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REVIEW OF PV ARRAY INTERCONNECTION SCHEMES FOR MAXIMUM POWER OPERATION UNDER PARTIAL SHADING

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ABSTRACT: Published results on the performance of photovoltaic arrays under partial shading conditions are thoroughly reviewed, for a variety of conventional array interconnections. New results are presented for a wide variety of realistic shading patterns, and for several new hybrid methods of interconnection. The fully cross-tied array is found to give the best performance, and the simple series – parallel array the worst. In the more favourable shading cases, much of the excess loss in available power due to the shading can be recovered by adding the interconnections. An important result is that most of the power recovery can usually be achieved using a hybrid array with fewer interconnections, and hence lower cabling costs, than the fully cross-tied form.
Keywords: Photovoltaic, PV Array, Total-Cross-Tied (TCT), Maximum Power, Hybrid Array

1 INTRODUCTION

One of the proposed solutions to mitigate the effect of partial shading on a PV array is interconnecting the PV modules in different ways, hence forming different array configurations [1]. Conventional configurations include: **Simple Series (SS)**, **Parallel (P)**, **Total-Cross-Tied (TCT)**, **Bridge-Linked (BL)**, and **Honey-Comb (HC).** Many new varants were developed in recent years [2], and their comparative performance under partial shading has been studied [3]. It has been concluded that the parallel array is more robust under shading effects, and less prone to mismatching losses, than all the other configurations, but its low output voltage may be impractical. Conversely, simple series connections of PV modules are most liable to substantial power reduction due to the the mismatching effect [4].

Studies [5, 6] have been made of the electrical behaviour of differently sized arrays in SP, BL and TCT configurations. A comprehensive comparative study was performed between 3×4, 4×3, 6×6, 6×2, 2×6 and 9×4 arrays considering the shading condition. Results were compared on the basis of the Fill Factor (FF) as well as the Global Maximum Power Point (GMPP).

Two modelling techniques, Piecewise-Linear Parallel Branches [PLPB] and Newton-Raphson models have been used by [7] to analyse the output performance of S, SP, TCT, HC and BL arrays under a particular shading case. Results again showed the TCT topology outperforming the other array configurations in terms of ouptut power, but only a single pattern of shading was considered. Authors in [8] tested various cases of a random shading on different PV array configurations by software simulation. They concluded that TCT is less susceptible to the effect of mismatch losses compared to the other array configurations. They also claimed that TCT and HC are the most suitable configurations for both symmetrical and asymmetrical arrangements of a PV array, respectively. Only a random shading pattern was considered, which may not give completely conclusive nor quantitatively realistic results.

Recent developments in PV array interconnection technique have led to renewed interest in deriving new hybrid PV array configurations by modifying the conventional array connections into **SP-TCT**, **BL-TCT** and **BL-HC** arrays.

A comparative simlulation study was carried out by [9] to analyse the shading effects on SP, BL and TCT configurations. The performance of these arrays was evaluated with and without protection diodes. As a result, TCT showed a better output performance than SP and BL topologies under PSCs. [10] conducted a simulation study on a 4×4 array size of TCT, BL and SP configurations under a moving shading pattern. In this study, the authors found that the maximum power is extracted by selecting an array configuration that is best suited to the shading conditions.

More general ways of interconnecting arrays have been considered [11-15] and raise the question of loss occurring in the longer interlinking cables, and their increased cost.

The present paper thoroughly reviews the traditional along with the hybrid array configurations and highlights their advantages and limitations. New results are presented on the basis of six different and more realistic shading patterns, as will be defined. The comparison study has been conducted on a 4×5 array. Performance of all the array topologies is mainly assessed by comparing their Global Maximum Power Points (GMPP), the Mismatch Power Loss (ML) and the Fill Factor (FF). Several recommendations are made for addressing the shading issue using different array schemes, and further discussions are included on how to select the optimal array connections with a smaller number of ties, thus decreasing the complexity of the PV system and also the cabling costs.

2 PV ARRAY INTERCONNECTIONS

The simplest form of PV array connection is one with all the modules connected either in series or parallel, and the authors in [16] have discussed the performance in detail. In a simple series string, a bypass diode is connected across each PV module to prevent it from operating in the reverse breakdown condition [17]. When one module is less illuminated, for example, its bypass diode may be activated so that the higher current from the more illuminated modules can still flow through the entire string. In this case, the module which receives less solar irradiance will be prevented from generating power. Similarly, in a parallel string, the blocking diode of the less illuminated module is activated and prevents it from either producing or absorbing power [18]. It is more likely that a bypass diode will be activated than a blocking diode in most shading conditions [19]. Though parallel connection appears to have better performance under non-uniform illuminations, its terminal voltage is significantly lower and may have to be boosted before being linked to the grid through an inverter [20]. This process will be inefficient for high voltage boost ratios, and a mixed series-parellel array is almost certain to be adopted in practice.

Authors in [21-24] have therefore proposed and tested several array interconnections such as SP, TCT, BL and HC, or any combination of two of these [11-15]; these can be classified into two groups, traditional and hybrid, as shown in Figs. 1(a-d) and Figs 2(a-c) respectively. These are now discussed.

2.1 Traditional Array Configurations

PV arrays connected in **series and parallel (SP)**,as shown in Fig.1 (a),are the most common configurations and [25] has discussed their performance in detail. In this topology, a few series strings of PV modules are connected in parallel as shown in Fig. 1(a) to obtain the required voltage level and current level. This SP topology has some advantages as it is easy to implement, has no redundant connections, and hence is more economical to build [26]. Convenient voltage and current levels can be achieved simultaneously [27]. It has no interconnection between two series strings, hence if one module is less illuminated, its bypass diode is activated and the series string's voltage will drop. Then all the modules of the same string may be prevented from generating power due to the requirement to activate the associated blocking diode [28].

Authors in [29] proposed the **tied-cross-tied (TCT)** connection which alleviates these issues of SP, and is derived through fully cross-tying the rows of junctions as in Fig.1(c). Thus, the total array voltage is determined by summing the voltage across the individual rows, and the overall current is the sum of the currents flowing in all the strings in the array. The cross ties within the TCT configuration reduce the possibility of turning on bypass diodes and can increase the lifetime of the PV array to nearly double that in SP form [30]. When one module is less illuminated, the higher current of the other more illuminated modules can flow in the other series strings through the cross ties without the need to activate the bypass diodes of the shaded module [31]. The ability of the current to flow from one series string to another also implies that one module can be open circuited. For example, [28] shows that since one short circuited module does not disable an entire string, the TCT scheme allows one module to be taken out for maintenance while other modules are in normal operation. It has been proven in [17] that the TCT topology offers a better output performance than the SP scheme. In this work, a mathematical modelling approach has been used to demonstrate that the mismatch power loss (ML) is significantly less than that of the SP scheme. The authors in [29] pointed out that the TCT topology offers a better output performance than the SP scheme under any kind of shading condition while those in [23] highlighted that, for most cases, there is only a single power peak in the power-voltage (P-V) characteristic of TCT arrays, especially when they experience column-wise shading. However, there are many redundant links (the cross ties) in TCT arrays and if all the PV modules are experiencing uniform illumination, there will be little or no current flowing through these links [22].

The many redundant links of TCT may incur some cost penalty, and several authors [21-24] proposed and tested alternatives. One is based on the **bridge link (BL)** topology as shown in Fig. 1(b). The modules are connected in a form reminiscent of a bridge rectifier circuit where every four neighbouring modules are grouped together. Between two groups of these modules, a cross –tie link is inserted to connect two adjacent series strings so that all the links resemble a brickwork pattern based on the stretcher bonding method [11]. Clearly this configuration shows fewer tie-cross links, but has more alternative current paths than the SP scheme so the ML is lower than that of SP under partial shading [32]. Considering Fig. 1(b), it can be seen that the number of these links in BL is half of that in TCT, so reducing wiring cost and installation time. The work in [24] showed that the BL form can achieve the highest maximum output power point compared to both the TCT and SP arrays, but this was only under certain shading patterns. Results in [26] showed that TCT outperforms BL under most partial shading conditions while work in [23] shows that BL can deliver the second highest maximum power among SP and TCT configurations under the column-wise shading. Therefore, the authors in [33] have clearly stated that BL is generally more sensitive to mismatch effects than TCT.

Another alternative configuration to BL topology is based on the **Honeycomb (HC)** structure as shown is Fig. 1(d).

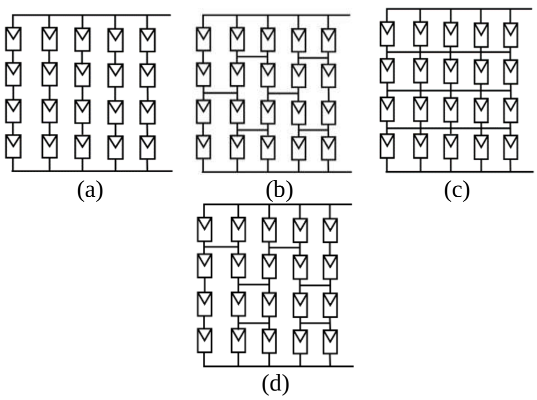


Fig. 1: Traditional PV array topologies; (a) SP; (b) BL; (c) TCT; (d) HC

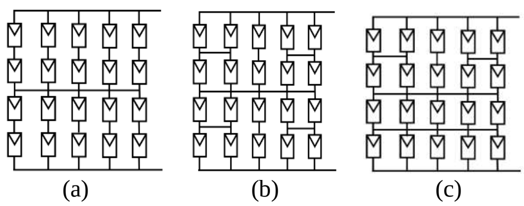


Fig. 2: Hybrid PV array topologies; (a) SP-TCT; (b) BL-TCT; (c) BL-HC

Similarly to the BL array, the cross-tie links connecting the adjacent series strings form a pattern like brickwork based on the combined stretcher and header bonding method [9]. For example if the first two columns from the LHS have a cross link at the first row from the top, the second and third columns have the cross link at the second row. Then the third and fourth columns have the cross link at the same row as the first two columns, and the fourth and fifth repeat the second and third. This configuration was claimed in [3] to combine advantages of both BL and TCT. According to [4], when the array columns and rows are not equal (asymmetrical), HC outperforms TCT in this case under specified shading conditions. However in the work in [33], TCT still generally shows the better output power performance than HC under most shading conditions, since the former still offers the maximum number paths for the current flow. Only a limited amount of research has been carried out on the HC configuration, which is still largely unexplored.

Among all the traditional array configurations, it is clear from the literature that though the cost is higher, TCT configuration is able to deliver the best performance.

2.2 Hybrid Array Configurations

Recent developments in the field of PV array interconnections have led to renewed interest in deriving new hybrid array configurations. Traditional array connections have been modified into **SP-TCT**, **BL-TCT** and **BL-HC** arrays as seen in Fig. 2(a-c), respectively. [15, 16] stated that these recently derived hybrid configurations can also generate better power levels than TCT under most PSCs.

SP-TCT [23] has rows completely cross linked at every other row, and can be characterized as the scheme with the lowest possible redundancy in terms of the number of internal connections, compared to either BL-TCT or BL-HC. However, SP-TCT usually generates less power than the other two hybrid configurations and presents more power peaks in the PV curve under most shading cases [16].

The work of [11] has shown that the hybrid BL-TCT topology can become an alternative solution to the shading effect and one which can replace TCT, as it reduces the number cabling connections compared to TCT which in turn minimises the stress on the PV modules. However, the performance of the three hybrid array configurations has been examined by [15, 16, 23, 24, 25] and compared with that of TCT along with another proposed reconfigured arrangements of PV arrays based on static reconfigurations techniques, where the electrical connections of the arrays are fixed while the location of the panels are re-shuffled within the array in order to disperse the shading effect widely over the entire array, thereby increasing the current of each row. The results showed that these reconfigurable arrays based on a particular shade dispersion puzzle pattern could overcome the limitations of both TCT and hybrid configurations, respectively, and also lead to higher power extraction.

3 DEFINITIONS OF PERFORMANCE INDICATORS SHADING PATTERNS FOR DIFFERENT PV ARRAYS

Some new results will now be given for traditional and hybrid arrays, using a greater variety of more realistic shading patterns. The common performance indicators which have been used to evaluate the arrays discussed in Section 2 include the Maximum Power (MP), Mismatch Power Loss (%ML) and Fill Factor (FF) of a PV array. The following sub-sections explain all these performance indicators and then show examples of several common shading conditions.

3.1 Assessment Criteria

Maximum Power (MP): The most straightforward indicator is the maximum amount of power that can be extracted from the PV array under a specific weather condition [23, 24]. Normally the peak point of the P-V characteristics of an array is the desirable operating point for maximum power extraction; this corresponds to specific voltage and current values. Due to the partial shading effects as described in Section 2, more power peaks can be present on the P-V characteristics and there is only one global peak point, P_{GMPP} that gives the highest power [16]. The voltage at which this operation occurs changes for different weather conditions. There is a huge amount of work has been done for tracking and controlling a PV array so that it always generates P_{GMPP}[25]. Even when a PV array is operating at P_{GMPP} point, not all PV modules are delivering their maximum powers due to the activation of the bypass and/or blocking diodes, as highlighted in Section 2.

All the results quoted below assume that only the total terminal voltage of the array can be varied by using a single variable ratio converter at the array output terminals. However, it is assumed that this voltage is freely variable and that the controller can always locate the value required to reach the array's global power peak.

Mismatch Power Loss (ML): This can be obtained using the following equation [23-25]:

$$\%ML = \frac{P_{sum} - P_{GMPP}}{P_{sum}} \times 100 \qquad (1)$$

where %ML indicates the percentage of the Mismatch Power Loss, P_{sum} is the total power available to all individual modules when they are connected separately to the system or load. This indicator is equal to one when all PV modules are delivering all their maximum powers.

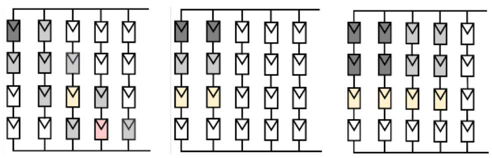
Fill Factor is the ratio between the global peak power and the product of the short-circuit current and open-circuit voltage of the PV array under the partial shading condition. The fill factor is determined as[23]:

$$FF = \frac{P_{GMPP}}{I_{SC} \times V_{OC}} \qquad (2)$$

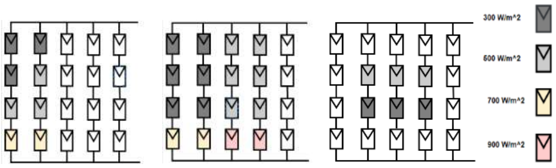
where I_{SC}, V_{OC} both refer to the short-circuit current and open-circuit voltage of the PV array respectively. Fill Factor of each array configuration is calculated and presented in Table III under different shading patterns.If the fill factor is close to unity, the array performance is considered to be better.

3.2 Shading Patterns

There are different types of shading patterns considered in the simulation study where PV modules receive different levels of solar irradiances, such as diagonal, Short-Narrow (SN), Short-Wide (SW), Long-Narrow (LN) Long-Wide (LW) and Centre shadings. As shown in Fig. 3, all these have been demonstrated through an example the 4×5 PV array and the shading patterns follow the description of the experimental work carried out by the authors in [24]. Additionally, specifications of a single PV unit are tabulated in Table I and applied for the Simulink model under standard uniform conditions where the solar irradiance is **1000 W/m²**, and the cell temperature is **25C⁰**.



(a) (b) (c)



(d) (e) (f)

Fig. 3: Different shading patterns; (a) Diagonal; (b) SN; (c) SW; (d) LN; (e) LW; (f) Centre

Table I: PV Module Specifications

Maximum Power P_{max}	**106.2468 W**
Open Circuit Voltage V_{oc}	**22.17 V**
Voltage at MPP V_m	**17.77 V**
Short Circuit Current I_{sc}	**6.573 A**
Current at MPP I_m	**5.979 A**
Number of cells in series	**42**

4 PERFORMANCE ASSESSMENT OF PV ARRAYS UNDER PARTIAL SHADING CONDITIONS

Using the indicators described in Section III, this section discusses the performance assessment of the traditional PV array configurations to decide the best array arrangement that leads to a significant power extraction.

The assessment is done on the example of a 4×5 PV array under different shading patterns as illustrated in Fig. 3. A comprehensive comparison between both the traditional and recently derived hybrid PV array configurations is presented under chosen realistic shading conditions. A **MATLAB/Simulink** software was used to simulate the array topologies under different PSCs.

4.1 Performance of the Configurations under Each Shading Pattern

Figs. 4 – 9 present the P-V characteristics of the traditional and the hybrid PV arrays under different shading conditions. The maximum global power of each array scheme is tabulated in Table II under the mentioned shading patterns and the performance of all arrays under each shading condition is discussed in the following sub-sections.

4.1.1 Diagonal shading (DS)

The simulation results reveal that TCT array configuration has the best power performance with P_{GMPP} of **1566W**. From the data in Table IV, it is observed that it has the lowest ML of **1.5%**. This configuration also produces no local power peaks when comparing to the other configurations under diagonal shading type, implying the bypass diodes are less like to be activated. From the data in Table II, the new hybrid array topology BL-HC shows relatively good results as compared to TCT. It has the second best performance delivering $P_{GMPP}$of **1484W**. This topology as well as BL-TCT only have slightly less ML than TCT. However, SP has the lowest power performance under this pattern. This topology and HC arrays have MLs of **28.8%** and **19.8%** respectively. In short, any array topologies having some tie-cross links will enable them to have higher MP and lower ML.

4.1.2 Centre shading (CS)

Under this pattern, TCT array is proved to have the best power performance having P_{GMPP} of **1384 W** with MLof **20.66%.** This is followed by BL-HC and BL-TCT generating P_{GMPP} of **1383 W** and **1379 W** respectively having ML of **20.95%** and **20.72%**. The P_{GMPP}in BL, HC and SP-TCT are less than that in TCT by **3.9%**, **3.76%** and **4.12%** respectively. On the other hand, SP configuration showed the lowest power performance; its P_{GMPP} is **8.16%** less than that of TCT.As more series strings are affected by shading, the MLs are slightly higher for all array configurations as compared to those of other shading patterns.

4.1.3 Short-Narrow shading (SN)

TCT configuration again has the highest P_{GMPP} of **1664** as shown in Table II and Fig. 6. P_{GMPP}in all BL related configurations including BL, BL-TCT and BL-HC are lower than that of TCT by less than 3% while in SP-TCT and BL-TCT, the percentage difference is in between 3-5%. SP has the lowest P_{GMPP} of **1552W**.

4.1.4 Short-Wide shading (SW)

As seen from the data depicted in Tables II&IV and Fig. 7, all the PV array configurations have almost similar range of P_{GMPP} where TCT, BL-TCT and BL-HC have the highest P_{GMPP} of **1201W** while it is **1160W** in SP. In terms of power loss, TCT, BL-TCT and BL-HC are considered as the most efficient configurations under this shading condition since they presented the lowest ML of **19.6%** while SP has ML of **22.3%**. Nevertheless, the mismatch power losses for all array configurations under this shading pattern can be as high as those under centre shading and as observed in Fig. 2, more series strings are experiencing non-uniform illumination levels.

4.1.5 Long-Narrow shading (LN)

The presented results in Table II and Fig. 8 reveal that TCT is the most efficient configuration under this shading pattern since it has P_{GMPP} of **1625W**. BL and SP-TCT have P_{GMPP} of **1599W** and **1598W** respectively while SP array produces P_{GMPP} of **1549W** when compared to the other array configurations. TCT has ML of **3.41%** followed by BL-TCT and BL-HC, all of which has MLs of **4.7%** and **4.5%** respectively. The ML of SP is the highest at **7.9%**, implying that the SP array is still highly vulnerable to the effect of this shading pattern. These and all the MLs of all traditional and hybrid array configurations are lower than other shading conditions. This may be mainly because most of the modules in the affected series strings are experiencing uniform solar illuminations though they are lower than those of the unshaded modules. Also SP configuration has three multiple local power peaks, but none of the other array configurations showed local peak points.

4.1.6 Long-Wide shading (LW)

The traditional and hybrid configurations showed very similar power performance where TCT and BL-HC have the highest P_{GMPP} of **1149W** followed by BL and HC configurations with P_{GMPP} of **1141W**. SP and SP-TCT have the lowest global power values. These values as well as those of other configurations are generally lower than those of other shading conditions. This could imply that more bypass diodes are likely to be activated when all the array configurations are experiencing this shading condition. TCT and BL-HC has the lowest mismatch power loss of **7.4%**.

Under all the above shading conditions, the performances of all the array configurations discussed in Section II can also be analysed in terms of their FFs using the data in Table III. TCT, BL-TCT and BL-HC appear to perform better than the other array schemes, as their FFs are close to unity under PSCs.

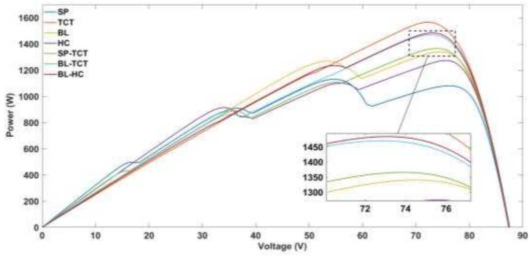


Fig. 4: Diagonal shading

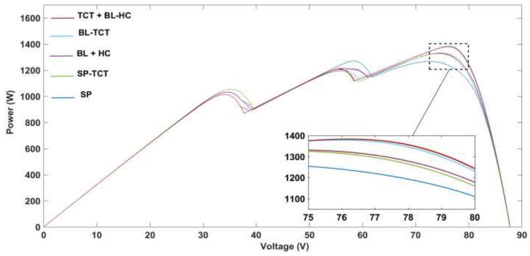


Fig. 5: Centre shading

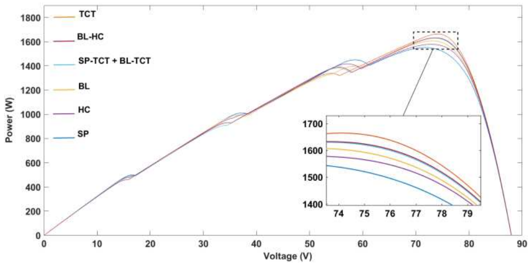


Fig. 6: Short-Narrow (SN) shading

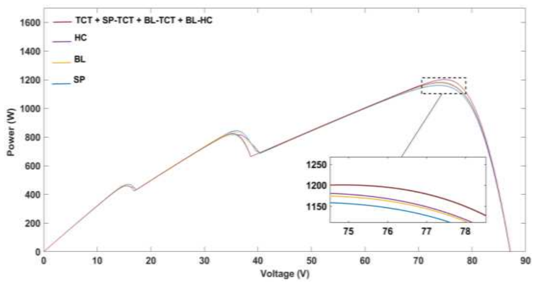


Fig. 7: Short-Wide (SW) shading

5 SUMMARY OF THE OBTAINED RESULTS AND RECOMMENDATOINS

From the above study, three insights can be generated for any pattern: the total power output P_{sum}, which is ideally possible under different shading patterns, the global peak power of each array topology can actually produce, and the mismatch power loss under all listed shading patterns.

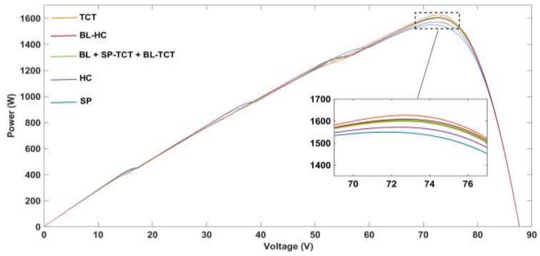


Fig. 8: Long-Narrow (LN) shading

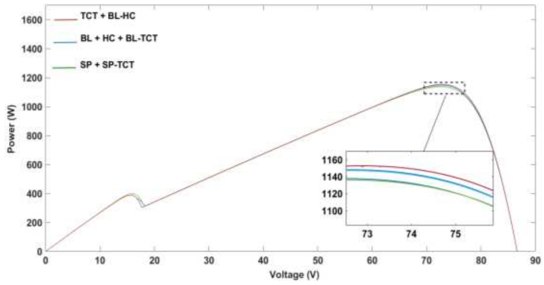


Fig. 9: Long-Wide (LW) shading

Out of six different shading conditions, one can see that LW gives the lowest P_{sum} of **1282 W** as shown in Table II. For this case, the average P_{GMPP} for all array topologies is a low **1141 W**, or **89%** of P_{sum} for this shading condition. The next lowest is SW, where P_{sum} a higher **1494 W**, and the average global peak power, P_{GMPP}, for all seven array connections is about **1188 W**, **80%** of its corresponding P_{sum}. Though, under both these shading conditions, P_{GMPP} values for TCT connection are the highest, and the results for the two hybrid topologies, BL-TCT and BL-HC, are close, the differences in P_{GMPP} for all array topologies, including TCT, are small. For example, for LW shading, P_{GMPP}/P_{sum} is **89%** for TCT and **88%** for SP. For SW shading, the corresponding figures are **80%** and **77%**. Hence, no array connection gives substantial improvement over SP, which proves to be the worst case for all the shading patterns. This is because these two shading patterns degrade most of the panels in a single row and the cross ties cannot do much to improve the output power. The above implies that under these two shading cases, changing the array configuration may not be cost effective.

On the other hand, the shading pattern SN has the highest P_{sum} of **1808 W**, because the shading area is the smallest. Consequently, the average P_{GMPP} for all topologies is a higher **1613 W**, **89%** of P_{sum} for this shading case. TCT gives the best power performance with P_{GMPP} being **92%** of its corresponding P_{sum} value, followed by three hybrid configurations. The poorest, SP, is about **86%**. Similarly for LN pattern, though in this case P_{sum} is lower than that of SN, TCT produce highest power with P_{GMPP} nearly **97%** of its P_{sum} and the lowest SP is just **92%**. The hybrid configurations remain close to TCT in performance. Thus under SN and LN shading patterns, the change of configurations can lead to up to more power.

For CN case the ideal power sum is a relatively high **1744 W**, but the array configurations give a low global maximum power with P_{GMPP} equal to **1271 W** for the SP array and averaging **1350 W** for the other arrays. Thus, for this shading pattern, it is worth changing from SP to TCT, BL-TCT or BL-HC, but the result is still substantially below the ideal.

The situation is different for the DS pattern, where there is a marked improvement for the TCT topology and its performance approaches the ideal. Interestingly, however, most of the performance can also be recovered with one of the hybrid connections.

This finding was unexpected and suggests that shading can substantially degrade the average performance of an array and that some other power optimisation algorithm should be invoked to increase the output power for the "bad" shading cases.

The percentage mismatch power loss %ML gives a clear impression of the performance loss caused by the unavoidable departures from individual maximum power points in the shaded array. It references the achievable array power P_{GMPP} to the ideal power P_{sum}, which itself varies with the shading, hence %ML and are not functionally related but they are highly correlated. Table IV shows %ML for the same array topologies under all 6 shading patterns. Under LN shading the average loss for all array connection is the lowest, this conforms to the Table II where the average P_{GMPP} in this case is very close to the corresponding P_{sum}. On the other hand, CN gives highest average loss. In all cases TCT gives lowest average loss compared to all the other topologies and SP's average loss is the highest.

Table III shows the calculated FF for the various shading patterns and array interconnections. The results show the same trends as the above two performance parameters, in that the TCT connection is the best and SP is the worst. Particular for DS shading pattern, TCT is as high as 70%, followed closely by two hybrid shading patterns, BL-TCT and BL-HC. However, for other shading patterns, the improvement offered by cross-tying the array is quite limited. The best cases of the hybrid arrays can offer much of the improvement offered by TCT with reduced interconnection costs.

6 CONCLUSION

The paper considered the potential of ameliorating the effect of partial shading on a PV array by optimising the array interconnections. The fully cross-tied (TCT) array is the best but similar improvements may be obtained from hybrid interconnections. There is some penalty in the cost of adding cabling to the array, and for many shading patterns the benefit is quite limited.

The simple cross – tied topologies considered here do not exhaust the possibilities. A more general modification can be defined conceptually by keeping the array interconnections, of whatever complexity, fixed but moving the panels to different physical locations with the array. Since however the panels are nominally identical, this can be reduced to an equivalent array with the panels not moved but with more general (and sometimes longer) interconnections. It can obviously change, and potentially improve, the average array performance since the shading patterns will exhibit statistical spatial correlations. Later work should evaluate the potential of these more general ways of cross-linking the array, whether in a static or adaptive configuration.

Table II: P_{GMPP} and P_{sum} of PV arrays under PSCs [W]

Shading case	P_{sum}	SP	**TCT**	BL	HC	SP-TCT	**BL-TCT**	**BL-HC**
Diagonal	1589	1131	**1566**	1340	1274	1366	**1470**	**1484**
Centre	1744	1271	**1384**	1330	1332	1327	**1379**	**1383**
SN	1808	1552	**1664**	1607	1579	1630	**1630**	**1632**
SW	1494	1160	**1201**	1175	1181	1200	**1201**	**1201**
LN	1682	1549	**1625**	1598	1571	1599	**1603**	**1607**
LW	1282	1135	**1149**	1141	1141	1134	**1140**	**1149**

Table III: Fill Factor (FF) of different PV arrays

Shading	SP	**TCT**	BL	HC	SP-TCT	**BL-TCT**	**BL-HC**
Diagonal	0.39	**0.70**	0.58	0.50	0.51	**0.61**	**0.64**
Centre	0.44	**0.48**	0.46	0.46	0.46	**0.48**	**0.48**
SN	0.54	**0.57**	0.55	0.55	0.56	**0.56**	**0.56**
SW	0.41	**0.42**	0.41	0.41	0.42	**0.42**	**0.42**
LN	0.61	**0.64**	0.63	0.62	0.63	**0.63**	**0.63**
LW	0.53	**0.53**	0.53	0.53	0.52	**0.53**	**0.53**

Table IV: Mismatch power loss (%ML) of different PV arrays

Shading case	SP	**TCT**	BL	HC	SP-TCT	**BL-TCT**	**BL-HC**
Diagonal	28.8	**1.47**	15.7	19.8	14.1	**7.51**	**6.6**
Centre	27.1	**20.7**	23.8	23.6	23.9	**20.9**	**20.7**
SN	14.2	**8**	11.2	12.7	9.9	**9.9**	**9.8**
SW	22.3	**19.6**	21.3	20.9	19.7	**19.6**	**19.6**
LN	7.9	**3.4**	5	6.62	4.9	**4.7**	**4.5**
LW	11.5	**10.4**	11	11	11.6	**11.1**	**10.4**

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