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ANALYTICAL INVESTIGATION OF PV ARRAY TOPOLOGIES UNDER VARIOUS PARTIAL SHADING CONDITIONS

A

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CANDIDATE'S DECLARATION

I, Karni Pratap Palawat, Roll No. 2K18/PSY/20 student of M.Tech (POWER SYSTEM), hereby declare that the project Dissertation titled "**Analytical investigation of PV Array topologies under partial shading conditions** " which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi

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CERTIFICATE

I hereby certify that the Project Dissertation titled " **Analytical investigation of PV Array topologies under various partial shading conditions** " which is submitted by KARNI PRATAP PALAWAT, whose Roll No. is 2K18/PSY/20, Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi **DR. VINOD KUMAR YADAV**

Date: (**SUPERVISOR)**

ABSTRACT

As solar energy has become, a crucial part of human life as well as renewable in nature leading to clean and green in nature. It is been observed that this is future viable source of energy generation. Many researcher and policy makers are advocating for this. As in near future taking slight shift towards solar energy. Before that we have to address some of the peculiar issues associated with solar PV modules. For that in this work author has tried to address some of the issues related to modules such as maximum power output during partial shading condition, hotspot, reduction in temperature rise. For this analysis we have used MATLAB/Simulink$^{@}$ for modeling of PV array (User defined) as per our requirement. And three topologies are simulated, further the same has been done using hardware 3*3 PV array is formed using EXIDE INDIA LIMITED (EIL-40) modules each have capacity of 40 W.

Further tried to replicate five partial shading conditions and results are formed and compared and best suited topology is advised for particular shading pattern.

As in experiment author has tried to relate and compare the simulation and hardware analysis which has good experience altogether. Comparison is done mostly based upon fill factor, performance ratio, maximum power etc.

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TABLE OF CONTENTS

CANDIDATE'S DECLARATION	ii
CERTIFICATE	iii
ABSTRACT	iv
ACKNOWLEDGEMENT	v
TABLE OF CONTENTS	vi
LIST OF FIGURES	viii
ACRONYMS	x
CHAPTER 1 INTRODUCTION	1
1.1: INTRODUCTION	1
1.2 ENERGY	2
1.2.1 PRIMARY AND SECONDARY ENERGY SOURCES	2
1.3 RENEWBLE ENERGY SOURCES	2
1.4 GLOBAL INITIATIVES	3
1.5 MOTIVATION	4
1.6 PROBLEM STATEMENT	4
1.7 PARTIAL SHADING	5
CHAPTER 2 THEORETICAL BACKGROUND	6
2.1 SYMBOLIC MODEL OF PV CELL	6
2.2 OBJECTIVE OF THESIS	7
2.3 LITERATURE SURVEY	8
2.4 PARAMETERS FOR PERFORMANCE EVALUATION	9
2.5 CIRCUIT TOPOLOGIES	11
2.5.1 SERIES-PARALLEL (SP)	11
2.5.2 BRIDGE LINK (BL)	12
2.5.3 TOTAL CROSS-TIED (TCT)	12
2.6 SCHEME OF EXPERIMENT	13
CHAPTER 3 SOFTWARE ANALYSIS AND STUDY	15
3.1 RATINGS OF PV MODULE	15
3.2 SIMULINK MODEL	15
3.2.1 SERIES PARALLEL (SP)	15
3.2.2 BRIDGE LINK (BL)	16

3.2.3 TOTAL CROSS TIED (TCT) 16
3.2 PARTIAL SHADING CONDITIONS 17
3.3 RESULTS 19
3.4 PARAMETERS CALCULATION 22
CHAPTER 4 HARDWARE ANALYSIS AND STUDY 26
4.1 TOPOLOGIES 26
4.2 EXPERIMENTAL SETUP 27
4.3 DESCRIPTION OF PARTIAL SHADING CONDITIONS 28
4.4 GRAPHS 31
4.5 GLOBAL AND LOCAL MAXIMA 34
4.6 PARAMETERS 34
CHAPTER 5 CONCLUSION AND OBSERVATIONS OF EXPERIMENT 37
5.1 SUMMARY 37
5.2 MATLAB/Simulink@ model observations. 37
5.3 Hardware observations: - 38
5.4 FUTURE SCOPE 39
PUBLICATIONS 40
REFERENCES 41

LIST OF FIGURES

Figure 1 Partial shading causes, effects and mitigations[13] 5
Figure 2. Single cell model of PV Cell [14] 6
Figure 3. Partial shading scenario. 8
Figure 4. Reverse biasing of PV cell. 9
Figure 5. Graphical representation of parameters. 10
Figure 6. Scheme of series parallel 11
Figure 7. scheme of Bridge link topology. 12
Figure 8. Scheme of TCT topology 13
Figure 9. Flow chart of experiment 13
Figure 10 MATLAB/Simulink@ model for Series-parallel topology 16
Figure 11 Bridge link topology Simulink model 16
Figure 12 MATLAB/Simulink model of TCT topology. 17
Figure 13 Scheme of partial shading conditions 18
Figure 14 PV graph of Series parallel topology 19
Figure 15 IV plot of Series parallel topology 20
Figure 16 PV plot of Bridge link topology 20
Figure 17 IV plot of Bridge link topology 21
Figure 18 PV plot of TCT topology 21
Figure 19 IV plot of TCT topology 22
Figure 20 Circuit topologies of experiment 27
Figure 21 experimental setup details 28
Figure 22 Row shading PV module 28
Figure 23 Representation of column shading 29
Figure 24 Diagonal shading representation 29
Figure 25 Random shading using cardboard 30
Figure 26 Partial shading using leaves 30
Figure 27 PV plot of series parallel topology 31
Figure 28 IV plot of series parallel topology 31
Figure 29 PV plot of bridge link topology 32
Figure 30 IV plot of Bridge link topology 32
Figure 31 PV plot of TCT 33
Figure 32 IV plot of TCT topology 33

LIST OF TABLES

Table 1 Types of renewable energy sources 3
Table 2 Breakeven given to INDC 3
Table 3 Ratings of module used for experiment 5
Table 4 Ratings of PV modules utilised. 15
Table 5 GMPP and LMPP table during partial shading conditions 23
Table 6 Parameter's table during various PSC's 24
Table 7 Optimal power table 25
Table 8 Ratings of a PV module 26
Table 9 global and local maxima power points 34
Table 10 Parameters analysis of experiment 35
Table 11 Suggestion of maximum power points 36
Table 12 Optimal power output 38
Table 13 Hardware observations 38

ACRONYMS

PSC	Partial shading condition
UNFCCC	United nation framework convention on climate change
PV	Photo voltaic
CHPs	Combined Heat and Power plants
NOx	Nitrous oxide
CO_2	Carbonic Dioxide
CH_4	Methane Gas
SOx	Sulphur oxides
NS	Non shaded

CHAPTER 1

INTRODUCTION

1.1: INTRODUCTION

Presently, the policymakers, researchers and investors are weighing towards a bringing a paradigm change in energy generation globally, from the conventional to renewable technologies to mitigate global warming and climate change. And due to this joint effort of all the stake holders, a technological revolution has taken place over the last two decades, which have made PV energy more economic than all other energy conversion technologies ever known to the mankind.

However, there are some issues associated with PV technologies, such as PSCs and aerosol deposition, which are the barrier against its utilization to its full potential [1]. PSC impacts the PV module performance in multiple ways – in additional to lowering the power output, it also causes several peaks (global and local ones) in the I-V and P-V characteristics [2], which makes maximum power point tracking (MPPT) extremely challenging. Secondly, under PSC the affected cells act as a load (instead of a generator) and are reverse biased, hence the temperature of those cells rises. Due to which, the efficiency and power output drops further, and the reliability of the PV modules are impacted as well. Due to reverse break down of the affected cells, secondary break down or thermal break down occurs leading to rise in temperature to as higher as 400 ^{o}C [3], which eventually results in irreparable damage of the PV module.

The PSCs may be created by dust accumulations, bird droppings, shadow of nearby structure, fallen leaves, etc. [4]. Several solutions are proposed to mitigate the impact of PSC on performance and reliability by the researchers in the past, such as innovative hotspot mitigating circuit [3], module level dc-dc converters [5] and inverters [6], differential converters and innovative array topologies [6]. In the present work the comparative performance of three such array topologies, which are series-parallel (SP), bridge-link (BL), and Total cross tied (TCT), are studied under varying shading pattern and intensities, simulated in MATLAB/Simulink$^{@}$ platform and on hardware setup.

1.2 ENERGY

Energy is one of the main inputs for any country's economic growth. In the case of developing countries, the energy sector takes on crucial importance given the ever-increasing energy needs, which need huge investment to meet them.

The Energy consumption is growing at a rapid pace while the resources available remain small. Every year, the global need for energy rises by around 2.4 per cent on average. More than 85 percent of the total amount of primary energy comes from fossil fuel. Current fossil fuel consumption, particularly oil, in the long-term unsustainable.

Carbon use also impacts our natural environment significantly. There is ample evidence of human activities causing climate change, mainly linked to energy use.

It is good time to change towards renewable energy sources which are green and clean in nature. And reduce carbon emission.

1.2.1 PRIMARY AND SECONDARY ENERGY SOURCES

Primary sources are those which are directly extracted or captured from natural sources

Further divided into two groups.

- Renewable (solar, wind, geothermal, tidal, biomass, hydel etc.)
- Non-renewable (fossil fuels: crude oil and its products, coal, natural gas, nuclear, etc.)

Primarily energy sources are mostly converted in industrial utilities into secondary energy sources; for example, coal, oil or gas converted into steam and electricity. As in this document our prime focus is on renewable sources and mainly on solar energy sources.

1.3 RENEWBLE ENERGY SOURCES

As it is very well known in many articles that fossil fuel-based energy generation is polluting in nature. And became major source of $NO_{x,}$ $SO_{x,}$ CO and PM 4 and PM 10 which leads to causation of many disease mostly of respiratory type of illness.[7,8]. So, for better health and clean environment it is required to shift toward renewable energy sources. As policy makers, environmentalists and scientists are suggesting to take a shift towards it. As Renewable energy sources are safe for environment and abundantly available. Just a need to address some of the problems and we are good to shift towards them. Area of improvements are efficiency improvement, and related technical issues. Types of renewable energy sources are mentioned in Table 1.

Table 1 Types of renewable energy sources

SOURCE	RENEWABLE RESOURCES	OUTPUT
Biological materials	Burns of animal waste and plant material	Heat energy and fuel
Hydro power	Water flowing through dams	Electric Energy
Wind energy	Collection of winds by turbines	Electric energy
Geothermal	Extracting steam, hot water from earth	Electricity and heat
Solar energy	Storing heat from sun	Electricity and heat
Hydrogen Fuels	Burning hydrogen gas	Motion power
Nanotechnology	Using unique property of material	Electric energy

1.4 GLOBAL INITIATIVES

- As per Paris summit (2015), united nations conference on climate change, conference of parties (COP 21) in series to RIO EARTH summit 1992 (COP 1) to UNFCCC (united nations framework convention for climate change) at conference all member nations have given INDC (intended nationally determined contribution). At this INDC India has committed to achieve 175 GW by renewable energy. Breakeven is given in Table 2 as follows. [9]

Table 2 Breakeven given to INDC

Type of renewable energy source	Capacity committed in INDC
Solar Energy	100GW
Wind energy	60GW
Biomass energy	10GW
Hydel energy	5GW

As from above table it is very clear that India is seeking solar energy as one of the most favourable candidates.

- As in SDG (sustainable development goal) united nations (UN) specially designate two goals SDG 7 and 13 for clean and green energy generations.[10]

1.5 MOTIVATION

Use of Renewable sources is increasing day by day, it is the source of energy of the future, as the demand of energy is escalating rapidly fossil fuels and other nonrenewable energy sources are not enough to meet the demands and needs of the world hence we have to start practicing and enhancing the use of non-conventional energy sources. Sun is one of the major source of energy and it is an important source of renewable energy but according to current technologies the energy produced by the sun which we termed as solar energy is not that efficient and reliable so we need to devise some technology which can help us to improve the performance of the solar energy.

Research has already been done in this field but then also there is vast area to research is still left. As PV system consists of many components such as converters, inverters, batteries, MPPT techniques and each system can be studied individually hence there is much research content in this area and as practically it's actually the major energy source of future so to work on improving its performance is essential.

1.6 PROBLEM STATEMENT

Solar is our main source of energy generation as considered by Government of India. While generation from PV array some challenges are their which are required to be addressed to achieve goal of sustainable development which utilise only that much, which doesn't create scarcity for upcoming future generations. So, for that one has to make some modifications in order to achieve better efficiencies and address some issues which are as follows.

Issues related to PV module are hotspot creation, power mismatch losses, partial shading condition issues, localised heating, low fill factor, low efficiency etc [6,11,12]. In this document author has tried to address issue of partial shading rest others are its consecutive effects. For that author has used hardware and simulation to study the behaviour and quantitate analysis of PV module.

Table 3 Ratings of module used for experiment

Ratings (at standard test conditions)	Data
Pmax	40W
Voltage at Pmax	18.00V
Current at Pmax	2.22A
Open circuit voltage (Voc)	22.18V
Short circuit current (Isc)	2.40A
Tolerance	+0 to 5 W

All the above mention quantities are at standard test conditions (STC) 1000W/m^2, AM 1.5, temp 25^{0}C. Ratings of hardware and software modules are taken similar to each other for ease of comparative study.

1.7 PARTIAL SHADING

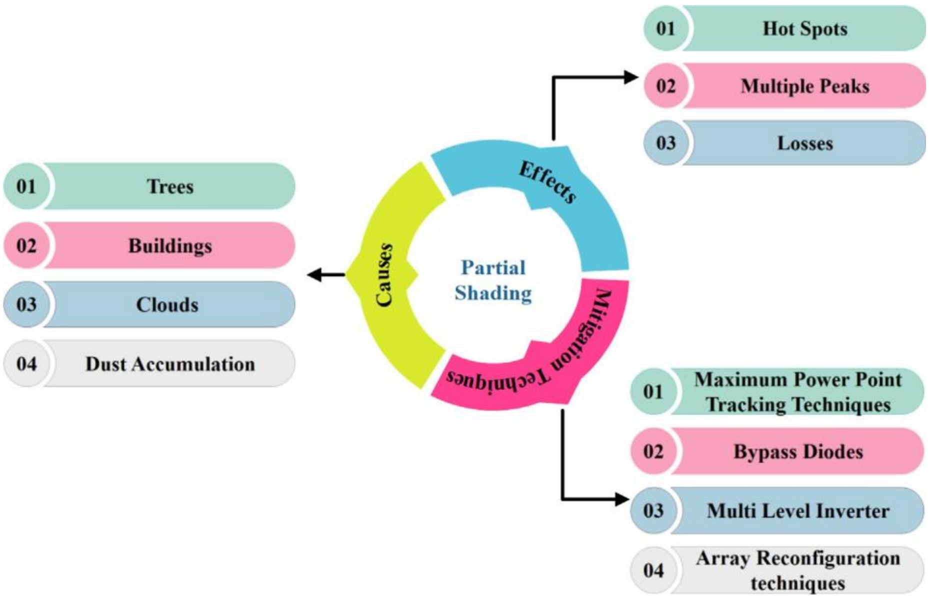

Figure 1 Partial shading causes, effects and mitigations[13]

As from above flow chart one can observe that causes are genuine enough so that one cannot avoid them because of they are natural phenomena and common in occurrence. So, for mitigation there are four methods are there as of now discovered by researchers and scientists so far. One of the method array reconfigurations is being implemented and detailed study done by author in both simulation and hardware as well.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 SYMBOLIC MODEL OF PV CELL

Single cell model: -

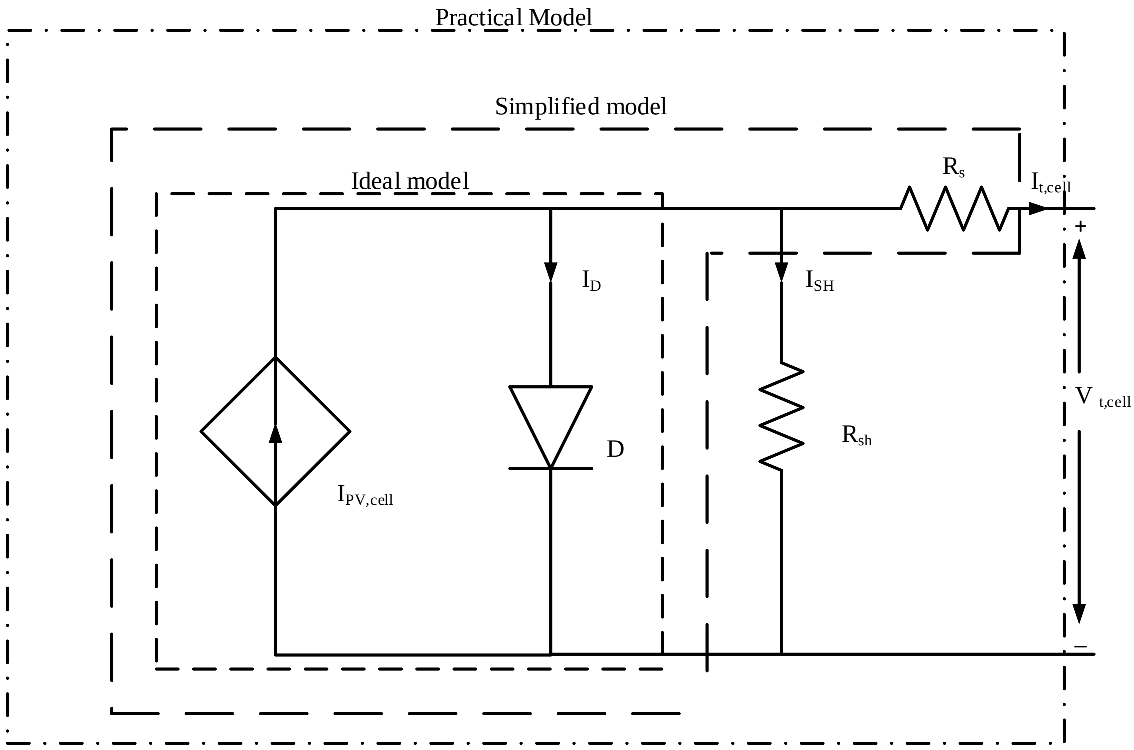

Figure 2. Single cell model of PV Cell [14]

In fig 1 one of the models have been taken from the literature as a symbolic representation of PV cell, where these considered variables behave to make it like , ideal model such as this photodiode behaves as an open circuit where when there is fall of photo light it than leads to direct photocurrent toward output terminal. Hence output voltage with respective polarities are being formed. Here as Fig 1 consist of Photocurrent (I_{Ph}) and a photodiode (D), a parallel resistance(R_{sh}) Representing the Leakage current, a series resistance (R_s) presenting the internal resistance of solar cell [12].

Voltage current equation is as follows [12,14–16]

$$I_{t,cell} = I_{PV,cell} - I_D - I_{SH} \quad (1)$$

and

$$I_D = I_r \left[\exp\left(\frac{V_{t,cell}+R_s I_{t,cell}}{V_{t,cell} \propto}\right) - 1\right] \quad (2)$$

and

$$I_{SH} = \frac{V_{t,cell}+R_s I_{t,cell}}{R_{sh}} \quad (3)$$

So, from above three equations, by substituting equation 2 and 3 into equation 1, we get equation (4).

$$I_{t,cell} = I_{PV,cell} - I_r \left[\exp\left(\frac{V_{t,cell}+R_s I_{t,cell}}{V_{t,cell} \propto}\right) -1\right] - \frac{V_{t,cell}+R_s I_{t,cell}}{R_{sh}} \quad (4)$$

Here taken $I_{PV,\ cell}$, I_r *and* $I_{t,\ cell}$ is current generated from solar incident radiation, diode reverse leakage current(A) and terminal current of PV cell(A), $V_{t,\ cell} = k\frac{T}{q}$ are the terminal voltage of PV cell, k is Boltzmann's constant (1.38060503 x10^{-33} J/K), T is a cell operating temperature (K), q is a charge of an electron (1.6x 10^{-19} c), R_s and R_{sh} is series and shunt resistance and "$\propto$" is diode emission coefficient. the ideal value of $\propto$ is 1. There are different methods to calculate the value of "$\propto$" to extract maximum power is given in [15,17].

2.2 OBJECTIVE OF THESIS

This analysis provides numerical data for the analysis and comparison of various topologies that is useful in comparing topologies under various partial shading conditions.

- Useful in analysis of quantum of partial shading and effects on PV array which is while using MATLAB/Simulink$^{@}$.
- Useful in comparing different topologies in terms of maximum power output, fill factor, efficiency, performance ratio.
- A bit of comparison among hardware and Simulink in terms of power output. And other parameters.
- Providing suggestion to power producers that under such shading circumstances which of the circuit topology is best suited to get maximum power output.
- Providing reason to shift on particular circuit topology for extracting maximum power with adequate reasoning.

2.3 LITERATURE SURVEY

Many of the authors suggested many issues related to PV array and module which are briefly explained in this section.

- Partial shading: As name suggests, that module is partially shaded which mean area is less for generation or less area is exposed to solar irradiance. figure 2.

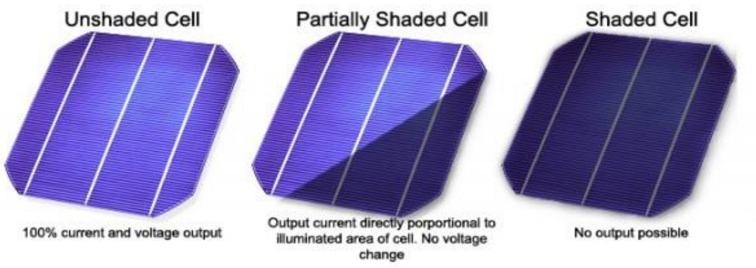

Figure 3. Partial shading scenario.

As panel is exposed to a shading such as falling of leaves, bird droppings, dust accumulation, or and shadow of nearby structure. Leads to drastic reduction in power output and consecutive effects such as hotspot creation, rise in panel temperature, mismatch power loss, and finally reduction in efficiency.

- Reversing of PV cell due to partial shading: - whenever cells are generating energy then voltage is also there at terminals of each cells but when a cell is partially shaded then voltage is absent at terminals so this partially shaded cell became reverse bias and current started flowing inside this cell leads to local heating and creation of hotspot. See figure 3
- Multiple peaks: - this is more common issue and widely discussed by many authors in many articles. Multiple peaks are introduced due to partial shading conditions. Here this also cause issues for tracing of maximum power point. As conventional algorithms get stuck in local maximum power point despite having more potential to provide power [11,18]. As we can see in figure 3

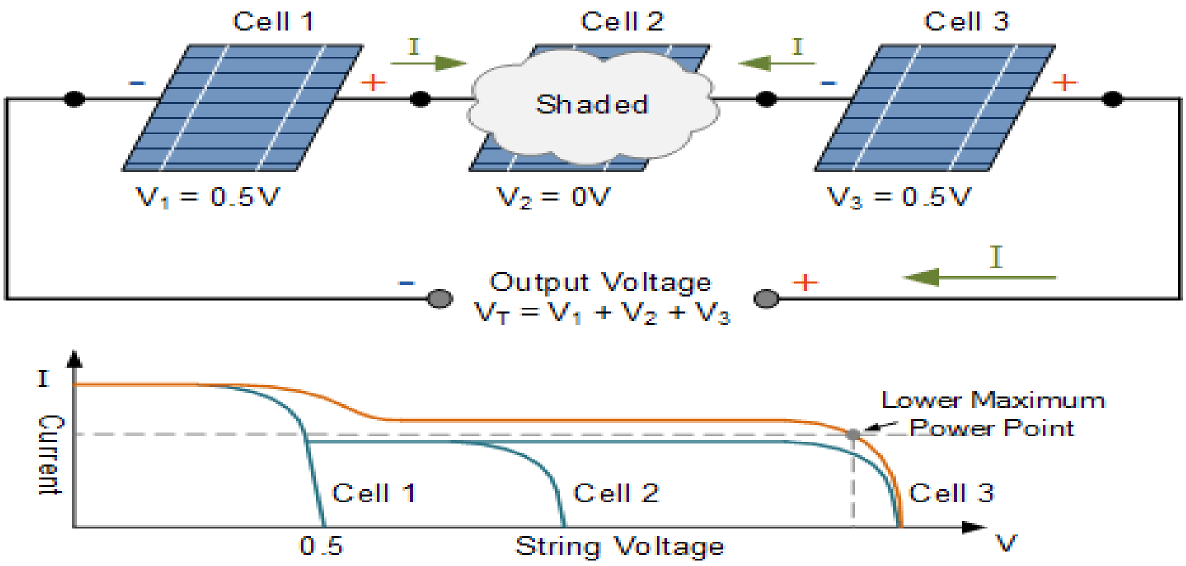

Figure 4. Reverse biasing of PV cell.

- Hotspot: - Whenever a PV cell is shaded than it behaves like a resistance and current starts flowing and continuous heating of that particular cell leading to rise in local temperature leading to formation of hotspot which sometimes leads to irreversible damage in the module.[11,18,19]. Some authors suggest some ideas to reducing localized heating provided hotspot mitigation circuit (HSMC).[3,18]
- Rest other issues are also there such as reduction in efficiency due to PSC, and reduction in performance ratio, etc.

2.4 PARAMETERS FOR PERFORMANCE EVALUATION

These parameters provide adequate information about experimental circuit topologies under partial shading conditions. And tell us about which circuit configuration is better than another under which type of PSC. The performance assessment is assessed for circuit topologies concerning mismatching power loss, efficiency, fill factor (FF) and performance ratio (%).

- Mismatching power loss. (ΔP_L) is given by equation 5.[6,15]

$$\Delta P_L(\%) = \frac{P^{mpp} - P^{psc}}{P^{mpp}} \times 100 \qquad (5)$$

where PMPP is maximum power under uniform irradiance which is achieved by multiplying V^{mpp} and I^{mpp}. And P^{PSC} is maximum power under partial shading condition which is obtained by multiplying V^{oc} and I^{sc} generated.

- Efficiency(η). is defined as the ratio of output by input whereas here input is considered as solar power input which is computed by multiplying solar intensity per meter square (I) and area of PV array 'A' divided by output which is P_{MPP} which is a multiplication of V^{mpp} and I^{mpp}.
- Fill factor. (FF): It is derived from the IV plot by multiplying V^{mpp} and I^{mpp} and divide by V^{oc} and I^{sc}

$$FF = \frac{V^{mpp} * I^{mpp}}{V^{oc} * I^{sc}} \quad (6)$$

- Performance ratio (%PR): This is defined as the ration of Power at GMPP and Maximum power at Normal condition [6].
- Misleading power: It is simply the difference between global maximum power point and local maximum power that this mis leads the MPPT algorithms

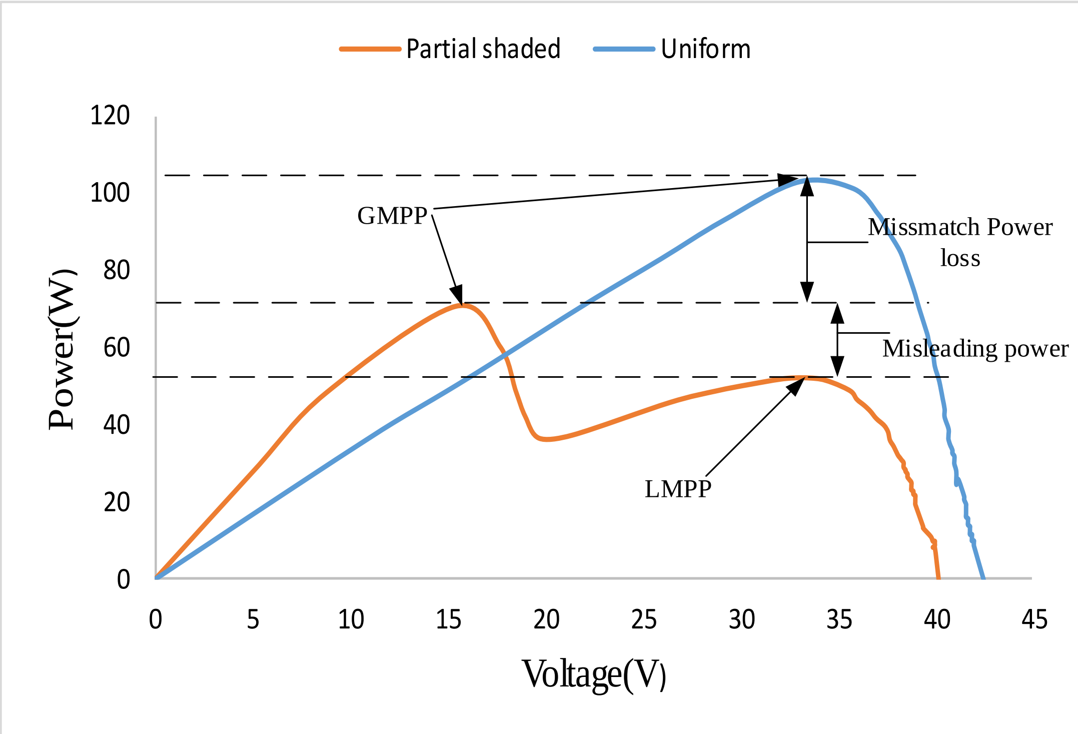

Figure 5. Graphical representation of parameters.

So above explained parameters are used for discussing experiment. and comparing them on multiple fronts.

2.5 CIRCUIT TOPOLOGIES

As we have taken 3*3 PV array so total number of possible circuit topologies are five but for experiment purpose and practical consideration we have gone for widely used 3 circuit topologies which are as follows

1) Series-parallel (SP)
2) Bridge link (BL)
3) Total cross-tied (TCT)

2.5.1 SERIES-PARALLEL (SP)

As name itself suggest that by connecting some in series and some in parallel as shown in experiment we have taken 3 PV panels which are connected firstly in series than connected in parallel as shown in figure 5. This circuit configuration is widely used in industrial application because of easy in application and less wires are required for connection. Many authors have widely studied this topology and recommended as best when there is no partial shading.[12,14,19–21].

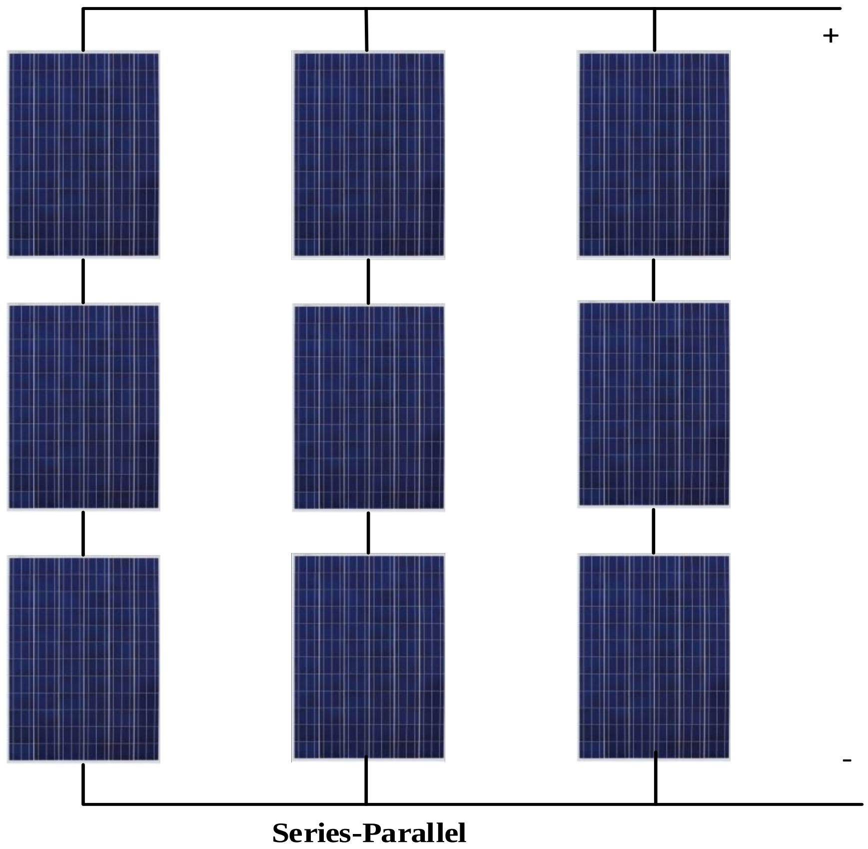

Figure 6. Scheme of series parallel

2.5.2 BRIDGE LINK (BL)

This circuit configuration is like a structure of bridge between two parallel paths so that is why it is named as bridge link. Having a greater number of connection than series parallel as shown in figure 6. widely used or supported by authors in several documents.[14,20–22].

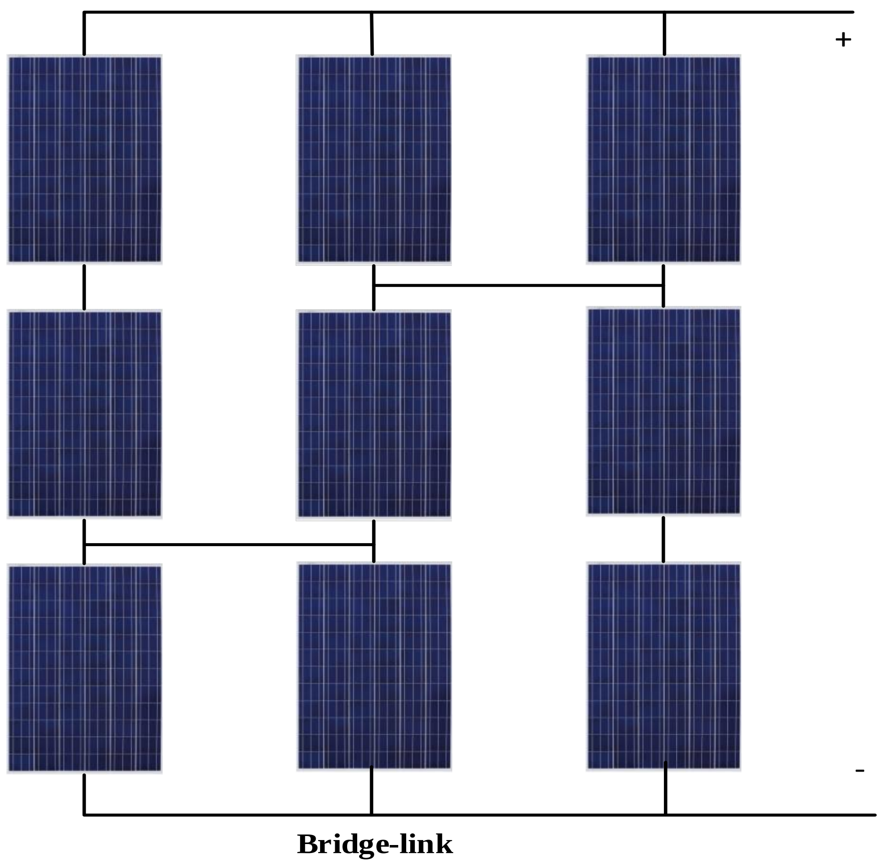

Figure 7. scheme of Bridge link topology.

2.5.3 TOTAL CROSS-TIED (TCT)

TCT circuit topology is considered as one of the best performers topology as compared to BL and SP. Widely advocated by authors and researchers during PSC, TCT is consisting of many paths to pass the current through all the modules which are connected to each other nearby panels which are also observed in this experiment too. Scheme can be seen in figure 7 [6,20,21,23].

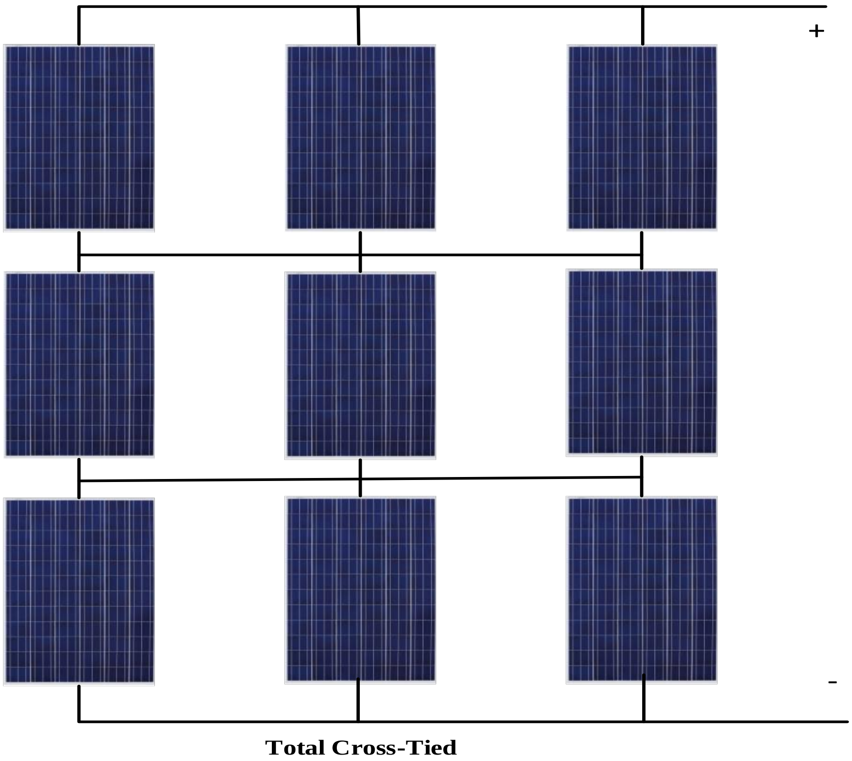

Figure 8. Scheme of TCT topology

2.6 SCHEME OF EXPERIMENT

Scheme of experiment is seen in flow chart as shown in figure 8.

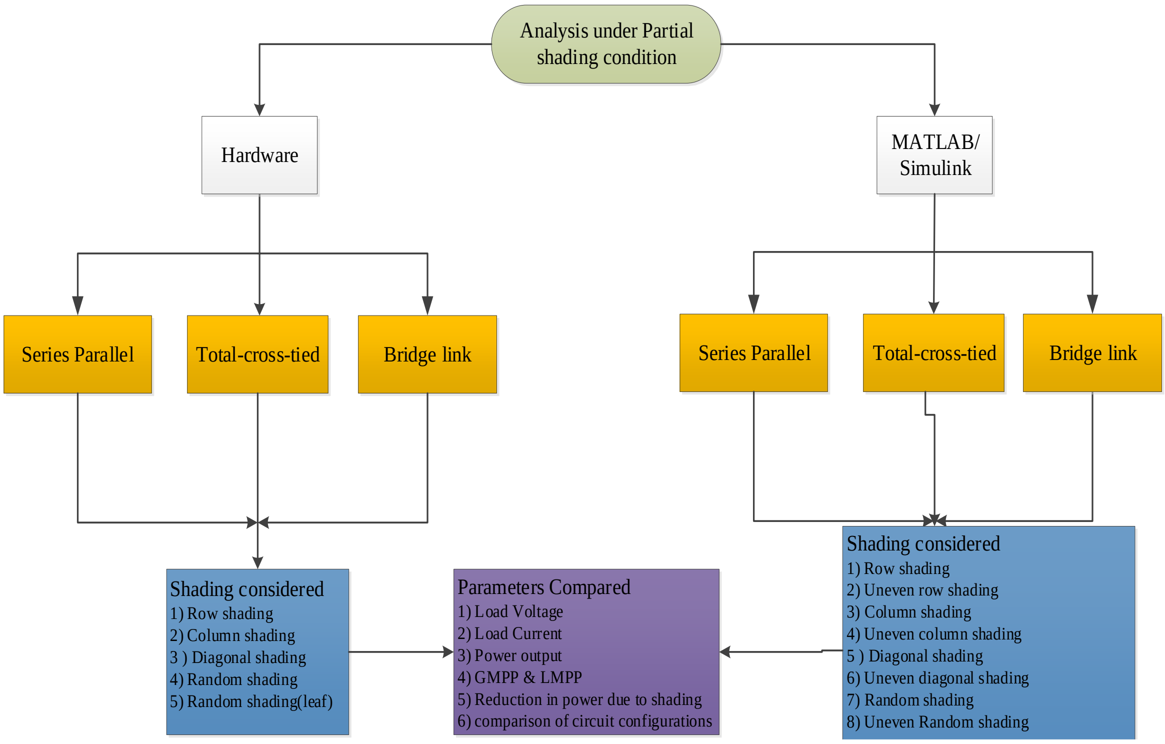

Figure 9. Flow chart of experiment

First of all, a topology is simulated and taken for experiment and then all PSC are tried on it and results are formulated and latter for second topology same process is repeated. Similarly, for hardware whole process is repeated. For example, Series parallel is taken for experiment all 3*3 PV modules are connected in this topology. Further all 5 partial shading conditions are employed on that topology if hardware and if MATLAB/Simulink$^{@}$ than 4 partial shading conditions employed on it. Then PV and IV plot are drawn. Further based on them parameters are calculated and based upon them comparison is done among all three. By iterating same process for all topologies[24][19].

CHAPTER 3

SOFTWARE ANALYSIS AND STUDY

As experiment is to simulate and check the behaviour of PV array under partial shading conditions, parameters are to be calculated respectively:

3.1 RATINGS OF PV MODULE

Ratings of PV modules utilised for experiment are given below and according to that similar hardware module is made. Utilised PV module is user defined as per need in experiment as shown in Table 4.

Table 4 Ratings of PV modules utilised.

Type of module	User defined
Number of cells	36 cells
Open circuit voltage (Voc)	22.65 V
Short circuit current (Isc)	2.428 A
Maximum power point (Pmpp)	42.5034 W
Voltage at maximum power point (Vmpp)	18.52 V
Current at maximum power point (Impp)	2.295 A

For better comparison of hardware and software it is desirable to consider in such a manner.

3.2 SIMULINK MODEL

This section refers to modelling of Simulink model which depict the behaviour as equal to the real or practical model for three different topologies we have modelled that can be seen in coming pictures:

3.2.1 SERIES PARALLEL (SP)

As this topology is simple, easy to describe and implement. This consist of three limbs which are parallel to each other consisting of 3 PV modules in series to each other. See figure 9 [14,20].

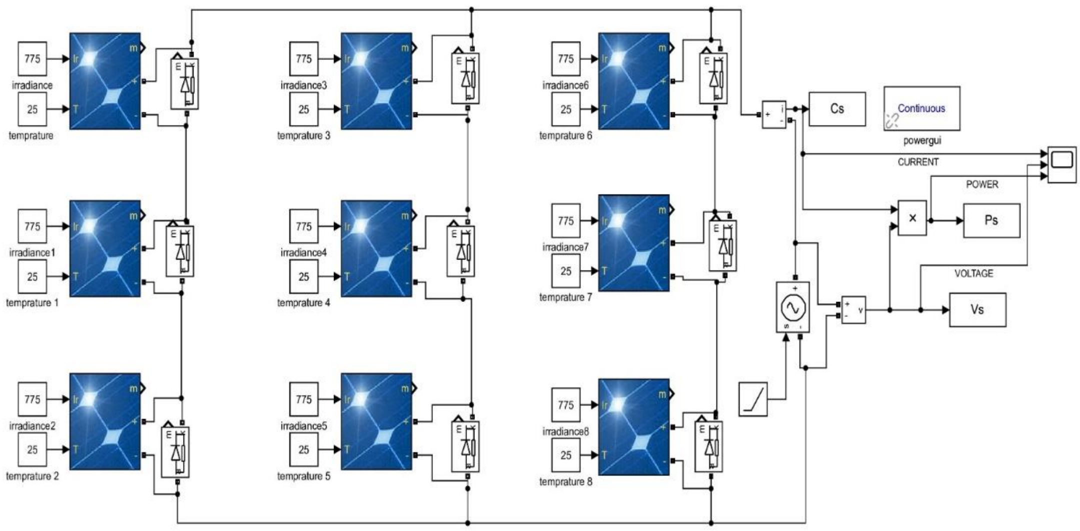

Figure 10 MATLAB/Simulink@ model for Series-parallel topology

3.2.2 BRIDGE LINK (BL)

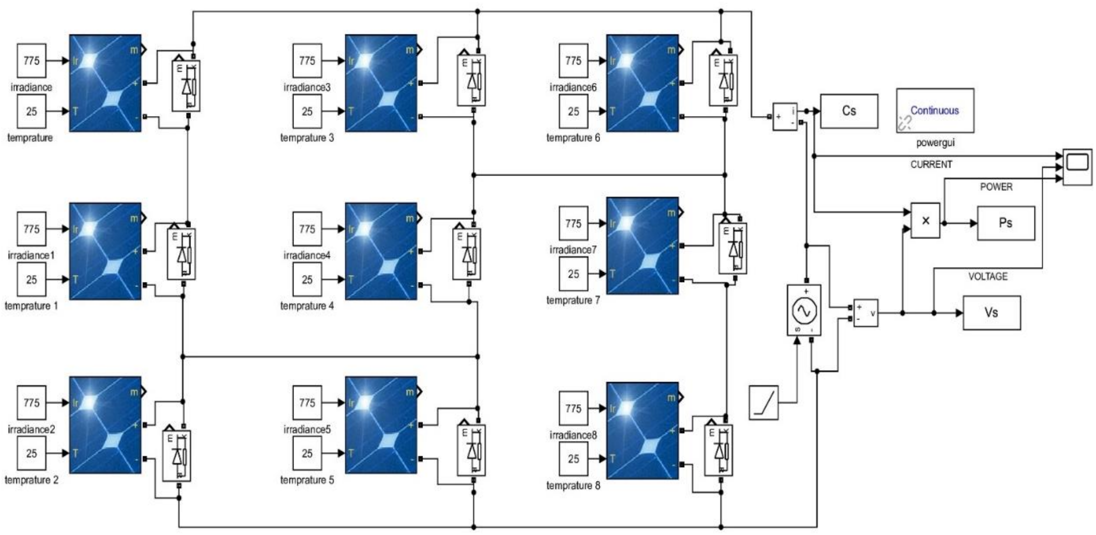

Figure 11 Bridge link topology Simulink model

As the name suggests, the structure of topology is like two adjacent paths connected by bridge like structure. Similarly, here two parallel limbs are connected to each other by a connecting wire or bridge type of structure. Due to the presence of more connecting wires provides benefit to reduce voltage mismatch losses[14,20].

3.2.3 TOTAL CROSS TIED (TCT)

This topology consists of a greater number of connecting paths which in return reduces the voltage mismatch loss and provides optimal power output whenever subjected to partial shading condition (PSC's)[6,20,21,23]. Above shown models are taken for experiment and simultaneously results are being formulated. Analysis is being done making understanding more holistic in nature.

3.2 PARTIAL SHADING CONDITIONS

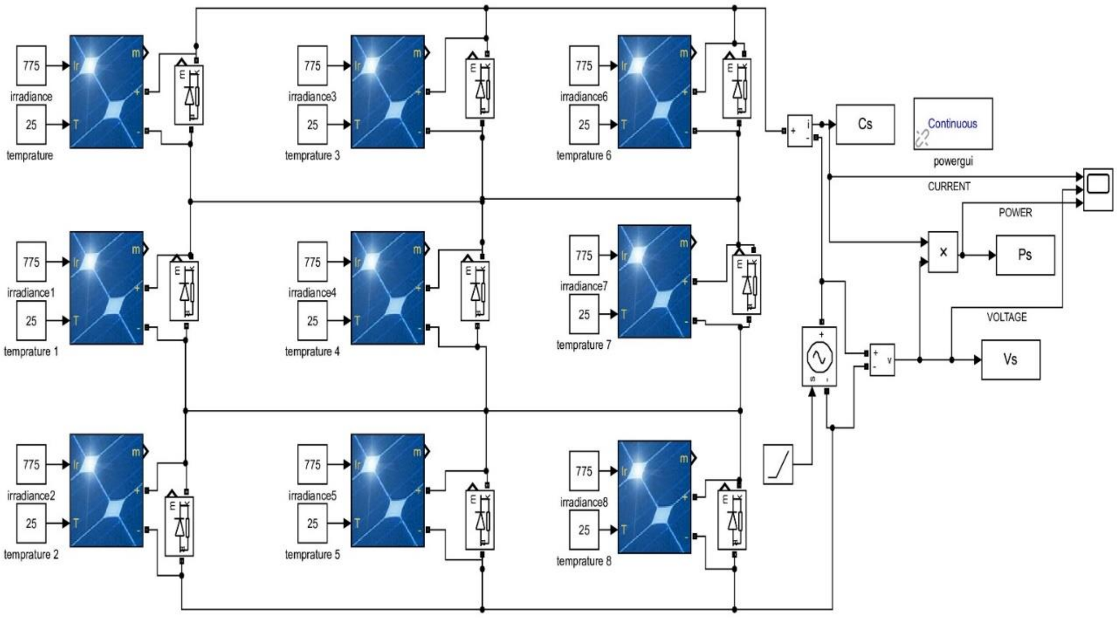

Figure 12 MATLAB/Simulink model of TCT topology.

As the experiment is performed on these topologies, we have to take some of the pre-defined partial shading conditions which helps in making overall prospective to understand behaviour of PV array under partial shading conditions. As in this experiment we have taken 9 partial shading conditions[25].

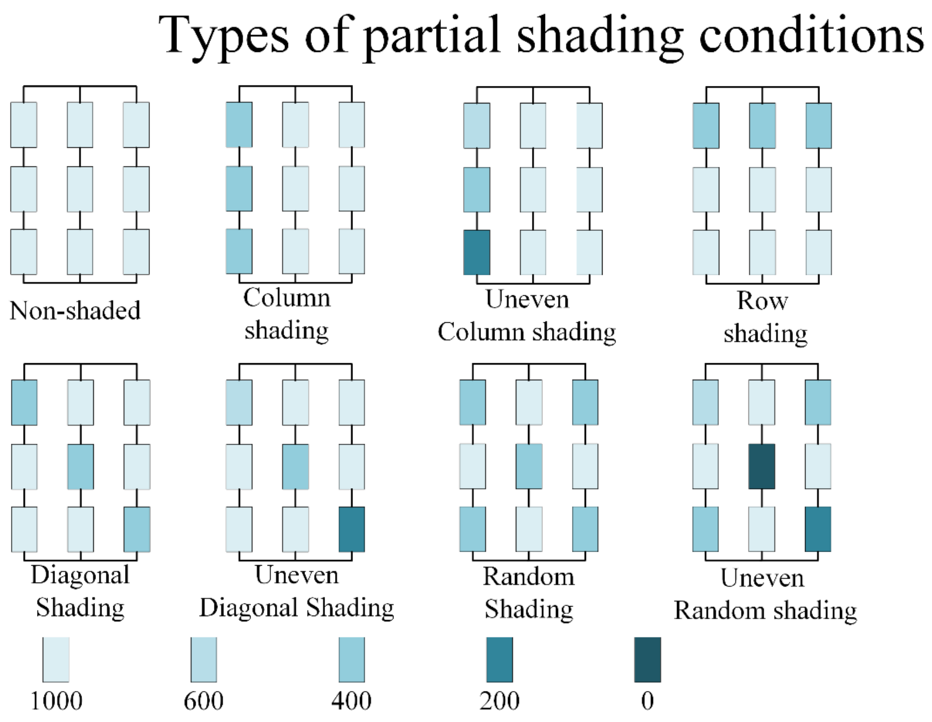

Figure 13 Scheme of partial shading conditions

All above shown shading patterns are taken for analysis and behaviour of PV array. Irradiance is taken in Watt/M^2. and temperature is taken at 25^{O}C which is at standard test conditions.

Non shaded (Unshaded) (NS): - under this shading condition none of the module is shaded which means all are fully illuminated at 1000 watt/m^2

Column shading (CS): - when a column is uniformly shaded, it has been taken 400 watt/m^2 as a radiation.

Uneven column shading (UCS): - when a column is partially shaded but all modules are not uniformly shaded which means all are differently shaded as shown in figure 12.

Row shading (RS): - when a row of modules is shaded at uniform rate. 400 watt/m2 as shown in figure 12.

Uneven row shading (URS): - In this shading pattern a row of module is shaded non uniformly as shown in figure 12.

Diagonal shading (DS): - all diagonally connected modules are uniformly shaded which is at 400 watt/m^2.

Uneven diagonal shading (UDS): - all diagonally connected modules are not uniformly shaded as shown in figure 12.

Random shading (RS): - random shading is like modules are randomly shaded, but at uniform rate of irradiance at 400 watt/m^2.

Uneven random shading (URS): - random modules are shaded at non uniform rate of irradiance as shown in figure 12.

All above described shading patterns are taken for experiment and their results are computed respectively. These shading patterns are taken from various documents such as [14].

3.3 RESULTS

Simulation results are as follows which is consisting of IV and PV graphs of respective topology under experimented partial shading conditions which in return provide behaviour of topology. These are useful in calculation, form factor (FF), Performance ratio (PR), power loss(ΔP_L) etc. and tells which is best suitable topology for optimal power output.

Series parallel (SP): - series parallel topology is subjected to all three partial shading conditions and PV and IV graphs are computed.

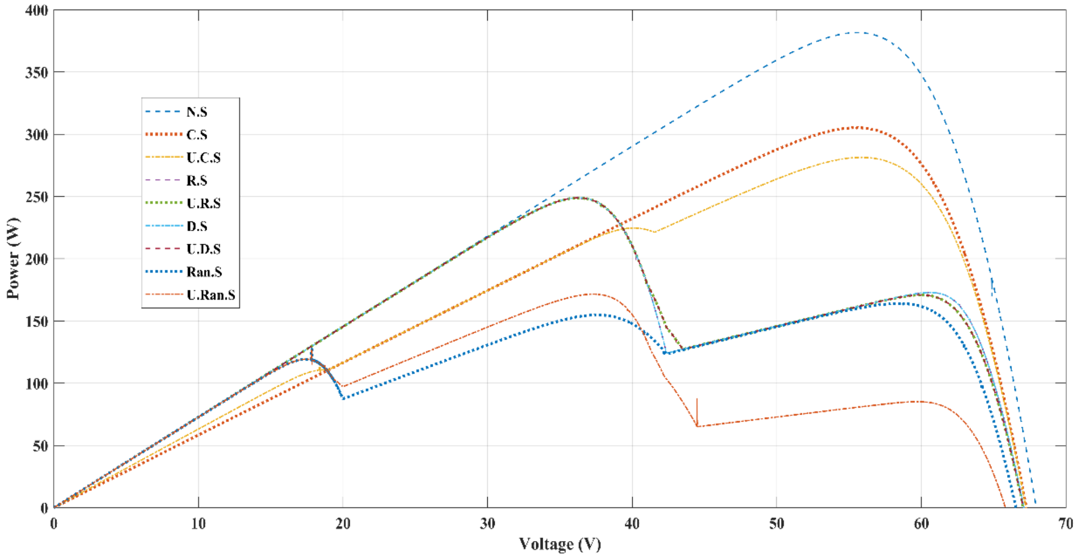

Figure 14 PV graph of Series parallel topology

Here one can see that when PV array is subjected to PSC than above shown power outcome can be seen.

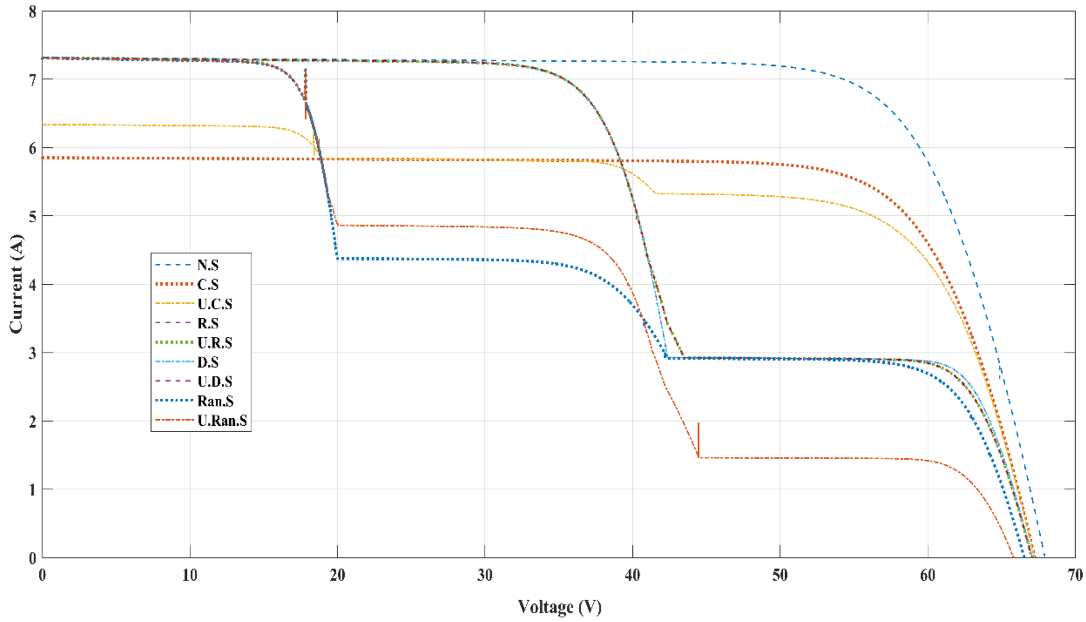

Figure 15 IV plot of Series parallel topology

It is seen from PV and IV graphs that maximum power output is at 381.6 watt under uniform irradiance at 1000 watt/m^2.

Bridge link (BL): - bridge link topology is simulated and IV and PV graph is drawn. And all 9 different Partial shading conditions are established.

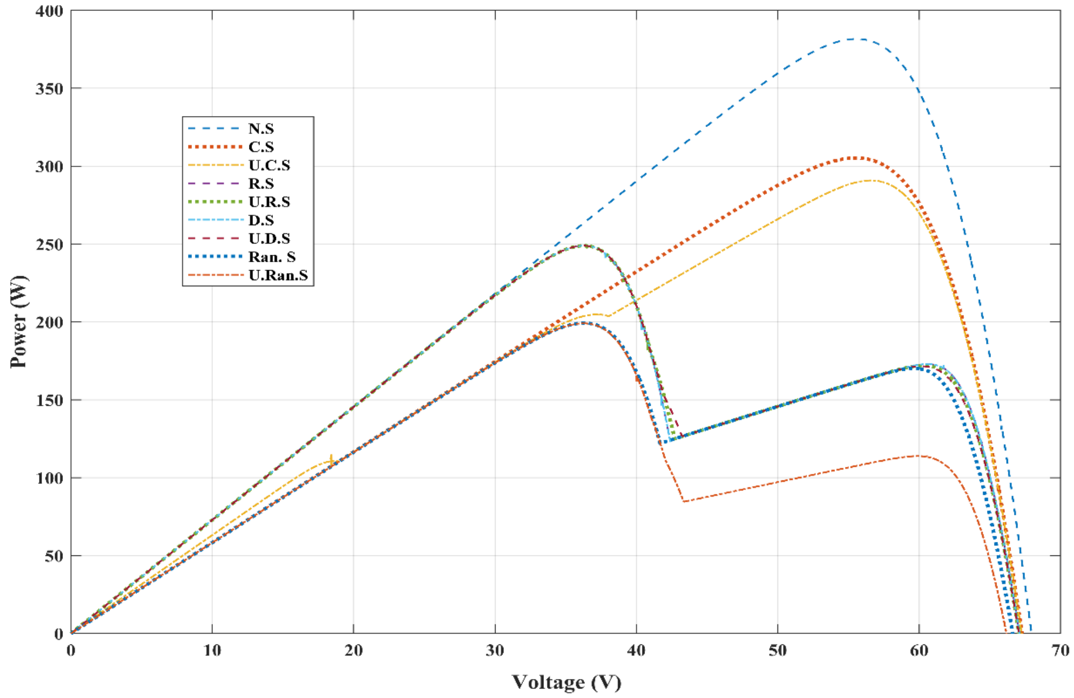

Figure 16 PV plot of Bridge link topology

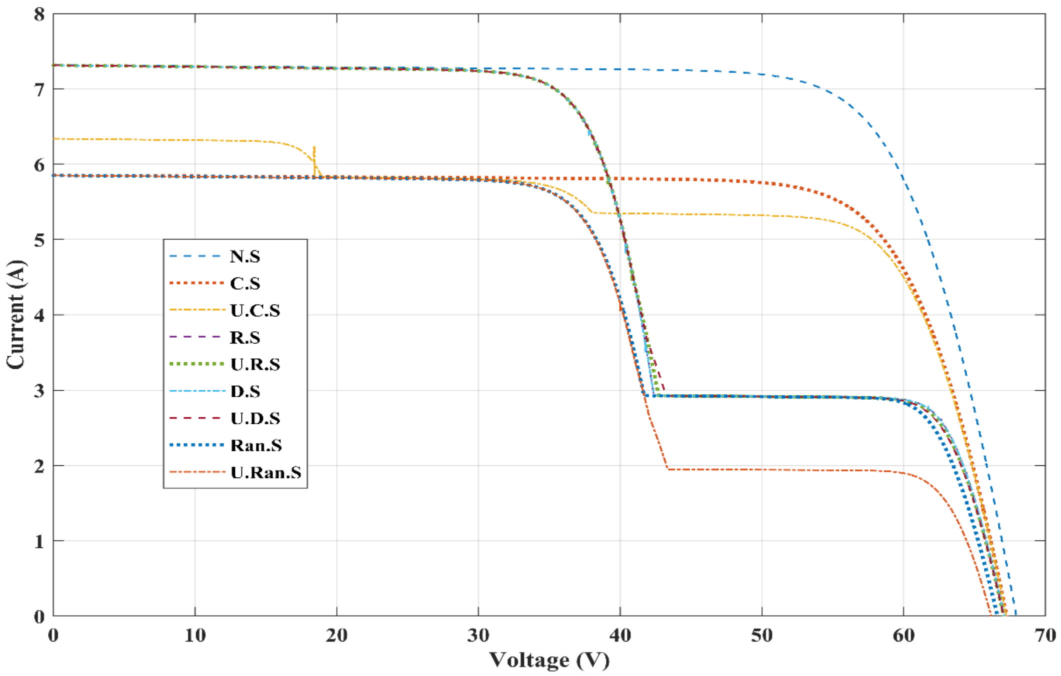

Figure 17 IV plot of Bridge link topology

as it can be seen from IV and PV graph that maximum power under uniform irradiance is 381.6 watt. And respective results.

Total cross-Tied (TCT): - total cross ties topology is simulated and all the partial shaded conditions are accompanied. PV and IV curves are being plotted.

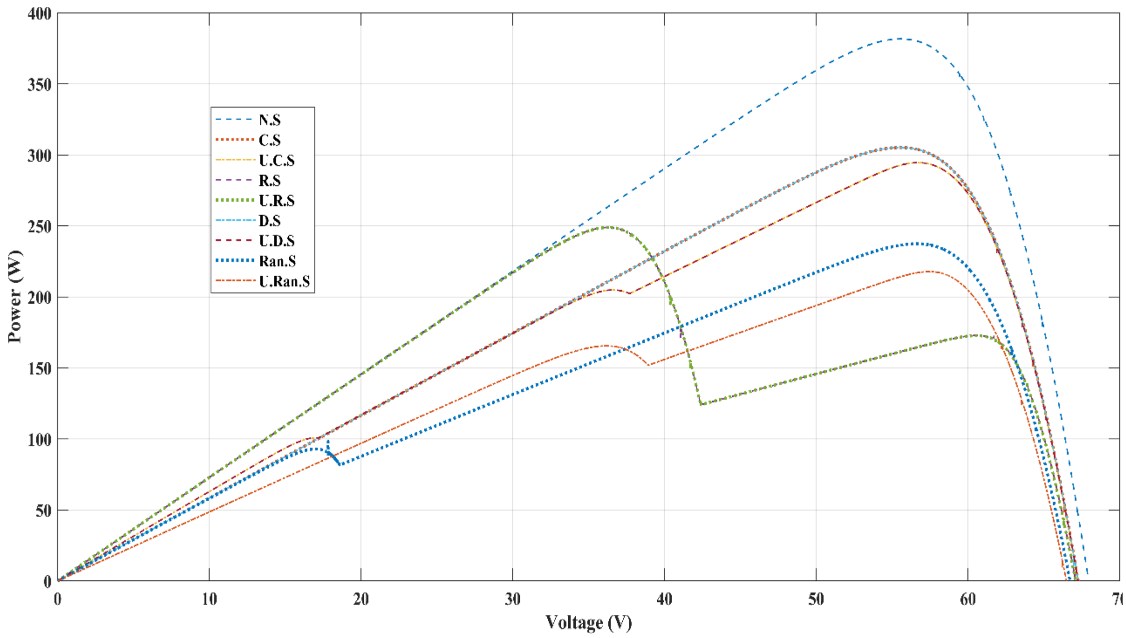

Figure 18 PV plot of TCT topology.

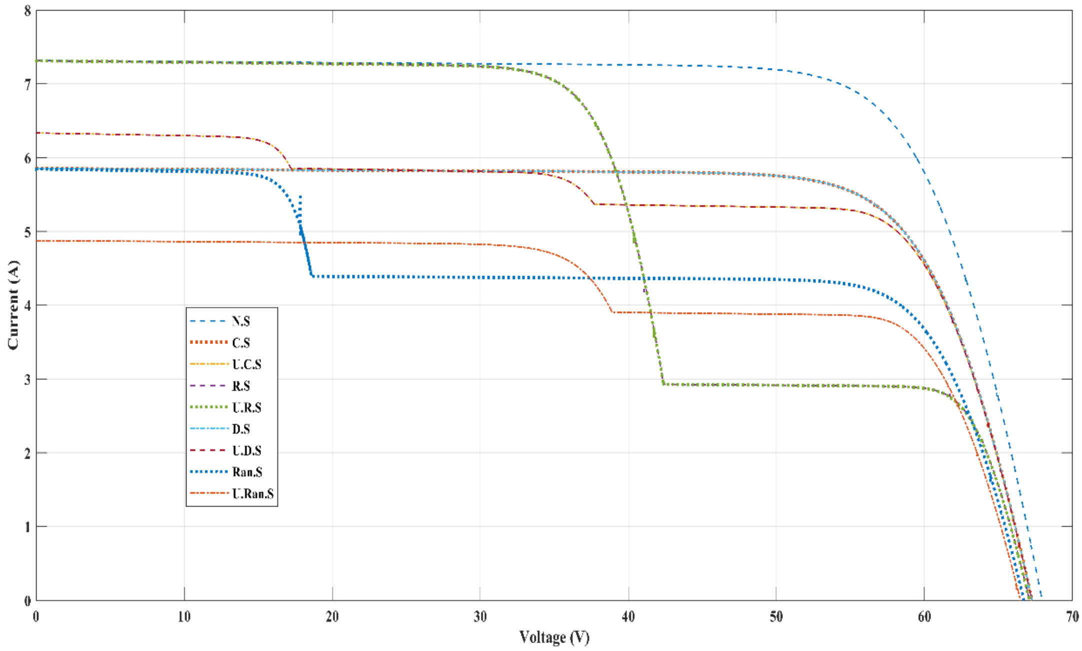

Figure 19 IV plot of TCT topology

TCT topology IV and PV graph suggest that maximum power output is at 381.6 watt at uniform irradiance 1000 watt/m^2.

3.4 PARAMETERS CALCULATION

All parameters such as form factor (FF), performance ratio (%PR), mismatch power loss (ΔP_L), are calculated from above PV and IV plots respectively. These parameters are well expressed in chapter 2. Two analysis are being done under this heading.

- As when partial shading happens, multiple maximum power points are inducted in PV plot which creates problem in tracing maximum power point. Conventional maximum power point algorithm has high chance to get stuck at local maximum which is not desirable[26]. So, this is one of the reasons that why power producers are avoiding partial shading conditions.
- Secondly, is that these partial shading conditions reduce form factor, performance ratio and increase mismatch power losswhich has to be studied and an understanding is required to develop. And parameters also suggest that which topology is best suitable for particular type of partial shading condition.

Global and local maxima power points

Table 5 GMPP and LMPP table during partial shading conditions

Topology	P.S.C	GMPP			LMPP					
		Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	V	I	P
Series-Parallel (SP)	NS	55.78	6.84	381.6	--	--	--	--	--	--
	CS	55.44	5.50	305.2	--	--	--	--	--	--
	UCS	56.01	5.02	281.4	40.9	5.49	224.7	--	--	--
	RS	36.28	6.86	248.9	60.58	2.85	172.9	--	--	--
	URS	36.28	6.86	248.9	59.94	2.85	170.9	--	--	--
	DS	36.28	6.86	248.9	60.58	2.85	172.9	--	--	--
	UDS	36.28	6.86	248.9	59.9	2.85	171	--	--	--
	Ran.S	58.30	2.81	164.0	37.74	4.10	154.8	17.44	6.84	119.3
	U. Ran.S	37.31	4.59	171.9	17.44	6.84	119.3	59.76	1.42	85.18
Bridge-link (BL)	NS	55.3	6.9	381.6	--	--	--	--	--	--
	CS	55.31	5.51	305.2	--	--	--	--	--	--
	UCS	55.65	5.22	290.8	37.2	5.50	204.8	18.33	6.03	110.6
	RS	36.28	6.86	248.9	60.57	2.85	172.9	--	--	--
	URS	36.28	6.86	248.9	60.8	2.82	172	--	--	--
	DS	36.28	6.86	248.9	60.58	2.85	172.9	--	--	--
	UDS	36.28	6.86	248.9	60..38	2.84	171.6	--	--	--
	Ran.S	36.3	5.48	199.3	59.58	2.85	170.1	--	--	--
	U. Ran.S	36.32	5.48	199.1	60.54	1.88	114.3	--	--	--
Total cross-Tied (TCT)	NS	55.76	6.84	381.6	--	--	--	--	--	--
	CS	55.51	5.49	305.2	--	--	--	--	--	--
	UCS	56.73	5.19	294.5	36.57	5.60	204.9	--	--	--
	RS	36.28	6.86	248.9	60.66	2.85	172.9	--	--	--
	URS	36.28	6.86	248.9	60.66	2.85	172.8	--	--	--
	DS	55.51	5.49	305.2	--	--	--	--	--	--
	UDS	56.69	5.19	294.5	36.58	5.60	204.9	--	--	--
	Ran.S	56.63	4.19	237.4	17.01	5.46	92.96	--	--	--
	U. Ran.S	57.2	3.78	217.9	35.95	4.60	165.5	--	--	--

As it can be seen that multiple power points are there, some are global and some are local power points which creates issues for conventional power tracing algorithms.

Parameters: -

Table 6 Parameter's table during various PSC's

Topology	Partial shading conditions (PSC)	Open circuit voltage (V^{oc})	Short circuit current (I^{sc})	Performance ratio (% PR)	Fill factor (FF)	Power loss (ΔP_L)
Series parallel (SP)	NS	67.93	7.3203	100	0.7673	0
	CS	67.93	5.8562	79.99	0.7671	20.02
	UCS	67.93	6.3409	73.74	0.6532	26.25
	RS	67.93	7.3178	65.22	0.5007	34.77
	URS	67.93	7.3178	65.22	0.5007	34.77
	DS	67.93	7.3178	65.22	0.5007	34.77
	UDS	67.93	7.3178	65.22	0.5007	34.77
	Ran.S	67.93	7.3128	42.97	0.3301	57.02
	U. Ran.S	67.93	7.3128	45.04	0.3460	54.95
Bridge-link (BL)	NS	67.93	7.3208	100	0.7673	0
	CS	67.93	5.8562	79.99	0.7671	20.02
	UCS	67.93	6.3400	76.20	0.6752	23.79
	RS	67.93	7.3178	65.22	0.5007	34.77
	URS	67.93	7.3178	65.22	0.5007	34.77
	DS	67.93	7.3178	65.22	0.5007	34.77
	UDS	67.93	7.3178	65.22	0.5007	34.77
	Ran.S	67.93	5.8543	52.22	0.5011	47.77
	U. Ran.S	67.93	5.8538	52.17	0.5006	47.82
Total cross-tied (TCT)	NS	67.93	7.3203	100	0.7673	0
	CS	67.93	5.8562	79.99	0.7671	20.02
	UCS	67.93	6.3343	77.17	0.6758	22.82
	RS	67.93	7.3178	65.22	0.5007	34.77
	URS	67.93	7.3178	65.22	0.5007	34.77
	DS	67.93	5.8562	79.97	0.7671	20.02
	UDS	67.93	6.3343	77.17	0.6844	22.82
	Ran.S	67.93	5.8463	62.21	0.5977	37.78
	U. Ran.S	67.93	4.8777	57.10	0.6576	42.89

From above Table 6 it can be seen that open circuit voltage is almost constant which didn’t get affected because due to partial shading conditions. But short circuit current is widely varied. As more and more area are under shading it is reducing short circuit current. Performance ratio is also reduced as the shading is more intruded into system. Same for fill factor.

Table 7 can help in finding which of the topology is best suitable under which of partial shading condition.

Table 7 Optimal power table

Partial shading conditions (PSC)	**Best suitable topology**	**Maximum power (Watt)**
NS	All are at same power output	381.6
CS	All are at same power output	305.6
UCS	Total cross tied (TCT)	294.5
RS	All are showing same performance	248.5
URS	All are showing same performance	248.5
DS	Total cross tied (TCT)	305.2
UDS	Total cross tied (TCT)	294.5
Ran.S	Total cross tied (TCT)	237.4
U. Ran.S	Total cross tied (TCT)	217.9

CHAPTER 4

HARDWARE ANALYSIS AND STUDY

As in previous sections, behavior of MATLAB/Simulink@ model has been analyzed and studied extensively. This section refers to similar study on hardware model which is of following rating.

Ratings of a PV module: -

Table 8 Ratings of a PV module

Maximum Power (P^{max})	40W (36 cells)
Voltage max. Power (V^{mp})	18.00V
Current at Max. Power (I^{mp})	2.22A
Open circuit voltage (V^{oc})	22.18V
Short circuit current (I^{sc})	2.40A
Tolerance	+0 to 5W

Above shown ratings are of single module. Such 9 modules are taken for experimental study which are used to form an array which is connected in three different topologies which are as follows:

4.1 TOPOLOGIES

We have gone for three different topologies for experiment purpose which reflect behavior at different shading patterns:

- Series-parallel (SP): - this topology is widely accepted and taken for project implementation by various power producers due to the ease of connection and implementation. Topology is consisting of some series path and some parallel path as per the need of voltage and current handling of inverters.
- Bridge-link (BL): - BL is consisting of a greater number of parallel paths compared to series parallel which helps in reducing voltage mismatch loss and increase in performance ratio. Structure is like a bridge connecting two nearby roads so similarly two parallelly connecting paths are connected by a connecting lead as shown in figure. 19.
- Total cross-tied (TCT): - Structure is like a greater number of connecting paths than series parallel and bridge link which helps in reducing voltage mismatch

losses. And increase in performance ratio and efficiency. And in some of the partial shading conditions maximum power output can be seen as well[27].

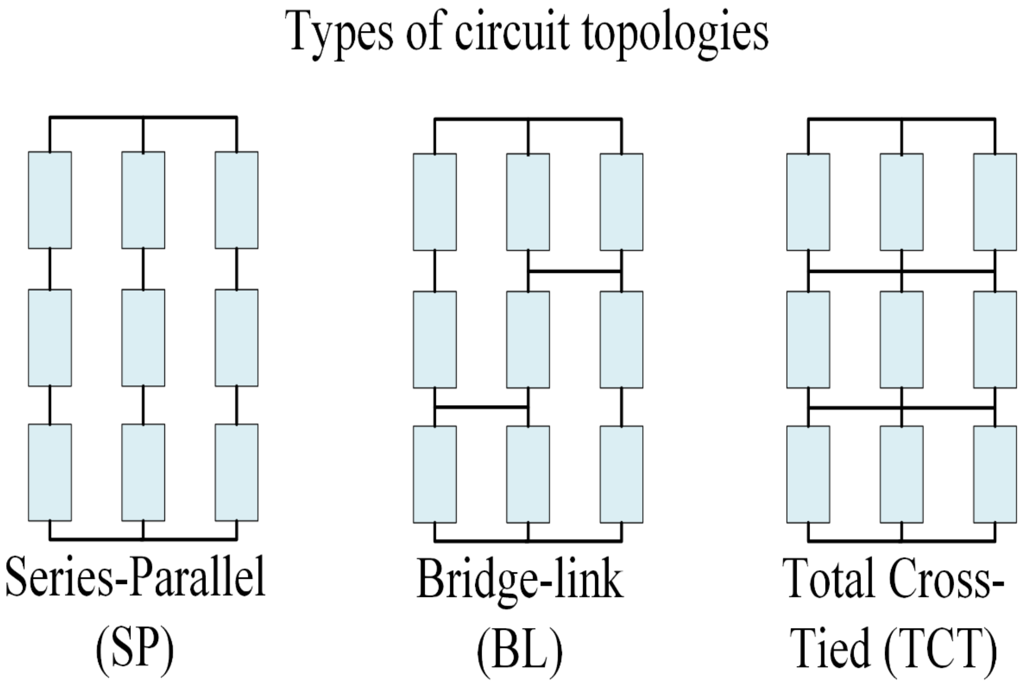

Figure 20 Circuit topologies of experiment

4.2 EXPERIMENTAL SETUP

Experimental setup is consisting of following devices:

- PV array
- Pyranometer
- Rheostat
- Multimeter
- Connecting leads

In experimental setup as shown in figure 20, we have taken variable rheostat which help in varying load and help in tracing maximum power point. Pyranometer helps in observing irradiance which helps in calculation of efficiency. Multimeters are used to measure voltage and current at particular load point. Connecting leads are used to connect modules as per requirement or topology.

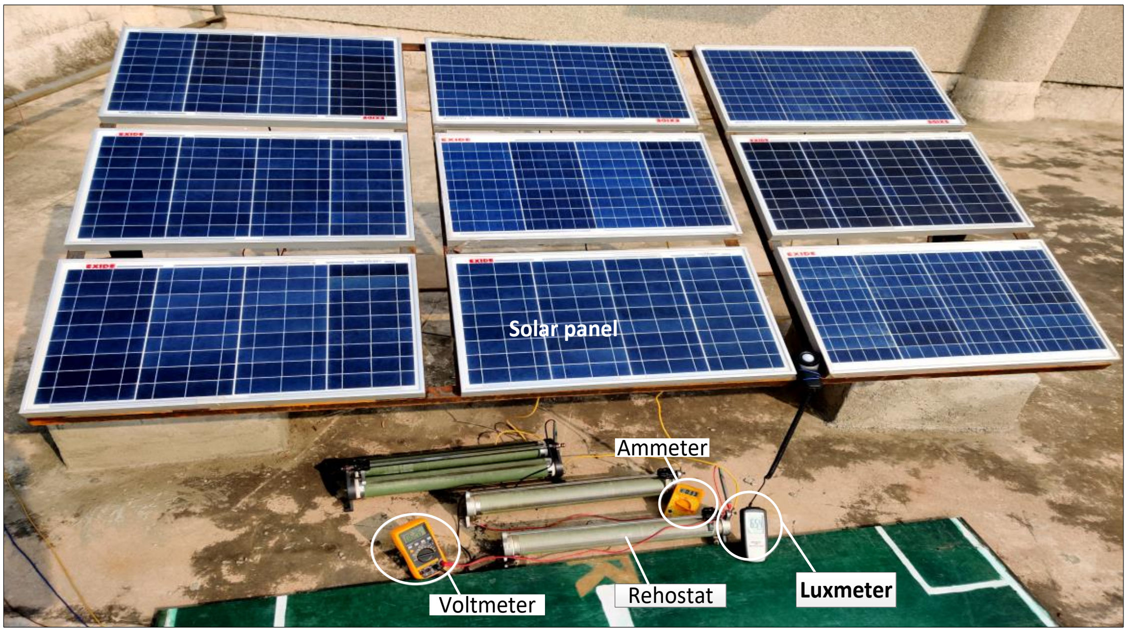

Figure 21 experimental setup details

4.3 DESCRIPTION OF PARTIAL SHADING CONDITIONS

As a core of experiment this is section which creates difference in results among each other topology. There are five different partial shading conditions are taken for experiment.

- Row shading
- Column shading
- Diagonal shading
- Random shading using cardboard
- Random shading using leaves.

1) Row shading (RS): - all modules in a row are being shaded as shown in figure 21.

Figure 22 Row shading PV module

2) Column shading (CS): - entire column of PV array is shaded as shown in fig 22.

Figure 23 Representation of column shading

3) Diagonal shading (DS): - all diagonally connected modules are partially shaded which reflect behaviour.

Figure 24 Diagonal shading representation

All shading is accomplished using carboard to provide hindrance to solar irradiance and further resistance is varied and maximum power point is traced.

4) Random shading using cardboard (RSC): - random shading using carboard is implemented as shown in figure 24.

Figure 25 Random shading using cardboard

5) Random shading using leaves (RSL): - random shading using leaves, which is most common in nature and frequent reason to power loss and hot spot creation.

Figure 26 Partial shading using leaves

4.4 GRAPHS

All the graphs are between power-voltage (PV) and current- voltage (IV) which are drawn by varying resistances and by doing that maximum load which system can support is found out. For all three topologies and all five shading conditions PV and IV graphs are plotted.

1) PV and IV graph of series-parallel (SP): -

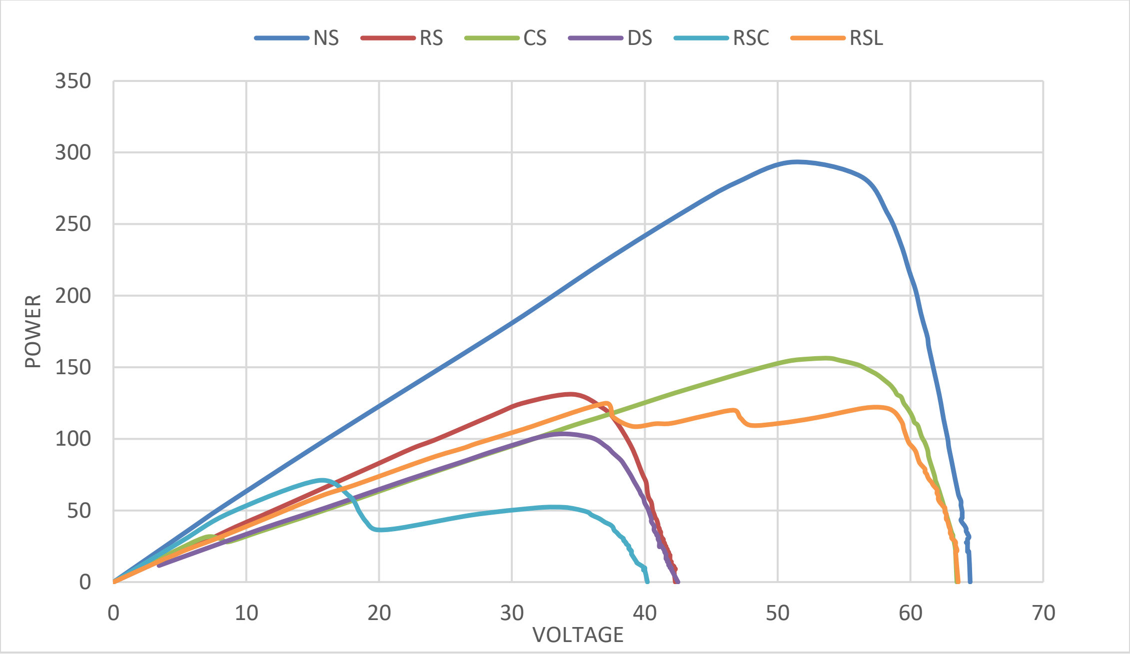

Figure 27 PV plot of series parallel topology

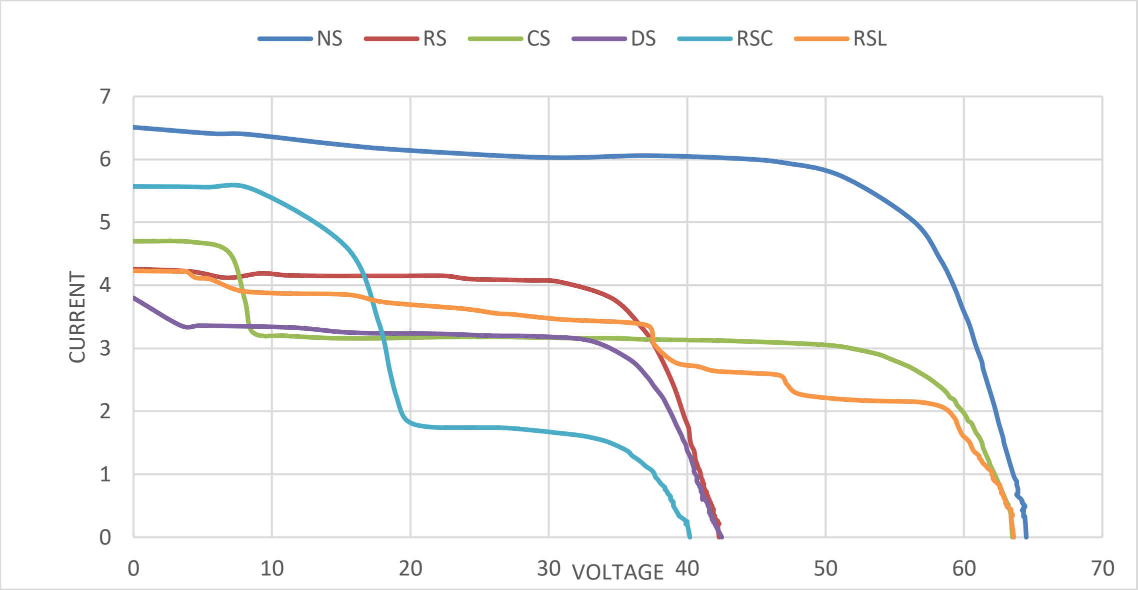

Figure 28 IV plot of series parallel topology

2) PV and IV plot of Bridge link

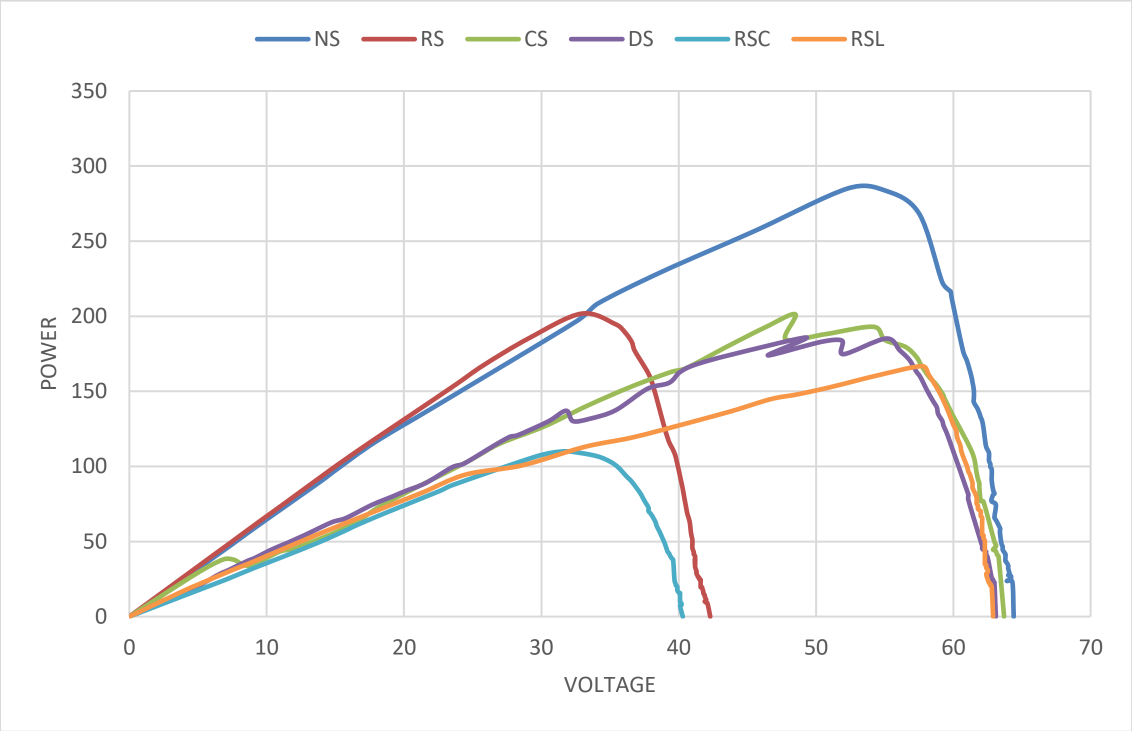

Figure 29 PV plot of bridge link topology

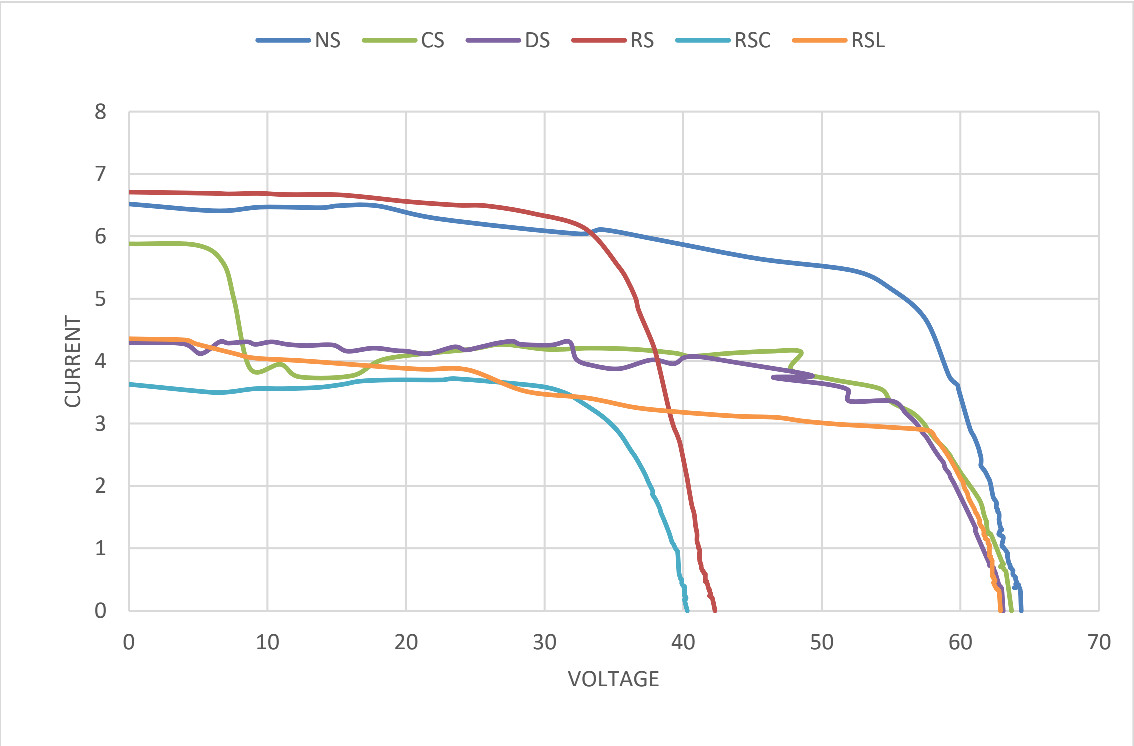

Figure 30 IV plot of Bridge link topology

3) PV and IV plot of total cross tied.

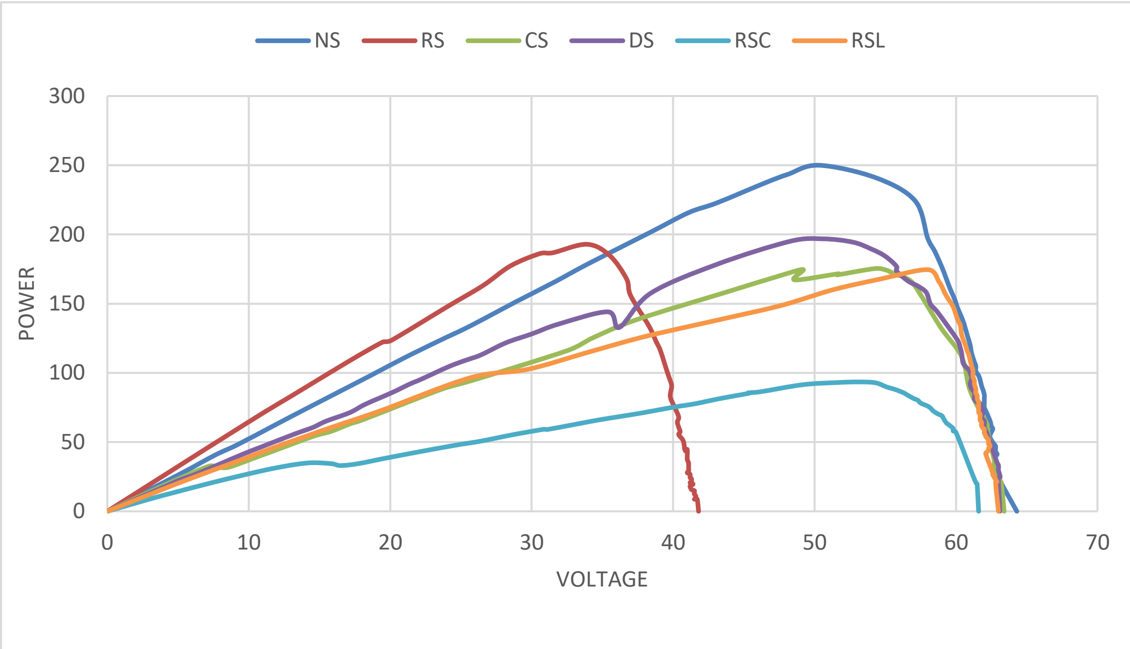

Figure 31 PV plot of TCT

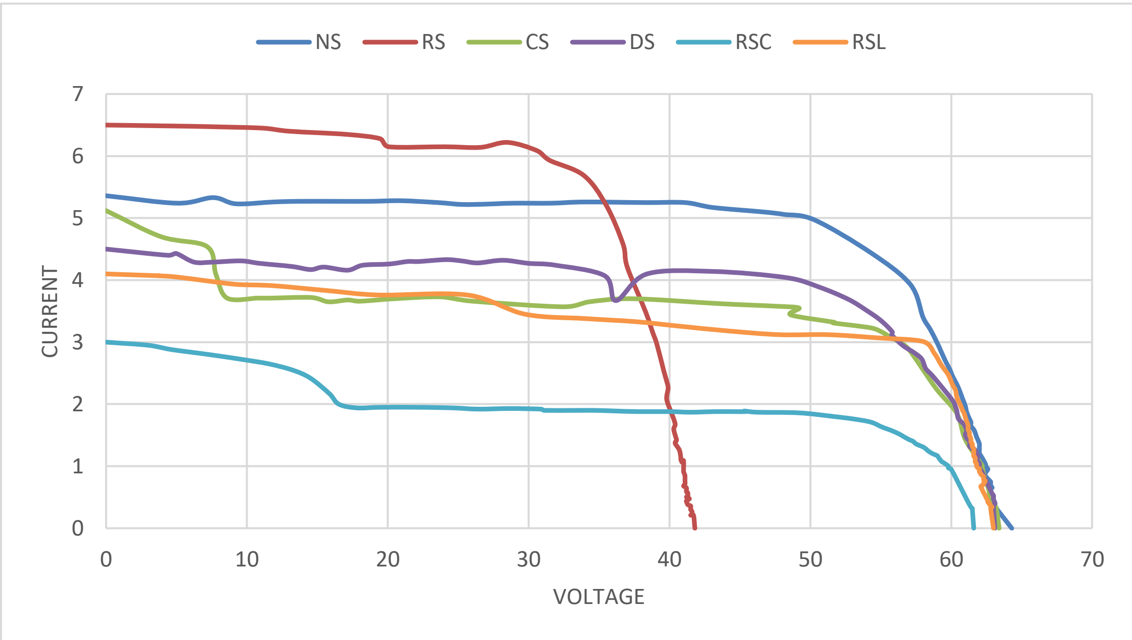

Figure 32 IV plot of TCT topology

4.5 GLOBAL AND LOCAL MAXIMA

Table 9 global and local maxima power points

			GMPP			LMPP								
						1			2			3		
S.no	Topology	P.S.C	V	I	P	V	I	P	V	I	P	V	I	P
1	S. P	N. S	51.2	5.73	293.376	-	-	-	-	-	-	-	-	-
		R. S	34.6	3.79	131.134	-	-	-	-	-	-	-	-	-
		C.S	53.9	2.9	156.31	-	-	-	-	-	-	-	-	-
		D.S	33	3.12	102.96	-	-	-	-	-	-	-	-	-
		R.S.C	15.41	4.6	70.866	32.44	1.61	52.2284	-	-	-	-	-	-
		R.S. L	37.04	3.37	124.8248	46.7	2.57	120.019	58	2.1	121.8	-	-	-
2	B. L	N. S	52.4	5.45	285.035	-	-	-	-	-	-	-	-	-
		R. S	32.9	6.13	201.677	-	-	-	-	-	-	-	-	-
		C.S	48.5	4.15	201.275	54.2	3.56	192.952	-	-	-	-	-	-
		D.S	55.1	3.36	185.136	32.3	4.03	130.169	55.1	3.36	185.136	51.9	3.54	183.726
		R.S.C	31.5	3.49	109.935	-	-	-	-	-	-	-	-	-
		R.S. L	57.7	2.89	166.753	-	-	-	-	-	-	-	-	-
3	T.C. T	N. S	50.3	4.97	249.991	-	-	-	-	-	-	-	-	-
		R. S	33.9	5.69	192.891	-	-	-	-	-	-	-	-	-
		C.S	54.3	3.23	175.389	-	-	-	-	-	-	-	-	-
		D.S	50.6	3.89	196.834	35.4	4.07	144.078	-	-	-	-	-	-
		R.S.C	53.1	1.76	93.456	14.5	2.42	35.09	-	-	-	-	-	-
		R.S. L	58.0	3.01	174.58	-	-	-	-	-	-	-	-	-

As in above table supports that due to partial shading condition, there is high chance of occurrences of multiple maximum power points which creates problem for conventional power point tracing algorithms. They get stuck at local maximum power point rather than reaching to global maximum power point. But as one can notice that partial shading is necessary condition for multiple peaks but not in some of the cases such as row shading (RS).

4.6 PARAMETERS

As discussed in earlier sections that parameters like fill factor (FF) , performance ratio (PR), power loss (ΔP_L), etc are being calculated from the data produced from graphs during experiment. These parameters are.

- Mismatching power loss. (ΔP_L) is given by equation 5.[6,15]

$$\Delta P_L(\%) = \frac{P^{mpp} - P^{psc}}{P^{mpp}} \times 100 \tag{5}$$

where PMPP is maximum power under uniform irradiance which is achieved by multiplying V^{mpp} and I^{mpp}. And P^{PSC} is maximum power under partial shading condition which is obtained by multiplying V^{oc} and I^{sc} generated.

- Efficiency(η). is defined as the ratio of output by input where the input is considered as solar power input which is computed by multiplying solar intensity per meter square (I) and area of PV array 'A' divided by output which is P_{MPP} which is a multiplication of V^{mpp} and I^{mpp}.
- Fill factor. (FF). it is derived from the IV plot by multiplying V^{mpp} and I^{mpp} and divided by V^{oc} and I^{sc}

$$\mathrm{FF} = \frac{V^{mpp} * I^{mpp}}{V^{oc} * I^{sc}} \tag{6}$$

- Performance ratio(%PR). This is defined as the ration of Power at GMPP and Maximum power at Normal condition [6,13].

Table 10 Parameters analysis of experiment

S.no	**Topology**	**P.S.C**	**V^{MPP}**	**I^{MPP}**	**P^{MPP}**	**V^{OC}**	**I^{SC}**	**FF**	**%PR**	**Miss match power loss (%)**
1	SP	NS	51.2	5.73	293.376	64.5	6.51	0.6986	100	0
		RS	34.6	3.79	131.134	42.3	4.26	0.7277	44.69	55.30
		CS	53.9	2.9	156.31	63.5	4.7	0.5237	53.27	46.72
		DS	33	3.12	102.96	42.5	3.8	0.6375	35.09	64.90
		RSC	32.44	1.61	52.2284	40.2	5.57	0.2332	17.80	82.19
		RSL	37.04	3.37	124.8248	63.6	4.23	0.4639	42.54	57.45
2	BL	NS	52.3	5.45	285.035	64.4	6.52	0.6777	100	0
		RS	32.9	6.13	201.677	42.3	6.71	0.7105	70.75	29.24
		CS	48.5	4.15	201.275	63.7	5.88	0.5373	70.61	29.38
		DS	55.1	3.36	185.136	63.1	4.3	0.6823	64.95	35.04
		RSC	31.5	3.49	109.935	40.3	3.63	0.7514	38.56	61.43
		RSL	57.7	2.89	166.753	62.9	4.36	0.6080	58.50	41.49
3	TCT	NS	50.3	4.97	249.991	64.3	5.36	0.7253	100	0
		RS	33.9	5.69	192.891	41.8	6.5	0.7099	77.15	22.84
		CS	54.3	3.23	175.389	63.4	5.12	0.5403	70.15	29.84
		DS	50.6	3.89	196.834	63.1	4.5	0.6931	78.73	21.26
		RSC	53.1	1.76	93.456	61.6	3	0.5057	37.38	62.61
		RSL	58.0	3.01	174.58	63.0	4.1	0.6758	69.83	30.16

- Optimal power flow can be cited using Table 11which helps us in identifying which of the topology is best suitable for maximum power outcome.

Table 11 Suggestion of maximum power points

Partial shading condition	Topology	Maximum power point
Non shaded	Series-parallel	293.376 watt
Row shaded	Bridge link	201.677 watt
Column shaded	Bridge link	201.275 watt
Diagonal shaded	Total cross tied	196.834 watt
Random shading using carboard	Bridge link	109.935 watt
Random shading using leaves	Total cross-tied	174.58 watt

CHAPTER 5

CONCLUSION AND OBSERVATIONS OF EXPERIMENT

5.1 SUMMARY

In this investigative study of PV array, following actions are performed which helped in identifying the pros and cons of solar energy generations.

- Firstly, a MATLAB/Simulink@ model is simulated as shown in figure 9. Then all considered Partial shading conditions (PSC) are employed on circuit and results are computed and investigation has been done, for all and findings are as shown in Table 12. Numerical analysis also been done and parameters such as form factor, power loss and performance ratio also computed which is given in Table 8,9.
- Secondly, Hardware setup has been accomplished followed by various partial shading conditions considered for experiment and results are calculated respectively. As similar to first case all parameters are calculated for all circuit topologies in Table 10,11. Further understanding of optimal power under all partial shading condition is taken in Table 13.
- Lastly, tried to conclude both on MATLAB and hardware model by comparing and analysis of respective topologies.

5.2 MATLAB/Simulink@ model observations.

- As in following experiment, it is widely observed that different circuit topologies are promising for different partial shading conditions in which it provides optimal power flow which can be seen in Table 12.

Table 12 Optimal power output

Partial shading conditions (PSC)	Best suitable topology	Maximum power (Watt)
NS	All are at same power output	381.6
CS	All are at same power output	305.6
UCS	Total cross tied (TCT)	294.5
RS	All are showing approximately same performance	248.5
URS	All are showing approximately same performance	248.5
DS	Total cross tied (TCT)	305.2
UDS	Total cross tied (TCT)	294.5
Ran.S	Total cross tied (TCT)	237.4
U. Ran.S	Total cross tied (TCT)	217.9

5.3 Hardware observations: -

- Partial shading condition occurring in nature are generally complex in nature and most of the time like leaves, dust, bird droppings etc. Which generally create hotspot and reduce power outcome drastically despite they didn't cover much surface area on PV module but make power output significantly low. For solution we have to remove shading by wiping out or by changing circuit topology we can easily extract optimal power. Such as TCT, bridge link is best suited for this type of partial shading condition.

Table 13 Hardware observations

Partial shading condition	Topology	Maximum power point
Non shaded	Series-parallel	293.376 watt
Row shaded	Bridge link	201.677 watt
Column shaded	Bridge link	201.275 watt
Diagonal shaded	Total cross tied	196.834 watt
Random shading using carboard	Bridge link	109.935 watt
Random shading using leaves	Total cross-tied	174.58 watt

5.4 FUTURE SCOPE

From above understanding of partial shading which is not suitable for power generation one can understand the gravity of the problem. So, by changing circuit configuration one can generate optimal power output which is best suitable for respective partial shading conditions which can be seen from above table or one can perform experiment if partial shading condition is miscellaneous type and different possible solutions for issue are listed below.

- Removing partial shading by cleaning or changing position of plated.
- By using automatic circuit to switch among circuit configuration. Primarily by using monitoring[28][29] .For optimal power output[30].

PUBLICATIONS

- Karni P. Palawat, **Vinod Kumar Yadav,** R. L. Meena, "Performance evaluation of solar PV array under various partial shading conditions," Electric Power and Renewable Energy Conference (EPREC-2020), Springer. (Accepted & Presented).

- Karni P. Palawat, **Vinod Kumar. Yadav,** R. L. Meena, S. Ghosh, "Comparative Performance of Different PV Array Topologies under Simulated Partial Shading Conditions, Power Electronics Drives and Energy System, IEEE, PEDES, 2020, (Under Review).

- Karni P. Palawat, **Vinod Kumar Yadav,** R.L. Meena and S. Ghosh, "Experimental Investigation of Performance of PV Array Topologies under Simulated PSCs," Applied Soft Computing & Embedded System Application in Solar Energy, CRC Press, Taylor & Francis.

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