

RELIABILITY IMPROVEMENT OF PV MODULE THROUGH MODIFIED BYPASS ARRANGEMENT

A DISSERTATION

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IN
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Submitted By

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CERTIFICATE

I hereby certify that the Project Dissertation titled “TO IMPROVE THE RELIABILITY OF PV MODULE UNDER DIFFERENT PARTIAL SHADING CONDITIONS BY MODIFIED BYPASS CIRCUIT” which is submitted by ASHWANI SRIVASTAV, whose Roll No. is 2K20/PES/06, Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment 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.

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ABSTRACT

Photovoltaic (PV) generation systems are being developed in response to the rapidly depleting conventional energy sources and the growing demand for alternative energy sources. PV technology is the most widely chosen alternative source among the various options because it is the most abundant. But one of the major problems associated with this technique is the generation of Hotspot in PV panel and this long standing problem is still present even after so much advancement in the technique. However, it does not affect the performance but seriously affect the safety and reliability of the system.

In this paper, solution to this problem is proposed which is cost effective and also does not increase the complexity of the circuit. A hotspot mitigation circuit is proposed in which a Mosfet is used, as a switch, which will cut off the entire panel which is under the partial shading condition and the rest of the connection can continue to work smoothly at reduced voltage but at very minute power loss as compared to the prior design.

The performance of the modified bypass circuit is demonstrated using a simulation model of a 3×3 Photovoltaic (PV) panel system, and the results are then compared in terms of current-voltage and power-voltage characteristics under various partial shading conditions, with and without modified bypass circuit. . The results are then validate through hardware experimentation on a 3×3 PV panel using EXIDE INDIA LIMITED (EIL-40) modules each have capacity of 40 W.. The results reveal that the proposed modified bypass arrangement effectively reduced the temperature of the affected cell hence the reliability is improved.

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LIST OF SYMBOLS AND ABBREVIATIONS

List of Symbols

I_P	Photo Current generated by PV Cell (A)
I_D	Diode Current (A)
I_{Sh}	Shunt Current (A)
I_{pv}	PV Module Current (A)
I	PV cell terminal Current (A)
V	PV cell terminal Voltage (V)
V_d	Diode Voltage (V)
V_{pv}	PV Module Voltage(V)
V_R	Reverse voltage across shaded cell (V)
V_F	Voltage supplied by illuminated cells (V)
N	Number of serially connected cells in a sub-panel
R_{Se}	Series resistance of Photovoltaic cell (Ω)
R_{Sh}	Shunt resistance of Photovoltaic cell (Ω)

List of Abbreviations

BPD	Bypass Diode
CS	Column shading
DS	Diagonal shading
GMPP	Global maximum power point
HSMC	Hotspot mitigation circuit
LMPP	Local maximum power point
MOSFET	Metal- Oxide- Semiconductor Field Effect Transistor
NS	Non shading
PSC	Partial shading condition

RAS	Random shading
RS	Row shading
SP	Series- parallel
TCT	Total cross tied

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Continual increase in demand, due to growth in population, technology development, manufacturing advancement and industrial expansion, has led to the expansion of the alternative source of the energy generation system. Due to Environmental issues concern with greenhouse effect and diminution of natural reserves of conventional energy source, globally researchers and investors are trying to develop technologies to harvest energy from renewable source like solar, wind, nuclear etc. Out of them, solar energy is most abundant and easier to convert in required electrical energy.

Photovoltaic (PV) generation systems are being developed in response to the rapidly depleting conventional energy sources and the growing demand for alternative energy sources. PV technology is the most widely chosen alternative source among the various options because it is the most abundant. Its first application in satellites [1] brings it into focus in 1958. PV was only used in a techno-commercial application for a few terrestrial applications for another three decades after that, but the situation has changed with the dawn of the twenty-first century. It is currently more appealing than any other power generation technology ever devised by mankind. As a result, PV technology is currently generates 821 TWh of energy [2].

Fig.1.1 shows the typical PV system, which comprises of solar panels, power converter modules, energy storage systems and then connected to the distribution utilities. The number of modules or array used in a PV system depends upon the total output current and voltage requirement of the system it is feeding. A battery storage system (BMS) is required for the stand-alone system to maintain the supply in night and bad weather conditions.

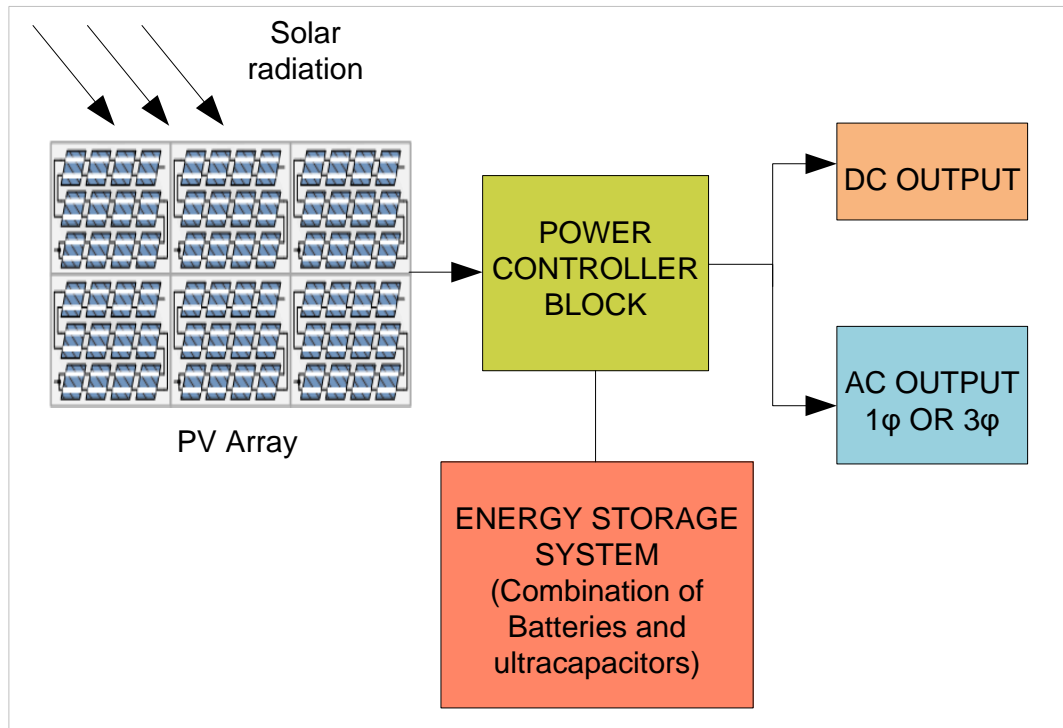


Fig 1.1: A Typical Solar Powered System

Apart from all the advantages it possesses, there are some issues which are still needed to be taken care of such as, PSCs, deposition of aerosol and the most important among them is generation of hotspot and this long standing problem is still present even after so much advancement in the technique. However, it does not affect the performance but seriously affect the safety and reliability of the system. Also such problems restrict the system against its full utilization. Depending upon current and voltage level PV systems are basically combination of the PV cells in different configuration. These combinations make the PV systems highly sensitive towards mismatch of PV cells [3].

Practically, cell properties differ greatly from each another because of the prevalence of parametric drifts, surface flaws, lack of homogeneity micro cracks, and caused by potential induced degradation (PID), light induced degradation (LID), and non-uniform ageing of PV cells [4]. Also there are some issues that act as a barrier against the full utilization of the PV technologies such as partial shading condition and aerosol deposition [5].

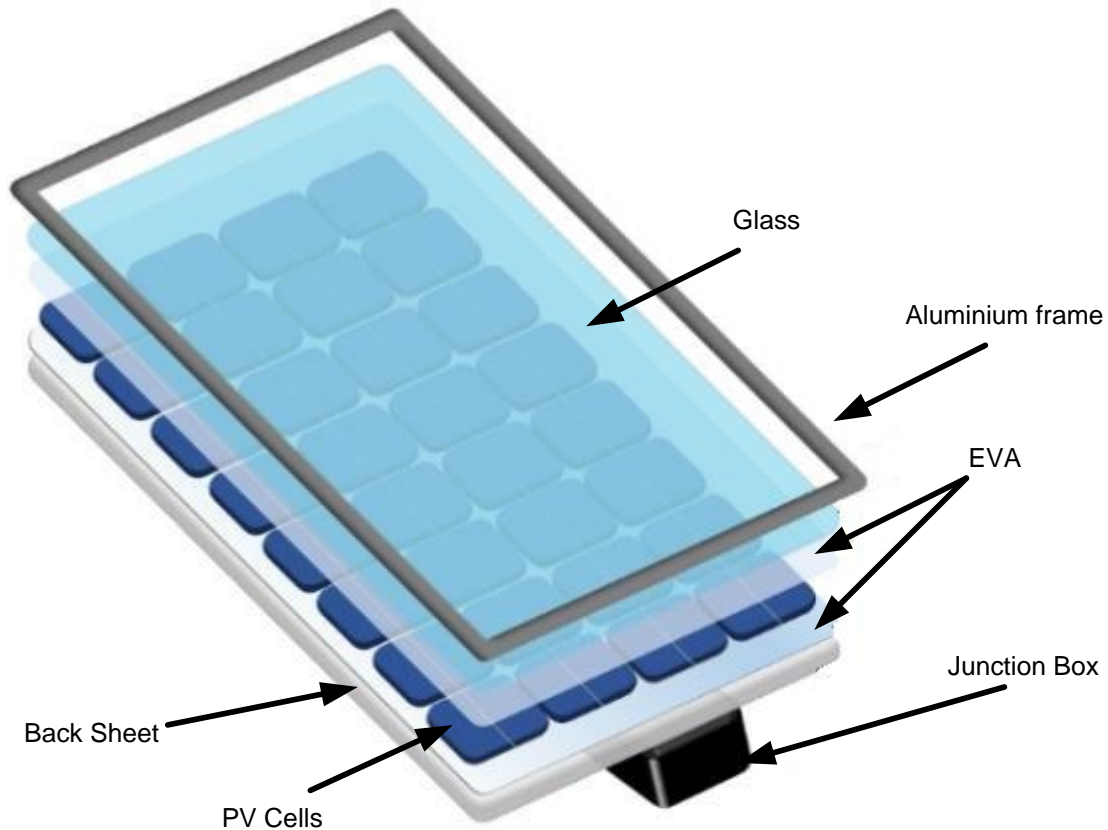


Fig 1.2: PV Module Structure

Thermal runaway or secondary breakdown may occur as a result of elevated temperature, resulting in the flow of reverse current. The PV cells could be irreversibly damaged if the temperature rises to 400°C [6-7]. Under controlled environmental condition, different Experimental investigation shows that PV cell may get damage permanently at 4.6 A of reverse current [8].

Due to the generation of extremely high temperatures, the electrical joints become fragile with time, causing electrical arcing and, in certain cases, shattering of protective glass. Furthermore, the material used in solar modules is highly flammable and can catch fire at high temperature when exposed to oxygen [9]. As a result, adverse climatic variables and mismatch situations have a negative impact on PV module efficiency and performance ratios, as well as posing serious safety and reliability concerns for PV systems [10-13].

Combination of multiple PV cells serially and parallelly makes one PV array which are then connected in different configuration to maximize the output generated. To enhance the terminal voltage photovoltaic cells are connected serially, similarly to enhance the output current photovoltaic cells are connected parallelly. The solar energy is the most popular form of renewable energy as it is available most abundantly, lower cost of generation, produce clean and green energy but along with all the advantages it possess , it also has certain serious issues associated with it like deposition of aerosol, partial shading condition (PSCs) and generation of hotspot. Researches and study are being done to resolve these issues in order to produce a PV system with high efficiency, low cost and high reliability [14]. Some of the methods are differential converters and innovative array topologies [15], proposing a new innovative hotspot mitigation technique, module level dc-dc converters [16] and inverters [15].

In the present work a hotspot mitigation circuit is proposed which enable the panel to be completely cutoff from the string which is under the condition of PSCs such that the partially shaded cell will no longer experience the reverse voltage across itself hence there will be no generation of hotspot will . This prevents the possibility of thermal runaway, increase the life of the PV cell and also the reliability of the system will be increased. The modified circuit is simulated in MATLAB/Simulink platform and the corresponding results are observed. Then later the results are validated through hardware implementation.

1.2 RENEWABLE ENERGY RESOURCES

From different researches and articles it is clearly established that energy producing from fossil fuels is polluting the environment and become one of the major source of greenhouse gases like oxides of nitrogen and sulphur, carbon monoxide, PM4 and PM10 which results in occurrence of major issue like respiratory diseases [17-19]. So for the betterment of both environment and the health of the people, steps are taken to shift the power generation more towards renewable energy sources. Certain issues related to renewable energy generation, such as improving efficiencies, reliability, and related technical issues, are the subject of research and development.

Different types of renewable energy sources are mentioned in Table 1.1.

Table 1.1: Different types of renewable energy sources

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

1.3 GLOBAL INITIATIVES

India has set more ambitious targets for 2030 in order to achieve net zero emissions by 2070, including installing 500 Giga watts of renewable energy capacity, lowering its economy's emissions intensity by 45 percent, and reducing a billion tones of CO₂. These goals are ambitious, however the best part is that India is well on its way to becoming a clean energy powerhouse. It has already met 40% of its power capacity from non-fossil

fuels, nearly nine years ahead of commitment made at COP 21- Paris Summit, and the share of solar and wind in India's energy mix has increased dramatically [14].

India is gaining more renewable electricity capacity as compared to other major economy, with new capacity expected to double by 2026. The country is also one of the largest producers of modern bio energy in the world, with big plans to expand its use throughout the economy. After the United States and Brazil, the IEA predicts that India will surpass Canada and China in the coming years to become the world's third largest ethanol market.

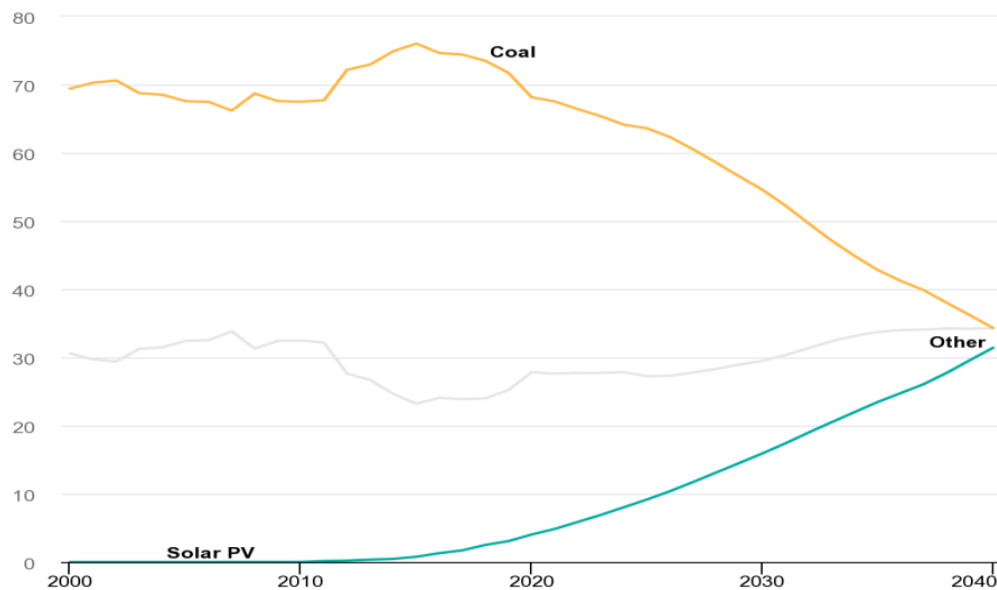


Fig 1.3: Changes in share of power generation in India in the Stated Policies Scenario, 2010-2040 [17]

1.4 PROBLEM STATEMENT

Renewable energy source is the future of electrical energy generation as they are environmental friendly and also because conventional energy sources are not enough to meet the demand. But with current technologies and practices we are not able to generate its full potential. Among different renewable sources available, solar energy is the most promising method due to its widespread availability, relatively lower cost of generation,

produces clean and green energy. But despite of all of its advantages it is not efficient and reliable and largely depends on the Partial shading conditions. The generation of hotspot is the main drawback of the PV system. Under partial shading condition, the shaded cell experience the reverse biased voltage which causes generation of hotspot and lead to sudden rise in temperature which in turn can permanently damage the PV cell, can cause fire, joints may become fragile or shattering of protective glass. To overcome the problem of hotspot generation we need to research and study the methods which can make the photovoltaic system more reliable and hence improve its performance. So in this work, a new mitigation circuit is proposed whose objective is to improvise the photovoltaic system such that effect of partial shading over it can be reduced.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 MODELLING OF PV CELL

A PV panel contains number of photovoltaic cell which are interconnected serially or parallelly as per the output voltage and output current requirements. Fig. 2.1 shows the circuit diagram of a photovoltaic cell. In the Fig. 2.1, I_p is photocurrent, I_d is photodiode current, R_{sh} is shunt resistance depicting leakage current and R_{se} is series resistance depicting internal resistance of the cell, I is cell current and V is voltage produce by one cell [20].

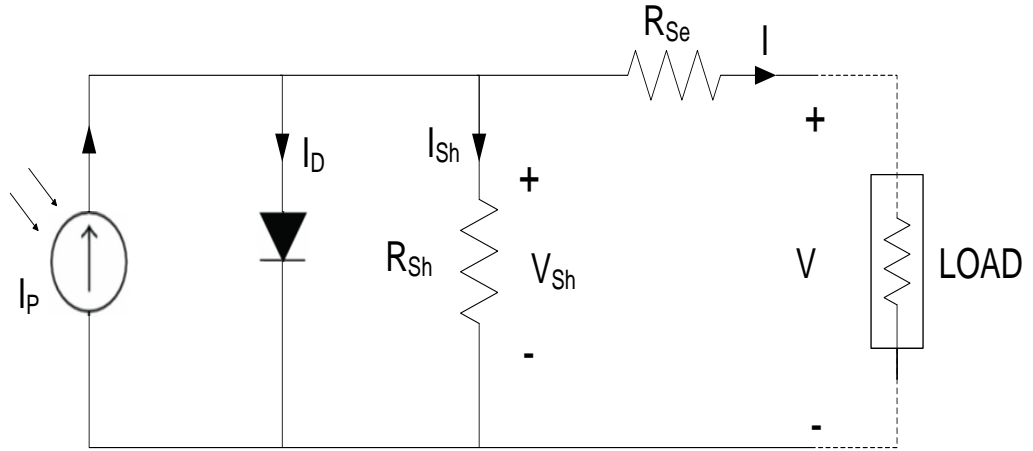


Fig 2.1: Equivalent circuit diagram of Photovoltaic cell

Current and voltage equations of a photovoltaic cell are as follows [21]:

$$I = I_p - I_d - I_{sh} \quad (2.1)$$

$$I_d = I_o \left[e^{\frac{V+IR_{se}}{V^\alpha}} - 1 \right] \quad (2.2)$$

$$I = \frac{V + IR_{se}}{R_{sh}} \quad (2.3)$$

From equations (2.1), (2.2), (2.3) we get:

$$I = I_p - I_o \left[e^{\frac{V+IR_{se}}{V_t}} - 1 \right] - \frac{V + IR_{se}}{R_{sh}} \quad (2.4)$$

Where I_o is saturation current of the photodiode, $V_t = \frac{AkT}{q}$ in which A is ideality factor, k is Boltzmann constant, T is temperature of the cell (Kelvin) and q is elementary charge[22,23]. From above equations it can be inferred that photocurrent is dependent upon the temperature of the cell. Generated photocurrent rise slightly with rise in temperature but the saturation current reduces exponentially with rise in temperature hence decreasing cell voltage hence the efficiency and reliability of PV system decreases [24].

If N_s numbers of cells are connected serially and N_p numbers of cells are connected parallelly in the photovoltaic array than array current I_A is:

$$I_A = N_p I_p - N_p I_o \left[e^{\frac{V+IR_{se}}{V_t}} - 1 \right] - \frac{N_p V + I N_s R_{se}}{N_s R_{sh}} \quad (2.5)$$

2.2 POWER DISSIPATION ACROSS SHADED SOLAR CELLS

To decrease the effects of the partial shading condition, bypass diode is use which is connected in antiparallel manner across a panel. Under full illumination, the Bypass diode is reversed biased and the entire output current is passed through panel itself but under the condition of partial shading the bypass diode get forward biased due to the reversal of voltage across the shaded cell and bypass the entire PV panel across which it is connected [25-28].

To understand the mechanism, consider a sub panel in which N solar cells are connected serially with a bypass diode, if a cell experienced partial shading than its photo generated current is significantly degrade which in turns limit the serial current. A bypass

diode is used across the panel to rectify this problem, which gets forward biased during shading condition and provide an alternate path for series current which reverse bias the shaded cell.

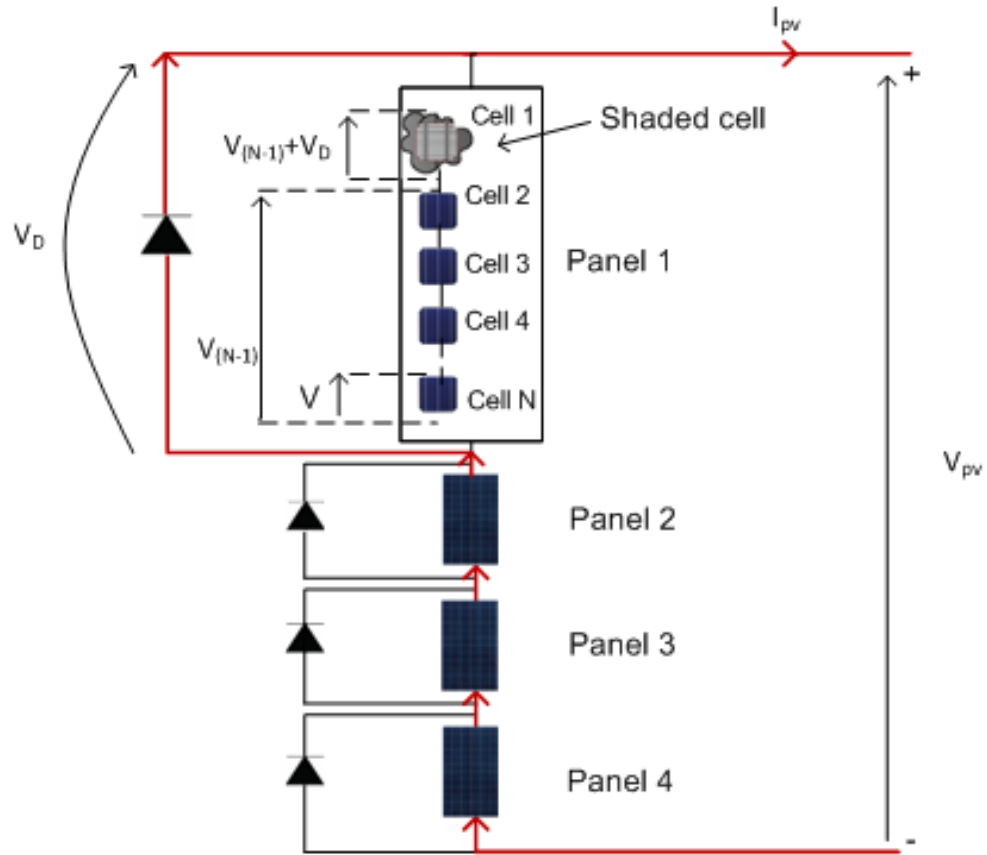


Fig 2.2: Reverse voltage across shaded cell with BPD

For the close loop created by the BPD, we can use Kirchhoff's voltage law to quantify reverse voltage across shaded cells as in (2.6).

$$-V_{R(\max)} = \sum_{N=1}^{m-1} V_{OC,N} + V_D \quad (2.6)$$

The current-voltage characteristic corresponding to the effected cell is explained in Fig. 2.3, in which slope is determined by the shunt resistance. The electrical power dissipated by the shaded cell which is under reverse bias condition can be determined by

means of geometrical approach [29]. In Fig. 2.3, the point represents the point of operation of a solar cell that is partially shaded and product of the current-voltage gives the corresponding dissipated power. It should be observed that partially shaded region causes the maximum amount of power produced by the illuminated cells to be absorbed by the shaded cell, which results in a larger temperature rise [30].

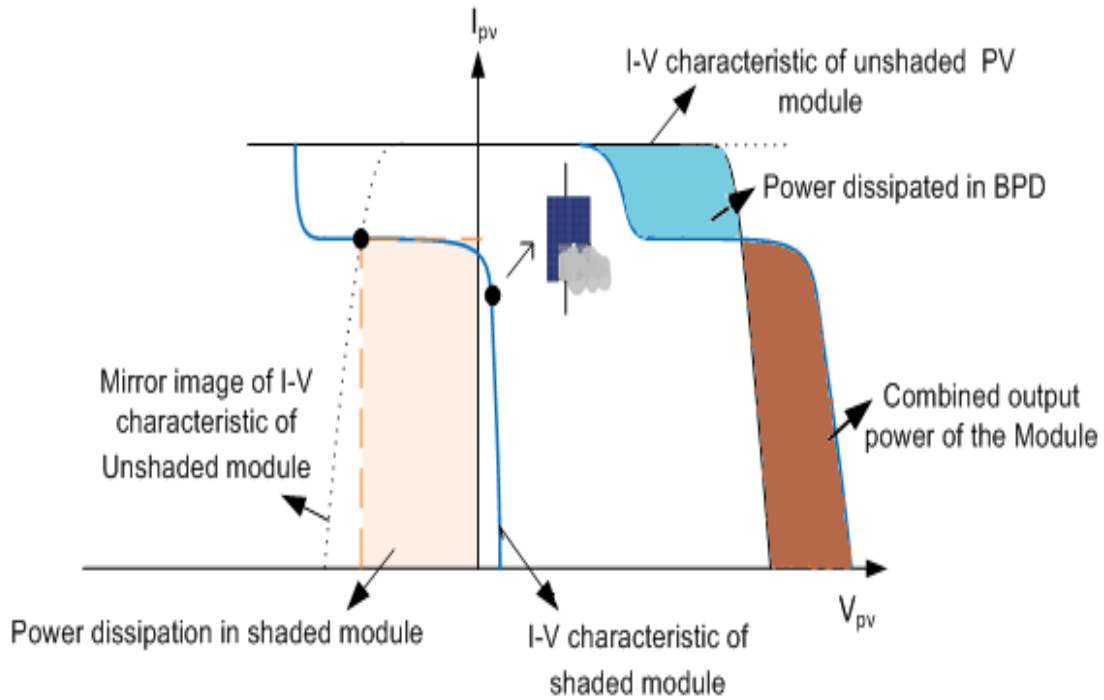


Fig 2.3: I-V characteristic of PV module under the partial shading condition

Maximum reverse voltage for 0.5V forward voltage drop of BPD and 0.6V open circuit voltage of PV cells is calculated as 19.1V, 14.3V and 11.9V for 96, 72.60 cell module respectively [31]. This much voltage level should be under safe limits and there effects could be neglected but by different Reverse breakdown characteristics of PV cells changes due to different manufacturing processes as micro defects get generated.

2.3 PROPOSED HOT SPOT MITIGATION CIRCUIT

The circuit connection for proposed topology is shown in Fig. 2.4. Here MOSFET is used as a voltage controlled switch which offers very low on state resistance to serial

current [32]. When the panel is under the condition of full illumination, the voltage at the output terminal is high, which coincides with the MOSFET's input voltage, causing it to turn on and offer extremely low resistance. However, when the panel is under partial shading condition, the voltage at the input terminal is low, reducing the input of the MOSFET and thus its current capability. In this case, the MOSFET will turn off and the serial current would flow through bypass diode, resulting in an overall voltage across the MOSFET and the panel equal to V_D . As a result of the MOSFET, the peak reverse voltage across the shaded cell gets reduced. This condition is formulated as follows:

$$V_R = (N - 1)V_F + V_D - V_{DS} \quad (2.7)$$

By this arrangement it was found that reverse voltage across shaded cell is decreased significantly. This is shown in the next section through simulation results and the various results are then compared for different shading condition. The reduced voltage across the shaded cell also implies that corresponding power dissipated by the shaded cell is also decreased which in turn results in negligible temperature rise hence the problem of hotspot mitigation is largely reduced. The presence of MOSFET reduces the possibility of solar panel to reach the unsafe temperature which could damage the possibility of the rupturing of module. It should be noted that rest of the power which earlier dissipated by the shaded cell is now dissipated by the MOSFET so care should be taken during the selection of the MOSFET and other components. Also the overall cost of the design is also negligible with respect to the advantage it generates.

A gate triggering circuit would be needed to automatically generate the gate pulse for the MOSFET by monitoring the hot spot condition, halting the tracking of the maximum power point, and frequently measuring the module's impedance, all of which would make the circuit more complex. The switch activation circuit's reliability, as well as its reliance on site conditions and non-significant cost concerns, has all prevented the widespread use of various similar active bypass switches reported by researchers over the years [33-34].

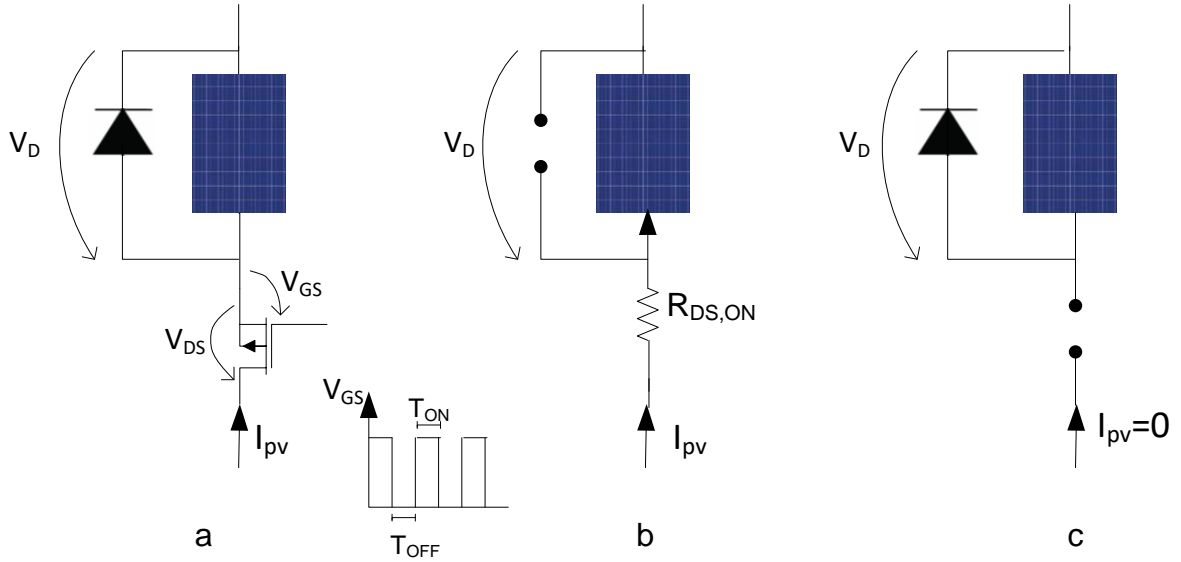


Fig 2.4: (a) schematic diagram of proposed bypass circuit with MOSFET (b) panel under fully illuminated condition (c) panel under partial shading condition

2.4 CIRCUIT TOPOLOGIES

PV panels may be rearranged in a variety of methods to minimize the effects of partial shading and maximize power generation. The ratings of the PV system to be developed will influence the number of PV panels to be linked in series or parallel. Photovoltaic cells are linked serially to increase terminal voltage, while photovoltaic cells are connected parallelly to increase output current. Series-connected PV systems are the most common arrangement. On this basic design, the reconfiguration entails extra connections. The interconnection technique lowers power mismatch losses and partial shading effects [25,35,36]. Different topologies are suggested by many scholars having different advantages over each other. In this work, 3×3 PV array is used for the analysis so total 3 topologies are possible which are as follows:

- 1) Series-parallel (SP)
- 2) Bridge link (BL)

3) Total cross-tied (TCT)

2.4.1 SERIES-PARALLEL (SP)

In this configuration certain number PV panels are connected serially to form a string than numbers of strings are connected parallel. This configuration is widely use in industrial application because of its simplest connection. Many authors recommended that this topology generates maximum power output in the absence of partial shading. It has less number of wires so easy to connect and price is least among all the topologies.

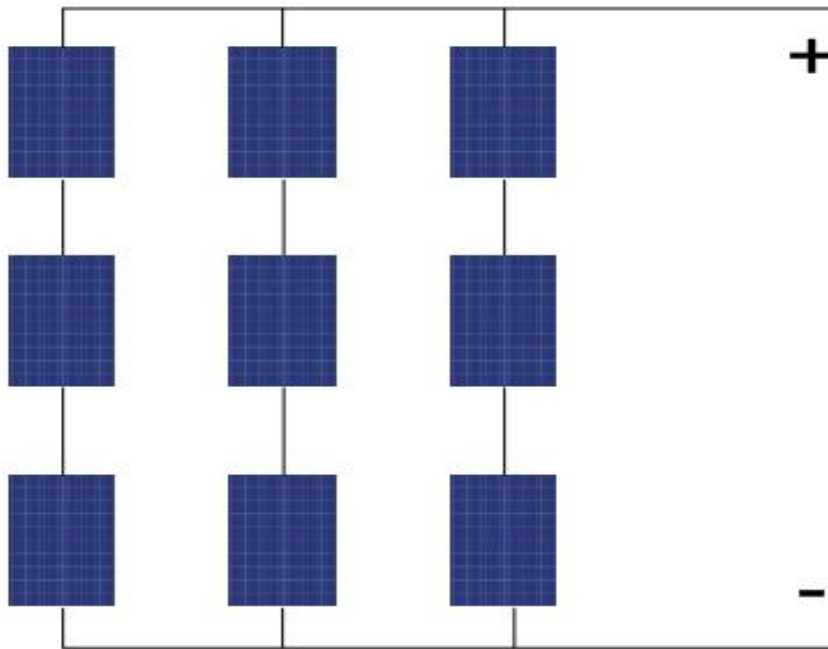


Fig 2.5: Scheme of series-parallel topology

2.4.2 BRIDGE LINK (BL)

Bridge link configuration is modified version of series-parallel configuration in which alternate panels are connected together. It is a bridge like structure between two parallel strings. The impact of partial shading is lesser compared to the series parallel configuration.

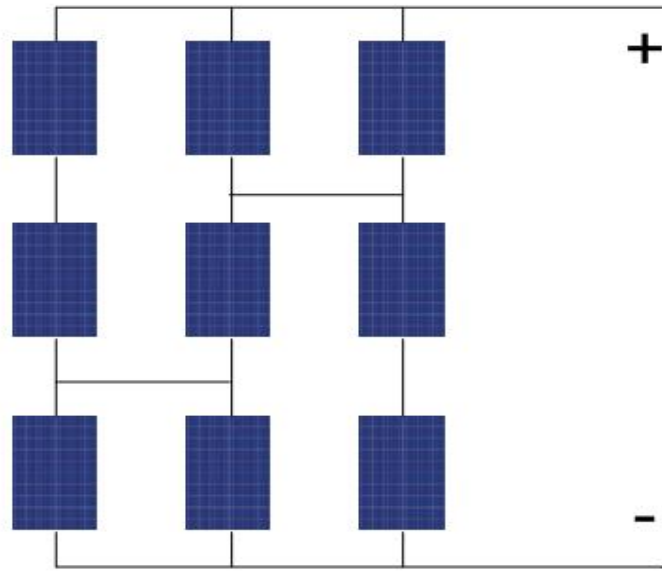


Fig 2.6: Scheme of Bridge link topology

2.4.3 TOTAL CROSS-TIED (TCT)

This topology is most supported by the scholars through different studies. In this configuration, all the panels are interconnected providing alternate path for current in case of partial shading hence the effect of partial shading is least in this case proved later in this work.

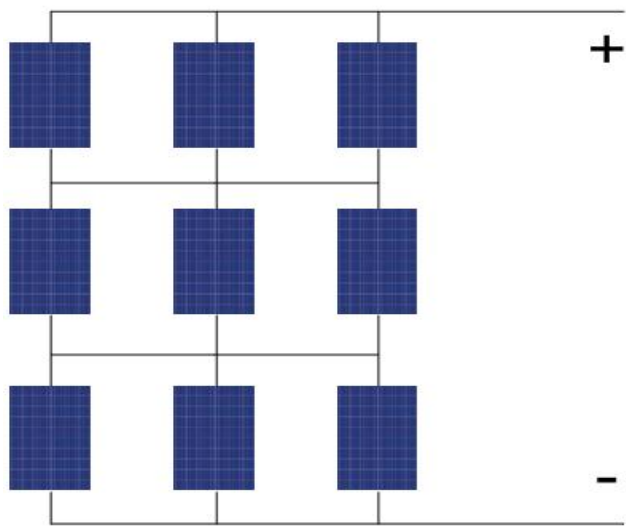


Fig 2.7: Scheme of TCT topology

2.5 SCHEME OF EXPERIMENT

Scheme of experiment is demonstrated through flow chart as shown in Fig. 2.8.

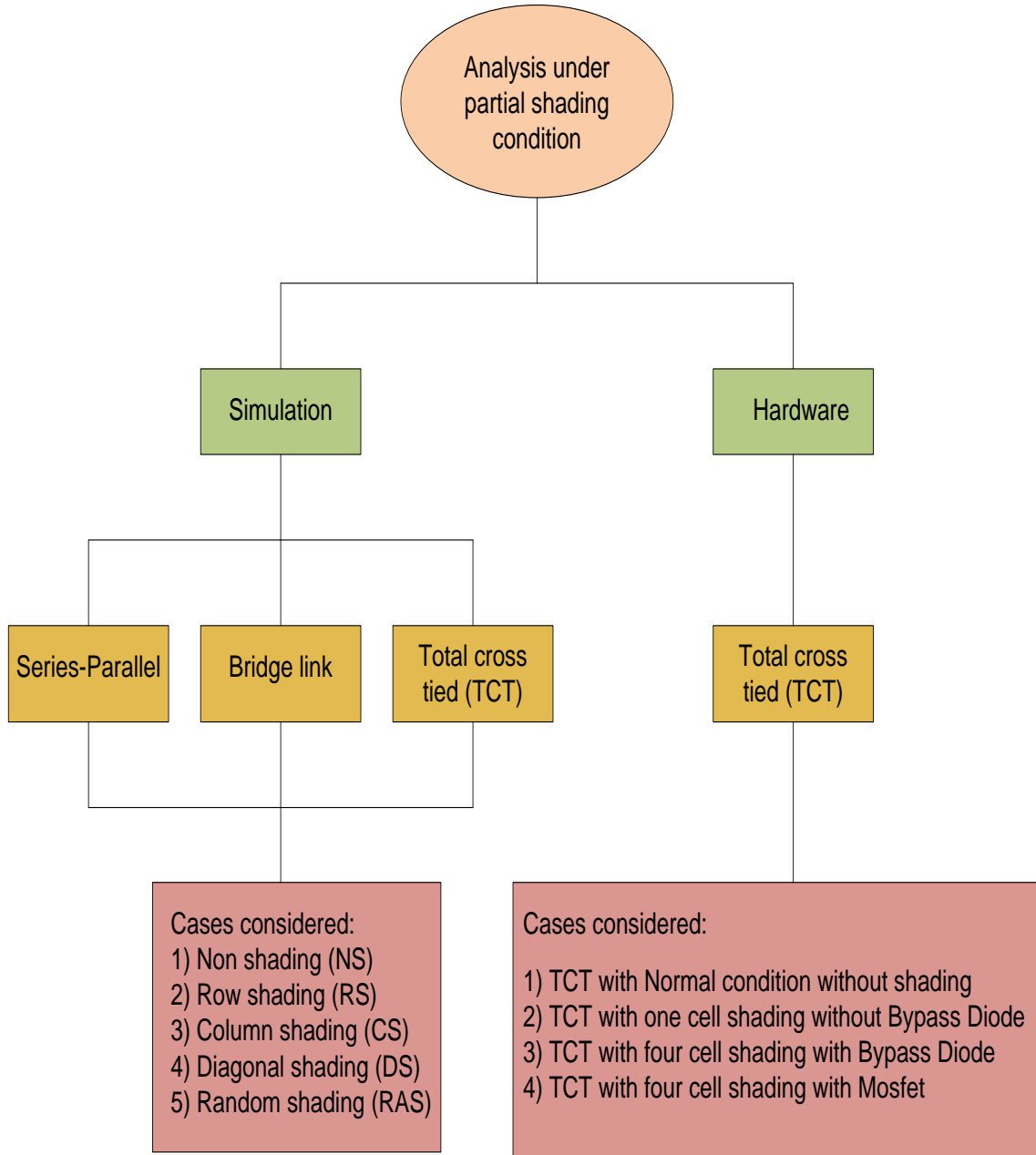


Fig 2.8: Flowchart of Work done

First all the topologies are studied and simulated along with hotspot mitigation circuit (HSMC) under different partial shading condition through MATLAB/SIMULINK

software. The results are then formulated and compared in terms of maximum power generated and the effect of partial shading conditions. From the results, it is inferred that TCT is best configuration and generate maximum power during partial shading hence latter only TCT is performed on the Hardware setup of 3×3 PV array. Again P-V and I-V characteristics are plotted and the corresponding results are analyzed. Also Thermographic images are taken for four different cases and are then compared to judge the temperature difference. Then finally on the basis of the results generated the study is concluded.

CHAPTER 3

SIMULATION MODELING AND RESULTS

In this chapter simulation results of the experiment under different partial shading conditions and the corresponding inference are included.

3.1 RATINGS OF PV MODULE

For simulation the Panels are designed for the ratings same as taken for the hardware analysis. The panel's specifications are listed in Table 3.1 below.

Table 3.1: Ratings for the PV Module used for Simulation

Electrical parameters	Ratings
Number of cells	36
Maximum Power (P_{max})	40W
Voltage at Maximum Power (V_{mp})	18.00V
Current at Maximum Power (I_{mp})	2.22A
Open Circuit Voltage(V_{oc})	22.18V
Short Circuit Current (I_{sc})	2.40A
Temperature at STC	25 °C
Irradiance at STC	1000 watt/m ²

For better comparison between hardware and software results, it is better to use the equipments of similar ratings.

3.2 Simulation Modeling

In this section, the simulation modeling of a 3×3 PV array is discussed, and the associated findings are provided for two distinct topologies, namely series-parallel and TCT, at a constant temperature of 25° C, as well as under various solar irradiances measured in watt/m² [37]. The design voltage level of the plant and the nominal voltage of the modules dictate the number of modules that should be linked serially. The number of strings (serially linked modules) that can be connected parallelly is determined by plant capacity and land availability. [21, 38] explains the linkages and comparative study of the various topologies in detail.

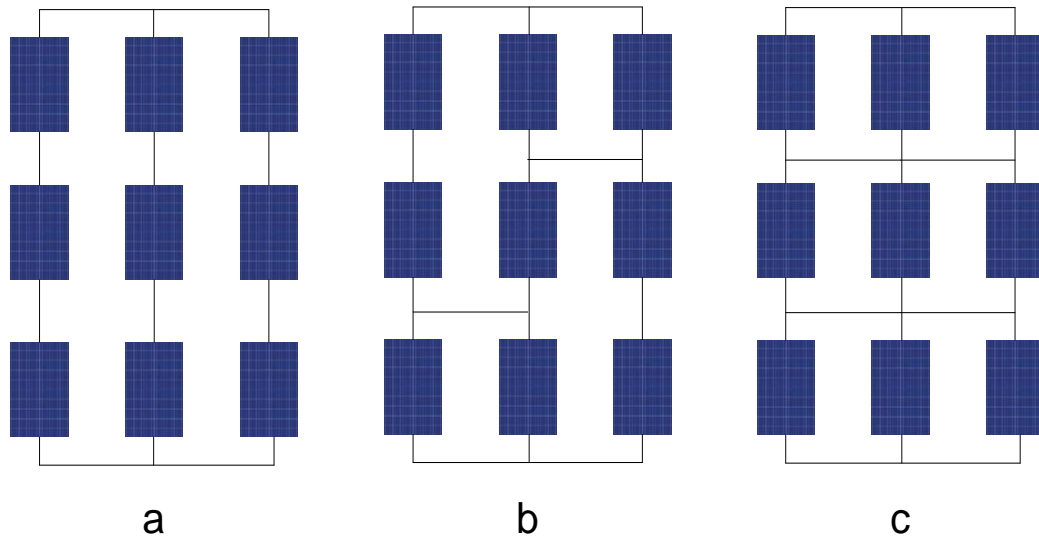


Fig 3.1: 3×3 PV array in (a) SP configuration, (b) Bridge link configuration (c) TCT configuration

For understanding the behavior of PV array during various partial shading conditions (PSC), we have taken 4 different condition of partial shading. Those are: non shading (NS), row shading (RS), column shading (CS), diagonal shading (DS) and random shading (RAS).

Non-shaded Condition (NS): In this case all the panels are fully and uniformly illuminated.

Row Shading Condition (RS): In this case, first panel of each string which are connected parallelly are shaded i.e. one row is shaded

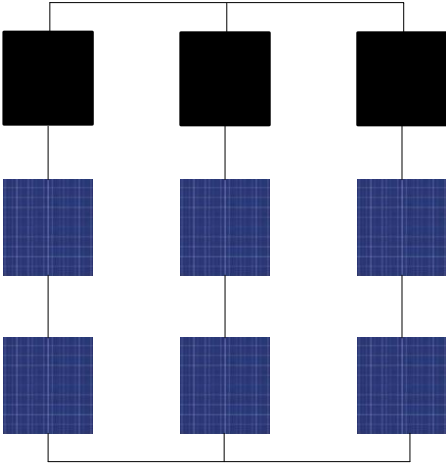


Fig 3.2: Representation of Row shading

Column Shading Condition (CS): In this case, one entire string i.e. serially connected panels are shaded.

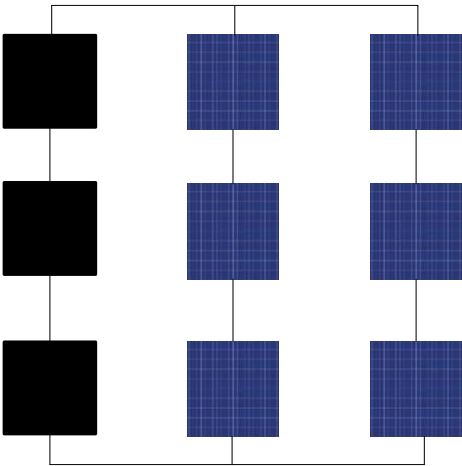


Fig 3.3: Representation of Column shading

Diagonal Shading Condition (DS): In this case, diagonal panels of PV array matrix are shaded.

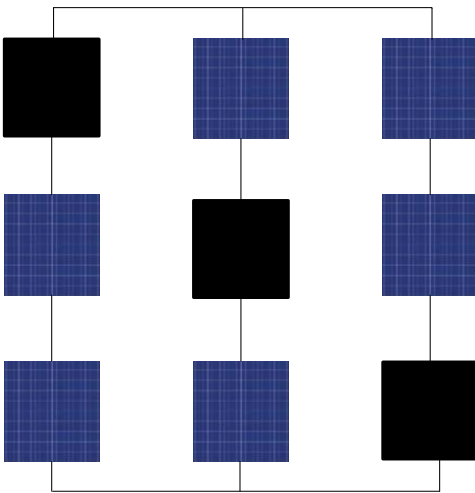


Fig 3.4: Representation of Diagonal shading

Random Shading Condition (RAS): In this case, panels are shaded randomly i.e. they do not form any specific pattern.

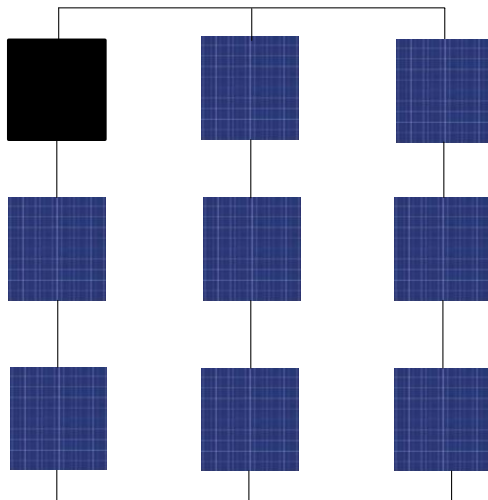


Fig 3.5: Representation of Random shading

All the cases of shading are taken for the analysis of PV system. For fully illuminated condition, Irradiance is taken 1000watt/m^2 . For the shading condition the, 600 watt/m^2 irradiance is taken. For all the test condition, 25°C temperature is taken.

The MOSFET in the proposed mitigation circuit is in the conduction state in full illumination and should be switched off in partial shade (PSC). The terminal voltage of each panel is monitored and compared in a logic circuit for regulating gate pulses, and no gate pulse is generated for the panel with the lowest voltage. As a result, when the panel is partially shaded, it is completely shut off from the remainder of the connection, and the serial current passes through the bypass diode. Although the total power and current output will be lowered, when the panel is cutoff, the temperature will not rise and will remain within the safety limit, resolving the problem of hotspot generation.

3.3 RESULTS

Current-Voltage and Power-Voltage characteristics for various topologies, as well as variable configuration and shading irradiance, are included in the simulation results. In [39,40] the current-voltage and power-voltage characteristics without a mitigating circuit are explained. The Fig. 3.6 to Fig. 3.11 indicates the results of the proposed mitigation circuit:

3.3.1 Series parallel (SP)

Due to the ease of connection and implementation, this topology is widely accepted and used for project implementation by various power producers. According to the voltage and current handling requirements of inverters, topology consists of some series paths and some parallel paths.

Series Parallel configuration is subjected to different partial shading conditions and current-voltage and power-voltage characteristics are plotted.

From current-voltage and power-voltage characteristics, it can be observed that maximum power output is 359.7 watt at 53.33 V under uniform irradiance at 1000 watt/m².

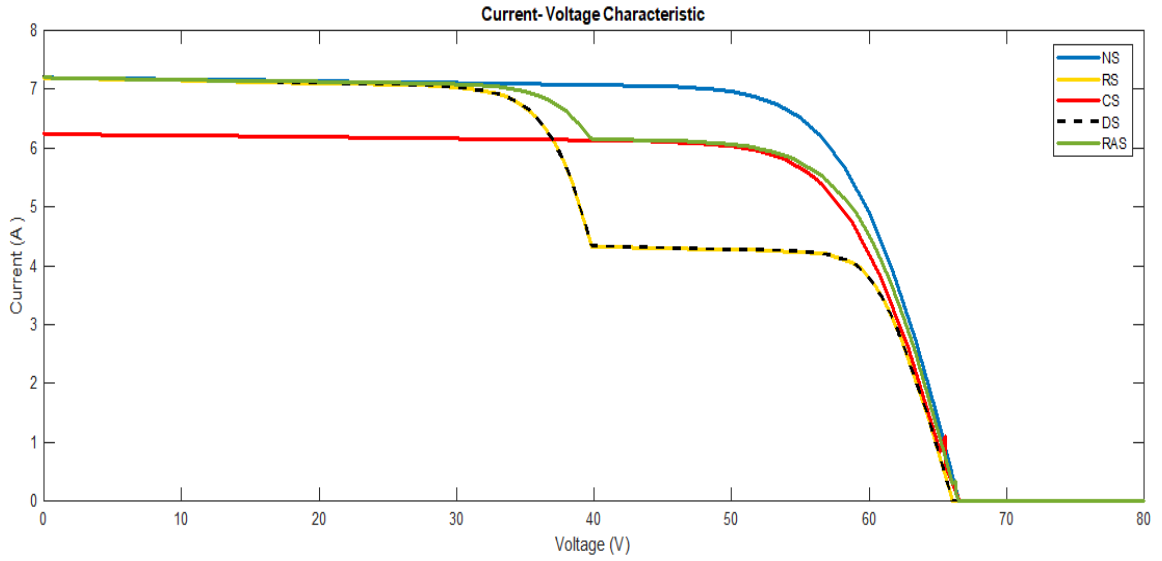


Fig 3.6: I-V plot for series-parallel configuration under different PSC for 1000 watt/m^2

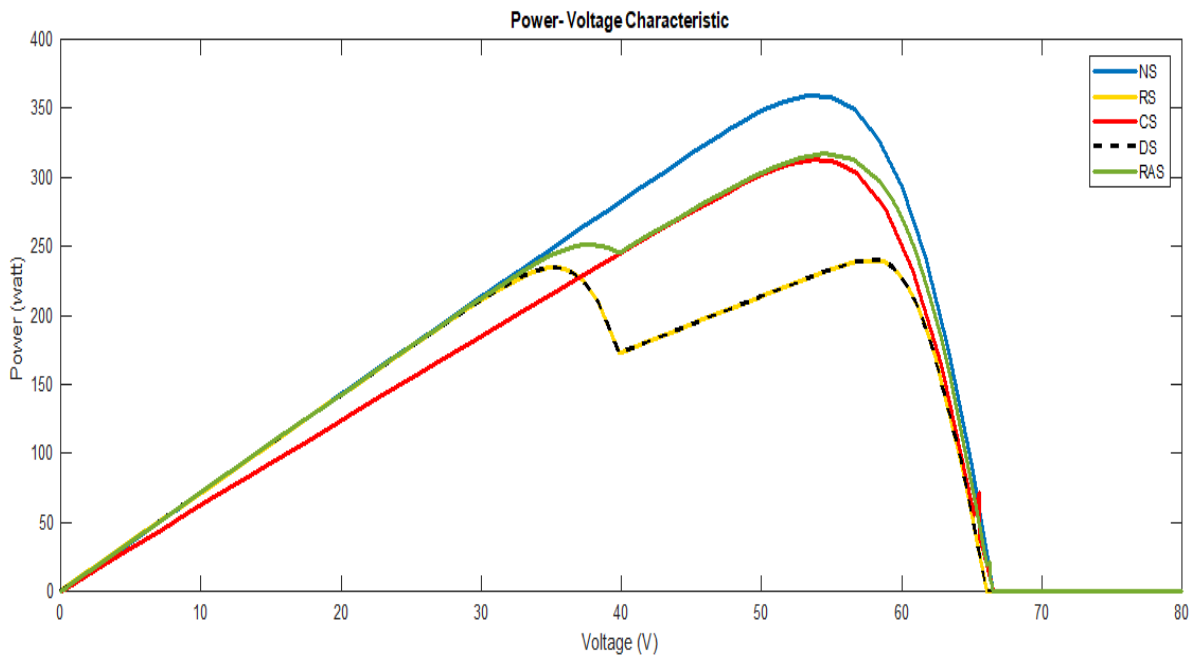


Fig 3.7: P-V plot for series-parallel configuration under different PSC for 1000 watt/m^2

3.3.2 Bridge link (BL)

When compared to series parallel, BL has a higher number of parallel paths, which helps to reduce voltage mismatch loss and improve performance ratio. A connecting lead

connects two parallel connecting paths in the same way that a bridge connects two nearby roads.

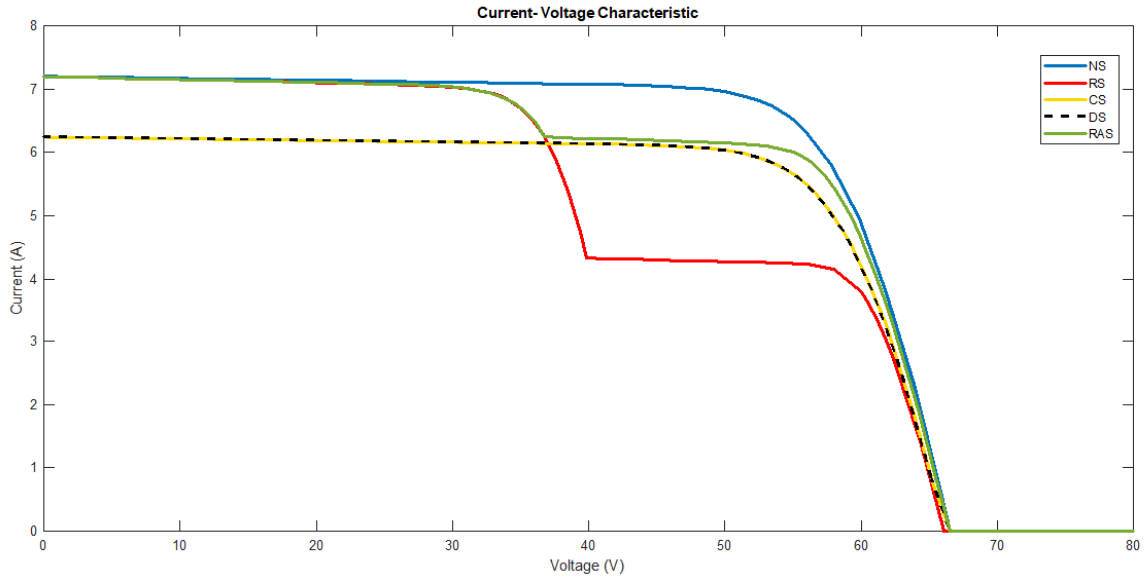


Fig 3.8: I-V plot for bridge link configuration under different PSC for 1000 watt/m^2

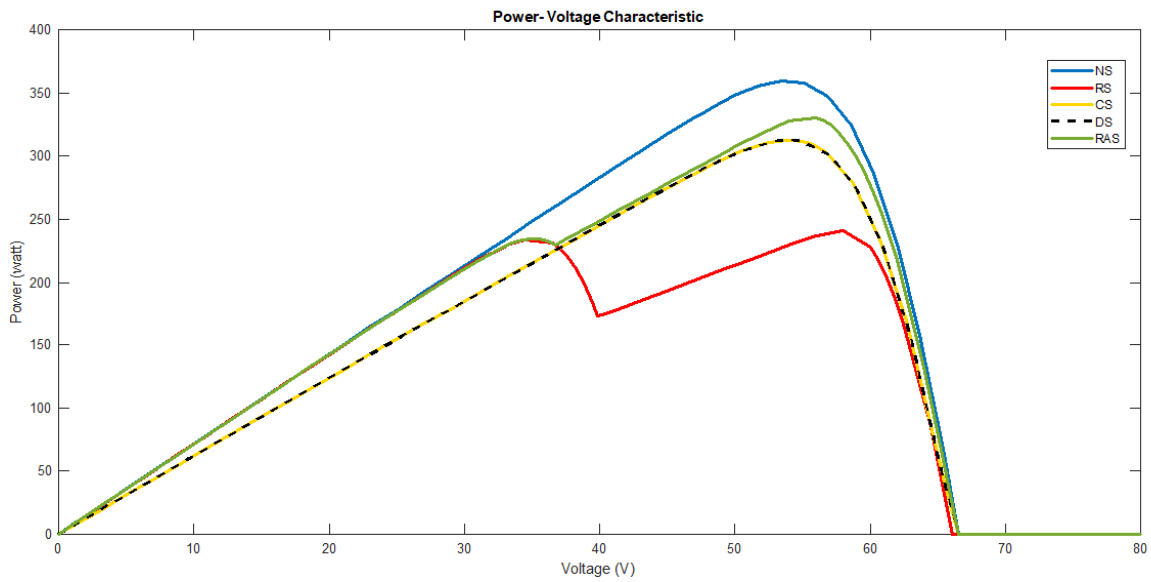


Fig 3.9: P-V plot for bridge link configuration under different PSC for 1000 watt/m^2

Bridge link configuration is subjected to different partial shading conditions and current-voltage and power-voltage characteristics are plotted.

From current-voltage and power-voltage characteristics, it can be observed that maximum power output is 359.7 watt at 53.42 V under uniform irradiance at 1000 watt/m².

3.3.3 Total cross-Tied (TCT)

In comparison to series parallel and bridge links, the structure has a greater number of interconnecting paths, which helps to reduce voltage mismatch losses and provide an alternate path for current in the event of partial shading. It improves the efficiency and performance ratio.

Total cross-Tied configuration is subjected to different partial shading conditions and current-voltage and power-voltage characteristics are plotted.

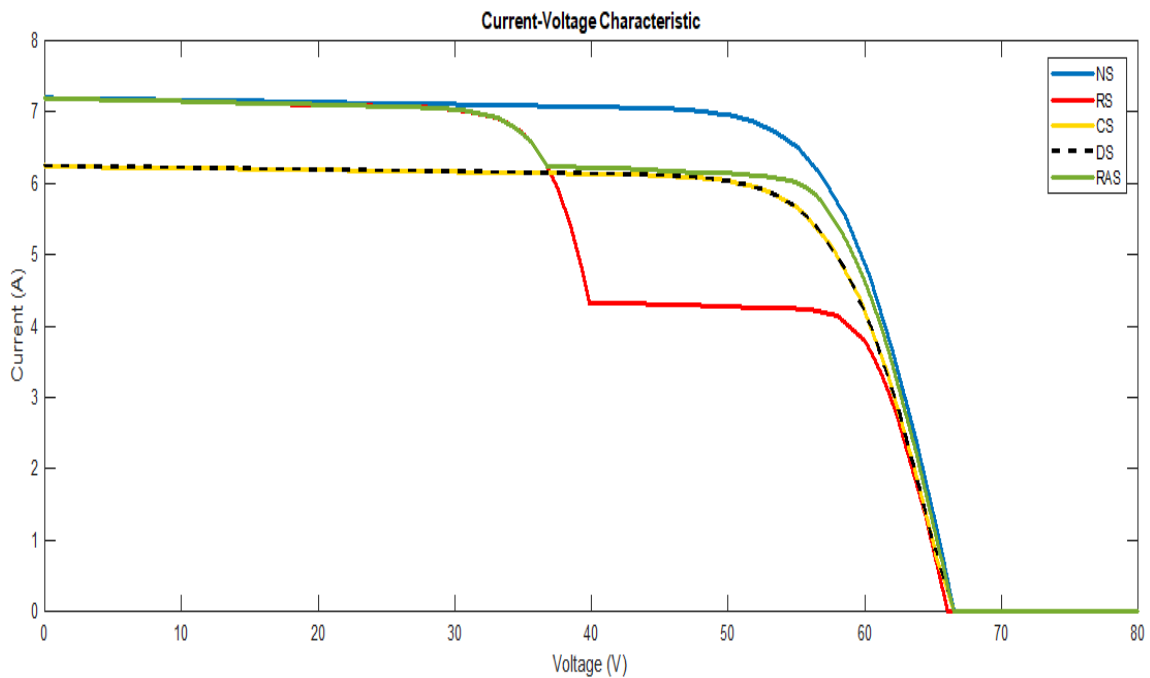


Fig 3.10: I-V plot for TCT configuration under different PSC for 1000 watt/m²

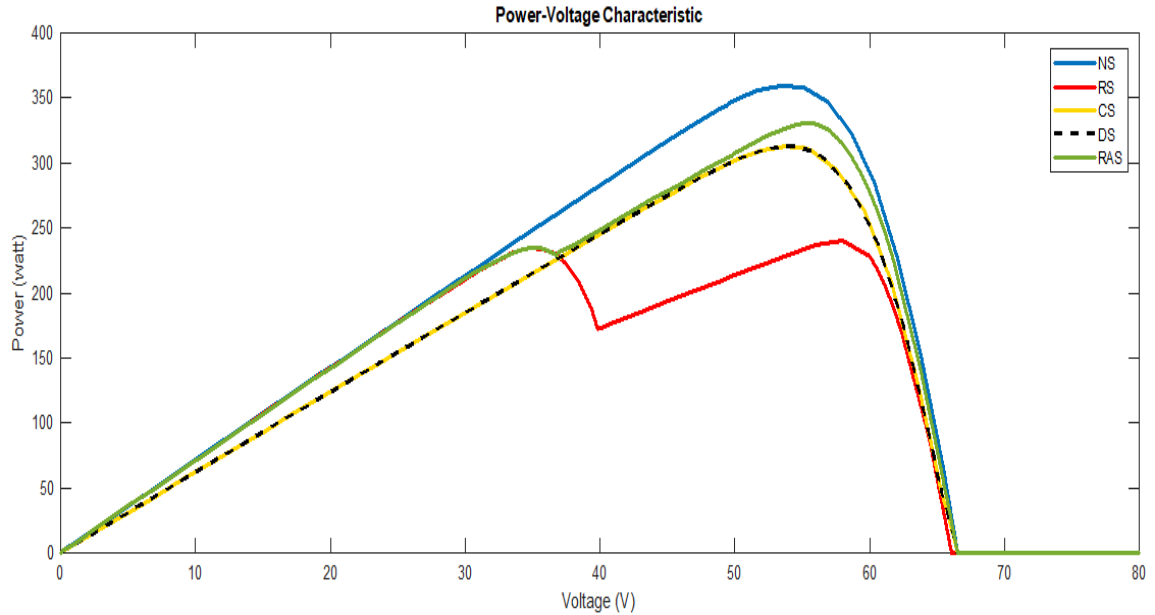


Fig 3.11: P-V plot for TCT configuration under different PSC for 1000 watt/m²

From current-voltage and power-voltage characteristics, it can be observed that maximum power output is 359.7 watt at 53.44 V under uniform irradiance at 1000 watt/m².

The current-voltage and power-voltage characteristics of various configurations are illustrated in Fig. 3.6 to Fig. 3.11, indicating that the panel's performance may be enhanced by employing a modified bypass design. By analyzing several attributes, it can be deduced that the TCT configuration produces the best outcomes and has the smallest drop. As a result, we picked TCT setup for the experiment, and the resulting findings are reported in the next section.

From Table 3.2 it can be observed that there are different power points, also we get global maximum and local maximum power points which cause problem for conventional power tracing algorithms.

Table 3.2: GMPP and LMPP during various partial shading conditions

Topology	PSCs	GMPP			LMPP		
		Voltage (V)	Current (A)	Power (watt)	Voltage (V)	Current (A)	Power (watt)
Series-Parallel	NS	53.33	6.743	359.7	-	-	-
	RS	58.6	4.091	239.7	35.41	6.62	234.4
	CS	54.55	5.742	312.4	-	-	-
	DS	58.6	4.091	239.7	35.41	6.62	234.4
	RAS	54.55	5.809	316.9	37.92	6.628	251.3
Bridge-Link	NS	53.42	6.725	359.7	-	-	-
	RS	58	4.151	240.8	34.15	6.707	233.9
	CS	53.79	5.808	312.5	-	-	-
	DS	53.79	5.808	312.5	-	-	-
	RAS	54	6.123	326.1	35.56	6.707	234.3
TCT	NS	53.44	6.732	359.7	-	-	-
	RS	58	5.376	240.8	35.76	6.589	233.9
	CS	54.17	5.77	312.5	-	-	-
	DS	54.17	5.77	312.5	-	-	-
	RAS	55.17	4.28	330.9	34.96	6.707	234.4

The current-voltage and power-voltage characteristics of various configurations are illustrated in Fig. 3.6 to Fig. 3.11, indicating that the panel's performance may be enhanced by employing a modified bypass design. By analyzing several attributes, it can be deduced that the TCT configuration produces the best outcomes and has the smallest drop. As a result, we picked TCT setup for the experiment, and the resulting findings are reported in the next section.

CHAPTER 4

HARDWARE IMPLEMENTATION AND RESULTS

In the previous section, simulation results has been analyzed and studied extensively and among different topologies it was observed that TCT configuration generates best results under partial shading conditions. TCT has maximal connectivity, which gives it the benefit of improved efficiency since the interconnection would provide an alternate channel to the current that was altered owing to partial shade [41]. TCT configuration is utilized for hardware validation of the proposed mitigation circuit

The panel's specifications are listed in Table 4.1 below.

Table 4.1: Ratings for the PV Module-EIL40 used for Hardware implementation

Electrical parameters	Ratings
Number of cells	36
Maximum Power (P_{max})	40W
Voltage at Maximum Power (V_{mp})	18.00V
Current at Maximum Power (I_{mp})	2.22A
Open Circuit Voltage(V_{oc})	22.18V
Short Circuit Current (I_{sc})	2.40A
Tolerance	0 to 5 W
Temperature at STC	25 °C
Irradiance at STC	1000 watt/m ²

4.1 Hotspot Mitigation Circuit

The conventional Bypass diode has the disadvantage of not completely cutting off a panel that is partially shaded, allowing some current to pass through. Although it would be lesser than the load current, it is sufficient to generate hotspot in the panel. As a result, we need a circuit that will completely turn off the panel, allowing the panel's temperature to be maintained even when partially shaded. The hotspot mitigation circuit is designed to solve this problem by acting as a switch to turn off the panel when it is partially shaded.

The mitigation circuit employs a MOSFET, which is a bidirectional device, necessitating the usage of an external triggering circuit to generate the gate pulse. The triggering circuit measures the voltage and current of each panel constantly, calculates the average value, and deducts the voltage and current values of each panel from the average value. Because the panel that is shaded has the greatest difference, an external triggering circuit is used to switch off the MOSFET attached to that panel. This will disconnect the whole panel from the rest of the system. The terminal voltage will stay same as the configuration is TCT, and the reduction in power is insignificant in comparison to the increased reliability.

4.2 Experimental setup

In the experimental setup following devices are utilized:

- 3×3 PV module
- Luxmeter
- Rheostat
- Ammeter
- Connecting leads

- Hotspot Mitigation Circuit

The Experiment is being performed on the 3×3 PV module connected in TCT configuration. Variable rheostat of 100Ω/5A is used to vary load and hence trace the power-voltage and current-voltage characteristics. Luxmeter is a device which measures the amount of light falling on an area and is used for observing irradiance which helps in calculation of efficiency. Ammeter and voltmeter are used to measure voltage and current at particular load point. Connecting leads are used to connect modules as per requirement or topology. Hotspot mitigation circuit is connected in series with the panel which is under the affect of partial shading.

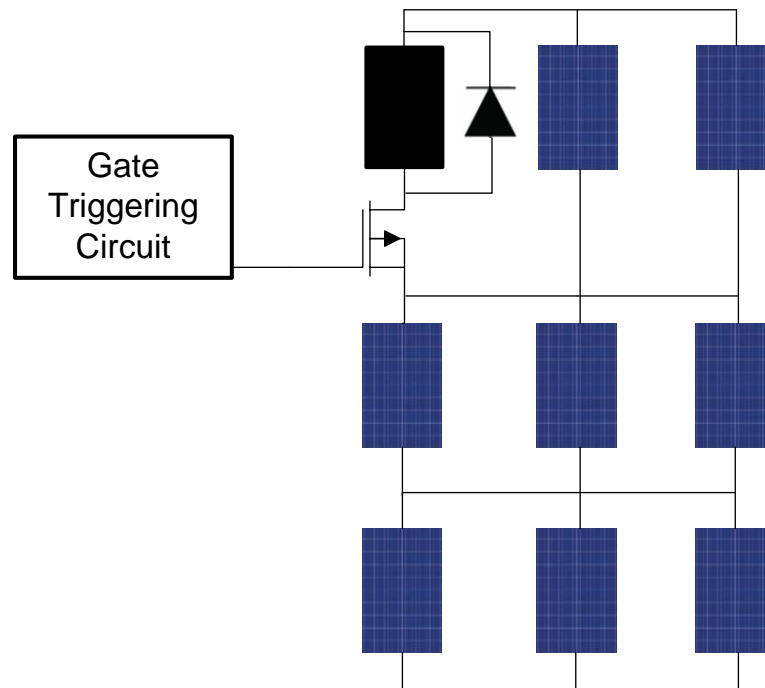


Fig 4.1: Schematic diagram of hardware implementation

Fig. 4.1 depicts the schematic circuit design for the Hardware implementation set up. For hardware experimentation, shading over one panel is chosen for legibility and clarity, and the associated results are observed.

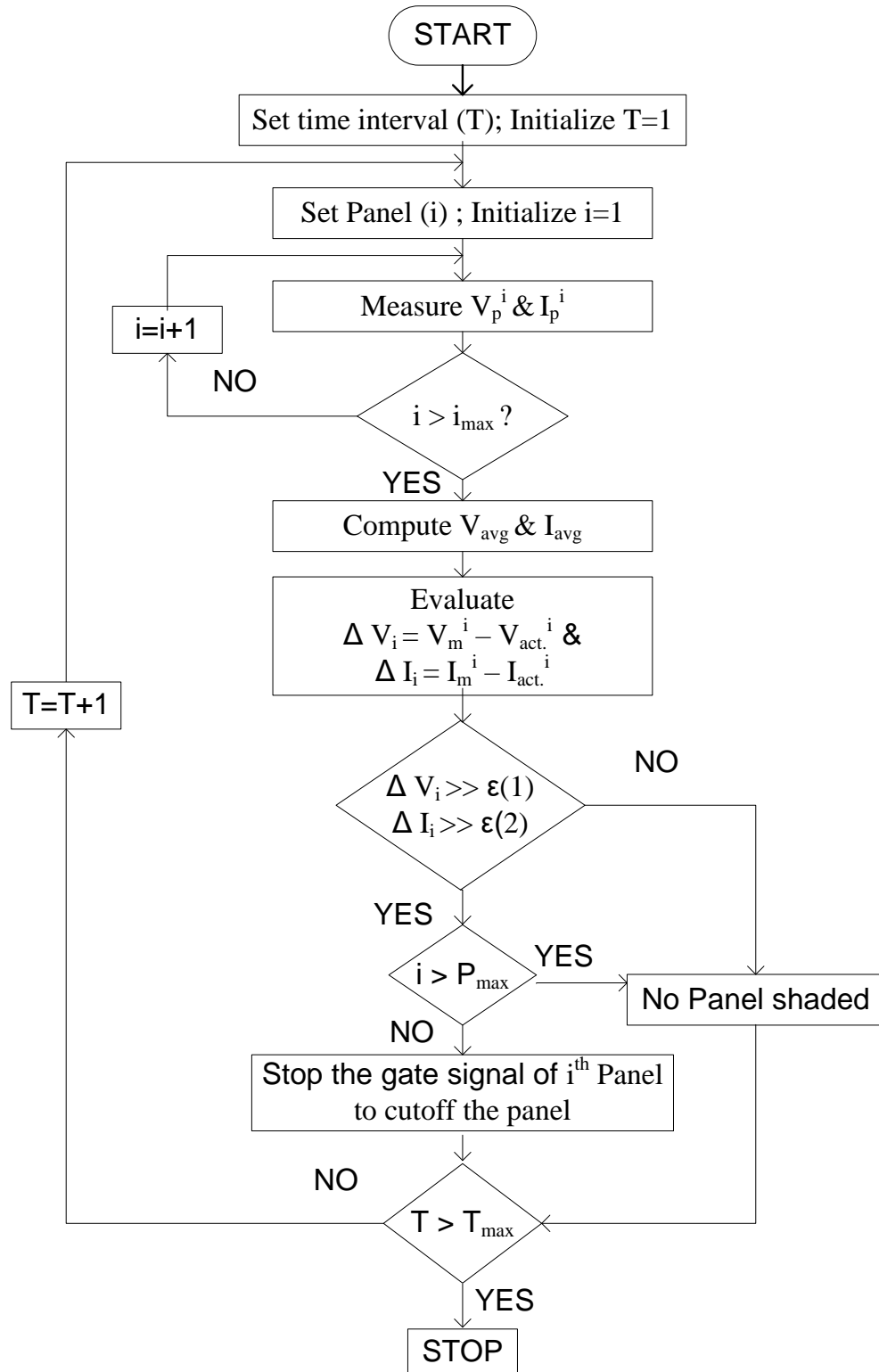


Fig.4.2 Flowchart of working of proposed HSMC

Following Figs shows the experimental setup. A total of 3×3 panels, each rated at 40 watts, are used. To create the requisite V-I and P-V characteristics, a rheostat of 100Ω/5 A is utilized as a load. Natural irradiance ranges from 650 watt/m² to 800 watt/m². The experiment uses IRFP 260 since its R_{DS(ON)} is exceptionally low, at 0.055Ω. So each MOSFET's on-state power loss is 0.266 watt, and the overall set power loss is 2.394 watt, which is quite low and thus acceptable. It can be seen from the characteristic that when four cells are shaded and a MOSFET is employed, the produced power is lower than when simply BPD has been used. However, this loss is sparse and may be overlooked if the accompanying increase in reliability is large.

All four cases were photographed in the same environment and under the same operational conditions.

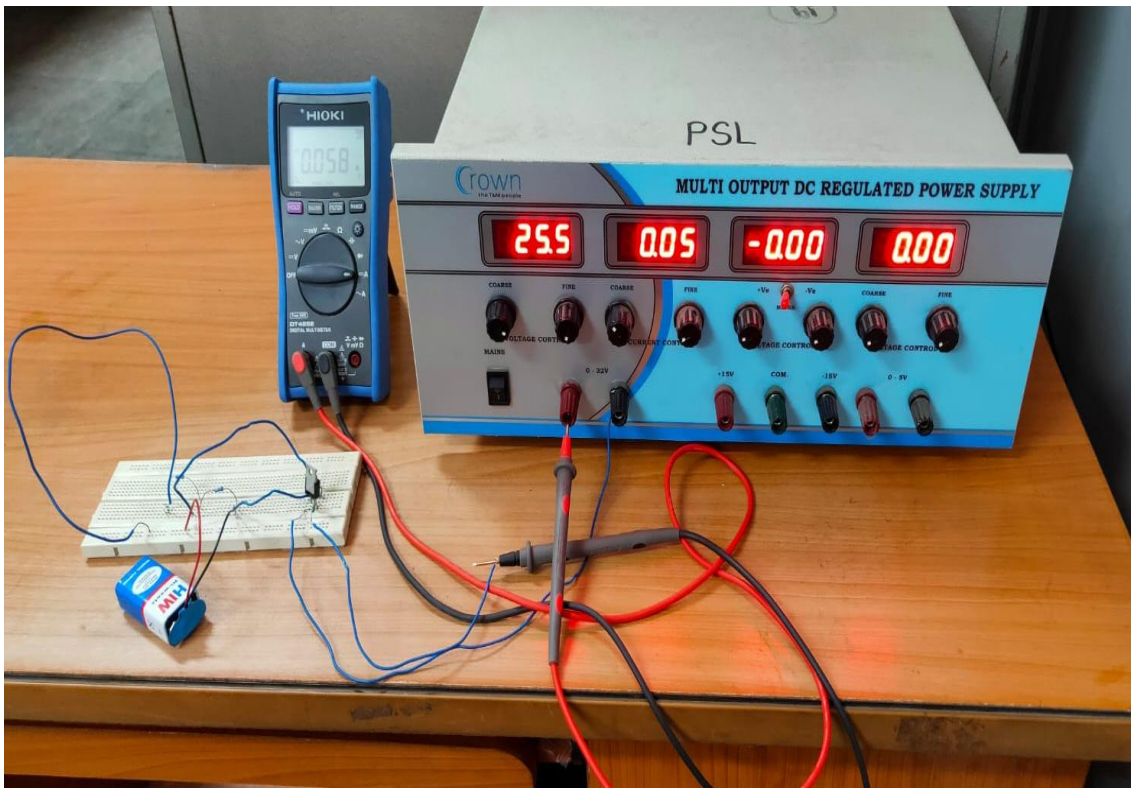


Fig 4.3: Lab testing of proposed mitigation circuit

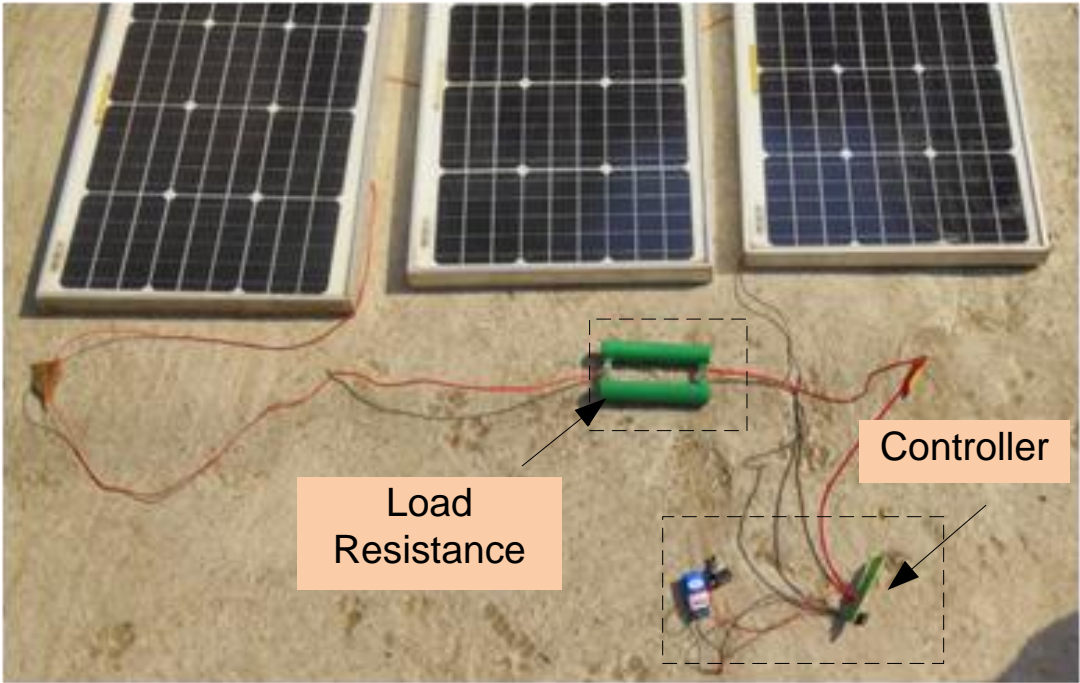


Fig 4.4: Controller testing circuit

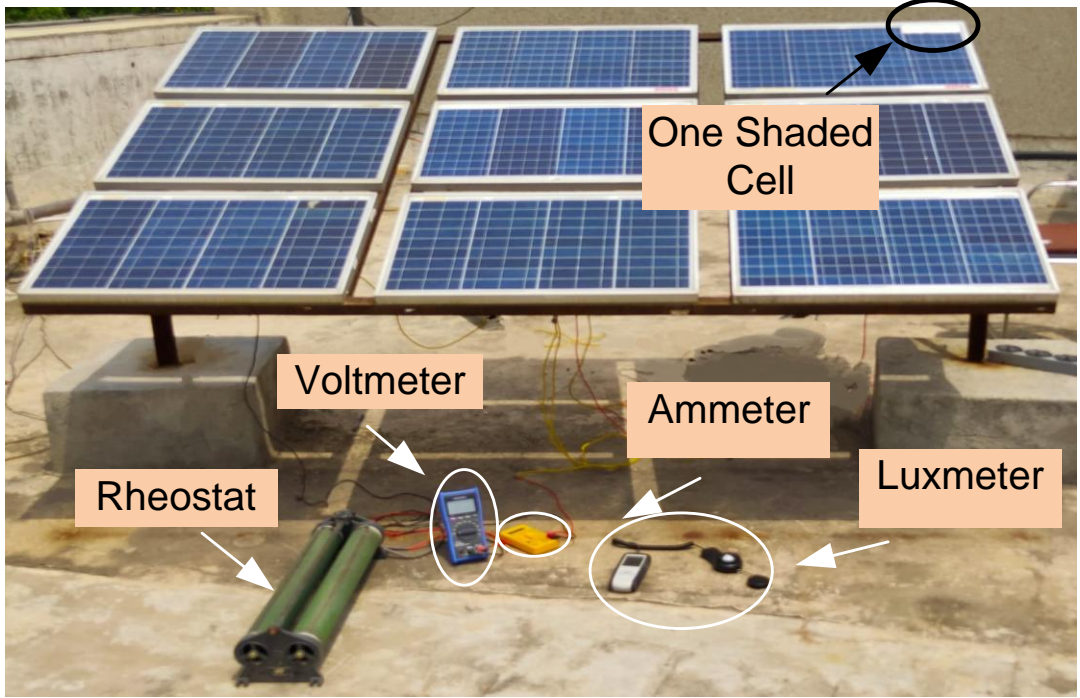


Fig 4.5: Experimental setup for one cell shading without Bypass Diode

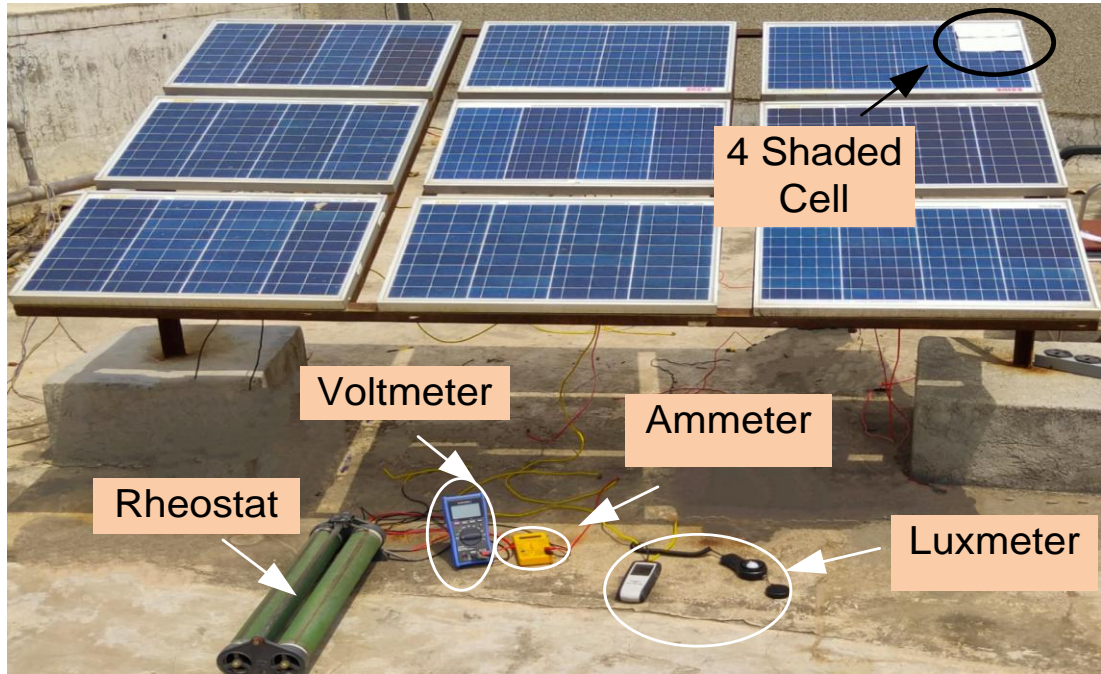


Fig 4.6: Experimental setup for four cell shading with Conventional Bypass Diode

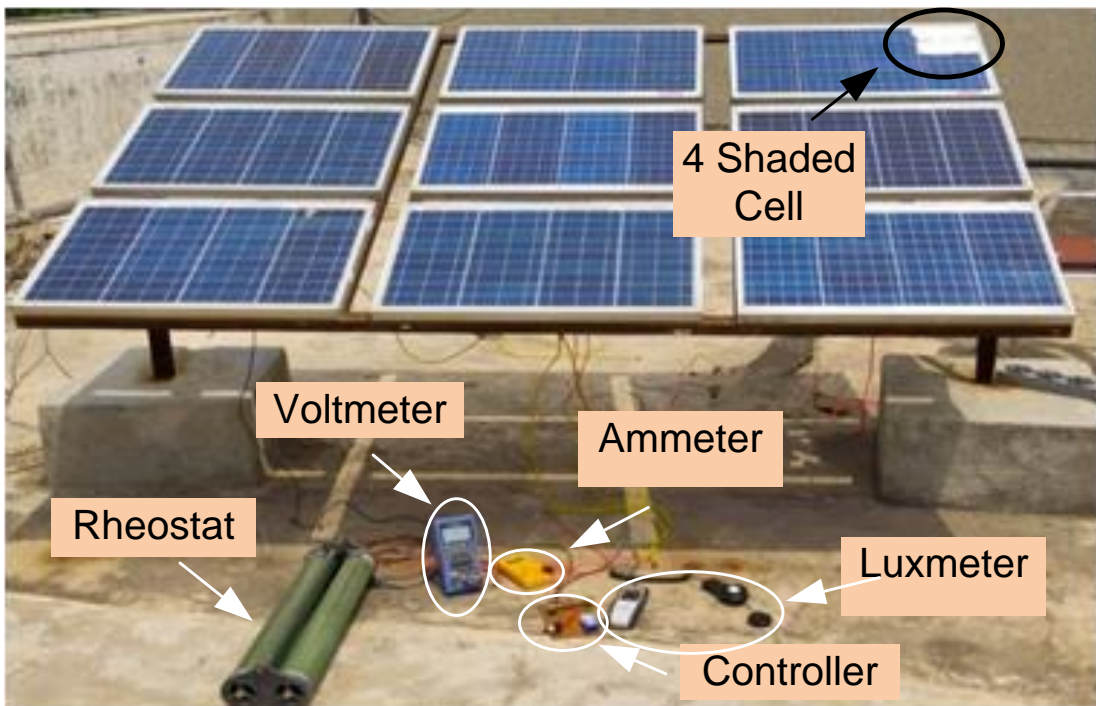


Fig 4.7: Experimental setup for four cell shading with Hotspot Mitigation circuit

4.3 Graphs

The first case is TCT with no shading, while the second case has one shaded cell. In the second scenario, it was discovered that when up to two cells are shaded, the bypass diode does not become forward biased. In the third case, four cells are shaded at the same time, and BPD gets forward biased. Four cells are shaded in the fourth case, along with the proposed mitigation circuit.

Characteristic of current-voltage are exhibit in Fig. 4.8 and Fig. 4.9 demonstrate the power-voltage characteristics obtained by altering the load from open circuit to short circuit. It can be seen from the characteristic that when four cells are shaded and a MOSFET is employed, the produced power is lower than when simply BPD has been used. However, this loss is sparse and may be overlooked if the accompanying increase in reliability is large.

As shown in the Table 4.2, there is a high chance of multiple maximum power points arising due to partial shading, which causes a problem for traditional power point tracing algorithms. Rather than reaching global maximum power, they become stuck at local maximum power.

From Table 4.2 it can be observed that due to controller the global maximum power generated is 158.7 watt and the local maximum power generated is 117.7 watt while with bypass diode the global maximum power generated is 161 watt and the local maximum power generated is 119.7 watt. The power difference between the global maximum power generated and the local maximum power generated in two cases are 2.3 watt and 2 watt respectively. The power drop due to Controller is negligible which can be ignored if the reliability is significantly improved.

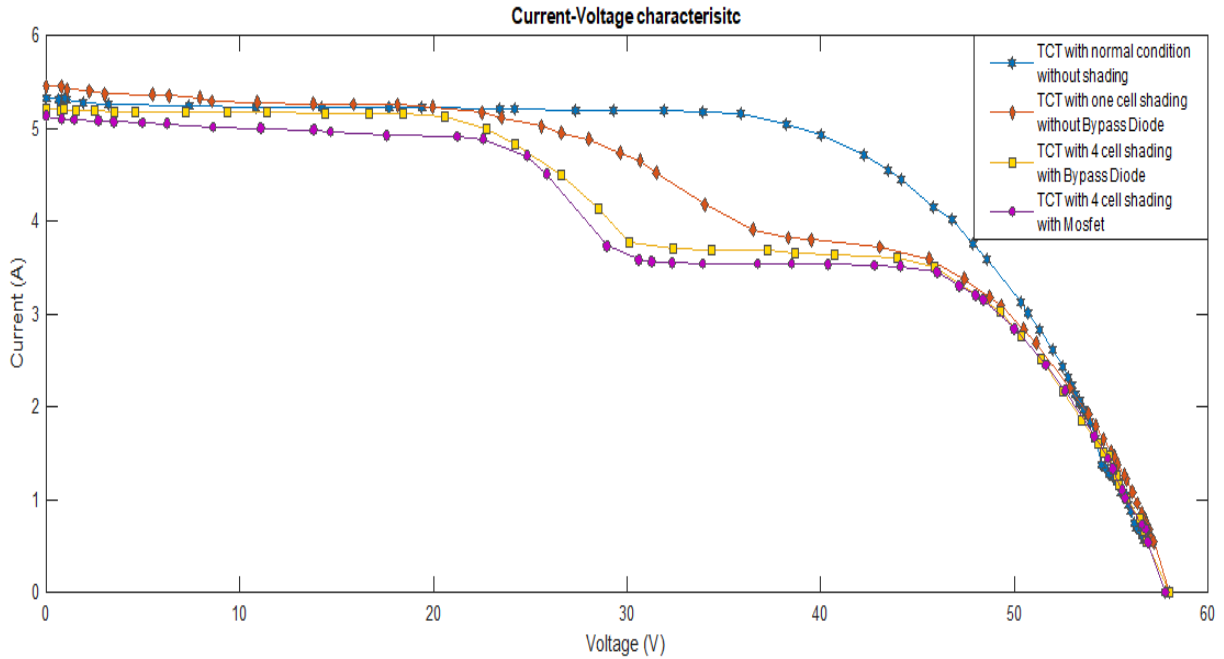


Fig 4.8: I-V Plot for Hardware implementation of TCT configuration for four different conditions for radiation 650 to 850 watt/m²

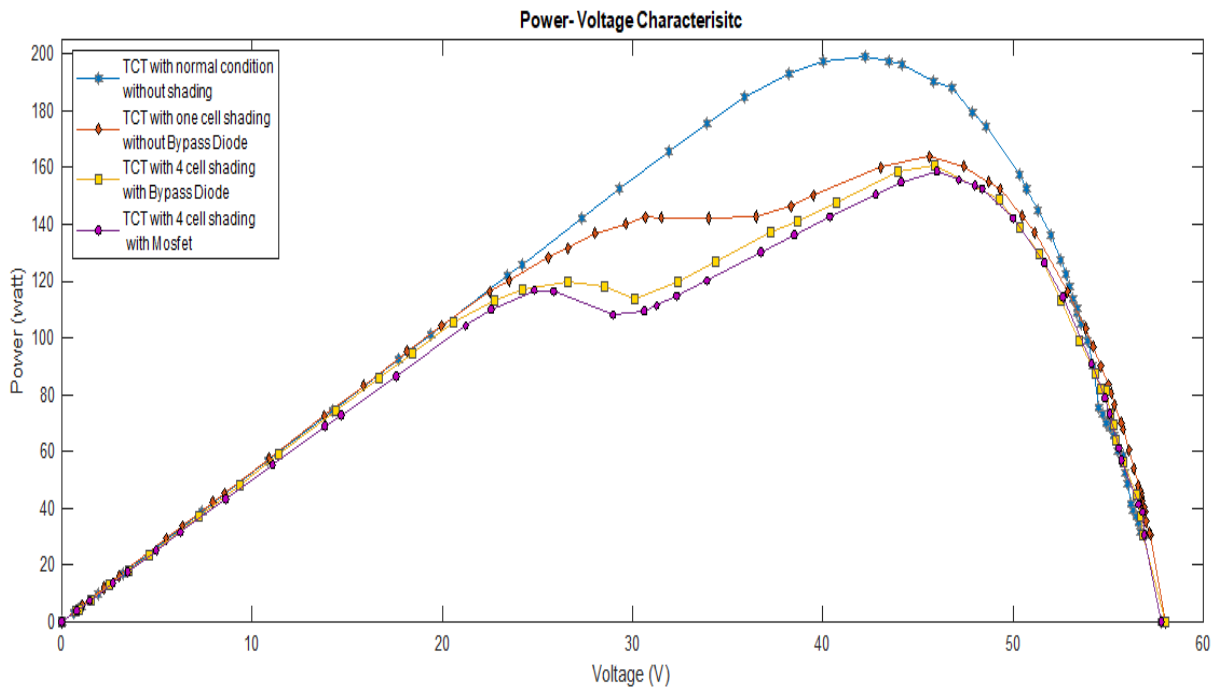


Fig 4.9: P-V plot for Hardware implementation of TCT configuration for four different conditions for radiation 650 to 850 watt/m²

Table 4.2: GMPP and LMPP during various conditions considered

Condition	GMPP			LMPP		
	Voltage (V)	Current (A)	Power (watt)	Voltage (V)	Current (A)	Power (watt)
TCT with normal condition without shading	42.22	4.71	198.9	-	-	-
TCT with one cell shading without Bypass Diode	45.62	3.59	163.8	30.67	4.65	142.6
TCT with 4 cell shading with Bypass Diode	45.86	3.51	161	26.59	4.5	119.7
TCT with 4 cell shading with MOSFET	46	3.4	158.7	28.96	4.02	117.7

4.4 Thermographic pictures

Thermographic pictures are captured for all three conditions, as shown in Fig. 4.9 to Fig. 4.11, because it is the most effective way for identifying the position of a hotspot as well as its temperature, which may be used to estimate the mismatch condition and remark on reliability improvement [42].

Fig. 4.10 shows that when only one cell is shaded for 10 minutes, the temperature of the hotspot formed rises to 85°C, while the balance of the panel remains at 52.1°C. The temperature has risen by 32.9 °C or 63.14 percent. Fig. 4.11 and Fig. 4.12 show that when the temperature of the shaded cell is 47.2°C and the panel temperature is 61.3°C, the temperature differential is 14.1°C or 23 percent of the panel temperature. The temperature of the shaded cell is reduced to 48.5 degrees Celsius using HSMC, while the remainder of the panel is 59.4 degrees Celsius, resulting in a temperature differential of 10.9 degrees Celsius, or 18.35 percent of the panel temperature. With HSMC, the temperature drops by 4.65 percent more than without it. As a result, the reliability has greatly improved. The above results are tabularized in Table 4.3.

Table 4.3: Temperature of the panel under various Conditions considered

Condition	Temperature of Non Shaded area of the panel	Temperature of the Shaded area of the panel	Temperature Difference
TCT with one cell shading without Bypass Diode	52.1°C	85°C	32.9°C
TCT with 4 cell shading with Bypass Diode	61.3°C	47.2°C	14.1°C
TCT with 4 cell shading with MOSFET	59.4°C	48.5°C	10.9°C

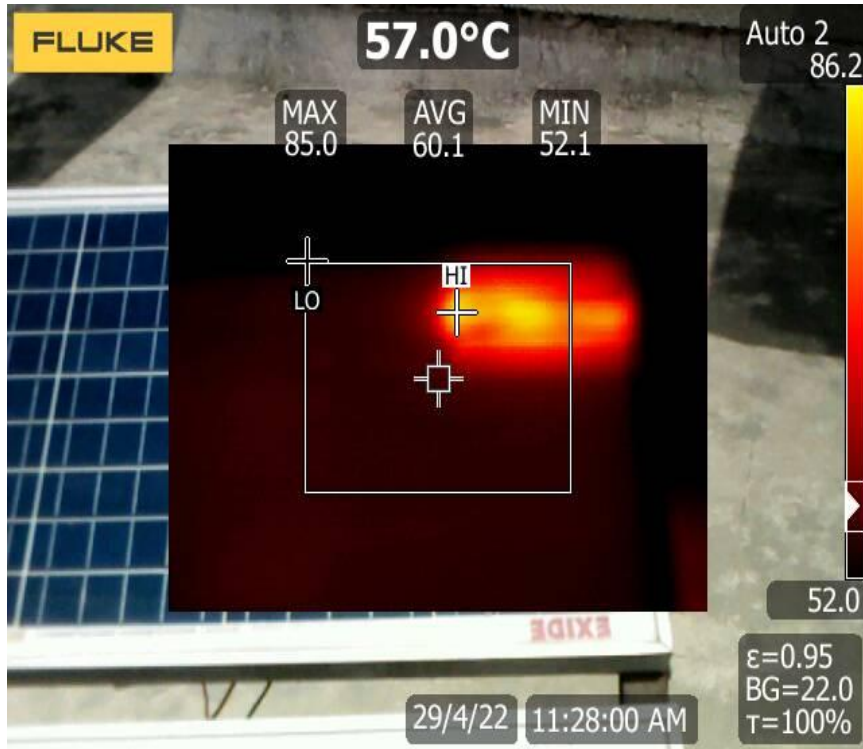


Fig 4.10: Thermal images of panel under one cell shading without Bypass Diode

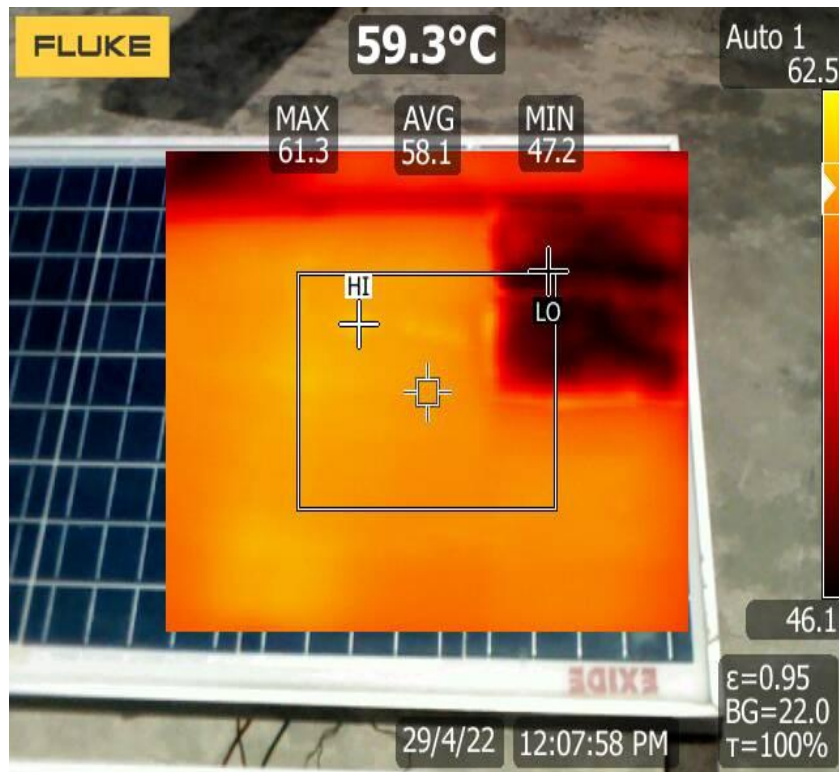


Fig 4.11: Thermal images of panel under four cell shading with Bypass Diode

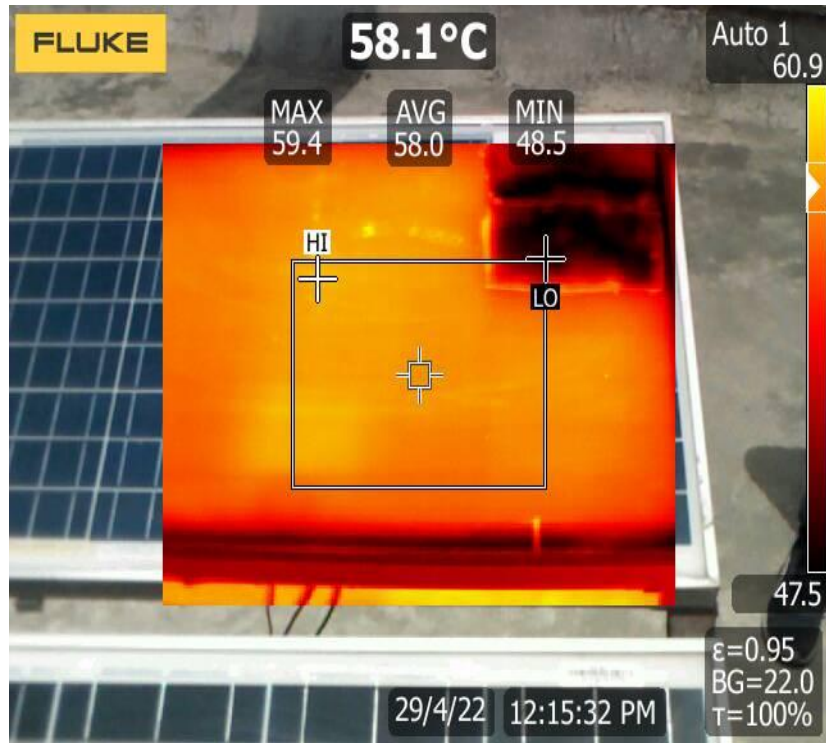


Fig 4.12: Thermal images of panel under four cell shading with MOSFET

CHAPTER 5

CONCLUSION AND OBSERVATIONS OF EXPERIMENT

5.1 SUMMARY

In this study controller is designed and tested successfully to improve the reliability of the PV panel under partial shading condition. Following actions have been performed to get the desired results.

- Firstly, advantage of the Photovoltaic system is studied the problem associated with the hotspot generation is analyzed and the level of problem it could create is understood in details
- Secondly, the hotspot mitigation circuit is proposed and designed and then tested in laboratory with regulated DC supply under all favorable and secured conditions.
- Thirdly, a MATLAB/Simulink model is simulated for different configuration under different PSCs. Then corresponding results are being investigated in chapter3 and it was observed that under full irradiance all the topologies generated same maximum power but under partial shading condition, TCT configuration generates maximum power also the effect of the partial shading is minimum on the PV panel in this configuration. Hence TCT is opted for further analysis.
- Fourthly, Hardware setup is accomplished for TCT configuration with and without controller and different observation are taken explained in detail in chapter 4. The current voltage and power voltage characteristics are plotted with the help of varying load under different conditions and then the results are tabulated for GMPP and LMPP.
- Lastly, Thermographic images are taken for analyzing the temperature of the shaded and unshaded area of the PV panels in chapter 4. It was observed that the temperature difference in the two areas is lesser in case when proposed hotspot mitigation circuit is connected compared to that when conventional BPD is connected.

5.2 OBSERVATION

A Hotspot mitigation circuit is proposed in this paper, and the temperature of the hotspot is monitored. The simulation results indicate that the TCT arrangement generates more power than the Series parallel configuration. Partial shading has a smaller effect on PV panels when linked in TCT arrangement. When one panel with HSMC is shaded, simulation results show that the global maximum power for TCT is 348.3 watt, whereas the global maximum power for Series parallel is only 335.2 watt with 1000 watt/m² irradiance. As a consequence, it can be inferred that the TCT arrangement produces the best outcomes. As a result, panels are joined in a TCT arrangement for hardware validation. For irradiance ranging from 750 watt/m² to 850 watt/m², the worldwide maximum power is 161 watt with BPD and 160.8 watt with HSMC, according to current voltage and power voltage characteristics. As a result, the power loss caused by HSMC is not large. Furthermore, the MOSFET is chosen with the lowest feasible $R_{DS(ON)}$ to minimize conduction loss. As a result, efficiency is effectively maintained. Thermal pictures show that while using HSMC, the temperature drops by 4.65% more than just using BPD alone. As a result, it can be inferred that HSMC is enhancing reliability.

5.3 FUTURE SCOPE

In this study, the hotspot mitigation circuit is proposed and implemented successfully. But this is the new topic of research area where methods are being proposed for increasing the reliability of the system so this area demand more research in terms of designing a more suitable controller or a method. Also, a new triggering circuit can be proposed which can reduce the complexity of the controller further using voltages and current of each of the panel of PV array.

List of Publications

List of SCI Journals:

- **Ashwani Srivastav**, Vinod Kumar Yadav, M. Rizwan, “Improving Reliability of PV Module through Modified Bypass Arrangement using MOSFET,” *IEEE Transactions on Device and Materials Reliability*, 2022. *Impact Factor: 1.761*. (Communicated).

List of Conferences:

- **Ashwani Srivastav**, Vinod Kumar Yadav, M. Rizwan, “Comparative Analysis of Conventional and Intelligent Methods for Speed Control of Induction Motor,” *3rd Electric Power and Renewable Energy Conference (EPREC-2022)*. (Accepted).
- **Ashwani Srivastav**, Vinod Kumar Yadav, M. Rizwan, “Comparative Analysis of Series Parallel and Bridge link Configurations Under Various Partial Shading Conditions,” *SIGMA-2022: 2nd International Conference on Signals, Machine, and Automation-2022*. (Accepted).

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