A Novel Improved Total Cross Tied Interconnection Scheme to Improve Power Generation from Photovoltaic Modules During Uncertainty in Weather Conditions

Malavya Udugula and Asha Rani M. A.*

Department of EE, National Institute of Technology, Silchar, Assam, India.
*Corresponding Author: asharani@ee.nits.ac.in

Abstract: The shade on rooftop Photovoltaic (PV) array is mainly due to the chimney on rooftop, cell towers, neighbouring building and trees etc, which cannot be avoided due to the place constraint in cities and towns. But the green energy production from solar PV modules is much more important in cities and towns to meet the increased demand of energy. In most of the cases, the static shade on PV modules is subjected to last rows or columns which are very near to the PV array boundaries. Hence, the popular PV modules connection i.e conventional Total Cross Tied (TCT) connections need to be modified to improve the generation of power during uncertainty in weather conditions. An attempt has been made on conventional TCT to improve its electrical connections for enhanced power output, reduction in power loss, optimum space and less financial requirement by omitting one PV module using the proposed Improved TCT (ITCT) connections by changing the last row of array connections only, during the installation stage itself. The performance analysis has been compared among the proposed ITCT scheme and the existing electrical configurations such as Series-Parallel, Honey-Comb, Bridge-Link, and TCT, which is validated with the mathematical analysis and MATLAB/Simulink simulations. The proposed scheme has shown better overall performance compared to the existing electrical configurations in terms of reduced number of PV modules under all the shading cases. Further, the maximum power loss has been reduced with the proposed ITCT over the conventional TCT under all shading pattern, achieved maximum power enhancement of 16.74%, and single peak power under all shading cases shows an advantage of its adaptability in real time large scale PV array.

Keywords: TCT, Improved TCT, Enhanced Power Generation, Photovoltaic Arrays, Partial shaded conditions

NOMENCLATURE

G	Solar Irradiation or Insolation, W/m^2
I_d	Current flow in diode, A
I_{mp}	Peak power current, A
I_{pho}	Photo current generation at STC, A
I_{pr}	Parallel or shunt resistance current, A
I_{pvm}	PV cell net current, A
I_R	Row currents order in the ascending order of the modules get bypassed, A
I_s	Diode current in reverse saturation, A
I_{sc}	Module current at short circuit, A
I_{so}	Diode current in reverse saturation at STC, A
P	Rated PV module power, W
R_{sh}	Resistance connected in shunt, Ω
T	Thermal temperature, °C
V_{mp}	Peak power voltage, V
V_{oc}	Open circuit voltage, V
V_t	Thermal voltage, V

Received: February 24th, 2025. Accepted: March 19th, 2025
DOI: 10.15676/ijeei.2025.17.1.3

1. Introduction

The faster depletion of fossil fuels and their severe impact on human life makes us to move towards the renewable sources of energy. Among the renewable sources of energy, solar becomes more popular. The abundant solar energy in the world and the advancements in the photovoltaic (PV) power generation promise the human kind to get the clean energy for all the applications. Because of the increased demand in energy throughout the world and the concerns about the environmental pollution, all the countries increases their budget and sets the target of achieving gigawatts of photovoltaic power [1]. Now a days, there are large scale ground mounting, rooftop, floating, and marine photovoltaic power plants installation in the countries like Australia, America, and European countries. There is a quick start for large capacity installations with the same trend in India and Asian countries. The global warming may limits to 1.5 ºC with the fast transition from conventional power generation to solar power generation. This brings the net negative green house gas emissions and reducing budget for the removal of pollutants due to the conventional energy sources. There is a growth of 40.7% in the total PV installed capacities which amounts to 305.2 GW and the every year enhancement of 41.4% amounts to 70.3 GW from the year 2000 to 2016 [2]. The solar power generation becomes the cheapest and clean energy for the years ahead in almost all the regions of the world as quoted by the International Energy Agency (IEA). Further, the high penetration of power from solar has been observed because of the cost optimization and improved efficiencies. S. A. Mozdawar *et. al* also discusses the various policies developed to know the impact of penetration of green energy sources into the multiple open electricity market [3-4].

However, there are multiple challenges for the PV system's performance, because of dynamic changes in irradiation, temperature, and partial shade conditions. Further, the peak power from the PV modules can be achieved by incorporating the conventional Maximum Power Point Tracking (MPPT) methods in PV systems with the a variety of interconnection schemes such as Series (S), Series-Parallel (SP), Parallel-Series (PS) [5]. But, the dynamic weather conditions and partial shade due to neighboring buildings, trees, clouds, bird pits e.t.c becomes major concern to tract the peak power from modules. Because of partial shade, there are more than one peak in power versus voltage (P-V) characteristics with the above mentioned methods [6]. In such cases, the conventional MPPT methods fail to track the global peak power. Hence, the global MPPT (GMPPT) methods had developed and tracked the maximum power under dynamic weather conditions [7-8]. Further, the researchers had developed the conventional interconnection schemes such as Honey Comb (HC), Bridge Link (BL), and Total Cross Tied (TCT) to enhance the power output from the partially shaded PV modules. In addition, the power extraction had been improved with the hybrid reconfiguration techniques such as BL-TCT, SP-TCT, SP-HC, HC-TCT, SP-BL [9]. Even though, the power extraction is less with these developed methods. Hence, the dynamic reconfiguration techniques had been developed to tract peak power under uncertainty in weather conditions [10].

Shuainan Hou *et. al.* proposed Improved Hybrid Particle Swarm Optimization (HPSO) with the concept of genetic algorithm hybridization and weight decrease in nonlinear method for implementing with TCT connections [11]. But the drawbacks of it such as sensors requirement, more cost and complex circuit operation avoided by developing the static reconfiguration techniques [12]. The existing literature can be found with the various developed reconfiguration techniques under static mode using the various puzzle methods such as Jigsaw puzzle method, where the mismatch losses had been reduced by rearranging the panels physical location [13]. A Ken-Ken puzzle method conducted a study on 4x4 TCT configurations and shows better performance matrices such as fill factor, power loss, and execution ratio [14]. The developed Dual Exponential Sawtooth method shows the energy savings, economic aspects and increased 41.48% power over TCT configuration [15]. Further, the proposed method on Latine Square dispersed the shade uniformly on PV modules and reduced more number of peaks in P-V characteristic curves [16]. This method implemented with MATLAB simulations on 9x9 PV array and show superior performance in terms of number of peak powers, power loss compared to TCT and SUDOKU methods [17]. The one time Lo Shu pattern with theoretical and simulations shows advantages in 8 performance indices compared to the existing methods. The additional parameters such as execution ratio, performance index, capacity factor, and capture loss also considered [18].

The advantages and disadvantages of various methods such as static, dynamic, game based, mathematical based, puzzle based in terms power, fill factor, mismatch losses, performance indices were discussed. However, these techniques implementation becomes complex because of the involvement of puzzle patterns. Moreover, all these reconfiguration techniques were compared with TCT to prove their efficacy in all performance parameters. Because of simple and easy implementation of conventional TCT, the respective technique is more adaptable in real time PV systems [19]. Further, Hicham Oufettoul *et. al* focused on the research to achieve the reduced effect of partial shade with the novel interconnections in TCT by involving the PV modules inner parts in the developed connections [20]. Further, the cross ties in conventional TCT configuration had been reduced with the chemical compound benzene structure proposed method to get the superior performance over conventional methods [21].

But, it has drawback like the connections to the inner parts of modules makes complex circuit. Hence, there is a necessity to develop the easy and simple connections for TCT to improve its performance and wide range of adaptability in real time applications. After extensive review of literature, the authors found the following drawbacks of the existing TCT connections: (i) Low peak output power under partial shade conditions (PSCs), (ii) More than one peak in P-V characteristics, (iii) Puzzle based and more complex implementation with the reconfiguration techniques. Hence, the aforementioned problems have been addressed by developing the proposed method with the following objectives: (i) Enhanced peak output power under partial shaded conditions, (ii) Single peak in P-V characteristics, (iii) Simple and easy implementation of connections. Hence, the proposed improved TCT connections have been developed to improve the overall performance from the simple and basic connections of PV modules. Further, the MPP tracking can be easily achieved with the conventional MPPT methods because of the single peak in P-V characteristics. This paper flow is as follows: Introduction and literature review in section-1, the mathematical modeling of PV module in section-2. Further, the section-3 deals with the various conventional interconnection schemes. Subsequently, section-4 gives an emphasis on analysis of the proposed ITCT interconnection scheme along with an algorithm and flowchart. The results have been elaborately presented in section-5, and finally, the end remarks of the proposed method and future scope have been presented at the end in conclusion section.

2. PV Cellmathematical Modelling

The PV cell mathematical model as shown in Fig. 1 is used to design in MATLAB/Simulink environment. The PV module is designed with the following equations.

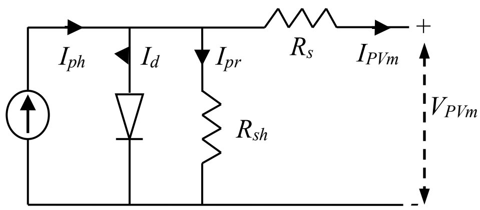


Fig. 1. PV cell equivalent circuit

The current generated by photons of the light

$$I_{ph} = \mathrm{I_{pho}} \times \frac{\mathrm{G}}{\mathrm{G_O}} \times \left[1 + \mathrm{k_i} \times \left(\mathrm{T} - \mathrm{T_{ref}}\right)\right] \tag{1}$$

At Standard Test Conditions (STC), current generated by photons and current during short circuit is equal. The module thermal voltage is expressed as given in equation (2).

$$\text{Thermal voltage } V_t = \frac{Ns \times k \times T}{q} \tag{2}$$

At STC, the generated current in reverse saturation of the diode is given in equation (3).

$$I_{SO} = I_{SC} \times \frac{1}{\exp\left(\frac{V_{OCm}}{A \times V_t}\right) - 1} \tag{3}$$

For dynamic change in T, the generated current in reverse saturation of the diode is given in equation (4).

$$I_S = I_{SO} \times \left(\frac{T}{T_{ref}}\right)^3 \times \exp\left[\left(\frac{q \times E_g}{A \times k}\right) \times \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{4}$$

Hence, the diode net flow of current is given in equation (5).

$$I_d = I_S \times \exp\left[\left(\frac{V_{PVm} - I_{PVm} \times R_S}{A \times V_t}\right) - 1\right] \tag{5}$$

The parallel or shunt branch resistance current flow is given in equation (6).

$$I_{pr} = \frac{V_{PVm} - I_{PVm} \times R_S}{R_{SH}} \tag{6}$$

Therefore, the PV cell generated net current is expressed as

$$I_{PVm} = I_{ph} - I_d - I_{pr} = I_{ph} - I_S \times \exp\left[\left(\frac{V_{PVm} - I_{PVm} \times R_S}{A \times V_t}\right) - 1\right] - \frac{V_{PVm} - I_{PVm} \times R_S}{R_{SH}} \tag{7}$$

The PV module parameters considered in MATLAB/Simulink simulations are mentioned in Table 1.

Table 1. The parameters of the PV module

S.No.	Parameters	Each Module
1	Short circuit current	4.7 A
2	Open circuit voltage	21.6 V
3	Current at maximum power	4.44 mA
4	Voltage at maximum power	18 V
5	Rated PV module power	80 W

3. Various Conventional Interconnection Schemes

This paper emphasises on four basic connections such as SP, BL, HC, TCT, which are mostly used in solar PV systems along with the analysis of proposed ITCT connections.

A. SP Connection

The series combinations of modules are connected parallel to form the SP topology as shown in Fig. 2 (a). The other way SP connections are also possible by combining the parallel combination of modules in series connection. It is one of the most popular method in real time PV systems.

B. BL Connection

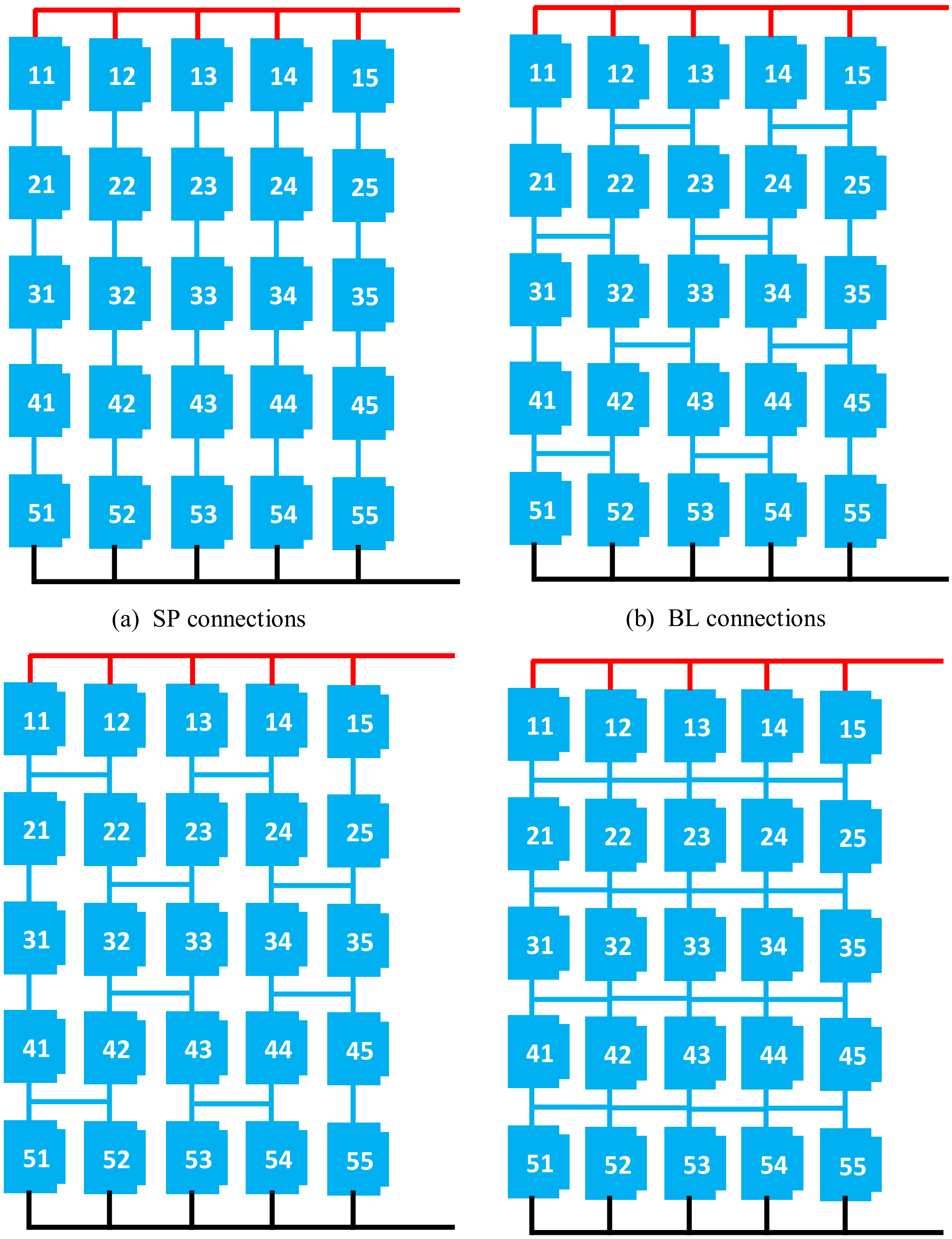
The scheme of interconnection for BL has been obtained from a wheat-stone bridge rectifier. In this, the most of the interconnections between the strings have been removed as shown in Fig. 2(b). Hence, the corresponding wiring losses and associated cost have been reduced.

C. HC Connection

The HC is the hexagonal arrangement of the modules as shown in Fig. 2(c). This is also called as domestic utensils method because the numbering of modules will be in the shape of a big utensil. The HC connections gives the advantages of both BL and TCT connections.

D. TCT Connection

This is obtained from the SP connections by providing cross ties between the junctions of the strings as given in Fig. 2(d). In this connection, the equal voltages found across the ties same and summation of currents from the ties are same. Finally, the TCT topology reduces the overall effect of mismatch from SP.



(a) SP connections (b) BL connections

(c) HC connections (d) TCT connections

Fig. 2. Various basic interconnection schemes in PV system

4. Analysis of The Proposed Method

The proposed ITCT configuration for 5 x 5 connections is as shown in Fig. 3. The electrical connections of last row modules only are altered without changing in its physical location. The implementation of the proposed method reduces one PV module during the installation stage itself. Therefore, the corresponding advantages such as space, cost and connections can be reduced as compared to the conventional TCT. Further, the proposed method gives an enhanced power output even one of PV module reduced from the overall PV array. The proposed method reconnection is explained with an algorithm given in Section 4.1 for any order of PV array. Further, the array of *m* x *n* explains by following the steps in algorithm as follows: Consider PV array size as and start the procedure with *i*=1(i.e row-1) and *j*=1 (i.e column-1). Then, increase row number by '1'. If the increased row number is not equal to the array row size (*m*), then increase the row number till it reaches to the array row size (*m*). If the increased row number equals to the array row size (*m*), then the corresponding module is connected across *j* x *j* (i.e first row and first column). Then increase the column number (*j*) by 1 and repeat the above procedure till it reaches to less than array column size (*n*). Finally, if '*j'* equals to array column size (*n*), then the respective *i* x *j* module electrical connections are given across *(i-1)* x *j* (i.e last but one row) or omitted. In this way, the connections can be given to any PV array size by following the illustrated flowchart as shown in Fig. 4.

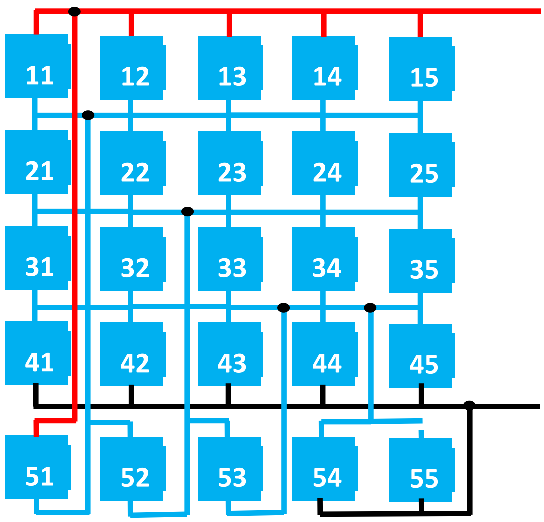


Fig. 3. Proposed Improved TCT connection

A. Algorithm

Step 1:	Read PV array as '*m*' rows and '*n*' columns.
Step 2:	Read number of rows as '*i*' and number of columns as '*j*' and *j*=1
Step 3:	Start the procedure with *i*=1
Step 4:	Increase '*i*' value by 1.
Step 5:	If '*i*' equals to the number of rows: Yes means proceed to Step-6. No means go back to Step-4.
Step 6:	The respective module electrical connection across *j* x *j.*
Step 7:	Increase '*j*' value by 1.
Step 8:	If '*j*' is less than the number of columns: Yes means go back to Step-3. No means go to Step-9.
Step 9:	The respective *i* x *j* module electrical connection is omitted.
Step 10:	End

B. Flowchart

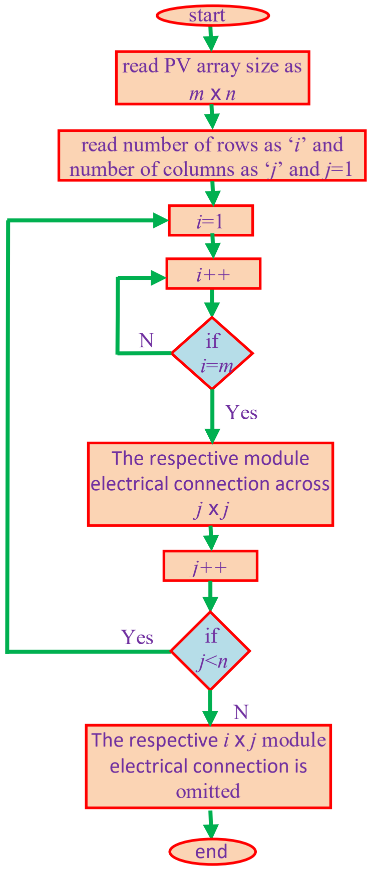


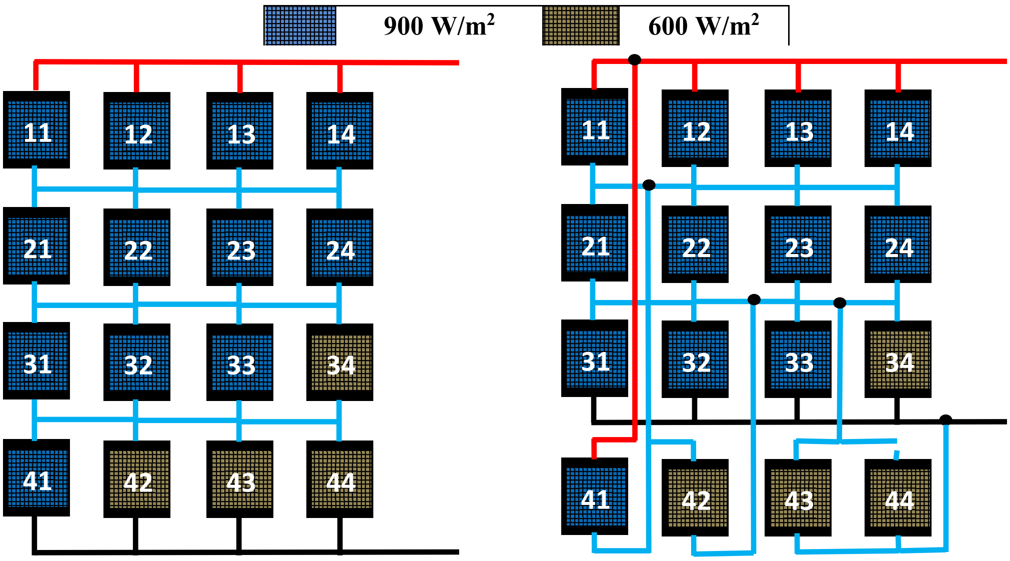
Fig. 4. Proposed method flowchart

5. Results Analysis & Discussion

The performance of various interconnection schemes such as SP, BL, HC, conventional TCT and proposed ITCT methods have been studied under different shading configurations. The performance is analysed using theoretical calculations and MATLAB/Simulink simulations. The tests on conventional and proposed methods are carried out with each of 80 W PV modules in an array with the specifications as mentioned in Table 1. Further, the power loss, maximum power, local maximum power points using different interconnection schemes under various shading cases have been investigated along with the proposed method.

A. Short Narrow (SN) shading pattern.

The SN shading pattern on conventional TCT and ITCT interconnections is shown in Fig. 5. The insolation with 900 W/m^2 is considered as unshaded modules and the other reduced insolation of 600 W/m^2 is considered as shaded modules. The ITCT electrical connections have been provided without any change in modules physical location from TCT connection by following the flowchart in Fig. 4. The corresponding row currents are calculated in TCT using equations (8)-(10) and ITCT row currents are calculated using equations (11)-(13). Then, the currents are arranged in the ascending order of row currents as the modules get bypassed when shading increases. Further, the ascending order of row currents are multiplied with respective voltages in the descending order. Whenever there is a change in row current, the array voltage reduces to next lower level and the product of corresponding row current and voltage gives the respective power. The corresponding calculations are tabulated in Table 2.



a) TCT connections

b) Improved TCT connections

Fig. 5. TCT and Improved TCT connections under SN shading pattern

The following are the theoretical calculations of row currents in TCT configuration.

$$I_{R1} = I_{R2} = 4\times\left(\frac{900}{1000}\right)I_m = 3.6I_m \tag{8}$$

$$I_{R3} = 3\times\left(\frac{900}{1000}\right)I_m + 1\times\left(\frac{600}{1000}\right)I_m = 3.3I_m \tag{9}$$

$$I_{R4} = 1\times\left(\frac{900}{1000}\right)I_m + 3\times\left(\frac{600}{1000}\right)I_m = 2.7I_m \tag{10}$$

The following are the theoretical calculations of row currents in ITCT configuration.

$$I_{R1} = 5\times\left(\frac{900}{1000}\right)I_m = 4.5I_m \tag{11}$$

$$I_{R2} = 4\times\left(\frac{900}{1000}\right)I_m + 1\times\left(\frac{600}{1000}\right)I_m = 4.2I_m \tag{12}$$

$$I_{R3} = 3\times\left(\frac{900}{1000}\right)I_m + 2\times\left(\frac{600}{1000}\right)I_m = 3.9I_m \tag{13}$$

Table 2. Theoretical calculations of TCT and ITCT methods under SN shading pattern

TCT				ITCT			
I_R		Voltage (V_a)	Power (P_a)	I_R		Voltage (V_a)	Power (P_a)
I_{R4}	$2.7I_m$	$4V_m$	$10.8V_mI_m$	I_{R3}	$3.9I_m$	$3V_m$	$11.7V_mI_m$
I_{R3}	$3.3I_m$	$3V_m$	$9.9V_mI_m$	I_{R2}	$4.2I_m$	$2V_m$	$8.4V_mI_m$
I_{R2}	$3.6I_m$	$2V_m$	$7.2V_mI_m$	I_{R1}	$4.5I_m$	V_m	$4.5V_mI_m$
I_{R1}	$3.6I_m$	$2V_m$	$7.2V_mI_m$	-	-	-	-

B. Long Wide (LW) shading pattern

The LW shading pattern on conventional TCT and ITCT interconnections is shown in Fig. 6. The insolation with 900 W/m^2 is considered as unshaded modules and the other reduced insolation of 600 W/m^2 is considered as shaded modules. The ITCT electrical connections have been provided without any change in modules physical location from TCT connection by following the flowchart in Fig. 4. The corresponding row currents are calculated in TCT using equations (14)-(15) and ITCT row currents are calculated using equation (16). Then, the currents are arranged in the ascending order of row currents as the modules get bypassed when shading increases. Further, the ascending order of row currents are multiplied with respective voltages in the descending order. Whenever there is a change in row current, the array voltage reduces to next lower level and the product of corresponding row current and voltage gives the respective power. The corresponding calculations are tabulated in Table 3.

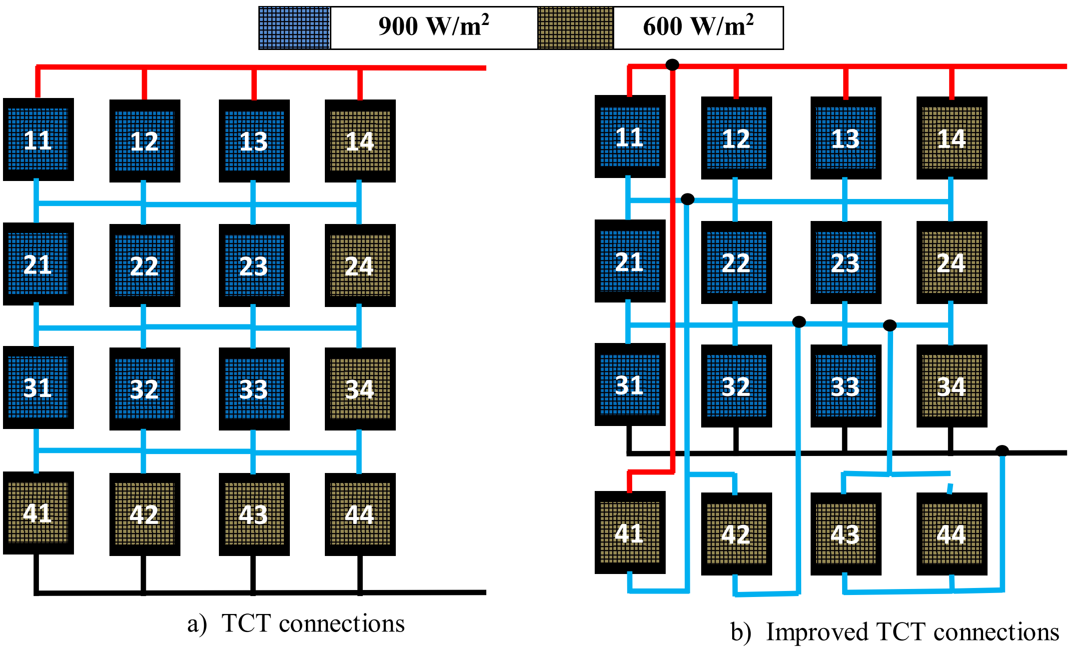


Fig. 6. TCT and Improved TCT connections under LW shading pattern

The following are the theoretical calculations of row currents in TCT connection.

$$I_{R1} = I_{R2} = I_{R3} = 3\times\left(\frac{900}{1000}\right)I_m + 1\times\left(\frac{600}{1000}\right)I_m = 3.3I_m \quad (14)$$

$$I_{R4} = 4\times\left(\frac{600}{1000}\right)I_m = 2.4I_m \quad (15)$$

The following are the theoretical calculations of row currents in ITCT configuration.

$$I_{R1} = I_{R2} = I_{R3} = 3\times\left(\frac{900}{1000}\right)I_m + 2\times\left(\frac{600}{1000}\right)I_m = 3.9I_m \quad (16)$$

Table 3. Theoretical calculations of TCT and ITCT methods under LW shading pattern

TCT				ITCT			
I_R		Voltage (V_a)	Power (P_a)	I_R		Voltage (V_a)	Power (P_a)
I_{R4}	$2.4I_m$	$4V_m$	$9.6V_mI_m$	I_{R3}	$3.9I_m$	$3V_m$	$11.7V_mI_m$
I_{R3}	$3.3I_m$	$3V_m$	$9.9V_mI_m$	I_{R2}	$3.9I_m$	$3V_m$	$11.7V_mI_m$
I_{R2}	$3.3I_m$	$3V_m$	$9.9V_mI_m$	I_{R1}	$3.9I_m$	$3V_m$	$11.7V_mI_m$
I_{R1}	$3.3I_m$	$3V_m$	$9.9V_mI_m$	-	-	-	-

C. Long Narrow (LN) shading pattern

The LN shading pattern on conventional TCT and ITCT interconnections is shown in Fig. 7. The insolation with 900 W/m^2 is considered as unshaded modules and the other reduced insolation of 600 W/m^2 is considered as shaded modules. The ITCT electrical connections have been provided without any change in modules physical location from TCT connection by following the flowchart in Fig. 4. The corresponding row currents are calculated in TCT using equations (17)-(18) and ITCT row currents are calculated using equations (19)-(20). Then, the currents are arranged in the ascending order of row currents as the modules get bypassed when shading increases. Further, the ascending order of row currents are multiplied with respective voltages in the descending order. Whenever there is a change in row current, the array voltage reduces to next lower level and the product of corresponding row current and voltage gives the respective power. The corresponding calculations are presented in Table 4.

The following are the theoretically calculated row currents in TCT connection.

$$I_{R1} = I_{R2} = I_{R3} = 3\times\left(\frac{900}{1000}\right)I_m + 1\times\left(\frac{600}{1000}\right)I_m = 3.3I_m \quad (17)$$

$$I_{R4} = 1\times\left(\frac{900}{1000}\right)I_m + 3\times\left(\frac{600}{1000}\right)I_m = 2.7I_m \quad (18)$$

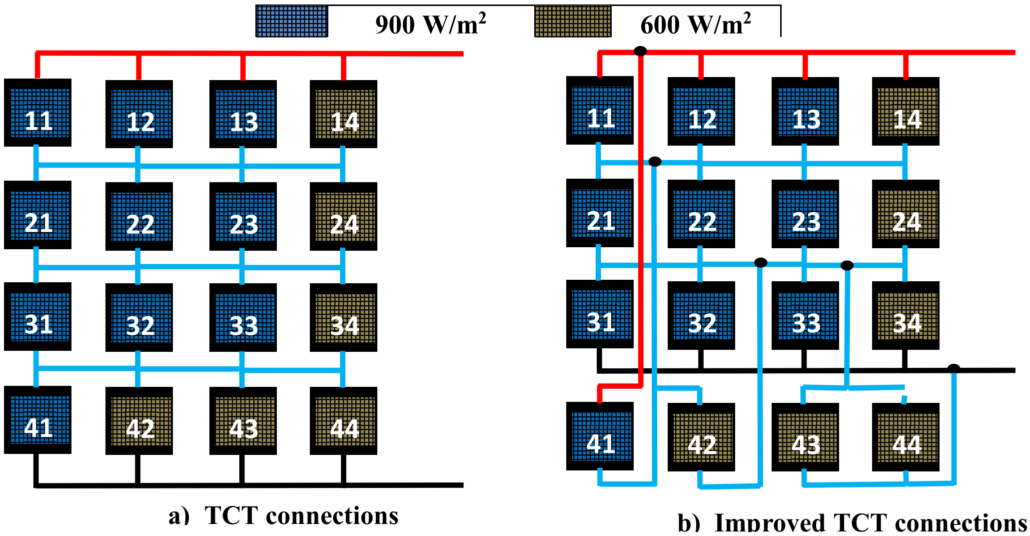


Fig. 7. TCT and Improved TCT connections under LN shading pattern

The following are the theoretical calculations of row currents in ITCT configuration.

$$I_{R1} = I_{R2} = 4\times\left(\frac{900}{1000}\right)I_m + 1\times\left(\frac{600}{1000}\right)I_m = 4.2I_m \quad (19)$$

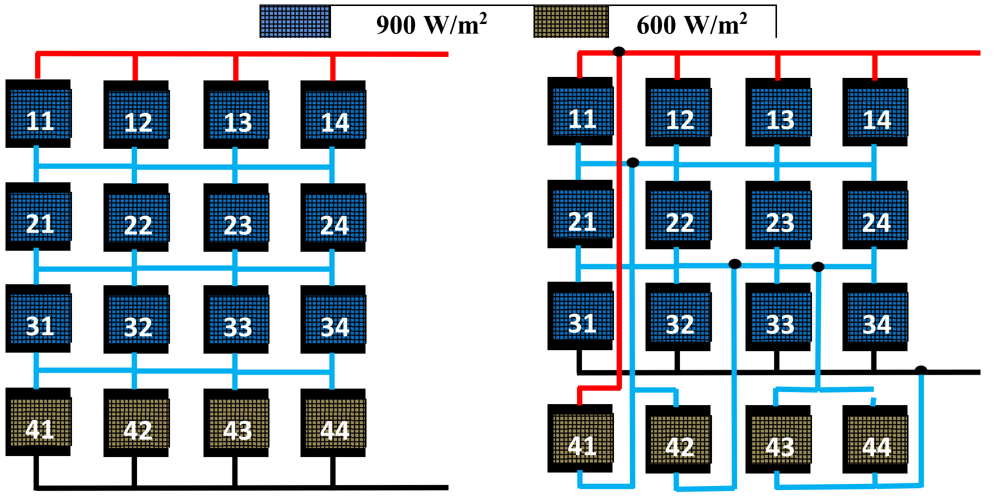
$$I_{R3} = 3\times\left(\frac{900}{1000}\right)I_m + 2\times\left(\frac{600}{1000}\right)I_m = 3.9I_m \quad (20)$$

Table 4. Theoretical calculations of TCT and ITCT methods under LN shading pattern

TCT				ITCT			
I_R		Voltage (V_a)	Power (P_a)	I_R		Voltage (V_a)	Power (P_a)
I_{R4}	$2.7I_m$	$4V_m$	$10.8V_mI_m$	I_{R3}	$3.9I_m$	$3V_m$	$11.7V_mI_m$
I_{R3}	$3.3I_m$	$3V_m$	$9.9V_mI_m$	I_{R2}	$4.2I_m$	$2V_m$	$8.4V_mI_m$
I_{R2}	$3.3I_m$	$3V_m$	$9.9V_mI_m$	I_{R1}	$4.2I_m$	$2V_m$	$8.4V_mI_m$
I_{R1}	$3.3I_m$	$3V_m$	$9.9V_mI_m$	-	-	-	-

D. Short Wide (SW) shading pattern

The SW shading pattern on conventional TCT and ITCT interconnections is shown in Fig. 8. The insolation with 900 W/m^2 is considered as unshaded modules and the other reduced insolation of 600 W/m^2 is considered as shaded modules. The ITCT electrical connections have been provided without any change in modules physical location from TCT connection by following the flowchart in Fig. 4. The corresponding row currents are calculated in TCT using equations (21)-(22) and ITCT row currents are calculated using equation (23). Then, the currents are arranged in the ascending order of row currents as the modules get bypassed when shading increases. Further, the ascending order of row currents are multiplied with respective voltages in the descending order. Whenever there is a change in row current, the array voltage reduces to next lower level and the product of corresponding row current and voltage gives the respective power. The corresponding calculations are tabulated in Table 5.



a) TCT connections

b) Improved TCT connections

Fig. 8. TCT and Improved TCT connections under SW shading pattern

The following are the theoretical calculations of row currents in TCT configuration.

$$I_{R1} = I_{R2} = I_{R3} = 4 \times \left(\frac{900}{1000}\right) I_m = 3.6 I_m \tag{21}$$

$$I_{R4} = 4 \times \left(\frac{600}{1000}\right) I_m = 2.4 I_m \tag{22}$$

The following are the theoretical calculations of row currents in ITCT configuration.

$$I_{R1} = I_{R2} = I_{R3} = 4 \times \left(\frac{900}{1000}\right) I_m + 1 \times \left(\frac{600}{1000}\right) I_m = 4.2 I_m \tag{23}$$

Table 5. Theoretical calculations of TCT and ITCT methods under SW shading pattern

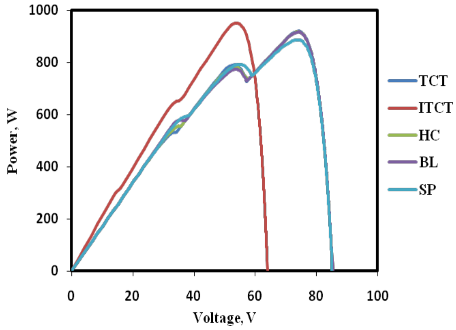
TCT				ITCT			
I_R		Voltage (V_a)	Power (P_a)	I_R		Voltage (V_a)	Power (P_a)
I_{R4}	$2.4I_m$	$4V_m$	$9.6V_mI_m$	I_{R3}	$4.2I_m$	$3V_m$	$12.6V_mI_m$
I_{R3}	$3.6I_m$	$3V_m$	$10.8V_mI_m$	I_{R2}	$4.2I_m$	$2V_m$	$12.6V_mI_m$
I_{R2}	$3.6I_m$	$3V_m$	$10.8V_mI_m$	I_{R1}	$4.2I_m$	$2V_m$	$12.6V_mI_m$
I_{R1}	$3.6I_m$	$3V_m$	$10.8V_mI_m$	-	-	-	-

E. Power Loss

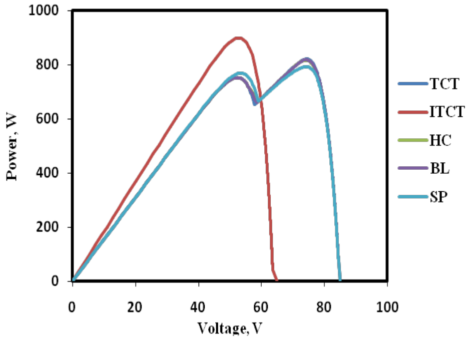
It is the difference of the peak power output from the modules under standard insolation and the global peak output power from the modules at the instant insolation.

Power Loss (P_L)= $P_{max\ (standard\ insolation)}$-$P_{Gmpp\ (instant\ insolation)}$ (24)

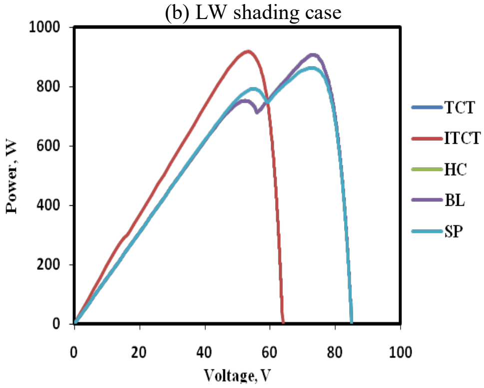
The P-V performance characteristics of SP, BL, HC, TCT, and ITCT under various shading cases are shown in Fig. 9.



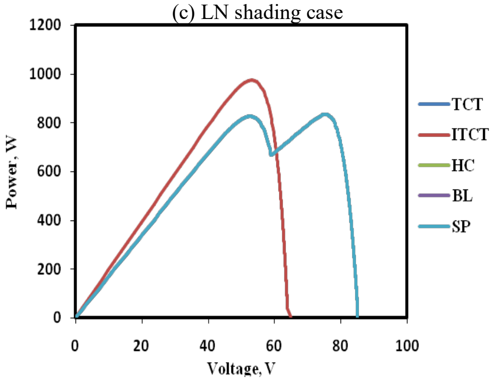
(a) SN shading case



(b) LW shading case



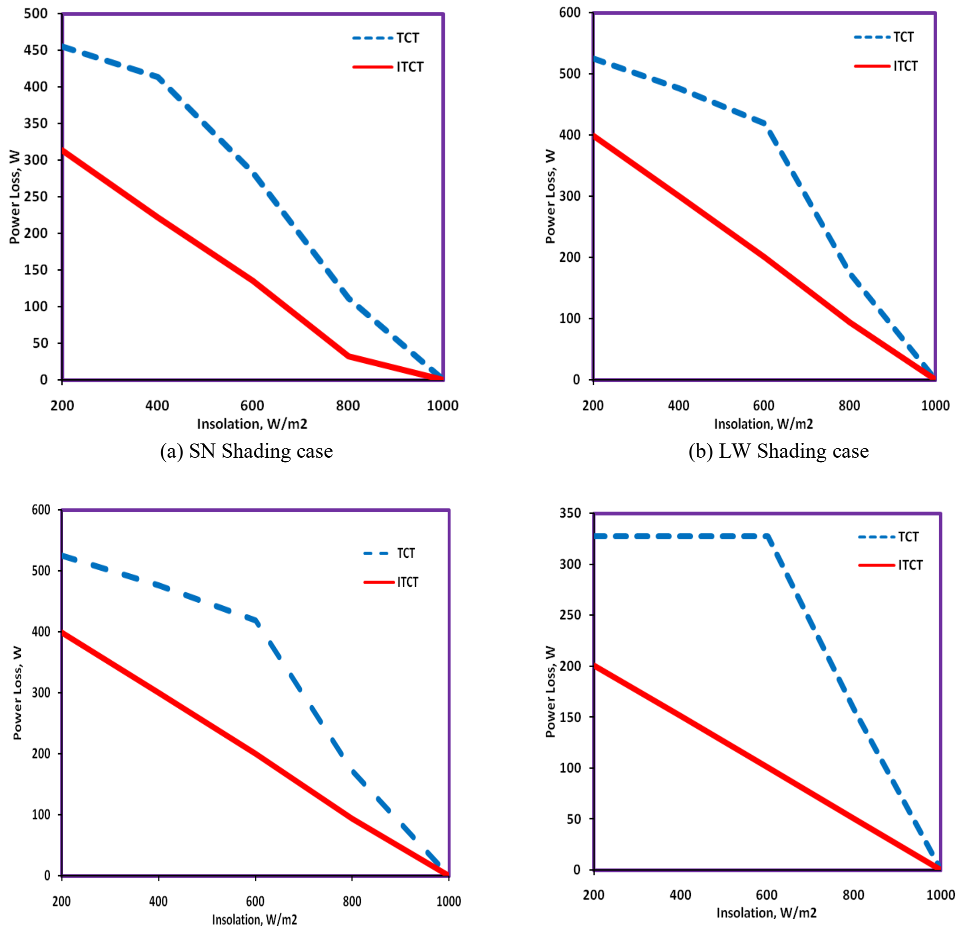
(c) LN shading case



(d) SW shading case

Fig. 9. Power versus Voltage characteristics

Even though, there is a reduction in the voltage approximately equals to one module's voltage, it's effect is minimum in the large PV arrays. There is a minimum of 23.98% power loss under LW and LN shading cases. The power loss at different insolations from 200 W/m^2 to 1000 W/m^2 under various shading cases for conventional TCT and proposed ITCT methods have been observed and plotted as shown in Fig. 10. The maximum power loss of 70.78% has been observed under SN shading pattern in conventional TCT configuration. The maximum and minimum power enhancement of 16.74% and 6.52% has been observed over conventional TCT in both LN and LW shading patterns with ITCT method. The corresponding obtained results are given in Fig. 11. The conventional configurations experience multiple peaks where as the proposed ITCT experiences single peak power under all the shading cases. The Local Maximum Power Points (LMPPs) in different interconnection schemes under various shading cases have been observed and plotted as shown in Fig. 12. The comparative analysis of the proposed method with the existing methods for various parameters is tabulated in Table 6.



(a) SN Shading case

(b) LW Shading case

(c) LN Shading Pattern

(d) SW Shading Pattern

Fig. 10. Power Loss versus Insolation under various shading cases

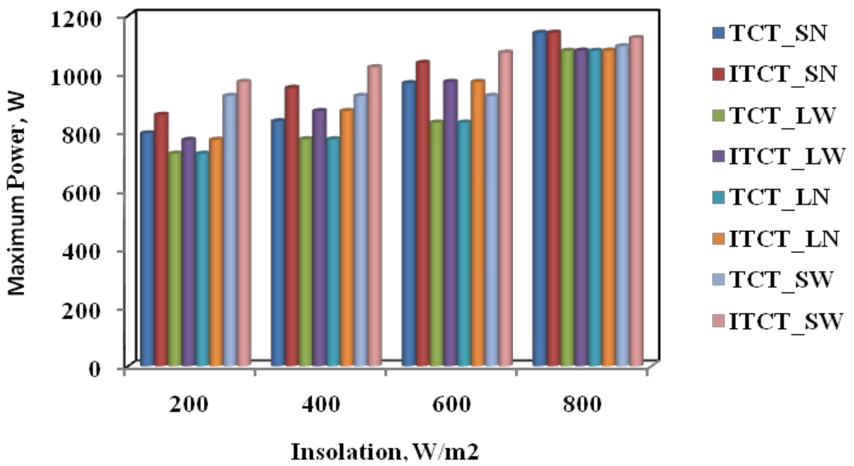


Fig. 11. Maximum Power versus Insolation under various partial shading cases

The proposed method has been tested to know the performance under shading irradiation or insolations such as a least of 200 W/m2, 400 W/m2, 600 W/m2, 800 W/m2 and maximum of 1000 W/m^2 (Standard Insolation). The correspnding data has been used to draw the waveforms in Fig. 10 by calculating the power difference between at standard insolation and instant insolation using equation (24) in Section 5.5. Hence, the power loss at reduced insolation can be known from Fig. 10 under various shading conditions.

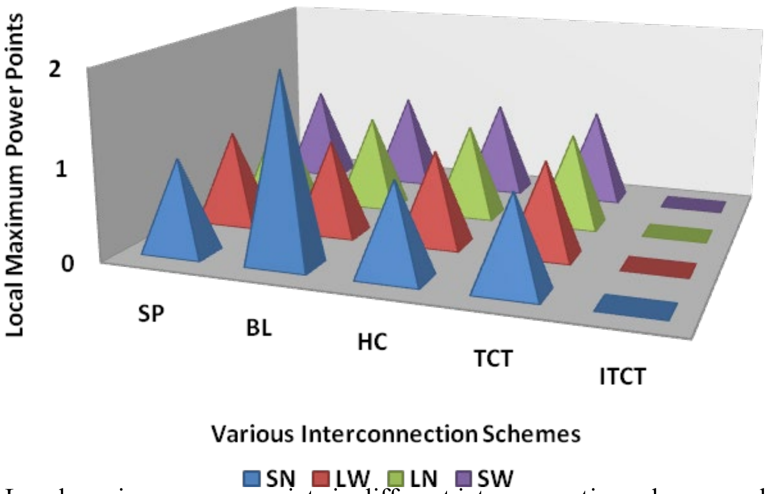


Fig. 12. Local maximum power points in different interconnection schemes under various partial shading cases

Table 6. Comparative analysis of the proposed method with the existing methods

S.No	Parameters		SP	BL	HC	TCT	Proposed Method
1.	Maximum Power under Partial Shading Cases	SN	1449.9W	1477.5W	1470.9W	1445.2W	1567.1W
		LW	1224.9W	1245.3W	1243.3W	1247.7W	1378.6W
		LN	1395.1W	1422.2W	1416.5W	1431.2W	1437.7W
		SW	1259.3W	1259.3W	1259.3W	1259.3W	1407.6W
2.	Power Loss w.r.t Proposed Method	SN	117.2W (7.47%)	89.6W (5.71%)	96.2W (6.14%)	121.9W (7.78%)	-
		LW	153.7W (11.15%)	133.3W (9.67%)	135.3W (9.81%)	130.9W (9.51%)	-
		LN	42.6W (2.96%)	15.5W (1.08%)	21.2W (1.47%)	6.5W (0.45%)	-
		SW	148.3W (10.54%)	148.3W (10.54%)	148.3W (10.54%)	148.3W (10.54%)	-
3.	Required MPPT under Partial Shading		GMPPT	GMPPT	GMPPT	GMPPT	Conventional MPPT
4.	Maximum Number of LMPPs		1	2	1	1	0
5.	Reduction in Space & PV Modules		No	No	No	No	Yes
6.	Reduction in Cost		Low	Medium	Medium	Low	Low

6. Conclusion

This paper investigated the performance of novel improved TCT connections, conventional TCT, HC, BL, and SP connections under various partial shaded cases. The proposed method addressed the various performance matrix indices such as maximum power loss of 70.78% in conventional TCT, peak power enhancement of 16.74%, elimination of local maximum powers to reach MPPT quickly, easy approach with single global maximum powers, and performance P-V characteristics had been observed and also compared with the existing configurations. The proposed ITCT in all the shading cases, obtained better results with its performance when compared to the aforementioned existing methods. This is evident that ITCT with more power extraction, less local peak powers, and less mismatch power loss shows its efficacy to adapt in real time PV systems. Further, the research of the proposed scheme can be extended with the techno-economic evaluation and payback period calculation to show the greater advantage of its adaptability in real time large scale PV array.

7. References

[1]. C. Breyer *et al.*; "On the history and future of 100% renewable energy systems research"; *IEEE Access*, 10, pp. 78176-78218, 2022. DOI: 10.1109/ACCESS.2022.3193402.

[2]. M. Yao, and X. Cai; "An overview of the photovoltaic industry status and perspective in China"; *IEEE Access*, 7, pp. 181051-181060, 2019. DOI: 10.1109/ACCESS.2019.2959309.

[3]. L. Sens, U. Neuling, and M. Kaltschmitt; "Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines-Development by 2050"; *Renew. Energy*, 185, pp. 525-537, 2022. DOI: 10.1016/j.renene.2021.12.042.

[4]. Mozdawar S. A, Akbari-Foroud A, and Amirahmadi M; "Multiple electricity markets competitiveness undergoing symmetric and asymmetric renewables development policies"; *IJEEE*, 18, 1, 2022. DOI:10.22068/IJEEE.18.1.2014.

[5]. M. Kumar, K. P. Panda, J. C. Rosas-Caro, A. Valderrabano-Gonzalez, and G. Panda; "Comprehensive review of conventional and emerging maximum power point tracking algorithms for uniformly and partially shaded solar photovoltaic systems"; *IEEE Access*, 11, pp. 31778-31812, 2023. DOI: 10.1109/ACCESS.2023.3262502.

[6]. M. Kumar; "Enhanced solar PV power generation under PSCs using shade dispersion"; *IEEE Transactions on Electron Devices*, 67, 10, pp. 4313-4320, 2020. DOI: 10.1109/TED.2020.3015171.

[7]. C. Manickam, G. P. Raman, G. R. Raman, S. I. Ganesan, and N. Chilakapati; "Fireworks enriched P&O algorithm for GMPPT and detection of partial shading in PV systems"; *IEEE Transactions on Power Electronics*, 32, 6, pp. 4432-4443, 2017. DOI: 10.1109/TPEL.2016.2604279.

[8]. A. Ali *et al.*; "Investigation of MPPT techniques under uniform and non-uniform solar irradiation condition–A retrospection"; *IEEE Access*, 8, pp. 127368-127392, 2020. DOI: 10.1109/ACCESS.2020.3007710.

[9]. P. K. Bonthagorla, and S. Mikkili; "Performance investigation of hybrid and conventional PV array configurations for grid-connected/standalone PV systems"; *CSEE Journal of Power and Energy Systems*, 8, 3, pp. 682-695, 2022. DOI: 10.17775/CSEEJPES.2020.02510.

[10]. Aidha Muhammad Ajmal, Thanikanti Sudhakar Babu, Vigna K. Ramachandaramurthy, Dalia. Yousri, Janaka B. Ekanayake; "Static and dynamic reconfiguration approaches for mitigation of partial shading influence in photovoltaic arrays"; *Sustainable energy technologies and assessments*, 40, 100738, 2020. DOI: 10.1016/j.seta.2020.100738.

[11]. Hou. S, Zhu. W; "Dynamic reconfiguration method of photovoltaic array based on improved HPSO combined with coefficient of variation"; *Electronics,* 12, 2744, 2023. DOI: 10.3390/electronics12122744.

[12]. Bapurao K. A, Mikkili S, and Bonthagorla P. K; "A Review on static reconfiguration techniques of solar PV to mitigate mismatch loss and minimize partial shading effect"; *IETE Journal of Research*, 69*,* 9, pp. 6356-6386, 2021. DOI: 10.1080/03772063.2021.1987992.

[13]. Palpandian Murugesan, Prince Winston David, Rajvikram Madurai Elavarasan, G. M. Shafiullah, Praveen Kumar Balachandran, and Thanikanti Sudhakar Babu; "A jigsaw puzzle-based reconfiguration technique for enhancing maximum power in partially shaded hybrid photovoltaic array-methodology"; *Green energy systems*, pp. 207-221, 2023. DOI: 10.1016/B978-0-323-95108-1.00009-4.

[14]. M. Palpandian, D. P. Winston, B. P. Kumar, C. S. Kumar, T. S. Babu, and H. H. Alhelou; "A New Ken-Ken puzzle pattern based reconfiguration technique for maximum power extraction in partial shaded solar PV array"; *IEEE Access*, 9, pp. 65824-65837, 2021. DOI: 10.1109/ACCESS.2021.3076608.

[15]. Muhilan Paramasivam, Rakesh Namani, Senthilkumar Subramaniam, Malavya Udugula, and Chandana Karnati; "Performance enhancement and techno-economic analysis of photovoltaic modules under dynamic weather conditions using dual exponential sawtooth method"; *Next Energy*, 4, 100149, pp. 1-12, 2024. DOI: 10.1016/j.nxener.2024.100149.

[16]. Gurusamy Madhusudanan, Subramaniam Senthil, Anand I, and Padmanaban, Sanjeevikumar; "A shade dispersion scheme using Latin Square arrangement to enhance power production in solar photo voltaic array under partial shading conditions"; *Journal of Renewable and Sustainable Energy*, 10, 5, 2018. DOI: 10. 10.1063/1.5046366.

[17]. Mikkili S, Bapurao K. A, and Bonthagorla P. K; "Sudoku and Optimal Sudoku reconfiguration techniques for power enhancement of partial shaded solar PV system"; *J. Inst. Eng. India Ser. B,* 103, pp. 1793–1807, 2022. DOI: 10.1007/s40031-022-00760-4

[18]. R. Venkateswari, and N. Rajasekar; "Power enhancement of PV system via physical array reconfiguration based Lo Shu technique"; *Energy Convers. Manag.* 215, 112885, 2020. DOI: 10.1016/j.enconman.2020.112885.

[19]. R. K. Pachauri *et al.*; “Impact of partial shading on various PV array configurations and different modeling approaches: A Comprehensive review”; *IEEE Access*, 8, pp. 181375-181403, 2020. DOI: 10.1109/ACCESS.2020.3028473.
[20]. Hicham Oufettoul, Saad Motahhir, Ghassane Aniba, Mehedi Masud, and Mohammed A. AlZain; “Improved TCT topology for shaded photovoltaic arrays”; *Energy Reports*, 8, pp. 5943-5956, 2022. DOI: 10.1016/j.egyr.2022.04.042.
[21]. C. Saiprakash, A. Mohapatra, B. Nayak, T. S. Babu, and H. H. Alhelou; “A Novel benzene structured array configuration for harnessing maximum power from PV array under partial shading condition with reduced number of cross ties”; *IEEE Access*, 10, pp. 129712-129726, 2022. DOI: 10.1109/ACCESS.2022.3228049.