

**STUDYING THE PERFORMANCE OF DIFFERENT PHOTOVOLTAIC
ARRAY POWER CONTROL METHODS UNDER ENVIRONMENT
SCENARIOS USING SIMULINK**



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ABSTRACT

As a means of generating renewable power, photovoltaic array (PV array) has been increasingly harnessed. To regulate the output power of a PV array to the power grid, power controllers are needed. There are multiple electronic controlling methods which can manipulate the output power of PV array whilst not changing the PV array structure, light irradiance or temperature. The output power of the PV array can be affected by changing the environment, such as light and temperature, thus changing performance of the controllers. The goal of this thesis project was to test how well power control methods adapted to environmental changes as well as advantages and disadvantages when compared to each other.

Matlab and Simulink were chosen to conduct the tests on due to the high mathematical and electrical accuracy as well as the fact that data can be easily transferred between two platforms for visualizing results and programming. Control methodologies used in the project were fixed-voltage output control (known as PWM control), maximum power point tracking control (MPPT) and PI based maximum power point tracking control (MPPT-PI). Two environment scenarios common in real life where the PV array was tested were multiple seasons and partial shading. On the thesis project, several materials and models from different journals, Mathworks websites as well as Matlab library were used.

After the tests, it was clear that a PWM controller could give the most stable voltage and the lowest power output compared to the other two. On the contrary, MPPT and MPPT-PI favoured power output with an unstable voltage depending on environmental factors. The MPPT controller had a higher power output than the MPPT-PI controller.

Keywords Control, MPPT, MPPT-PI, power, PV array, PWM, scenarios.

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1 INTRODUCTION

In the 21st century, the energy crisis and global warming escalated to be the biggest threat to the world. To minimize these mentioned problems, renewable sources of energy are put into use. One of them is photovoltaic (solar) power. Thanks to the photovoltaic (PV) array, light can be converted into electricity. Depending on the electrical loads, solar array power needs to be regulated to meet different purposes.

Due to the characteristics of the P-N junction of semiconductor cells which are the main components of PV array, its output power varies when there is a change in light irradiance or temperature of the cells. The change in power output can affect the performance of controllers. In this study, fixed-voltage controller (PWM), maximum power point tracking (MPPT) and PI based maximum power point tracking control method (MPPT-PI) are put into the test. By using Simulink and Matlab to simulate PV array controlled by the mentioned methods during two cases: partial shading and different seasons and compare the results from the simulations, different methods of power output control can be tested to measure how well and efficiently they can adapt to external interferences.

2 CHARACTERISTICS OF PV CELL

2.1 PV cell circuit model and output current formula.

Figure 1 shows the equivalent circuit of a PV cell, where R_s is series resistance, R_p is shunt resistance, I_D is electric current running through P-N junction, I_L is current generated by the cell, V is cell open voltage.

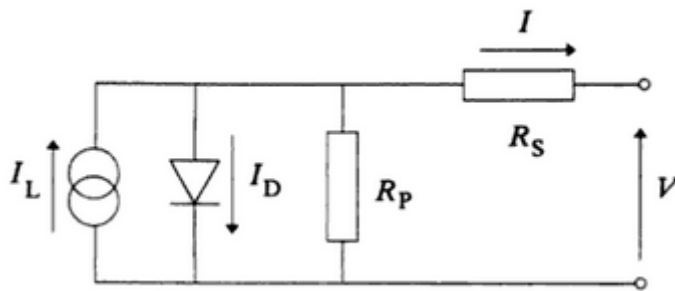


Figure 1: Equivalent open circuit of a PV cell (Lorenzo, 1994)

Using Kirchhoff's law, output current I can be calculated through formula:

$$I = I_L - I_p - I_D$$

$$I = I_L - I_0 \cdot \left[\exp\left(\frac{V+I.R_s}{V_T}\right) - 1 \right] - \frac{V+I.R_s}{R_p} \quad (1)$$

Where:

I_L is the Insolation current,
 I is the Cell output current,
 I_0 is the Reverse saturation current,
 V is the Cell voltage,
 R_s is the Series resistance,
 R_p is the Parallel shunt resistance,
 V_T is the Thermal voltage.

2.2 Characteristic simulation of PV cell.

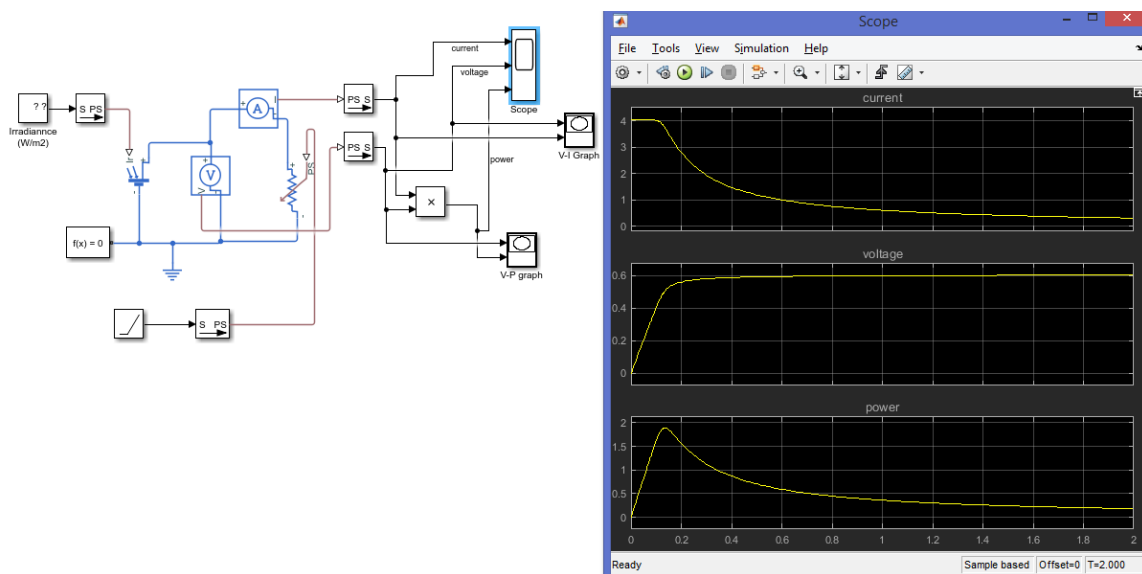


Figure 2: Solar cell output power with variable voltage (Gotika, 2015)

As Figure 2 illustrates, while the output voltage increases and the current decreases, there is a power peak. This peak is called the maximum power point.

When a PV array circuit is simulated at different temperature and irradiance, the graph presented in Figure 3 can be obtained:

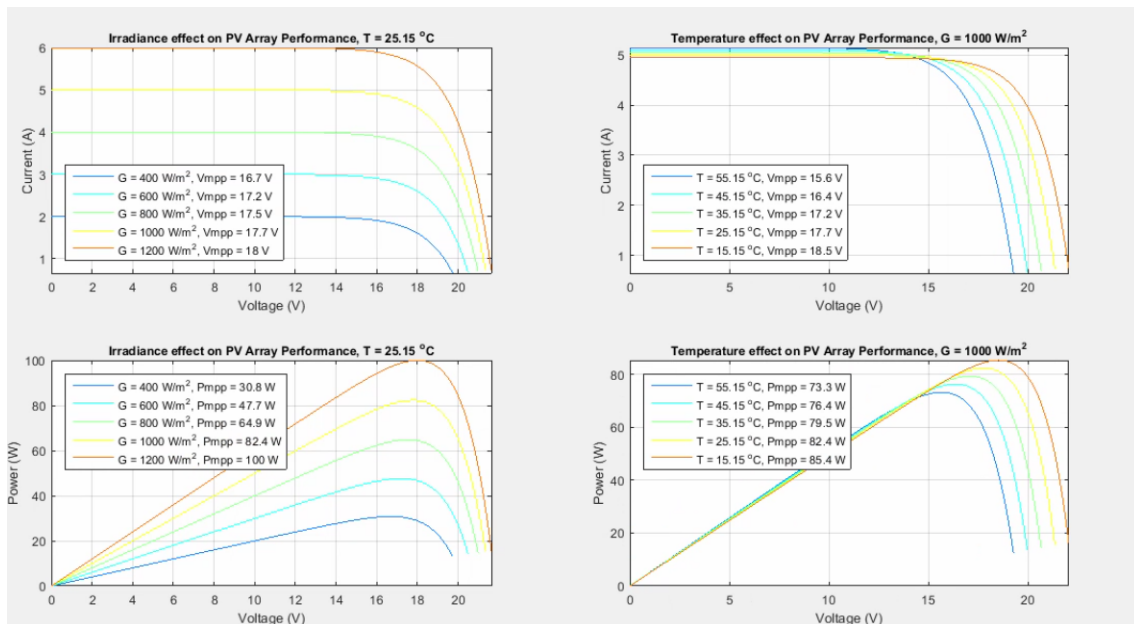


Figure 3: Effect of irradiance and temperature on output power (Gotika, 2015)

From Figure 3, it can be seen that power increases as the irradiance rises and the temperature falls. Based on these characteristics, the output power of PV arrays can be controlled to achieve fixed voltage by using PWM controller or to achieve maximum power point by using MPPT.

2.3 Solar array specification used in simulation

The PV array module used in the study is specified in Figure 4. The data shown in the Module data section is the result from testing the module under condition: light irradiance 1000W/m² and temperature 25 °C.

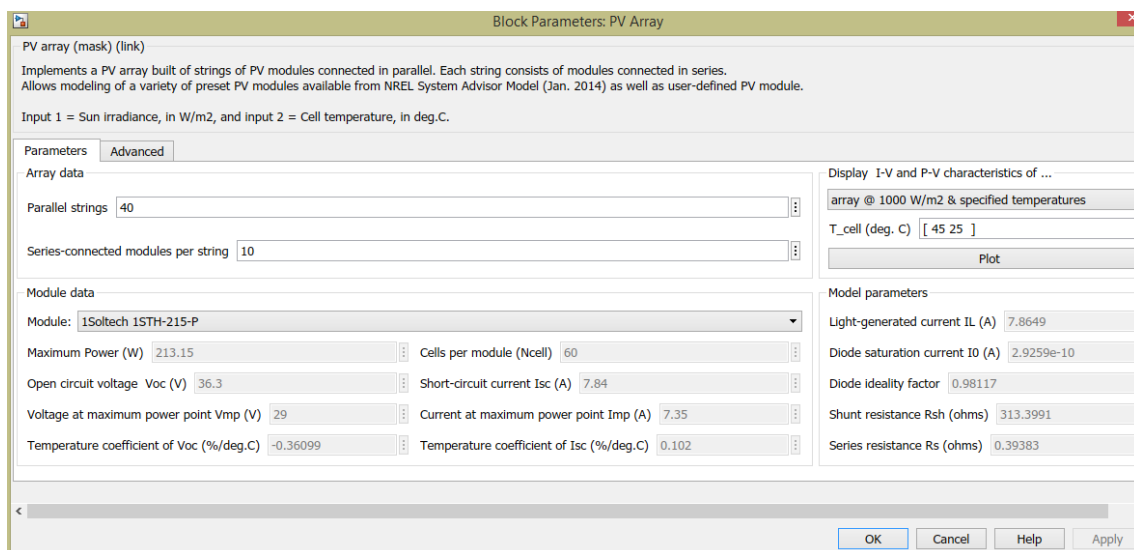


Figure 4: PV array specification used in simulation

3 WORKING PRINCIPLES OF CONTROLLERS

3.1 PWM controller

PWM controller has its voltage meter that measures output voltage and compares it with preset voltage. Based on the result, processor tries to adjust a pulse generator controlling a DC-DC converter (in this case it is a boost converter) that regulates output voltage and current of PV array.

Figure 5 shows the operation flowchart of a PWM controller. Figure 6 illustrates the Simulink circuit of the controller itself.

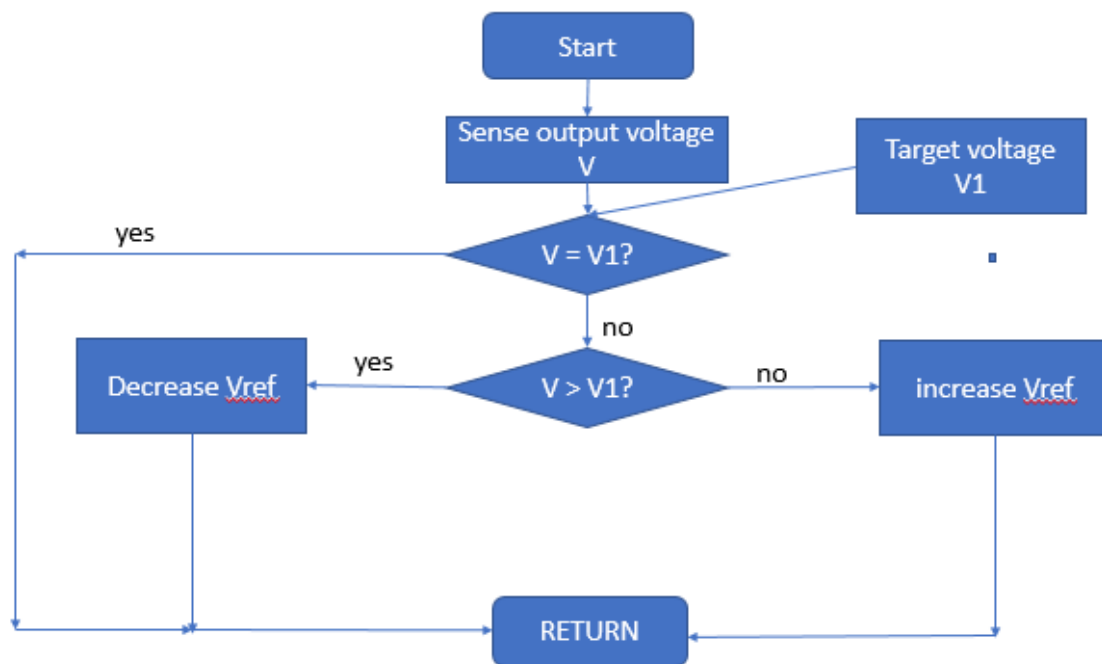


Figure 5: Operation of PWM controller

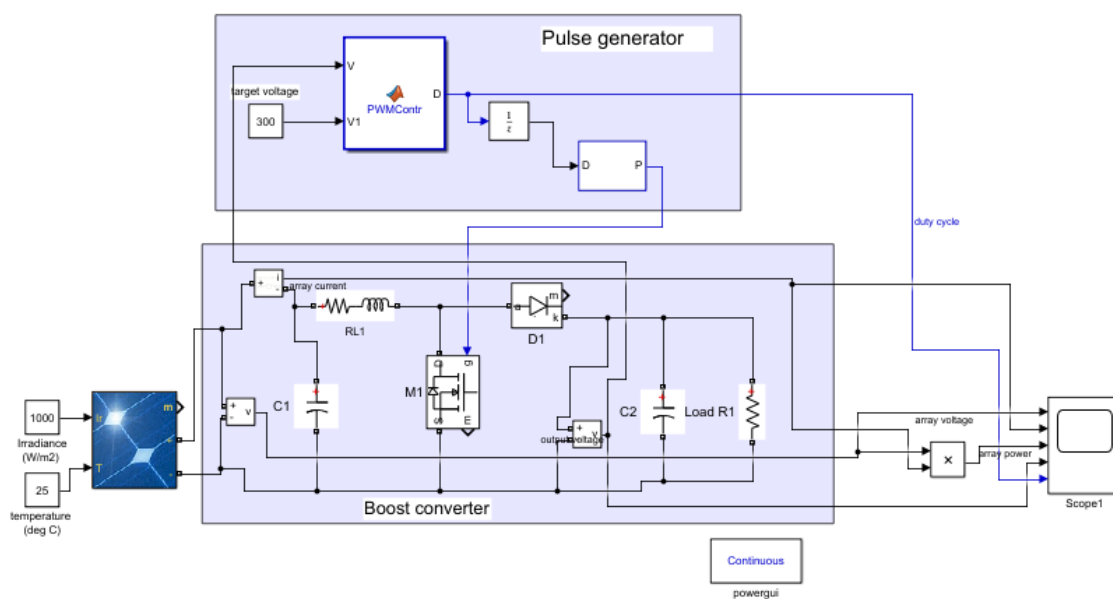


Figure 6: PWM control circuit in Simulink

```

Editor - Block: pwmshading/*
* x +
1 function D = PWMContr( V, V1)
2 persistent Dold;
3 deltaD = 1e-3;
4 dataType = 'double';
5
6 if isempty(Dold)
7
8     Dold=0.9;
9 end
10 if V ~= V1
11     if V < V1
12         D = Dold - deltaD;
13     else
14         D = Dold + deltaD;
15     end
16 else D=Dold;
17 end
18 if D >= 0.99 | D<= 0.01
19     D=Dold;
20 end
21 Dold=D;

```

Figure 7: PWM control script.

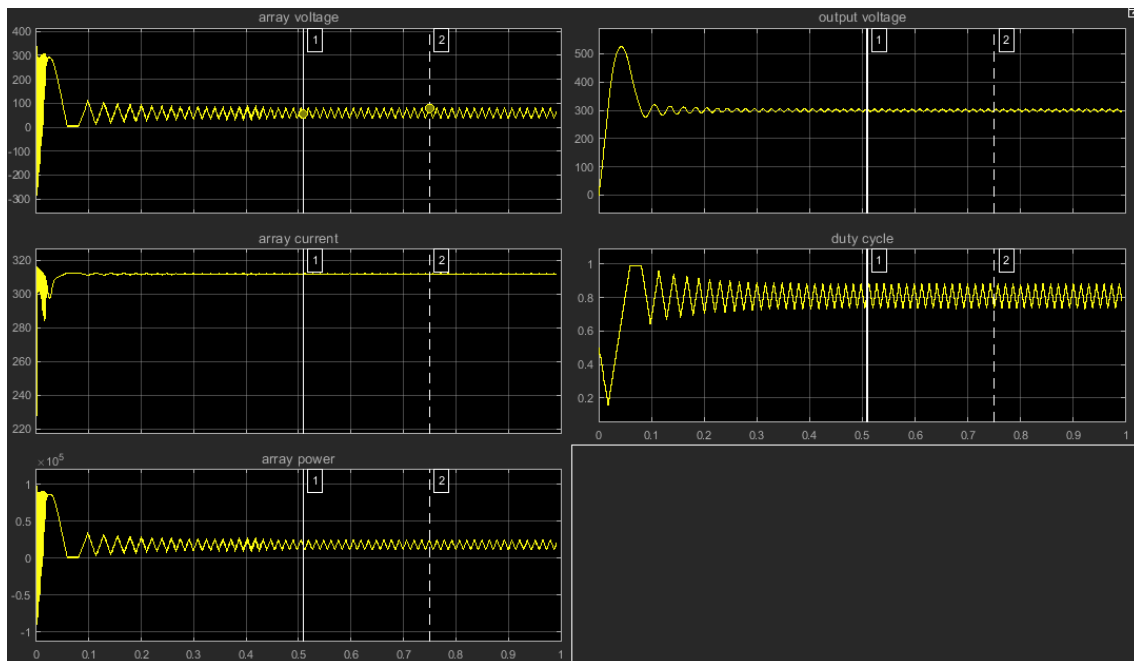


Figure 8: PWM controller test (irradiance 1000W/m². temperature 25degC)

3.2 MPPT controller

Figure 9 presents the change in power and current when changing the variable resistance of the circuit.

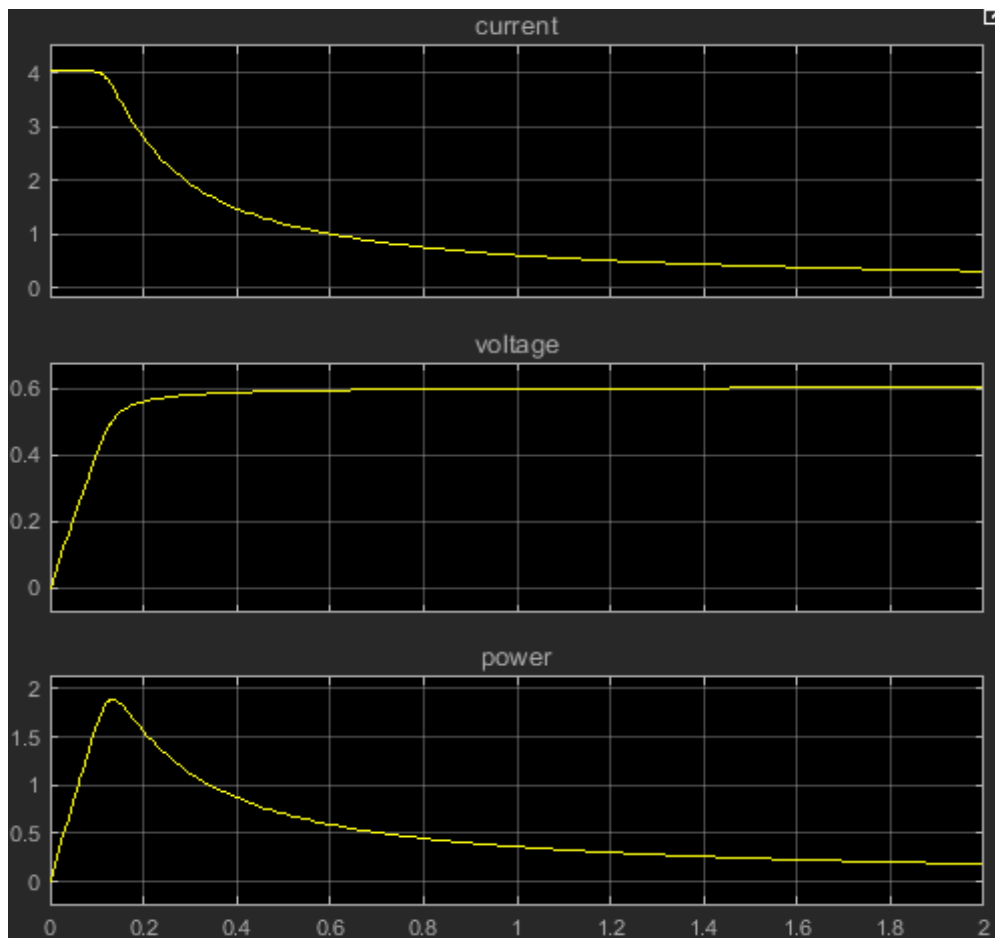


Figure 9: change in output current and power of PV array when changing load resistance (Gotika, 2015)

As the output voltage changes due to resistance change, there is a peak in the output power. This is called the maximum power point (MPP). When the PV array is connected directly to a load, its operating point is hardly maximum power point. By using MPPT algorithm to adjust duty cycle for a PWM generator to control a DC-DC converter, energy flow to load is regulated.

There are multiple algorithms that can be used, the most common one which is also used in simulation circuit is Perturbation and Observation (Pando) algorithm. Detail of the algorithm operation can be seen in Figure 10.

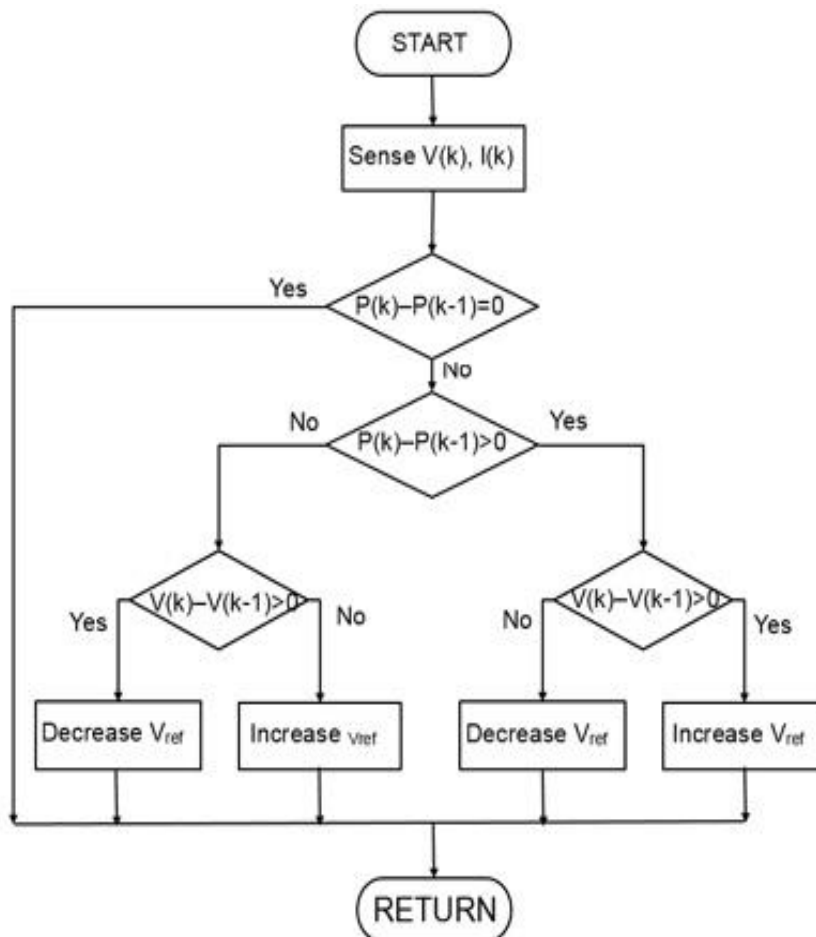


Figure 10: Working principle of Perturbation and Observation algorithm. (Mathworks, n.d.)

To change V_{ref} , controller changes duty cycle of PWM generator (a number range from 0 to 1) by ΔD . The smaller ΔD is, the smaller error output power gets and the slower it is.

Figure 11 shows the main components of MPPT controller and control circuit used in Simulink. Figures 12, 13 and 14 visualize the MPPT controller circuit diagram and script used. The script used in this study was the same as that in 400-kW Grid-Connected PV Farm (Average Model) extracted from Matlab library by using command `power_4PVarray_400kW`.

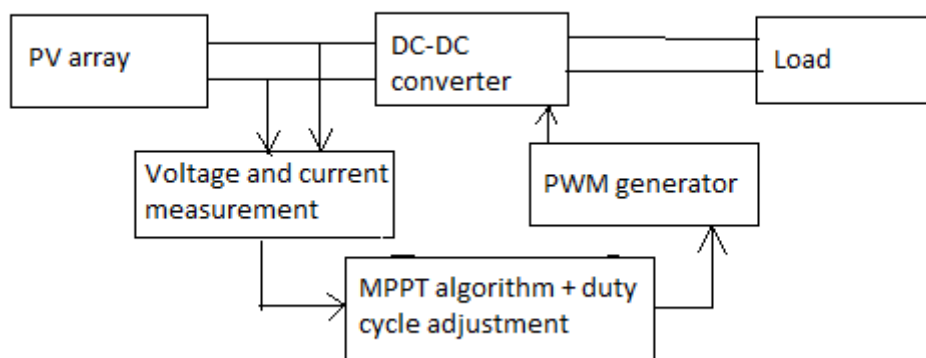


Figure 11: Main component of MPPT controller (Gotika, 2015)

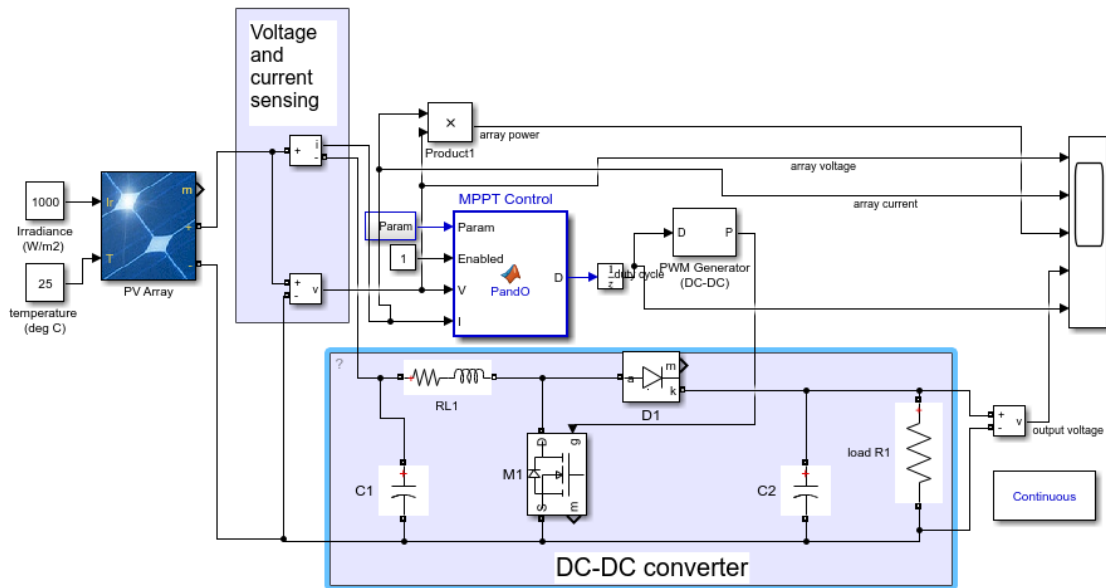


Figure 12: Simulink MPPT control circuit (Tuan, 2019)

Parameters for Perturb and Observe Algorithm:

(D = Boost converter duty cycle)

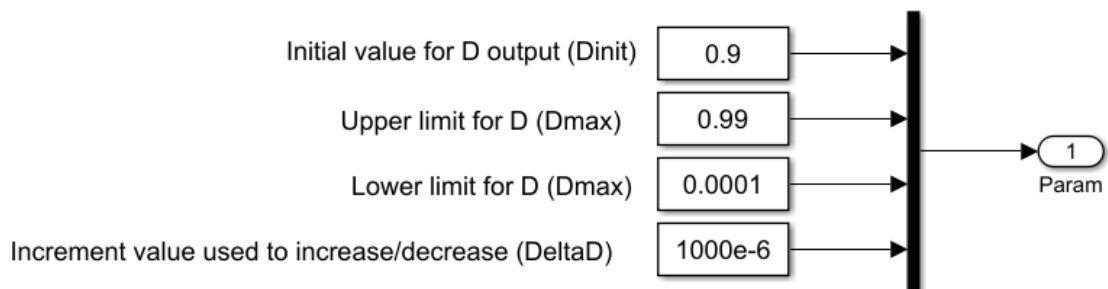


Figure 13: Parameter inputs for control block (Mathworks, n.d.)

```

1 function D = PandO(Param, Enabled, V, I)
2     Dinit = Param(1); %Initial value for D output
3     Dmax = Param(2); %Maximum value for D
4     Dmin = Param(3); %Minimum value for D
5     deltaD = Param(4); %Increment value used to increase/decrease the duty cycle D
6     % ( increasing D = decreasing Vref )
7     persistent Vold Pold Dold;
8     dataType = 'double';
9     if isempty(Vold)
10        Vold=0;
11        Pold=0;
12        Dold=Dinit;
13    end
14    P= V*I;
15    dV= V - Vold;
16    dP= P - Pold;
17    if dP ~= 0 & Enabled ~=0
18        if dP < 0
19            if dV < 0
20                D = Dold - deltaD;
21            else
22                D = Dold + deltaD;
23            end
24        else
25            if dV < 0
26                D = Dold + deltaD;
27            else
28                D = Dold - deltaD;
29            end
30        end
31    else D=Dold;
32    end
33    if D >= Dmax || D<= Dmin
34        D=Dold;
35    end
36    Dold=D;
37    Vold=V;
38    Pold=P;

```

Figure 14: MPPT control script (Mathworks, n.d.)

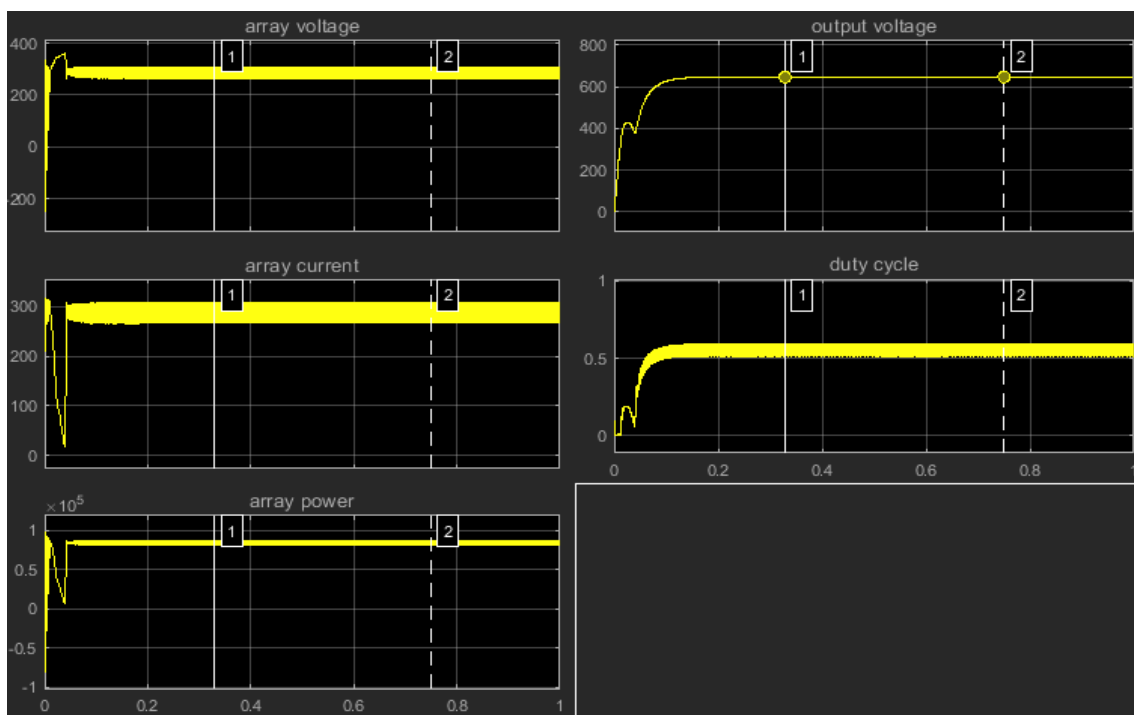


Figure 15: MPPT controller test (irradiance 1000 W/m², temperature 25degC)

3.3 MPPT-PI controller

Figure 16 visualizes the $\Delta P/\Delta V$ value of different parts of PV array power curve. It is noticed that only $\Delta P/\Delta V$ value of MPPT peak equals 0. By using the $\Delta P/\Delta V$ value as an input error of the PI controller, the duty cycle of the DC-DC converter can be adjusted to meet the power peak. Figure 17 illustrates the circuit diagram of the MPPT-PI controller for testing. Figure 18 shows the script used by the controller and Figure 19 shows the result of the circuit test.

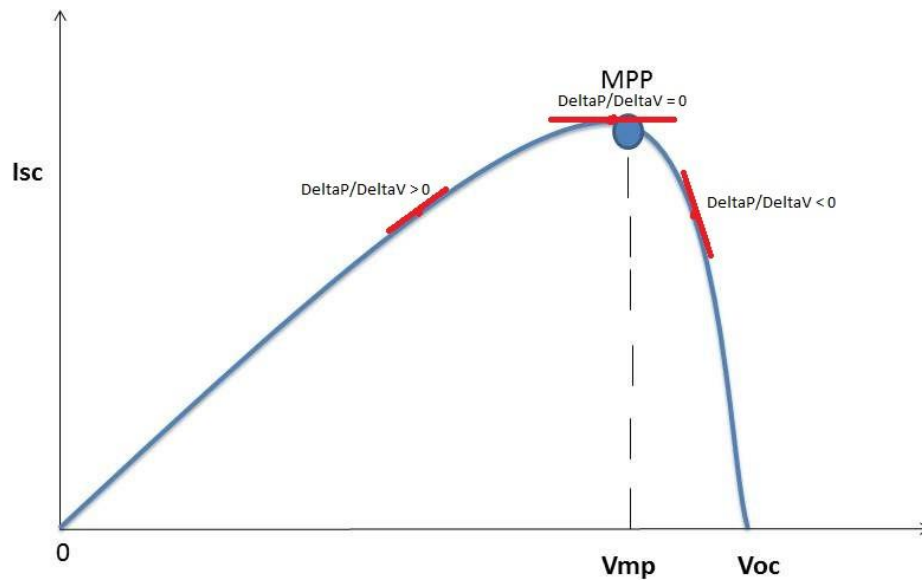


Figure 16: $\Delta P/\Delta V$ value of PV array power curve

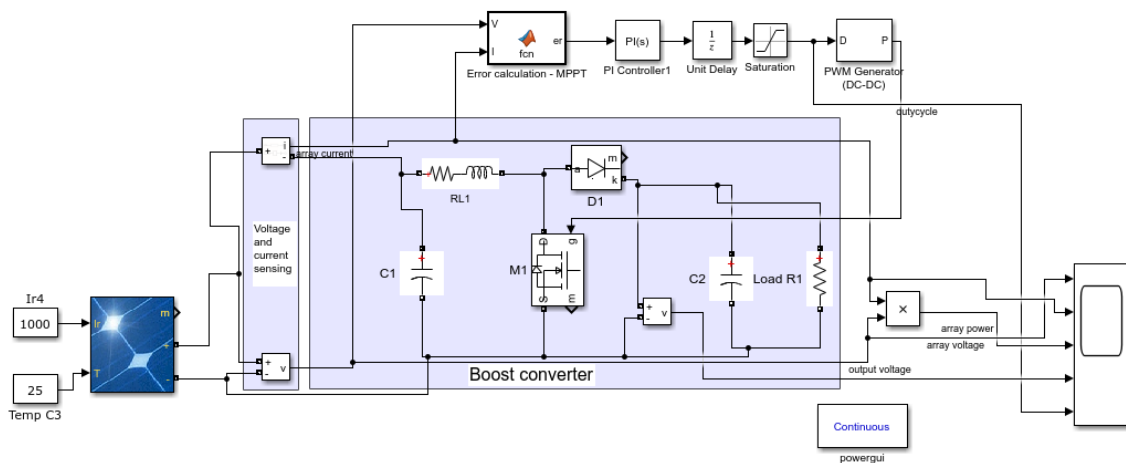


Figure 17: Simulink MPPT-PI circuit

```

1  function er = fcn(V,I)
2
3  - persistent Vold Pold;
4
5  - dataType = 'double';
6
7  - if isempty(Vold)
8      Vold=0;
9      Pold=0;
10 - end
11 - P= V*I;
12 - dV= V - Vold;
13 - dP= P - Pold;
14
15 - if dV == 0
16 -     dV1 = 1;
17 - else dV1=dV;
18 - end
19 - e1=dP/dV1;
20 - if V > Vold
21 -     er=e1;
22 - else er=e1*(-1);
23 - end
24
25 - Vold=V;
26 - Pold=P;
27

```

Figure 18: MPPT script used in MPPT-PI controller

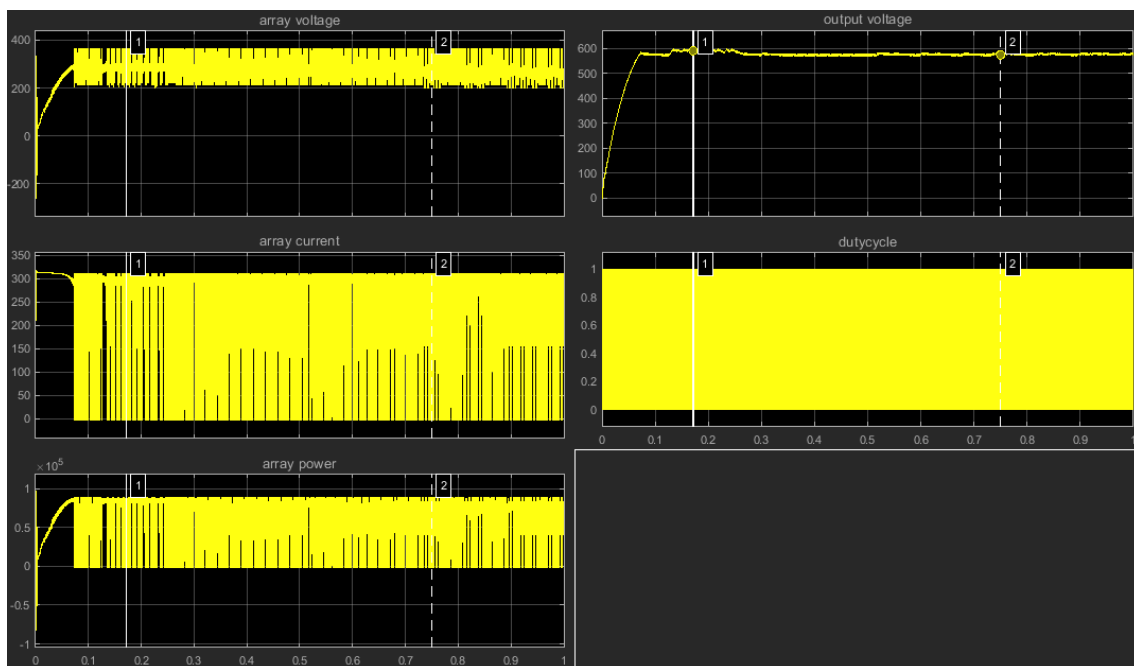


Figure 19: MPPT-PI controller test (light irradiance 1000W/m², temperature 25degC)

4 DC-DC CONVERTER

A DC-DC converter is used to regulate array voltage and output voltage to load. With MPPT and MPPT-PI controllers, the goal of the MPPT is to match the impedance of load to the optimal impedance of PV module thus changing array voltage and current (Kolsi & Samet & Ben Amar, 2014, p.1). Figure 2 suggests that by adjusting the array voltage, the PV array power can be changed as well, thus affecting the output power to load. In the case of PWM controller, converter is used to adjust output voltage to match the preset target voltage. In this study, boost converter is used by all controllers. Simulink circuit of the converter can be seen in figure 5. Value of components can be seen in table 1.

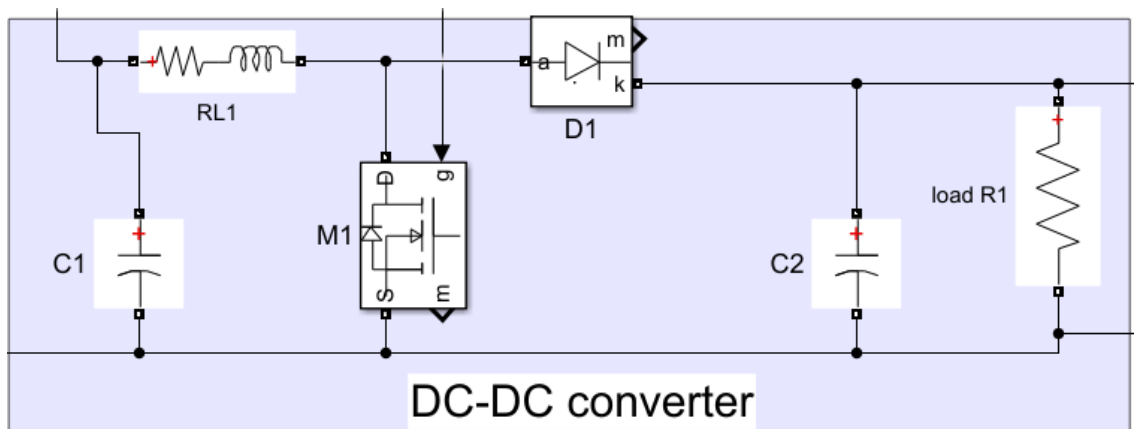


Figure 20: Boost converter circuit

Table 1: Specifications of DC-DC boost converter circuit parts

Circuit parts	Value
Capacitor C1	Capacitance C 200e-6 F
Resistor Inductor series RL1	Resistance R 1e-3 Ohms, inductance L 250e-6 H
Mosfet M1	FET resistance Ron 1e-3 Ohms, Internal diode resistance Rd 1e-3 Ohms, Internal diode forward voltage Vf 0 V, Snubber resistance Rs inf, Snubber capacitance Cs inf
Capacitor C2	Capacitance C 1000e-5 F
Diode D1	Resistance Ron 1e-3 Ohms, Forward voltage Vf 0 V, Snubber resistance Rs inf, Snubber capacitance Cs inf
Load R1	5 Ohms

5 ENVIRONMENT SCENARIOS USED IN THE STUDY

There were two environment scenarios where control methods were simulated in:

- Partial shading.
- Different seasons.

5.1 Partial shading

Usually, PV modules which consist of PV cells are connected in series, then these PV cell strings are connected in parallel to form PV array as in Figure 21.

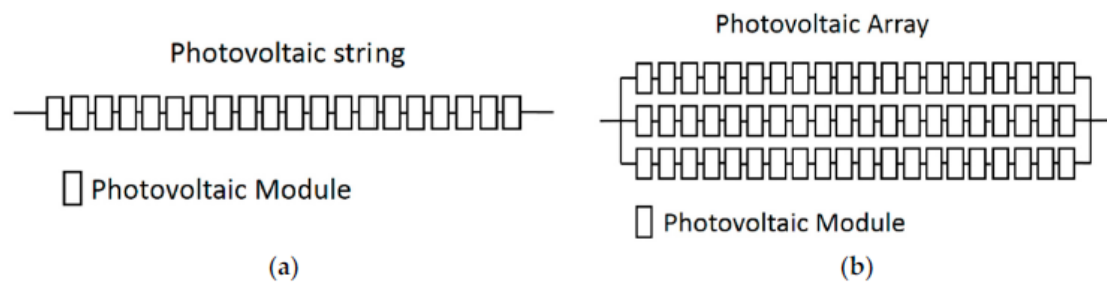


Figure 21: Photovoltaic array a) PV string; b) PV array (Teo & Tan & Mok & Ramachandaramurthy & Tan, 2018)

Partial shading happens when a part of PV array is shaded, leading to the difference in irradiance of light received by series of PV cells. Simulink was used to study the effect of partial shading on PV array. Circuit used in Simulink and the results are illustrated in Figure 22 and 23 respectively.

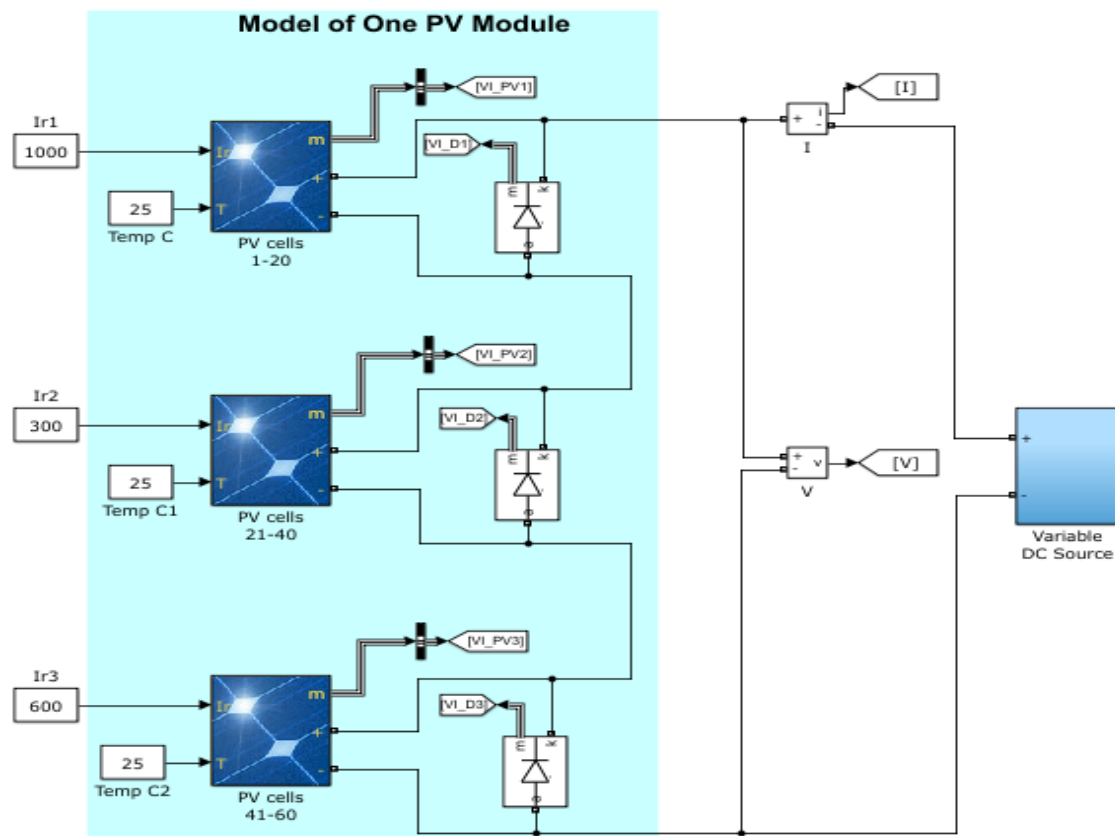


Figure 22: PV array used in partial shading study (Mathworks, n.d.)

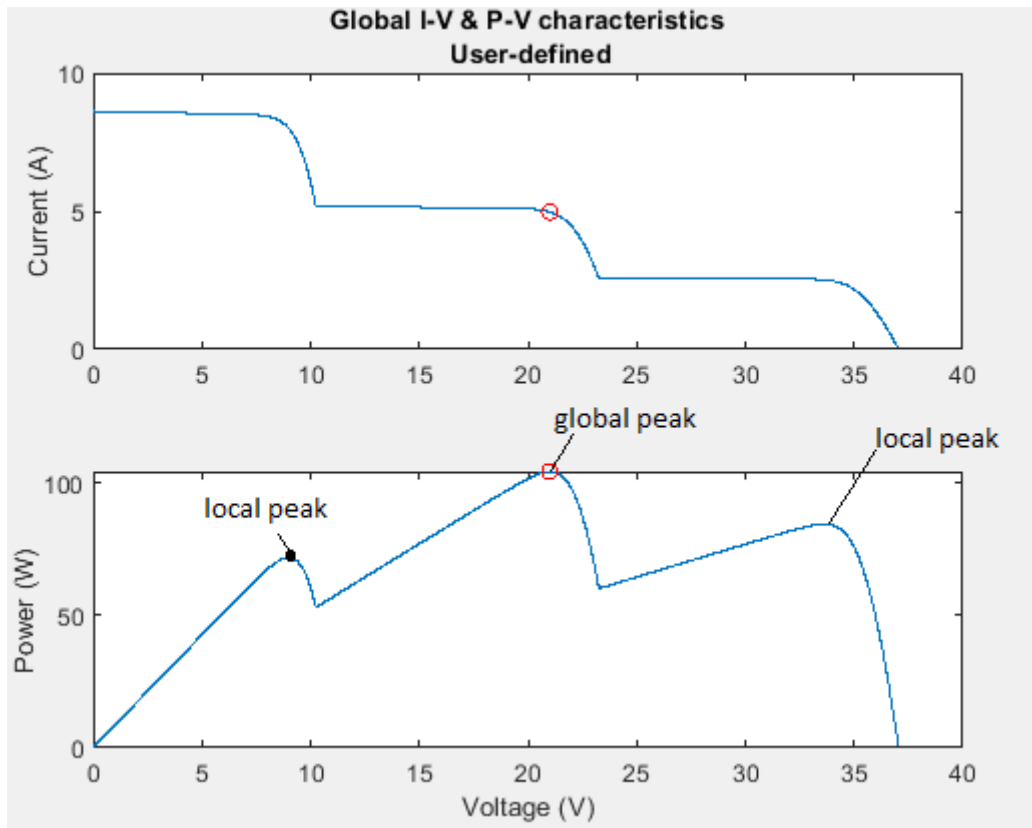


Figure 23: I-V and P-V characteristics of partially shaded PV array in experiment (Mathworks, n.d.)

Due to the difference in current produced by PV cells and bypass diodes, multiple peaks are created. The highest one is called the global peak while other ones are local peaks.

5.2 Multiple seasons.

As seasons change from summer to winter and vice versa, light irradiance and temperature also change, which can affect PV array performance. Figure 3 describes that simulated PV array output power increases as temperature falls and irradiance rises. Figure 24 and 25 represent the Simulink circuit designed to study unregulated PV array power output in the scenario and results.

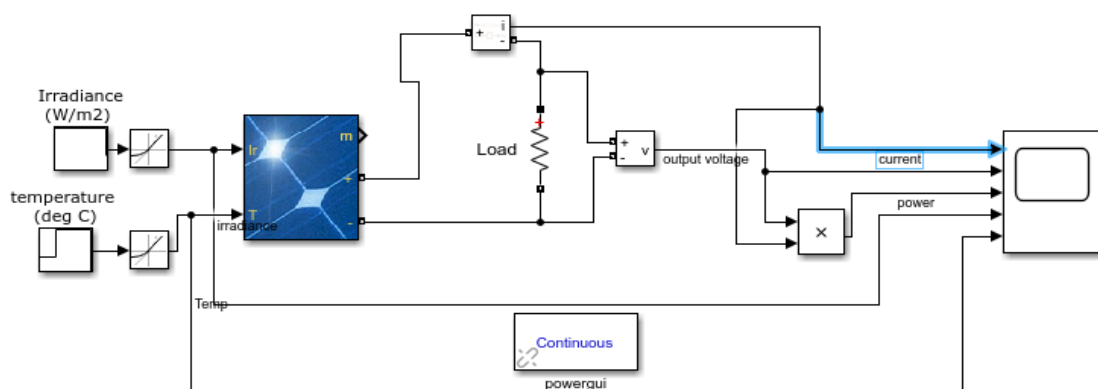


Figure 24: Unregulated solar array simulated in Simulink in different seasons scenario

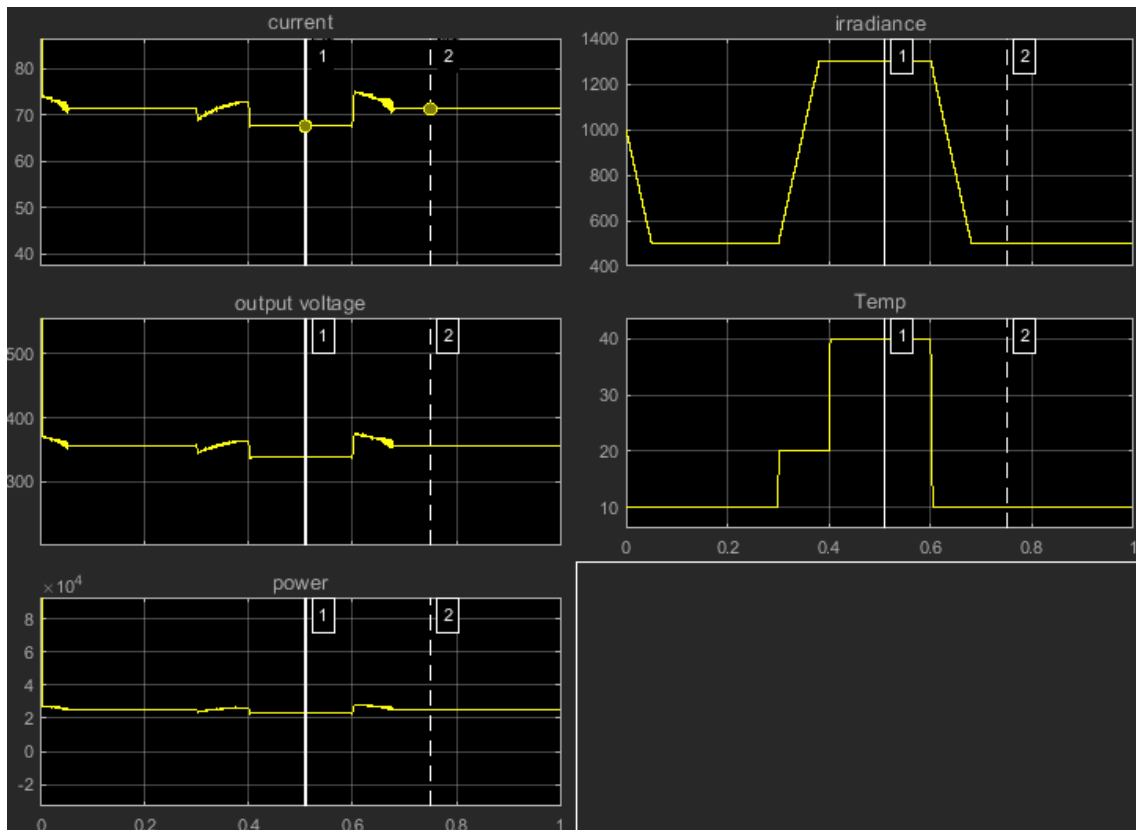


Figure 25: Solar cell unregulated output power in simulated scenario.

6 SIMULATION CIRCUITS AND RESULTS

6.1 Partial shading

6.1.1 Simulation strategy

To test how controllers adapted to the peaks formed by partial shading, 2 out of three arrays will have their irradiance dropping from 1000 W/m² to 600 W/m² and 300 W/m² after 0,3s.

6.1.2 PWM controller simulation in partial shading case

Figures 26, 27 show the PWM circuit and simulation results in partial shading scenario.

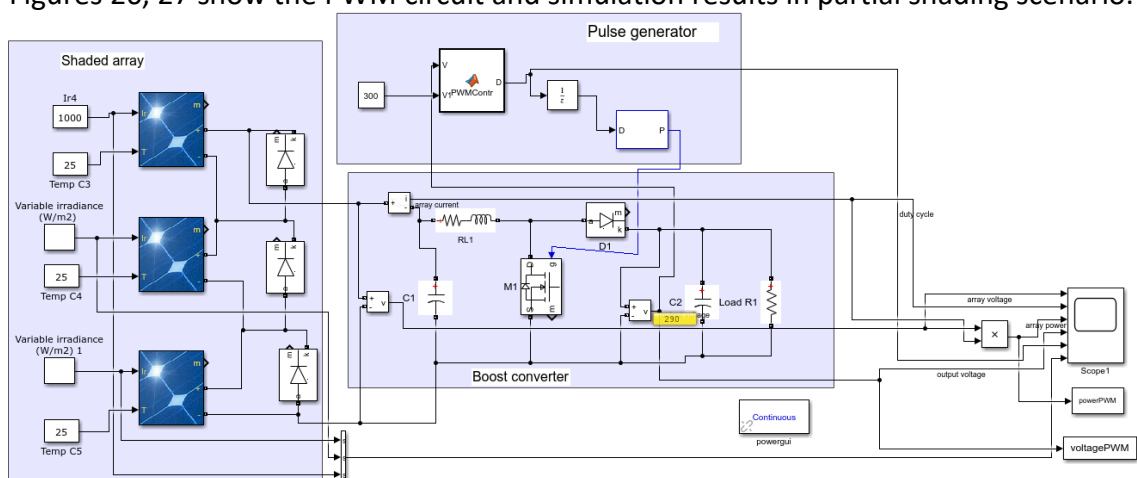


Figure 26: PWM controlled PV array in Simulink (partial shading)

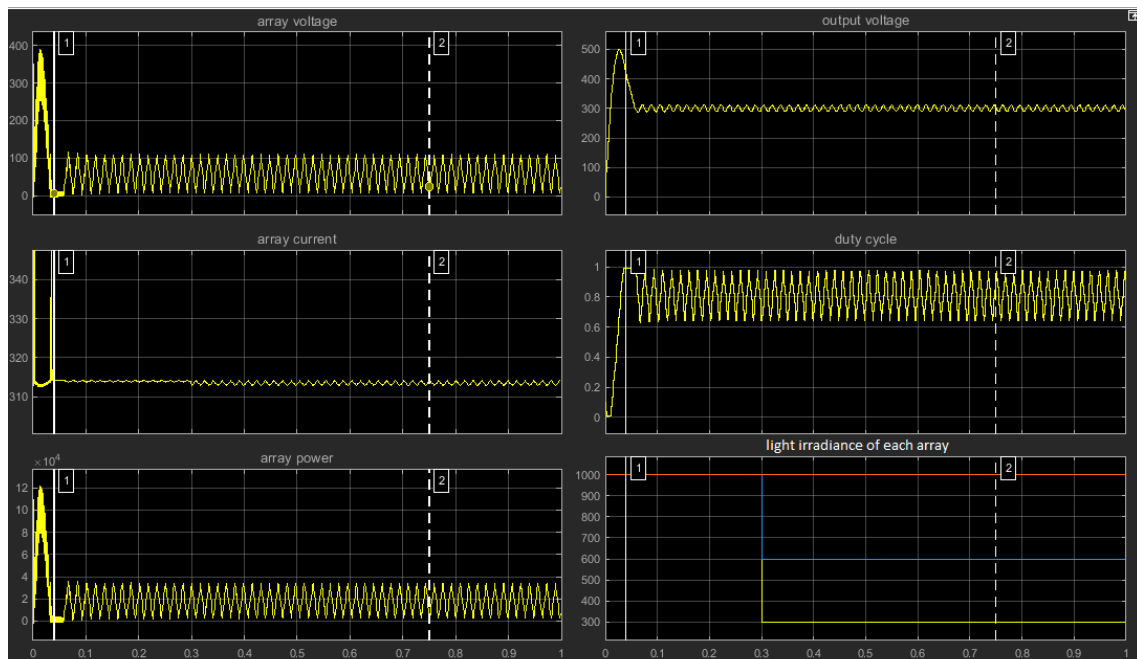


Figure 27: array power, output voltage and duty cycle from PWM controller with setpoint voltage 300V

6.1.3 MPPT controller simulation in partial shading case

Figures 28 and 29 visualize the MPPT controller circuit and simulation results in partial shading scenario with both starting duty cycle.

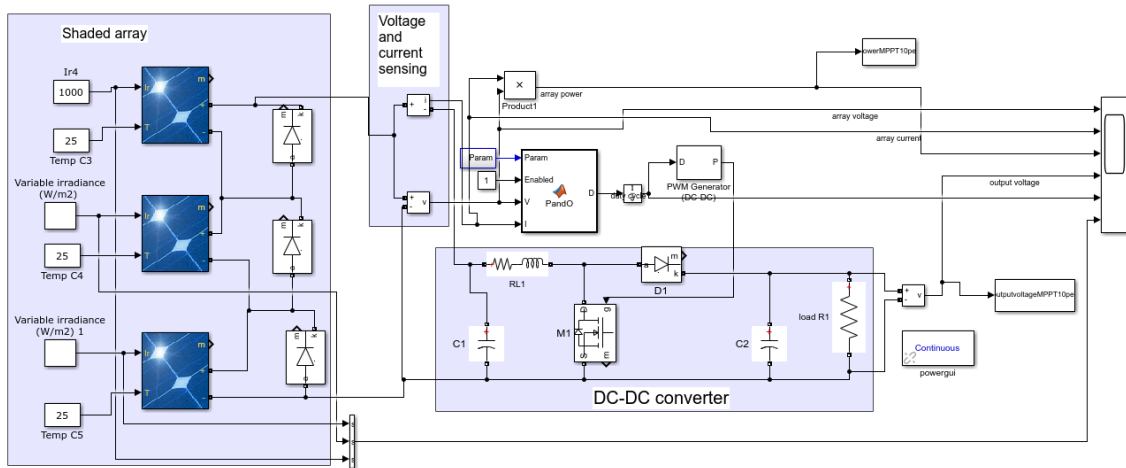


Figure 28: MPPT controlled PV array in Simulink (partial shading)

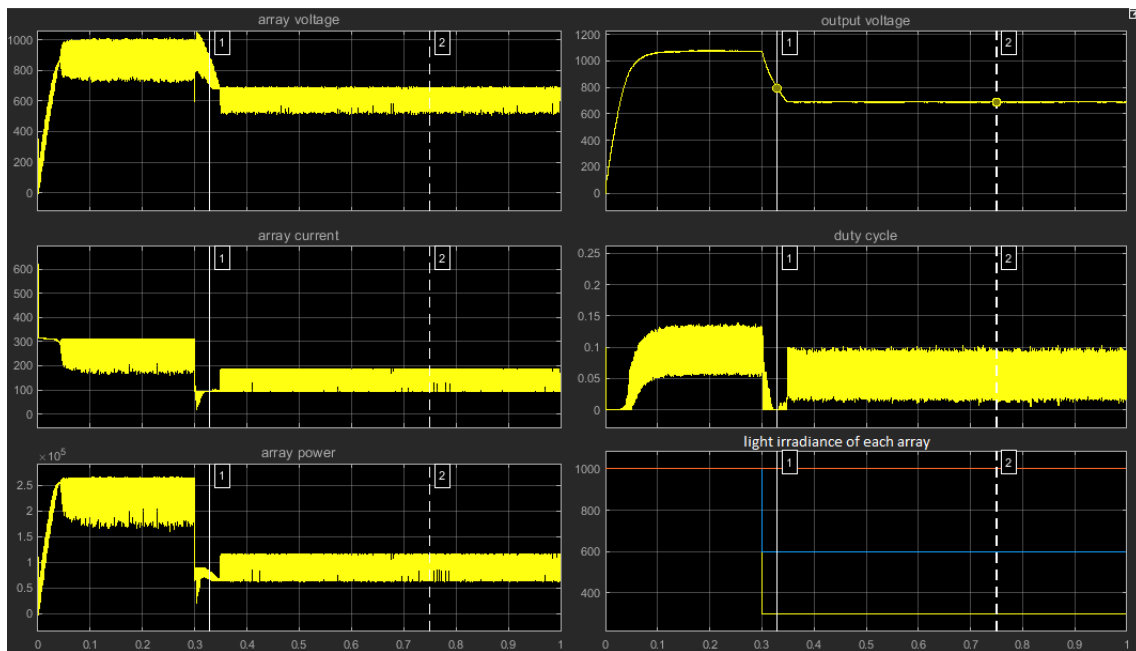


Figure 29: MPPT PV array voltage, current and power before converter and output voltage, duty cycle of converter

6.1.4 MPPT-PI controller in partial shading scenario

Figures 30 and 31 visualize the PWM circuit and simulation result in partial shading scenario.

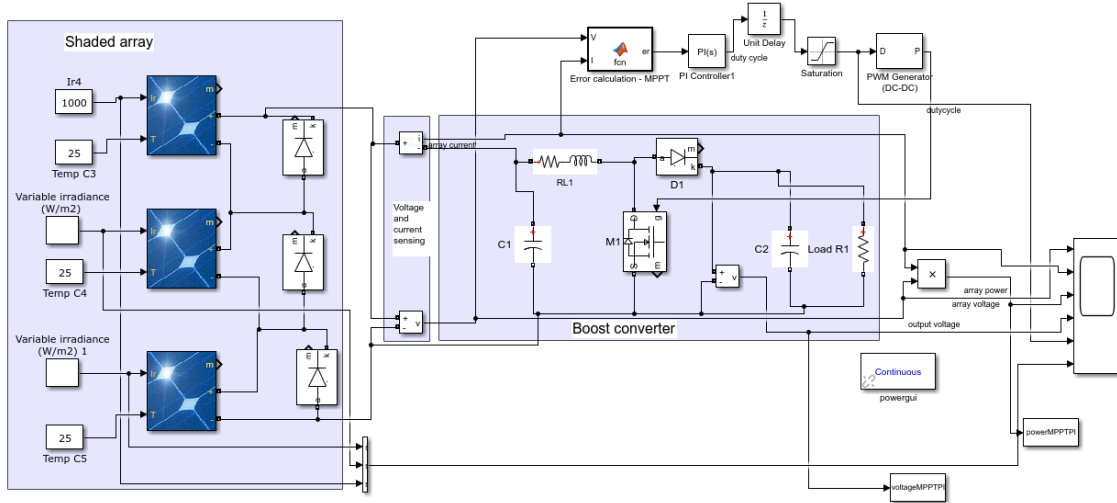


Figure 30: Partially shaded PV array MPPT-PI controller

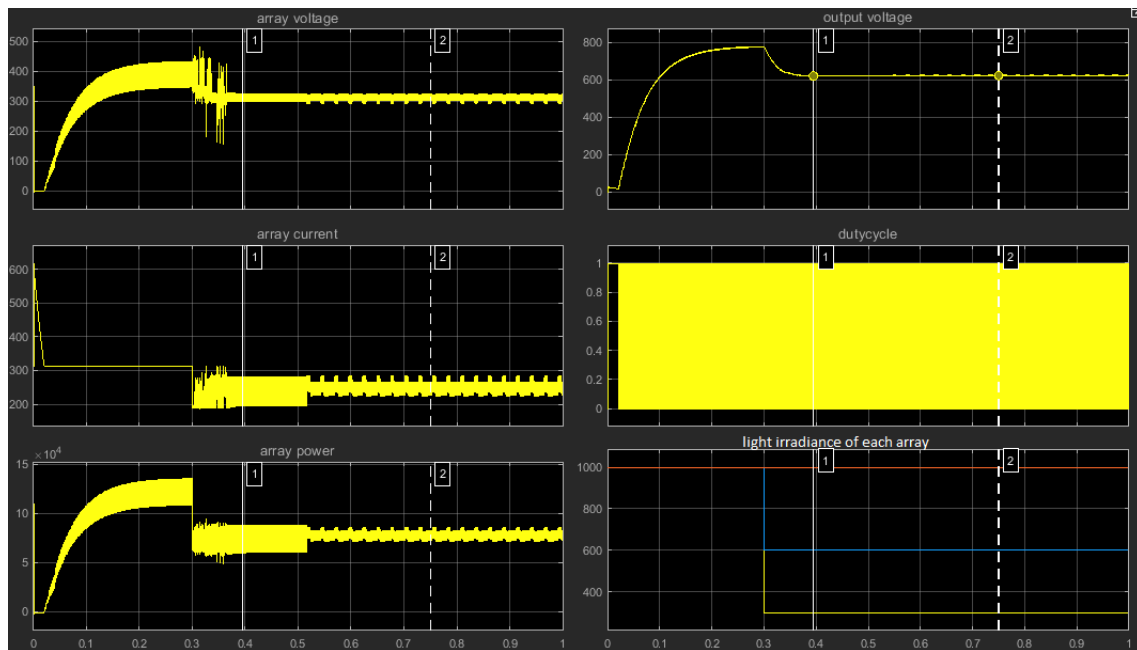


Figure 31: partially shaded PV array power before converted and output voltage from converter, duty cycle of converter

6.2 Different seasons

6.2.1 Simulation strategy

To test how controllers adapted to different power levels generated during different seasons, light irradiance and temperature were changed over time to simulate seasons. Two main seasons were selected: a hot season with a high temperature and a high light irradiance and a cold season with a low light irradiance and a low temperature.

6.2.2 PWM control method during different seasons case.

Figures 32, 33 and 34 visualize PWM control circuit and simulation results in different seasons case.

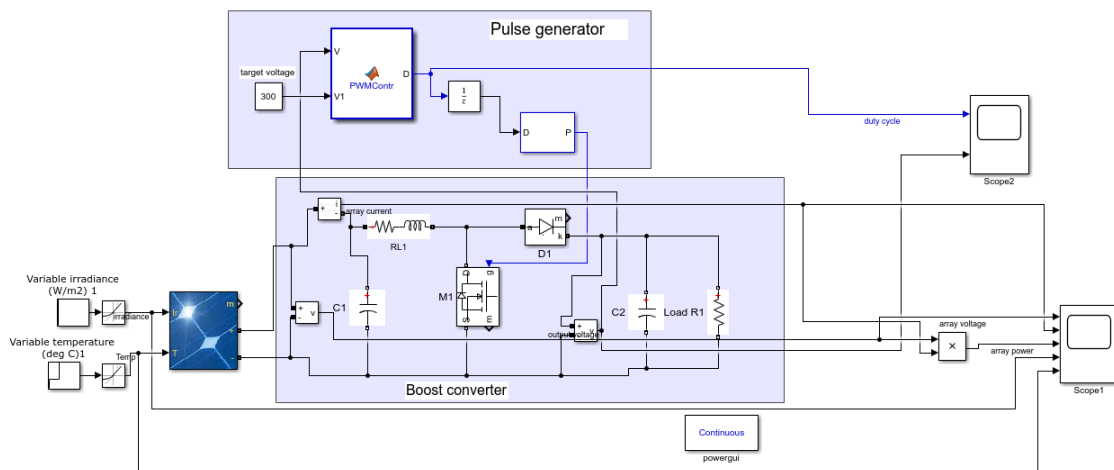


Figure 32: PWM control PV array circuit in Simulink (different seasons)

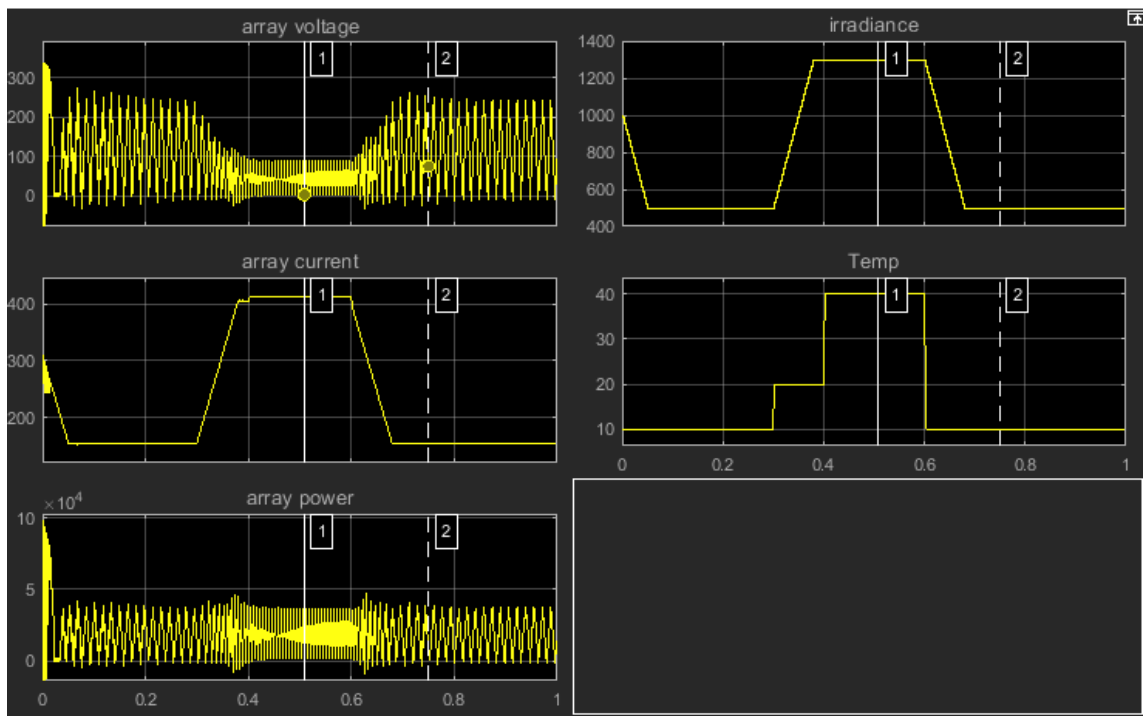


Figure 33: power from PV array, irradiance and temperature

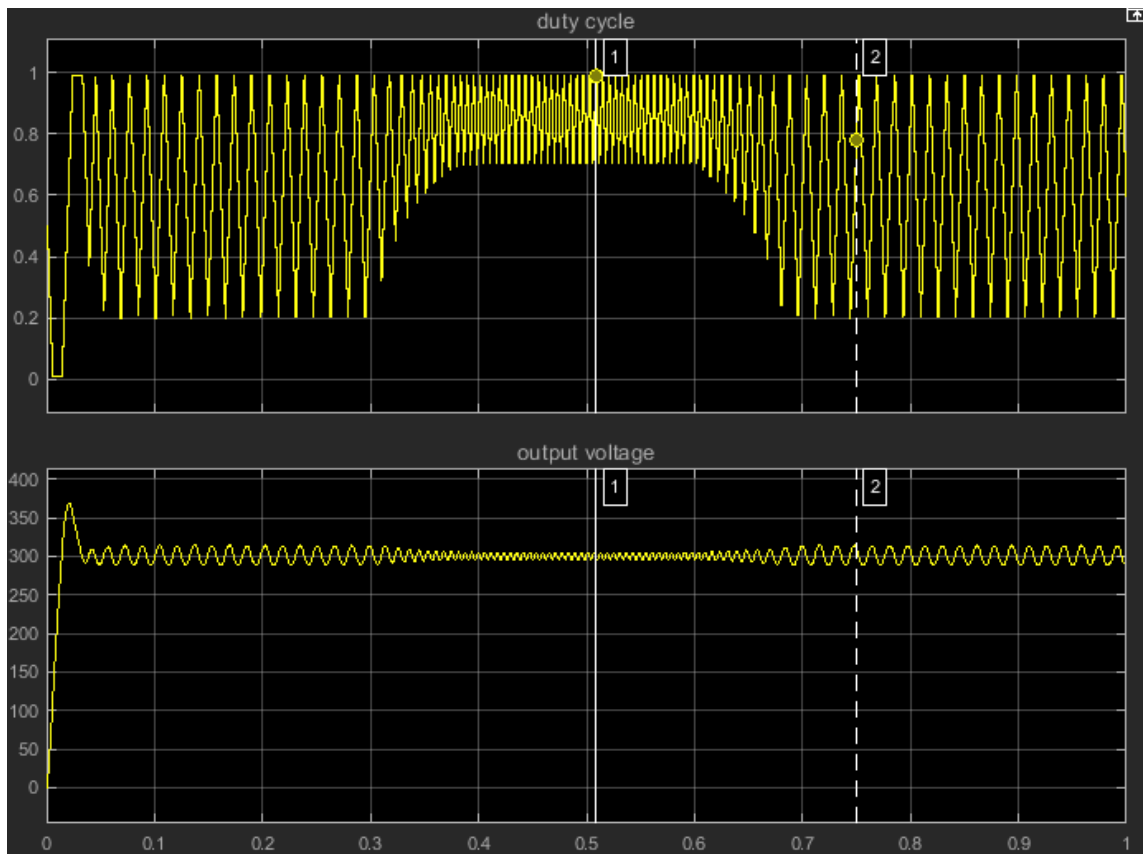


Figure 34: output voltage and duty cycle of converter

6.2.3 MPPT control method in different seasons case

MPPT control circuit and simulation results when seasons change are shown in Figures 35, 36 and 37.

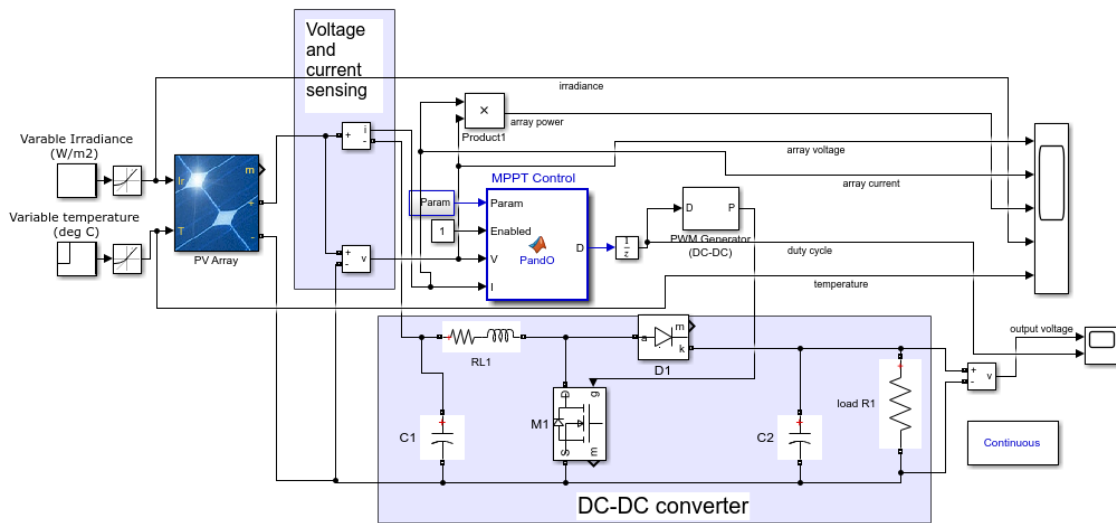


Figure 35: MPPT controlled PV array in Simulink (different seasons)

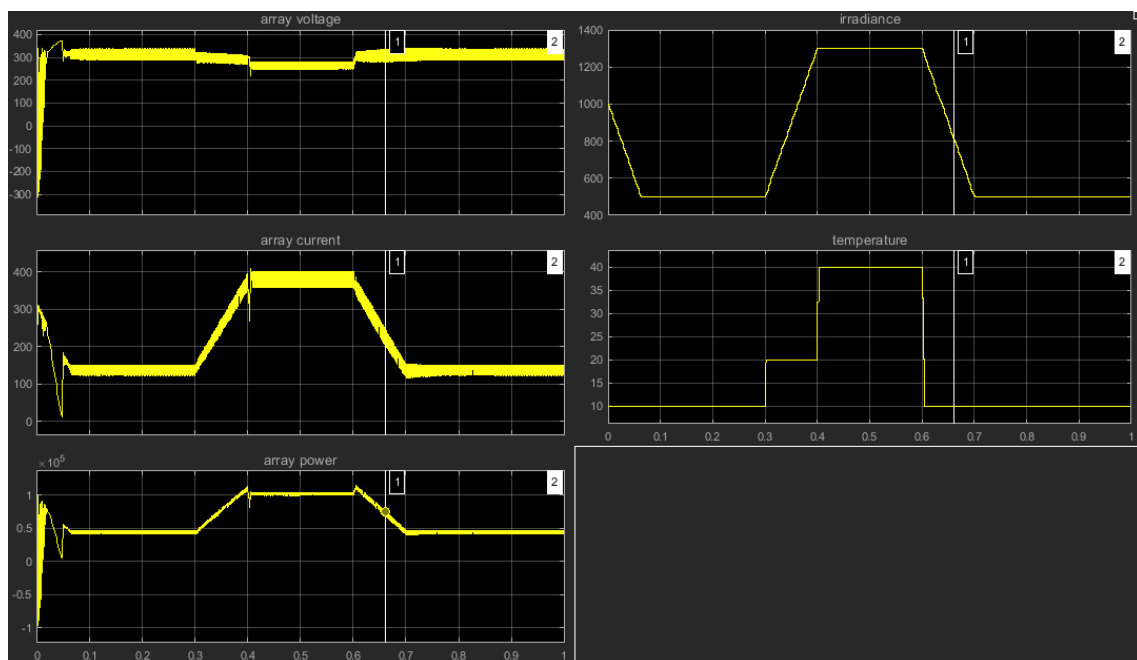


Figure 36: array voltage, current, power, irradiance and temperature during different seasons

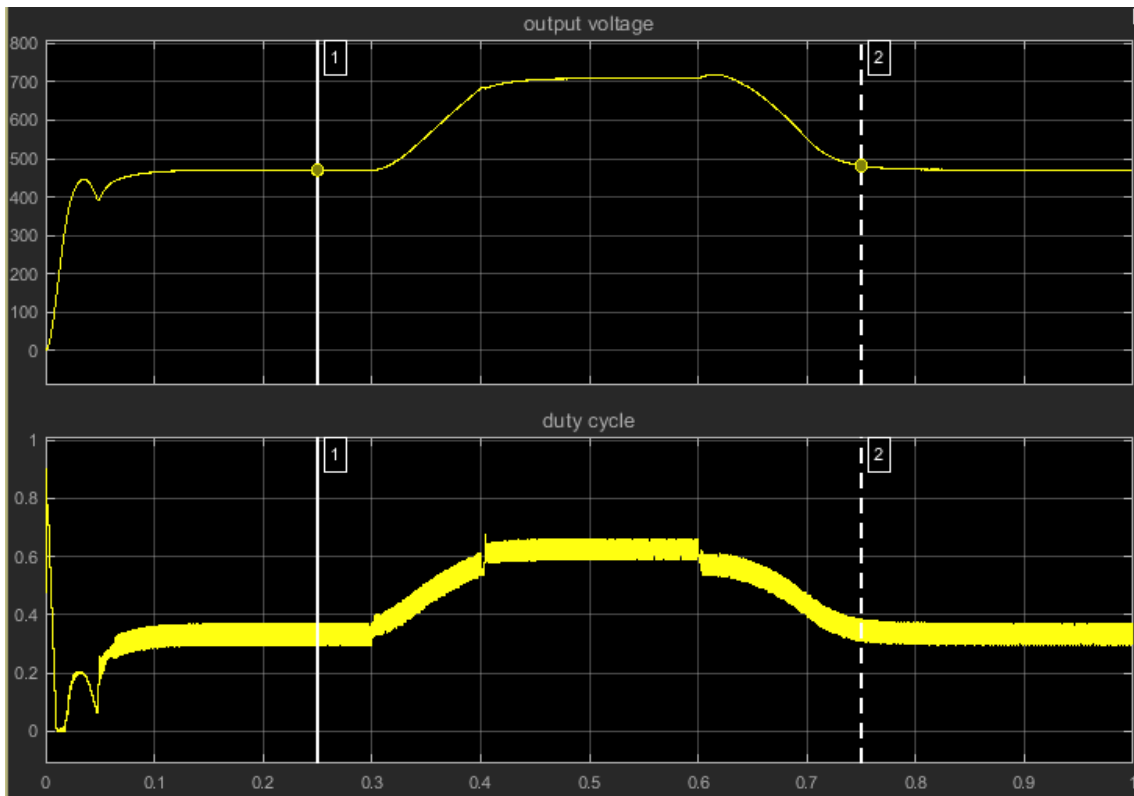


Figure 37: output voltage and duty cycle of DC-DC converter MPPT control method in different seasons scenario

6.2.4 MPPT-PI control method in different seasons scenario

Figures 38, 39 and 40 visualize MPPT-PI control circuit and simulation results in different seasons case.

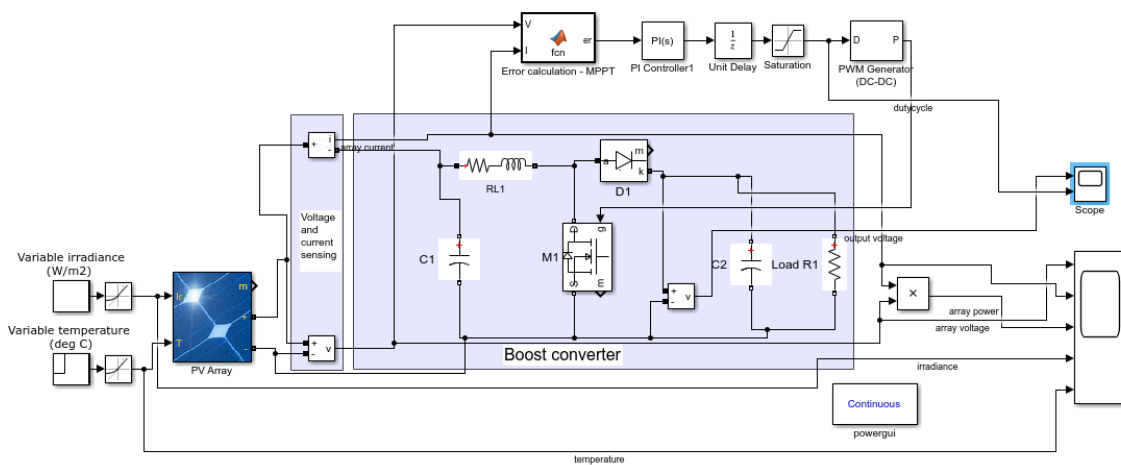


Figure 38: MPPT-PI controller used in different seasons case

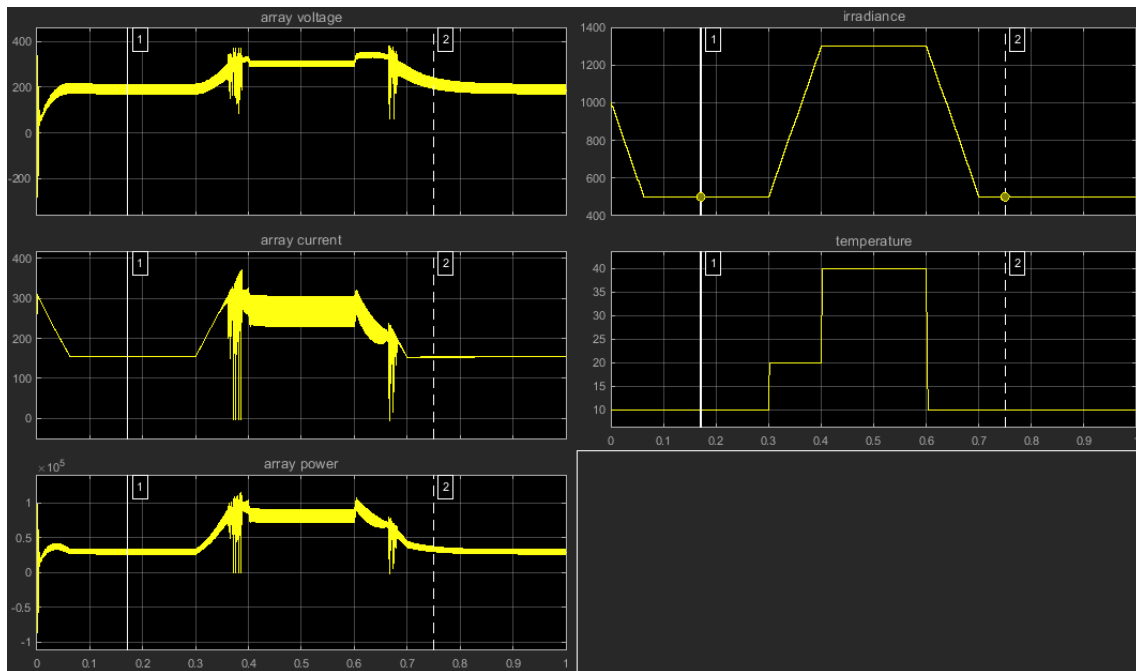


Figure 39: array voltage, current, power, irradiance and temperature during different seasons

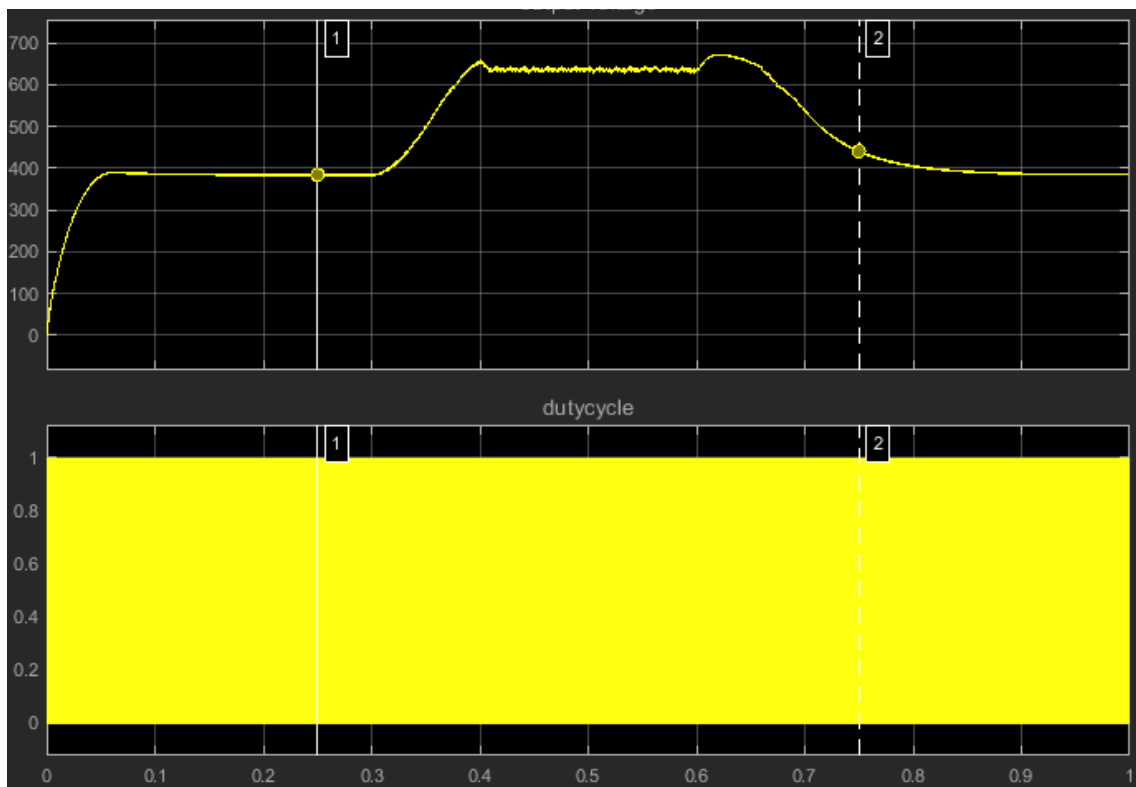


Figure 40: output voltage and duty cycle of controller during different seasons

7 RESULTS AND COMPARISON OF SIMULATIONS

7.1 Partial shading scenario

Figures 41 and 42 illustrate the output voltage and the array power of control methods extracted from the simulation results for comparison.

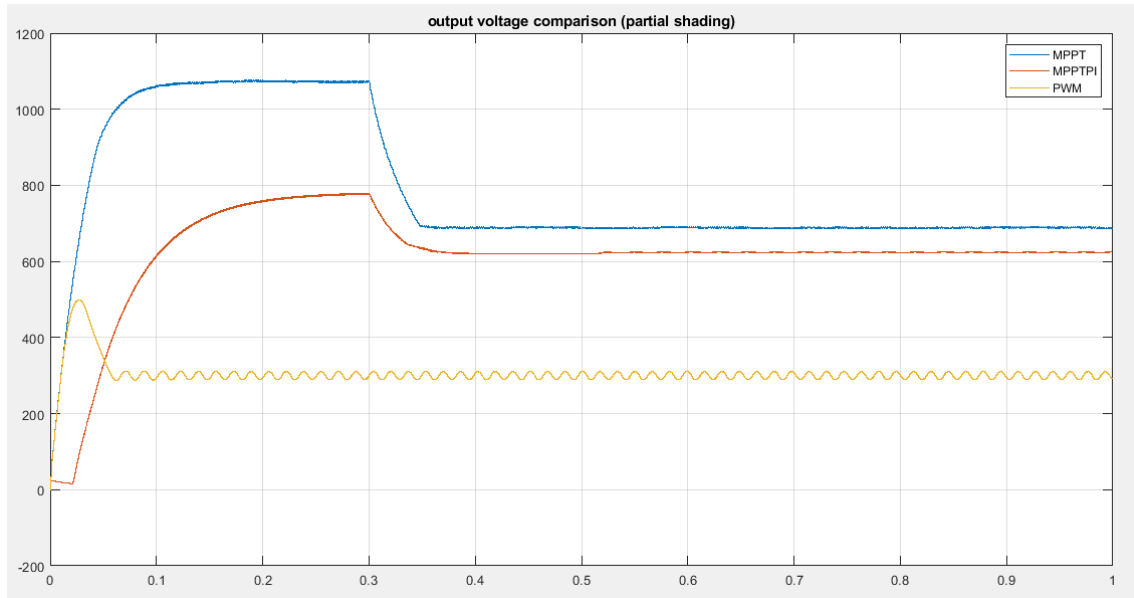


Figure 41: output voltage of three methods (partial shading)

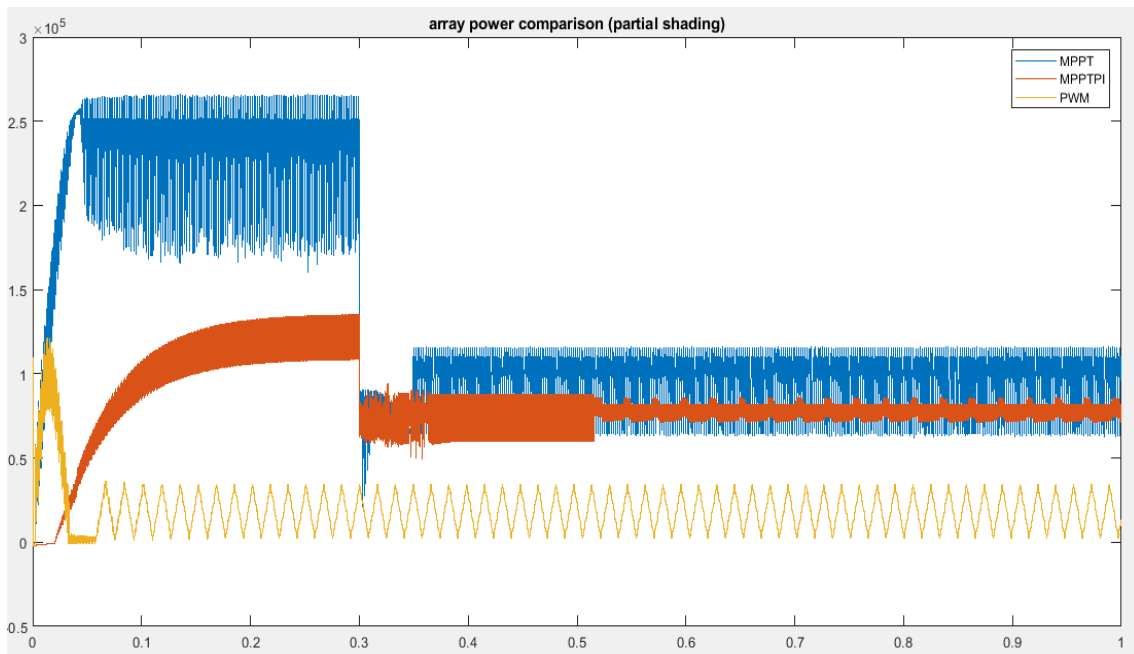


Figure 42: array power comparison of three methods (partial shading)

Table 2 was made for an analysis of the data.

Table 2: Result comparison between three methods (partial shading case)

	PWM	MPPT	MPPT-PI
Output voltage	300V	720V	620V
Array power	20000 W average	110000 W average	80000 W average

Based on the results, it was clear that while the PWM controller had an output voltage close to the setpoint voltage, it had the lowest array power. The MPPT controller had higher output voltage and array power than the MPPT-PI controller.

7.2 Different seasons scenario

Figures 47 and 48 visualize the data on the output voltage and array power extracted from different seasons scenario simulations of all three methods.

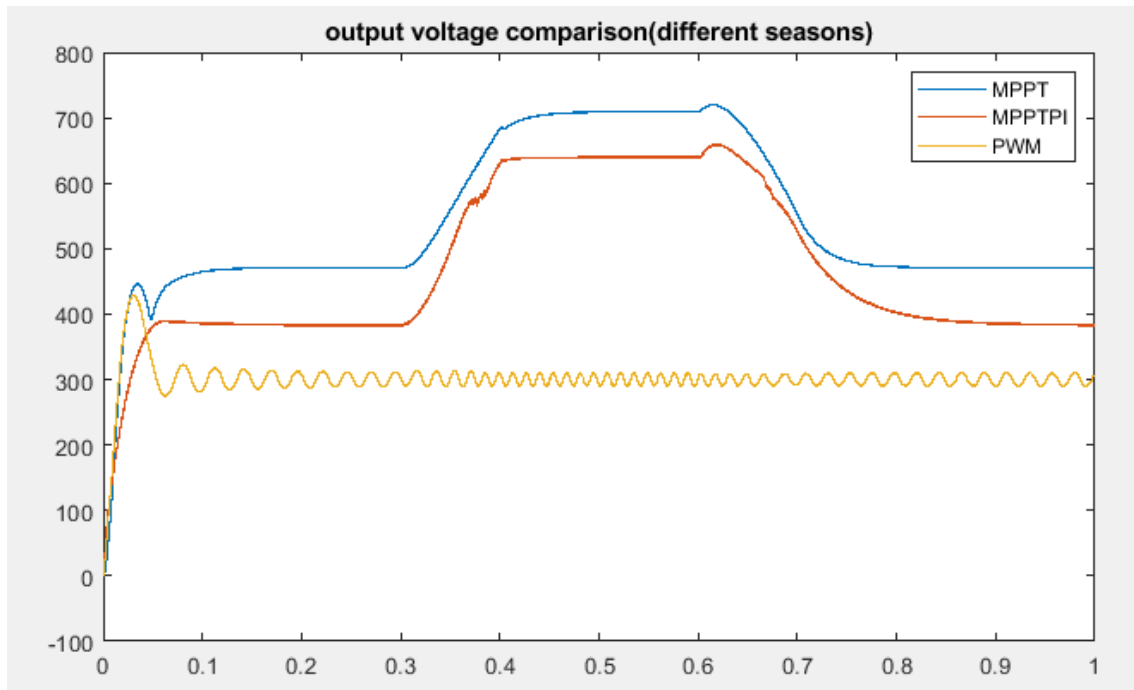


Figure 43: Output voltage comparison (different seasons)

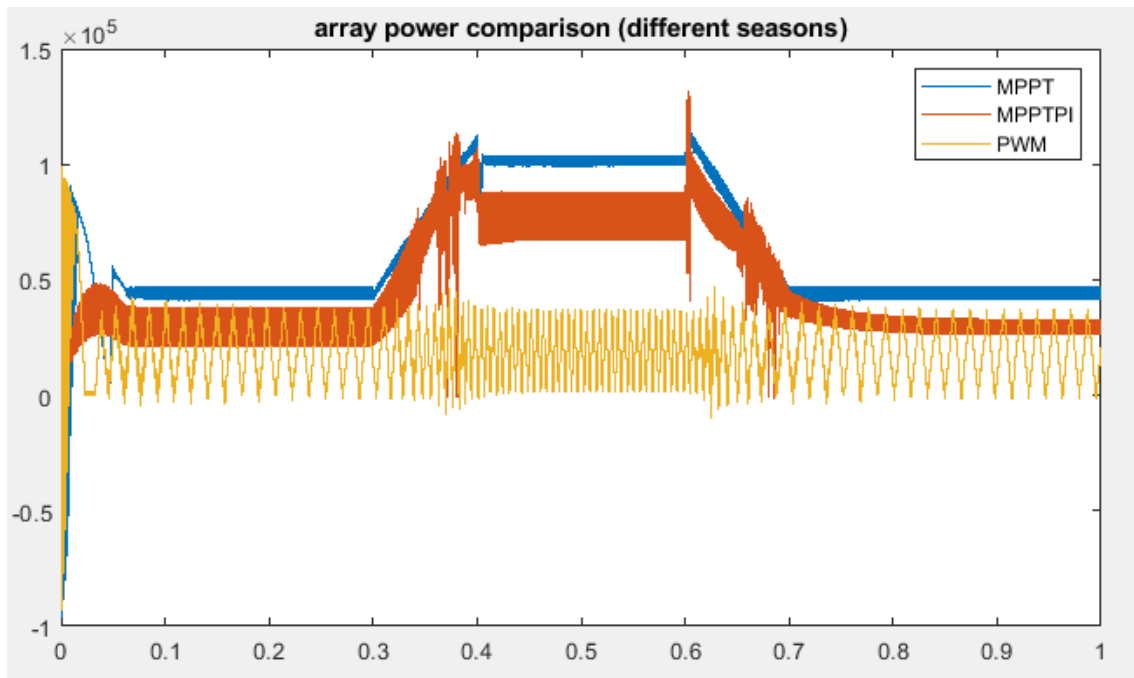


Figure 44: Array power comparison (different seasons)

Using the results from the simulation, Table 3 could be made.

Table 3: Result comparison from three control method simulations (different seasons scenario)

	PWM		MPPT		MPPT-PI	
	Cold season	Hot season	Cold season	Hot season	Cold season	Hot season
Output voltage	300V	300V	720V	480 V	390V	640V
Array power	25000 W average	25000 W average	50000 W average	100000 W average	35000 W average	80000 W average

Between all three methods, the PWM controller yielded the most stable output voltage over two seasons, which was the same as the target voltage with the lowest array power. Both the MPPT and MPPT-PI methods had an output voltage changing over seasons, which were higher during a hot season than during a cold season. The MPPT controller had an output voltage and array power higher than those of the MPPT-PI controller.

8 CONCLUSION

Based on the simulation results, the PWM controller clearly has the most stable output voltage while having the lowest power and the simplest design out of the three methods compared. The MPPT and MPPT-PI methods have an output voltage varying depending on light irradiance and temperature.

The MPPT method has a higher output voltage and power than the MPPT-PI method. Due to the characteristics of the controllers, the PWM controller is suitable for feeding power from a PV array directly to electronic devices with a specified input voltage while the MPPT and MPPT-PI methods are suitable for feeding electricity with the highest efficiency to an electrical grid or devices that can regulate the output voltage.

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