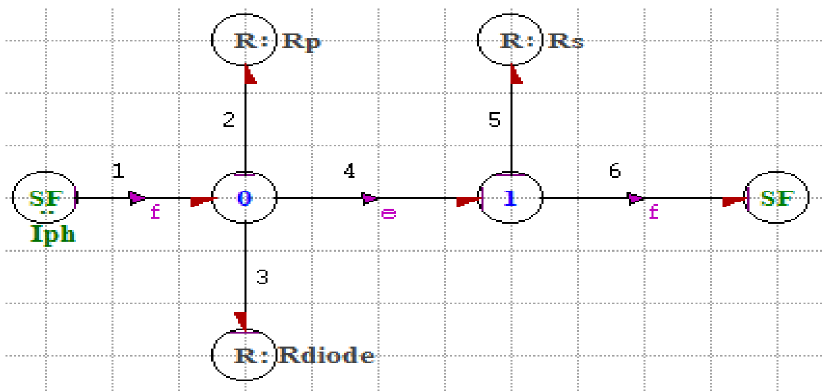


Figure 3. Bond graph model of PV

III.2. Alternative topologies for PV arrays

Mismatch losses are almost always present in photovoltaic arrays, be it in PV modules or PV plants, simply because electrical characteristics in photovoltaic devices are not identical for each element of the array. The difference between the output power of the array and the sum of the output powers of its elements represent the amount of losses by element mismatch, better known as mismatch losses [33].

Previous research on modifying PV array interconnections of cells in PV modules [34] - [35] has shown promising simulation results of alternative cell interconnection schemes which reduced from 18% to 7% the amount of power lost in a module of 36 cells due to partial shadowing. In this paper, the alternative topologies will be used on an array of PV modules.

Figure (3) and figure (4) represents the bond graphs models of the PV installation in SP and TCT configurations respectively.

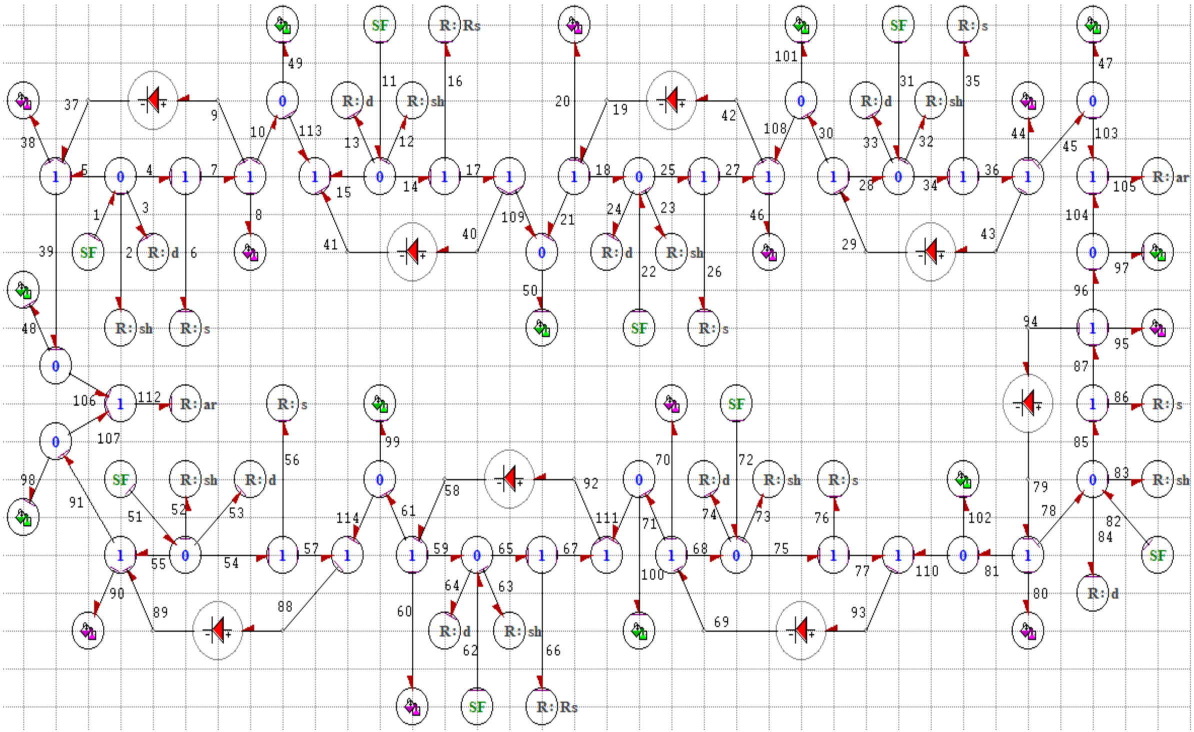


Figure 3. Bond graph model of PV installation SP

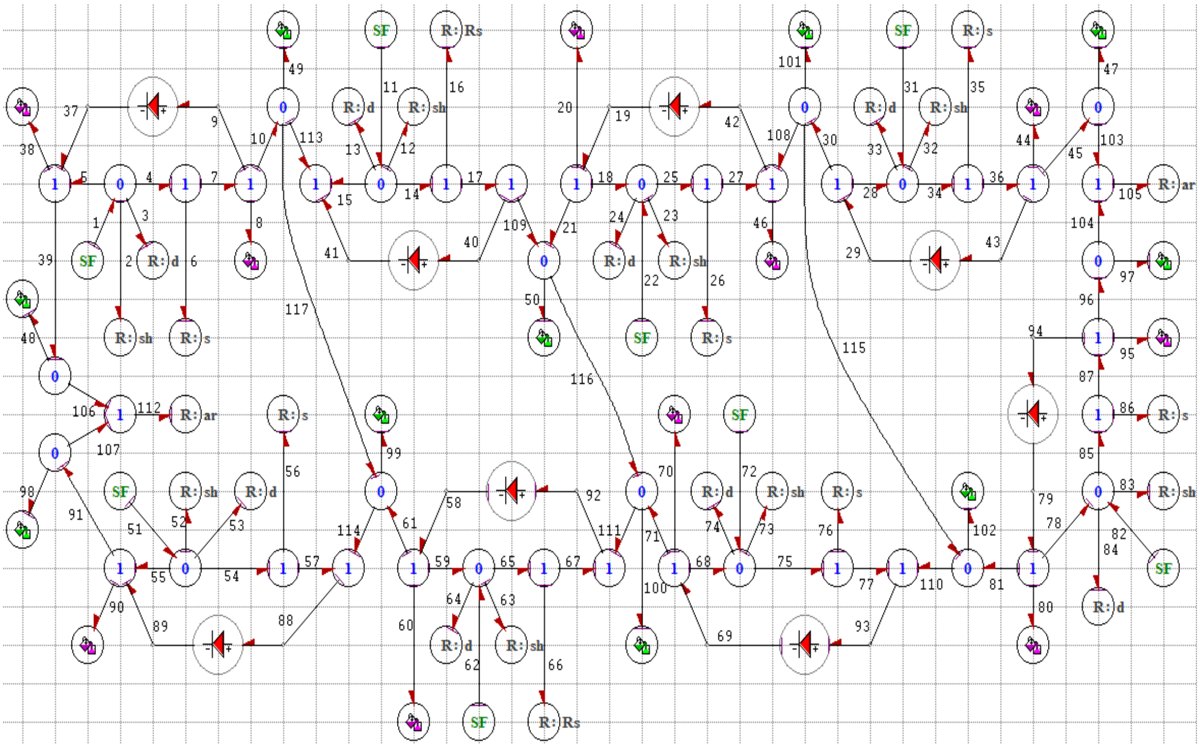


Figure 4. Bond graph model of PV installation TCT.

IV. Simulation Results

Modeling is to build the bond graph model into the software. In our case we have chosen the SYMBOLS that is powerful for research. SYMBOLS is object oriented hierarchical hybrid modeling, simulation and control analysis software. It allows users to create models using bond graph, block-diagram and equation models. Differential causalities and algebraic loops are solved out using its powerful symbolic solution engine. This software can also make out the fault detection and isolation matrix, to model a system of oversight on this program we must construct capsules that contain the various components of the system, therefore a capsule is the bond graph of each part of the system that assigns a representative icon. These capsules are connected with sensors that are coupled to junctions. In SYMBOLS we have only capsules of process engineering, hence the need to build our own capsule to our system. In this section, we will give the results obtained from the developed method.

IV.1. Influence of the Shadows and the Effect of Bypass Diodes

The PV characteristic curve of a photovoltaic module is affected by shadows, depending on the shaded area of the PV module, and the radiation received by the shaded areas. Another factor in the shape of the I-V curve of a PV module, is the configuration of the electrical connection between its cells and bypass diodes. Bypass diodes are installed in the modules to prevent power consumption when they are shaded or damaged; they also prevent cells from working near the avalanche zone. There exist many papers containing the analysis of the behavior of the photovoltaic PV cells under partial shadowing [36] - [37], taking into account the diode. But there are only a few that actually take into account the importance of the diodes configuration [38].

This section examines the performance of a photovoltaic array. A PV array consists of modules connected between them. Particularly, the configuration with bypass diodes overlapped is analyzed, showing that totally or partially shaded modules can consume some of the power generated by other modules of the PV array. This effect is also present in low power PV arrays. In these cases, the power dissipated by a diode is small; but if there are many diodes, the power dissipated by all the diodes can be comparable with the power produced by various PV modules.

Several profile of shading has been performed on the test module using two different systems configuration, SP and TCT. The shading effect was artificially generated by covering parts of the module with plastic film which reduces the incoming solar radiation by approximately (40%).

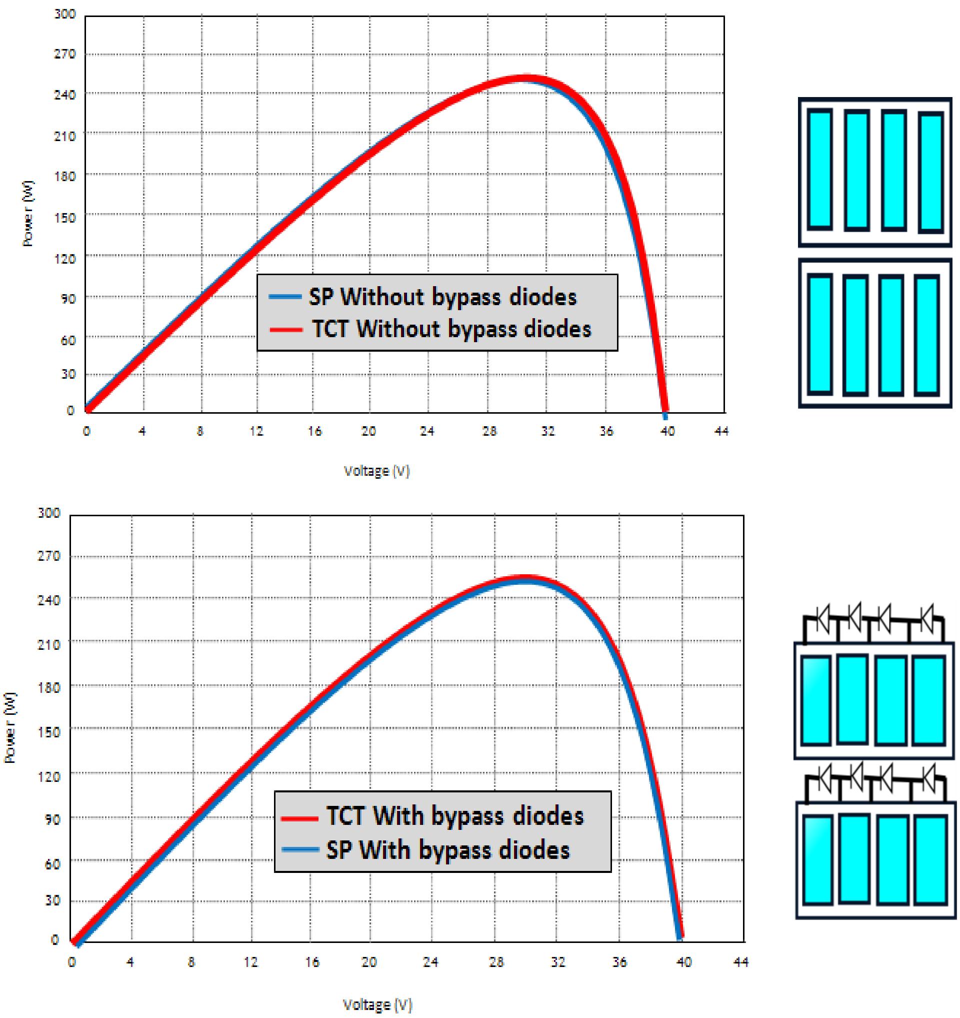


Figure 5. P-V without shading

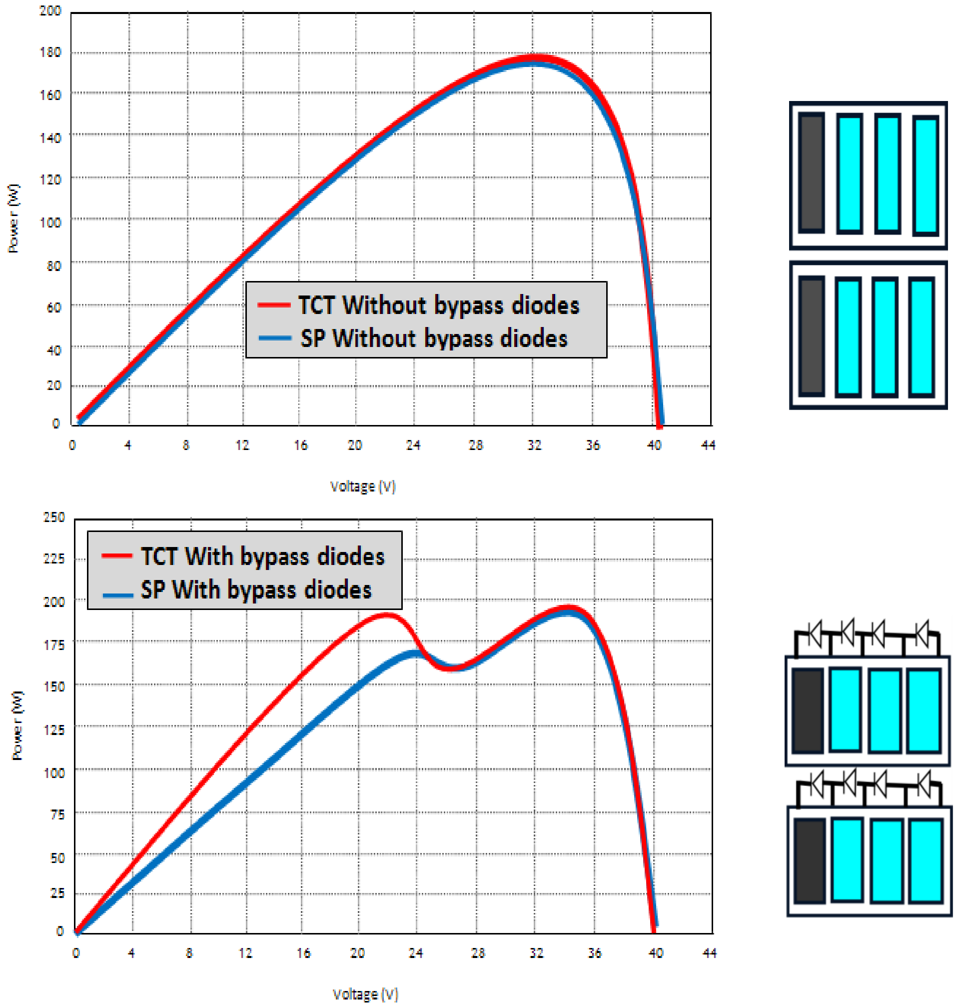
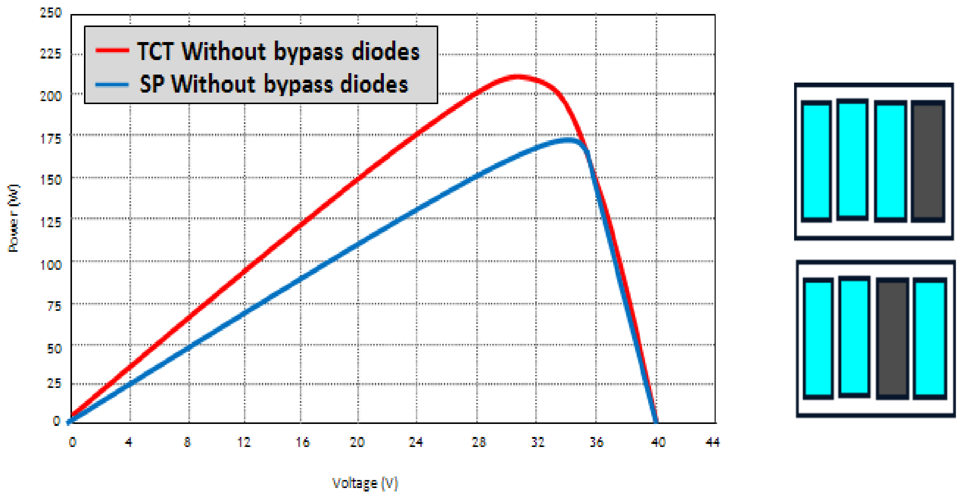


Figure 6. P-V with shading (10001000)



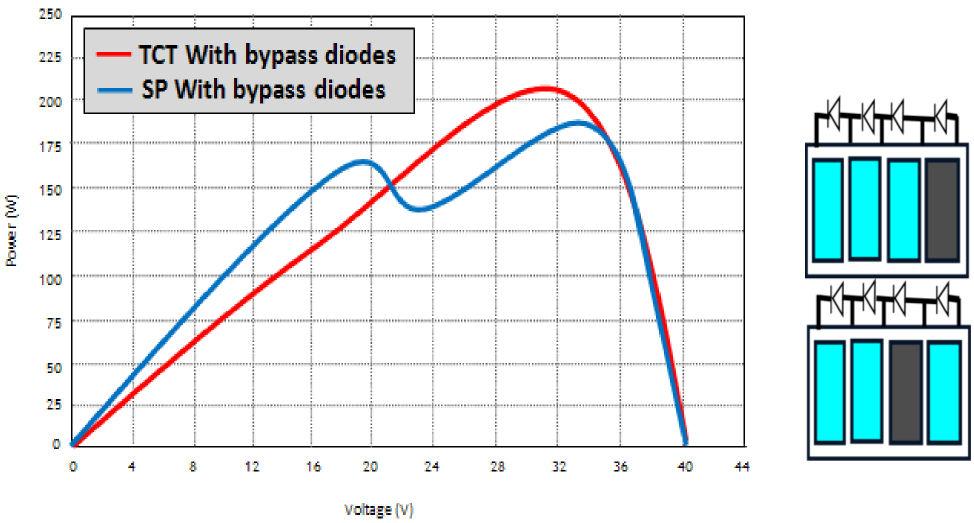


Figure 7. P-V with shading (00010010).

V. Experimental measurements

To validate the bond graph and its ability to detect defaults in the PV system, a series of measurements will be compared with simulations using the proposed model. This section introduces the measurement setups and their respective simulations parameters.

V.1. Measuring equipment

The measuring bench is composed of three elements: the PV module, the bypass diodes, the connection platform and the I-V Tracer. They are all represented in fig. 8.

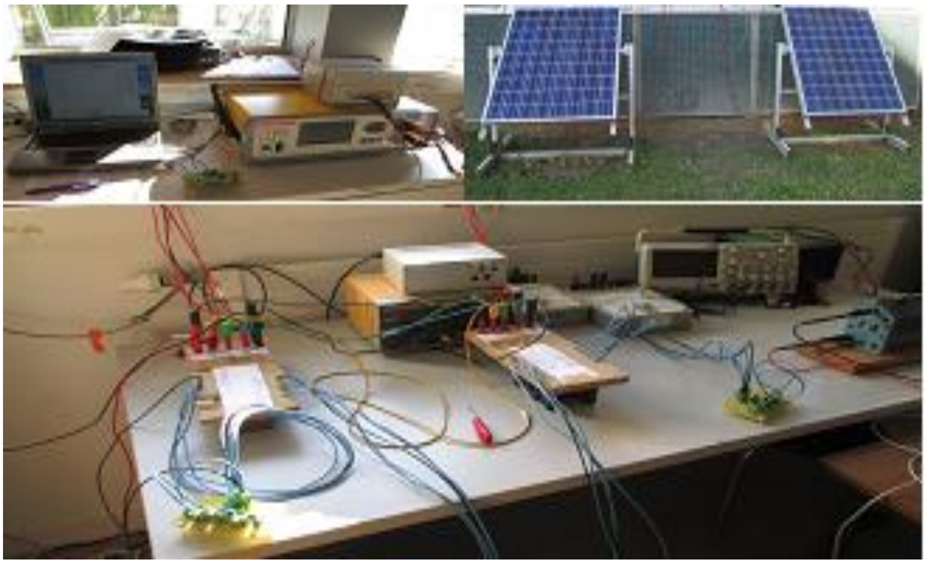


Figure 8. The experimental benchmark

The I-V Tracer is a PVPM 1000C40, whose measured curves have 100 points and are traced in a few milliseconds. The PV module is a photowatt PW1650. Its parameters are described in table I.

TABLE I. THE parameters of the PV module

Parameters	Value and units
Maximum power Pmax	165W
Current peak power Imp	4.8 A
Voltage peak power Vmp	34.4 V
Short circuit current Isc	5.1 A
Open circuit voltage Voc	43.2 V
Bypass diodes	4
Number of cells per module	72

Two modules were specially equipped for this study. Their junction box was opened, their diodes unsoldered and replaced by cables.

V.2. Effect of Bypass Diodes (faultless operation)

This section gives the comparison between mean value of the power for several configurations without bypass diodes and with bypass diodes (four bypasses per module) for shading patterns.

This study can be extended to select the optimum number of diodes used in a module to get the maximum power under partial shaded conditions. If the number of bypass diodes used in a module is increased or in other words the number of cells grouped is minimized, the maximum output can be obtained

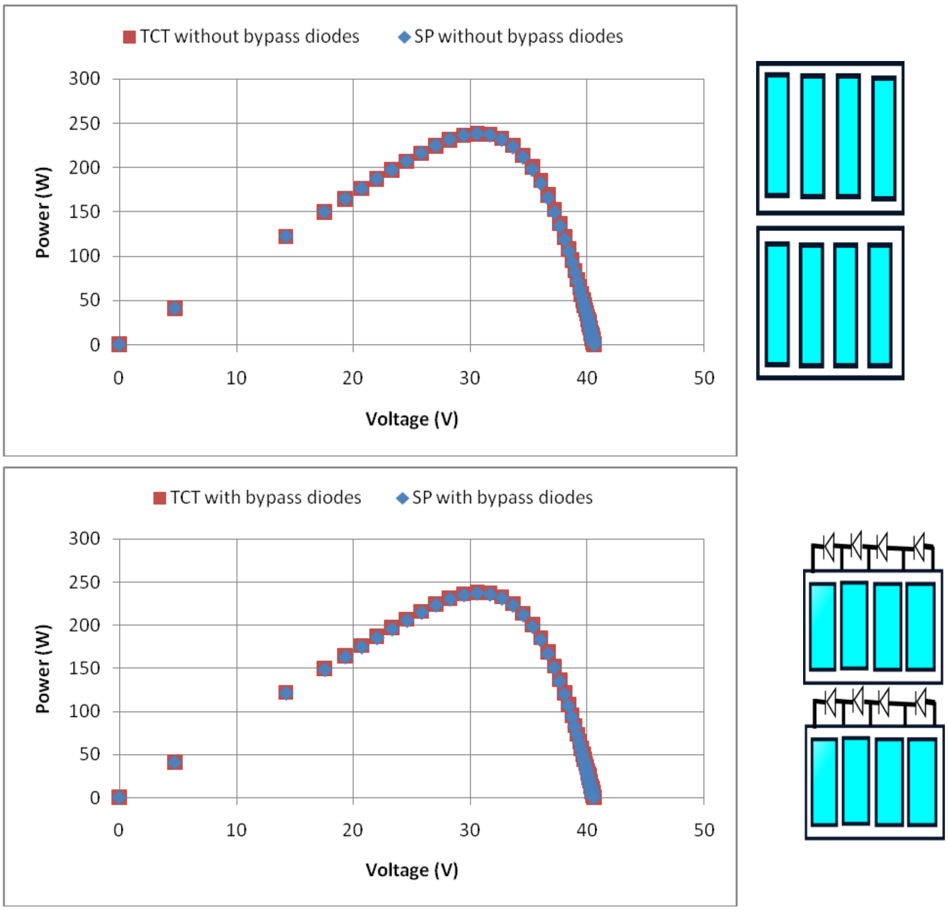


Figure 9. P-V without shading

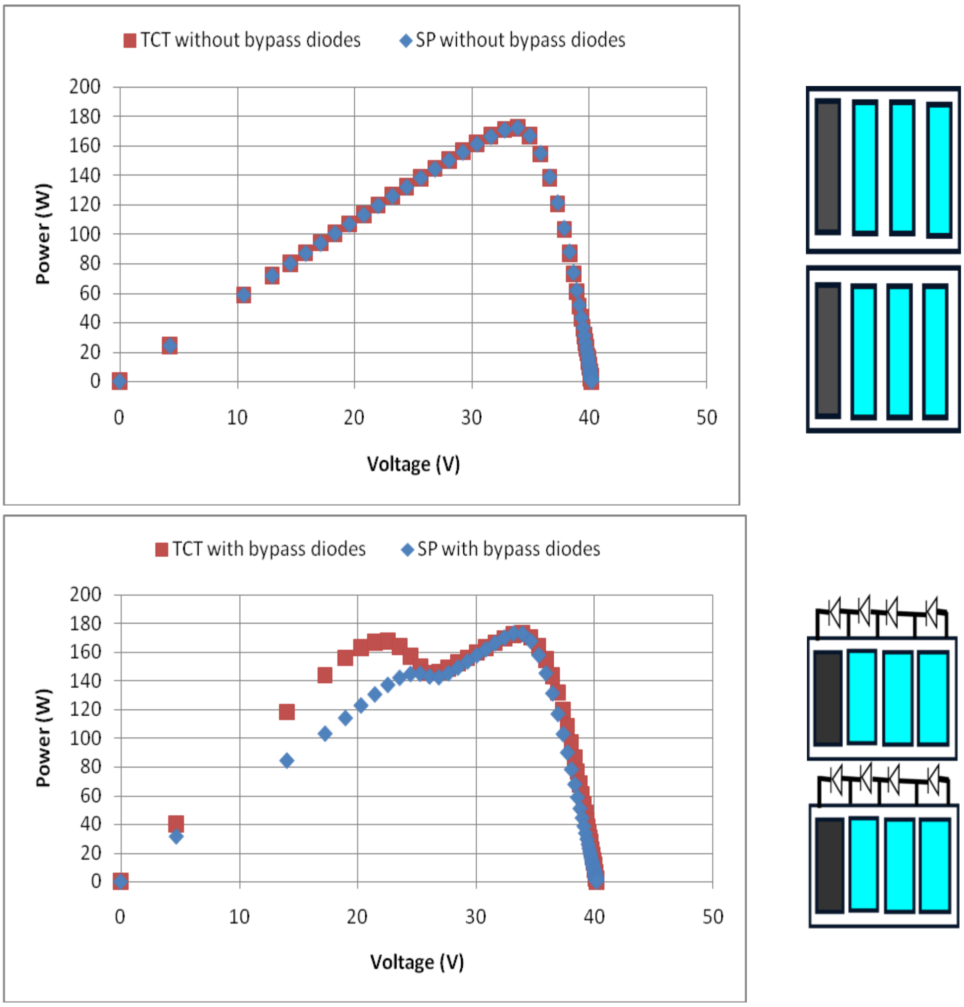
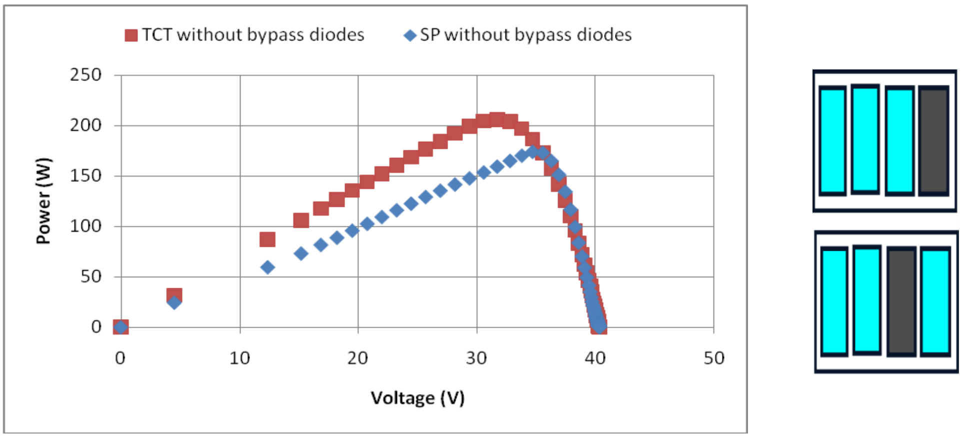


Figure 10. P-V with shading (10001000)



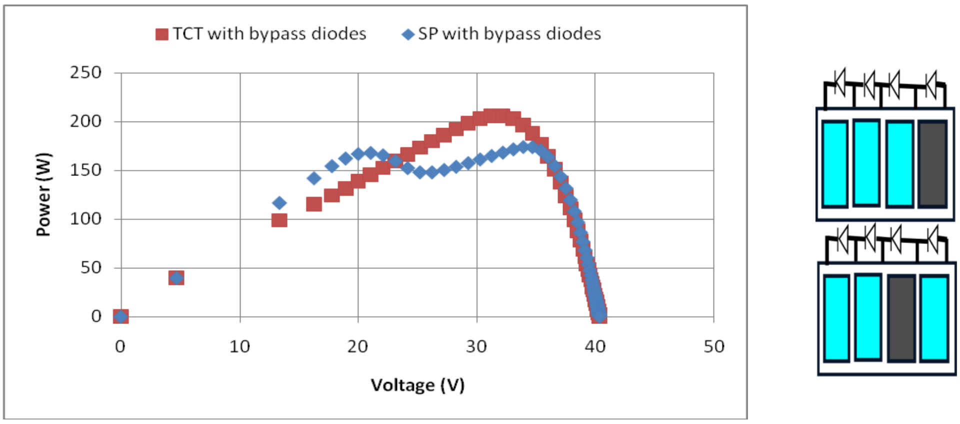


Figure 11. P-V with shading (00010010)

V.3. Shadow and diagnosis identification code

In order to easily reference any shadow without or with bypass diodes and in order to easily reference any fault of bypass diodes (open circuit or short circuit) an identification code is proposed. Fig. 12 shows an example of three shadows and their associated ID codes.

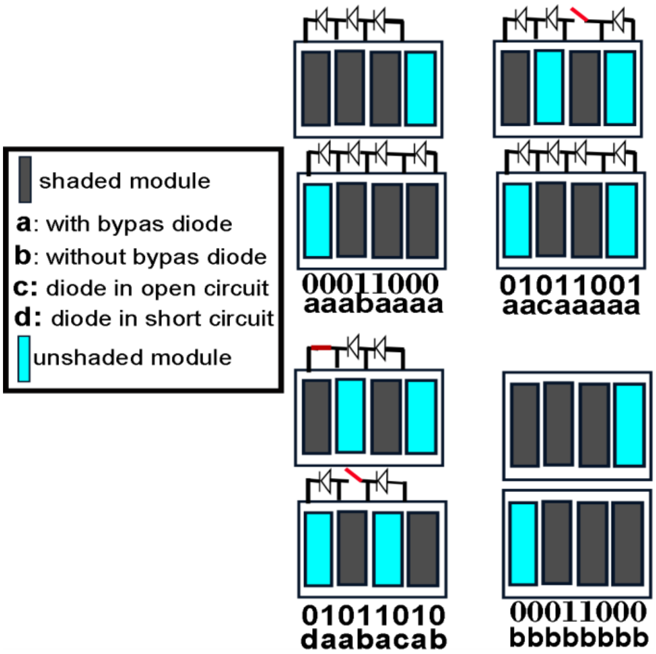
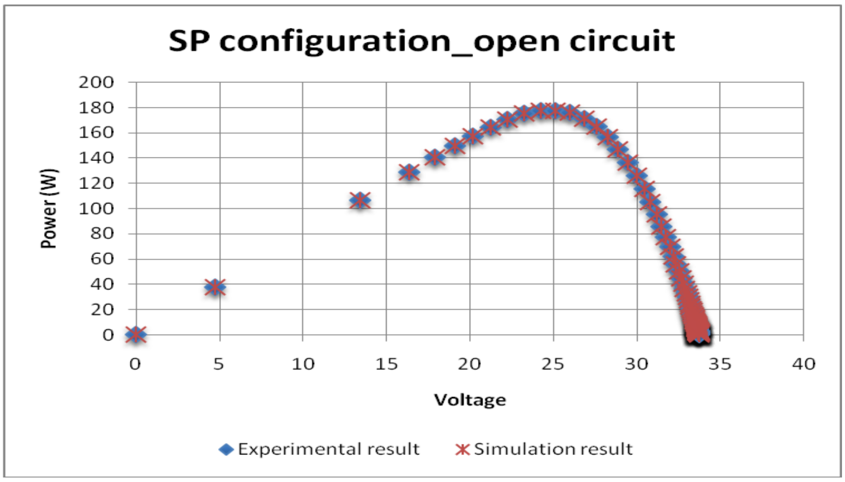
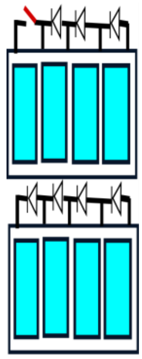


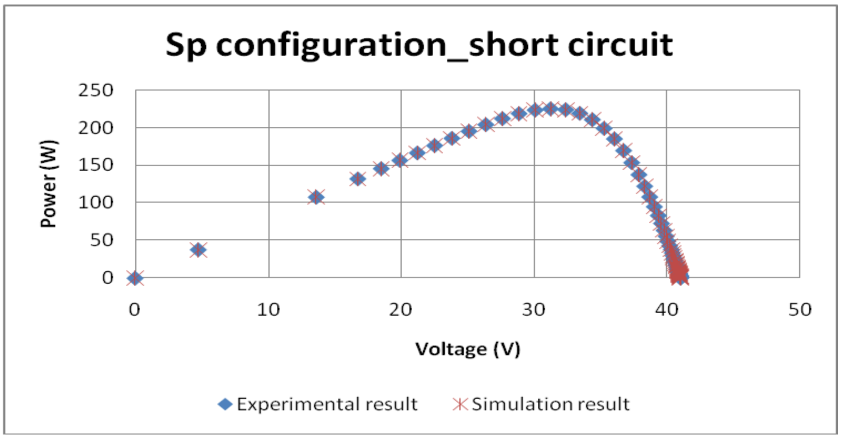
Figure 12. Four different shadows with/without bypass diodes and diagnosis with their respective shadow ID codes

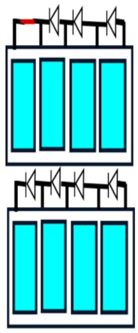
V.4. Effect of Bypass Diodes (operation with defects)

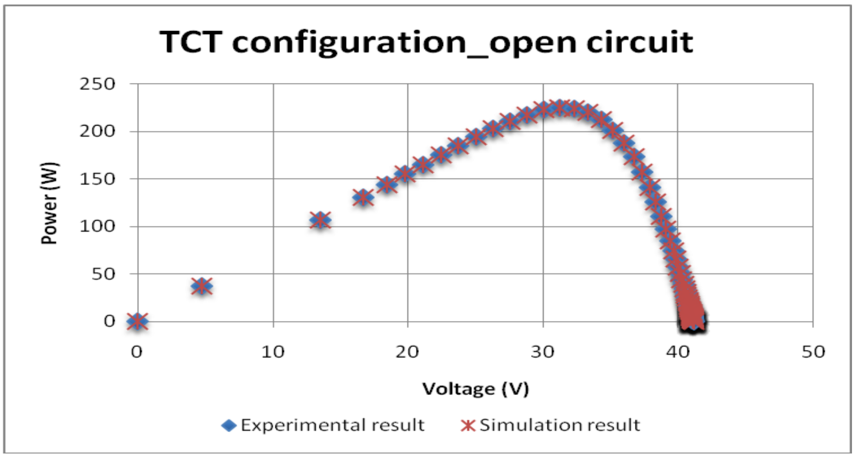
In this case, a fault is introduced in the different bypass diodes during the simulation. This fault is due to open circuit or short circuit on the bypass diode which results in many local maximum power points.

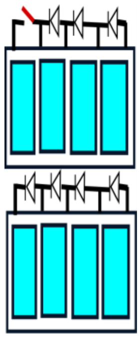

SP configuration_open circuit
Power (W)
200
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
Voltage
Experimental result
Simulation result




Sp configuration_short circuit
Power (W)
250
200
150
100
50
0
0
10
20
30
40
50
Voltage (V)
Experimental result
Simulation result




TCT configuration_open circuit
Power (W)
250
200
150
100
50
0
0
10
20
30
40
50
Voltage (V)
Experimental result
Simulation result



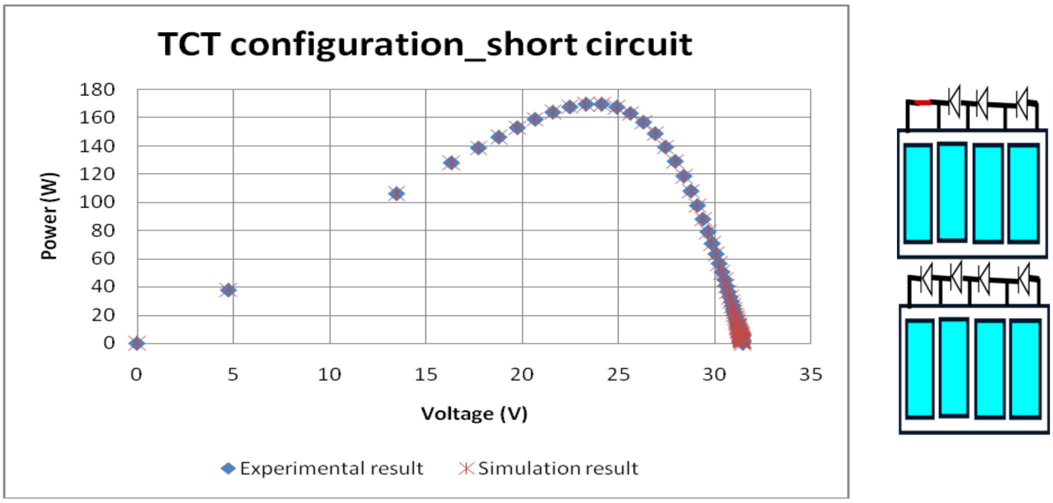
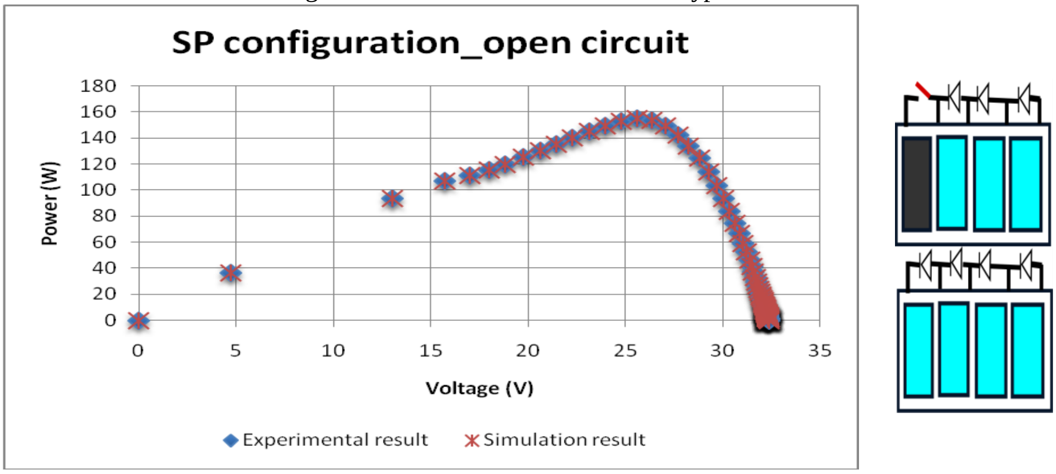
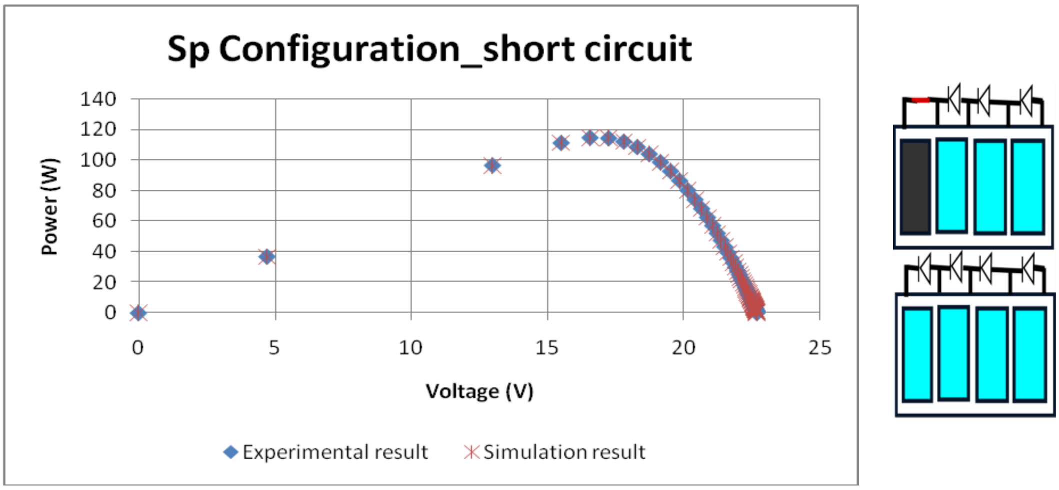


Figure 13. P-V curves – fault in first bypass diode





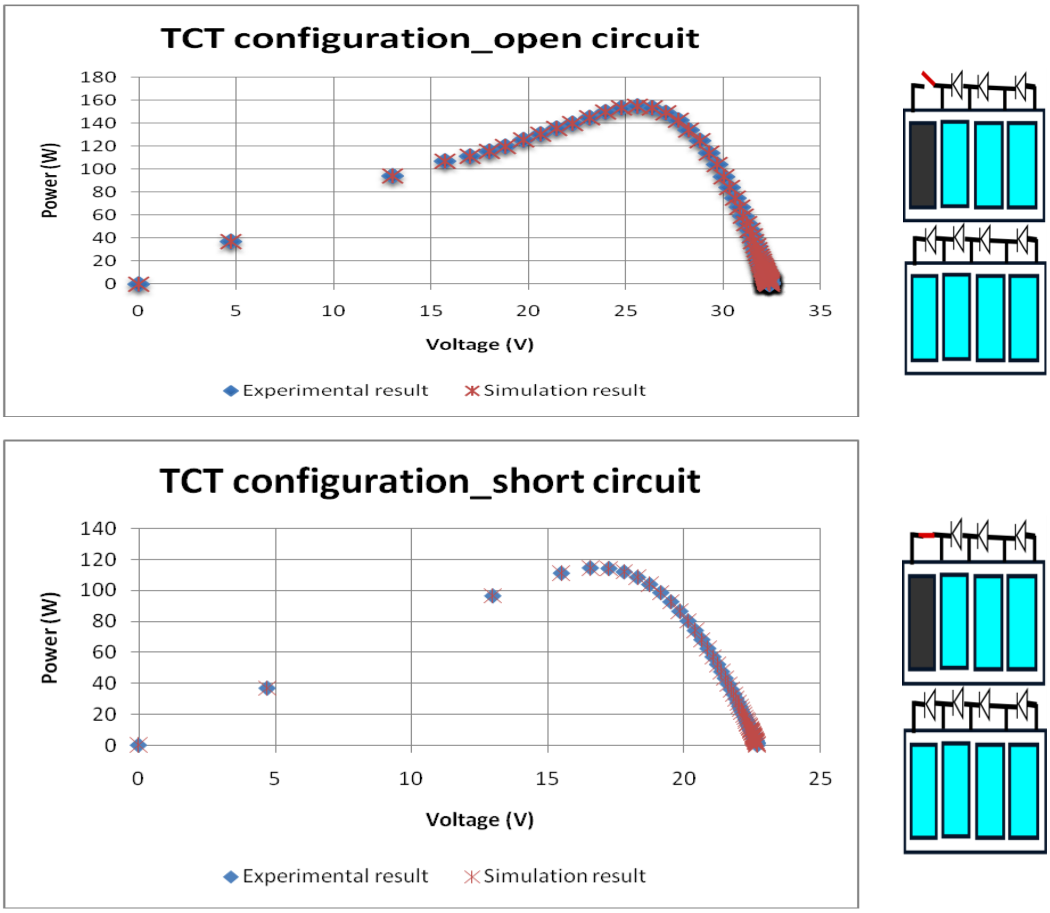
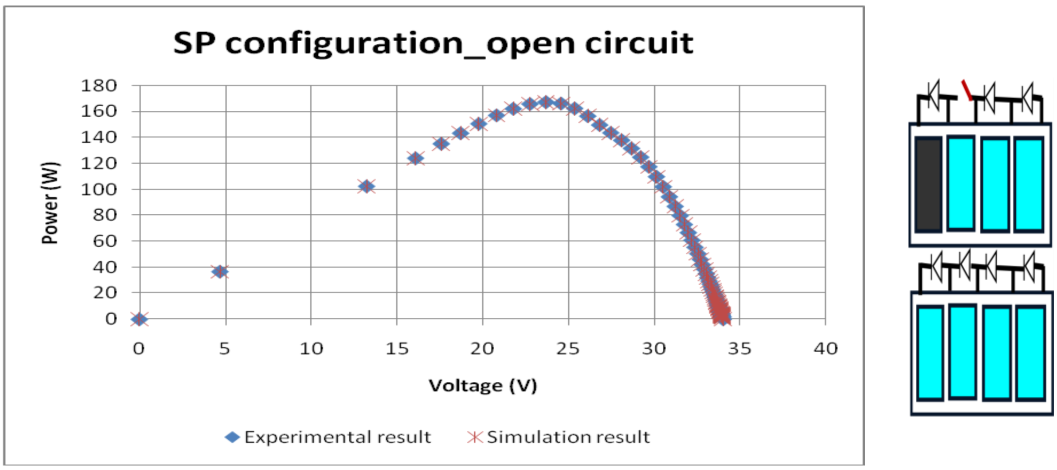


Figure 14. P-V curves – fault in first bypass diode



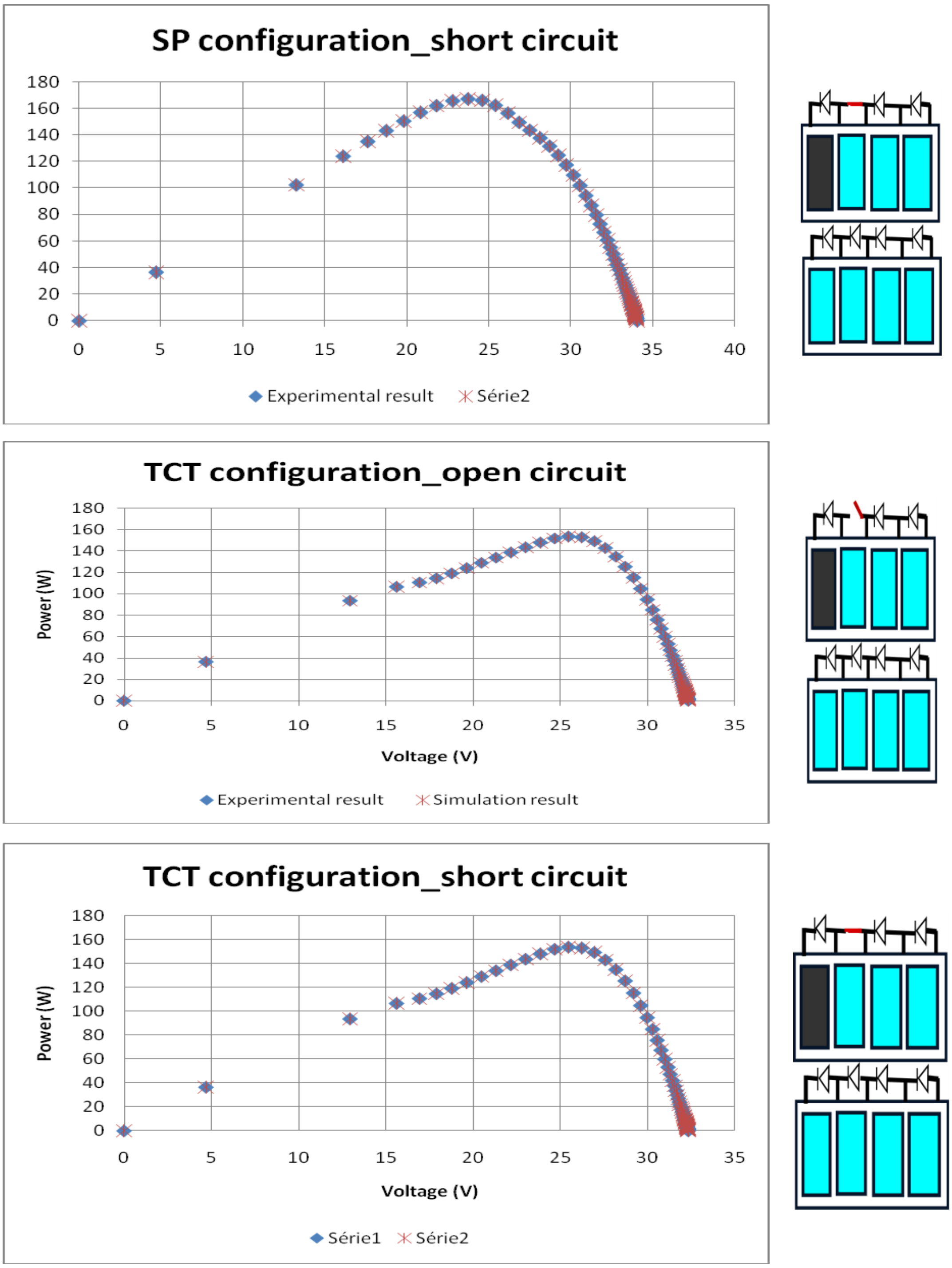
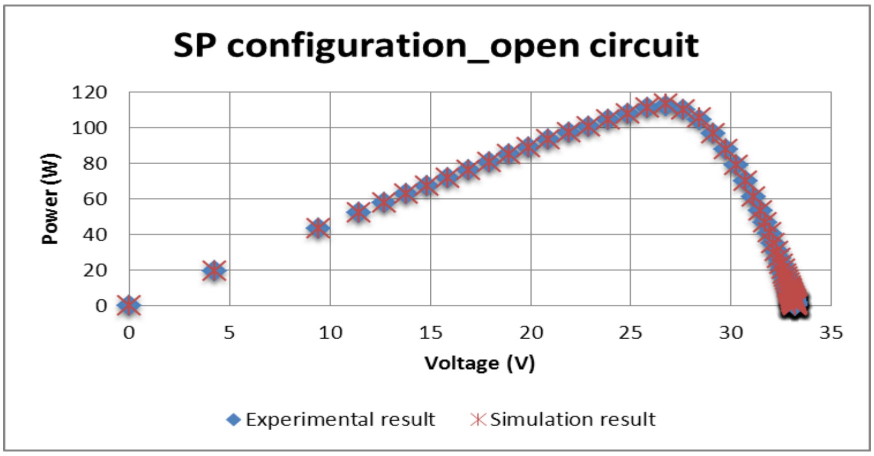
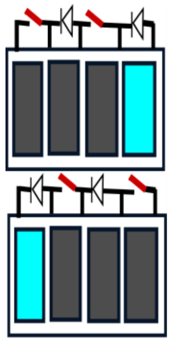
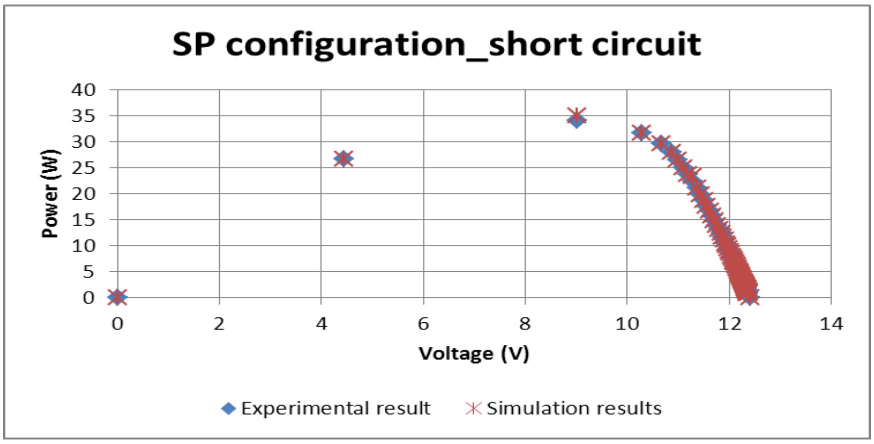
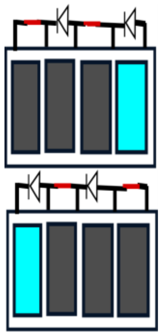


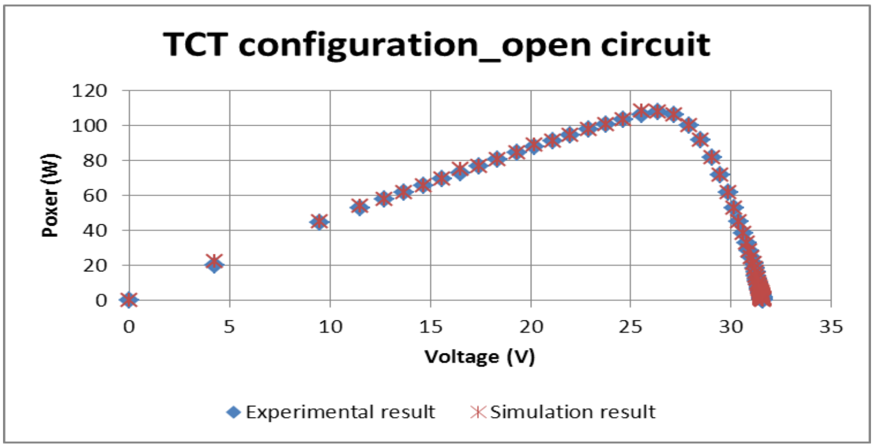
Figure 15. P-V curves – fault in second bypass diode

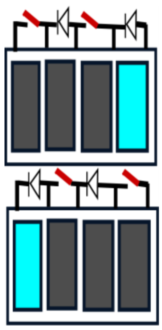

SP configuration_open circuit
Power (W)
Voltage (V)
Experimental result
Simulation result




SP configuration_short circuit
Power (W)
Voltage (V)
Experimental result
Simulation results




TCT configuration_open circuit
Poxer (W)
Voltage (V)
Experimental result
Simulation result



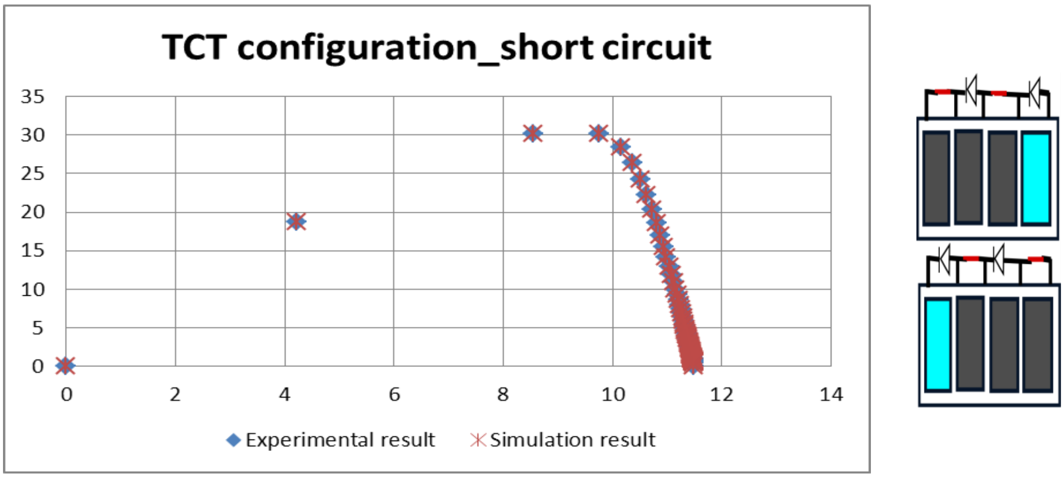


Figure 16. P-V curves – fault in 1DD3D6D8 bypass diode

VI. Results and Discussion

The experimental results are quite satisfactory, showing the effectiveness of the bond graph model proposed in improving the power quality and the reliability of the power supply.

The conclusions of these analyses are summed in the following table (Table II).

Table 2. Overall comparison between embedded PV systems

PV in faultless operation		
Identification code	SP	TCT
00000000 aaaaaaaa	High	High
00000000 bbbbbbbb	High	High
10001000 aaaaaaaa	Medium	High
10001000 bbbbbbbb	Medium	Medium
10101101 aaaaaaaa	Medium	High
10101101 bbbbbbbb	Medium	High
PV in operation with faults		
10000000 adaaaaaa	High	Medium
10000000 acaaaaaa	High	Medium
10000000 daaaaaaa	Medium	Medium
10000000 caaaaaaa	High	High
00000000 daaaaaaa	High	Medium
00000000 caaaaaaa	Medium	High

11100111 cacaacac	High	Medium
11100111 dadaadad	High	Medium

These results confirm that topologies can have a direct impact in power production, depending on the shadow type and the fault type (local and type of fault in bypass diode). It is also clear that the TCT topology might be the best solution to mitigate external mismatch for most of the shadow types in case of faultless operation.

In the case of operation with defects it is also clear that the SP topology might be the best solution to mitigate external mismatch for most of the shadow types.

Based on the previous results, the optimal topology is the one that, for a given shadow, uses the minimum number of sensor but all component of PV system is monitorible.

VII. Conclusion

An advantage of the presented simulation procedure is the possibility of simulation the whole PV array introducing different input, parameters for each one of the modules presents in the PV generator, making possible the study of different shadow patterns as well as temperature variations in particular solar cells. Partial shading of PV installations has a disproportionate impact on power production. For a single-string grid-tied PV system, a shadow can represent a reduction in power over 30 times its physical size. In order to accurately predict the power lost due to shaded conditions, it is necessary to identify the bypass diode placement in the PV modules, as bypass diodes regulate the impact of shading on a particular module or group of cells.

Partial shadowing is a major reason for the energy yield reduction of photovoltaic systems. Its early detection is important, not only due to the immediate power reduction of the PV array, but also to protect the shadowed cells from long-term exposure to increased temperature. In order to detect such events, a method based on bond graph approach has been proposed. The main advantages of this method are the simple expression, high sensitivity to even a relatively small area of partial shadow and very good robustness.

This paper has performed an experimental study of PV characteristics under various shading conditions. Based an experimental result, an effective technique to model PV characteristics has been proposed.

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