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A REVIEW ON PHOTOVOLTAIC ARRAY BEHAVIOR, CONFIGURATION STRATEGIES AND MODELS UNDER MISMATCH CONDITIONS

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ABSTRACT

A review of the algorithms for pursuing the PV configuration methods within non-uniform conditions is implemented in this study. As has been exposed, there are many methods of distinguishing and PV alignment techniques that strive for mitigating the effect of mismatch conditions (which include the rapid and unbalance changing of the weather conditions like the radiation and temperature) on the PV system. Nonetheless, in this research they are grouped as Series Parallel (SP) interconnection, Total Cross Tied (TCT) interconnection, and finally Bridge Linked (BL) interconnection technique. In contrast to the BL and SP, in the TCT there is a substantial reduction in mismatch losses that occur due to partial shading, beside to it has greater reliability comparable with others interconnections. Furthermore, the focus of this research is also to review modeling the PV arrays under mismatch conditions. A way to decrease the mismatch effect on the PV modules discussed in this study. Also, the challenges might face these reconfiguration methods and PV modeling has been illustrated and presented. Finally, this study can be considered as a valuable indication for those who are interested in PV modeling and reconfiguration.

Keywords: PV modeling, photovoltaic array, mismatch conditions, shadowing losses, reconfiguration.

1. INTRODUCTION

The need for having additional sources of energy is increasing in the present time since the world wants to decrease its excessive dependence on conventional sources of energy. In this situation, the photovoltaic (PV) energy could be the most appropriate solution. Since PV cells compete well with substitute sources in economic terms, they are incorporated into space and terrestrial applications. The latter part of the 20th century showed very high growth rates of 30% per year in the PV industry It was predicted that by 2010, the cost of PV modules would be 1.50€/WP, with the systems costing 3.00 €/WP[1].

There are typically three groups of PV systems, grid-connection, stand-alone and hybrid systems. Stand-alone PV power supply systems are used as substitutes in those places that are located at a large distance from regular power generation systems. In the distant rural villages, some of which are not completely covered by the grid connections, these systems can prove to be reliable and economic electricity sources. These systems function on two levels: on a smaller level ranging from 1 to 10kW in which they supply electricity for the so called solar home systems, SHS. Meanwhile, system with capacity in the range of 10 to 100kW in which it is installed as distribution generation systems or on rooftops of the buildings. They are usually applauded for their simple system configuration and a control mechanism that is easy to use [1].

The greatest amount of PV power produced depends on the load-line regulation when different environmental conditions are used. Several situations also require the load to have a constant level of power supply. Lead-acid batteries are normally used as they are quite easily available in different sizes, are reasonably priced and have performance features that are easily understood.

The suggested techniques in [11-13] presented to track the global points in the PV characteristic curves (P-V and I-V) in most of cases by doing a wide-range search, and the extracted power from the photovoltaic array under partial shaded is much as compared to the other conventional techniques. While the system proposed in [14] suggested two stages of tracking of the maximum power point in the PV system within the partial shade condition, when divided the control strategy in two stages and depended on the instant online measurement. Mathematical model and experimental study performed in [15, 17] to build PV array system and find the maximum power point for system affected by the partially shaded conditions. When paper [17] presents a fuzzy logic method to truck and extract the MPP global point in photovoltaic array system working through partial shade conditions. That proposed MPP trucker had been fulfilled by linking fuzzy logic MPP trucker with a system of scanning and storing.

In [2] the authors claimed that when arrays are not cleaned, there can be a reduction in 8 – 10% of the power losses. In the meanwhile, a study was also carried out in Italy using a 1-MWp PV system, which showed that there is 6.9% power losses on plants constructed on sandy soil, while plants constructed on comparatively compact soil show a power loss of 1.1% [2].

The objective of the current study is to present a general view on the current research works related to the development of PV arrays reconfiguration techniques. PV arrays interconnection strategies are described first and

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then PV systems performance under mismatch condition is discussed. Finally, models for PV array considering the shadow effect are discussed.

2. PHOTOVOLTAIC MODULES INTERCONNECTION STRATEGIES.

As can be observed from Figure- 1, there are three main ways in which the PV modules can be linked to each other; series-parallel (SP), total-cross-tied (TCT) and bridge-linked (BL). The SP interconnection has modules joined together in a series which creates strings that form a parallel connection to each other. Meanwhile, the modules are connected to each other in parallel in the TCT interconnection, with the parallel circuits being linked to each other in series. On the other hand, the BL interconnection lies between the extreme SP and TCT interconnections. In contrast to the SP, in the TCT there is a substantial reduction in mismatch losses that occur due to partial shading [3-5].

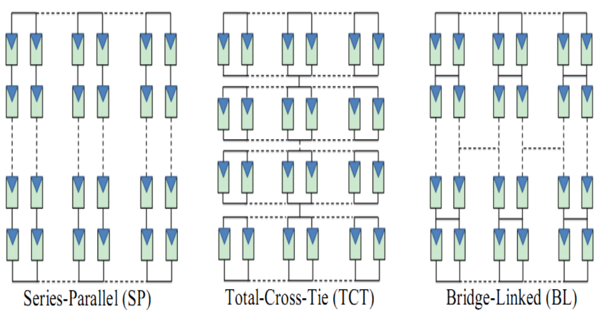

Figure-1. The PV Module interconnections style, (a) SP interconnection. (b) TCT interconnection. (c) BL interconnection.

The short circuit currents of the modules are influenced by partial shading which has an impact on the output currents of the modules at their MPPs. The result is that the MPPs of the modules and that of the arrays become inconsistent, an issue of greater importance for the SP, as compared to the TCT[6]. This is because the SP has a greater number of series strings in comparison to the TCT. There is also lesser likelihood of switching ON by-pass diodes in the TCT interconnection which causes lesser corresponding losses. With respect to manufacturing tolerance mismatch, the TCT, in comparison to the SP, can also bring a greater decrease in mismatch losses [4]. Technological developments have, however, reduced these losses to less than 1%.

The TCT has a greater amount of parallel circuits as compared to the SP. Hence, there is greater reliability of the TCT interconnections as compared to the SP, with TCT having the capability to increase the operational duration of the array by two times, as has been demonstrated in theoretical evaluations regarding the reliability of PV arrays [7]. According to a study assessing the manufacturing cost of TCT-connected modules, TCT-connected modules do not cost more than the SP-connected modules during mass level production. It can, hence, be seen that TCT connection are better than the SP for aspects like lesser mismatch losses and greater reliability. In addition, the manufacturing cost of the TCT would be comparable to that of the SP.

a) SP configuration based photovoltaic modules string model

A PV string constructed using various modules connected in a series is depicted in Figure- 2 [8]. A PV module refers to a series connection of cells which are secured using a bypass diode. Two or three modules that are connected in a series normally make up the commercial PV panels which make it possible to obtain a nominal power of a few hundred watts. The blocking diode is used to complete the string in Figure- 2. This is normally used to make sure that current does not flow backwards. The string depicted in Figure- 2 is analyzed subsequently. This analysis can be expanded to any number of strings connected in parallel without any difficulty.

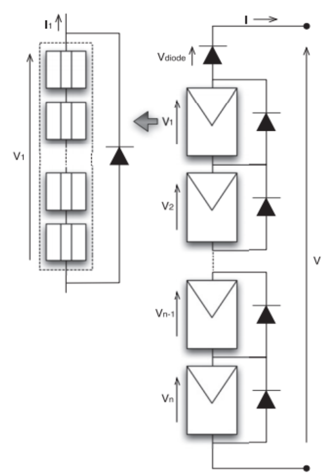

Figure-2. String of n series PV modules and blocking diode[9].

Figure-3 illustrates a circuit model which explains each module. This model consists of the photocurrent generator, the diode D which shows the non-linearity of the PV module, the bypass diode Db and the resistances Rs and Rh which refer to the separate loss systems in the module [10].

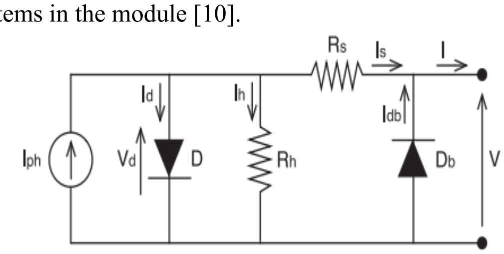

Figure-3. Circuit model of a PV module with bypass diode.

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Equations (1) – (5) represent a non-linear system which shows that current is an implicit function of voltage V, and that the dependent factors consist of temperate T, irradiance G and the properties of semiconductor material which are measured through several parameters.

$$Id = Isat.d\,(eVd/Vt.d - 1) \tag{1}$$

$$Idb = Isat.db\,(e\text{-}V/Vt.db - 1) \tag{2}$$

$$I = Idb + Iph - Id - Ih \tag{3}$$

$$Vd = V + RSIS = V + RS\,(I - Idb) \tag{4}$$

For the PV module and the bypass diode, the thermal voltages are represented by Vt, d and Vt, db, while the saturation current is represented by Isat, d and Isat, db respectively. The Iph current is linearly related to irradiance and temperature. Each module is formed by N cells that are joined to each other in series, hence, to achieve the value of thermal voltage and resistances of the modules, the cell values were multiplied by Ns [8].

b) TCT configuration based photo-voltaic modules string model

When a clear relationship between the voltage and current in the PV panel is used with series and parallel resistance in the PV model being ignored [11-13], Equation (6) is attained in which it refers to the voltage(V) current(I) in the PV panel. Using the datasheet information pertaining to a specified temperature and irradiance, the parameters can be analyzed using Equations (7)-(10). In these Equations that refer to the *Isc* (short-circuit-current) and Voc (open-circuit voltage) of the Standard Test Conditions (STC). This rate of parameters is in STC, while the current and voltage of the PV module are there in the MPP for specified irradiance and temperature conditions. The current and voltage temperature coefficients are there ultimately. This module's major parameters include: 5.0%, 11.05%, 4.72%, 9%, 80%, and 0.065%.

$$i_{pv} = i_{sc} - A \,.\exp(B \,. v_{pv}) \tag{5}$$

$$i_{sc} = i_{STC} \cdot \frac{G_{pv}}{G_{STC}} \left(1 + \alpha_t \,.(T_{pv} - T_{TCT}\right) \tag{6}$$

$$B - \frac{B_{STC}}{(1 + \alpha_v \,.(T_{pv} - T_{TCT})} \tag{7}$$

$$B = \frac{\ln\left(1 - \left(\frac{i_{mpp}}{i_{STC}}\right)\right)}{v_{mpp} - v_{ocSTC}} \tag{8}$$

$$A = i_{STC} \,.\exp(-B_{STC} \,. v_{ocSTC}) \tag{9}$$

The position of the module in the row does not determine the current of a row of PV modules in TCT connections, as was discussed earlier and can be seen in Figure-4(b).

The explicit PV model presented in Equation (6) shows that the current of a PV which has M parallel modules and voltage is obtained as follows:

$$i_r = i_{eq} - \phi(v_r) \tag{10}$$

$$i_{eq} = \sum_{i=1}^{i=M} i_{sc,i} \,,\ \phi(v_r) = \sum_{i=1}^{i=M} A_i \,.\exp(B_i \,. v_r) \tag{11}$$

In this Equations (11 and 12), the module parameters are represented by ir and ieq and the equivalent electrical circuit is represented by $\phi(vr)$. It can be observed from Equation (13), the row current has a negative value because the panel parameter values are positive at all times, that a distinct. The row current is created by each row voltage. Equation (13) also makes certain that it constantly declines.

$$\frac{\partial i_r}{\partial v_r} = -\sum_{i=1}^{i=M} A_i \,. B_i \,.\exp(B_i \,. v_r) < 0 \tag{13}$$

In addition, Figure-4 (b) provides another significant aspect using a practical TCT configuration. According to this aspect, bypass diodes are included in commercial PV modules which have been added by the manufacturer with the purpose of securing the modules from the negative currents which create hotspots that have the ability to disintegrate the array [14, 15]. The PV module and bypass diodes are kept parallel to each other, with the diodes forcing the modules to have zero voltage when the current provided to the PV panel is greater than the Isc, which is determined by irradiance to a large extent [10, 17]. The connected row is forced to produce zero power (null voltage in a single module). This also creates changing of the characteristic curves from level to another of both P and I [11]. Figure- 5 (b) provides a demonstration of this condition multiple maximum power points (MPP), which are the result of activation and deactivation of the PV panels' bypass diodes, are demonstrated by the power versus voltage curve when the PV system functions in varying conditions[18, 19]. The maximum power value in the PV system determines these activations and deactivations, and also the interconnection arrangement of the PV Modules such as [10-12, 20-22].

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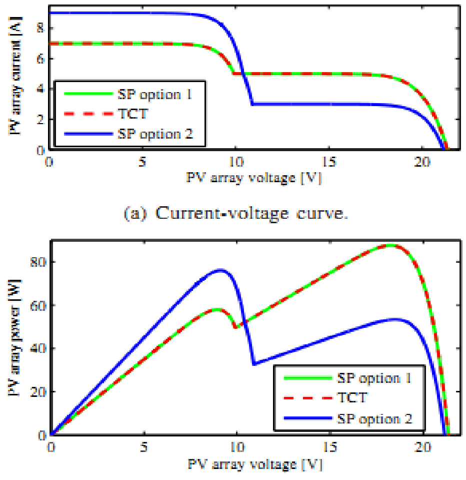
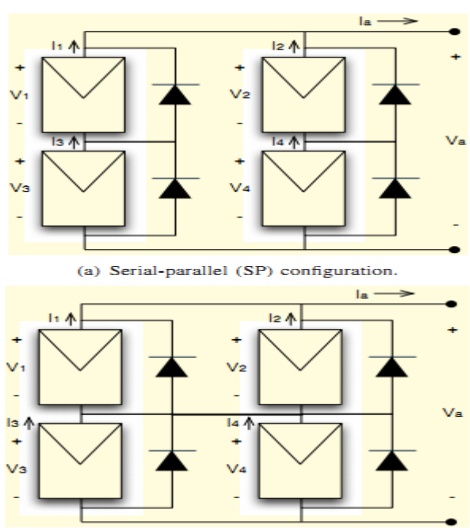


(a) Current-voltage curve.

(b) Power-voltage curve.

Figure-4. SP and TCT in mismatching conditions[16].



(a) Serial-parallel (SP) configuration.

(b) Total cross-tied (TCT) configuration.

Figure-5. V arrays with two columns and two rows[16].

Series Parallel (SP) and Total Cross-Tied (TCT) configurations are most widely used for PV arrays. Literature also makes reference to other configurations such as bridge-linked (BL) or honey comb (HB) [20]. The PV modules are linked together in series in the SP arrangement, which creates strings and these strings are then linked together in parallel to create the array (see Figure- 1(a)). There are several models for SP arrangement in literature, and these models differ in their calculation speeds and accuracies such as [10-12, 23], which is because of the extensive application of this configuration in PV arrays of various sizes. The PV modules are linked to each other in parallel creating rows, and these rows are then linked to each other in series in the TCT arrangement (see Figure- 1(a)). The TCT arrangements are widely used in PV arrays because they reduce the impact of mismatching conditions as can be seen in [20, 21, 24, 25]. However, literature does not provide much information about the way PV arrays are constructed in TCT arrangements. The Eqs for determining the answer to equivalent circuit of a rectangular TCT arrangement have been presented in [20], however, it is essential that a system of non-linear Eqs. is solved in a TCT arrangement that has N rows of M PV modules linked together in parallel.

This means that several computations have to be made which will require a large degree of calculation time. The SP and TCT arrangements of a PV array which is formed from four PV modules linked together in two columns and two rows (2 × 2) are illustrated in Figure- 4. It can be observed in the circuit illustrated in Figure- 4 (a) that in SP arrangement, each string possesses its own current which is determined by the mismatching levels present in the PV modules in the string. Hence, different maximum power points (MPP) can be obtained when PV modules arranged in rows are substituted, as is evident from the widespread literature on the topic [24]. For instance, consider the case where four modules shown in Figure- 4 (a) have varying irradiance conditions. When the positions of modules 3 and 4 are switched. On the other hand, when the modules are shifted in the same way in TCT arrangement (see Figure- 4(b)), there is no effect on the array power or current because the row current stays the same no matter what the position of PV modules is and whether any module is added or eliminated. The SP and TCT configurations shown in Figure- 4 were simulated to demonstrate this kind of electrical behaviour.

This was done by taking into account the BP585 PV modules (which were half of the panel shown in [3] using severe mismatching conditions with the irradiance of the four PV modules being 1=1000/2, 2=400/2, 3=800/2, and 4=200/2. The outcomes obtained through simulation are demonstrated in Figure- 5 in which the SP and TCT both produce similar power profile when the same mismatching profile is provided (SP and TCT option 1). When partial shading is provided to the PV array by means of a fixed obstruction like a post or a tree, a scenario quite normal in urban areas, there is a shift in irradiance if the position of sun also shifts which results in shaded modules becoming un-shaded and vice-versa. The movement of clouds can provide the same results. A model of this condition can be constructed by shifting irradiances of modules 3 and 4, which results in a change in power curve in the SP (SP option 2) with universal MPP, however, in TCT there is no change in the PV power curve.

Hence, when mismatching profile is not kept constant or is unknown, which is quite common, TCT arrangements prove to be an interesting alternative. However, the SP arrangements are used in small and large PV plants to a large extent which is why there is a need to have an instrument for comparing the two arrangements. It is also becoming quite important to find out the most appropriate reconfiguration for small PV systems, where the purpose of active reconfiguration of the array is to achieve the highest PV power possible. The TCT

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arrangement is largely accepted as a reconfiguration method in these situations [21, 26, 27], making it imperative to have an appropriate MPPcalculation method.

3. PV SYSTEM WITHIN MISMATCH CONDITIONS

One of the major issues experienced by the PV solar cells is shadowing which creates the hot spot problem. This is why several investigations were carried out earlier to solve the issues created by shadowing. If one cell in a series string of solar cells is shadowed. The phenomena of reverse bias and consecutive micro plasma breakdown has been explained and modelled by [9]. A comprehensive assessment was carried out by [28] who used Bishop's model to reach deductions pertaining to the creation of hot spot and reduction of the PV array output. The model parameters were obtained from calculations made by [28]. It was noted by all authors that there is a greater variation observed in solar cell I-U properties in reverse bias as compared to forward bias, which was statistically validated by [29].

It was also determined by [28] that greater energy losses result because of an incorrect PV array arrangement when there is shadowing, with even the smaller shadows having a significant impact on the energy yield. Bypass diodes were used to secure the shadowed solar cells from disintegrating. Several authors investigated how the PV modular design could be made optimal and tried to find out the greatest number of solar cells per bypass diodes essential for preventing the creation of hot spots in the 1980s [30-32]. As per IEC 61215 (1993), a test for hot-spot endurance became an essential aspect of the acceptance for crystalline silicon modules. When a solar cell string that has N cells and one bypass diode, the breakdown voltage of a reverse biased solar cell should have an absolute value which should be greater than 'n' and up to n11 times 0.5V. The approximate value of this is equivalent to the MPP voltage of the n21 un-shaded crystalline silicon cell conFigure-d in series in addition to the transmission voltage of a silicon bypass diode, that is, from 0.5 to 1 V. The solar cell that has the maximum breakdown voltage and, therefore, the maximum leakage current [33, 34] is the weakest connection of the cell string. The breakdown voltage of a solar cell for crystalline silicon modules of the current times is normally taken to be below 210V which is why one bypass diode is applied most of the times for 18 cells in a series. In the present times, multiple parallel interconnections present between cell strings in a particular module are not applicable anymore, as has also been discussed in the past studies. The commercially available reverse biased, a 1.4 A with maximum cell temperature rising up to 125.8 C at 210 V reverse voltage. This investigation shows that the reverse bias behaviour is particularly for the cell type being studied [34, 35]. Identical outcomes were obtained in the studies performed recently, which allowed for making the conclusion that the production process should consist of cell sorting with respect to leakage of current.

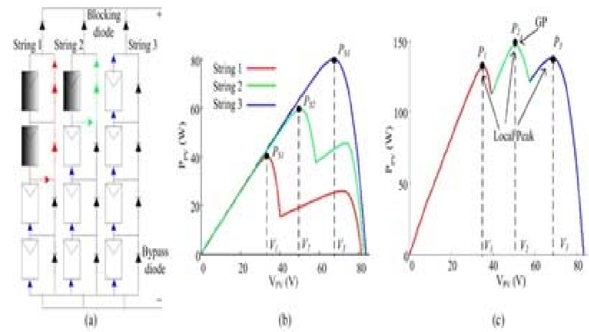

Figure-6. PV array operation under partial shading (a), P-V characteristic curves for each string (b), P-V characteristic curve for entire PV(c) [36].

This would allow few cells to be used for a single bypass diode in those modules which were particularly produced from cells with greater leakage current and breakdown voltage [37]. The mid 1990s saw a growth in the architectural integration of the PV into facades and roof arrangements because of which it was being asked whether it would be possible to eliminate or decrease the number of large external bypass diodes. The outline presented by the German federal research and development (R & D) project, was used to carry out the research. These researches showed that for glass/glass modules, unless there are changes in the module design through application of wider cell connectors, the bypass diodes should not be removed [38]. A maximum breakdown voltage of 27.2 V has been noticed when these measures for peak solar cells are applied. This causes a decrease in leakage temperature by around 16 K [38]. Reference [39] calculated PV modules and simulated using cast shadows. The study showed that the removal of bypass diodes is only feasible when the allocation of irradiance is almost always homogenous. It is also important that all cells used behave in the same way under reverse bias, with the shunt resistance not being very high. In many circumstances, partial shadowing can lead to hot spot and cells spoil and come with MPP having different positions on the characteristic curve of modules. Having done so, partially shadow can avoid by selecting many techniques [40]. This case normally happened within the central inverter technique [41].

In reference [34] demonstrated that the configuration of the PV modules has a main role in determination magnitude of the global peak which depends mainly on the shading pattern besides the commonly known factors, i.e., temperature and insolation level. It was also verified that, if the prospective partially shading form on the PV system is identified can build a manageable model to initiate the optimal configuration of the PV system to track the maximum power and at the same time to avoid the expected hot spot on the PV system[34].

Beside to these topologies in mitigating the partial shadow losses, proposed a situation of configuration that insert a parallel bypass diode with each

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module for the whole system when effective irradiance levels seen by each module are shown in Figure-6. have reduced partial shading losses when turning ON of bypass diodes[36].

4. CONCLUSIONS

In this paper, the state of the art of PV reconfiguration algorithms has been reviewed. As has been established, there are many techniques of configuration and grouping the methods for interconnection the PV generator. However, in this article the Series Parallel (SP) interconnection, Total Cross Tied (TCT) interconnection, and finally Bridge Linked (BL) interconnection techniques were those selected and developed in depth.

Most of the reviewed articles claimed that, Total Cross Tied (TCT) interconnection has particular feature comparing with the other two selected techniques which it has a substantial reduction in mismatch losses that occur due to partial shading, beside to it has greater reliability comparable with others interconnections. In addition, the manufacturing cost of the TCT would be comparable to that of the SP.

Also investigated that, the methods of interconnection SP and TCT supposed to be more popular and more widespread than BL interconnection method, so it less focused from the others. Furthermore, an assessment of the manufacturing cost of TCT-connected modules, TCT-connected modules do not cost more than the SP-connected modules or BL –connected modules during mass level production, but in general the TCT has a greater amount of parallel circuits as compared to the SP. On the other hand, the TCT has a greater amount of parallel circuits as compared to the SP and the BL interconnections.

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