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Analysis and Experimental Validation of a Partially Shaded PV Array with different configurations

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Abstract: Partial shading of photovoltaic (PV) modules can affect a wide variety of plants ranging from utility-sized solar trackers to residential building-integrated PV, resulting in lower energy production yields. This paper presents background and experimental results from a PV system, operated under a variety of shading conditions. A procedure of simulation and modeling solar cells and PV modules, working partially shadowed in symbols environment, is presented. Simulation results have been contrasted with real measured data from a commercial PV module of Photowatt PW1650. Some cases of study are presented as application examples of this simulation methodology, showing its potential on the design of bypass diodes configuration to include in a PV module and also on the study of PV generators working in partial shading conditions.

Key words: Photovoltaic, Partial Shading, Maximum Power Point Tracking, Configuration

1. 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]. Photovoltaic (PV) system is one of the potential renewable energy sources which being continuously developed and attracted much attention worldwide.

The reduction of output power in PV modules can be attributed to many factors, but may be the most important are mismatch effects and shadows. Most manufacturers include bypass diodes in their PV modules in order to prevent hot spot formation, in partial shadowing conditions of work. Hot spots appear when a solar cell, normally forming part of a solar cell string of serially connected solar cells, becomes reverse biased and dissipates power in form of heat [2].

The most important component that affects the accuracy of the simulation is the PV cell model. Modeling of PV cell involves the estimation of the I–V and P–V characteristics curves to emulate the real cell under various environmental conditions. The most popular approach is to utilize the electrical equivalent circuit, which is primarily based on diode. Many models have been proposed by various researchers; the simplest is the basic single-diode model. It comprises of a linear independent current source in parallel to a diode [3]–[6]

Once the appropriate model and its computational model have been identified, a complete PV system simulation can be developed. A good PV simulation package should fulfill the following criteria: (1) it should be fast but can accurately predict the I–V and P–V characteristic curves; including special conditions such as partial shading (2) it should be a comprehensive tool to develop and validate the PV system design inclusive of the power converter and MPPT control. Although existing software packages

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like PSpice, PV–Design Pro, Solar Pro, PV cad, and PV syst are available in the market, they are expensive, unnecessarily complex and rarely support the interfacing of the PV arrays with power converters [7]. Over the years, several researchers have studied the characteristics of PV modules under partial shading condition, [8].

There exist many papers containing the analysis of the behavior of the photovoltaic PV cells under partial shadowing [9]-[11], taking into account the diode. But there are only a few that actually take into account the importance of the diodes configuration [8]. This article studies the individual behavior of a PV module and a photovoltaic array of PV modules (PV array) connected to an inverter with shadows in both cases.

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. [11] Other recent works include simulations of partially shaded PV cells [12], [13], experimental results of different maximum power point tracking algorithms under shaded conditions [14] and the effect of shade on PV system performance [15], [16].

In view on the importance of this issue, this paper proposes a practical modeling and simulation method, which can predict the I–V and P–V characteristics of large PV arrays. It can be used to study the effect of temperature and insolation variation, varying shading patterns, and the role of array configuration on the PV characteristics. The simulation is developed using the Symbols environment.

2. 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 [17], [18]. 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.

3. System Configuration

One of the main causes of losses in energy generation within photovoltaic systems is the partial shading on photovoltaic (PV modules). These PV modules are composed of photovoltaic cells (PV cells) serial or parallel connected, with diodes included in different configurations.

The curve of a PV cell varies depending on the radiation received [1], [2] and its temperature. Furthermore, the modules have diodes that allow the current flows through an alternative path, when enough cells are shaded or damaged. There are two typical configurations of bypass diodes: [3] overlapped (Fig. 1a) and no-overlapped (Fig. 1b). It should be noted that the analysis in modules with overlapped diodes is a more complex one, because there may be different paths for current flow.

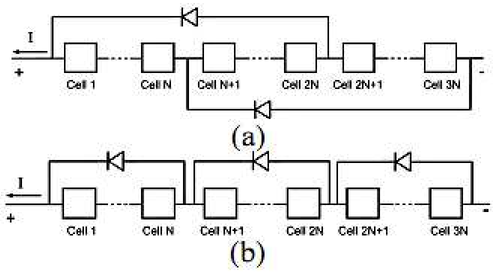


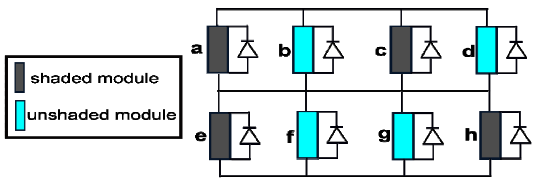
Fig. 1 Bypass diodes (a) overlapped (b) no-overlapped

3.1. Identification code

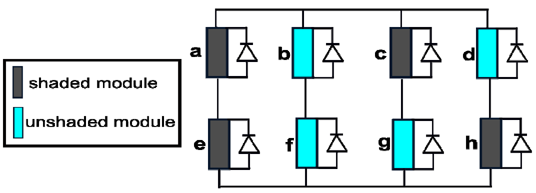
In a not shaded PV array, with no deteriorated PV modules, all the PV modules have the same MPP. But when some PV modules are totally or partially shaded, the I-V curve of PV array changes, hence, the MPP of each PV module can be different. This would produce energy losses. The energy loss caused by shadows on the PV modules is not proportional to the area of the shadow, it may be much higher. The losses in a PV array will depend basically on:

- The configuration of the bypass diodes
- The inverter voltage limits in the dc side
- The layout of the modules
- The electrical configuration

In order to easily reference any shadow with bypass diodes an identification code is proposed. Figure 1 shows an example of three shadows and their associated ID codes.



(a) SP



(b) TCT

Fig. 2 SP and TCT connection configurations

4. Modeling of Photovoltaic System

4.1. Models of the panels

A Photovoltaic (PV) system directly converts sunlight into electricity. The basic device of a PV system is the photovoltaic cell; they may be grouped to form panels or arrays [19], [20]. This model is the most classical one found in the literature and involves: a current generator for modeling the incident luminous flux, two diodes for the cell polarization phenomena, and two resistors (R_s and R_{sh}) for the losses. 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 [21]. (see figure 4).

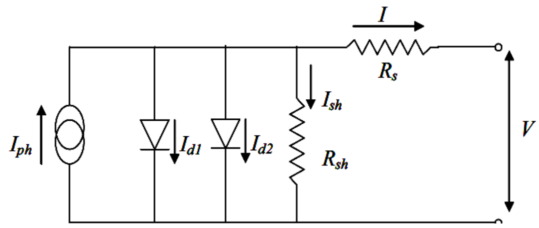


Fig. 3 Equivalent electrical circuit of a cell

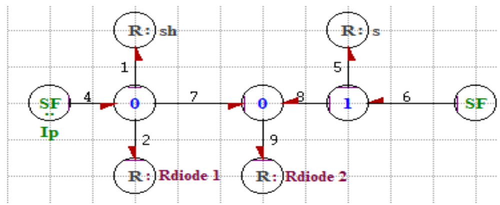


Fig. 4 Bond graph model of PV with tow diodes

4.2. Buck-Boost DC/DC converter

DC/DC converter performance optimization is important to accommodate the growing need for efficiency in portable electronic device battery life and an ever increasing world climate of energy maximization. The equivalent circuit of the converter is illustrated in figure (5).

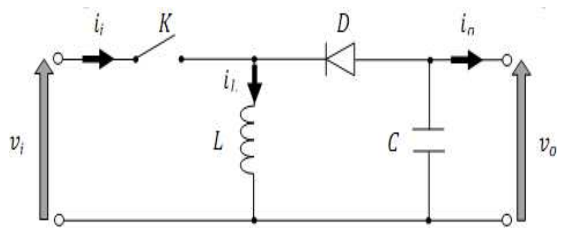


Fig. 5 Equivalent circuit of a buck-boost converter

To ensure the charge and the discharge of the storage battery, the current must be reversible so that the energy transfer would be in the two directions, from the DC-Bus to the battery and vice versa. For that a Reversible current DC/DC converter is necessary, it's realized by associating a boost chopper and a buck one as shown in figure (6).

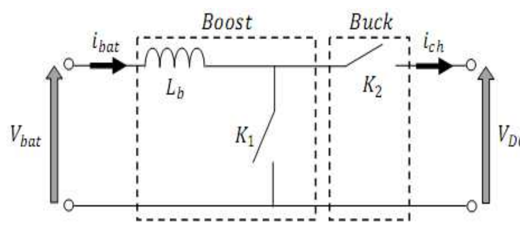


Fig. 6 Equivalent circuit of a the reversible current DC/DC converter

The bond graph model of converter DC/DC is thus given by the figure (7).

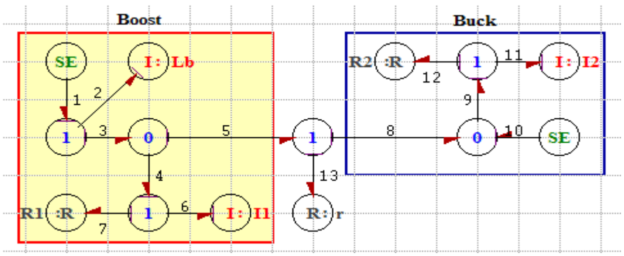


Fig. 7 Bond graph model of boost-up chopper

5. Perturbation and Observation (P&O)

The P&O algorithm is probably the most frequently used in practice, mainly due to its easy implementation [22].

Its operation is briefly explained as follows: assume that the PV array opera test a given point, which is outside the MPP. The PV array operational voltage is perturbed by a small DV, and then the change in the power (DP) is measured. If DP >0, the operation point has approached the MPP, and therefore, the next perturbation must take place in the same direction as the previous one (same algebraic sign).If, on the contrary, DP <0, the system has moved away from the MPP and, consequently, the next perturbation must be performed in the opposite direction. As stated before, the advantages of this algorithm are its simplicity and easy implementation. However, it has limitations that reduce its tracking efficiency. When the light intensity decreases considerably, the P–V curve becomes very flat. This makes it difficult for the MPPT to locate the MPP, since the changes that take place in the power are small as regards perturbations occurred in the voltage.

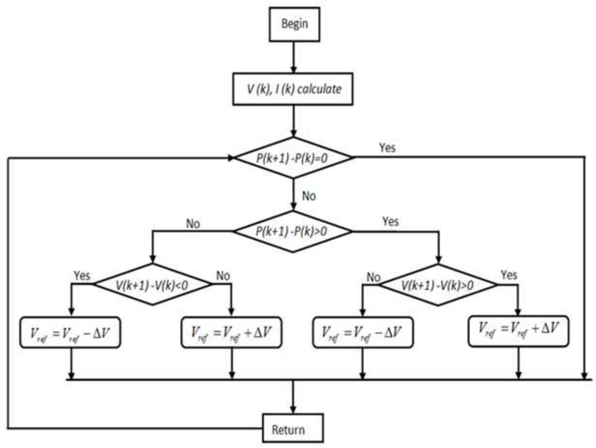


Fig. 8 Flowchart of perturb and observe method

Another disadvantage of the “P&O” algorithm is that it cannot determine when it has exactly reached the MPP. Thus, it remains oscillating around it, changing the sign of the perturbation for each DP measured. It has also been observed that this algorithm can show misbehaviour under fast changes in the radiation levels [23]. The flowchart of the P&O method is shown in figure (8).

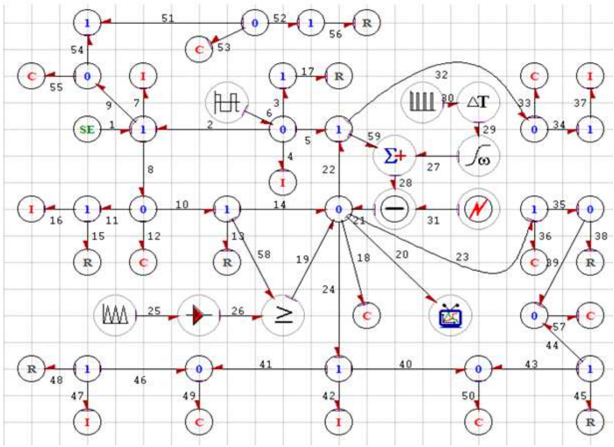


Fig. 9 Bond graph MPPT control

This method with the characteristic to have a structure of regulation simple and little parameter of measurement. It operates by disturbing the panel voltage periodically, and by comparing energy previously delivered with the news after disturbance, while following the flow chart appears.

The controller senses the solar array current and voltage to calculate the solar array output power, power slope and SE1 (figure 9) for maximum power control. The bond graph control requires that variable used in describing the control rules has to be expressed in elements of bond graph (elements R, I and C) with bond graph junction (0, 1 and TF). In this paper, the bond graph control MPPT method has two input variables, namely ΔP(k) and ΔU(k), at a sampling instant k.

6. Experimental Test

In order to verify some of the simulated curves of the previous section, an experiment was conducted on a PHOTOWATT PW1650 multi-crystalline silicone PV panel using a PVPM 1000C40curve tracer. The electrical specs of the 165 W panels (at standard temperature conditions) are described in Table 1.

Table 1 Parameters of the PV module

Parameters	Value and units
Maximum power P_{max}	165W
Current peak power I_{mp}	4.8 A
Voltage peak power V_{mp}	34.4 V
Short circuit current I_{sc}	5.1 A
Open circuit voltage V_{oc}	43.2 V
Bypass diodes	4
Number of cells per module	72

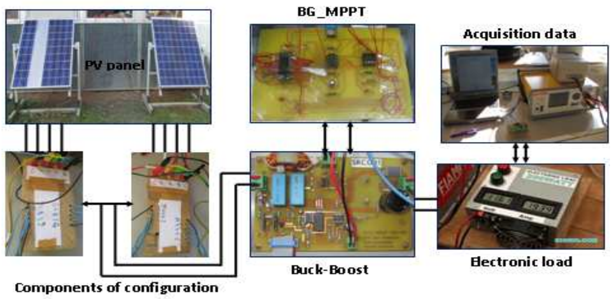


Fig. 10 The experimental benchmark

The PHOTOWATT PW1650 photovoltaic panel has the electrical configuration of the cells and bypass diodes. To create a partial shadowing condition, 18 cells belonging to the 2 string were covered with a sheet of cardboard, which makes the shadowing close to 100%, i.e., near zero solar irradiation on the covered area.

6.1. Limits of inverter

An inverter that is connected to the PV array can't always achieve the MPP because of his voltage range of work and the tracking MPP algorithm. In figure 11, where the P-V curve is represented, there are four types of points where the inverter could think that there it is the MPP. The inverter can only work in three of them. The absolute maximum is out of its working voltage range.

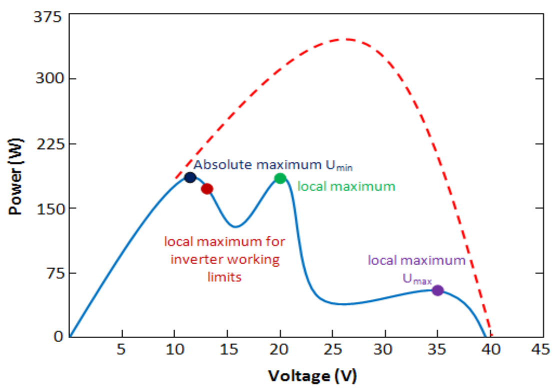


Fig. 11 Maximum and local power points of a P-V curve

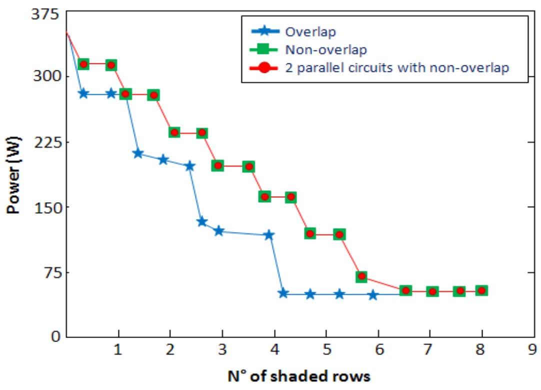


Fig. 12 Maximum MPPs of the PV arrays in function of the bottom rows shaded

Figure 13 shows the different types of MPPs against the number of inferior rows shaded in the PV array for the different configurations. On examination, in configuration A , the power losses can reach 40%, while in configuration B and C the losses are 20%. Also, the same power is generated if 12 rows are shaded in configuration A, 20 rows in configuration B and 16 in C. In other words, the PV arrays with bypass diodes (Configuration A) are more susceptible to lose power due to the shadowing of their PV modules.

Figure 13 shows the absolute MPP achieved in the three PV array configurations. The similarity of configuration B and configuration C is apparent.

In a not shaded PV array, with no deteriorated PV modules, all the PV modules have the same MPP. But when some PV modules are totally or partially shaded, the I-V curve of PV array changes, hence, the MPP of each PV module can be different. This would produce energy losses. The energy loss caused by shadows on the PV modules is not proportional to the area of the shadow, it may be much higher. The losses in a PV array will depend basically on:

- The configuration of the bypass diodes
- The inverter voltage limits in the dc side
- The layout of the modules
- The electrical configuration

The analysis will consider a PV array consisting of 2 PV modules with its 1 inferior rows shaded. The sunny cells are irradiated by 796 w/m^2.

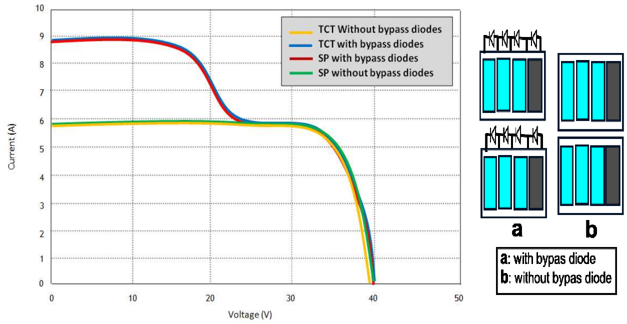


Fig. 13 I-V with shading

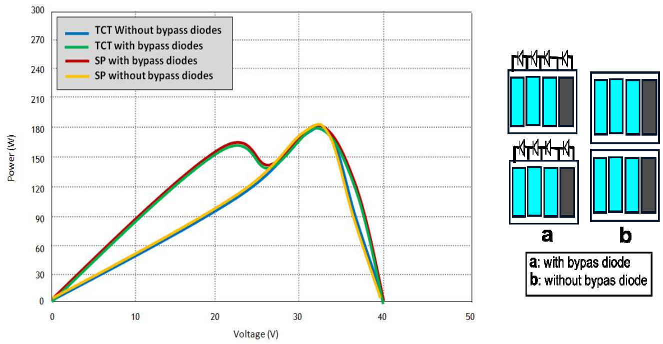


Fig. 14 P-V with shading

In partially shaded conditions photovoltaic plants, I–V curves present two main properties: maximum power reduction and appearance of multiple power peaks. The first effect is a consequence of lower in coming solar power on to the array. The appearance of multiple peaks is due to module mismatch, which may be accentuated by bypass diode operation. The multi-peak effect is visible on the simulation results, presented in figure 13, in case of partial shading of an array. Al though all two topologies show inflexion points on their current–voltage characteristics, TCT arrays have smoother curves consequently lessening the multi-peak effect. Furthermore, measurements show an increase of roughly 4% and 2.5% in maximum power for the TCT interconnection scheme. In other words, the PV array is able to produce 4% more power than the SP topology by simply modifying the array interconnections of the plant into a TCT configuration.

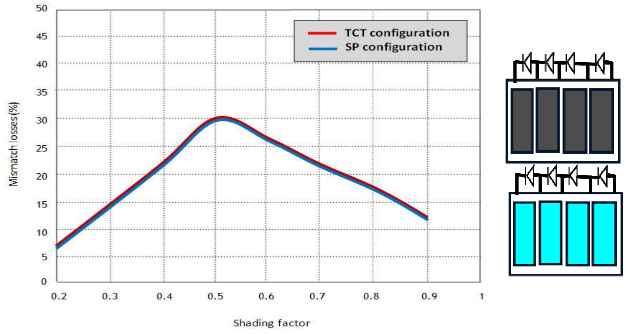


Fig. 15 Mismatch losses for short and wide shadow type

Figure 15 shows that none of the reference topologies can mitigate the external mismatch for short and wide shadow types, no matter the shading factor.

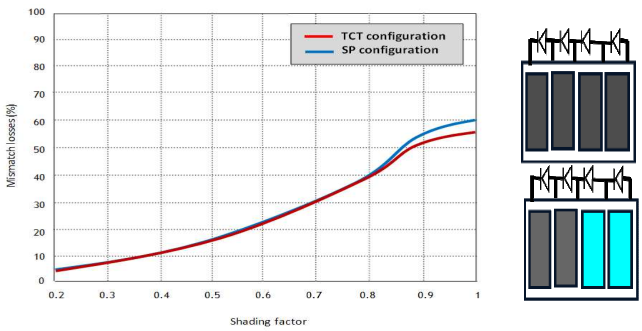


Fig. 16 Mismatch losses for long and wide shadow type

There is a significant reduction in mismatch losses for higher shading factors. As shading factor rises, the power available in the bypassed modules represents a smaller share of the total theoretical power. In addition, since the mismatch losses were defined as a ratio between the power produced by un-shaded modules and total theoretical power, the ratio simply diminishes.

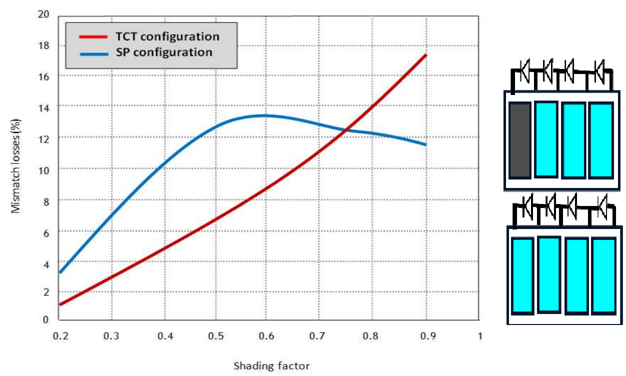


Fig. 17 Mismatch losses for short and narrow shadow type

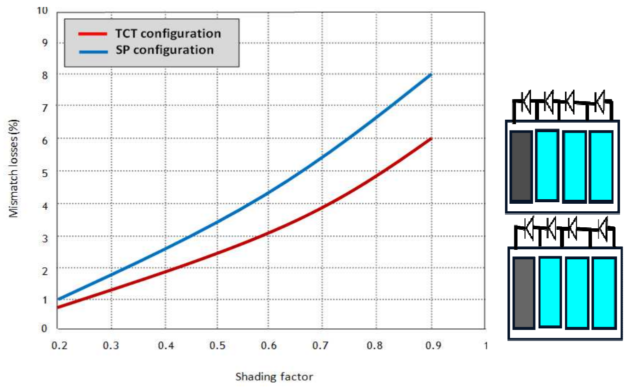


Fig. 18 Mismatch losses for long and narrow shadow type

Figure 16 shows that all four topologies have virtually the same performance when most of the modules are shaded. This implies that once the shadow is spread over most of the PV field, the topologies are no longer available solution to the external mismatch problem, no matter the shading factor.

Figure 17 shows that for short and narrow shadows, changing the topology is an interesting solution to mitigate the external mismatch, depending on the shading factor. In this case, the TCT topology is most effective against mismatch losses for low shading factors, while SP minimizes mismatch losses for higher shading factors.

Figure 18 shows that the TCT is the topology with the best performance for long and nar row shadows, no matter the shading factor. It also shows that SP is less interesting, which indicates that the connections among the modules have a direct impact over power production in this case.

7. Conclusion

The diagnostic strategy and the form in which knowledge is available conditioned the method used to design the monitoring algorithm. According to the type of knowledge, the criterion of classification of the monitoring method distinguishes between two types of approaches: methods with or without model. Our contribution relates to the methods containing model.

In this paper, a new algorithm is introduced for an MPPT controller developed by means of the bond graph approach. The use of an MPPT control plays the important role of significantly increasing the efficiency of a photovoltaic generating system. Also this paper has demonstrated that the tracking speed of the proposed method is significantly improved compared to the other method.

Experimental results show that the TCT topology seems to be the most efficient for lessening mismatch losses during PV array shading without penalizing the overall efficiency of the plant in non shaded scenarios.

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