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Effect of Non-uniformity of Irradiance on the Performance of Solar PV Array

by

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A THESIS

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ABSTRACT

The growing demand of energy due to socio-economic growth and industrialization, causes a gradual increment in the use of renewable energy resources. Among the renewable energy sources, power production from solar PV system is dominating other resources due to clean, greener and easy easier production process. But the solar photovoltaic system power output is environment dependent i.e., the power output from solar photovoltaic system depends on the solar irradiance, temperature, humidity, geographic location etc. The most prominent factor that affects the power output is solar irradiance. The solar radiation received by the solar photovoltaic module surface can be affected by moving cloud, nearby building, leaf falling from tree, dust etc. In this thesis, a reference solar PV array system of 6.72 kW is simulated using MATLAB/Simulink.

The result of this study show that the performance parameters of the solar photovoltaic array are greatly impacted by the changes in irradiance level received by the solar photovoltaic module surface. Under non-uniform solar irradiance conditions, the P-V characteristics of solar photovoltaic array exhibit multiple peaks in the characteristics curve. Under defined conditions of shading, when the irradiance level is reduced by 50% from Standard Test Condition (STC), the traditional configuration i.e., series-parallel configuration, power output reduced by almost 48% compared to STC conditions. By changing the configuration type to bridge-linked and total cross-tied configuration, the photovoltaic array performance can be improved. The simulation results show that under defined shading conditions, when the irradiance level is reduced by 50% from STC, the Total cross-tied (TCT) configuration produces 4.75% and 2.21% more power output than the Series-parallel (SP) and Bridge-linked (BL) respectively. Other parameters, such as fill factor and shading loss, also improve with the TCT configuration under shading conditions. The Monte Carlo simulation for various shading scenarios shows that these shading scenarios have a similar impact on the maximum power output of PV array and found that, for the system under study, the maximum power output of 3360 watt has a maximum probability of 16% under shading conditions.

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LIST OF ABBREVIATIONS

PV	Photovoltaic
BL	Bridge-linked
TCT	Total cross-tied
STC	Standard Test Condition
SP	Series-Parallel
FF	Fill Factor
SO	Sulphur-oxide
NO	Nitrogen-Oxide
SPM	Suspended Particle Matter
CAGR	Compound Annual Growth Rate
GW	Gigawatt
IRENA	International Renewable Energy Agency
DC	Direct Current
AH	Ampere-hour
UPS	Uninterrupted Power Supply
MPP	Maximum Power Point
GMPP	Global Maximum Power Point
MPPT	Maximum Power Point Tracking
MC	Monte Carlo

CHAPTER 1: INTRODUCTION

1.1 Background

The global demand for the use of electrical energy is growing everyday due to the increase in the world population and the invention of modern technology. Electric power is required for a wide range of applications, as it becomes an integral part of daily human life. Energy resources that produce electrical energy can be broadly classified into two categories: renewable and non-renewable sources of energy. The non-renewable energy sources include petroleum, coal, natural gas, and nuclear energy. The production of electrical energy from non-renewable resources has an adverse impact on environment. The non-renewable power generation system produces a large number of sulfur-oxides (SO_x), nitrogen oxide (NO_x) and suspended particle matter (SPM), which are responsible to pollute the environment and ultimately lead to global warming (Tripathi & Murthy, 2017). Such type of pollutant materials may deteriorate human health as well as harm other living beings. The main disadvantage of non-renewable energy is that its sources may deplete, and it has an adverse impact on the environment, that look towards the use of clean and green renewable energy technology (Nehrir et al., 2011). The increasing global concern for the environment has led to a surge in interest in energy technologies, driven by agreements and commitments to reduce harmful emissions, such as carbon.

With the progress of socio-economic factors and industrial advancements, it has become increasingly crucial to explore alternative means of producing electricity. The trend of harnessing electricity from renewable energy resources is increasing rapidly. Because of direct conversion of solar energy into electricity without any moving or rotating parts, solar power generation becomes most favourable and effective technology. Because of improvement in technology, the installed cost for solar PV system dropping, and they can be installing on land, roofs as well as floating on the water. One of the major sources of renewable energy is photovoltaic solar energy; it has grown in many countries like the USA, China, India, Germany, Spain etc., in the last few years. Many Countries have been engaged in solar PV electricity and they have set ambitious targets for producing power from this green source to meet the expected demand by incorporating energy mix possibilities in the coming years. Solar PV manufacturing has increased at a compound annual growth rate (CAGR) of more than

40% during the past 15 years, making it one of the fastest industries to grow globally. Total installed capacity of solar PV in the world is 580 GW which shares about 2% of the total generation mix, with China having the largest installed capacity of 205 GW (IRENA, 2019), and India sharing about 67 GW contribution. In order to obtain high output power, it is important to study and analyse the performance of solar PV panels under certain conditions for future improvement. External varying conditions have a significant effect on the output from solar panels. Solar energy harvesting is inconsistent in nature, depending on the weather condition such as temperature, wind, cloud movement etc. External conditions cause hindrances to the path of sunlight and hence producing complex characteristics(Mäki & Valkealahti, 2012) .

Total or partial shadowing of the panel surface, temperature variations, and the amount of solar radiation are the most common external environmental parameters affecting the performance of a solar PV panel. When it comes to solar energy, the most typical issue is complete or partial shade. Since PV technology has been around for a while, the effect of partial or total shade has substantially effect on the optimal performance of solar PV panels (Li & Zheng, 2011). Along with reducing the power output of the solar PV module, partial shading also causes the module to degrade over time. Under the uniform irradiance level, the output characteristics curve exhibits a single peak but if there is partial shade, the P-V curve will have several peaks due to use of bypass diodes(Teo et al., 2018). The focus of this thesis is studying the effect of the non-uniformity of solar irradiance under certain defined shading on the performance of various configurations of solar PV array using MATLAB/Simulink. For PV modules, MATLAB/Simulink is a useful simulation program that is simple to use and capable of producing accurate and valid results. A positive outcome is anticipated since MATLAB simulation is used to design, model, test, and simulate PV modules.(Kumari et al., 2012). In this assignment, Simulink will be used to create the PV panel model initially, the model is used to develop array configurations and then studied under different partial shading conditions. Finally, the results will be formulated by analysing the output of array system under the partial shading conditions. Additionally, Monte Carlo simulation is also performed using Python programming language to check the impact of various shading scenarios on the maximum power output from solar PV array.

1.2 Problem statement

Though the solar energy has advantages of clean, green, portable, and scalable, the conversion efficiency of commercial solar panel is below 30%. Therefore, today's main concerns on solar PV technology are to increase its conversion efficiency. Since PV cells electricity production depends on the sun radiation they receive, when shading is occurs, some negative impacts are deriving on the performance. Shading on the solar panel may occurs due to the clouds' passing, dust deposited on the surface of the panel, leaf falling on it, trees, neighbouring buildings and module, poles etc.(Patel & Agarwal, 2008). Shading cause reduction in the solar radiation received by the solar module thereby reducing the energy produced by the solar panel. Under uniform-shading condition, all the cells of panel receive same amount of solar insolation and if the density of shading is high there is a substantial decrease in the power output from the solar panel (Ballal et al., 2015). While due to non-uniform shading, current mismatch phenomenon occurs thereby reducing the output of the panel as well as array and causing the hotspot problem (Tubniyom et al., 2018). PV cell technologies, such as mono-crystalline silicon (mc-Si), poly-crystalline silicon (pc-Si), and amorphous silicon (a-Si), have an impact on the performance of PV panels as well(Ye et al., 2014).

To examine the impact of insolation, temperature on the characteristics of PV module and variation of load on the available power, a MATLAB-based model proposed by (Walker, 2001). Nevertheless, shading's impact on the operating output characteristics of solar PV module does not consider by this model. An experimental study conducted by(Alonso-García et al., 2006) to determine the I-V and P-V characteristics under partial shading limited for PV module only and not consider the shading impact on the solar PV array. Therefore, it becomes prime necessity to study the I-V characteristics, P-V characteristics, and power output from solar panel as well as from the array under various shading scenario. This thesis analyses the impact of different static shading (non-uniform irradiance) condition on the performance of solar pv array of ICTC Building, Pulchok Campus using Matlab/Simulink.

1.3 Objective

1.3.1 Main Objective

The main objective is to evaluate the performance characteristics and parameter of solar PV array under static partial shading (non-uniformity of irradiance) condition using MATLAB/Simulink.

1.3.2 Specific Objective

- To evaluate the performance of existing solar array (Series-parallel connected) under non-uniformity of solar radiation under define scenario of partial shade.
- To analyse characteristics of existing system by changing the connection into BL and TCT type connection under non-uniformity of solar radiation under define scenario of partial shade.
- To carry out the comparative analysis of the performance of different solar PV array connection under non-uniformity of solar radiation under define scenario of partial shade.

1.4 Limitation

This thesis will consider the case of uniform partial shade only. The thesis will concentrate exclusively on examining how partial shade impacts the performance of solar PV arrays, and it may not address other factors that may have an influence on the solar PV systems efficiency, such as temperature effects or system aging. The thesis might be limited to certain shading patterns or scenarios, and the conclusions drawn may not be applicable to all potential shading conditions. The primary emphasis of the study will be on the electrical performance of the solar PV array, and there may be limited exploration of other aspects like mechanical stresses or the long-term durability of the array under various shading scenarios. Additionally, the thesis not include an economic analysis of the cost-effectiveness associated with implementing shading mitigation techniques. Time and resource constraints may also limit the scale and scope of the experiments or simulations conducted.

CHAPTER 2: LITERATURE REVIEW

2.1 Working principle of solar PV cell.

Based on the photovoltaic effect, a solar PV cell transforms light energy directly into electrical energy. Basically, a PV cell is a type of semiconductor device i.e., a p-n junction diode shown in Figure 2.1. Semiconducting components like silicon, germanium, etc. are doped in the PV cell to create a P-N structure that serves as an internal electric field. (PVinsights, 2020). Positive-type silicon (p-type) preferentially accepts electrons, whereas negative-type silicon (n-type) preferentially gives up electrons and gains holes. When the energy of incident light is sufficient such that it can separate the covalent electron of the semiconductor material, an electric current will be generated (Villalva et al., 2009) . When sufficient light energy strike on the junction several electrons-hole, pairs formed. The thermal equilibrium of p-n junction break by the incident photon such that free electrons can come to the n-type side and free holes to the p-type side from the depletion region (Electrical 4 U, 2020). Due to the barrier potential of the p-n junction, the newly formed free electrons and free holes cannot be able to cross the junction further. As a result, electrons become major charge carrier on n-side, hole becomes major charge carrier on p-side, and hence a voltage is set up in the junction. When a small load is, connect across the junction, a small current start to flowing through it and the output characteristic curve of cell is shown in Figure 2.2.

2.2 Solar PV array connection configuration

To acquire the desired level of power output, series, and parallel connection of a number solar PV modules are made. The series connection of PV module increases the voltage level while the value of current is increased in the parallel connection increases. There were various configuration of solar PV array. There are three different connections among them: configurations that are series-parallel, bridge-linked, and total cross-tied of 3*3 array is shown in figure 2.3. Series-parallel connection is the well-known array configuration in which modules were initially connected in a series string, and then these strings were joined in a parallel fashion. The bridge-linked design is made up of four solar modules, two of which are connected in series and two of which are

connected in parallel to form a bridge structure by cross ties (Malathy & Ramaprabha, 2015). The total crossties configuration is derived from series-parallel configuration by

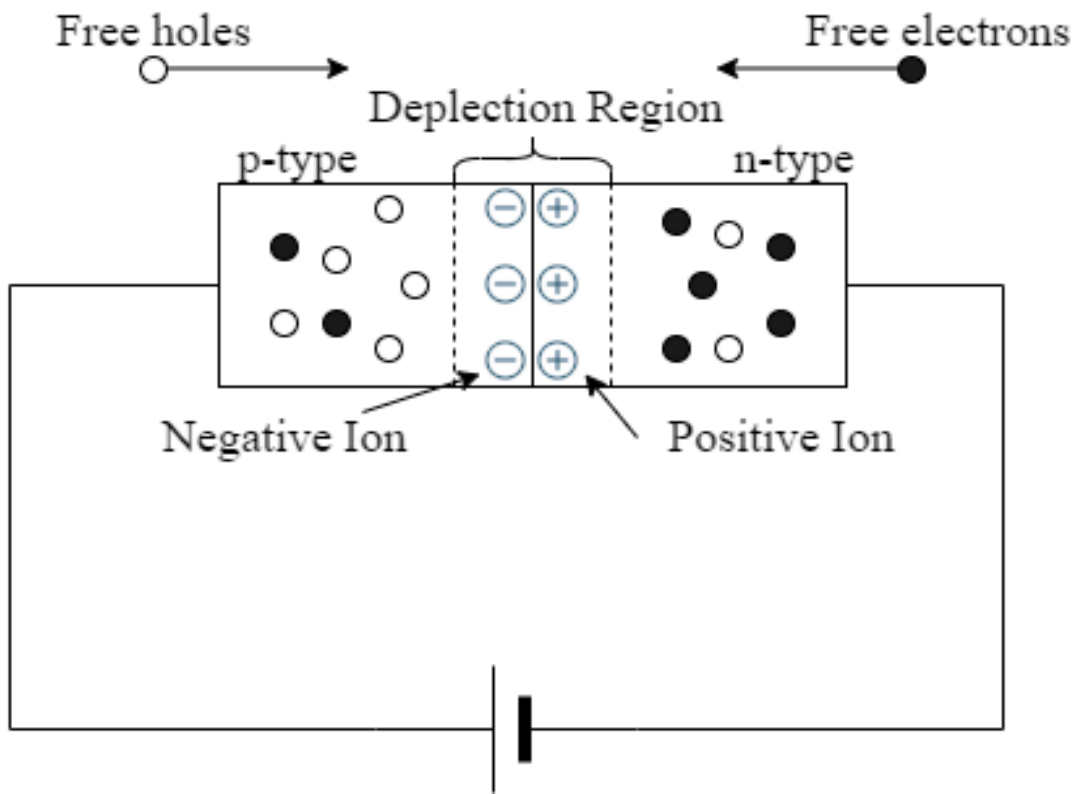


Figure 2.1: p-n junction diode

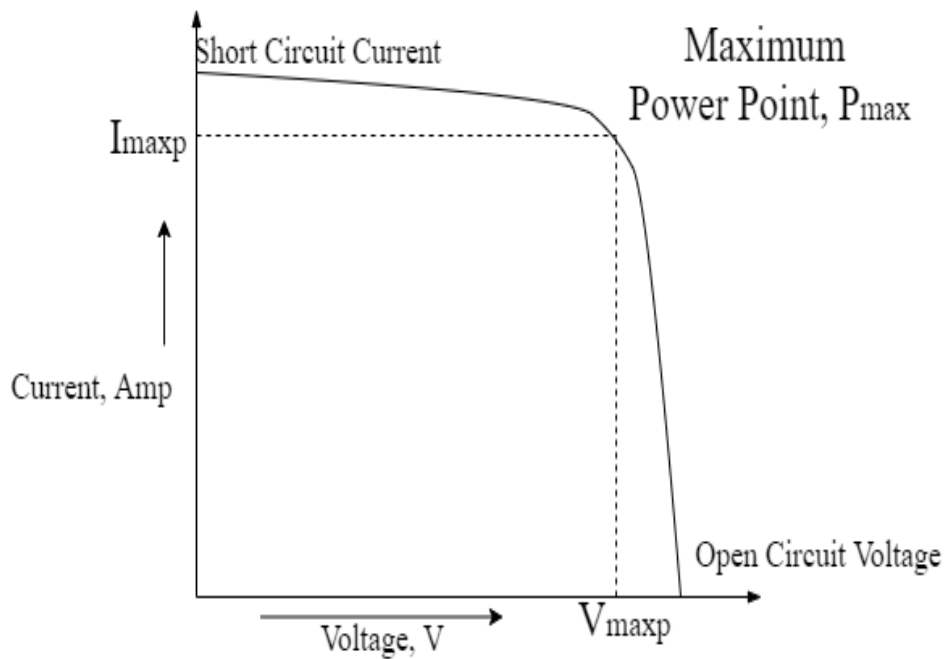


Figure 2.2: Characteristics of PV cell

providing additional cross-ties across each row (Balhachat & Larbes, 2015). Under normal condition of irradiance, all the array configuration will be same but when shading occurs the additional loop in bridge-linked and total cross-tied configuration provides alternate path for current there by maintaining the output power (Balhachat & Larbes, 2015) (Pareek & Dahiya, 2016) (Bana & Saini, 2017).

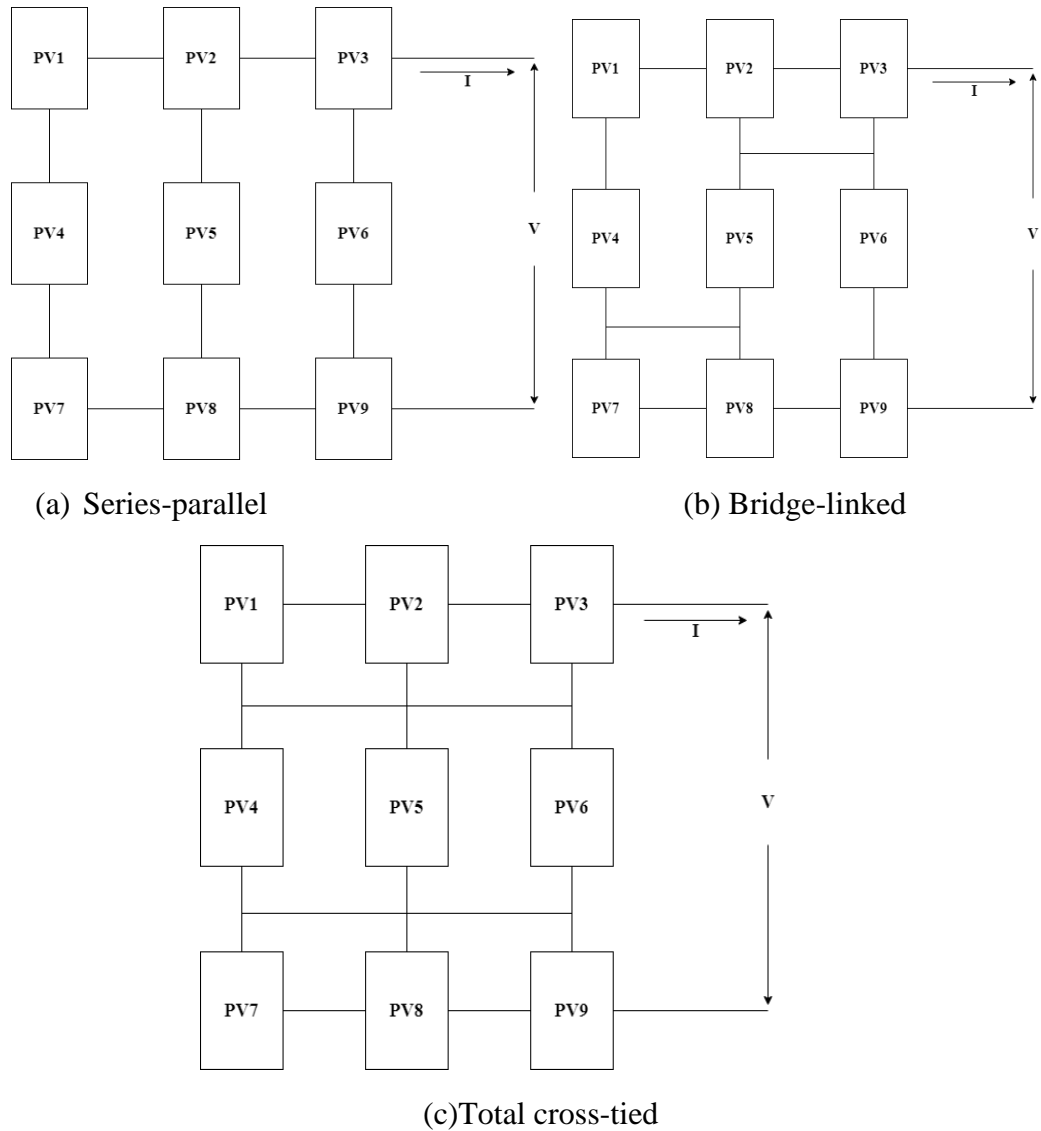


Figure 2.3: Solar PV array connection configuration

2.3 Shading and its effect

The system architecture, array arrangement, shading pattern, solar irradiation, temperature, and perhaps aging-induced deterioration effect all influence solar PV system output power and performance characteristics (Manganiello et al., 2015). Among all these parameters change in temperature and solar irradiance are the most

affecting variables for reduction in output power. Shading may be of two types: uniform shade and irregular/partial shade depending upon the shading objects. Under uniform shading, all the solar cell/modules receive the same amount of solar irradiance and there is single maximum power point in the I-V and P-V characteristics (Pendem & Mikkili, 2018). when solar radiation reaches a solar PV panel uniformly, the P-V characteristics of PV module exhibits a single peak called global peak, which represents the maximum power from the PV module (Bouselham et al., 2017). Non-uniform shading may occur due to buildings, trees, leaf's, passing clouds, utility and telephone poles and wires etc. due to which the solar cells/modules receive unequal irradiance and dissimilar cell temperature. (Pendem & Mikkili, 2018). The solar PV panel's partial shadowing is a severe problem because : i) the power loss within each shaded cell would have resulted in local heating, raising the temperature of the cell and the entire module on the thermal stress, creating a hotspot that could lead to failure of the entire PV panel, ii) in extreme circumstances of shade, the solar cells' the reverse bias voltage may surpass its breakdown voltage, resulting in cracks and a short circuit at the serial branch to which the cell is connected (Madessa, 2015) (Tripathi & Murthy, 2017). Due to the usage of bypass diodes, there are several maxima on the P-V characteristic of PV modules when partial shade occurs. The greatest peak is the global peak, which reflects the module's maximum power output, while the others are the local peaks (Chaieb & Sakly, 2018).

Two types of partial shading occur in the PV module: dynamic and static shading. In dynamic shading, shadow move over the PV module such as cloud moving and in static shading the shadow stays on the module for a time (Ahmed & Salam, 2015). Shadow lowers the overall power output in two different ways: by rising energy loss and lowering energy input to the module,. In a 36 serial solar cells PV module, complete shading of a cell can reduce the power output by 32.5% (Mamun & Selvaraj, 2017) . The experimental results of (Bana & Saini, 2017) showed that there is more than 60 % reduction in energy generation when the array 50% uniformly shaded. The study of (Bingol & Ozkaya, 2018) illustrate that the maximum power output from total cross-tied array configuration under non-uniformity of irradiance is higher as compared to another configuration as this configuration has lowest mismatch factor and fill factor. MATLAB model for calculating the maximum power of series and series-parallel configuration developed by (Patel & Agrawal, 2008) showed that there exists non-linear I-V and P-V characteristics of array under partial shading condition. The bypass diode

connected across selected cell/module helps in overcoming the problem of hotspot. Use of a bypass diode under a partial shading state permits the current from an unshaded module to flow into the diode's short circuit, but it also results in many peaks on the characteristics curve (El-Khozondar et al., 2015).

2.4 Performance parameters

Maximum power, fill factor (FF), and mismatch power loss are three metrics that may be used to assess the performance of a solar PV array arrangement ((Bingol & Ozkaya, 2018) (Maharana et al., 2020) .

Maximum Power:

The most important indicator is the maximum amount of power that the PV array can produce under a given specific condition of irradiance and temperature. Generally, the peak point of the P-V characteristics curve represents the maximum power extraction point from the array.

Fill Factor:

It is the ration of actual maximum power that can be generated to the product of short circuit current (I_{sc}) and open circuit voltage (V_{oc}).

$$FF = \frac{P_{mpp}}{I_{sc} * V_{oc}}$$

Where, P_{mpp} = maximum extractable power

I_{sc} = Short circuit current

V_{oc} = open circuit voltage

The performance of the solar PV array is said to be better, if fill factor is close to unity.

Mismatch power loss:

It is the difference between the PV array's maximum power under STC and the array maximum power during mismatch/shading conditions.

$$SL = P_{m,STC} - P_{m,mismatch}$$

Here, $P_{m,STC}$ represents maximum power available from array under standard test condition and $P_{m,mismatch}$ represents amount of available maximum power of module under shading condition.

2.5 Monte Carlo Simulation

Monte Carlo (MC) simulation is a kind of computing used to forecast the results of complicated systems or processes using statistical and random sampling. It draws its name from the Monte Carlo Casino in Monaco because of the element of chance involved in the method. Computer systems employ this technology to analyse previous data and anticipate a range of future outcomes based on a choice of action. There are several possible outcomes, and their associated probability are shown by the Monte Carlo simulation from many random data samples. In contrast to a deterministic forecast, it provides a clearer picture. The findings are computed using statistical analysis and repeated random sampling. In MC simulation, each input parameter can be sourced from a statistical distribution, which depicts the input variables' values. For each set of input parameters, a set of parameters for the output is obtained. The results of several simulation runs are gathered, the values of the output parameters are statistically analysed, and the output variations are eventually described using the output parameter sampling statistics. In general, the actions listed below are carried out for the MC simulation of a physical process: creation of static models, identification of input distributions, production of random variables, analysis, and decision-making (Institute of Electrical and Electronics Engineers., 2008). MC simulation can be used in various fields such as engineering, online gaming, business, and finance. There are various options to perform MC simulation in computer such as higher levels programming languages like C++, Python, Java, .NET programming languages introduced by Microsoft® and the standalone software packages.

2.6 Software and Tools

Software and tools that are used for the implementation of this thesis are MATLAB/Simulink and Python (Programming Language) which are described below:

2.6.1 MATLAB/Simulink

The exclusive programming language and multi-paradigm numerical computer environment developed by the MathWorks corporation known as MATLAB. Users can visualize functions and data, manipulate matrices, create user interfaces, implement algorithms, and connect to other programming languages using MATLAB. Simulink is integrated with MATLAB, a model-based design and simulation platform for integrated

and interactive systems. A block diagram platform for multi-domain simulation and model-based design is called Simulink in the MATLAB programming language. Simulink is a tool for modelling, simulating, and analysing multi-domain dynamic systems in a data flow graphical programming language. It is a graphic module-diagramming tool featuring several programmable block libraries (MathWorks, 2020). Math and computation, modelling, simulation, data analysis, scientific and engineering graphics, developing prototypes, algorithmic development, exploration, and visualization, as well as application development, including the creation of Graphical User Interfaces (GUIs), are all typical areas in which MATLAB is utilized.

2.6.2 Python (Programming Language)

Python is a powerful, dynamically typed, high-level programming language renowned for its clarity and readability. Because it uses effective high-level data structures, it provides a straightforward and efficient solution to object-oriented programming. Its graceful syntax, dynamic typing, and interpreted nature makes it ideal for fast development of applications across a wide range of areas and scripts. Python has a sizable standard library that covers a variety of typical programming tasks as well as an integrated development and learning environment (IDE)(Hetland, 2008). In this thesis study, it is used for the MC simulation to stud the effect of random shading scenarios in the power output of solar PV array.

CHAPTER 3: METHODOLOGY

The basic flow chart for the methods adopted is shown in Figure 1.

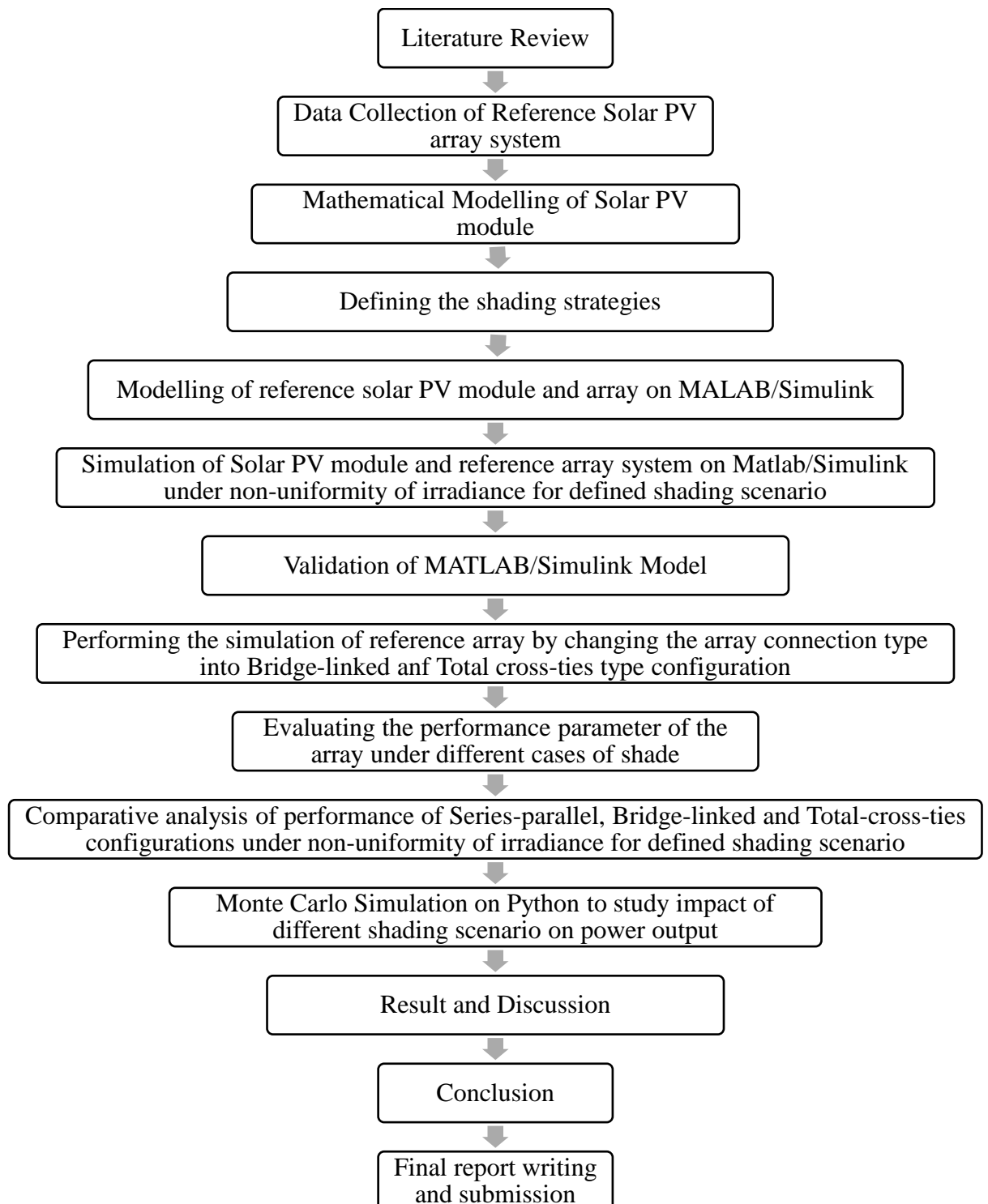


Figure 3.1: Flow chart of methodology

3.1 Data collection of reference solar PV array

For the study, the solar PV array installed at ICTC building, Pulchowk Campus taken as a reference system. The array is made up of three strings, each with eight 280 W_p, 24 V solar modules connected in series. The detailed parameters of the module under STC and details of solar PV array were taken from ICTC building administrations & presented in the Table 3.1 and Table 3.2.

Table 3.1:Parameter of PV module (280P-24)

Parameters	Value
Maximum power point (P _m), W	280
Voltage at maximum power (V _{mp}), V	36.3
Current at maximum power (I _{mp}), A	7.72
Open circuit voltage (V _{oc}), V	44.3
Short circuit current (I _{sc}), A	8.36
Total numbers of cell in series (N _s)	72
Short circuit current temperature coefficient (K _i)	0.06%/°C
Module efficiency	14.39%
Power tolerance	+/- 3%
Module Area	46.3 m ²

Table 3.2: Details of PV array system

Solar Array	3 nos. of string 8 nos. of 280W LDK panel
PV combiner box	1 no. of box with 3 nos. of 16A DC breaker
Solar Charge Controller	1 no. of 240 V
Battery Bank	20 nos. 12V/200AH: all in series to form 240V bank (EXIDE)
Online UPS (KI Power:C15KS)	1 no. of 176-300V/ 10 kW _{ac}

3.2 Mathematical modelling of solar PV cell/module

In many research various models such as R_p-model, R_s-model and two-diode model have been used by the researcher for the investigation of the characteristics of solar

cell/module. In this thesis R_p -model known as single diode model is used because of its wide application areas and simpler to illustrate. Figure 1 shows the R_p -model's equivalent circuit, which comprises of a single diode paired in parallel with a linear current source known as photocurrent, a parallel resistance expressing leakage resistance, and a series resistance expressing solar cell internal resistance (Institute of Electrical and Electronics Engineers et al., n.d.) .

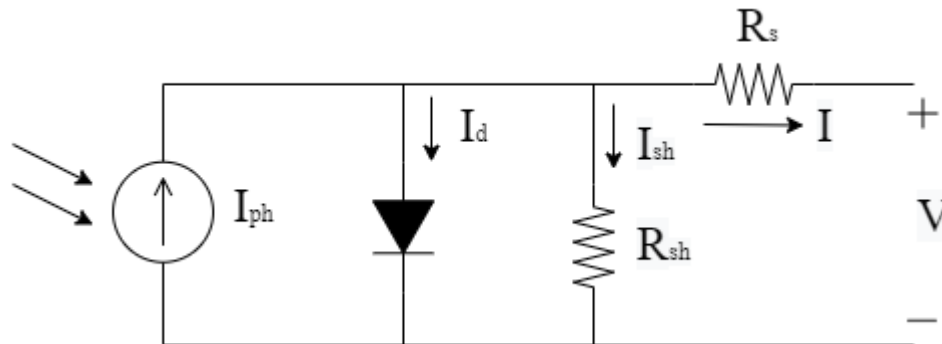


Figure 3.2: Equivalent Circuit of one-diode model solar cell

The characteristics equation that describes the equivalent circuit of a solar cell describe in the following equation (Institute of Electrical and Electronics Engineers et al., n.d.) (Krismadinataa & Selvaraja, 2013) (Zainal & Yusoff, 2016).

The relationship between output current, I and voltage, V can be described by the following equation:

$$I = I_{ph} - I_d - I_{sh}$$

$$I = I_{ph} - I_s \left\{ e^{\frac{q(V + R_s I)}{nKT}} - 1 \right\} - I_{sh} \dots \dots \dots (1)$$

Where, I_{ph} = Photocurrent (A)

$$I_d = I_s \left\{ e^{\frac{q(V + R_s I)}{nKT}} - 1 \right\}, \text{ called diode current}$$

I_s = Diode saturation current (A)

I_{sh} = Current through shunt resistor (A)

q = Electronic charge (1.6021×10^{-23} C)

R_s = Series resistance (Ω)

n = Diode ideality factor which varies in range between 1-2 for silicon cell

K = Boltzmann constant ($1.38 * 10^{-23}$ J/K)

T = Solar Cell working temperature (K)

The photocurrent, I_{ph} from solar cell depends mainly on the solar radiation/irradiance and cells working temperature as:

$$I_{ph} = [I_{sc} + K_i (T - T_{ref})] \frac{G}{1000} \dots\dots\dots (2)$$

Where, I_{sc} = Short circuit current of solar cell (A)

K_i = Solar cell's short circuit current temperature coefficient

T_{ref} = Reference temperature at STC = 25 °C

G = Irradiance on the surface of solar cell W/m²

The diode saturation current, I_s varies with cell temperature as described by following equation:

$$I_s = I_{rs} \left(\frac{T}{T_{ref}} \right)^3 e^{\left\{ \frac{qE_g}{nK} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right\}} \dots\dots\dots (3)$$

Where, E_g = Band gap energy of semiconductor

$$= 1.16 - \left(\frac{T^2}{T-1108} \right) * 7.02 * 10^{-4} \dots\dots\dots (4)$$

I_{rs} = Reverse saturation current

$$= \frac{I_{sc}}{e^{\left(\frac{V_{oc}}{nV_t} \right) - 1}} \dots\dots\dots (5)$$

Where V_{oc} = Open circuit voltage of cell at STC

V_t = Thermal voltage

$$= \frac{KT}{q} \dots\dots\dots (6)$$

The current through shunt resistor is given as:

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \dots\dots\dots (7)$$

There have been various methods proposed by the researchers to determine the value of shunt and series resistor. Among them the simpler method described by (Tian et al., 2012) is applied in this thesis as

$$R_{sh} > 10 \frac{V_{oc}}{I_{sc}} \dots\dots\dots (8)$$

$$R_s < 0.1 \frac{V_{oc}}{I_{sc}} \dots\dots\dots (9)$$

Since the output from a cell is small i.e., typically less than 2 W at 0.5 V output voltage (Tsai, 2010). To get a sufficient amount of power and voltage at the output, numerous solar cells are connected in series and parallel to form a solar PV module. As a result, the equivalent circuit of a solar PV module with N_s number of series cells and N_p number of parallel cells is shown in figure 1. Moreover, the relation between the output current and voltage become as follows (Bingol & Ozkaya, 2018):

$$I = N_p I_{ph} - N_p I_s \left\{ e^{\frac{q}{nKT} \left(\frac{V}{N_s} - \frac{IR_s}{N_p} \right)} - 1 \right\} - \frac{N_p V + IR_s}{R_{sh}} \dots\dots\dots (10)$$

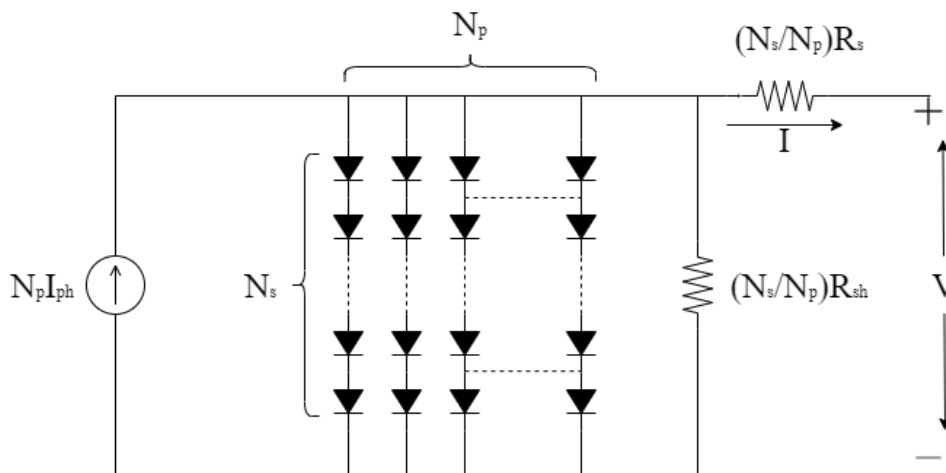
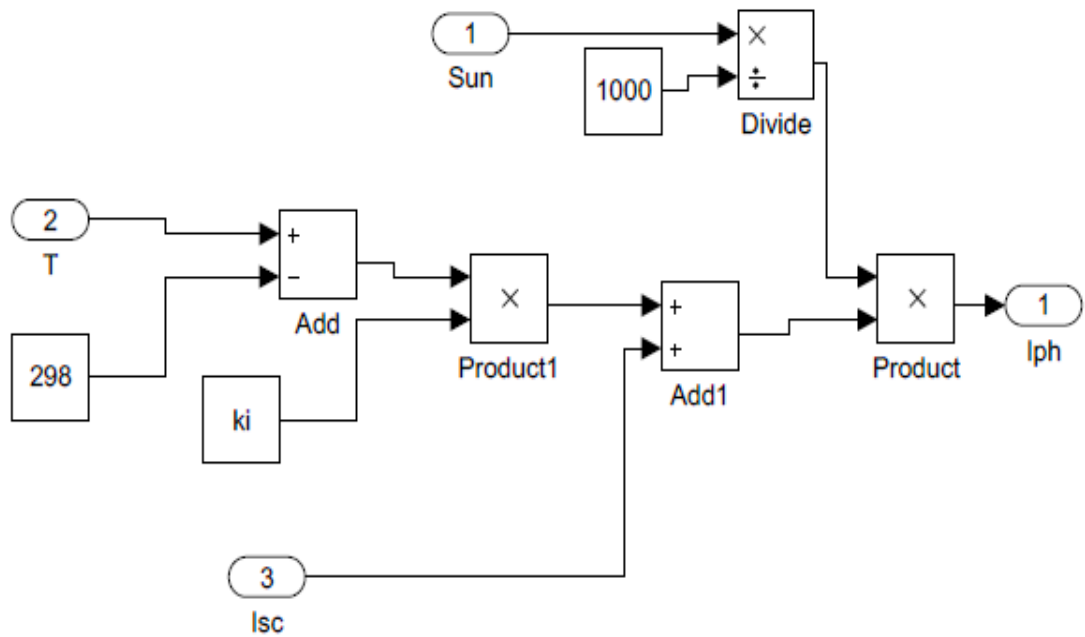


Figure 3.3: Equivalent circuit of solar PV module

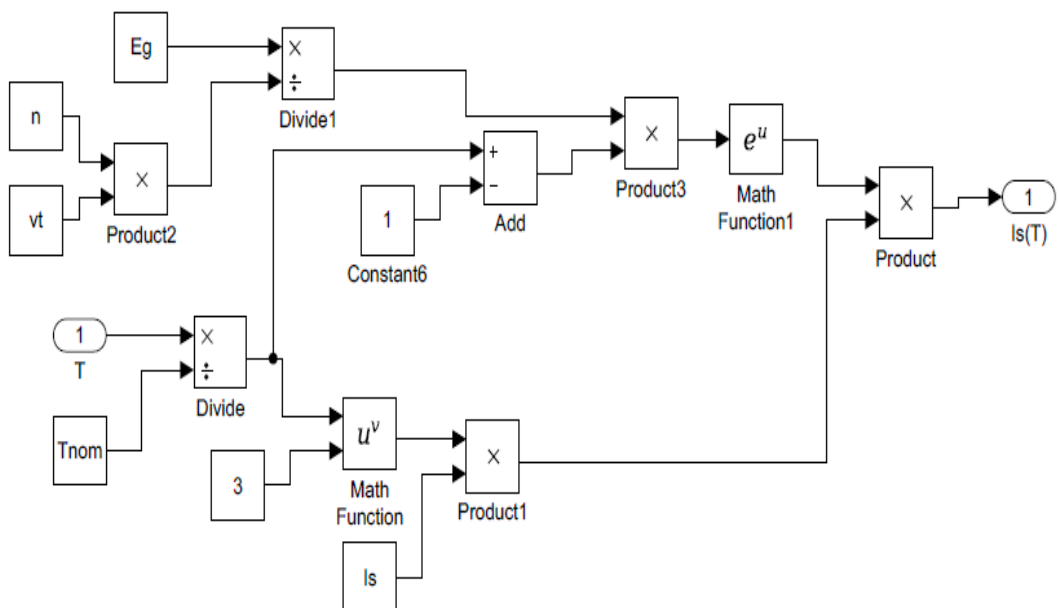
3.3 Modelling of reference solar array system on MATLAB/Simulink

MATLAB/Simulink provides a platform for conducting the simulation to measure output from solar panel and plotting the P-V and I-V characteristics curve. Using equation (1) to (10), firstly a solar PV module formed on the Simulink. Since, array is the series and parallel connection of solar PV module, the reference solar PV array

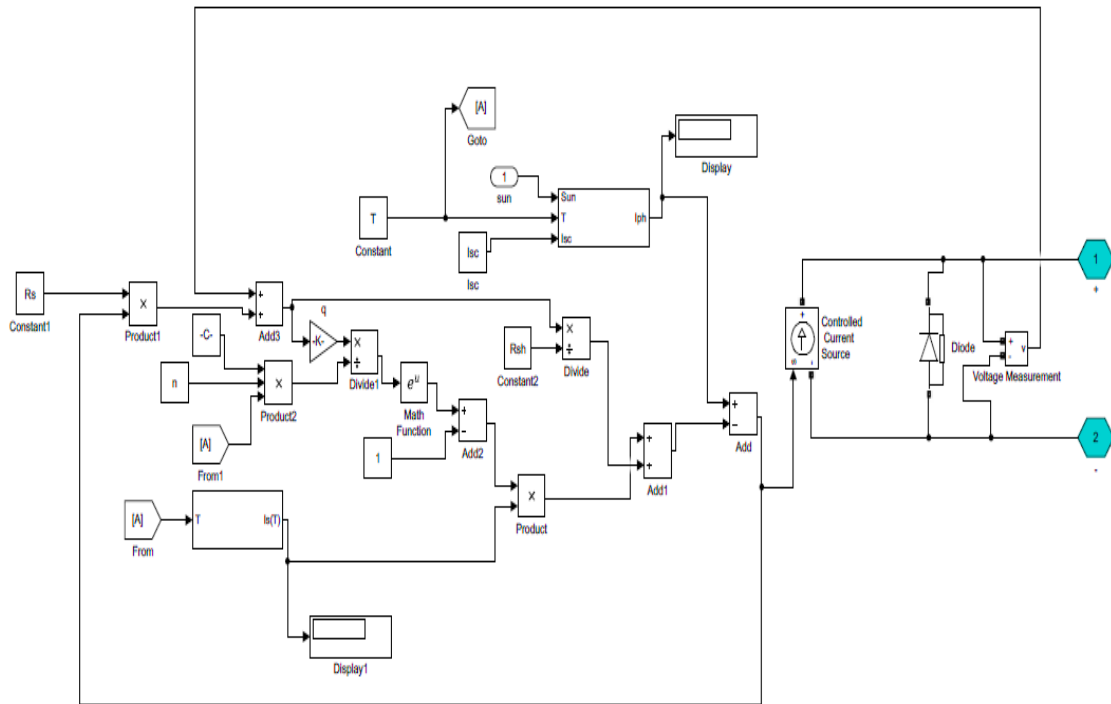
(3*8) system is used for simulation. The solar PV module block received the irradiance, open circuit voltage, and short circuit current as input signals. Different shading tactics can be developed by adjusting the solar module's irradiation value. By altering the signal's strength in the signal building block attached to each set, solar cells/solar panels in the simulation is subjected to various shading strategies.



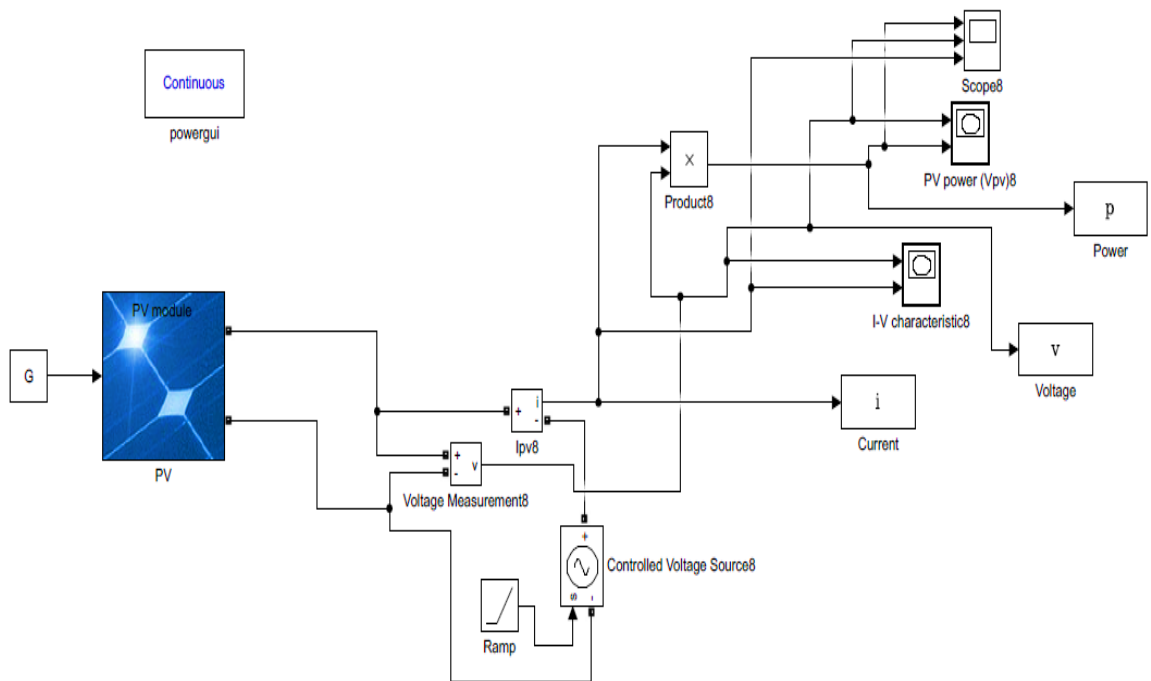
a) Modelling of Photo-current



b) Modelling of diode saturation current



c) Modelling of output current from solar PV module



d) Final model of solar PV module

Figure 3.4: Modelling of solar PV module

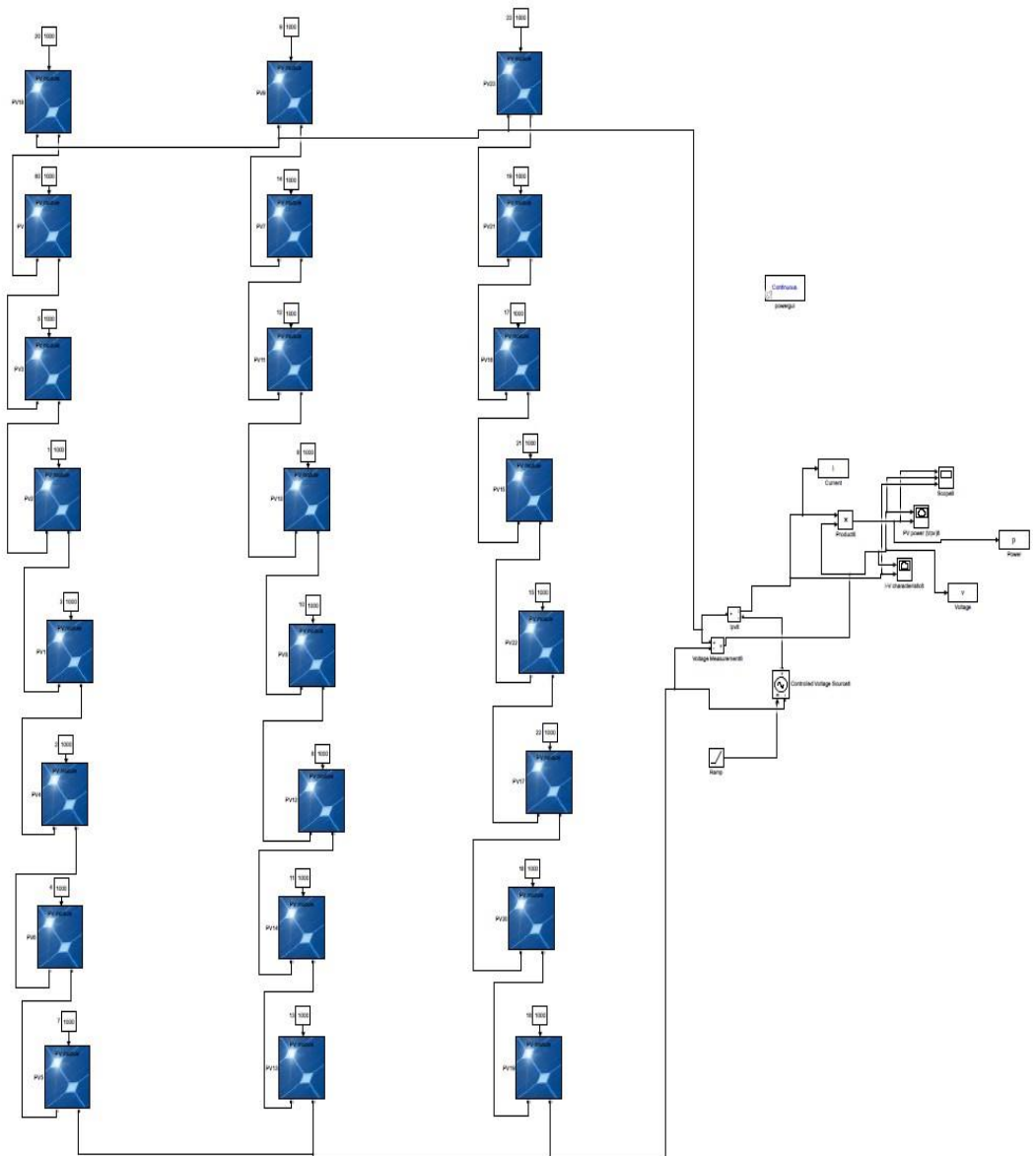


Figure 3.5: Model of reference solar PV array on MATLAB/Simulink

3.4 Shading strategy

To analyse the performance of reference system of 3* 8 solar PV array configuration, different shading cases where irradiance level of twelve module array changing from 10% to 90 % of were defined as shown in Figure 3.6. The irradiation values used in simulation for study are: 1000 W/m² , 900 W/m² , 800 W/m² ,700 W/m² , 600 W/m² , 500 W/m² , 400 W/m² , 300 W/m² , 200 W/m² and 100 W/m². For each condition of shading, the I-V and P-V characteristics curves are obtained by keeping temperature constant at 25 °C.

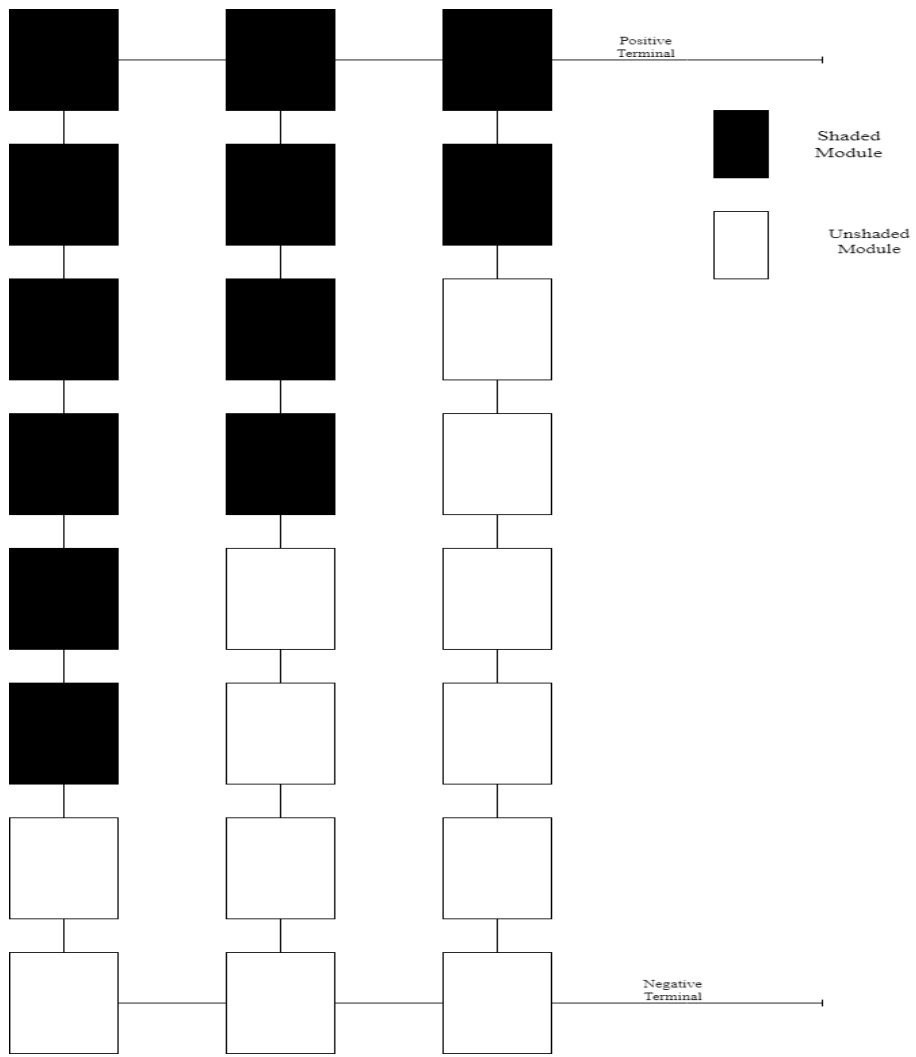


Figure 3.6: Shading pattern on solar PV array

CHAPTER 4: SIMULATION AND VALIDATION

4.1 Simulation of Simulink solar PV module and reference PV array

The input variables of the solar PV module given through the MATLAB m-code as well as the characteristics curves plotted using MATLAB m-code. The simulation is carried out by using MATLAB/Simulink at constant temperature (25°C) and varying the irradiance (1000 W/m², 900 W/m², 800 W/m², 700 W/m², 600 W/m², 500 W/m², 400 W/m², 300 W/m², 200 W/m² and 100 W/m²) under above defined shading scenario. The simulation output under various irradiance level for the PV module validated through the experiment and the simulation for the array is carried out later. After module validated through experiment, the Simulink module used to study the different cases of the reference array under defined shading scenario with varying irradiance level.

4.2 Validation of solar PV module

To validate whether the Simulink module will provide accurate result or not, an experiment carried out on a SW020P model, 20 W_p polycrystalline PV module. A PV module, variable resistor, pyranometer and multimeters are taken for the experiment. A 10 Ω variable resistor is connected across the PV module and the power output from PV module measured by changing irradiance level and the photograph of experiment setup is annexed. The simulated result and the experimental result i.e., power output compared under similar condition of experiment and the result tabulated in Table 4.1.

Table 4.1: Comparative result of Module validation

S.N.	Irradiance (W/m ²)	Experimental Output (W)	Simulation Output (W)	Variation
1	780	9.56	10.09	0.53
2	740	7.03	7.63	0.60
3	540	4.63	4.99	0.36
4	320	2.31	2.1	0.21
5	120	0.21	0.23	0.02

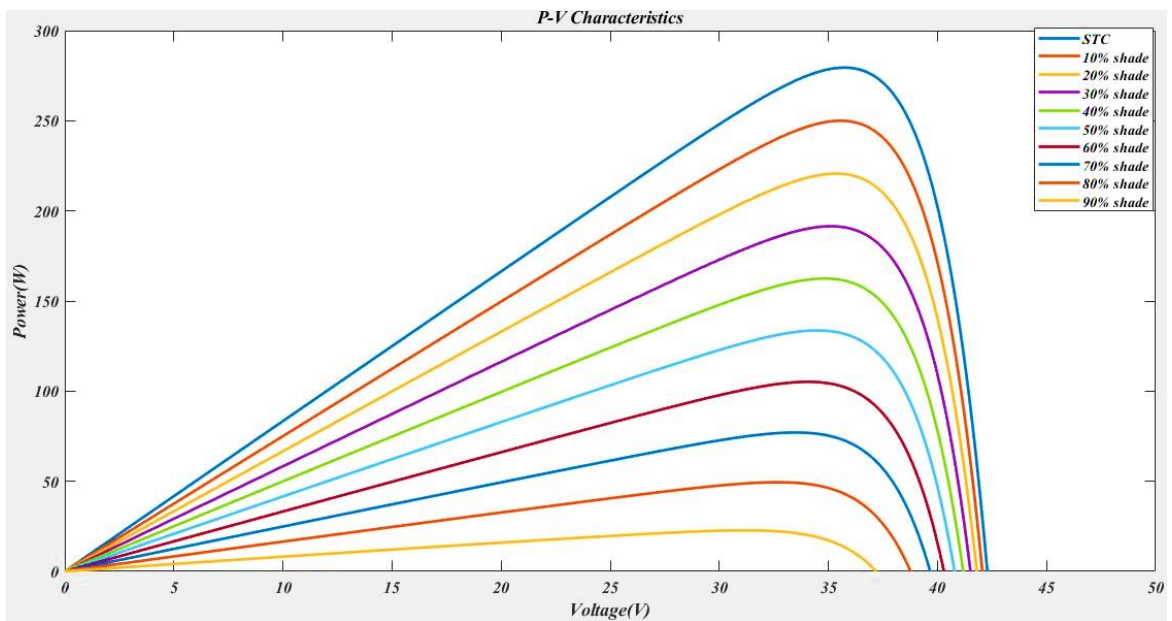
It has been found that, there is slight difference between the experimental and simulation result which might occur due to instrumental error. This indicates that, the Simulink module can be used for the further study on the array.



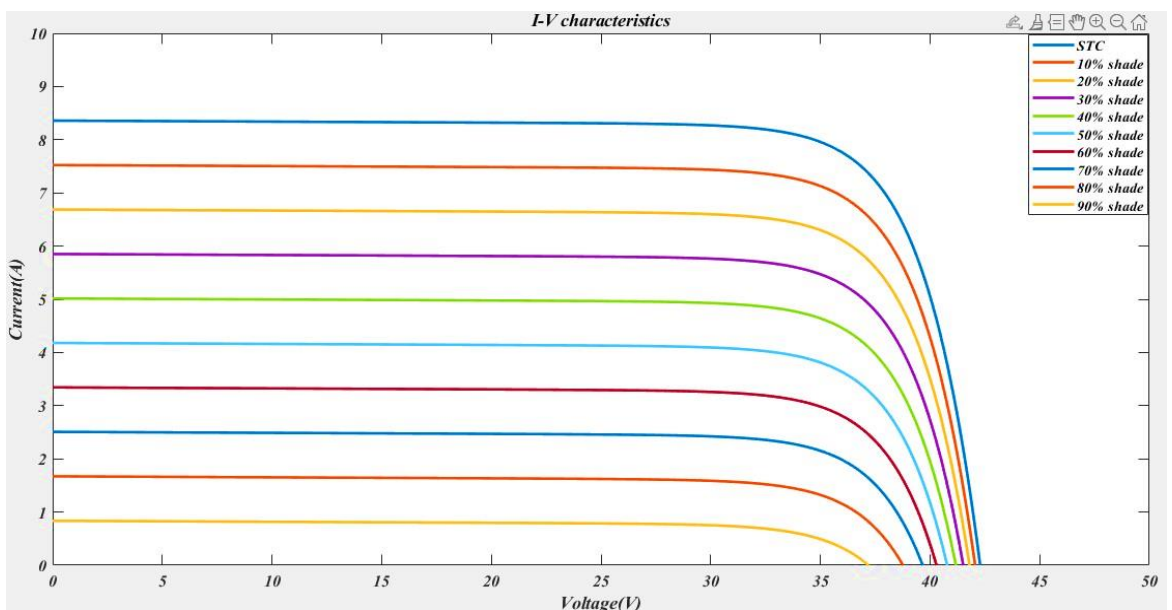
Figure 4.1: Photograph of instrumental setup for model validation

CHAPTER 5: RESULTS AND DISCUSSION

The I-V and PV characteristics curve of a module under defined shading scenario with varying irradiation values shown in Figure 5.1 (a) and (b). From the curve, when the value of irradiation goes on reducing, the open circuit voltage and short circuit current of the PV module decreases. Additionally, the maximum power output also decreases along with the irradiance level because of which the MPP on the P-V curve shifted towards the left i.e., the voltage and current at maximum power reduces.



(a) P-V characteristics curve of single module



(b) V-I characteristics curve of single module

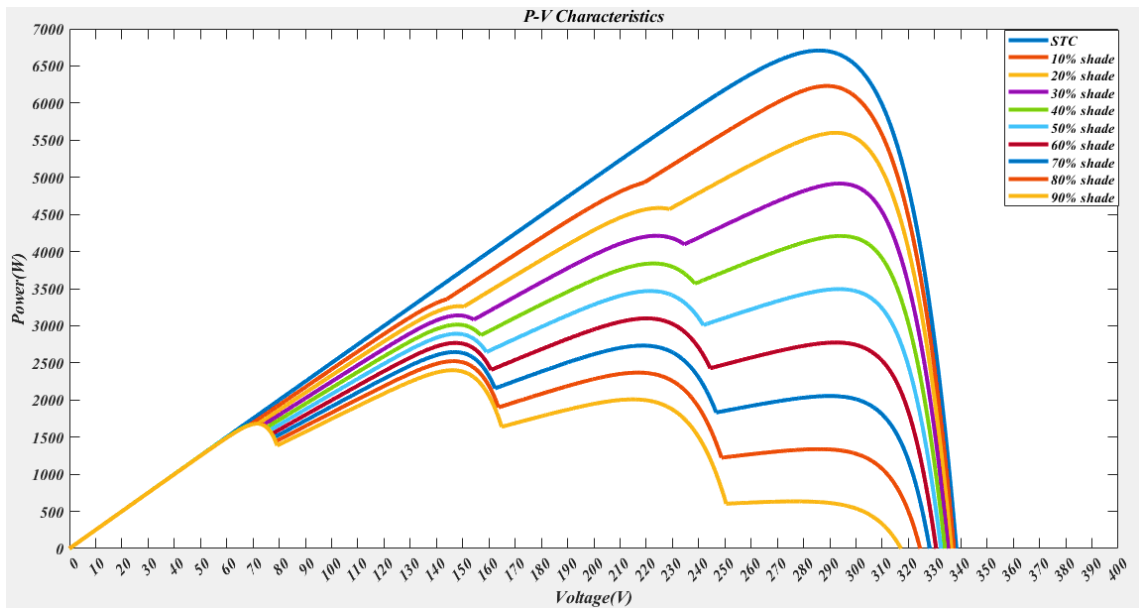
Figure 5.1: Characteristics curve of single module at different irradiance level

From the I-V characteristics curve, for the same value of voltage, the current is less with reduction in irradiance level received by the PV module. So, from Ohm's law, for the fixed value of voltage, the current is reducing which means the value of resistance is increasing. This indicates that when the irradiance level reducing the value of module resistance increases. When the irradiance level is varying from 1000 W/m^2 to 100 W/m^2 , the voltage is slightly affected but the current reduces proportionally with the irradiance level. And hence, the power output from the module reduced.

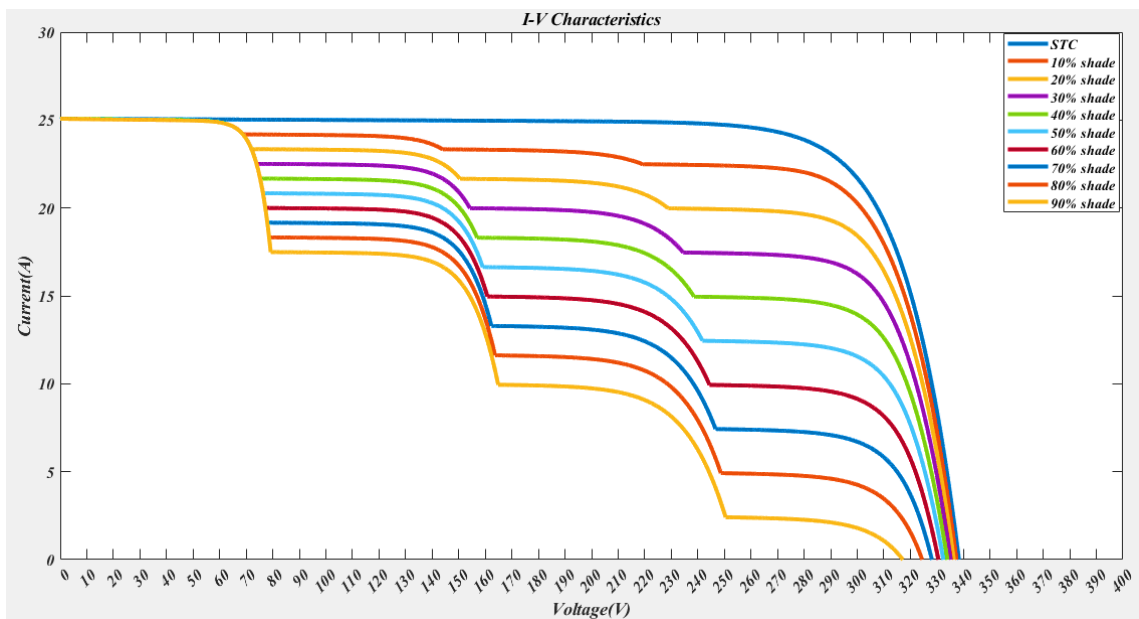
To study the effect of shading on array, simulation carried out under defined shading scenario with different irradiance cases at constant temperature of 25°C and the conclusion drawn.

5.1 Simulation of series-parallel connected solar PV array under shading conditions

Under STC, all the module on the PV array is subjected to equal amount of irradiance i.e., 1000 W/m^2 at 25°C . The characteristics of PV array under this condition generates maximum power of 6708 W with single MPP. shown in Figure 5.2 (a) and (b). The output from simulation shows that the changes in the irradiance under shading has an impact on the performance of the reference array. Under uniform shading, there is an equal distribution of solar radiation within the module of array and hence no mismatch between the modules. But under non-uniform shading cases, the mismatch causes several peaks on the P-V characteristics curve. The peaks on P-V curves are due to varying irradiance level and interaction between shaded and unshaded modules. Because the PV cells short-circuit current is proportionally affected by the level of insolation, the shaded PV modules photocurrent is decreases due to the non-uniformity of irradiance while the unshaded modules continue to function at a greater photocurrent. Since the string current must be the same through all modules that are connected in series, the shaded modules operate in the reverse bias zone to carry the higher current of the unshaded modules. The modules draw power due to the reverse voltage polarity. As a result, the maximum power that can be extracted from the PV array in shade decreases.



(a) P-V characteristic curve



(b) I-V Characteristic curve

Figure 5.2: Characteristic curves of SP configuration array under varying irradiance of defined shading condition

The maximum power output, fill factor and mismatch losses for the different conditions of shading for the series-parallel connected solar PV array presented in table.

Table 5.1: Performance parameter of SP connected solar PV array at different shading conditions.

Irradiance level/Shading	Global Maximum Power, P_{mp}	Fill Factor (FF)	Mismatch/Shading Loss (%)
STC	6708	0.79	0%
10% shade	6231	0.74	7.11%
20% shade	5599	0.66	16.53%
30% shade	4915	0.58	26.73%
40% shade	4210	0.50	37.24%
50% shade	3494	0.42	47.91%
60% shade	3100	0.37	53.79%
70% shade	2733	0.33	59.26%
80% shade	2524	0.31	62.37%
90% shade	2401	0.30	64.21%

5.2 Simulation of reference array by changing the connection into BL and TCT type

The module connection of the original reference array changed into BL and TCT type connection and the modified array then simulated under the different cases of the irradiance level. The results of this simulation will help to investigate how the changes in array configurations affects the parameter of performance of the solar PV array under shade.

5.2.1 Simulation of BL array configuration

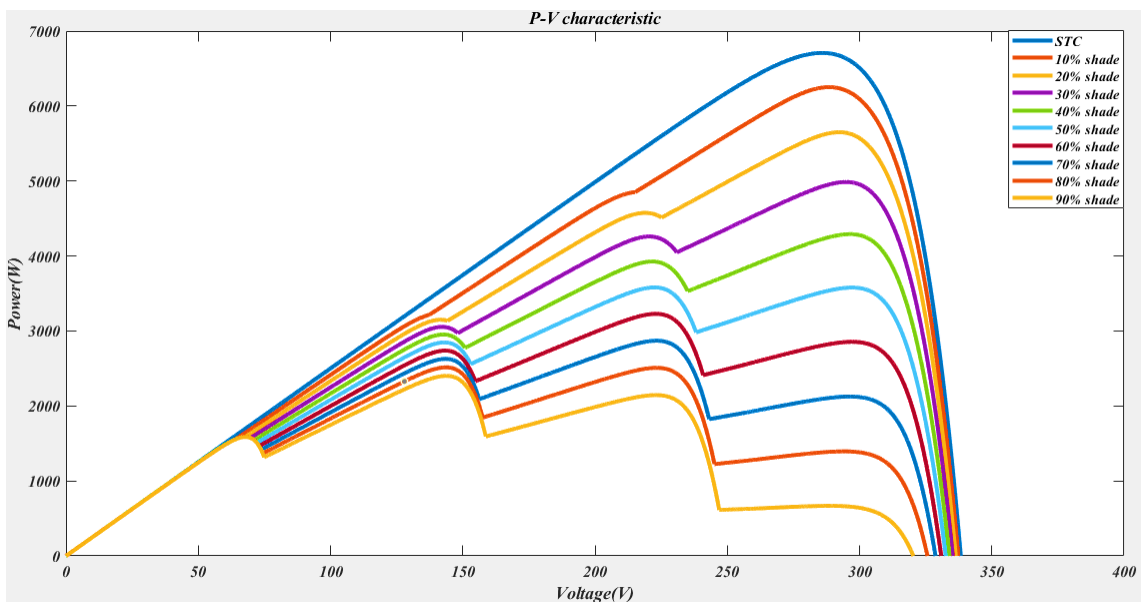
The reference SP array configuration changed into BL type configuration by introducing some additional cross-connection in bridge rectifier fashion within four module and simulation carried out. Under defined shading conditions of shading, the irradiance received by the shaded module is varied as 1000 W/m^2 (STC), 900 W/m^2 (10% shade), 800 W/m^2 (20% shade), 700 W/m^2 (30% shade), 600 W/m^2 (40% shade), 500 W/m^2 (50% shade), 400 W/m^2 (60% shade), 300 W/m^2 (70% shade), 200 W/m^2 (80% shade) and 100 W/m^2 (90% shade), and the characteristic curve are plotted shown in Figure 5.3. And other performance parameters are measured and calculated. From Figure, under same irradiation on the whole module there is single peak point on the P-V characteristics curve, however when there in non-uniform irradiance level given to the shaded and unshaded module, due to irradiance mismatching, the array has numerous peak locations on the characteristics curve.

5.2.2 Simulation of TCT array configuration

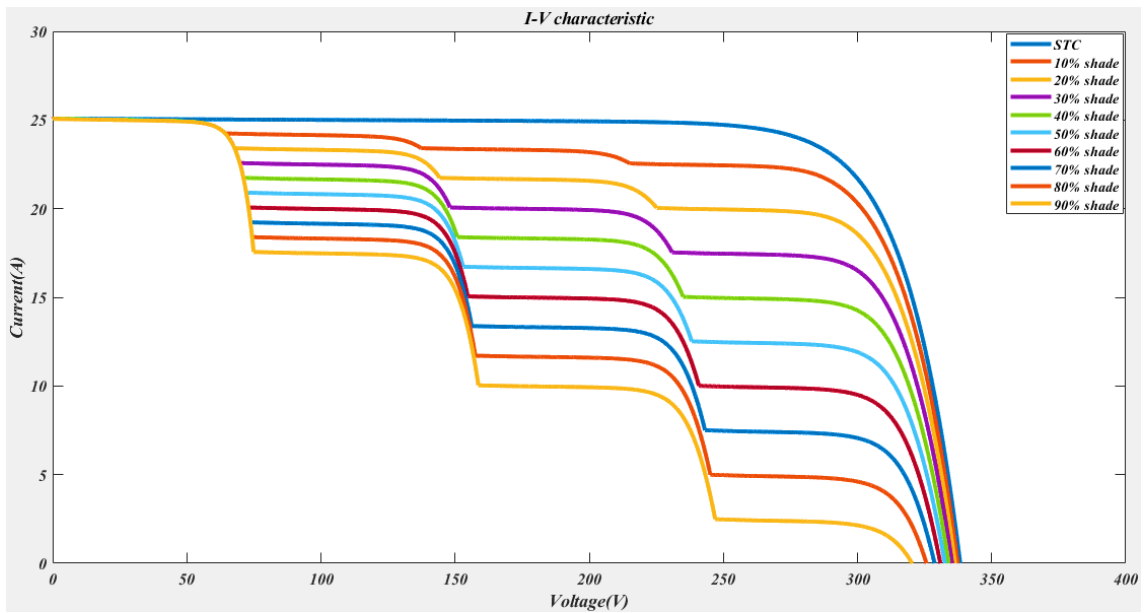
The original SP array setup transformed into a TCT configuration by adding cross-connections within each row. These cross-connections were designed so that the total current meeting at each connection point is equal, and the voltage across each connection point is also equal. Following this modification, a simulation conducted.

During this simulation, specific shading conditions were defined, where the irradiance (amount of sunlight) received by the shaded module varied systematically. This variation ranged from 1000 W/m² under standard test conditions (STC) to as low as 100 W/m² with 90% shading. A characteristic curve that depicts the relationship between current and voltage (P-V characteristics) generated by the simulation is shown in Figure 5.4.

The results depicted in the curve are notable: when the entire module receives uniform irradiation, there is only one maximum point on the P-V curve. However, when non-uniform irradiance levels were applied, with some modules in the shade and others in full sunlight, the curve displayed multiple peak points. These additional peaks are a consequence of the uneven distribution of sunlight across the array.

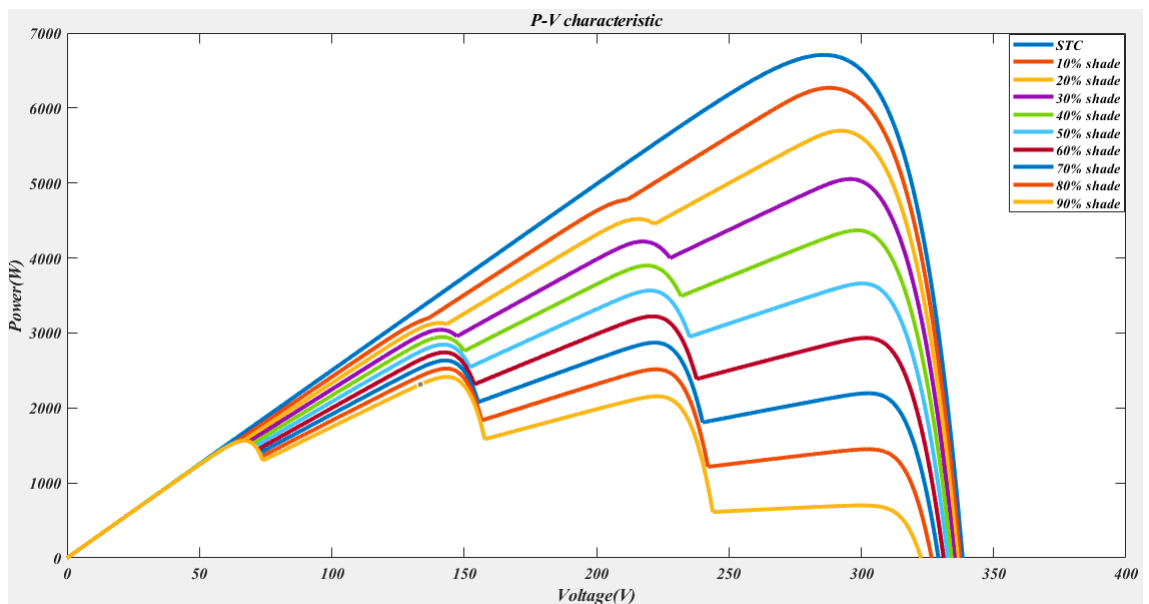


(a) P-V characteristics curve

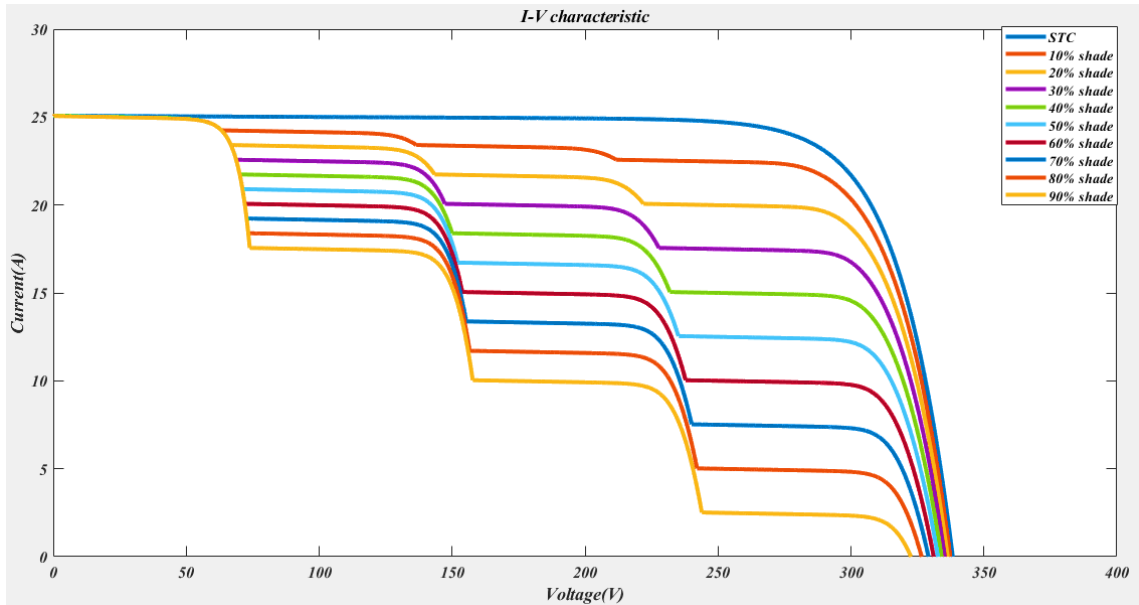


(b) I-V characteristics curve

Figure 5.3: Performance characteristics of BL configuration under varying irradiance of defined shading condition



(a) P-V characteristics curve



(b) I-V characteristics curve

Figure 5.4: Performance characteristics of TCT configuration under varying irradiance of defined shading condition

5.3 Comparison of the performance of BL and TCT arrays with SP connection of PV array

The simulation evaluated and discussed the PV array performance parameters, such as maximum power output, fill factor (FF), and mismatch loss for every case of shading/irradiance for each array connection:

5.3.1. Maximum Power

Under uniform irradiance, all three SP, BL and TCT connection exhibits the same characteristics with only one maximum power point in the P-V characteristics curve, however under non-uniformity of the irradiance all three-array configuration has several peaks in the characteristics curve in which the higher one is called global maximum power point (GMPP) and others are called local maximum power point. The GMPP usually represents the maximum extractable power from the array under given situations of the irradiance level and the temperature value. According to Table 5.2 following results were obtained:

For case I (STC), all configurations SP, BL and TCT have same maximum power output of 6708W.

For Case II (10% shade), TCT configurations give maximum power of 6269W followed by BL at 6251W and SP at 6231W.

For case III (20% shade), TCT configurations gives maximum power output of 5697W followed by BL and SP configurations.

For Case IV (30% shade), TCT configurations give maximum power following BL and SP of lowest value of 4915W.

For Case V (40% shade), TCT configuration presents maximum extractable power of 4360W, and SP has lowest of 4210W.

Table 5.2: Simulation results of shading cases showing maximum values.

Irradiance/Shading	Global Maximum Power, P_m (W)		
	Series-Parallel	Bridge-Linked	Total-Cross-Tied
STC	6708	6708	6708
10% shade	6231	6251	6269
20% shade	5599	5650	5697
30% shade	4915	4986	5053
40% shade	4210	4291	4360
50% shade	3494	3581	3660
60% shade	3100	3228	3222
70% shade	2733	2870	2871
80% shade	2524	2515	2525
90% shade	2401	2401	2414

For Case VI (50% shade), TCT configuration presents maximum extractable power of 3660W. It is followed by BL configuration at 3581W and SP has lowest performance of 4210W.

For Case VII (60% shade), BL configuration has better performance with maximum extractable power of 3228W. It is followed by TCT (3222W) and SP has lowest of 3100W.

For Case VIII, (70% shade), TCT configuration presents maximum extractable power of 2871W, followed by BL (2870W) and SP (2733W).

For Case IX (80% shade), TCT configuration has better performance with maximum extractable power of 2525W and is followed by SP (2524W). The BL configuration has lowest performance (2515W).

For Case X (90% shade), TCT configuration presents maximum extractable power of 2414W while BL and SP has same performance of 2401W.

In Figure 5.5, the maximum extractable power under different shading conditions for each array configuration is given.

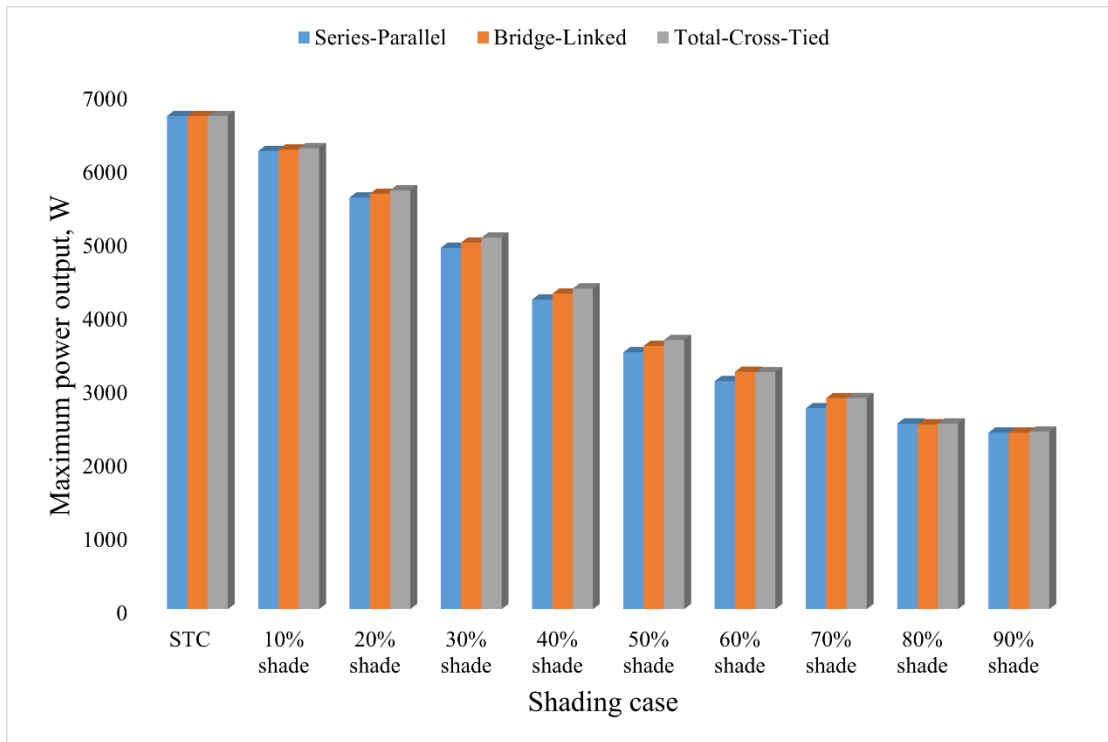


Figure 5.5: Maximum power at different shading conditions

5.3.2 Fill Factor (FF)

The maximum power, array open circuit voltage, and array short circuit current all relate to a solar PV array's fill factor. The short circuit current and open circuit voltage for each shading cases is given in Table 5.3.

Here from Table 5.3, the open circuit voltage is changes slightly and short circuit current is almost same in each case of shade. This is because the open circuit voltage is mostly governed by the semiconductor materials bandgap energy used in solar cell. Shading doesn't drastically alter the bandgap energy, so the voltage across the cell remains relatively constant. Additionally, temperature also affects the open circuit voltage, but here we assume constant temperature for all cases. Moreover, when solar cell is shaded, the shaded area effectively acts as a resistor, limiting the current flow, but because solar cells generally have low internal resistance, the effect of shading on the short circuit current is relatively small.

Table 5.3: Open circuit voltage and short circuit current for each shading case

Shading/Irradiance	Open circuit Voltage, V_{oc} (V)			Short circuit current, I_{sc} (A)		
	SP	BL	TCT	SP	BL	TCT
STC	338.3	338.3	338.3	25.08	25.08	25.08
10% shade	337.36	337.37	337.37	25.064	25.053	25.049
20% shade	336.36	336.38	336.38	25.064	25.053	25.049
30% shade	335.24	335.29	335.29	25.064	25.053	25.049
40% shade	333.94	334.04	334.04	25.064	25.053	25.049
50% shade	332.41	332.6	332.6	25.064	25.053	25.049
60% shade	330.55	330.88	330.88	25.063	25.053	25.049
70% shade	328.11	328.71	328.71	25.064	25.052	25.049
80% shade	324.45	325.69	325.69	25.064	26.052	25.049
90% shade	317.16	320.32	320.32	25.064	25.053	25.049

Table 5.4: Fill Factor (FF) at different shading cases

Irradiance/Shading	Fill Factor		
	Series-Parallel	Bridge-Linked	Total-Cross-Tied
STC	0.791	0.791	0.791
10% shade	0.737	0.740	0.742
20% shade	0.664	0.670	0.676
30% shade	0.585	0.594	0.602
40% shade	0.503	0.513	0.521
50% shade	0.419	0.430	0.439
60% shade	0.374	0.389	0.388
70% shade	0.332	0.349	0.348
80% shade	0.310	0.296	0.309
90% shade	0.302	0.299	0.301

Figure 5.6 gives the fill factor for different shading conditions for SP, BL and TCT configurations. Fill factor is tabulated in Table 5.4 for all configurations under various shading conditions. For STC, SP, BL and TCT configurations has same fill factor value while for other most of the cases, TCT have higher FF value than BL and SP configuration. With increase in the shade amount the fill factor decreases because of reduction in maximum extractable power.

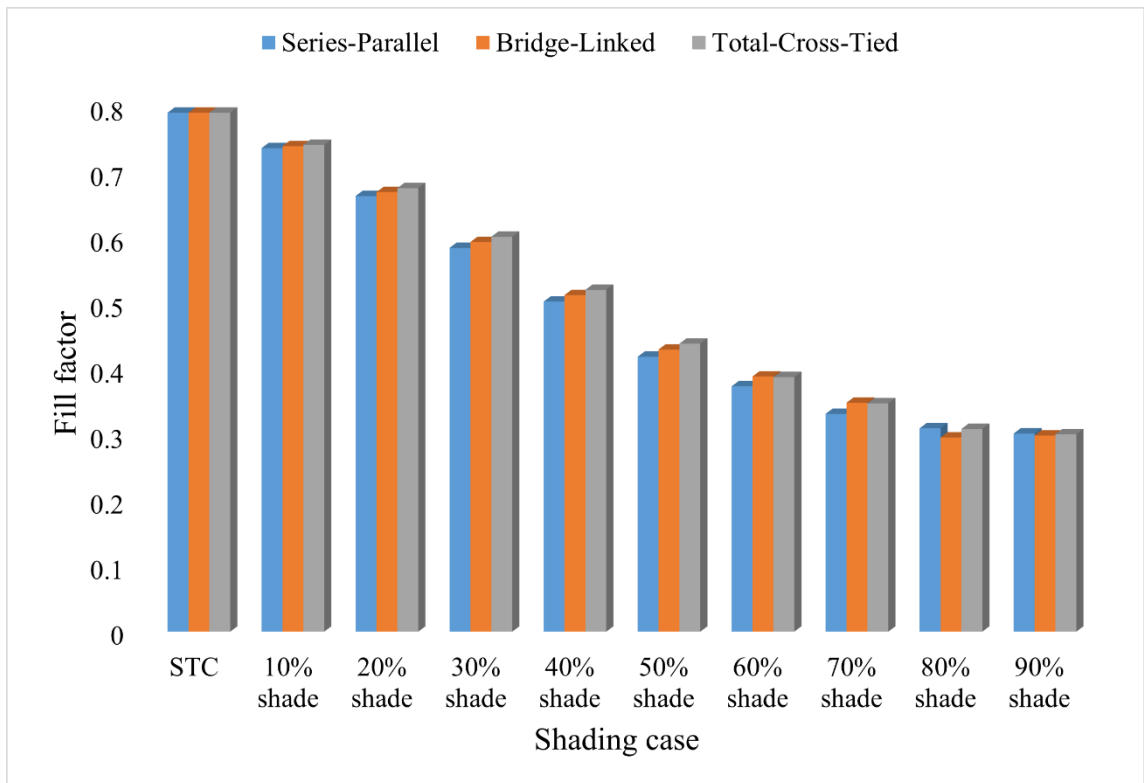


Figure 5.6: Fill factor at different cases of shading

5.3.3 Mismatch Power loss

In Table 5.5, the mismatch power loss for all configurations has been tabulated. From the it has been seen that the power losses are higher for SP configuration followed by BL and TCT configuration. This suggests that TCT arrangement outperforms other configuration in terms of performance under the defined condition of shading with non-uniformity of irradiance level.

Table 5.5: Mismatch power loss at different shading cases

Shading case	Global Maximum Power Under shading(W)			Mismatch Power Loss (%)		
	SP	BL	TCT	SP	BL	TCT
10% shade	6231	6251	6269	7.11%	6.81%	6.54%
20% shade	5599	5650	5697	16.53%	15.77%	15.07%
30% shade	4915	4986	5053	26.73%	25.67%	24.67%
40% shade	4210	4291	4360	37.24%	36.03%	35.00%
50% shade	3494	3581	3660	47.91%	46.62%	45.44%
60% shade	3100	3228	3222	53.79%	51.88%	51.97%
70% shade	2733	2870	2871	59.26%	57.22%	57.20%
80% shade	2524	2515	2525	62.37%	62.51%	62.36%
90% shade	2401	2401	2414	64.21%	64.21%	64.01%

Figure 5.7 gives the percentage of mismatch power losses under different shading conditions for the different types of array configurations.

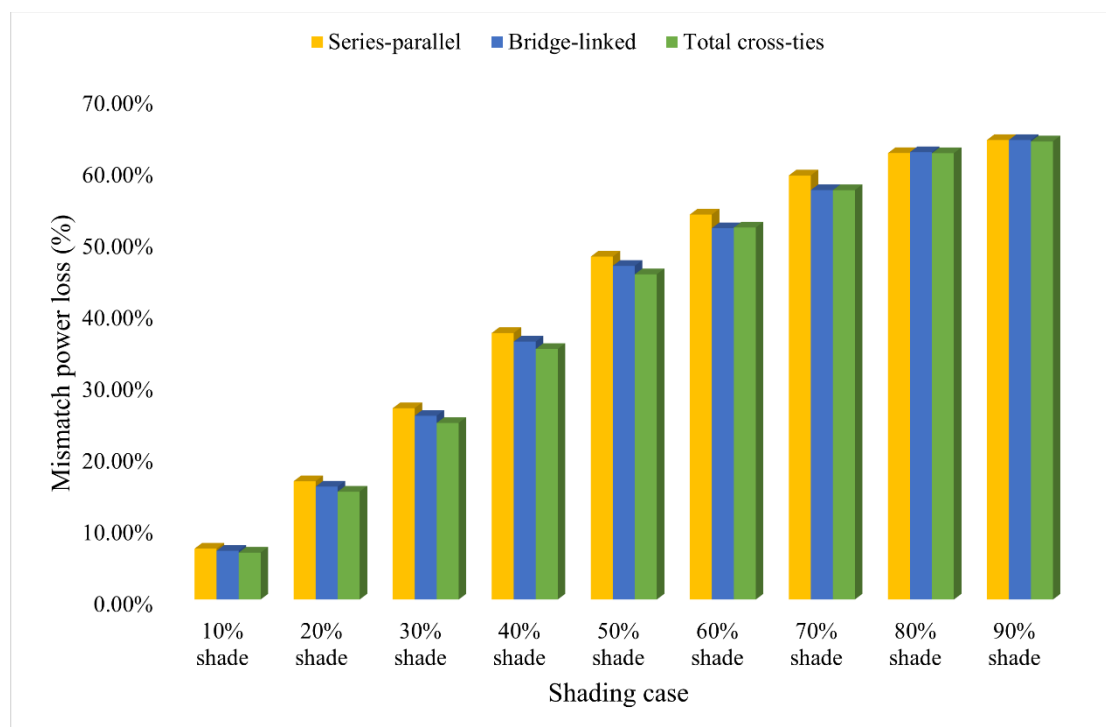


Figure 5.7: Mismatch power loss (%) at different shading conditions

5.4 Monte Carlo Simulation

Using Python programming language, the MC simulation for the reference array system has been performed. For each case of shading scenario, a set of output power is obtained. One million simulation runs have performed, and output powers are collected, probability distribution curve plotted on the values of the output power shown in Figure 5.8.

Here in the plot, the power output in watt is represented in x-axis and the probability (normalized frequency) for each power output values is by y-axis. A symmetrical bell-shaped curve is found from the simulation run which indicates normal probability distribution. This implies that most of the shading scenarios have a similar impact on the power output. The peak of the probability distribution curve i.e., 3360W is the most probable power output having probability of occurrence 0.16 which also represents the mean power output under shading conditions.

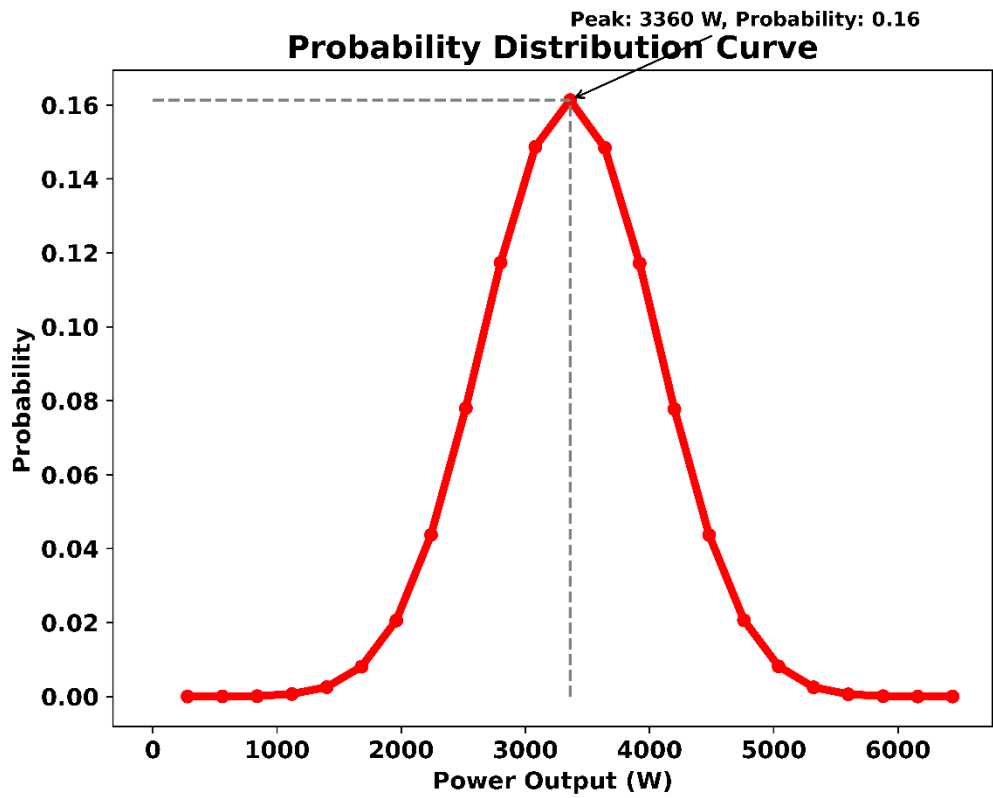


Figure 5.8: Probability distribution curve

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The results of the simulations showed that non-uniform irradiance distribution can lead to notable reductions in the overall performance of the PV array. And found that the TCT and BL configuration showed superior behaviour in terms of output power, fill factor and mismatch power loss than the SP configuration.

Under non-uniform shade, when level of irradiances reduces gradually, the maximum power output reduces accordingly and it has been found that, at 50% of solar Irradiance the maximum extractable output from series-parallel configuration is only 3494W which is 52.08% of STC. The effect of shading has been investigated on BL and TCT results showed that, these configurations also have multiple peaks under non-uniformity of irradiance and found that maximum power output is 3581W and 3660W at 50% of solar irradiance respectively which is 53.38% and 54.56% of STC.

It has been found that under uniform irradiance all three configuration have same performance. Under the define shading conditions and irradiance level, the performance parameter of three configurations has been analysed and but under non-uniformity of irradiance TCT and BL configuration have better performance than SP configuration. Under same shading conditions (50% irradiance) TCT produces 4.75% and 2.21% than SP and BL respectively. Also, TCT have lower mismatch loss of 45.45% than BL(46.62%) and SP (47.91%), & higher fill factor (TCT-0.439, BL-0.430 and SP-0.419).

6.2 Recommendations

Following recommendations has been made for the further detaile study and improvement:

- It is recommended to carry out further study by considering the seasonal weather variation and geography.
- Further study with incorporating electronic converter and storage system (battery bank) will give further insight.

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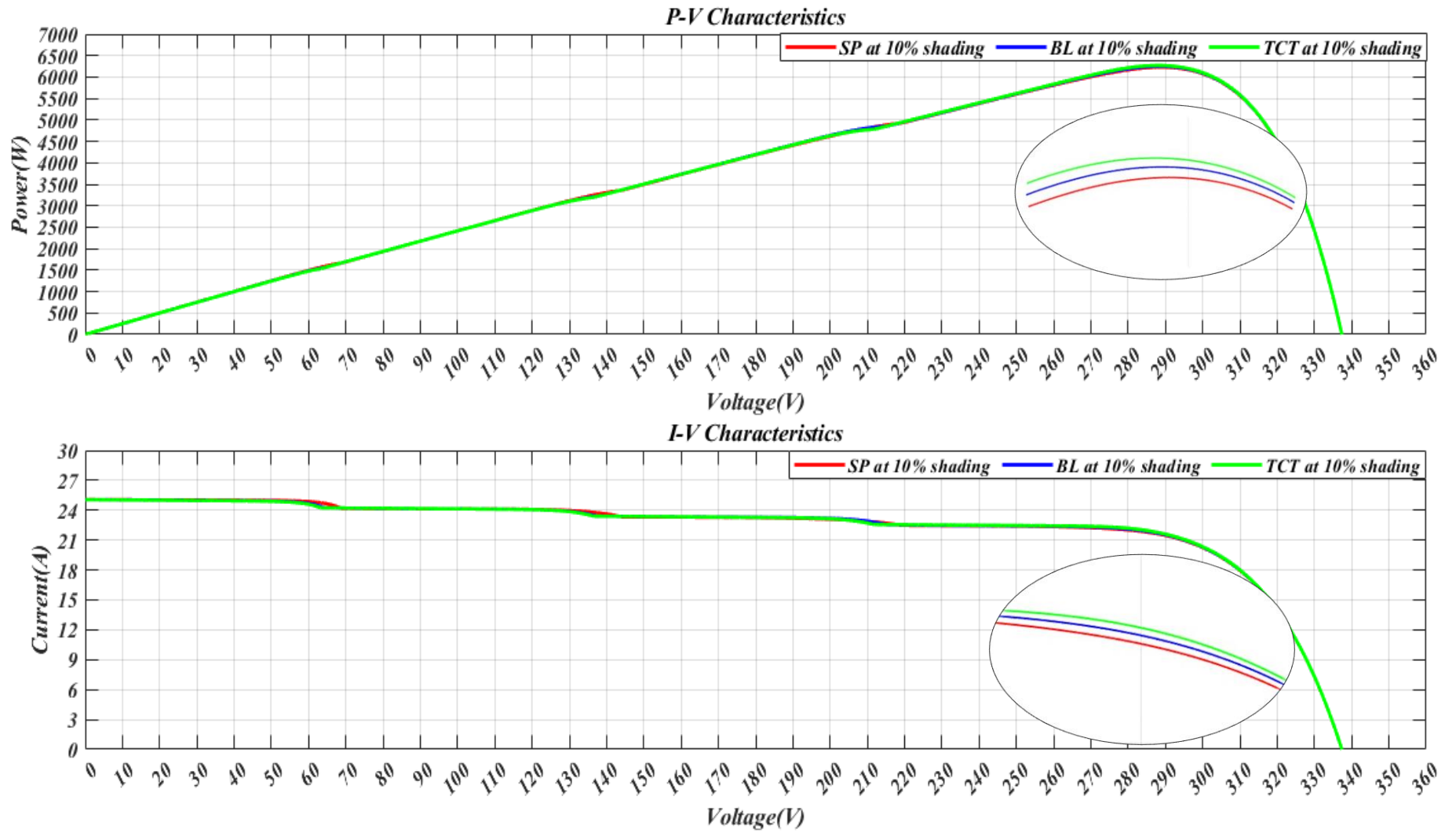
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,PV%20cells%20exercise%20this%20effect.&text=When%20sunlight%20hit%20the%20cell,(negative%2Dpositive)%20pairs.

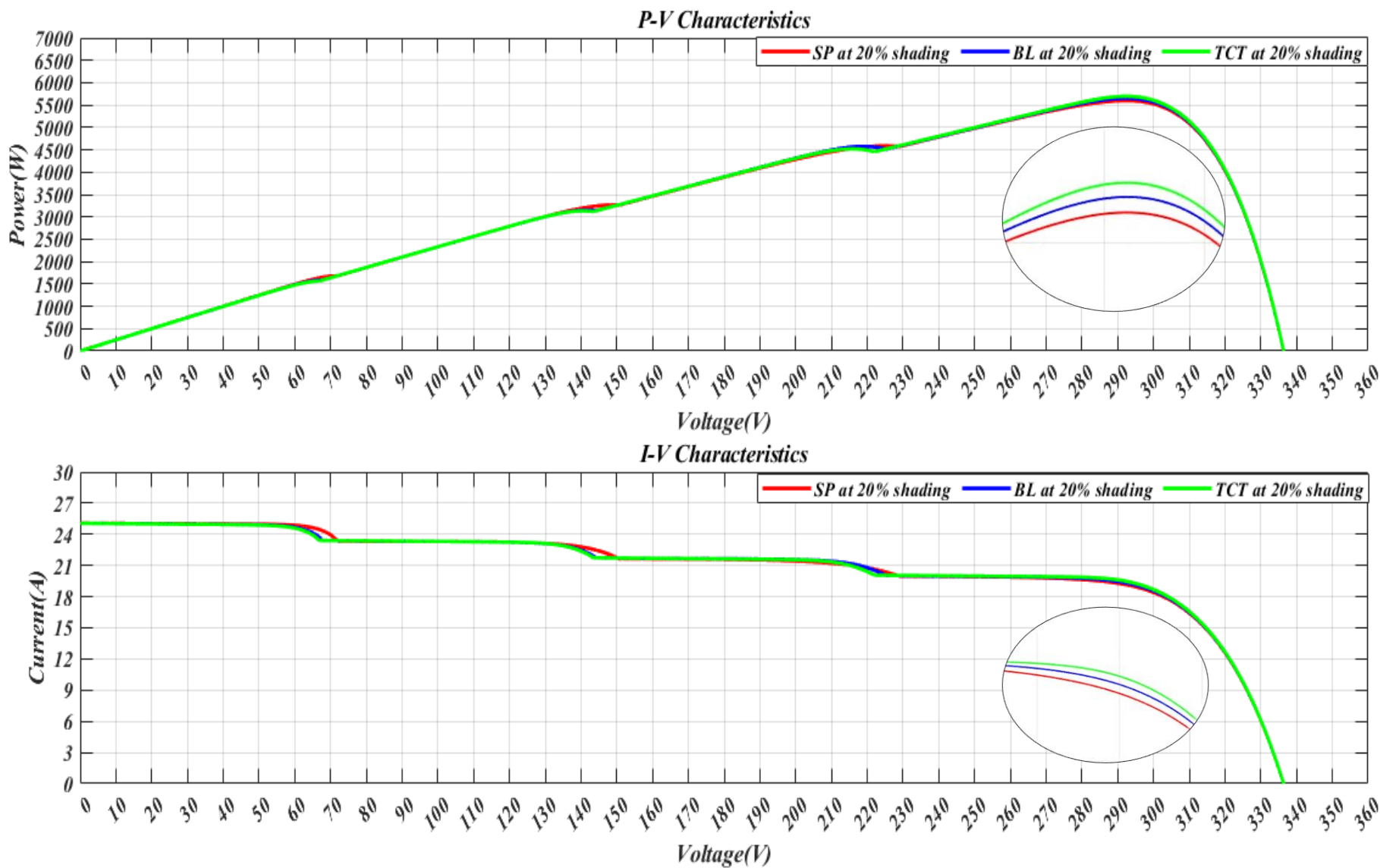
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APPENDICES

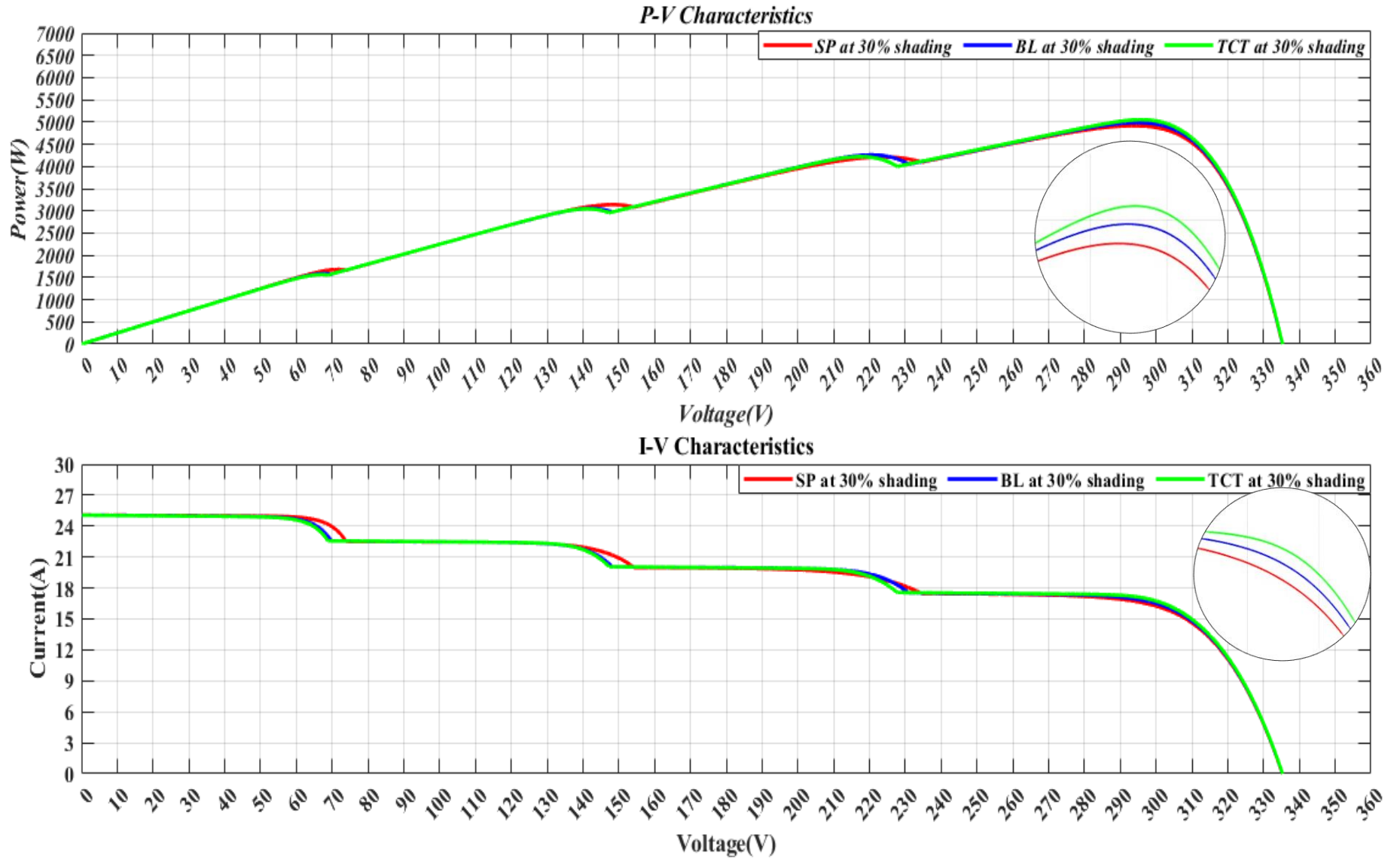
Appendix-A: Characteristics curve of SP, BL and TCT configuration under 10% shading



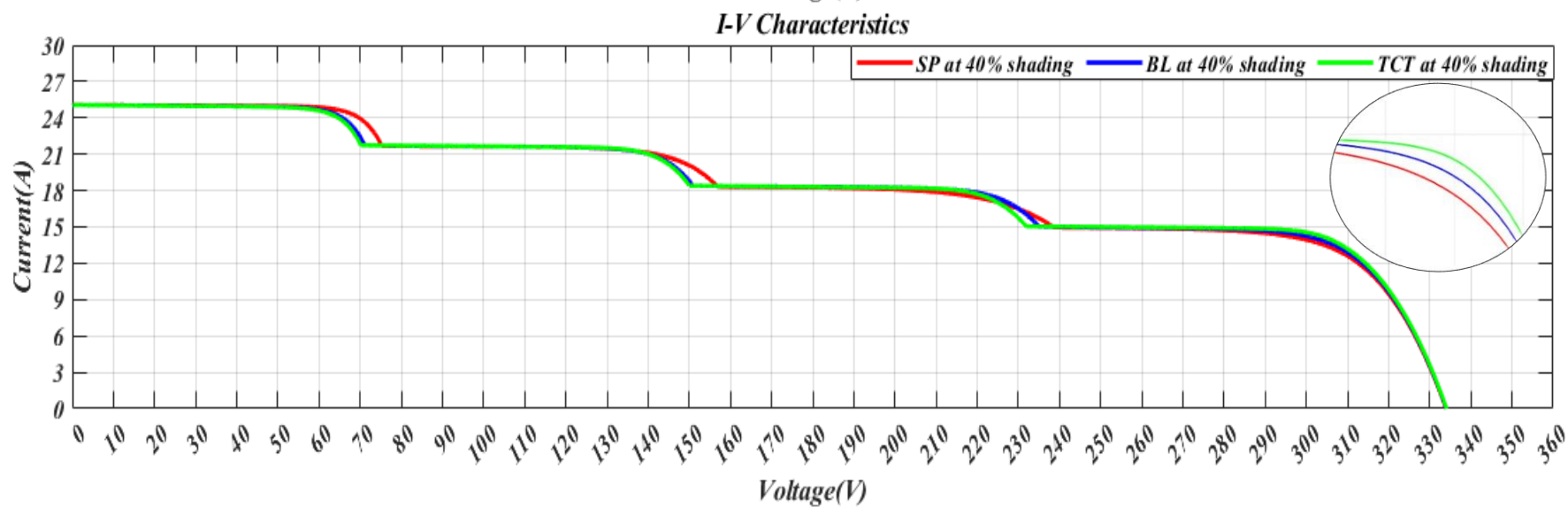
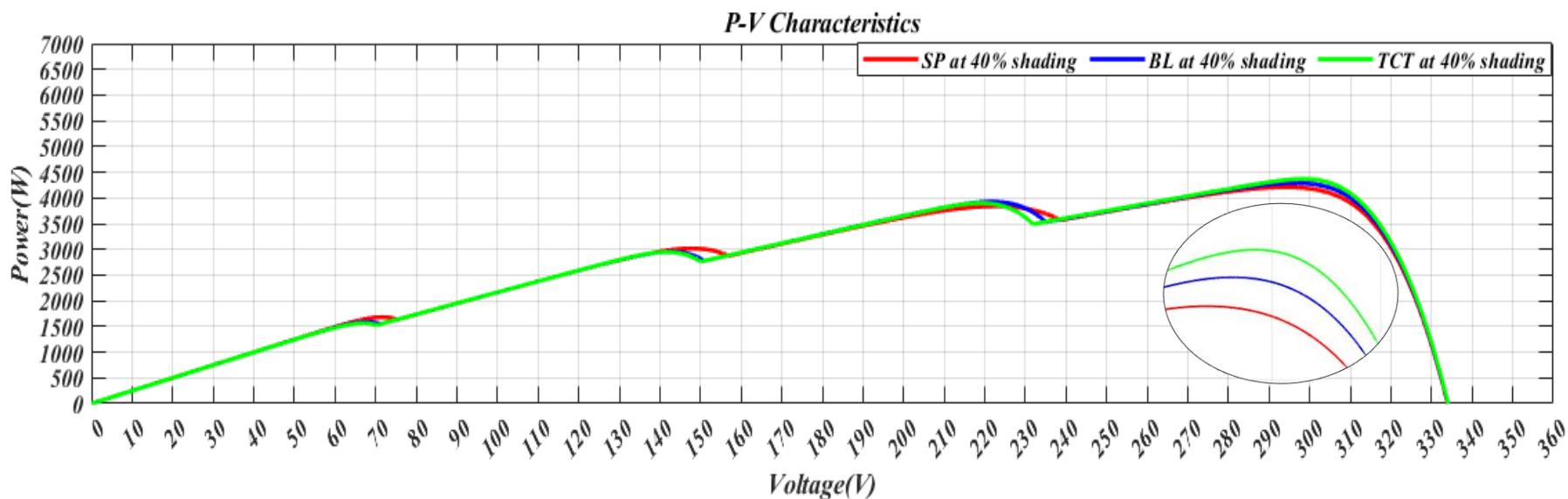
Appendix-B: Characteristics curve of SP, BL and TCT configuration under 20% shading



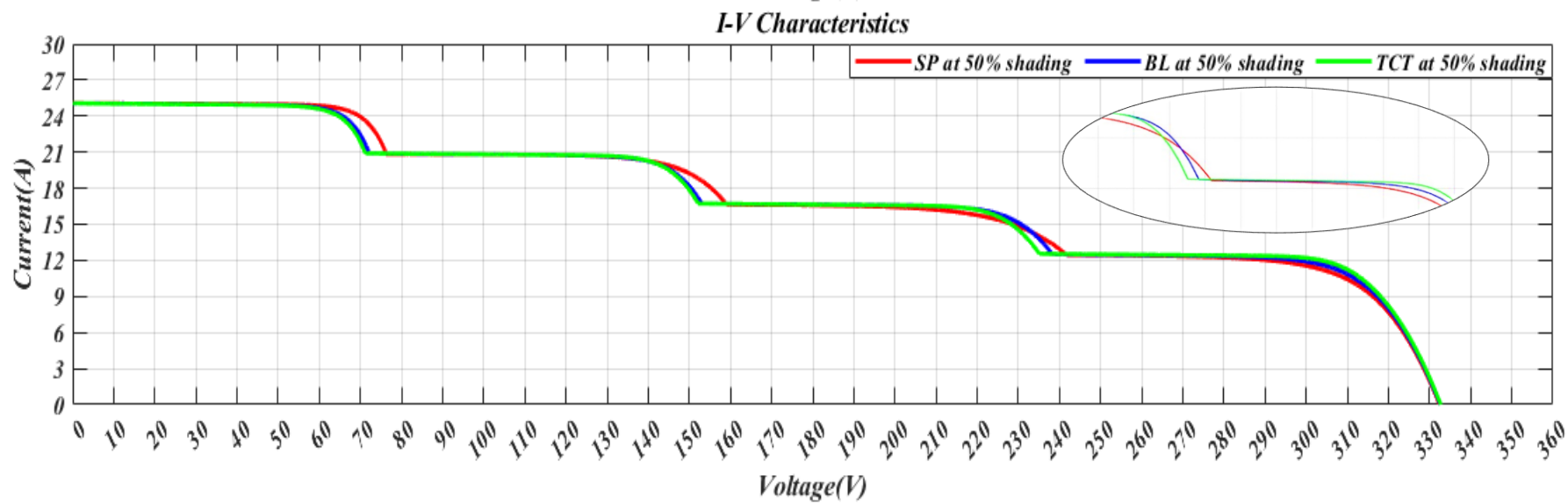
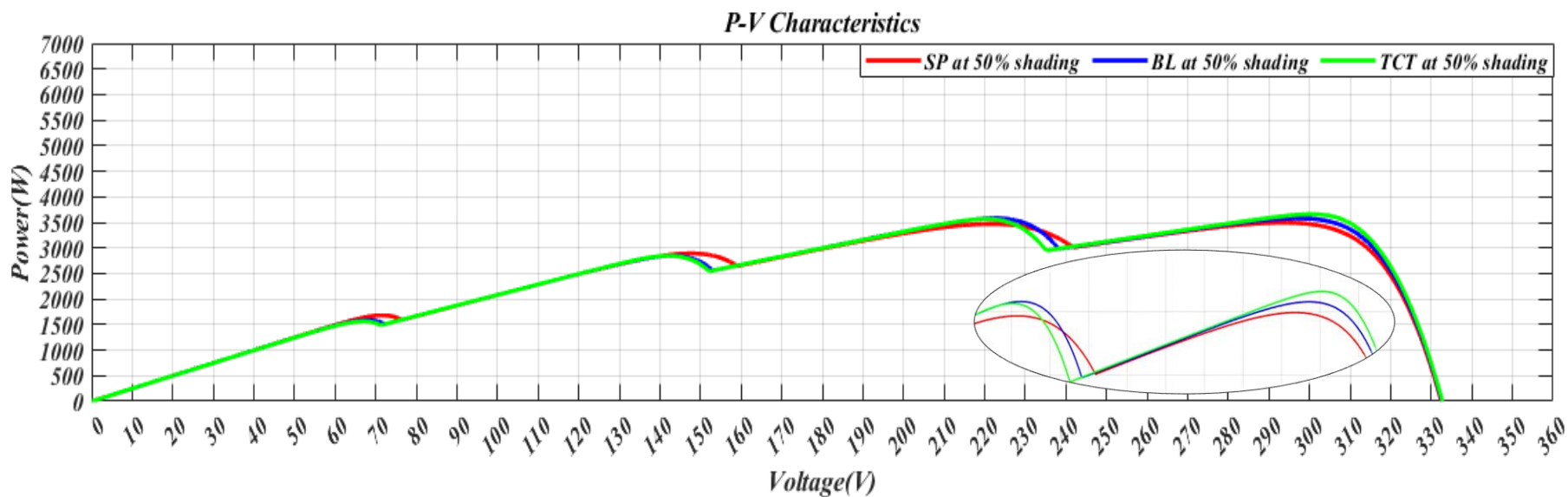
Appendix-C: Characteristics curve of SP, BL and TCT configuration under 30% shading



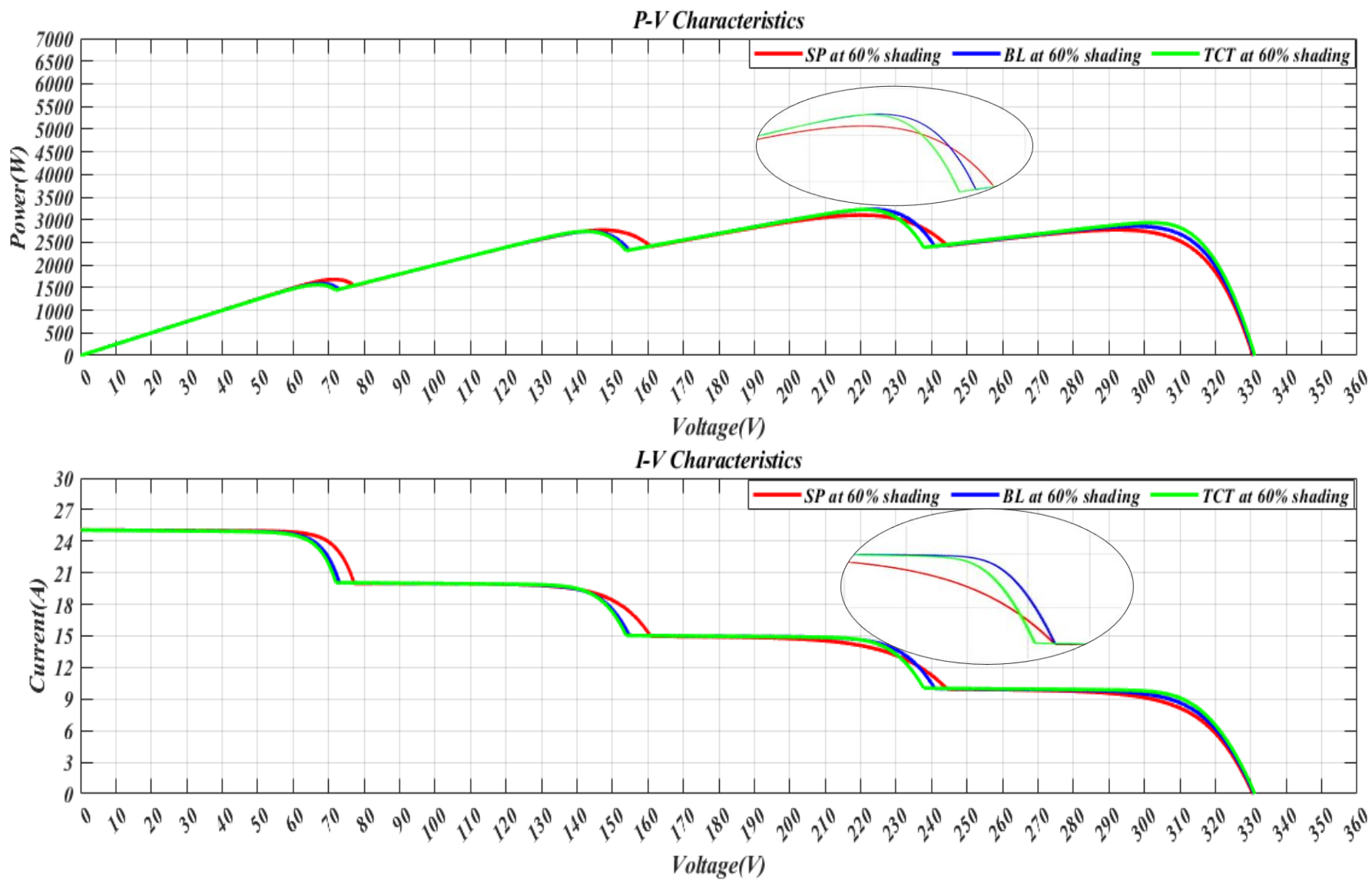
Appendix-D: Characteristics curve of SP, BL and TCT configuration under 40% shading



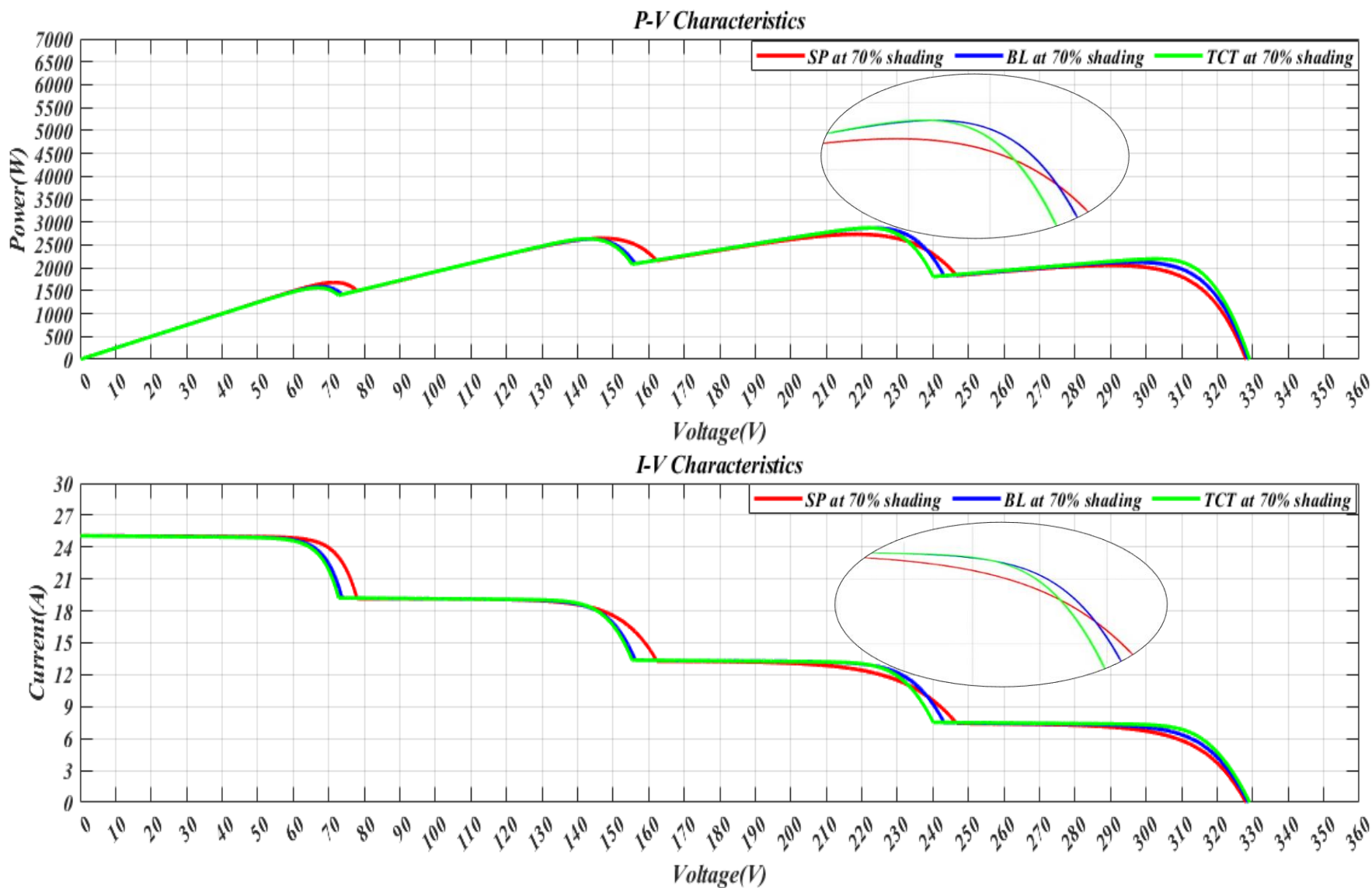
Appendix-E: Characteristics curve of SP, BL and TCT configuration under 50% shading



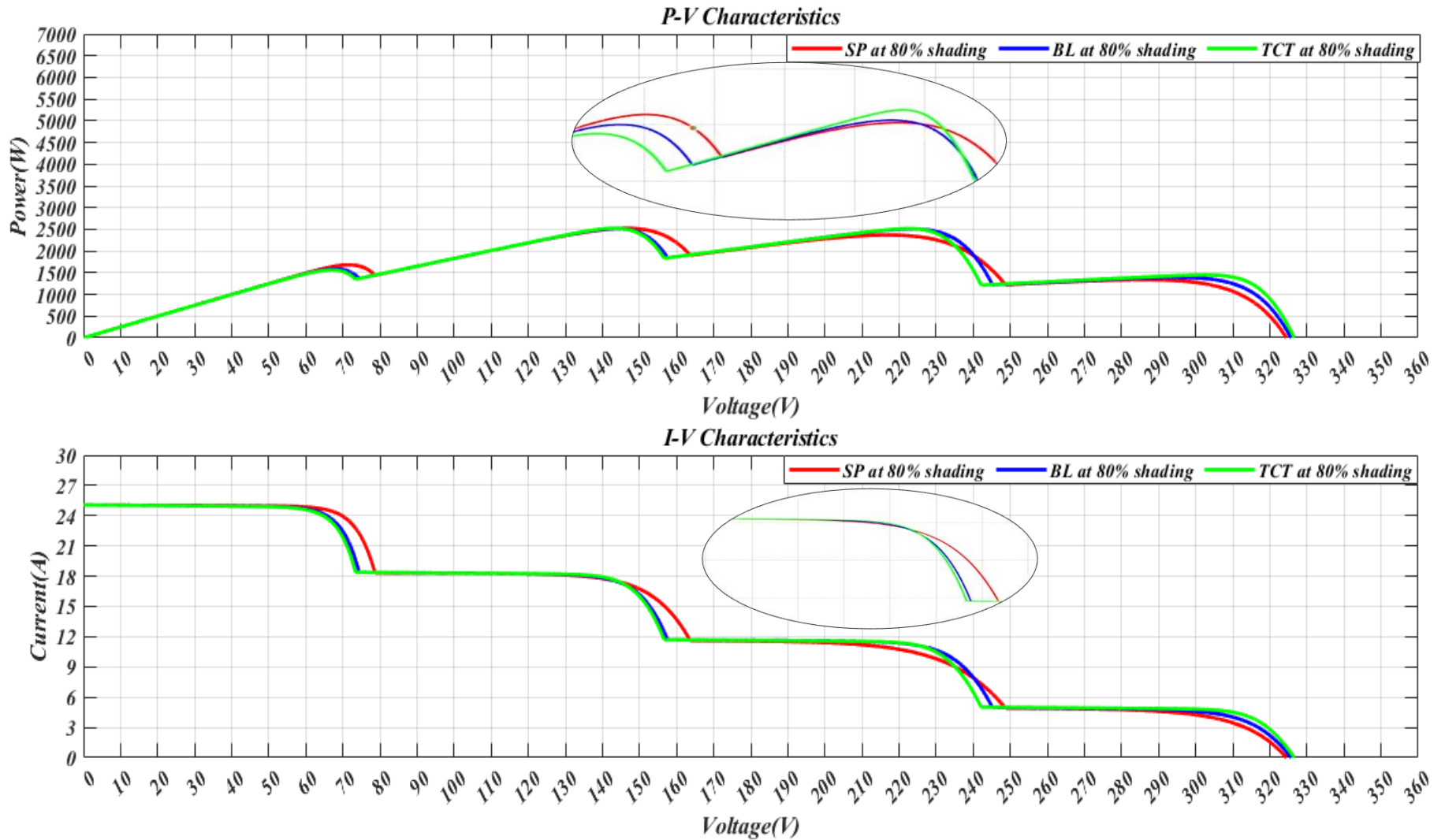
Appendix-F: Characteristics curve of SP, BL and TCT configuration under 60% shading



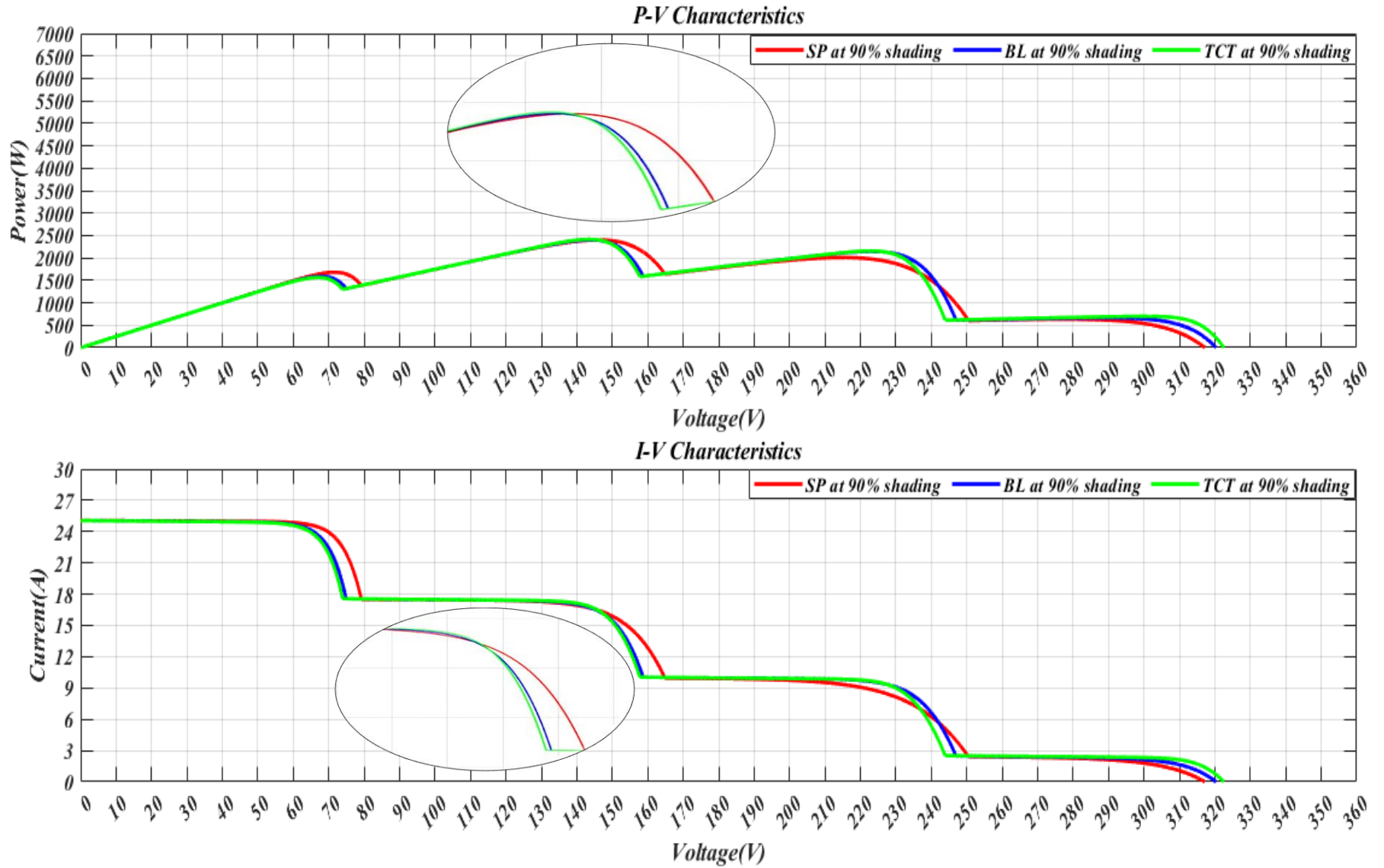
Appendix-G: Characteristics curve of SP, BL and TCT configuration under 70% shading



Appendix-H: Characteristics curve of SP, BL and TCT configuration under 80% shading



Appendix-I: Characteristics curve of SP, BL and TCT configuration under 90% shading



Appendix-J: M-files for the input parameters of solar PV module and to plot characteristics curve

```
%Input parameters of a reference module
Pmp = 280;           % Maximum power of solar PV module, W
Vmp = 36.3;         % Voltage at maximum power point, V
Imp = 7.72;         % Current at maximum power point, A
Isc = 8.36;         % Short circuit current, A
Voc = 44.3;         % Open circuit voltage, V
Eg = 1.12;          % Band gap energy, eV
n = 1.156;          % Diode ideality factor (1-2) for silicon cell
Tnom = 298;         % Reference temperature at STC 25 °C
k = 1.38e-23;       % Boltzmann's constant
q = 1.6e-19;        % Electronic charge
T = 298;           % Working temperature
Vt = (k*T)/q;       % Thermal voltage
Is = Isc/exp((Voc/(n*Vt))-1); % Saturation current
Ki = 0.0006;        % Short circuit current temperature coefficient
Ns = 72;           % No. of series connected solar cell in a module
Rs = 0.053;         % Series resistance
Rsh = 529.9;        % Shunt resistance

% plotting characteristics curve
figure
subplot(2,1,1)
% P-v characteristics curve plot
plot(v,p,v1,p1,v2,p2,v3,p3,v4,p4,v5,p5,v6,p6,v7,p7,v8,p8,v9,p9,'linewidth',3.0)
xlim([0 400]);
ylim([0 7000]);
title('P-V Characteristics');
set(gca,'xtick',[0:10:400])
set(gca,'ytick',[0:500:7000])
xlabel('Voltage(V)');
ylabel('Power(W)');
```

```

legend({'STC','10% shade','20% shade','30% shade','40% shade','50% shade','60% shade','70%
shade','80% shade','90% shade'},'location','northeast')
subplot(2,1,2)
%I-V characteristics plot
plot(v,i,v1,i1,v2,i2,v3,i3,v4,i4,v5,i5,v6,i6,v7,i7,v8,i8,v9,i9,'linewidth',3.0)
xlim([0 400]);
ylim([0 30]);
title('I-V Characteristics');
set(gca,'ytick',[0:3:30])
set(gca,'xtick',[0:10:400])
xlabel('Voltage(V)');
ylabel('Current(A)');
legend({'STC','10% shade','20% shade','30% shade','40% shade','50% shade','60% shade','70%
shade','80% shade','90% shade'},'location','northeast')

```

Appendix-K: Python programming code for MC simulation

```

rows = 8 #Series connected module

cols = 3 #No. of string

matrix = [[0] * cols for _ in range(rows)]

powerOfModule = 280

def calculate_total_power(matrix, power_of_module):

    total_power = 0

    for i in range(len(matrix)):

        for j in range(len(matrix[i])):

            total_power += matrix[i][j] * power_of_module

    return total_power

```

```

# Call the randomizeSolarPanel function on the matrix
randomizeSolarPanel(matrix)

# Print the modified matrix
for row in matrix:
    print(row)

import random

def randomizeSolarPanel(matrix):
    for i in range(len(matrix)):
        for j in range(len(matrix[i])):
            random_int = random.randint(1, 100)
            if random_int > 50:
                matrix[i][j] = 1
            else:
                matrix[i][j] = 0.25

import random

totalPowerList=[];

for i in range(100000):
    randomizeSolarPanel(matrix)
    totalPowerList.append(calculate_total_power(matrix,powerOfModule))

import matplotlib.pyplot as plt

from collections import Counter

# Count occurrences of each unique value

```

```
value_counts = Counter(totalPowerList)

# Calculate the total number of values

total_values = len(totalPowerList)

# Calculate the probability for each value

probability_distribution = {value: count / total_values for value, count in value_counts.items()}

# Sort values for plotting

sorted_values = sorted(probability_distribution.keys())

# Plotting the probability distribution curve

sorted_probabilities = [probability_distribution[value] for value in sorted_values]

fig = plt.figure(figsize=(5,4))

plt.plot(sorted_values, sorted_probabilities, marker='o')

plt.xlabel("Power Output (W)")

plt.ylabel("Probability")

plt.title("Probability Distribution Curve")

fig.savefig('Probability Distribution Curve.png', dpi = 500)

plt.show()

plt.close(fig)
```