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Design and Comparison Analysis of Maximum Power Point Tracker of SEPIC Converter with Different Control Methods

***Abstract**. The Sun is an energy source that can be utilized as an alternative to an electric generation source with the application of solar cells Photovoltaic (PV) that can replace the function of natural gas and coal. This paper explains the design of the solar power plant with the Off-grid concept using Simulink. The experiment results and simulation comparison from SEPIC Converter with PID Control MPPT resulted in the power up to 15.753,91 Watt and down to 15.547,60 Watt. While from the experiment results of the converter with Hill Climbing Method MPPT resulted in the power up to 16.856,04 Watt and down to 12.777,96 Watt. The simulations concluded that the system using PID control were having a faster response to achieve the peak point of DC Voltage of the SEPIC Converter. On the converter with PID Control MPPT, the Inverter output can generate the highest power of 15.991,469 Watt and the lowest of 15.641,38 Watts so it is capable to be applied on a power load of 12.000 Watt with an error percentage up to 9,621% and down to 3,258%.*

***Streszczenthe ie.** Słońce jest źródłem energii, które można wykorzystać jako alternatywę dla źródła wytwarzania energii elektrycznej przy zastosowaniu ogniw fotowoltaicznych (PV), które mogą zastąpić funkcję gazu ziemnego i węgla. W artykule wyjaśniono projekt elektrowni słonecznej z koncepcją Off-grid z wykorzystaniem Simulinka. Wyniki eksperymentu i porównanie symulacji z SEPIC Converter z PID Control MPPT dały moc do 15.753,91 Wat i spadek do 15.547,60 Wat. Natomiast z eksperymentu wyniki konwertera z Hill Climbing Method MPPT dały moc do 16.856,04 Watt i spadek do 12.777,96 Watt. Symulacje wykazały, że system wykorzystujący sterowanie PID miał szybszą reakcję, aby osiągnąć punkt szczytowy napięcia stałego przetwornika SEPIC. Na przetwornicy z PID Control MPPT, wyjście falownika może generować najwyższą moc 15 991 469 W i najniższą 15 641,38 W, dzięki czemu można go zastosować przy obciążeniu mocy 12 000 W przy procentowym błędzie do 9 621 % i spadł do 3258%. (**Projekt i analiza porównawcza modułu śledzenia punktu mocy maksymalnej konwertera SEPIC z różnymi metodami sterowania**)*

Keywords: Solar Power Plant, SEPIC Converter, Hill Climbing Method, PID Control
Słowa kluczowe: źródło fotowoltaiczne, przekształtnik SEPIC, sterowanie PID.

Introduction

The natural resources that have been utilized to generate electricity are decreasing quickly, causing energy costs to become more expensive. Therefore, it is the trend to search the alternative solution to generate electric energy. One of the optimum solutions is Photovoltaic Energy. Solar Panel is the basic energy conversion component of the Photovoltaic System. Since solar radiation is one of the renewable energy sources, Photovoltaics has an important role. The only emission involved with PV is only from the manufacture of the module. Photovoltaics produce electricity from solar radiation without generating gas emissions. Photovoltaic can produce more energy in the generation for 25 years [1-2]. The conversion efficiency depends on many extrinsic factors such as the insulation level and load condition. There are three main approaches to maximizing power extraction in medium-scale and large systems. They are the Solar Tracker, the Maximum Power Point (MPP) tracker, or both using the SEPIC converter [3]. MPP Tracking is very popular in the small-scale system based on economic reasons [4]. The recently used algorithm is the disturbance and observation method, dynamic approach method, and Adaptive Modified Firefly Algorithm [5]. The design of the charge controller based on the SEPIC and buck topology converter also becomes one of the trends using modified Incremental Conductance MPPT and comparing the performance [6-7]. Another research is the design of a Boost converter based on the Maximum power point resistance for Photovoltaic applications [8]. The mentioned research has become the trend and is being compared to other research that has used old methods such as Fuzzy, PID, and Perturb and Observe to find the best result [9-14]. The algorithms are going to keep evolving in the future to improve the PV array development better efficiency and optimum placement [15-16].

Therefore, the researcher designed and then analyzed the Solar Power Plant as a power saver using the comparison between the Hill Climbing method and the PID Control of the SEPIC Converter using Simulink Simulation, the average output sample of both methods produced the most efficient and reliable results.

Single-Ended Primary Inductor Converter (SEPIC)

The Converter is utilized as the voltage adjuster to decrease or increase the voltage output. Similar to the Buck-Boost Converter, the voltage output can be controlled from the switching of the MOSFET with the desirable Duty Value. If the Duty value is below 50%, the converter works as the voltage booster, while if the value is above 50%, the converter works as the voltage reducer.

Based on the objective requirement then applied 3 variety of loads with the value of 20 Ohm, 100 Ohm, and 200 Ohm with the specified voltage of 300 Volts. The calculation steps of the SEPIC converter are as follows:

1. *Duty Cycle Calculation*

$$D = \frac{V_{out}+V_D}{V_{in}+V_{out}+V_D} \tag{1}$$

2. *Output Voltage Calculation*

$$V_{out} = \frac{V_{in}+D}{1-D} \tag{2}$$

3. *Inductor Selection*

Ripple Current

$$\Delta I_L = I_{out} \times \frac{V_{out}}{V_{in(mins)}} \times 40\% \tag{3}$$

L1 Peak Current

$$I_{L_1(peak)} = I_{out} \times \frac{V_{out}+V_D}{V_{in(mins)}} \times \left(1 + \frac{40\%}{2}\right) \tag{4}$$

L2 Peak Current

$$I_{L_2(peak)} = I_{out} \times \left(1 + \frac{40\%}{2}\right) \tag{5}$$

Inductance

$$L = L_1 = L_2 = \frac{V_{in(mins)}+D_{maks}}{\Delta I_L \times f} \tag{6}$$

4. MOSFET Selection

(7) $$I_{Q_1(peak)} = I_{L_1(peak)} + I_{L_2(peak)}$$

RMS Current

(8) $$I_{Q_1(rms)} = I_{out}\sqrt{\frac{V_{out}+V_{in(mins)}+V_D+(V_{out}+V_D)}{V_{in}^2}}$$

5. Diode Selection

(9) $$V_{RD} = V_{in(maks)} + V_{out(maks)}$$

6. Input Capacitor Calculation

(10) $$I_{C_{in}(rms)} = \frac{\Delta I_L}{\sqrt{12}}$$

$$C_{in} = \frac{I_{C_{in}}}{2f}$$

7. RMS Current Calculation of $\boldsymbol{C_S}$

(11) $$I_{C_S(rms)} = I_{out} \times \sqrt{\frac{V_{out}+D}{V_{in(mins)}}}$$

$$\Delta V_{C_S} = \frac{I_{out}+D_{maks}}{C_S \times f}$$

$$C_S = \frac{I_{C_S}+D_{maks}}{\Delta V_{C_S} \times f}$$

8. Output Capacitor Calculation

ESR Calculation

(12) $$ESR = \frac{V_{ripple}+V_D}{I_{L_1(peak)} \times I_{L_2(peak)}}$$

C_{out} Calculation

(13) $$C_{out} = \frac{I_{out}+D_{maks}}{V_{ripple} \times f \times V_D}$$

PID Controller Method

The PID (Proportional Integral Derivative) Method is applied to boost a system' within the system. The control consists of three types which are P (Proportional), I (Integral), and D (Derivative).

The experiment trial of PID control can be done by comparing each PD control, PI control, and PID control transfer function.

1. Proportional-Derivative (PD) Controller

(20) $$H(S) = \frac{K_D S + K_P}{S^2+(10+K_D)S+(20+K_P)}$$

With: K_P = Proportional Gain; K_D = Derivative Gain; S = Setting time

2. Proportional-Integral (PI) Controller

(21) $$H(S) = \frac{K_P S + K_I}{S^3+10\,S^2+(20+K_P)S+K_I}$$

With: K_I = Integral Gain

3. Proportional-Integral-Derivative (PID) Controller

(22) $$H(S) = \frac{K_D S^2 + K_P S + K_I}{S^3+(10+K_D)S^2+(20+K_P)S+K_I}$$

Hill Climbing Method

Multiple methods can be applied to track the Maximum PowerPoint of the PV Panel. In this paper, the researcher selected the Hill Climbing method as the MPPT control algorithm since the calculation is easy and quick to operate. The algorithm starts by measuring the solar cell voltage $\boldsymbol{V(k)}$ and Current $\boldsymbol{I(k)}$ then the result value is applied to calculate Power $\boldsymbol{P(k)}$. The parameter of data will be compared between the pre-measurement and the post-measurement $\boldsymbol{P(k-l)}$ and $\boldsymbol{V(k-l)}$. The result of the comparison is the difference value of Power and Voltage $\boldsymbol{\Delta P}$ and $\boldsymbol{\Delta V}$. The formulas applied in the method are as follows:

(23) $$P(n) = V(n) \times I(n)$$

(24) $$\Delta P = P(n) - P(n-1)$$

(25) $$\Delta V = V(n) - V(n-1)$$

$$D = D(n) - 5\left[if\,\frac{\Delta P}{\Delta V} < 0\right]$$

$$D = D(n) + 5\left[if\,\frac{\Delta P}{\Delta V} > 0\right]$$

With: $P(n)$ = Solar Panel Input Power; $V(n)$ = Solar Panel Input Voltage; $I(n)$ = Solar Panel Input Current; D.= Duty

Research Method

The research is conducted based on the planned flowchart in Figure 1 as follows.

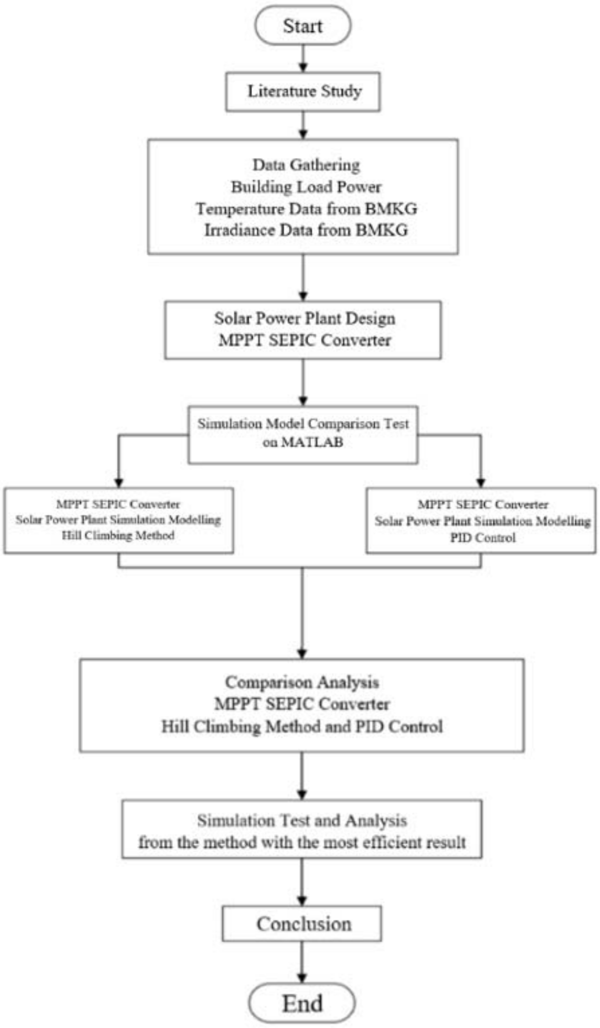

Fig. 1. Research Flowchart

Result and Discussions

SEPIC Converter Components Calculations

Table 1. SEPIC Converter Input Data

Parameter	Value
Input Voltage	36,2 V
Input Current	8,28 A
Current Ripple	40%
Voltage Ripple	2%
Frequency	25 kHz

a. Duty Cycle Calculation

$$D = \frac{V_{out}+V_D}{V_{in}+V_{out}+V_D}$$

$$D_{max} = \frac{V_{out}+V_D}{V_{in(maks)}+V_{out}+V_D} = \frac{43{,}4+0{,}5}{36{,}2+43{,}4+0{,}5}$$
$$= 0{,}54 = 54\%$$

$$D_{min} = \frac{V_{out}+V_D}{V_{in(mins)}+V_{out}+V_D} = \frac{43{,}4+0{,}5}{30+43{,}4+0{,}5}$$
$$= 0{,}59 = 59\%$$

b. Calculate Maximum and Minimum Output Voltage

$$V_{out} = \frac{V_{in}+D}{1-D}$$

$$V_{out(maks)} = \frac{V_{in}+D_{maks}}{1-D_{maks}} = \frac{35+0{,}59}{1-0{,}59}$$
$$= 50{,}36\ V$$

$$V_{out(mins)} = \frac{V_{in}+D_{mins}}{1-D_{mins}} = \frac{35+0{,}54}{1-0{,}54}$$
$$= 41{,}08\ V$$

c. Calculate Inductor Value

$$\Delta I_L = I_{out} \times \frac{V_{out}}{V_{in(mins)}} \times 40\%$$

$$\Delta I_L = 9{,}27 \times \frac{43{,}4}{30} \times 40\%$$
$$= 5{,}364\ A$$

L1 Peak Current

$$I_{L_1(peak)} = I_{out} \times \frac{V_{out}+V_D}{V_{in(mins)}} \times \left(1+\frac{40\%}{2}\right)$$

$$I_{L_1(peak)} = 9{,}27 \times \frac{43{,}4+0{,}5}{30} \times \left(1+\frac{0{,}4}{2}\right)$$
$$= 16{,}278\ A$$

L2 Peak Current

$$I_{L_2(peak)} = I_{out} \times \left(1+\frac{40\%}{2}\right)$$

$$I_{L_2(peak)} = 9{,}27 \times \left(1+\frac{0{,}4}{2}\right)$$
$$= 11{,}124\ A$$

Inductance

$$L = L_1 = L_2 = \frac{V_{in(mins)}+D_{maks}}{\Delta I_L \times f}$$

$$L = L_1 + L_2 = \frac{30+0{,}59}{0{,}5\times 25.000}$$
$$= 0{,}643\ \mu H$$

d. MOSFET Selection

$$I_{Q_1(peak)} = I_{L_1(peak)} + I_{L_2(peak)}$$
$$I_{Q_1(peak)} = 16{,}278 + 11{,}124 = 27{,}402\ A$$

RMS Current

$$I_{Q_1(RMS)} = I_{out}\sqrt{\frac{V_{out}+V_{in(mins)}+V_D+(V_{out}+V_D)}{V_{in}^2}}$$

$$I_{Q_1(RMS)} = 9{,}27\sqrt{\frac{43{,}4+30+0{,}5+(43{,}4+0{,}5)}{36{,}2^2}}$$
$$= 2{,}5005\ A$$

e. Diode Selection

$$V_{RD} = V_{in(maks)} + V_{out(maks)}$$
$$V_{RD} = 36{,}2 + 43{,}4 = 79{,}6\ V$$

f. Input Capacitor Calculation

The Input Capacitor is applied as the input voltage filter, reducing the ripple of voltage. The voltage ripple value is not allowed to be more than 3V, so the capacitor value is calculated as follows:

$$I_{C_{in}(RMS)} = \frac{\Delta I_L}{\sqrt{12}} = \frac{5{,}634}{\sqrt{12}} = 1{,}54\ A$$

$$C_{in} = \frac{I_{C_{in}}}{2f\times \Delta V_{C_{in}}} = \frac{1{,}54}{2\times 25.000\times 19{,}435} \times 25\%$$
$$= 3{,}96\ \mu F$$

The size of the input capacitor is 25% minimum of the calculation result. To reduce the voltage ripple then the converter applied $39\ \mu F$ capacitor

g. RMS Current Calculation

$$I_{C_S(RMS)} = I_{out} \times \sqrt{\frac{V_{out}+V_D}{V_{in(mins)}}}$$

$$I_{C_S(RMS)} = 9{,}27 \times \sqrt{\frac{43{,}4+0{,}5}{30}} = 11{,}213\ A$$

Calculate ΔV_{C_S}, consider the $C_S = 0.0002\ F$

$$\Delta V_{C_S} = \frac{I_{out}+D_{maks}}{C_S\times f}$$

$$\Delta V_{C_S} = \frac{9{,}27+0{,}59}{0{,}0002\times 25.000} = 1{,}972\ V$$

Then C_S value

$$C_S = \frac{I_{C_S}+D_{maks}}{\Delta V_{C_S}\times f} = \frac{11.213+0{,}59}{1{,}972\times 25.000} = 5{,}98\ \mu F$$

The capacitor must be 25% bigger than the maximum input voltage, so applied $59\ \mu F$ Capacitor.

h. Output Capacitor Calculation

$$V_{ripple} = 2\%\ V_{out} = 0{,}02 \times 43{,}4 = 0{,}868\ V$$

ESR Calculation

$$ESR = \frac{V_{ripple}+V_D}{I_{L_1(peak)}+I_{L_2(peak)}}$$

$$ESR = \frac{0{,}868+0{,}5}{16{,}278+11{,}214} = 2{,}3\ m\Omega$$

C_{out} Calculation

$$C_{out} = \frac{I_{out}+D_{maks}}{V_{ripple}\times f\times V_D}$$

$$C_{out} = \frac{9{,}27+0{,}59}{0{,}868\times 25.000\times 0{,}5}$$
$$= 50{,}408\ \mu F$$

Photovoltaic Testing

The test is conducted to achieve the PV parameter value. The parameter will be resulting in the P-V curve with irradiation value from the determined PV module. Figure 4 shows the PV simulation model to be tested in Simulink and Table 2 is the Test Result Data with Constant Temperature and Voltage Values and Varied Irradiance Values with the step of 100 W/m^2.

Table 2. Photovoltaic Simulation Test Result Data

Temperature (°C)	Irradiance (Watt/m^2)	Voltage (V)	Current (I)	Power (P)
30	800	20	297,3	5946
30	900	20	334,4	6688
30	1000	20	371,4	7428
30	1100	20	408,4	8168
30	1200	20	445,4	8908
30	1300	20	482,3	9646
30	1400	20	519,3	10386

SEPIC Converter

The test is conducted by adjusting the Duty Cycle values. Figure 3 and the following Table 3 show the converter configuration and results of the simulation test.

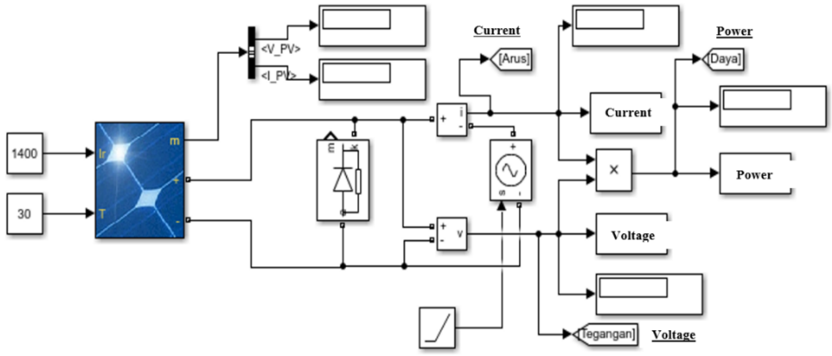

Fig. 2. Photovoltaic Simulation Model to be tested in Simulink

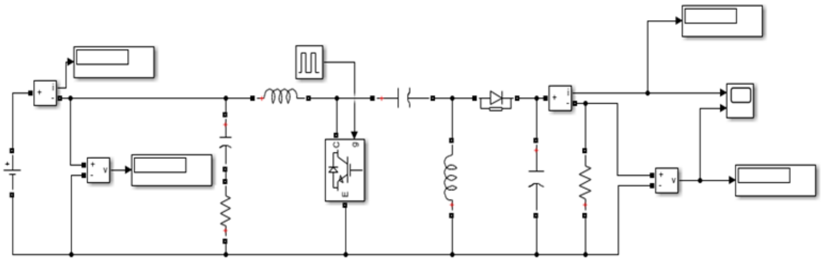

Fig. 3. SEPIC Converter Simulation Configuration

Table 3. SEPIC Converter Simulation Test Result

V_{in}	I_{in}	Duty	V_{out}	I_{out}
36,2	-53,59	10	10,83	1,083
36,2	-53,59	20	10,83	1,083
36,2	15.03	30	18,15	1,815
36,2	15,03	40	18.15	1,815
36,2	15,03	50	18.15	1,815
36,2	316,2	60	22,83	22,83
36,2	316,2	70	22,83	22,83

Inverter and Loads

The test is conducted by determining the size of applied loads with a minimum power generation of 5% of total overall power. Table 4 below shows the applied data of the building.

The load's size is determined by using the following equation:

$$P = \sqrt{3} \times I^2 R \cos\phi$$

$$R = \frac{P}{\sqrt{3}\times I^2 \cos\phi}$$

$$R = \frac{12505{,}401}{\sqrt{3}\times 20^2 \times 0{,}95} = 19\ \Omega$$

The simulation is using a voltage of 380 V, a current of 20 Ampere, $\cos\phi$ of 0,95, and a resistance of $19\ \Omega$

Table 4. Loads Data

Parameter	Value
Voltage	380 V
Current	20 A
$\cos\phi$	0,95
Power	12.505,401 Watt

SEPIC Converter MPPT Comparison Test

The test was conducted by comparing the converter MPPT with the PID Control and with the Hill Climbing method in a week. The simulation is conducted with parameter values such as the temperature and irradiance data that have been taken from the real-time environment measurement displayed in Table 5 as follows.

Table 5. Real-Time Temperature and Irradiance Data

Temperature ($^\circ C$)	Irradiance (Watt/m^2)
28,425	5126
27,725	1703
27,8	1142
28,425	1154
26,95	1253
28,7	1131
27,425	1821
28,275	1277

a. PID Control MPPT Test

Figure 4 below shows the simulation configuration of the MPPT with PID Control system with varied temperature and irradiance values based on the real-time environment measurement.

The simulation from Figure 4 starts with determining the Temperature and Irradiance value based on the measured data to the PV panel block. The next step is to simulate the system with the measured data, resulting in the value of Duty, DC Voltage and Current Input, DC Voltage and Current Output, and output power. The simulation is done as many as according to the available temperature and irradiance measured data, resulting in the data table of Table 6 below.

b. Hill Climbing MPPT Test

Similar to the previous simulation experiment, the simulation starts with determining the Temperature and Irradiance value based on the measured data to the PV panel block. The next step is to simulate the system with the measured data, resulting in the value of Duty, DC Voltage and Current Input, DC Voltage and Current Output, and output power. The simulation is done according to every available temperature and irradiance measured data, resulting in the data table of Table 7 below, and the following Figure 5 shows the simulation configuration of the Hill Climbing MPPT test.

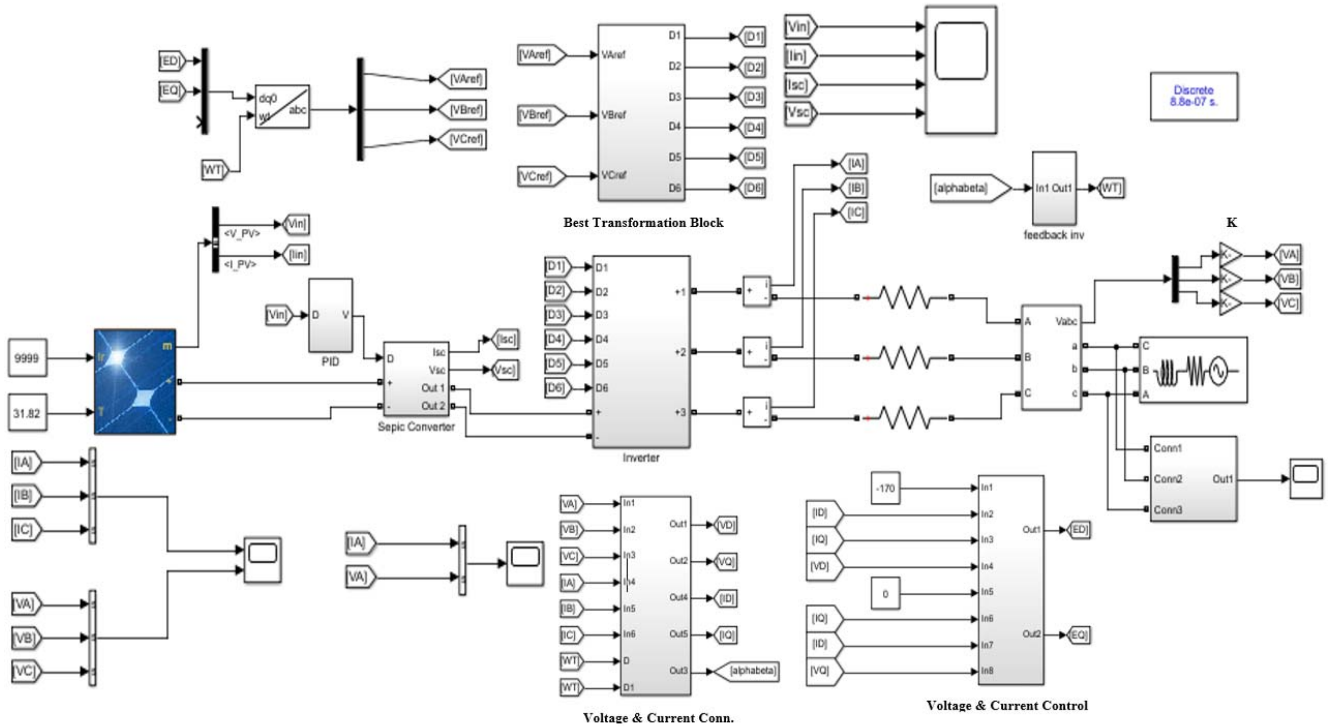

Fig. 4. PID Control MPPT Simulation Configuration

Table 6. PID Control MPPT Test Results

Temperature $(^\circ C)$	Irradiance (Watt/m^2)	Duty (%)	V_{DC}	I_{DC}	I_{out}	V_{out}	Power (Watt)
28,425	5126	1,875	42,96	25,041	25,04	379,93	15.653,88
27,725	1703	2,089	45,43	25,204	25,20	379,93	15.753,91
27,8	1142	2,078	45,05	25,196	25,15	379,93	15.722,65
28,425	1154	2,079	44,93	25,181	25,18	379,93	15.741,41
26,95	1253	2,095	45,07	25,189	25,19	379,93	15.747,66
28,7	1131	1,998	44,95	25,181	25,17	379,93	15.735,16
27,425	1821	2,122	45,45	25,204	25,19	379,93	15.747,66
28,275	1277	2,099	50,33	25,078	24,87	379,93	15.547,61

Table 7. Hill Climbing MPPT Test Results

Temperature $(^\circ C)$	Irradiance (Watt/m^2)	Duty (%)	V_{DC}	I_{DC}	I_{out}	V_{out}	Power (Watt)
28,425	5126	1,667	42,72	27,01	26,88	367,17	16.239,80
27,725	1703	1,803	68,11	27,92	27,70	367,17	16.735,21
27,8	1142	2,810	62,52	28,13	27,90	367,17	16.856,04
28,425	1154	2,810	62,52	28,13	27,90	367,17	16.856,04
26,95	1253	3,490	63,73	28,11	27,88	367,17	16.843,96
28,7	1131	2,810	62,52	28,13	27,90	367,17	16.856,04
27,425	1821	3,490	69,97	28,13	21,15	367,17	12.777,97
28,275	1277	3,490	63,73	28,11	27,88	367,17	16.843,96

Table 8. Simulation results of 6 months

Data Timestamp	Temperature	Solar Radiation	I_{out}	V_{out}	P_{out}
18/01/2021 00:00	32,2	9999	25,02	379,19	15.610,9
11/01/2021 00:00	31,8	761	25,16	379,19	15.698,3
20/02/2021 00:00	31,5	1538	25,2	379,19	15.723,2
09/02/2021 00:00	31,8	824	25,16	379,19	15.698,3
07/03/2021 00:00	30,8	9999	25,02	379,19	15.610,9
23/03/2021 00:00	33,4	2046	25,20	379,19	15.723,2
11/04/2021 00:00	33,5	1096	25,30	379,19	15.785,6
07/04/2021 00:00	31,2	894	25,30	379,19	15.785,6
08/05/2021 00:00	32,6	1297	25,16	379,19	15.698,3
20/05/2021 00:00	33	876	25,13	379,19	15.679,6
06/06/2021 00:00	34,9	1839	25,17	379,19	15.704,5
15/06/2021 00:00	34	1008	25,14	379,19	15.685,8

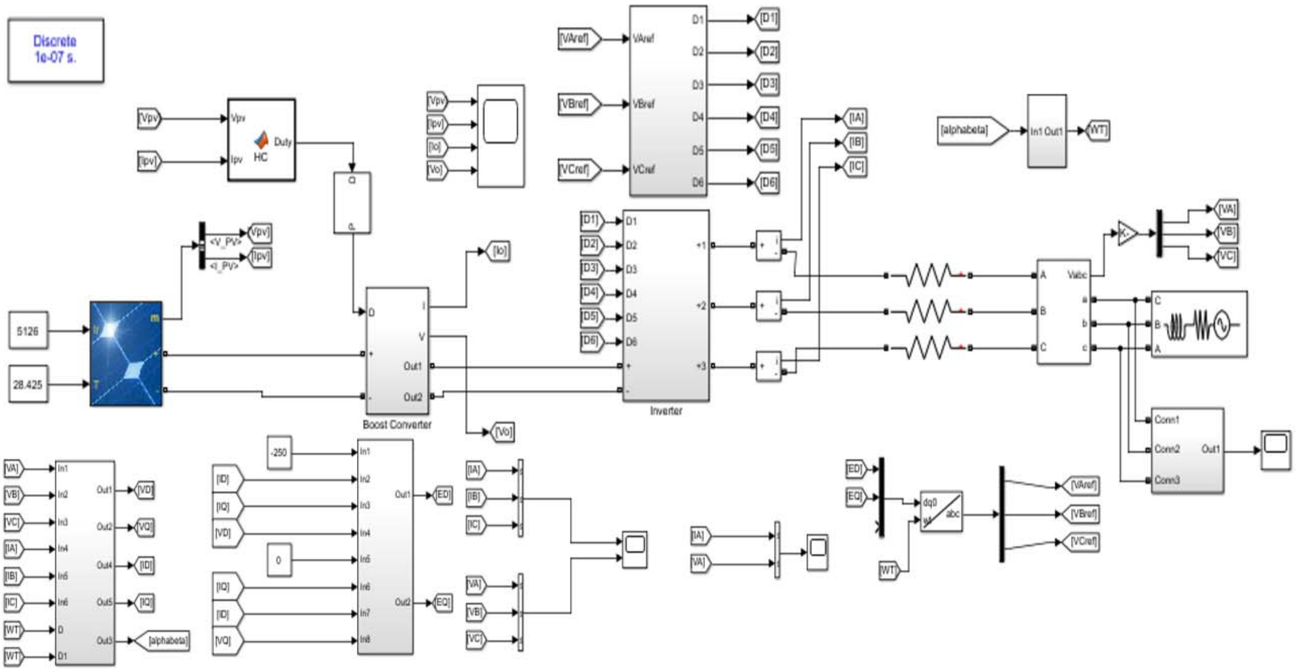

Fig. 5. Hill Climbing MPPT Simulation Configuration

c. *Comparison Result*

From the simulation configurations and tests of both MPPT methods above, it is concluded that the MPPT with PID Control system is having the best response than the Hill Climbing Method since the system can adapt to the temperatures and irradiances variation of the environment and has two seconds faster response when applied to the SEPIC Converter. Table 8 below shows the simulation result of 6 months of SEPIC Converter using the PID Control MPPT.

Efficiency and Error Calculation

The tests are conducted in 6 months with the Efficiency and Error calculated. Table 9 and Table 10 below show the Efficiency and Error-values of the 6 monthly experiments.

Table 9. The Efficiency Value of the 6 Months Test

Month	Efficiency Value (%)		
	Maximum	Average	Minimum
January	96,84	95,56	91,97
February	94,47	93,29	91,97
March	96,61	93,32	91,97
April	92,36	91,22	91,22
May	93,53	93,54	93,61
June	96,10	95,73	95,73

Table 10. The Error Value of the 6 Months Test

Month	Error Value (%)		
	Maximum	Average	Minimum
January	3,258	4,639	8,731
February	5,858	7,192	8,731
March	3,506	7,156	8,731
April	8,271	9,621	9,621
May	6,918	6,910	6,829
June	4,057	4,458	4,458

Conclusions

In this research, the MPPT system is designed using 40 units of solar panels with 300 WP capacity assembled in series-parallel and using SEPIC Converter with PID Control method. The test is conducted by comparing the PID Control MPPT with the Hill Climbing method and using BMKG data for 6 months. The system is generated power with the highest value of 15.991,469 Watts and the lowest value of 15.641,38 Watts and it is capable to handle a load of 12.000 Watt. The system produces an error percentage with a maximum of 9,621% and a minimum of 3,258%.

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