Analysis of Interconnection Schemes for PV Systems Operating under Shadow Conditions

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Abstract- The output power of a PV system consisting of multiple strings and arrays of PV modules reduces drastically as shading increases on it. The shaded module in a string limits the output current of the entire string thereby reduces its output power. Different techniques are used for the optimal interconnection of modules in a PV system that not only helps in reducing the deteriorating effects of partial shading but also enhances the output power of the overall PV system. The performance and the cost analysis of different interconnection schemes including series-parallel (SP), honeycomb (HC), bridge-linked (BL), and total cross tied (TCT) with bypass diode are presented. Commonly existing shading patterns including diagonal (DI), short wide (SW), long wide (LW), short narrow (SN) and short wide (SW) are evaluated. Results show that TCT exhibits better output power under all shade patterns. For a typical 4×4 PV system operating under diagonal shading condition, 15.1% gain in output power can be achieved through TCT connection in comparison to conventional SP interconnection. Further, it has been found that the cost of extra conductors incurred due to TCT connection can be recovered through enhanced energy output within three quarters of the year.

Keywords- Solar, Partial shadings, Photovoltaic, PV connections, Renewable energy.

1. Introduction

Pakistan is glorified with naturally abundant resources of renewable energy. However, there is a strong need for tapping this potential in an effective manner to create a harmony between supply and demand of energy. Electricity demand is related to an increase in GDP and improvement in lifestyle, especially in developing countries. In developing countries, it is often observed that a relationship exists between wealth, electricity usage and production activities [1]. Basically, Pakistan is an energy insufficient country. Pakistan's per capita energy utilization is only 3894 kWh in contrast of world's average 17620 kWh and ranks 100th around the nations of the world [2-3]. So, the analysis shows that Pakistan is a big importer of energy. With increasing population and enhanced dependency on modern digital technologies, the energy demand is consistently growing while the non-renewable resources are diminishing rapidly and the government is paying heavy import bills on oil [4-5]. Moreover, the consumption of non-renewable fossil fuel-based energy resources across the world is hazardous for environment, ecosystem and climate change.

Pakistan is facing a severe energy gap and many areas are still not connected with the national grid [6]. The country has limited fossil fuel resources; therefore, our economy is largely dependent on imported fuels [7-8]. Due to this shortfall, electricity remains unavailable for 10-12 and 16-18 hours in urban and rural areas respectively [9]. The power sector in Pakistan is directly or indirectly controlled by the government and private sectors which severely depends upon non-renewable resources. Pakistan's energy mix consists of 60% Regasified Liquefied Natural Gas (RLNG) and furnace oil, 27 % hydro whereas renewable energy sources like wind, solar, bagasse are less than 3% of the power generation capacity [10].

Non-renewable energy sources are limited in amount and take millions of the year for being replenished. Alternatively, renewable energy sources are the most viable option due to their environment-friendly and cost-effective nature. Numerous forms of renewable energy resources are available; however, out of all these renewable energy resources solar energy is the best option for developing countries like Pakistan which have higher incident solar energy. Further, solar energy can be easily deployed for business or home users and does not need any huge setup like hydro and wind power. Pakistan is located in the direction of the sunny belt. Therefore, this country is blessed with a large amount of solar energy. Pakistan has high incident insolation of about 5.3 kWh/m2/day [11].

Solar energy adaption is increasing day by day at residential, grid-connected and off-grid avenues, because it utilizes a renewable energy source and produces clean energy [12-14]. A solar cell produces output power as solar radiation falls on the panel. The output power of a PV cell depends on solar radiation intensity, the temperature of the solar module and shading on the solar panel. Shading effect is generally produced due to trees, nearby buildings, passing clouds, neighbor solar cell's shading, and bird droppings etc. When we consider this partial shading effect on a large scale, it decreases the efficiency of the solar module and also deteriorates the health of PV panels causing hotspots and subsequent damages in PV structure, making it useless [15]. Partial shading losses not only depend on partial shading area but it also depends on partial shading pattern, array configuration and the bypass diodes integration with PV modules [16]. Partial Shading results in the multiple MPPT's on the VI and PV characteristics and therefore, complex global maximum power point tracking schemes are needed to extract the maximum power in shading conditions [17].

In order to mitigate the detrimental effects of shading, various techniques are used. The bypass diode is a passive technique in which a diode is attached with the solar photovoltaic module to reduce partial shading effect [18]. In this technique, diode protects the solar array from the local heating and overall efficiency of the module will be increased under partial shading effect. But it also has many disadvantages. This technique cannot produce maximum power under partial shading. The second disadvantage is that the diode model increases the complexity to find Maximum Power Point Tracking (MPPT). Switching of the diode from ON state to OFF state is also a big disadvantage. The diode also needs some time to get OFF state to ON state. Diode produces losses due to ON state resistance.

Maximum Power Point Tracker with diverse algorithms have been proposed and modified by various authors. Hifsa et al. [19] proposed an incremental conductance algorithm based MPPT for indoor PV system (IPVS). Hifsa et al. [20] also proposed an improved temperature controller to achieve the maximum power out of the solar panel for IPVS. Krishna et al. compared different strategies for reducing partial effects in PV systems and concluded total cross tied (TCT) to be the most efficient among others. [21]

In multilevel inverter technique a combination of cascaded H-bridge, clamped capacitor and diode is used to mitigate the effect of partial shading by achieving independent voltage control for each module. By using this technique voltage stresses can be reduced and ac harmonic that appear on the output of the solar photovoltaic module can be minimized. To achieve optimal power point, this technique has more complicated control and optimization algorithms [22-24].

As mentioned above a lot of disadvantages occur in different techniques which are used to mitigate the effect of partial shading. Alternately, an optimization between the cost complexity and output power gains can be achieved through optimal interconnection topologies without the need of excessive control and communication requirements. In this paper, different possible interconnections schemes including such as Series-Parallel, Honey-Comb, Bridge-Link and Total-Cross-Tied are analyzed from output and cost perspective under various practically existing shading conditions. A 4×4 PV system (having 4 parallel strings of 4 panels each) is considered for analysis under long wide (LW), long narrow (LN), short wide (SW), short narrow (SN) and diagonal shading (DI) partial shading patterns. The analysis is generic and extendable to all other possible power ratings.

The organization of the paper is as follows: Section I provides an introduction to the utilization of solar PV systems and their limitations under shadow conditions. Section II explains the single diode solar cell model. Section III explains different connection techniques used for mitigating the effect of partial shading and Section IV explain the simulation results of different connection techniques and output power comparison between these techniques. Section V consists of the conclusion of this paper.

2. Single Diode Solar Cell Model

The photovoltaic solar cell is a device that is used to convert solar energy from the sun into electricity by using the photovoltaic effect. When sunlight falls on the solar cell, it can be absorbed, reflected, or passes. But only that light generates electricity which is absorbed by the surface of the solar cell. When we need to increase their utility, a large number of individual solar cells are connected together in a sealed and waterproof shape called a panel or module. To achieve required current and voltage, modules are connected into series and parallel manner to form a photovoltaic array. The flexibility of this modular PV system allows the engineer to build a solar PV array system that can easily meet an extensive variety of electrical demands.

For the development of an equivalent circuit of the photovoltaic cell, one thing is necessary to know about the physical configuration of elements of the cell and electrical characteristics of each cell. The single diode equivalent model of the solar photovoltaic cell is basically a current source parallel to diode and two lumped resistance i.e. parallel resistance and the series resistance. Single diode solar cell model is shown in Fig. 1. [25-28].

This model has a current source which originates photocurrent (I_{ph}) and overall solar cell model here is a single diode model with diffusion phenomenon presented by a current (I_d). The leakage current of the solar photovoltaic cell from shunt resistance is I_{sh} which is due to fabrication defects inside the solar photovoltaic cell structure. Series resistances R_S reduce the efficiency of the cell by consuming power in thermal through the whole junction substrate. Under irradiance, currently delivered by the solar cell is equal to photocurrent I_{ph} minus diode current I_d, and leakage current I_{sh} as given by (1) [29-31].

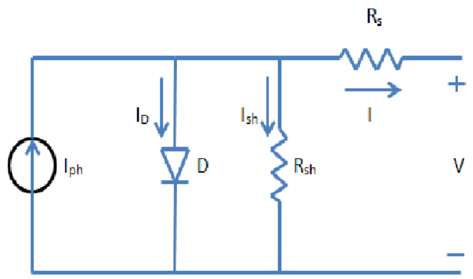

Fig. 1. Single diode equivalent photovoltaic cell model

$$I = I_{ph} - I_d - I_{sh} \quad (1)$$

The relationship between current Id and voltage V is represented by (2)

$$I_d = I_s \left[\exp\left(\frac{V+R_S I}{nV_t}\right) - 1\right] \quad (2)$$

Where Ish is a leakage current due to Rsh resistance and relationship with voltage V is:

$$I_{sh} = \frac{V+R_S I}{R_{sh}} \quad (3)$$

$$I = I_{ph} - I_s \left[\exp\left(\frac{V+R_S I}{nV_t}\right) - 1\right] - \frac{V+R_S I}{R_{sh}} \quad (4)$$

$$V_t = \frac{T_c K}{q} \quad (5)$$

Where,

I_s : Diffusion Reverse saturation current

n : Diode quality factor value between 1 and 2

R_s : Series resistance

R_{sh} : Shunt resistance

K : Boltzmann constant $\left(k = 1.38 \times 10^{-23}\ {}^{J}/_{K}\right)$

T_c : Operating cell temperature (°C)

q : Electron charge ($q = 1.6 \times 10^{-19}\ C$)

Equation (1) – (5) are used to find the current and voltage of a photovoltaic solar cell at standard test conditions (STC). These equations are not enough to find current and voltages at changing irradiance level or changing temperature due to some shading objects like trees, clouds, birds, buildings etc. So, this is compulsory to do some extra work on these equations for finding current and voltage under shadow conditions or changing temperature level. For a typical silicon-based solar panel, equations are [32-33].

$$I_{sc} = I_{scstc}\{1 + \alpha(T_c - T_{stc})\}\left(\frac{E_{instant}}{E_{stc}}\right) \quad (6)$$

$$V_{oc} = V_{ostc}\left\{1 + a\ln\left(\frac{E_{instant}}{E_{stc}}\right) + \beta(T_c - T_{stc})\right\} \quad (7)$$

$$I_{instant,mp} = I_{mstc}\left(\frac{I_{sc}}{I_{scstc}}\right) \quad (8)$$

$$V_{imp} = V_{mstc} + (V_{oc} - V_{ostc}) + R_s(I_{mstc} - I_{imp}) \quad (9)$$

$$P_{max} = V_{imp}.I_{imp} \quad (10)$$

Where,

I_{scstc} : Short circuit current at standard test condition (STC)

I_{mstc} : Current at max power at STC

I_{sc} : Short circuit current

α : Temperature coefficient for short circuit current

T_c : Operating Temperature

T_{stc} : Standard test condition temperature

$E_{instant}$: Instantaneous Irradiance

E_{stc} : Standard irradiance (1000W/m^2)

V_{ostc} : Open circuit voltage at STC

a : Irradiance correction factor of Voc

β : Temperature coefficient of open circuit voltage

I_{imp} : Instantaneous current at maximum power

V_{imp} : Instantaneous voltage at maximum power

V_{mstc} : Voltage at maximum power at STC

R_s : Series Resistance

P_{max} : Maximum calculated power

3. Methodology

In this paper, four different connection techniques are modeled in MATLAB Simulink. These techniques are SP, HC, BL, and TCT. For simulation purpose, a built-in model of PV array with bypass diodes is used. Fig. 2 shows that Irradiance and temperature are input parameters of the solar PV array model. We can change these parameters according to our requirement by giving different values to input parameter blocks. Fig. 2 shows three output parameters. First one is denoted with “m” which has five output values. The Second terminal is a positive connection and the third one is a negative connection of solar PV array. SunPower SPR-X20-250-BLK model is used in the PV array model. Table 1 presents the specification for PV array in which power, number of cells, voltage and current values are mentioned.

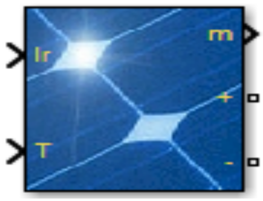

Fig. 2. Solar photovoltaic array Model in MATLAB

Table 1. SunPower SPR-X20-250-BLK Parameters

Parameter	Value
P max	249.952 W
Voc	50.93 V
Isc	6.2 A
Vmp	42.8 V
N cell	72
Imp	5.84 A

3.1. Series-parallel (SP) connection

PV arrays are attached in series-parallel manners as shown in Fig. 3. Four PV arrays are attached in a series manner in the first column. Second, third and fourth column also consists of four PV arrays in a series manner.

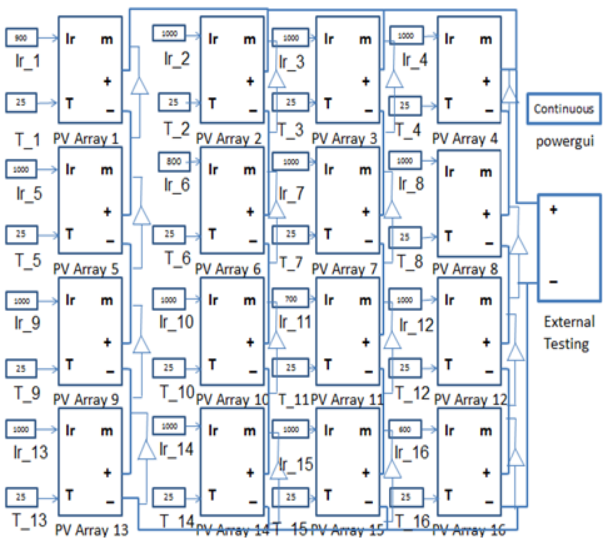

Fig. 3. 4×4 Series-parallel (SP) with a bypass diode connection model

These four columns are attached in a parallel manner to formulate a series-parallel configuration generally used in conventional installations. A block of external testing is shown in Fig. 3 which consists of a controlled voltage source with ramp function to get output I-V and P-V curve of the series-parallel model. One current measurement block from Simulink tools is used for measurement of current of the complete circuit. One voltage measurement block is used for measurement of the voltage of the whole circuit

3.2. Honey comb connection (HC)

This model is the same as the SP technique with some changing in connections of the different PV array to get a better result under different partial (PS) shading conditions. In the HC model, two parallel columns having three PV arrays are connected in series as shown in Fig. 4. This connection technique has the capability to provide an alternate path for currents in case if a certain PV cell is reverse biased due to shading. Therefore, it improves the current, voltage and output power of the PV system consisting of multiple arrays and modules. When PV cell will be under partial shading condition then PV array works as load but these extra connections allow and bypass this cell so the output power of this system will improve than SP connection. In some cases, it gives better output power under partial shading conditions.

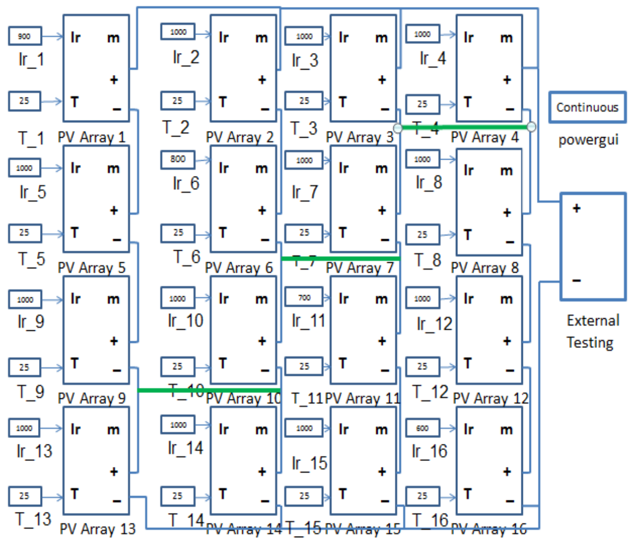

Fig. 4. 4×4 Honey comb (HC) with a bypass diode connection model

3.3. Bridge link connection (BL)

This is the modified form of the SP model in which four extra connections are used with bridge rectifier type manners to get better output power under different partial shading patterns Fig. 5. This model shows two parallel strings in a series manner. They are also connected to PV arrays and there exists a tie in the middle of the bridges.

3.4. Total cross tied connection (TCT)

This is also modified the form of SP model in which nine extra connections are used to mitigate the effect of different partial shading patterns like long wide (LW), short wide (SW), long narrow (LN), short narrow (SN), diagonal (DI) to get better output power. In this technique, columns are connected with the series manner and rows of the model are connected with parallel manners as shown in Fig. 6. Total cross tied technique needs an extra five meters cross tie connections between every two cells of PV array model. This technique requires extra connection wire from one PV array to another PV array in standard settings. This wire cost will be calculated below cost analysis section.

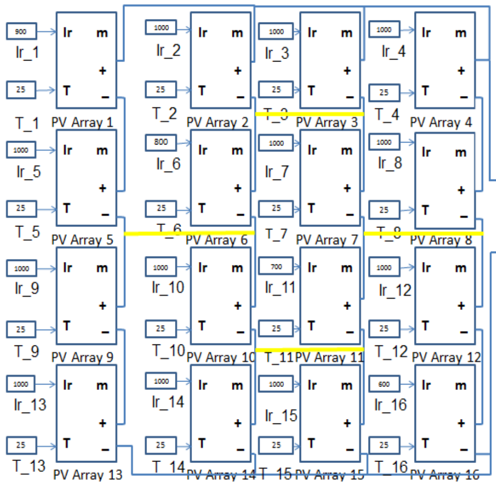

Fig. 5. 4×4 Bridge link (BL) with a bypass diode connection model

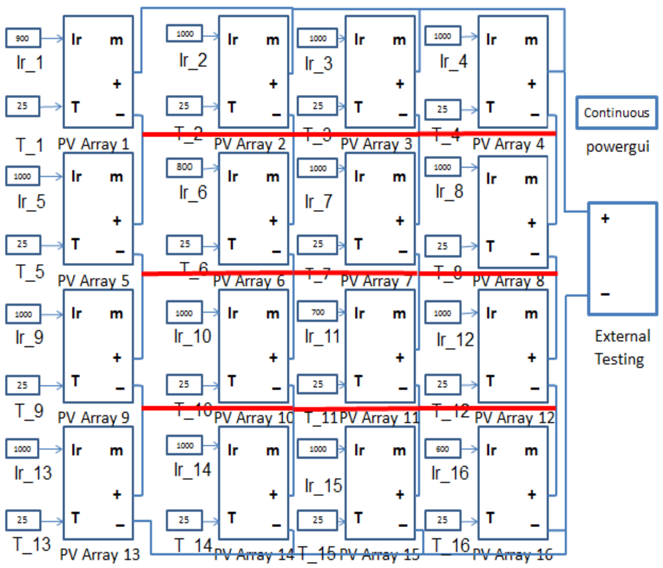

Fig. 6. Total cross tied (TCT) with bypass diode connection model

4. Results and Analysis

In this section, the simulated results of the deployed methodology have been presented and discussed. After finding the best possible technique, its cost analysis has been performed to calculate the payback time.

4.1. P-V curves under long wide (LW) shade pattern

In Fig. 7, the simulated P-V curves for the four connection techniques are shown as:

- Series-parallel technique - curve with only dots
- Honey comb technique - curve with dots and bar lines
- Bridge link technique - curve with only bar lines
- Total cross tied technique - curve with a solid line

Results show that total cross tied has maximum power than other connection techniques under long wide (LW) partial shading pattern.

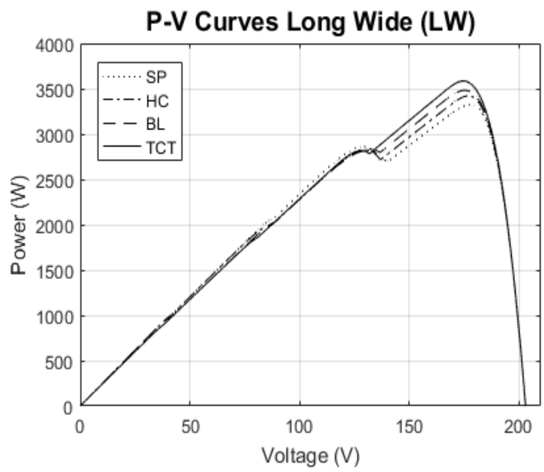

Fig. 7. P-V curves under long wide (LW) partial shading condition

4.2. P-V curves under long narrow (LN) shade pattern

Fig. 8 shows simulated I-V curves for different connection techniques under long narrow (LN) partial shading pattern. These curves are between voltage and current but total cross tied connection techniques has maximum current (I max) at the maximum power point (MPP) than other connection techniques. Hence total cross tied connection is suitable for long narrow (LN) type shading condition as evident from simulation results. In long narrow pattern, TCT connection technique has maximum power than other SP, HC and BL connection techniques. TCT curve shows in solid line having a very smooth curve to find maximum power point (MPP) than other connection techniques. TCT connection technique gets a maximum current (I_{max}) value than other techniques.

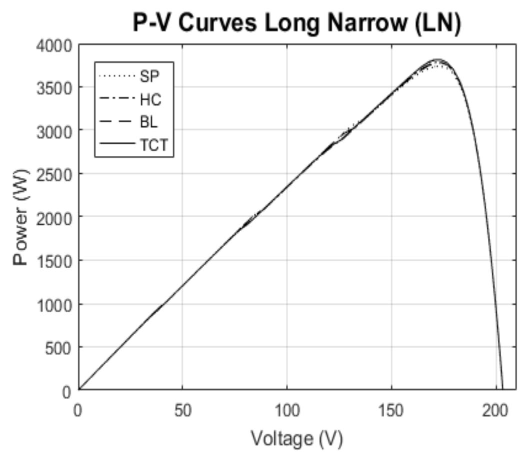

Fig. 8. P-V curves under long narrow (LN) partial shading condition

4.3. P-V curves under short wide (SW) shade pattern

Fig. 9 shows P-V curves for different connection techniques under short wide (SW) partial shade pattern. Those cells which will be under partial shade acts as a load. Some curves are overlapping each other due to nearly same output value. This is the reason four curves seems like two or three curves. Fig. 9 shows the TCT connection technique has maximum power (P_{max}) at maximum power point (MPP) than other SP, HC and BL techniques. TCT curve has very less complexity to find maximum power point (MPP) than other connection techniques. In Fig. 9, it can be easily seen that there is a lot of difference between TCT output power than other connection techniques. Results show that Modified total cross tied connection is a best option to mitigate the effect of short wide (SW) type shade pattern with maximum current (I_{max}) value at maximum power point (MPP).

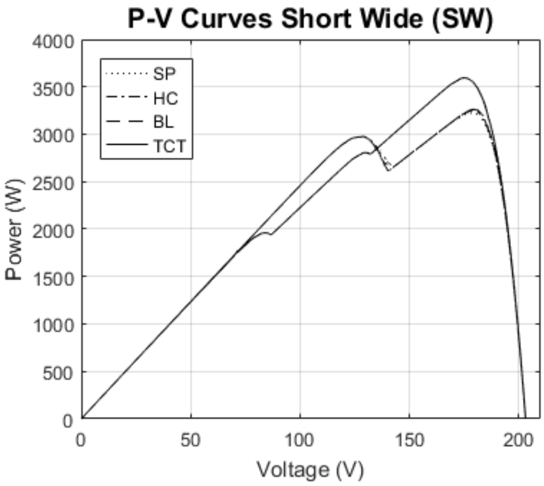

Fig. 9. P-V curves under short wide (SW) partial shading condition

4.4. P-V curves under short narrow (SN) shade pattern

Fig 10 shows a P-V curve for short narrow partial shading pattern. We can see easily a lot of difference between total cross tied curve and other connection technique curves. TCT technique gives maximum output power at maximum power point than other connection techniques. The complexity to find the maximum power point is very less in total cross tied connection technique.

4.5. P-V curves under diagonal (DI) shade pattern

This is a special case of partial shading pattern as compared to other partial shading pattern. TCT curve has only one maximum power point (MPP) than other techniques have 2 to 3 maximum power point. More than one maximum power point (MPP) creates complexity to find global maxima where the system giving the highest output power values. In diagonal (DI) type shade pattern total cross tied technique is the best option to get maximum output power with only one maximum power point. P-V Curves under Diagonal (DI) Partial Shading Condition have been shown in Fig. 11.

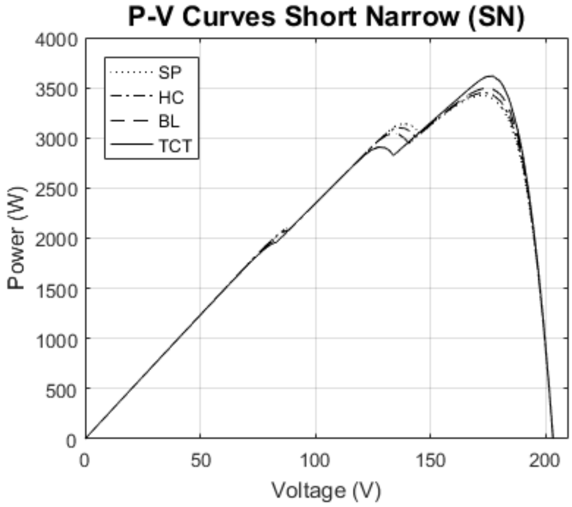

Fig. 10. P-V Curves under Short Narrow (SN) Partial Shading Condition

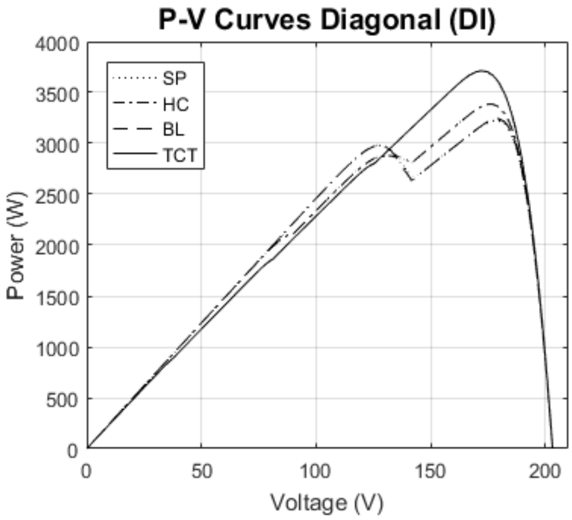

Fig. 11. P-V Curves under Diagonal (DI) Partial Shading Condition

4.6. Cost analysis and results

Cost analysis of TCT with nine extra connections has been done in this section. This cost analysis is taken from output power under diagonal shade (DI) pattern in which TCT technique performs 12.2% more efficiently than SP connections technique.

Table 2 shows the voltage, current, and power of the PV array model under partial shading condition. It can be seen that the total cross tied connection has maximum power in each case but current and voltage values vary in each partial shading condition.

Table 3 presents the output power comparison between four different connection techniques under five different partial shading patterns. Total cross tied connection shows better efficiency in each partial shading case. Maximum power gain of 15.1% was achieved in diagonal shade pattern by using a 4×4 PV array model.

Table 2. Power, Voltage and Current Values under Different Shade Patterns

Connection Techniques	P_{max} V_{max} I_{max}	LW (Long wide)	LN (Long Narrow)	SN (Short Narrow)	SW (Short wide)	DI (Diagonal)
SP (Series Parallel)	I_{max}	18.62 A	21.67 A	19.90 A	17.98 A	18.08 A
	V_{max}	178.49 V	172.54 V	171.91 V	179.31 V	178.40 V
	P_{max}	**3324.9 W**	**3739.2 W**	**3422.6 W**	**3224.9 W**	**3226.2 W**
HC (Honey Comb)	I_{max}	19.44 A	21.94 A	19.93 A	18.14 A	19.35 A
	V_{max}	175.85 V	172.54 V	173.06 V	179.31 V	174.91 V
	P_{max}	**3420.2 W**	**3786.3 W**	**3450.1 W**	**3252.8 W**	**3384.8 W**
BL (Bridge Link)	I_{max}	19.80 A	21.90 A	20.04 A	18.19 A	18.17 A
	V_{max}	175.85 V	172.54 V	174.36 V	179.31 V	178.40 V
	P_{max}	**3482.8 W**	**3780.3 W**	**3496.4 W**	**3263.4 W**	**3243.4 W**
TCT (Total Cross Tied)	I_{max}	20.37 A	22.11 A	20.59 A	20.42 A	21.58 A
	V_{max}	175.85 V	172.54 V	175.70 V	175.90 V	172.00 V
	P_{max}	**3583.1 W**	**3815.4 W**	**3619.4 W**	**3593.6 W**	**3713.3 W**

Table 3. Output Power Comparison between Different Connection Techniques

Connection Techniques	Powers (W) & Gain (%)	LW (Long wide)	LN (Long Narrow)	SN (Short Narrow)	SW (Short wide)	DI (Diagonal)
SP (Series Parallel)	SP Method	3324.9 W	3739.2 W	3422.6 W	3224.9 W	3226.2 W
	TCT Method	3583.1 W	3815.4 W	3619.4 W	3593.6 W	3713.3 W
	Improvement in power gain (%)	**7.77 %**	**2.04 %**	**5.75 %**	**11.43 %**	**15.1%**
HC (Honey Comb)	HC Method	3420.2 W	3786.3 W	3450.1 W	3252.8 W	3384.8 W
	TCT Method	3583.1 W	3815.4 W	3619.4 W	3593.6 W	3713.3 W
	Improvement in power gain (%)	**4.76 %**	**0.77 %**	**4.9 %**	**10.48 %**	**9.7 %**
BL (Bridge Link)	BL Method	3482.8 W	3780.3 W	3496.4 W	3263.4 W	3243.4 W
	TCT Method	3583.1 W	3815.4 W	3619.4 W	3593.6 W	3713.3 W
	Improvement in power gain (%)	**2.88 %**	**0.93 %**	**3.52 %**	**10.12 %**	**14.49 %**

SP Power (W) in diagonal Pattern = 3226.2 W

TCT Power (W) in diagonal Pattern = 3713.3 W

Power Gain = 100 x (3713.3 -3226.2)/3226.2 = 15.10%

The power difference between SP and TCT = 487.1 W

Partial shading duration in a day = 3 Hours

Power saving (W) in a day = $487.1 \times 3 = 1461.3$ W

Extra units in a day = $\frac{1461.3}{1000} = 1.461$ unit

Extra Units in a month = $\frac{\text{Watts} \times \text{hours}}{1000} \times 30$

Extra Units in a month = $\frac{487.1 \times 3}{1000} \times 30 = 43.8$ unit

The above performed calculations show that approximately 43.8 units (kWh) will be saved in a month using TCT technique.

4.7. Payback time for total cross tied (TCT) technique

TCT method has been proved to be an efficient one as compared to other techniques. The only addition of a wire can convert the old technique into TCT. That is why, the cost analysis is only based on the expenses of new wire addition.

Length of one wire in TCT method = 5 ft

Total length used in TCT method = $5 \times 9 = 45$ ft

Cost of one wire = 3.125 USD

Cost of nine wires = $3.125 \times 9 = 28.125$ USD

Save unit in one month = 43.8 unit

One unit cost commercial = 0.0714 USD

Save Dollars in one month = $43.8 \times 0.0714 = 3.128$ USD

Payback time in a year = $\frac{28.125}{3.128} = 9$ Months

We conclude from cost analysis only nine extra connections will be used for TCT connections to mitigate the effect of partial shading effect. Nine extra connections need extra 28.125 USD amount than series-parallel connections. Solar PV array has more than 25 years life and just within three-quarters of years, this amount returns back in the form of greater output power than series-parallel connection technique under diagonal shade pattern.

5. Conclusion

In this paper, we have mitigated the effect of different partial shading patterns like long wide (LW), long narrow (LN), short wide (SW), short narrow (SN), and diagonal (DI) patterns by using different connection techniques like SP, HC, BL, and TCT. Simulation results show that total cross tied (TCT) is the best technique to mitigate the effect of these partial shading patterns. Maximum efficiency of 12.2% has been achieved in diagonal (DI) shade pattern by using TCT connection technique. In this research work, multiple peaks which occurred during partial shading have been reduced using TCT technique which can be easily seen in the simulation results of MATLAB software. Five different shade patterns have been used in this research. TCT technique has maximum output power in every case. Due to extra connections which are used in TCT technique, the initial cost of the system will be a bit higher than the other techniques but this cost can be easily compensated within just three quarters of a year.

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