Journal of Theoretical and Applied Information Technology
30th November 2021. Vol.99. No 22

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

CHARACTERISTICS OF PHOTOVOLTAIC MODULES IN VARIOUS CONFIGURATIONS FOR PARTIAL SHADING CONDITIONS

[1,2]ASNIL, [1,2]KRISMADINATA, [1,2]IRMA HUSNAINI, [1,2]ERITA ASTRID

[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Negeri Padang, Indonesia

[2]Centre for Energy and Power Electronics Research (CEPER), Universitas Negeri Padang, Indonesia

E-mail: [1]asnil81@ft.unp.ac.id, [2]krisma@ft.unp.ac.id, [3]irma_hnni@ft.unp.ac.id, [4]erita.astrid@ft.unp.ac.id

ABSTRACT

Partial shading conditions (PSCs) can cause a significant reduction in energy output in photovoltaic (PV) systems. This paper recounts the characteristics of PV in various condition of PCSs. The compared PV characteristics involve voltage, current, generated power, fill factor, mismatching loss, and efficiency. Six configurations of the PV system are used in this research namely Series-Parallel (SP), Honey Comb (HC), Total Cross Tied (TCT), Bridge Linked Honey Comb (BLHC), Bridge Linked Total Cross Tied (BLTCT), and Series-Parallel Total Cross Tied (SPTCT). The PSCs are considered uniform, short and narrow, long and narrow, long and wide, short and wide, and corner. The result indicates that TCT configuration is the best configuration among others then followed by the BLHC, BLTCT, SPTCT, HC, and SP configurations.

Keywords: *Partial Shading Conditions; Photovoltaic System Configuration*

1. INTRODUCTION

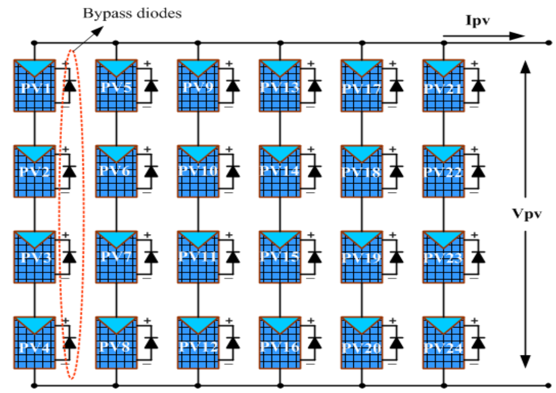
Solar energy is an abundant renewable energy source where electrical energy received from it is converted using solar cells/modules/arrays by applying the principle of photovoltaic effect. Environmental conditions such as the level of irradiance and ambient temperature have a great influence on the performance of the PV system's [1]. High levels of solar radiation increase the electric power generated [2]. Meanwhile, an increase in temperature value causes the reduction of output voltage. The energy produced is inefficient and can decrease solar panels' quality even though the current output increases. However, in the real condition, there are other factors that can affect the generated electrical energy and a shadow's presence. In PV system, there is condition when PV receives different levels of solar irradiation or exposure due to several factors such as clouds, shadows from trees and buildings, dust, and bird dropping. This phenomenon is known as a partial shading condition [3], [4]. When this condition happens, the power output of the shaded cells/modules/array decreases and it can reduce the current output and increase the temperature which lead to permanent damage of PV cells and can reduce the PV lifetime [5][6]. Moreover, the decrease in output power from [7], PSCs also cause multiple Maximum Power Points (MPPs) in the I-V and P-V characteristics of the output system, which can mislead conventional Maximum Power Point Tracking (MPPT) techniques [8][9]. The effect of PSCs is also influenced by the type of PV used, the string's configuration against solar irradiation and the level of shade, and the placement of the bypass diode [10][11]. In order to increase the efficiency of PV, especially those exposed to shade and for hotspot anticipation, a bypass diode is used and connected to the PV module [12]. This allows currents generated by the unshaded cells to pass through the shaded cells, but this causes multiple peaks to be produced in I-V and P-V characteristics [13]. Recently, many literature have been published on how to reduce the adverse effects of partial shadows that occur in PV systems [14][15]. The reduced power generated from the PV system as a result of PSCs can be overcome with several approaches, including the configuration of the PV array [16][17], the architecture of the PV system [18], the MPPT technique [19], and converter topology [20][21].

The PV system architecture, MPPT, and converter topology have more complex configurations and require advanced knowledge of power electronic converters and higher costs.

Therefore using the PV system configuration approach is an effective solution to combat the decrease in PV system output power caused by the phenomenon that occurs mainly due to PSCs based on various interconnection techniques between PV modules [22]. As a result, the research to mitigate the reduced performance of PV systems caused by partial shading has become a popular topic.

Similar topics observing the effects that occur due to the presence of PSCs have been successfully conducted and discussed by previous researchers. The author [3] performed a comprehensive review to analyze the advantages and disadvantages of various configurations of PCSs such as Simple – Series (SS), Parallel (P), Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Linked (BL) and Honey-Comb (HC). The results show that the TCT configuration produces lower energy in the absence of shadows but is recommended to be implemented in areas that have temporary shade. The authors [5][14] used the Matlab/Simulink software to compare various PV configurations at different shade levels in order to find out which configuration can produce maximum energy by reducing mismatching power losses. The research show that the TCT configuration is the best configuration among the others. The Bishop model is utilized and developed by the authors [22] to conduct a comprehensive study in predicting how and when to use the configuration of PV in the event of shading. Research conducted on the asymmetric configuration of 6 x 4 PV arrays shows that the choice of configuration depends on the intensity, pattern, location and type of shade. However, the TCT configuration performed best in most cases of PSCs. Meanwhile, the author [23] investigated the performance of the SP and TCT configurations on the condition of the occurrence of shadows using Matlab/Simulink. The results of the study show that the TCT configuration has a lower power loss and has a higher FF.

In this research, an effective solution is provided to determine the best PV array configuration when it is under PSCs. A detailed modeling and simulation of PV system with six configurations (SP, HC, CTC, BLHC, BLTCT and SPTCT) is presented as well as the parameters required to observe the performance of each configuration. This simulation is carried out on various shading patterns with a 4 x 6 PV array system. The topology that will be used to observe the performance of the 4 x 6 PV system can be seen in Figure 1. Meanwhile the model to assess PV system with those configurations to analyze their performance on various shading patterns are presented in Figure 2.



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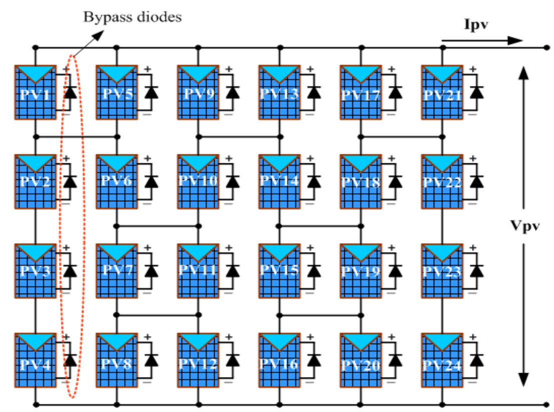

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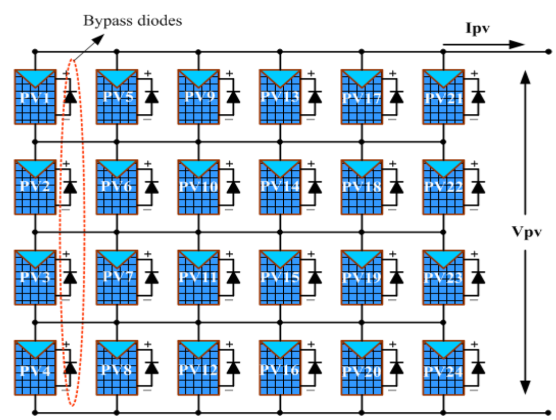

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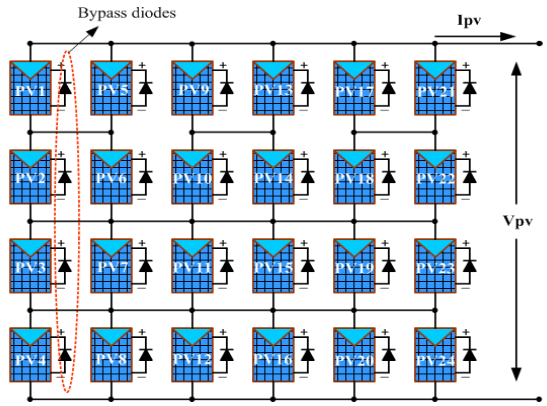

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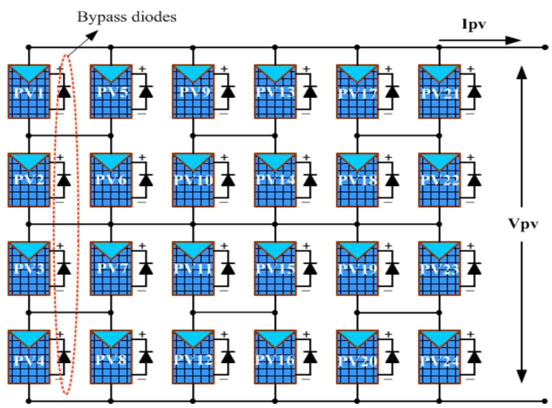

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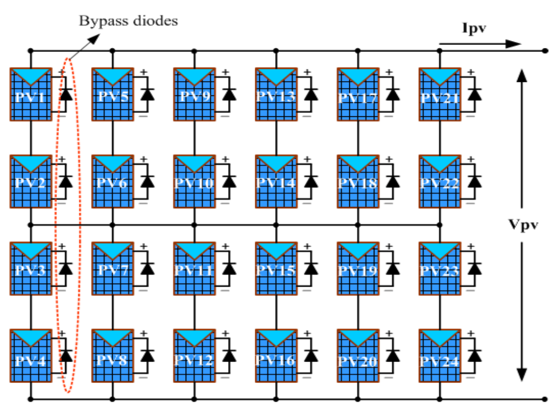

1. (f)

Figure 1. Configuration Of The PV System: (a) SP; (b) HC, (c) TCT, (d) BLHC, (e) BLTCT, (f) SPTCT

The PV system performances are observed and analyzed toward several parameters i.e short circuit currents (I_{SC}), open-circuit voltage (V_{OC}), global maximum power point (GMPP), local maximum power peaks (LMPPs), voltage and current at GMPP and LMPPs, fill factor (FF), mismatching power loss (MPL), and efficiency.

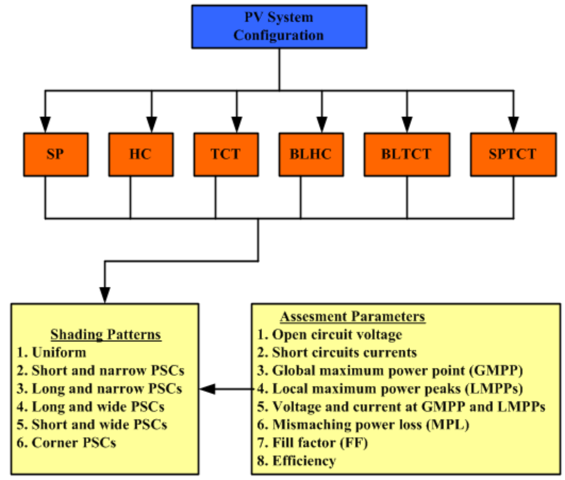

Figure 2. PV System Configuration And Parameters Used To Assess System Performance On PSCs

2. MATHEMATICAL MODELLING OF THE PV MODULE

The equivalent series of PV cells can be seen in Figure 3. This model is designed by connecting the semiconductor of type p and type n. Then the connection of semiconductor is manufactured in a thin film that allows it to convert the sun's energy into electrical power. Once the cell is exposed to sunlight, the photons that hit the cell will be absorbed by the semiconductor material, causing a transfer of electrons and producing electrical energy. The electrical energy produced by PV cells depends on the level of solar radiation and temperature.

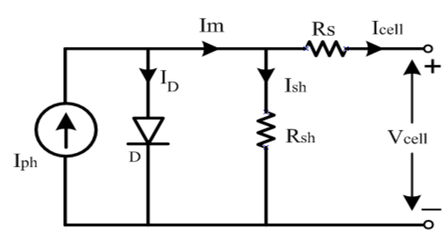

Figure 3. PV Cell Equivalent Circuit Model

The current value in a PV cell, as shown in Figure 3, can be calculated using Kirchhoff's law, according to equation (1).

$$I_{cell} = I_m - I_{sh} \quad (1)$$

where I_{cell} is the current generated by the PV cell (A), I_m is $I_{ph} - I_D$ and I_{sh} is the current through the shunt resistor (R_{sh}) and the amount is by

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equation (2). I_{ph} The resulting PV current (A) varies and is directly proportional to solar radiation at a specific temperature, and the magnitude is calculated based on equation (3). R_{sh} and R_s are the resistances in parallel and series (Ω).

$$I_{sh} = \frac{V_{cell}+I_{cell}+R_s}{R_{sh}} \quad (2)$$

$$I_{ph} = \left(I_{ph,n} + K_I \Delta T\right)\frac{G}{G_n} \quad (3)$$

where $I_{ph,n}$ is the nominal current during Standard Test Condition (STC), K_I is the temperature coefficient of I_{sc}, while G is solar insolation and G_n is nominal solar insolation.

$$I_d = I_0\left(exp\left(\frac{V_{cell}+I_{sh}R_s}{V_t\,\alpha}\right) - 1\right) \quad (4)$$

where $I_{ph,n}$ is the nominal current during Standard Test Condition (STC), K_I is the temperature coefficient of I_{sc}, while G is solar insolation and G_n is nominal solar insolation.

$$I_0 = \frac{I_{sc,n}+K_I\Delta T}{exp\left(\frac{V_{oc,n}+K_V\Delta T}{\alpha V_t}\right)-1} \quad (5)$$

The nominal short-circuit current is $I_{sc,n}$ (A), the nominal open-circuit voltage is $V_{oc,n}$ (V), the temperature coefficient from open-circuit voltage is K_V (V/ K), the number of cells in series is N_s, the Boltzmann's constant is k (1.3806503 x 10^{-23} J/K)), the operation temperature is T (K), and the electron charge is "q" (1.60217646 x 10^{-19} C)

$$V_t = \frac{N_s kT}{q} \quad (6)$$

The final expression for PV cell output current is given by equation (7).

$$I_{cell} = I_{ph} - I_0\left[exp\left(\frac{V_{cell}+R_sI_{cell}}{V_t\,\alpha}\right) - 1\right] - \left(\frac{V_{cell}+R_sI_{cell}}{R_{sh}}\right) \quad (7)$$

PV module is a combination of PV cells in series form, whereas PV array is formed from PV modules in parallel or series form, as shown in Figure 4. Equation 8 is used to examine the relationship between the voltage and current values generated from the PV module. While the equation 9 is used to identify the relationship between the current and the voltage generated from the PV array [24].

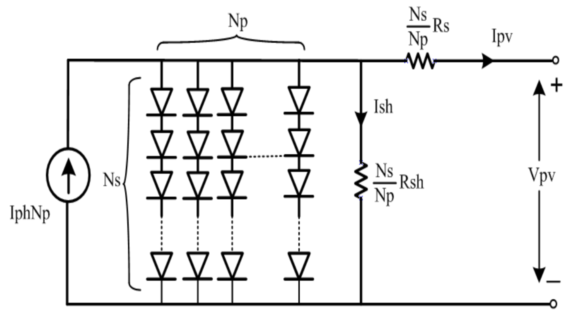


Figure 4. PV Array Equivalent Circuit

$$I_m = I_{ph}N_p - I_0\left[exp\left(\frac{q(V_m+R_sI_m)}{N_skT\alpha}\right) - 1\right] - \left(\frac{V_m+R_sI_m}{R_{sh}}\right) \quad (8)$$

$$I_{PV} = I_{ph}N_p - I_0N_p\left[exp\left(\frac{q\left(V_{PV}+R_s\left(\frac{N_s}{N_p}\right)I_{PV}\right)}{N_skT\alpha}\right) - 1\right] - \left(\frac{V_{PV}+R_s\left(\frac{N_s}{N_p}\right)I_{PV}}{R_{sh}\left(\frac{N_s}{N_p}\right)}\right) \quad (9)$$

In this research, a monocrystalline solar cell PV-MJT250GB from Mitsubishi is used with its detailed specification is presented in table 1.

Table 1: Electrical Specifications Of PV-MJT250GB Module

No	Parameters	Variable	Values
1	STC rated output	P_{mpp}	250 Wp
2	The rated voltage at STC	V_{mpp}	30.2 V
3	Rated current at STC	I_{mpp}	8.28 A
4	Open circuits voltage at STC	V_{oc}	37.4 V
5	Short circuits current at STC	I_{sc}	8.80
6	Number of cells	n_s	60
7	Temperature coefficient (I_{SC})	K_i	0.056%/^{0}C
8	Temperature coefficient (V_{OC})	K_v	-0.350%/^{o}C

The electrical characteristics of the PV-MJT250GB module at various levels of solar radiation with a constant operating temperature of 25 ^{0}C are shown in Figure 5

Journal of Theoretical and Applied Information Technology
30th November 2021. Vol.99. No 22

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

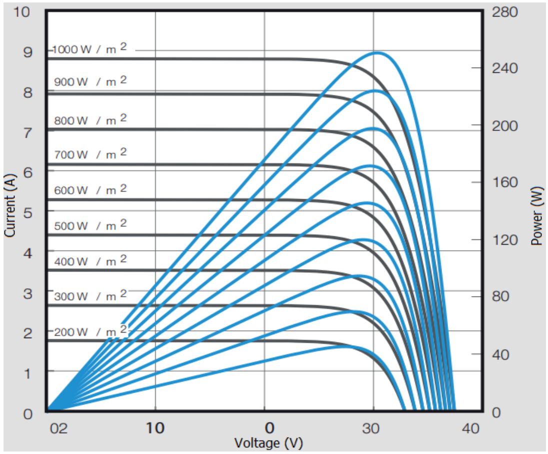


Figure 5. Electrical Characteristics From PV-MJT250GB

3. DESCRIPTION OF PSCs ON PV SYSTEM

The PV system's performance largely depends on the PSCs' condition so that the requirements of these PSCs significantly affect the energy generated by the system. In this paper, several forms of PSCs patterns is conditioned to see the performance of the 4 x 6 PV system array as illustrated in Figure. 6. The type of PV module used in this study is a crystalline model with the PV-MJT250GB series. For the specification of this PV module's is presented in table 1.

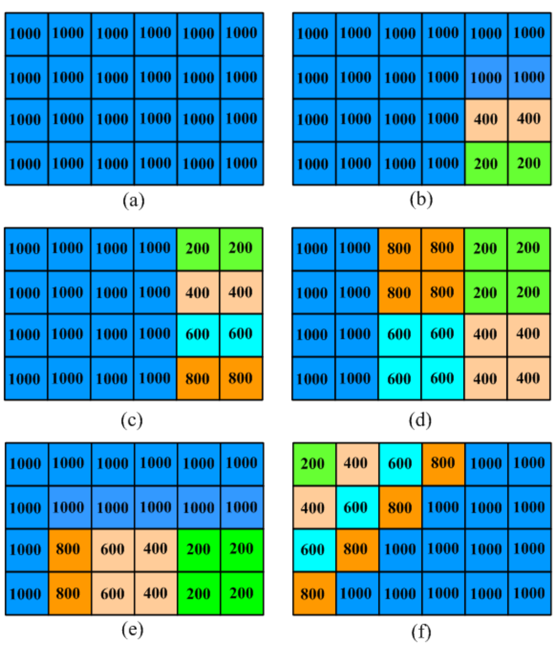


Figure 6. Shade Pattern; (a) Uniform, (b) Short And Narrow, (c) Long And Narrow, (d) Long And Wide, (e) Short And Wide, (f) Corner

4. RESULT AND DISCUSSION OF PV SYSTEM UNDER PCSs

This section discusses the result of simulation using various topology configurations of the PV system such as SP, HC, TCT, BLHC, BLTCT, and SPTCT. Performance of the PV system is analyzed across multiple shading patterns such as uniform, short and narrow, long and narrow, long and wide, short and wide, and corner. In addition, several parameters are taking into account to observe the performance of PV system such as Voc, Isc, GMPP, LMPPs, voltage and current at GMPP and LMPPs, FF, MPL, and Efficiency.

4.1 Series-Parallel (SP) Configuration System

The SP configuration is one of the most commonly used configurations due to its economy and more straightforward structure. The modules are connected in series to get the desired voltage level, also known as a string. Meanwhile, to get the required current value, the string configuration modules are connected in parallel way. It is more favorable in the SP arrangement if the PV is connected in parallel than than series, because overly lengthy series strings will also raise mismatch losses. Figure 7 shows the simulation results in the form of the I-V and P-V characteristics of the system under various shade conditions.

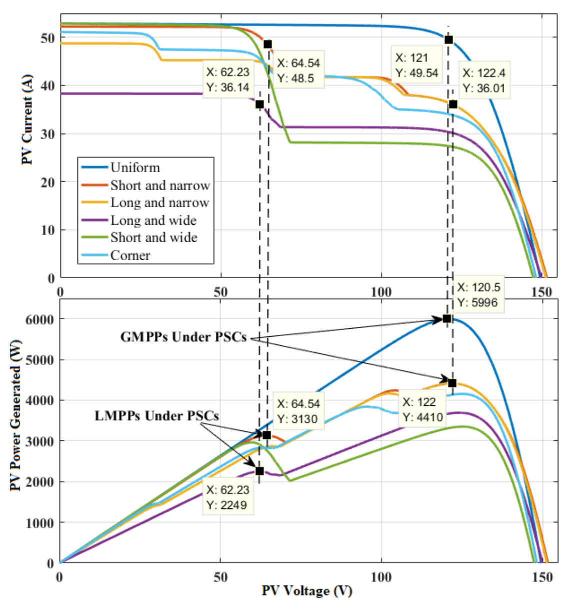


Figure 7. I-V And P-V Output Characteristics In The SP Configuration

4.2 Honey-Comb (HC) Configuration System

The weaknesses obtained from the SP configuration can be fixed using the HC configuration. In the HC topology configuration, the system has more electrical connections and fewer serial links than the SP configuration. If the series connection is more extended, it will cause the mismatching power loss to be increased. Therefore, the mismatching power loss from this configuration will be less than the SP configuration. Figure 8 shows the simulation results in the form of I-V and P-V characteristics of the system using the HC configuration under various shading conditions.

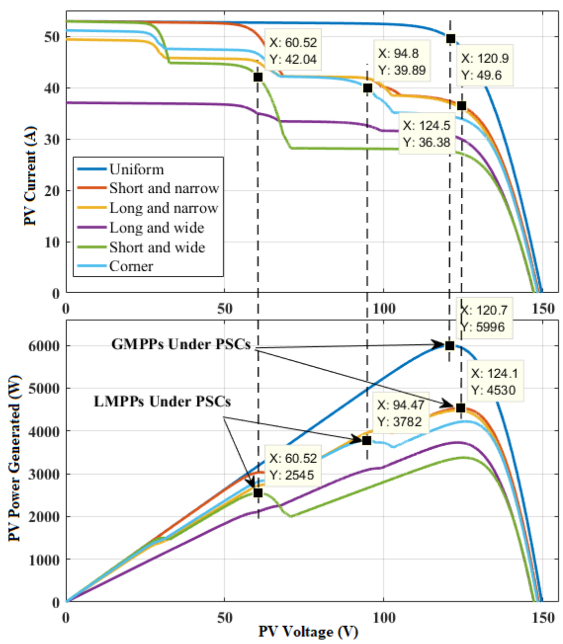


Figure 8. I-V and P-V Output Characteristics In The HC Configuration

4.3 Total Cross Tied (TCT) Configuration System

The TCT configuration is formed by connecting all the row's points in the SP configuration to create a connection like a symmetrical matrix. The multi-interconnect form of the configuration allows the bypass diode to be smaller to operate so that the multi-peak effect and mismatch losses can be reduced. Figure 9 is the form of I-V and P-V characteristics from the TCT system configuration simulation results under various shading conditions that occur.

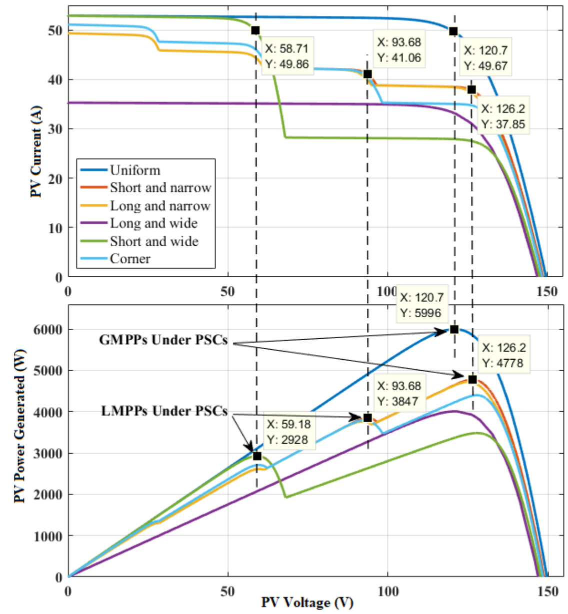


Figure 9. I-V And P-V Output Characteristics In The TCT Configuration

4.4 Bridge Linked Honey-Comb (BLHC) Configuration System

The configuration of the BLHC is similar to that of the TCT except for the first line PV module. The BLHC PV array configuration can be an alternative to overcome the shortcomings in the SP and HC configurations. The configuration features fewer serial relationships than the SP and HC setups, resulting in a lower mismatching loss value. The I-V and P-V characteristics of the BLHC system in the various shapes that occur is presented in Figure 10.

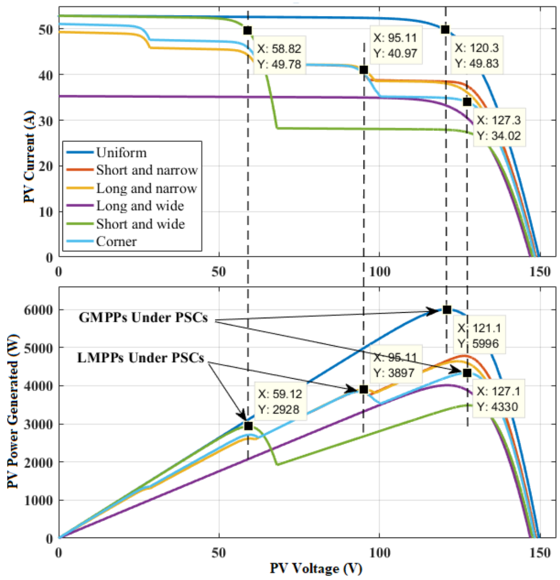


Figure 10. I-V and P-V Output Characteristics In The BLHC Configuration

4.5 Bridge Linked Total Cross Tied (BLTCT) Configuration System

The BLTCT has fewer serial-connected PV systems than in SP and HC but more than in TCT and BLHC based on its configuation. Therefore, the value of mismatching losses will be lower than SP and HC and will be slightly higher than the TCT and BLHC configurations. Figure 11 shows the shape of the I-V and P-V characteristics of the simulation results of the BLTCT system under various shading conditions that occur.

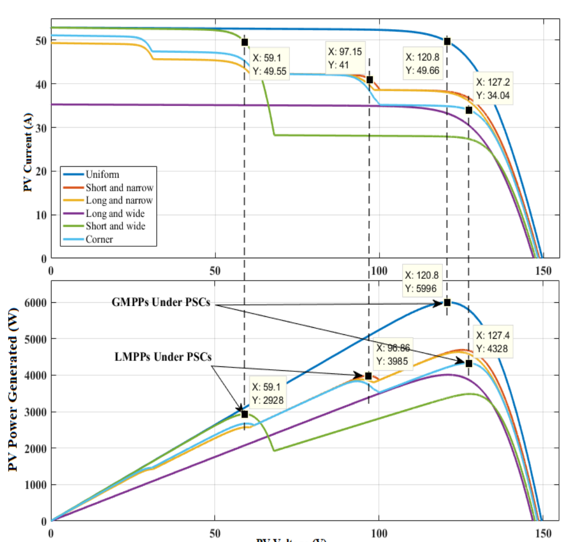


Figure 11. I-V and P-V Output Characteristics In The BLTCT Configuration

4.6 Series-Parallel Total Cross Tied (SPTCT) Configuration System

SPTCT configuration, PV module has a connection like SP configuration except in the middle row. This configuration has fewer serial-connected modules than the SP configuration. As a result, mismatching losses will be less substantial in the SP configuration and more severe in the HC, TCT, BLHC, and BLTCT configurations. Figure 12 shows the I-V and P-V characteristic shapes of the SPTCT system under various shading conditions.

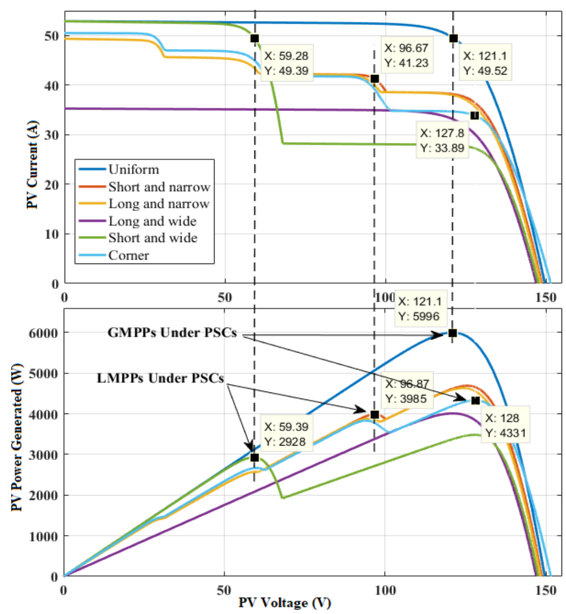


Figure 12. I-V and P-V Output Characteristics In The SPTCT Configuration

4.7 Performance Analysis Of PV System Under PSCs

This section describes the comparative assessment of the SP, HC, TCT, BLHC, BLTCT, and SPTCT implemented in two different conditions, with various model of shading and without the presence of shadow. The performance of each implementation is observed through the parameters of MPL, FF, and efficiency. MPL is represented as ΔP_L calculated as a percentage. To obtain the power loss mismatching value, equation (10) can be used. P_{MPP} is the maximum power value generated when there is no shade or uniform illumination. Whereas P_{PSC} is the maximum power value generated in PSCs conditions.

$$\Delta P_L(\%) = \frac{P_{MPP}-P_{PSC}}{P_{MPP}}\ x\ 100 \qquad (10)$$

The system's performance can be observed by calculating the fill factor value. If the FF value is close to unity, it means that the system performance is higher. I_{MPP} and V_{MPP}, respectively, are the values of current and voltage generated at certain PSCs, while I_{SC} and V_{OC} are the values of current and voltage generated at nominal operating conditions. To calculate the fill factor value, the equation (11) can be used.

$$FF = \frac{V_{MPP} x I_{MPP}}{V_{OC} x I_{SC}} \tag{11}$$

Efficiency is the ratio of maximum output power to input power which can be calculated using equation (12). I is the value the sun's intensity per square meter, while A is the area that receives solar radiation or the solar panel's surface area.

$$\eta = \frac{V_{MPP} x I_{MPP}}{I \ x \ A} \tag{12}$$

4.7.1. Uniform

Uniform here means that the test is carried out using the standard test condition parameters (STC). According to this standard, all PV modules in SP, HC, TCT, BLHC, BLTCT, and SPTCT configurations are uniformed at a temperature of 25^{0}C and solar radiation of 1000 W / m^2. The simulation results with various configurations used to produce rated voltage around 121 Volt and current 49.63 A. While the value of an energy output is 5996 watts and this value is used as a reference value for the global peak. In detail, the parameter values obtained from the various configurations used can be seen in Figure 13 to Figure 15.

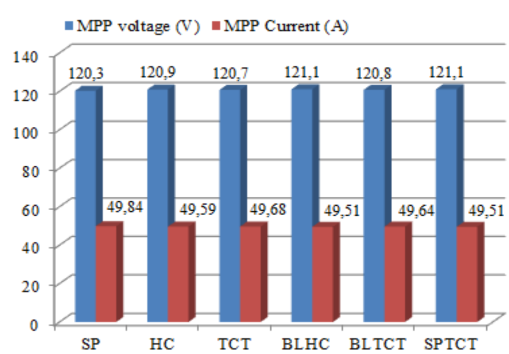


Figure 13. MPP Currents And Voltages Under Uniform Pattern

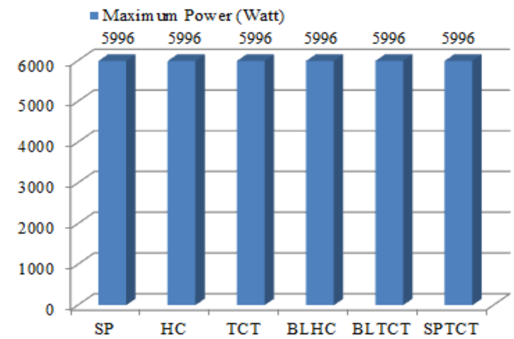


Figure 14. Maximum Power Generation Under Uniform Pattern

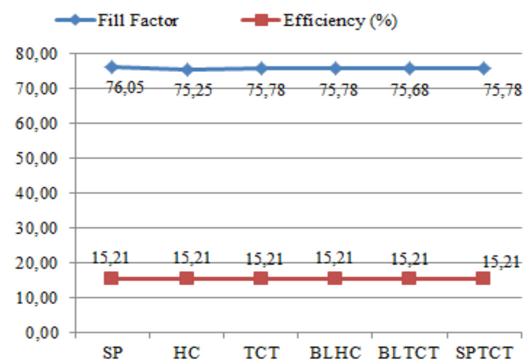


Figure 15. Fill Factor, Mismatching Loss, And Efficiency Under Uniform Pattern

4.7.2. Short and Narrow

As shown in the figure 6, all the configurations in the PV system receive the solar radiation. However, the TCT and BLHC configurations have the highest Maximum Power Point (MPP) voltage and current value which is 126.5 V and 126.6 V, respectively. These configurations also have the highest global peak value of 4778 W and the smallest mismatching power loss value, which is 20.31% each with a fill factor of 60.85% and an efficiency of 13.73%. All PV system configurations with short and narrow conditions have the same value of local peak which is two for each. Thus, the TCT and BLHC configurations in short and narrow shade conditions have better performance than other configurations. For more details, the exact parameter values obtained can be seen in Figure 16 to Figure 18.

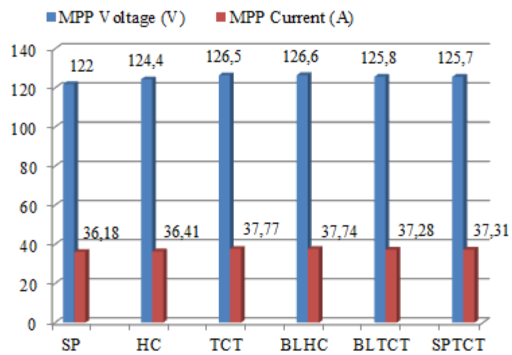


Figure 16. MPP Currents And Voltages Under Short And Narrow Pattern

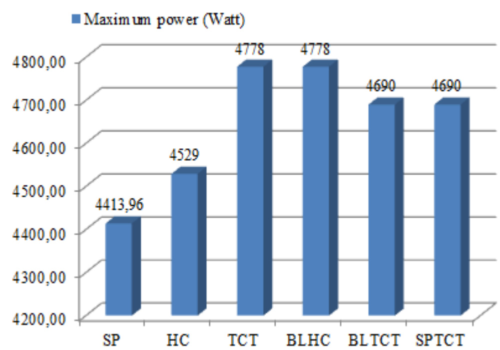


Figure 17. Maximum Power Generation Under Short And Narrow Pattern

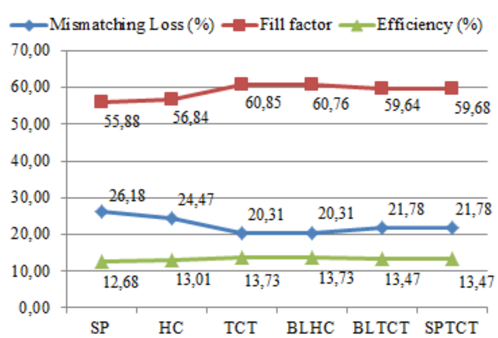


Figure 18. Fill Factor, Mismatching Loss, And Efficiency Under Short And Narrow Pattern

4.7.3. Long and Narrow

In this shade condition, the HC configuration only has a single local peak, the SP configuration has three local peak values, and the other configurations have two local peak values. The highest MPP value for both voltage and current is generated by the TCT configuration, 125.2 Volt and 37.72 A, respectively. The highest global peak value is still resulted from the TCT and BLHC configurations, 4722 W and 4637 W for each. In contrast, the SP configuration has the lowest global peak of 4410 W. TCT has the smallest mismatching power loss value of all the configurations tested, at 21.25 percent and up to 26.45 percent in SP configuration. Meanwhile, the TCT configuration has the largest fill factor value, with a value of 64.55 % and an efficiency of 14.38 %. As a result, the TCT configuration outperforms the BLHC, BLTCT, and SPTCT designs in long and narrow shading situations. Figures 19 to 21 show the parameter values obtained in further detail.

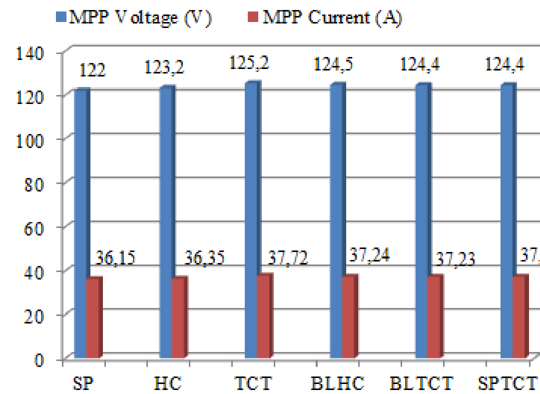


Figure 19. MPP Currents And Voltages Under Long And Narrow Pattern

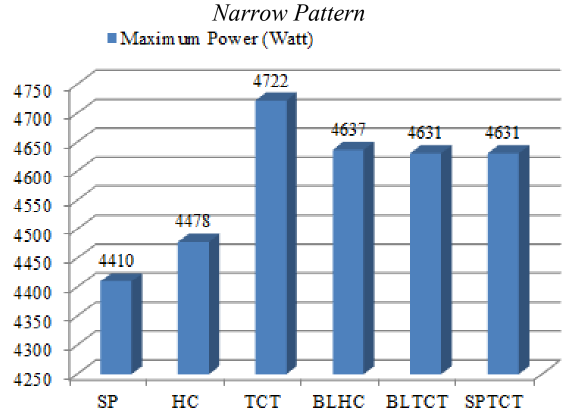


Figure 20. Maximum Power Generation Under Long And Narrow Pattern

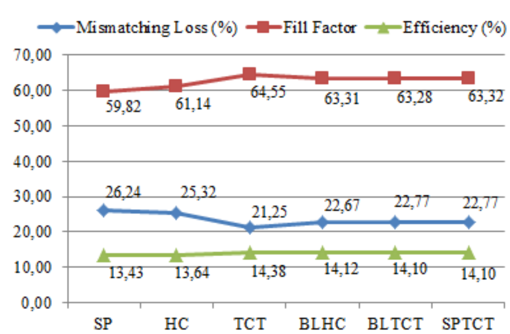


Figure 21. Fill Factor, Mismatching Loss, And Efficiency Under Long And Narrow Pattern

4.7.4. Long and Wide

In the SP configuration, the simulation results in the long and wide shade has a local peak value of 2249 W. The highest MPP value of the voltage and current generated by the SP configuration are up to 124.6 V 38.31 A, respectively. While the highest global peak value is the same for the fourTCT, BLHC, BLTCT, and SPTCT configurations which is 4009 W. In this shade condition, configuration TCT, BLHC, BLTCT, and SPTCT had the lowest mismatching power loss value of 33.14% with the highest fill factor value of 77.38% with an efficiency of 15.26%. As a result, the configuration of TCT, BLHC, BLTCT, SPTCT can be considered to have the optimum performance in all aspects with long and wide shade situations. The parameters of the full assessment result with various configurations with long and wide shade patterns are shown in Figures 22 to 24.

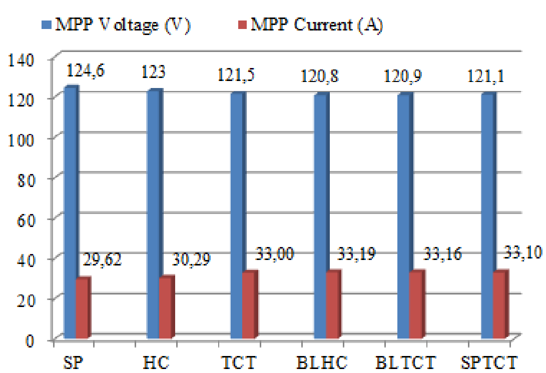


Figure 22. MPP Currents And Voltages Under Long And Wide Pattern

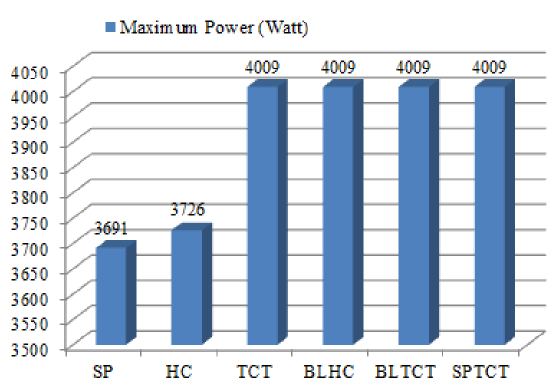


Figure 23. Maximum Power Generation Under Long And Wide Pattern

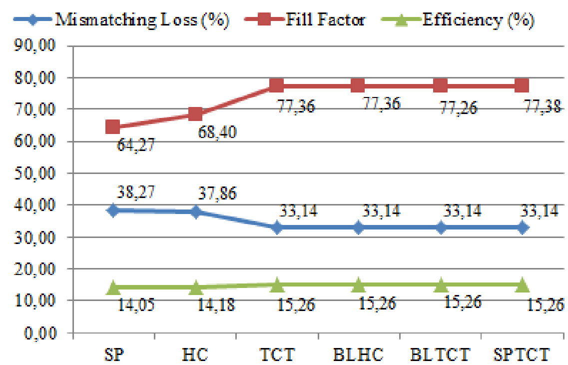


Figure 24. Fill Factor, Mismatching Loss, And Efficiency Under Long And Wide Pattern

4.7.5. Short and Wide

All configurations in this condition have a single local peak except for the HC configuration that has two local peak values. The highest voltage MPP values are received from BLTCT and SPTCT configurations where both configurations generate 128.3 Volt. Meanwhile, the highest current MPP value is generated by the TCT configuration with the value is 27.27 A. Moreover, all configurations produce the same results for global peak value which is 3482 W. These configurations also have the smallest mismatching power loss value which is 41.93% for each. However, in term of fill factor, the TCT configuration obtain the highest value up to 44.67%, with an efficiency of 11.52%.

Compared to other configurations, the TCT design may be the most effective. Figures 25 to 27 show the parameter values acquired throughout the simulation in further detail.

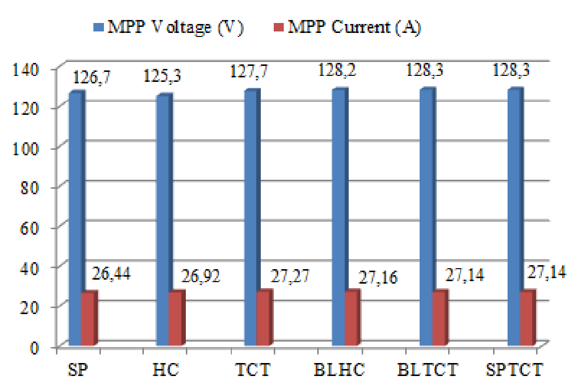


Figure 25. MPP Currents And Voltages Under Short And Wide Pattern

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

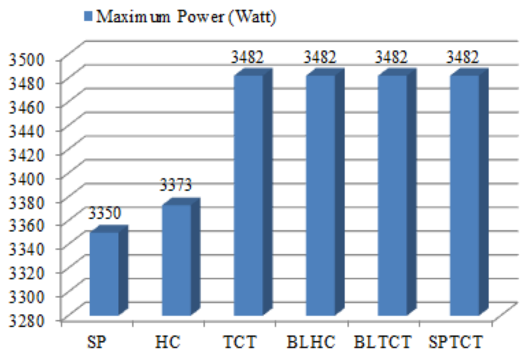


Figure 26. Maximum Power Generation Under Short And Wide Pattern

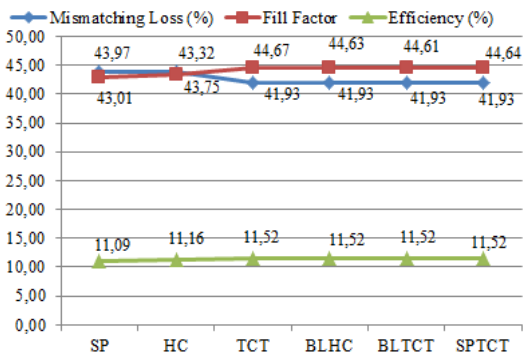


Figure 27. Fill Factor, Mismatching Loss, And Efficiency Under Short And Wide Pattern

4.7.6. Corner

In this condition, all configurations have shading in one corner of the PV system with a different shade value. According to the simulation results the SPTCT and TCT designs provide the highest voltage and current of MPP values. For the voltage value, the former generates 128.3 Volt, whereas the latter generates 34.43 A for the current value. Then followed by the BLHC and BLTCT configurations. The type of BLHC configuration has a maximum voltage and current for MPP value which is 127.3 V and 34.01 A, respectively. While, the MPP values for voltage and current of BLTCT are 127.4 V and 33.97 A. Furthermore, the TCT configuration produces the highest global peak value of 4400 W and achieves the smallest mismatching power loss value of 26.62%, with a fill factor value of 55.98% and an efficiency of 13.40%. All configurations have two local peak values. From the parameters obtained, the TCT configuration has a better performance among the others then followed by the SPTCT BLHC, and BLTCT. In detail, the parameter values obtained through the simulation can be seen in Figure 28 to Figure 30. The parameter assessment results of various configurations with corner shading patterns.

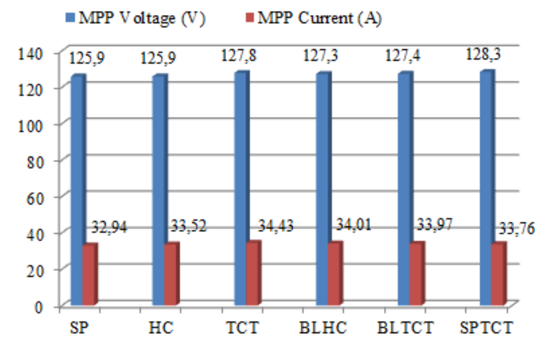


Figure 28. MPP Currents And Voltages Under Corner Pattern

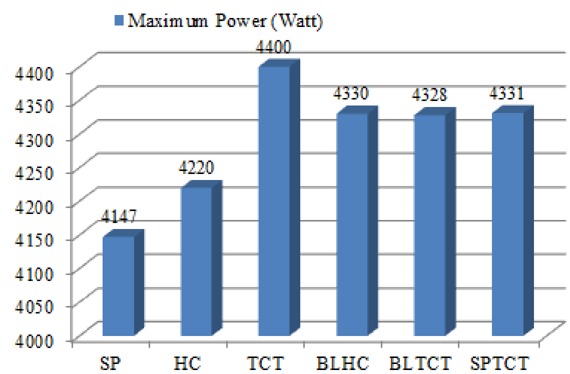


Figure 29. Maximum Power Generation Under Corner Pattern

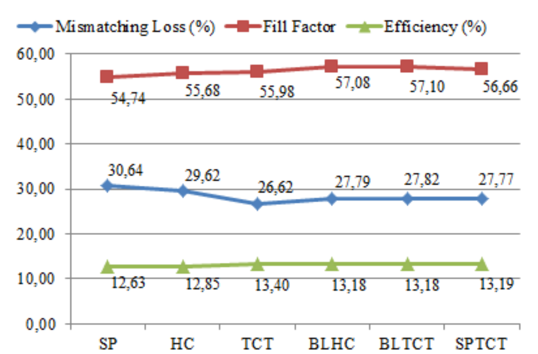
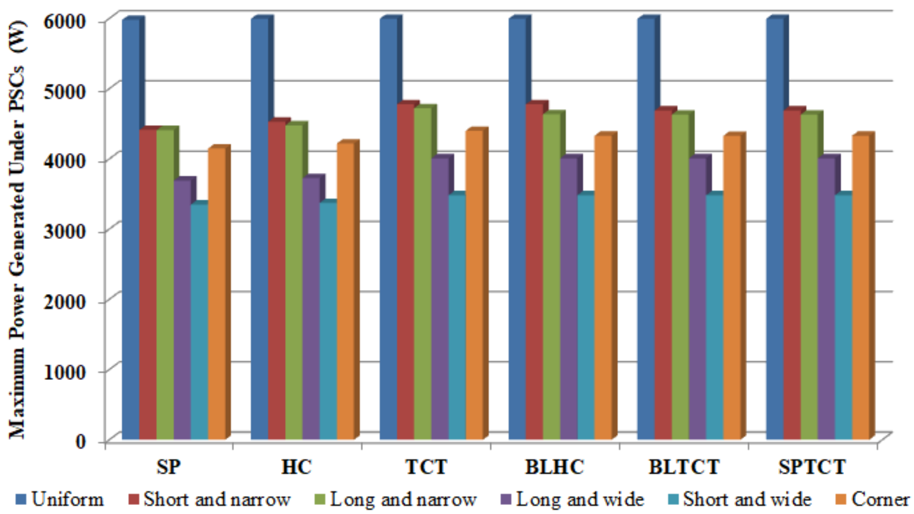


Figure 30. Fill Factor, Mismatching Loss, And Efficiency Under Corner Pattern

The comparison of the maximum power generated under PSCs in various configurations is presented in Figure 31. In general, the energy produced in each under PSCs configuration in the form of short and narrow and also long and narrow is better than the others. Meanwhile, the shade in the form of short and wide produces the lowest energy. Thus, the shading model that occurs dramatically influences the power that the system configuration can generate.



4. CONCLUSIONS

This article assessed the performance of 4 x 6 PV array topologies covering SP, HC, TCT, BLHC, BLTCT, and SPTCT under different shading patterns such as uniform, short and narrow, long and narrow, long and wide, short and wide and corner. According to simulation results, the amount of energy generated depends on the shape of the shade pattern and the radiation level, as well as the mismatching power loss, fill factor and efficiency. It is also known that the TCT arrangement clearly outperforms the other configurations particularly in terms of energy production, notably in the short and narrow, long and narrow, and corner shading patterns. Aside from that, for each configuration employed, the short and wide shading patterns produce the least amount of energy. In general, the TCT shows the best performance among other configurations in various shade conditions. The descending order of the configuration is as follows TCT, BLHC, BLTCT, SPTCT, HC, and SP array configuration. This research, however, is restricted only to the 4 x 6 asymmetric configuration. Therefore, further research to observe the performance of the symmetrical configuration should be carried out.

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