Maximum Power Estimation of Total Cross-Tied Connected PV Cells in different Shading Conditions for High Current Application

Project report submitted in partial fulfillment of the requirement for the degree of

Bachelor of Technology

In

Electronics and Communication Engineering/Electrical and Electronics Engineering

Submitted by

Anirudh Gaur (1810110029)

Under supervision of

Dr. Himanshu Sekhar Sahu
(Assistant Professor, Department of Electrical Engineering)

Department of Electrical Engineering
School of Engineering
Shiv Nadar University
(Spring 2022)

Candidate Declaration

I hereby declare that the thesis entitled "Maximum Power Estimation of Total Cross-Tied connected PV Cells in different shading conditions for High Current Application" submitted for the B Tech Degree program. This thesis has written in my own words. I have adequately cited and referenced the original sources.

(Signature)
Anirudh Gaur
1810110029
Date: 28/04/2022

CERTIFICATE

It is certified that the work contained in the project report titled “Maximum Power Estimation of Total Cross-Tied connected PV Cells in different shading conditions for High Current Application,” by “Anirudh Gaur” has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

(Signature)
Dr. Himanshu Sekhar Sahu
Dept. of Electrical Engineering
School of Engineering
Shiv Nadar University
Date: 28/04/2022

Abstract

In the existing solar photovoltaic modules, cells are connected in series. The performance of such module decreases severely during partial shading as even faulty cell experiencing partial shading causes the output of all the other cell to decrease if they are connected in series. Usage of bypass diode to solve this issue causes formulation of multiple peak thus making it difficult to track the global maximum power point in the I-V curve. Therefore, total cross tied (TCT) connection has been proposed in this paper to connect the cells in a module (TCT connected module) that gives a better performance during partial shading without multiple peak problem. In this paper, we have presented an analytical algorithm which is simple and robust which will help the photovoltaic installers to estimate the output power of a TCT connected module without using any measuring instruments except irradiance and temperature measurements. The output of the proposed algorithm will be verified using simulation.

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Chapter 1
Introduction

Solar photovoltaic energy has become cost competitive and affordable due to the reduction of its cost by almost 80%-85% in the last decade. PV generation has grown rapidly, from less than 1 GW in 2000 to about 2000GW-3000GW worldwide in 2017 [1]. To track the crucial market trends, the IRENA (International Renewable Energy agency) has developed cost and competitiveness indicators for rooftop solar PV. This has resulted in solar module prices declining by more than 80% in last 7 years [1],[2].

Despite such an enormous expansion of the solar market, in conventional series-connected PV modules, partial shading conditions (PSC) is mostly responsible for power loss. To prevent this situation, bypass diode has been used in high voltage applications which causes multiple peaks [3]. This causes MMPT (maximum power point tracking) to become more difficult as conventional algorithms can deal with only a single peak. For this reason, GMPPT algorithm has been proposed to track global peak however these algorithms are time consuming, complex and do not guarantee tracking of the global peak all the time. [3] has also discussed about DMPPT where a dedicated dc/dc convertor is connected across each PV module and the outputs of all these convertors are connected in series. To address this issue, a parallel-connected PV module has been designed in [4].

In [4], comparison between parallel-configured PV systems to traditional series connected PV systems through both hardware and computer simulations has been performed. This configuration is widely used for many consumer applications, such as PV vets for cell phone and music player.

1.1 Parallel Configuration

The PV array is constructed with a highly parallel, rather than serial, wiring configurations. It has 3 important characteristics-

1. Voltage of MPP is largely independent of illumination, or in other words, even at different irradiance levels, the MPP’s of cell connected in parallel occur at nearly a common voltage.
2. Slight deviation from MPP voltage only weakly affects produced power.
3. Voltage of MPP is only weakly sensitive to temperature over the usual range. As a result, the parallel- configured PV array is capable of making every cell in the panel generate nearly maximum power simultaneously.

It is reported in [5] that, at array level, short series connected strings are less prone to mismatch loss due to PSC’s compared to long series connected strings. Accordingly, total cross tied (TCT) connection is used at the array level. Subsequently, a lot of algorithms have been proposed in [6], [7], [8], [9] such as electrical array reconfiguration technique, Su Do Ku, Futoshiki, etc. but the modules in all these configurations comprises of series connected cells. Although TCT connection is used at array level, the same is not used at module level in current state of the art. Even though there are a lot of algorithms [10] available to estimate the output power from a TCT connected PV array, those cannot be used for TCT connected module as the behavior of solar PV is different in cell level compared to module level during PSC, where the short circuit current and fill factor (FF) plays an important role [11].

When the output current of each component cell in a series-connected PV module has some distribution due to the nonuniformity, the module’s I–V curve tends to show steps, each of which reflects the photocurrent of each cell. Herrmann and Wiesner [11] has reported that the increase in the nonuniformity results in underrating of Isc and overrating of fill factor, FF. Here, the FF is defined by FF = Pmax /(Isc · Voc), where the Voc denotes the open circuit voltage. Another major difference is temperature effect which in turn causes significant distinction between cell level and module-level power generation [12]. Like previous cases, the application of evolutionary algorithms and numerical methods [13-18] increases the computational complexity and convergence failure. Dependency on few parameters such as population size, objective function, etc. also threatens the accuracy as even a minor error in determining them can cause major deviation from expected results. Moreover, all these methods use iterative techniques causing an increase in time complexity.

Keeping all these things in view, I have tried to present a mathematical model in this project, which will help the PV installer to estimate the power generation from a TCT connected module in absence of bypass diode. This will be done with minimal measurement instruments as more instruments might lead to more proneness to error.

Advantages of this algorithm are as follows-

- Non-usage of electrical array reconfiguration makes the algorithm computationally efficient and free from convergence failure.
- Except for the datasheet values, no extra data is required for the estimation work. This makes algorithm simple with less computational time and minimal instrument requirements making it more user friendly compared to others.

1.1 Project Work:

Since the focus of this project revolves around TCT configuration, it is necessary to distinguish TCT configuration from series connected cells and series parallel connected cells. For this purpose we would compare a 4 cell TCT model with series and series parallel model under 4 different shading conditions to observe the difference. The fact that TCT connected modules give higher current during partial shading condition compared to other configurations need to be examined. The model simulation has been done both in MATLAB SIMULINK and a practical model has also been used. In the practical mode, PV module instead of cells has been used due to non-availability of cells and inside these modules, cells are connected in series.

Secondly, I have tried to show the current difference between the shaded row and unshaded row depending upon shunt resistance and similarly the voltage between shaded row and unshaded row depending upon series resistance of cells. A table has been made in which module current for all 4 different shading conditions has been defined in terms of row currents of each module, thus helping in understanding the difference between all 4 different shading patterns.

Chapter 2

Literature Review

The literature I have referred states that generation of power from a solar PV cell depends on several factors such as series resistance (R_s), shunt resistance (R_{sh}), diode current (I_0) and photo generated (I_{ph}) current as follows-

$$I = I_{ph} - I_0\left\{e^{\frac{V+IR_s}{V_t}} - 1\right\} - \frac{V + IR_s}{R_{sh}}$$

Hence, it is necessary to analyze after what point we observe a significant change in the current and voltage parameters of our model which I have tried to do in this paper. Apart from this, literature suggesting usage of TCT connected PV module in welding have been discussed as current in voltage can be adjusted more easily in TCT configuration by changing the size of the module.

Literature also states that at array level, short series-connected strings are less prone to mismatch losses due to PSC in comparison to long-series connected strings. Due to this reason, TCT connection is preferred at array level and even TCT connection to connect cells inside module has been proposed. It is also important to understand what fill factor (FF) is which can be defined as the ratio of maximum power to the theoretical power. It depends upon several factors and any sort of deviation from expected FF values may lead to the PV cell being considered as faulty. From in-depth analysis, it is noticed that the FF in the cell level and module level is not the same and depends on the difference between the G (irradiance) levels of the shaded and unshaded cells in PSC which is also a unique property we will try to incorporate in our algorithm.

Chapter 3

Work Done

I have considered a set of 2X2 identical cells connected in TCT fashion as a base model. Different types of PSC are considered which are shown in the figure below. The unshaded cells are exposed to the same amount of irradiance and thus, the general current and voltage are equal during no shading condition.

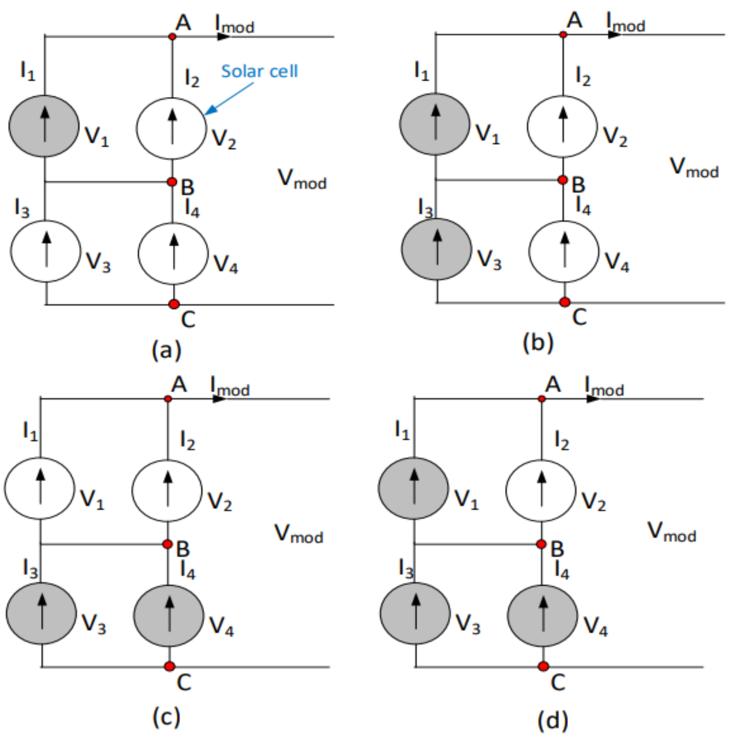


Fig 3.1 2 X 2 TCT Configuration

Using Kirchhoff's laws, the short circuit output current (I_{mod}) and open circuit voltage (V_{mod}) of the module at unshaded conditions are calculated as given in (2) and (3) respectively.

$$I_{mod} = I_1 + I_2 = I_3 + I_4 \tag{2}$$

$$V_{mod} = V_1 + V_3 = V_2 + V_4 \tag{3}$$

$$V_1 = V_2 \text{ and } V_3 = V_4 \tag{4}$$

Let us denote irradiance level by G so that irradiance in shaded and unshaded cell is represented by G_s and G_{un} respectively. Then the short circuit current produced during shaded condition (I_s) is calculated as (5).

$$I_s = \frac{G_s I_{un}}{G_{un}} \quad (5)$$

The current produced during unshaded condition is denoted by I_{un} and the amount of short circuit current (I_{red}) which is reduced due to shading is calculated as (6).

$$I_{red} = I_{un}(1 - \frac{G_s}{G_{un}}) \quad (6)$$

3.1 Analysis of 2 X 2 TCT connected cells in PSC

I would be showing analysis for PSC-1 and for the rest of PSC's we can calculate in a similar manner whose results table would be presented at the end of the analysis. In PSC-1, since only cell-1 is shaded, the individual current of other cells is expressed as:

$$I_{un(2),(3),(4)} = I_{ph} - I_0\left\{e^{\frac{I_{un(2),(3),(4)}R_s}{V_t}} - 1\right\} - \frac{I_{un(2),(3),(4)}R_s}{R_{sh}} \quad (7)$$

The current in the shaded cell is denoted by $I_{s(1)}$ which is reduced due to shading and is expressed as:

$$I_{s(1)} = I_{ph} - I_0\left\{e^{\frac{I_{un(1)}R_s}{V_t}} - 1\right\} - \frac{I_{un(1)}R_s}{R_{sh}} - I_{un(1)}\left(1 - \frac{G_s}{G_{un}}\right) \quad (8)$$

The current and voltage values at different levels are obtained from the manufacturer's datasheet and unknown parameters such as R_{sh}, R_s, I_0, I_{ph} are estimated through the algorithm presented in [21]. We have considered I_{mod1} as the combination of currents I_1 and I_2 i.e. the sum of current flowing through each individual cell in the first row and I_{mod2} as the sum of current flowing through each individual cell in the second row. By using (7) and (8) and substituting I_{mod1} ($I_1 + I_2$):

$$I_{mod_1} = 2I_{ph} - 2I_0\left\{e^{\frac{I_{un(1)}R_s}{V_t}} - 1\right\} - 2\frac{I_{un(1)}R_s}{R_{sh}} - I_{un(4)}\left(1 - \frac{G_s}{G_{un}}\right) \quad (9)$$

Similarly, the short circuit current in 2^{nd} row i.e. I_{mod2} is calculated as:

$$I_{mod_2} = 2I_{ph} - 2I_0\left\{e^{\frac{I_{un(1)}R_s}{V_t}} - 1\right\} - 2\frac{I_{un(1)}R_s}{R_{sh}} \quad (10)$$

$$I_{mod_1} = I_{mod_2} - I_{un(4)}\left(1 - \frac{G_s}{G_{un}}\right) \tag{11}$$

From (11), it can be clearly observed that $I_{mod1} < I_{mod2}$. Therefore, the short circuit module current is regulated by I_{mod1} such that (I_{mod}) => $I_{mod} \approx I_{mod1}$. After compiling the results for all the other 3 PSC's in a similar manner to PSC-1, we get a table whose results are as follows:

PSC	I_{mod_2} vs I_{mod_1}	$I_{mod} \approx$
PSC-1	$I_{mod_2} > I_{mod_1}$	I_{mod_1}
PSC-2	$I_{mod_2} = I_{mod_1}$	Either I_{mod_1} or I_{mod_2}
PSC-3	$I_{mod_2} < I_{mod_1}$	I_{mod_2}
PSC-4	$I_{mod_2} < I_{mod_1}$	I_{mod_2}

Table 3.1 Current Comparison

For the algorithm, PSC-1 will be considered. According to the table 3.1, I_{mod2} is greater than I_{mod1}. So, the outgoing module current would be represented as:

$$I_{mod} = min(I_{mod_1},\ I_{mod_2}) + \Delta I \tag{12}$$

The term ΔI introduced here depends on both I_{mod1} and I_{mod2}. In general, ΔI is a function of current difference (say I_{diff}) between I_{mod1} and I_{mod2}. Similarly, the circuit can be divided into two halves AB and BC with AB representing the upper two cells and BC representing the lower two cells. Since in PSC-1, cell 1 is shaded and cell 2 is unshaded so $V_1<V_2$ and therefore V_{AB} will be given as follows:

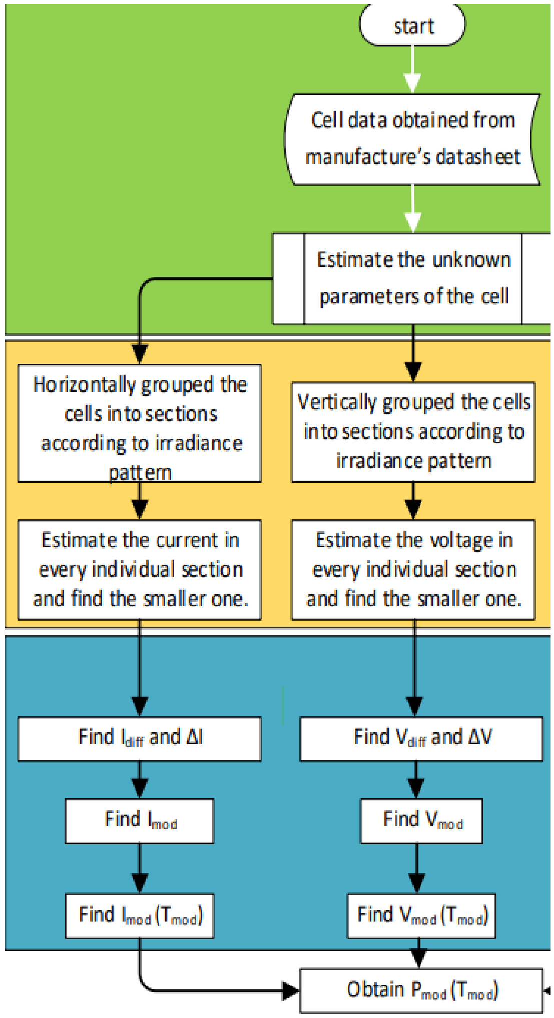
$$V_{AB} = min(V_1,\ V_2) + \Delta V_{AB} \tag{13}$$

Here, ΔV_{AB} mainly depends on Rs (series resistance of the cell) and the voltage difference between V_1 and V_2 (say V_{diff}). Finally the maximum power output from the module is calculated as:

$$P_{mpp} = FF \times V_{mod} \times I_{mod} \tag{14}$$

Here FF is the fill factor of the TCT connected module.

The final algorithm is presented as follows:



For this algorithm, the operating temperature (T_{mod}) of the TCT connected modules should also be known which is given as:

$$T_{mod} = T_{amb} + \frac{NOCT - 20}{800\ W/m^2} G_{avg} \tag{15}$$

Here, T_{amb} is the ambient temperature in ◦C and G_{avg} = Average G(irradiance) of all the cells. Now, following the same procedure described in [18], the voltage, current and FF of the TCT connected module at temperature Tmod are obtained as given in (47), (48) and (49).

$$V_{mod}(T_{mod}) = V_{mod} - 2.2 \times 10^{-3}(T_{mod} - 25) \tag{16}$$

$$I_{mod}(T_{mod}) = I_{mod}\{1 + 6 \times 10^{-4}(T_{mod} - 25)\} \tag{17}$$

$$FF(T_{mod}) = FF\{1 - 1.5 \times 10^{-3}(T_{mod} - 25)\} \tag{18}$$

3.2 ESTIMATION OF MPP IN PSC FOR DIFFERENT CONFIGURATIONS

As mentioned in the introduction section, it is important to understand the difference in MPP for TCT, series-parallel (SP), and series configuration for the 4 cell PV model we have considered. For the circuits I have done simulations on, bypass diode has been considered contrary to the literature works I have referred.

(i) TCT configuration

The MATLAB Simulink circuit used for TCT configuration is as follows-

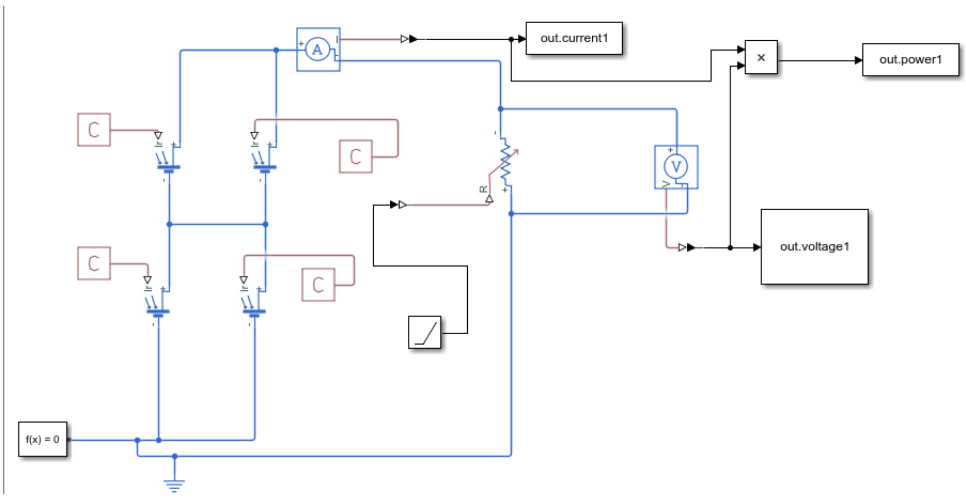


Fig 3.2 TCT Model

The 4 PV cells in the circuit are connected in such a way to make a 2X2 TCT configuration. They are interconnected in a series parallel manner without any blocking diode to avoid multiple peaks along with voltage sensors in parallel and current sensors in series which are going to the product block for obtaining power. The PS constant blocks connected to each cell is responsible for irradiance level (Standard conditions- 1000 W/m^2). In PSC-1, the first cell's irradiance is changed from 1000 to 200, in PSC-2 the first and third cell's irradiance is changed from 1000 to 200, in PSC-3 the entire 2nd row i.e. 3rd and 4th cell's irradiance is changed from 1000 to 200 and finally in PSC-4 the 1st, 3rd and 4th cell's irradiance is changed from 1000 to 200. A PS Simulink convertor is used to send the data obtained from SIMULINKS to MATLAB workspace and then the plotting is done for P-V and I-V characteristics.

(ii) Series Parallel (SP) configuration

In this configuration, 2 cell's on each side are connected in series and later those series connected cell's column is connected in parallel with no interconnections between individual cell's unlike TCT.

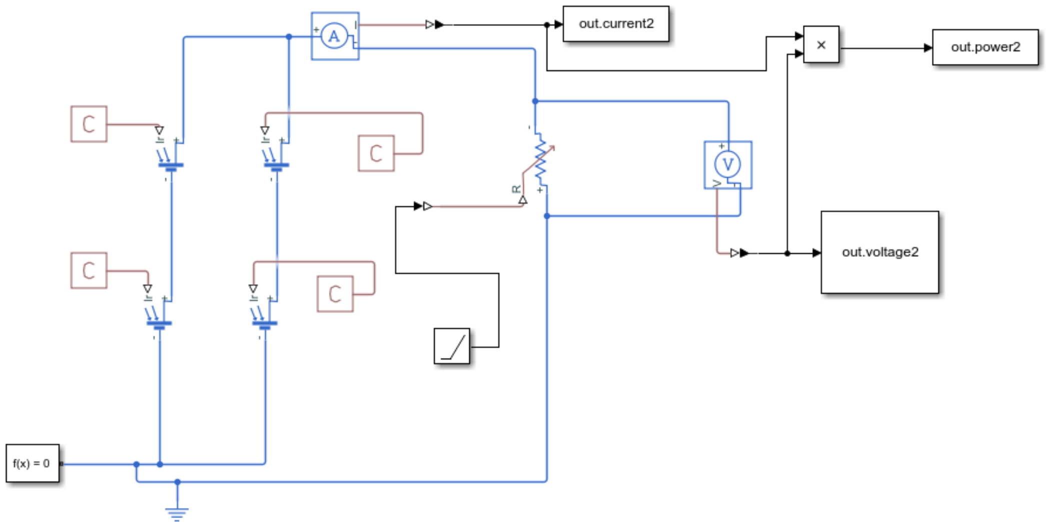


Fig 3.3 SP Model

The PSC conditions and rest of the circuit design is same as in TCT configuration except for no interconnection between cells.

(iii) Series configuration

In this configuration, all the 4 cells are connected in series. This causes the same MPP if the number of shaded cell's is same irrespective of where they are positioned.

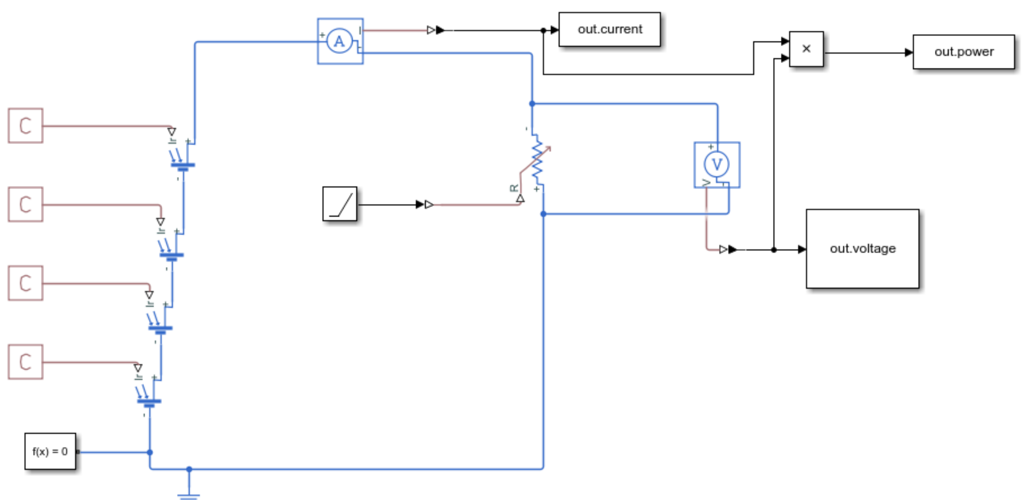


Fig 3.4 Series Model

The PSC conditions are same as SP and TCT configuration and since all the cell are in series, it is obvious that the MPP will decrease as the number of shaded cell's increase irrespective of where they are placed.

We have used two types of cells A and B which have different data parameters. The values of their respective parameters are given in the below datasheet:

Parameters	**Cell A**	**Cell B**
Open circuit voltage (V_{oc})[V]	0.641	0.603
Short circuit voltage (I_{sc})[A]	8.988	5.02
Maximum power [W]	4.58	2.31
Voltage at MPP (V_{mpp})[V]	0.542	0.505
Current at MPP (I_{mpp})[A]	8.448	4.579

Table 3.2 Datasheet Values

3.3 Calculation and Graph

The graph obtained for all 4 shading conditions for cell type A are given below for TCT, SP and series configuration are shown below:

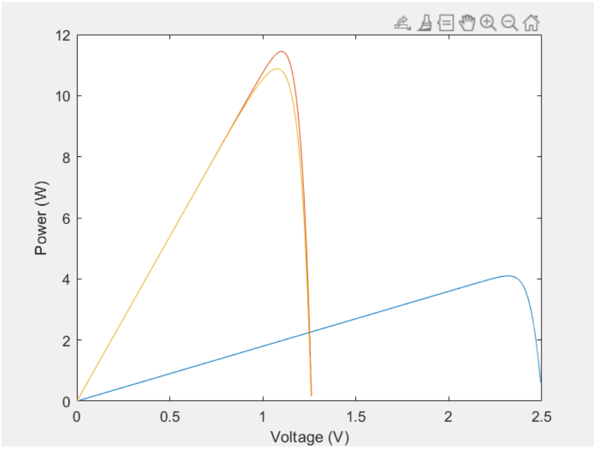


Fig 3.5(a) PSC-1

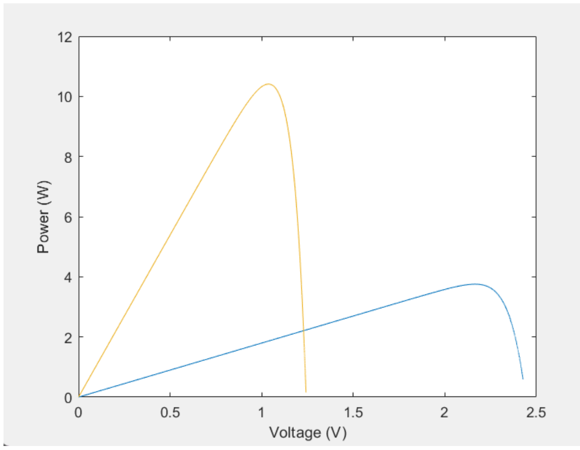


Fig 3.5(b) PSC-2

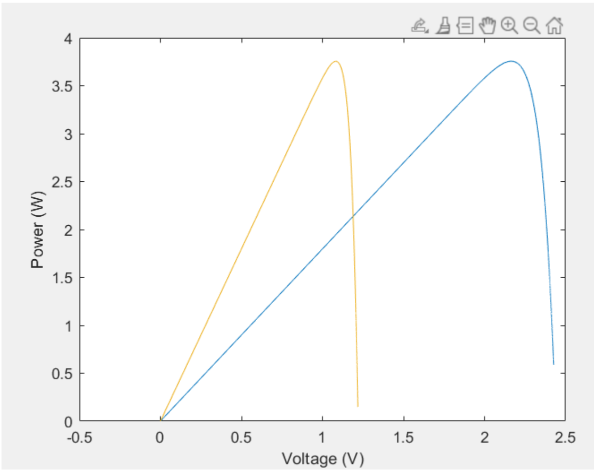


Fig 3.5(c)PSC-3

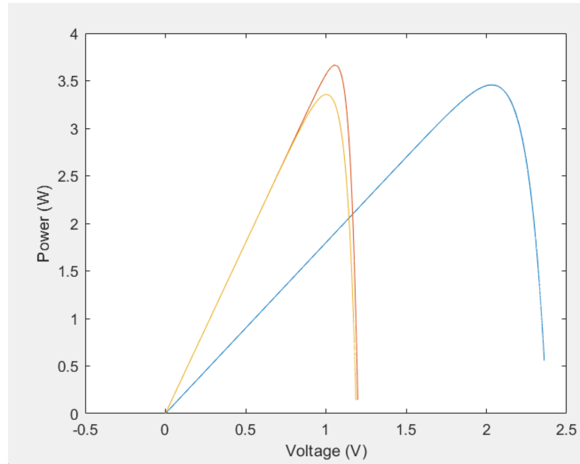


Fig 3.5(d) PSC-4

Fig 3.5 Cell A simulation

In the graph, yellow lines represent series-parallel (SP) configuration while blue and red line represent series and TCT configuration respectively. In all the 4 configurations, TCT performs better in comparison to SP and series as TCT gives a higher MPP (maximum power point). In PSC-2 and PSC-3, TCT performs marginally better than SP leading to overlapping lines in the graph. The observation table for this cell A will be shown in results section.

Similarly, we have obtained the graph for Cell type B for all different configurations in all 4 PSC.

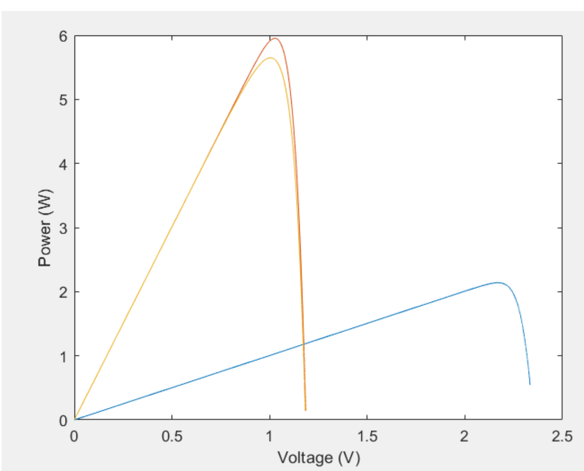


Fig 3.6 (a) PSC-1

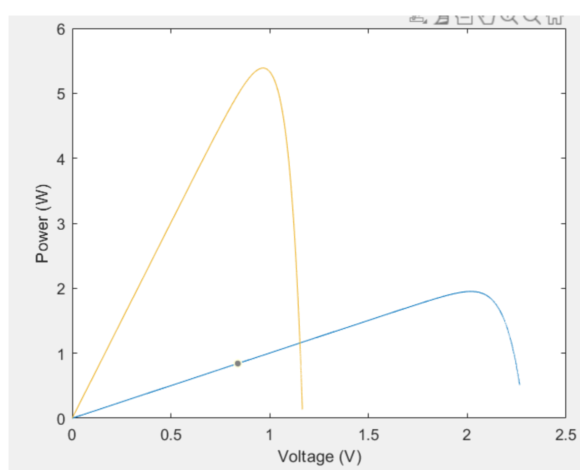


Fig 3.6(b) PSC-2

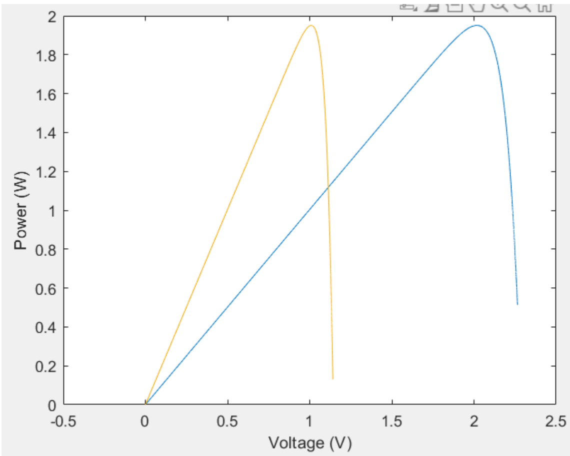


Fig 3.6(c)PSC-3

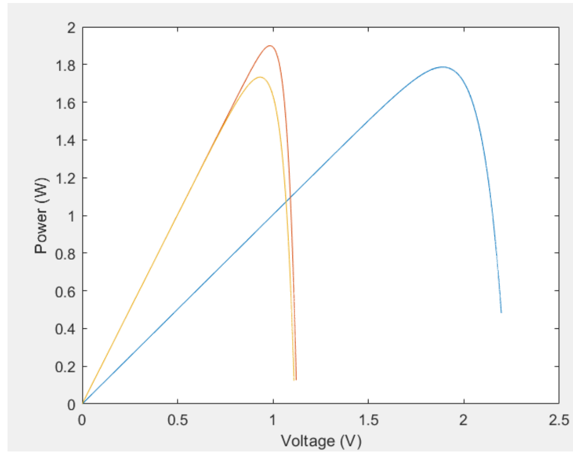


Fig 3.6(d) PSC-4

Fig 3.6 Cell B simulation

The color coding is same as that in previous graphs. It is evident that TCT performs better than SP and series in all 4 PSC. Usage of bypass diode at cell level would have led to series model performing better but would have also caused multiple peaks. Detailed analysis would be shown in table in results section.

3.4 Observation

The table showing P_{mpp}, I_{mod}, V_{mod} for different configurations along with performance improvement (PI) for SP and series with respect to TCT can be seen below:

	TCT			SP				Series			
Cell A	Pmpp	Vmod	Imod	Pmpp	Vmod	Imod	PI	Pmpp	Vmod	Imod	PI
PS-1	11.45	1.102	10.39	10.88	1.074	10.13	5.24%	4.099	2.32	1.76	179.34%
PS-2	10.41	1.04	10.009	10.41	1.04	10.009	0.00%	3.756	2.161	1.73	177.16%
PS-3	3.756	1.081	3.474	3.756	1.081	3.474	0.00%	3.756	2.162	1.73	0.00%
PS-4	3.664	1.061	3.453	3.356	1	3.356	9.18%	3.456	2.037	1.69	6.02%

Table 3.3 Cell A

	TCT			SP				Series			
Cell B	Pmpp	Vmod	Imod	Pmpp	Vmod	Imod	PI	Pmpp	Vmod	Imod	PI
PS-1	5.952	1.029	5.784	5.648	1.006	5.614	5.38%	2.139	2.171	0.985	178.26%
PS-2	5.388	0.968	6.074	5.388	0.968	6.074	0.00%	1.95	2.02	0.965	176.31%
PS-3	1.95	1.014	1.923	1.95	1.014	1.923	0.00%	1.95	2.016	0.967	0.00%
PS-4	1.9	0.983	1.932	1.733	0.934	1.855	9.64%	1.786	1.896	0.941	6.38%

Table 3.4 Cell B

For both cell type A and B, it is clearly evident that TCT performs better in all the cases than SP. In only a few cases does TCT performs equal to series-parallel.

3.5 Practical Modelling of 2X2 TCT

Along with the simulation part in MATLAB SIMULINK, it is also necessary to verify the 4 partial shading conditions in a practical model which would be done in this section.

Circuit Description:

Fig. 3.7(a) Circuit Model

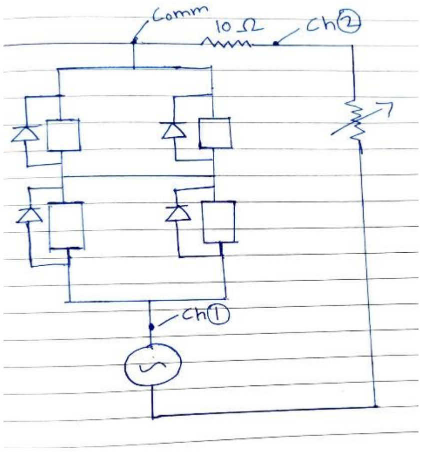


Fig 3.7 (b) Circuit tracing

Both the picture of the circuit along with the circuit diagram have been shown in Fig 3.7 (a),(b). Instead of using TCT cells, TCT modules have been used with each module containing 18 cells connected in series. Modules are basically cells connected in series so they can be imagined as a single cell amplified on a larger scale. Unlike earlier in the SIMULINK Model, in practical modeling we have considered the use of bypass diode as they were already connected to the modules. The 2X2 TCT connected modules are connected to a 10 ohm resistance (for the purpose of taking current reading from DSO) which is further connected to a rheostat. The Rheostat is finally connected to an autotransformer. Halogen light is used to give the necessary irradiance to the modules. A film sheet would be applied to the modules where shading is required. The normal irradiance level is 535 W/m^2 and irradiance received by the shaded modules is 467 W/m^2. Channel 2 of the DSO is being used for current which is obtained be dividing the value obtained by 10 as 10 ohm resistance has been used. Channel 1 is being used for measuring voltage and common ground has been made between the junction of 10 ohm resistance and top of the TCT module. The data for the module is given below.

Below is the graph for I-V characteristic for all the 4 partial shading configurations in 2X2 TCT modules.

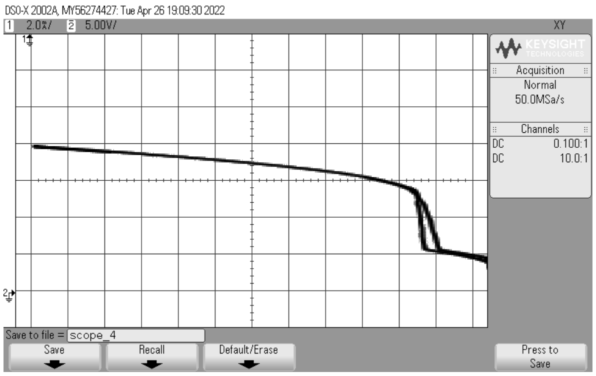


Fig 3.8 (a) PS-1 I-V Curve

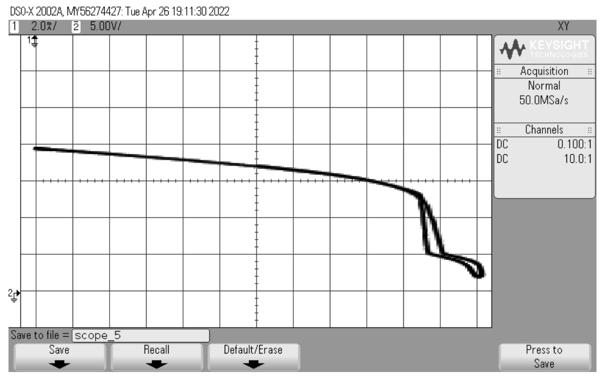


Fig 3.8 (b) PS-2 I-V Curve

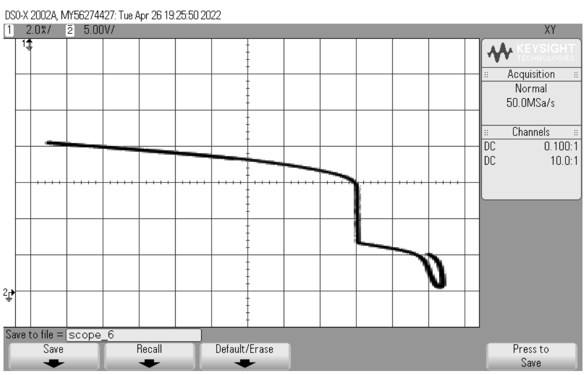


Fig 3.8 (c) PS-3 I-V Curve

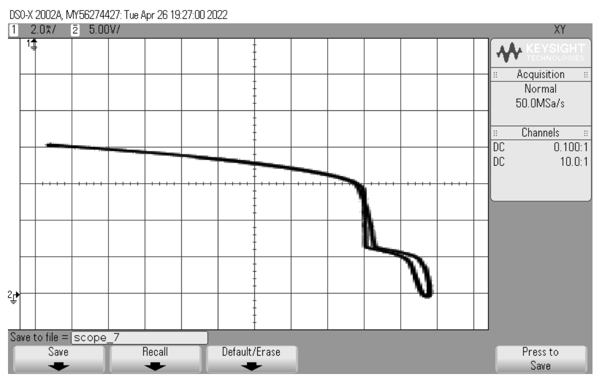


Fig 3.8 (d) PS-4 I-V Curve

The time domain analysis of both channel 2 and channel 1 representing current and voltage respectively are shown in the below figures:

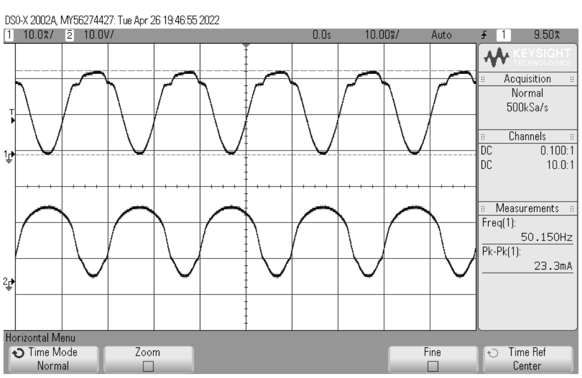


Fig 3.9 (a) Time domain analyses of PS-1

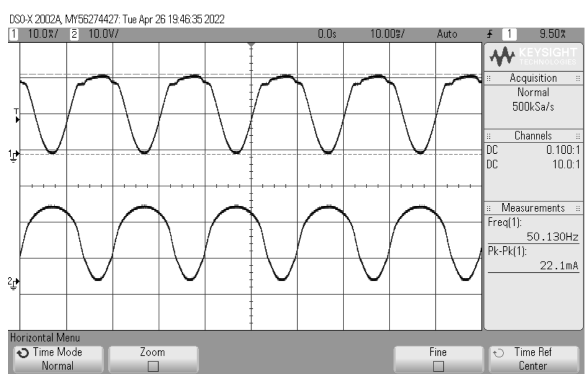


Fig 3.9 (b) Time domain analyses of PS-2

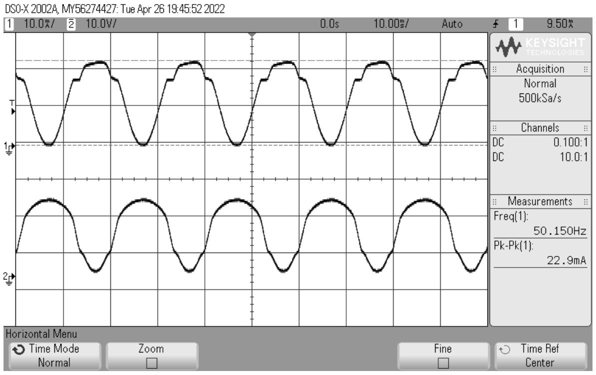


Fig 3.9 (a) Time domain analyses of PS-3

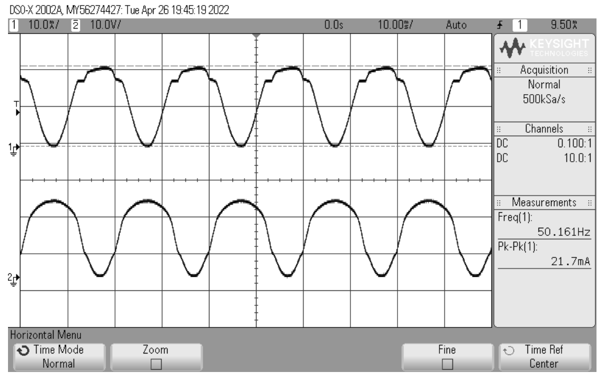


Fig 3.9 (a) Time domain analyses of PS-4

3.6 Observation for practical Model

The table below shows the maximum current and maximum voltage for each PSC for the TCT connected 2X2 modules.

Shading type	V_{max} (Volts)	I_{max} (Ampere)
PSC-1	26	2
PSC-2	24.4	1.95
PSC-3	22.8	2.1
PSC-4	21.6	2

Table 3.5 TCT Model values

It was observed from both the time domain and I-V curve that PSC-1 had the maximum power point as it had the maximum value of voltage in the time domain and a current value approximately 2A. The least maximum power point was of PSC-4 while P_{MPP} for both PSC-2 and PSC-3 were almost equal as in PSC-2 the entire first row was shaded and in PS-3 the entire second column was shaded. The maximum voltage kept on decreasing from PSC-1 to PSC-4. The order of P_{MPP} is almost the same as that in the SIMULINK model even though in the SIMULINK model cell instead of a module was considered and bypass/blocking diode were not taken into consideration.

Chapter 4
Conclusion

This project has tried to develop an analytical algorithm to estimate the MPP of TCT connected cells, which is free from computational complexity and convergence issues. Although the current generated in the shaded cell governs the overall current in TCT connected module, the difference between the shaded and unshaded current also plays a vital role in the overall generation of module and this has been used to identify voltages and current by dividing the entire module containing cells into individual rows and columns.

A 2X2 TCT connected cell model was used with different shading conditions to emphasize the point of why it performs better than series and series-parallel configuration at cell level. Same TCT model was then deployed but this time at module level instead of cell level with each module containing 12 cells in series. Certain observations were made from these models regarding the current and voltage distributions and value and comparison between the algorithm approach and our results was made even though the algorithm is valid for cell level and our practical model was made using PV modules.

Chapter 5
Future Prospects

Having analyzed the behavior of our TCT model and how current distribution takes place in it while also comparing it with SP and series model and analyses the TCT model in a 2X2 configuration at module level, our plan going forward would be to analyze this behavior in larger application (suppose 6X6) for TCT at cell level and apply the algorithm suggested on it. The next step for this is as follows-

- Using this algorithm PV installers can forecast the power generation of a TCT connected module in different PSC before installing the module.
- Error in the result of the algorithm compared to the TCT model we prepared needs to be seen at the cell level.
- The practical TCT model needs to be analyzed at cell level instead of module level which I was unable to do currently due to the unavailability of individual cells.
- Further calculations under different shading patterns such as SN, SW, LN, LW can be done to emphasize upon the accuracy of the algorithm.

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