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Comparison of Maximum Power Point Tracking Techniques on Photovoltaic Panels

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Research Article

Abstract − In this study, a simulation is performed in Matlab/Simulink to evaluate the energy production performance of the perturb & observe, incremental conductance, short circuit current and open circuit voltage techniques. In order to evaluate the performance of the techniques, they are tested under constant temperature and irradiation conditions, as well as variable temperature and irradiation conditions. In the study, 1Soltech 1STH-215-P model photovoltaic panel is used. The maximum power point tracking is applied with a DC-DC boost converter, and the energy is stored in the battery. Maximum power point tracking algorithms are applied with m-file code using Matlab Function block in Simulink. The m-file codes, the extracted power waveforms and the amount of produced energy are presented in the study. It is observed that the energy performance of the short circuit current and open circuit voltage techniques varies depending on the measurement period, especially in variable weather conditions, while the perturb & observe and the incremental conductance algorithms are the ones that produce the most energy. While the open circuit voltage technique produces more energy than the short circuit current at constant temperature and variable irradiation, the short circuit current algorithm at constant irradiation and variable temperature produces more energy. While two sensors are used for current and voltage measurement in perturb & observe and incremental conductance techniques, the use of a single sensor in short circuit current and open circuit voltage techniques and the simplicity of the algorithms are seen as the advantageous aspects of these techniques.

Keywords – *Photovoltaic panel, power electronics, maximum power point, mppt, solar energy,*

1. Introduction

Photovoltaic (PV) systems play an important role in increasing renewable energy use due to environmental factors and depletion of fossil fuels. While the photovoltaic system power installed worldwide in 2012 was 29.5 GW, this value reached 107 GW in 2018. Total installed power at the end of 2018 was 518 GW (Jager-Waldau, 2019). Electrical energy is produced from solar energy with the help of photovoltaic panels created using photovoltaic cells. Photovoltaic systems can be installed as grid connected or off-grid types that can transfer energy from panels to the network or to the load (Rawat, Kaushik, & Lamba, 2016). Photovoltaic systems have different types of application areas such as electrical energy supply of off-grid rural areas (Irfan, Zhao, Ahmad, & Rehman, 2019), network support with high power plant (Mensah, Yamoah, & Adaramola, 2019), energy injection to the network with residential PV applications (Kharrazi, Sreeram, & Mishra, 2020), water pumping systems (Sontake & Kalamkar, 2016), wastewater purification systems, greenhouse and fishing pond applications (Xue, 2017), traffic lights systems (Moghbelli et al., 2009). In order to produce energy efficiently in photovoltaic systems, it is necessary to control the extracted power from PV panels, continuously. This requirement comes from the operating characteristics of photovoltaic panels. The maximum power that a photovoltaic panel can deliver varies depending on the irradiation and cell temperature (Hasan & Parida, 2016). Therefore, maximum power point tracking (MPPT)

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algorithms are used in power electronic converters that control the energy drawn from panel. Perturb & observe (P&O), incremental conductance (IC), open circuit voltage (OCV) and short circuit current (SCC) techniques are some of developed techniques (Karami, Moubayed, & Outbib, 2017). P&O algorithm is often used in MPPT converters. There are studies on this technique to improve the performance in the literature. Dynamic step size is used in P&O algorithm in order to reduce the power oscillation in steady state. The step size is reduced in the maximum point area, thereby reducing the oscillation (Ahmed & Salam, 2015). In the P&O technique, which is developed using the artificial bee colony algorithm, local maximum power point tracking can be performed effectively in case of local shading (Pilakkat & Kanthalakshmi, 2019). In a study in which P&O algorithm and fuzzy logic technique are used together, using the advantageous sides of the two techniques, a fast dynamic response is obtained with low oscillation and overshoot in steady state operation (Zainuri, Radzi, Soh, & Rahim, 2014). In another technique, IC algorithm, a cleaner power with faster dynamic and stable less fluctuation applying adaptive fuzzy controller to DC-DC converter (Punitha, Devaraj, & Sakthivel, 2013). With IC algorithm in which the open circuit voltage is adapted, better results are obtained in terms of maximum power point tracking and output power in environments where rapid changes in weather conditions are experienced compared to traditional IC and P&O algorithms (Huynh, 2014). Another study in which the residual IC method is used, the oscillations around the maximum power point eliminated and the MPPT was improved (Alsumiri, 2019). Variable step size is applied to eliminate the dividing processes in the IC algorithm and to simplify the algorithm to reduce the processing load and the sampling time. Steady power oscillations are reduced and transient state response is improved (Zakzouk, Elsaharty, Abdelsalam, Helal, & Williams, 2015). Unlike the conventional IC, where the ratio of power change to voltage change is used, an improvement of the response speed and steady state error is achieved by determining the variable step range by using the ratio of power change to current change (Mei, Shan, Liu, & Guerrero, 2011).

In this paper, simulation study of MPPT techniques called P&O, IC, OCV and SSC are carried out. Performance analysis is performed using the four algorithms on the same system for the same environmental conditions. In the system, where a photovoltaic panel and boost type DC-DC converter are used, the energy produced by the panel is stored in the battery. The amount of energy produced in the same period is compared, and their superiority compared to each other is revealed. In addition, the system is simulated in Matlab/Simulink. The converter control is carried out with the m-file code and the codes used in all methods are presented in the study.

2. Maximum Power Point Tracking Techniques

Since the efficiency values of photovoltaic panels, which are one of the renewable energy sources, are low, the use of MPPT techniques becomes more important. With the developments in panel production, panel efficiency has increased to 22.8% today, while the efficiency of the panels used in the market, in general, is between 15% and 17%. Drawing as much power as possible from a low efficiency source ensures the efficient use of source power within the maximum limits. For this reason, MPPT algorithms are used in the control of the photovoltaic panel. This section provides information about the algorithms to be studied in this study.

2.1. Perturb & Observe Technique

Perturb & observe technique is the preferred technique among MPPT algorithms. Ease of application and accuracy is the reason for preference. In the application of this technique, panel output voltage and current are measured continuously, and panel power is calculated. The overall working principle of the technique is to observe the voltage and power change at the panel output, as seen in Figure 1 and expressed in Table 1, and to decide what should be done in the next step. The voltage and power differences between the two measuring points are used to determine the process to be performed in the next step. If the voltage and power variations are positive, it means the operating point goes to the maximum power point from the left side, however, if the voltage variation is positive and power variation is negative, it means maximum power point is passed as seen in Figure 1. Power control is provided by generating the necessary switching signals to change the panel output voltage value according to Table 1 by observing the other possible two situations.

(2.1) includes the mathematical expression of the control algorithm. As can be seen, the panel voltage value that should be in the next step is determined by the ratio of power change to voltage change. Depending on this ratio, the previous voltage value can be increased or decreased by the decrease voltage (V_{step}) and the new reference voltage value is obtained. The flowchart of the technique is given in Figure 2. The variation of the voltage at the panel output varies with the panel current. When the panel output voltage needs to be increased, the current drawn from the panel is reduced to increase the panel voltage. At this point, the power output is adjusted by changing the switching signal duty ratio of the power electronics converter at the output of the panel to increase or decrease panel current. Although it is simple in terms of working principle, even when working at the maximum power point, it is not fixed at this point due to the change in voltage and power compared to the previous step and it constantly works around the point. In other words, it oscillates around the maximum power point. This situation causes power loss. This technique also delays in reacting to rapid weather changes. The step size must be reduced in order to reduce the oscillating, but this increases the time to reach the maximum point (Kollimalla & Mishra, 2014).

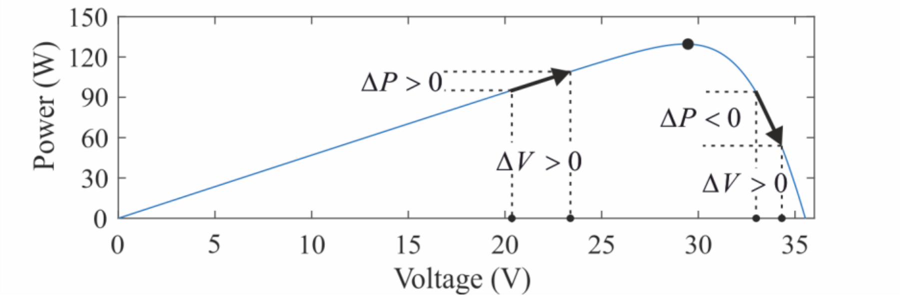


Figure 1. Maximum power point tracking in P&O

Table 1
Operation principle of P&O technique

Voltage change (ΔV)	Power change (ΔP)	Direction in next step
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

$$V_{ref} = \begin{cases} V + V_{step} & \dfrac{\Delta P}{\Delta V} > 0 \\ V - V_{step} & \dfrac{\Delta P}{\Delta V} < 0 \end{cases} \tag{2.1}$$

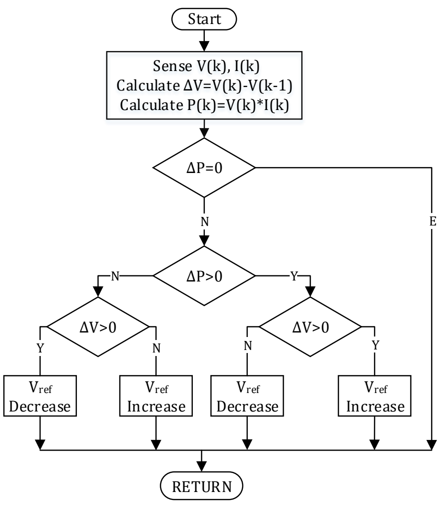


Figure 2. Flowchart of P&O technique

2.2. Incremental Conductance Technique

The incremental conductance (IC) technique operates on the principle that the derivative of the PV panel output power to panel voltage is zero. The expression di/dv seen in (2.2) is called incremental conductance. When the equation is rearranged, the expressions seen in (2.3) are obtained and the control is made according to these expressions. The result obtained by comparison shows the increasing or decreasing power state on the right or left side of the maximum power point. According to this result, necessary control is provided by changing the duty ratio of DC-DC converter switching signal. The flowchart of IC is seen in Figure 3. Firstly, the change in voltage is checked and if there is no change, the current change is checked. If there is no change in current, the flow diagram ends, which indicates that it is working at the maximum power point. The regions that depend on voltage and current variation occur in power curve as seen in Figure 4.

$$\frac{dp}{dv} = \frac{d\left(v \times i\right)}{dv} = i + v\frac{di}{dv} = 0 \tag{2.2}$$

$$\begin{aligned} &\frac{\Delta i}{\Delta v} = -\frac{i}{v} \quad \text{Maximum power point} \\ &\frac{\Delta i}{\Delta v} > -\frac{i}{v} \quad \text{Left side of maximum point} \\ &\frac{\Delta i}{\Delta v} < -\frac{i}{v} \quad \text{Right side of maximum point} \end{aligned} \tag{2.3}$$

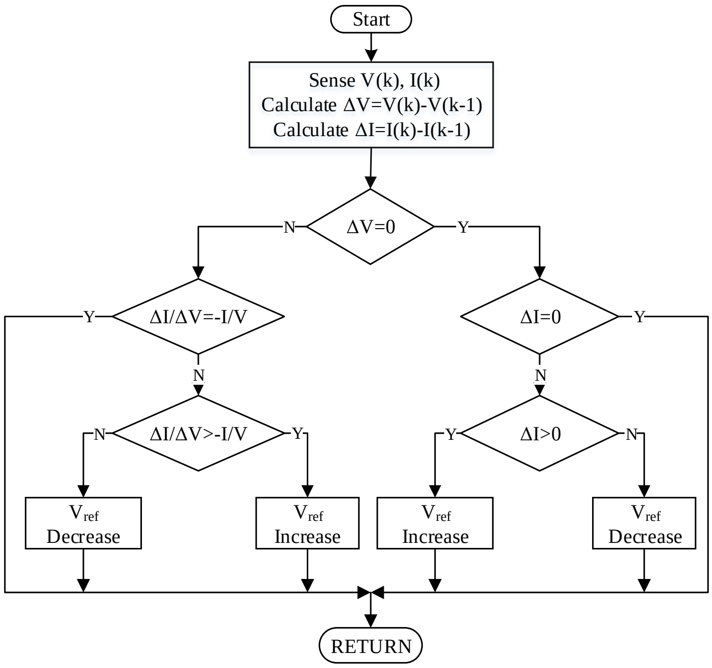


Figure 3. Flowchart of IC technique

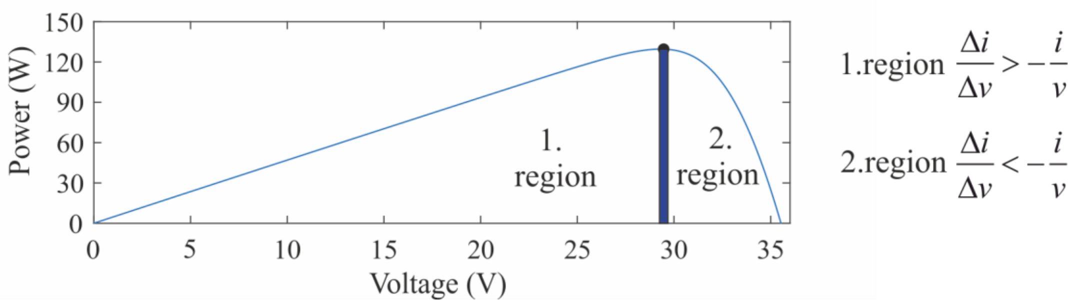


Figure 4. IC technique operating curve

2.3. Open Circuit Voltage Technique

Open circuit voltage (OCV) technique is one of the simplest maximum power point tracking algorithms. This technique is also called constant voltage technique. In this technique, the ratio of maximum power point voltage to open circuit voltage is used as given in (2.4). It has been reported in the literature that this ratio varies between 71% and 80% depending on photovoltaic cell parameters (Kumari, Babu, & Kullayappa, 2011). As seen in the flowchart given in Figure 5, panel is disconnected from the system at certain time intervals and panel output open circuit voltage is measured. These measurements continue periodically, and each measurement result is used to determine the maximum power point until the next measurement. In this technique, only panel voltage is used as input. K_{oc} value is calculated with the ratio of voltage at maximum power point to open circuit voltage in nominal conditions (Subudhi & Pradhan, 2011). This value is not completely constant, and it varies especially by temperature change. In this technique, no energy is drawn from the panel during the measurement of the open circuit voltage. Therefore, interruption in energy production occurs during measurement. The use of the voltage sensor is simple and advantageous in terms of cost, since only the voltage measurement is made in the algorithm.

$$\frac{V_{mpp}}{V_{oc}} \cong K_{oc} < 1 \tag{2.4}$$

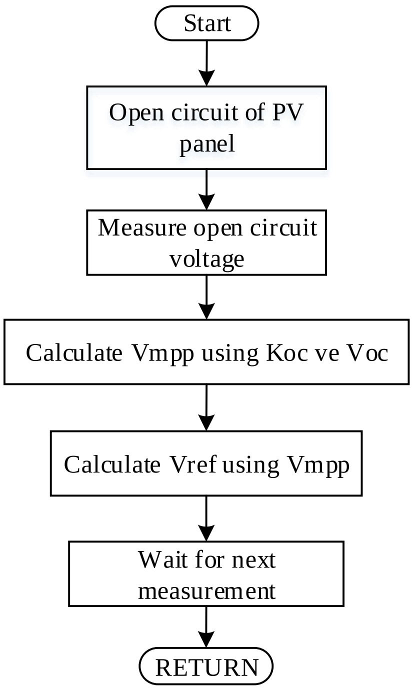


Figure 5. Flowchart of OCV technique

2.4. Short Circuit Current Technique

In the short circuit current (SCC) technique, similar to the open circuit voltage technique, short circuit current measurement is performed and the K_{sc} constant is calculated with the help of (2.5). As can be seen in the control algorithm given in Figure 6, the terminals of the PV panel are made short-circuited with a semiconductor switch that is connected parallel to the panel, firstly. The current value at the maximum power point and the reference voltage corresponding to this current is calculated by multiplying the momentary measured short circuit current by the K_{sc} value. Using this voltage value, switching signals are generated that will enable the converter at the panel output to draw the calculated current from the panel. In this technique, similar to the open circuit voltage technique, there is no energy flow from the panel to the load at the measurement moments. This means energy loss in direct proportion to the frequency of measurement. Increasing the measuring period reduces energy loss, making it difficult to follow the maximum power point that occurs in variable weather conditions. Keeping this interval short and increasing the number of measurements increases the maximum power point tracking performance while increasing the energy losses that occur during the measurement moments.

$$I_{mpp} \cong K_{sc} I_{sc} \tag{2.5}$$

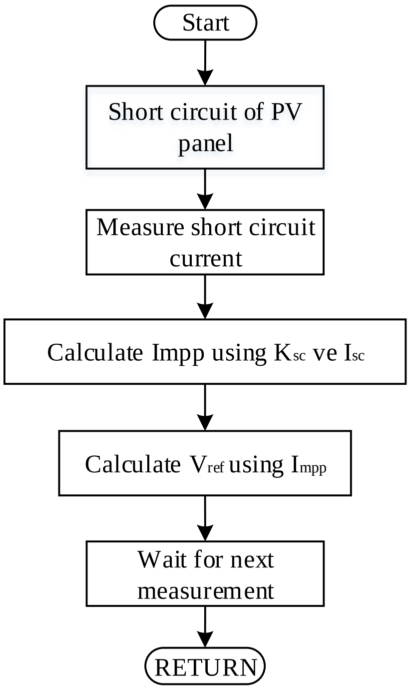


Figure 6. Flowchart of SCC technique

3. Simulation Results

The simulation study is carried out in Matlab/Simulink in order to reveal the advantages and weaknesses of the maximum power point tracking techniques described in the previous section. The same PV panel and a DC-DC boost converter are used in simulation studies for all techniques. In the system, a polycrystalline 1Soltech 1STH-215-P model panel is used as an energy source. The panel consists of 60 cells, and the specifications of the used PV panel are listed in Table 2. The specifications of the panel are taken from Simulink PV panel model. The power variation curves of the panel at different irradiation values for 25^{o}C and at different temperature values for 1000W/m^2 are seen in Figure 7 and Figure 8, respectively. When the Figure 7 and Figure 8 are examined, the maximum power points for the irradiation values of 1000W/m^2, 700W/m^2 and 500W/m^2 at a constant temperature of 25^{o}C are 213W, 151W and 108W respectively, while the maximum power values of the panel at a temperature of 15^{o}C, 25^{o}C and 35^{o}C for constant 1000W/m^2 irradiation are 221W, 213W and 204W, respectively.

Table 2
Specifications of PV panel

Parameters	**Value**
Maximum Power (P_{max})	213,15 W
Open circuit voltage (V_{oc})	36,3 V
Maximum power voltage (V_{mpp})	29 V
Short circuit current (I_{sc})	7,84 A
Maximum power current (I_{mpp})	7,35 A
Temperature coefficient of V_{oc}	-0,36099 %/^{o}C
Temperature coefficient of I_{sc}	0,102 %/^{o}C

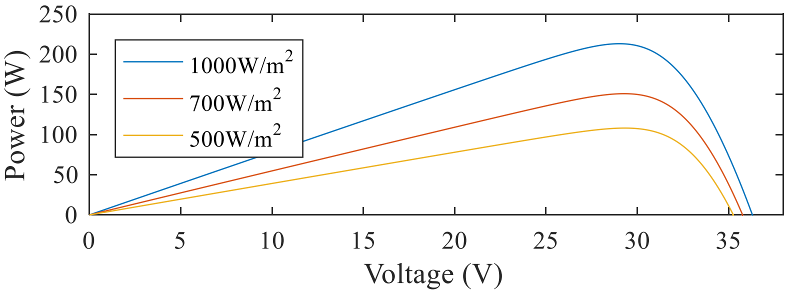


Figure 7. Panel output power curves at 25°C

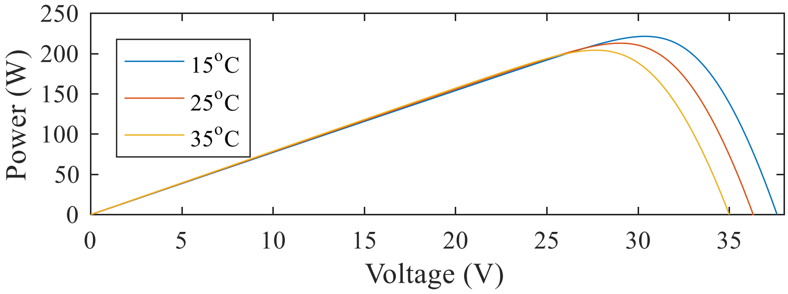


Figure 8. Panel output power curves at 1000 W/m^2

Considering the variables used in the control algorithm, the DC-DC boost converter seen in Figure 9 is used in the simulation study for P&O and IC techniques. As two algorithms use the same electrical quantities in the calculation, the same converter topology can be used for both algorithms without any additional component. In the examination of the P&O technique, a DC-DC boost converter is used at the PV panel output to increase voltage. The energy drawn from the panel is stored in the battery with the using of this converter. In the simulation study, control is provided with the m-file codes shown in Figure 10. Using the Matlab Function block that is seen in Figure 9 as MPPT, reference voltage is generated with the control code prepared as m-file. The converter is controlled by generating switching signals with the PWM Generator. The inputs of the control algorithm are panel voltage and panel current while the output is reference signal. With the change of the reference signal, the duty ratio of the switching signal changes and control is provided with pulse width modulation.

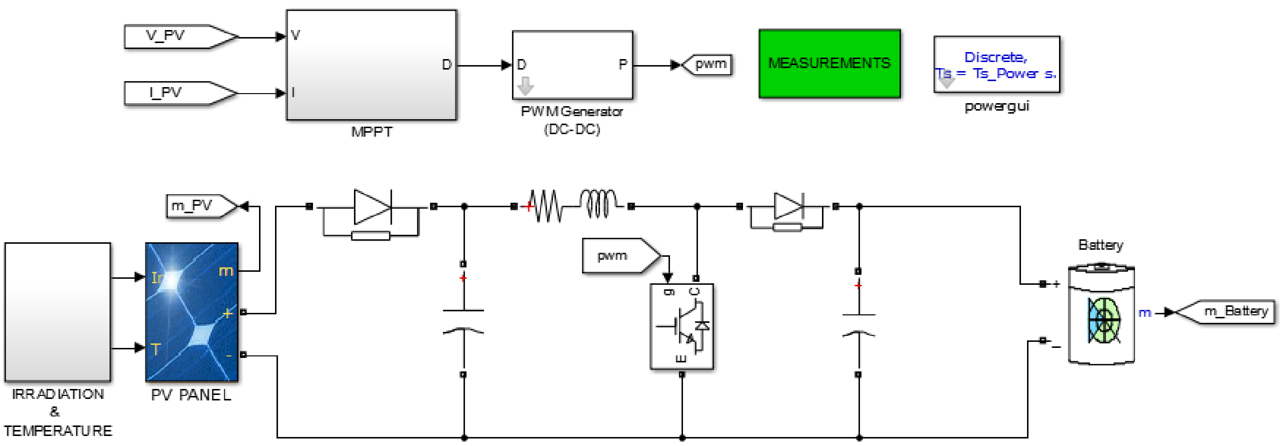


Figure 9. Simulation circuit for P&O and IC techniques

In order to analyze the performance of the converter in the simulation, the system is operated with different irradiation values. Weather conditions are determined as 25°C temperature and 1000W/m^2, 500W/m^2 and 700W/m^2, respectively. Under these conditions, the DC-DC converter is controlled by P&O technique and the power change seen in Figure 11 is obtained. When the change is analyzed, it is seen that the power change is directly proportional to the irradiation value and around 213W, 108W and 151W power is generated on average. These values coincide with the results obtained from the curves in Figure 7. It shows that the control algorithm works effectively. During this period, a total of 447.04 joules energy is produced. The algorithm is also tested in constant 1000 W/m^2 irradiation and variable temperatures. Figure 12 shows the power variation for different temperature, 25^{o}C, 15^{o}C and 35^{o}C. As seen in the figure, produced power is not affected from temperature change much. The power difference between variable temperatures is very small by comparison with variable irradiation. The produced power is the same with power values obtained from Figure 8 as 221W, 213W and 204W. During this period, a total of 447.04 joules energy is produced. In P&O algorithm, 50% decrease in irradiation causes 49.2% decrease in power while 43% decrease in temperature causes 7.69% decrease in power. The change in power is very higher in irradiation change than the power change in temperature change.

MPPT/MPPT ControllerP&O

```
function D   = PandO(V, I)
Dinit = 0.39;deltaD = 1e-3;Dmax=0.9;Dmin=0.1;
persistent Vold Pold Dold k Vtop Itop dP ...
    dV P Vort Iort;
if isempty(Vold)
    Vold=0;Pold=0;Dold=Dinit;k=0;Vtop=0;
    Itop=0;dP=0;dV=0;P=0;Vort=0;Iort=0;
end
k=k+1;Vtop=Vtop+V;Itop=Itop+I;
if k==30
    Vort=Vtop/k;Iort=Itop/k;P=Iort*Vort;
    dV= Vort - Vold;dP= P - Pold;
    k=0;Vtop=0;Itop=0;
    if dP~=0
        if dP > 0
            if dV > 0
                D = Dold - deltaD;
            else
                D = Dold + deltaD;
            end
```

MPPT/MPPT ControllerP&O

```
            if dV > 0
                D = Dold + deltaD;
            else
                D = Dold - deltaD;
            end
        end
    else
        D=Dold;
    end
else
     D=Dold;
end
if D >= Dmax || D<= Dmin
D=Dold;
end
Dold=D;
Vold=Vort;
Pold=P;
end
```

Figure 10. m-file code of P&O technique

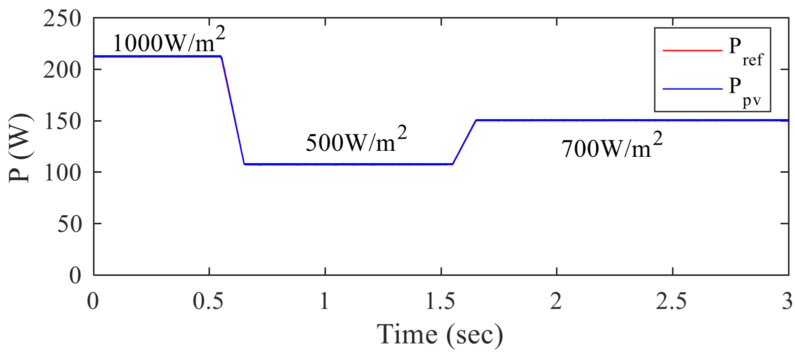


Figure 11. Power variation at 25^{o}C of P&O technique

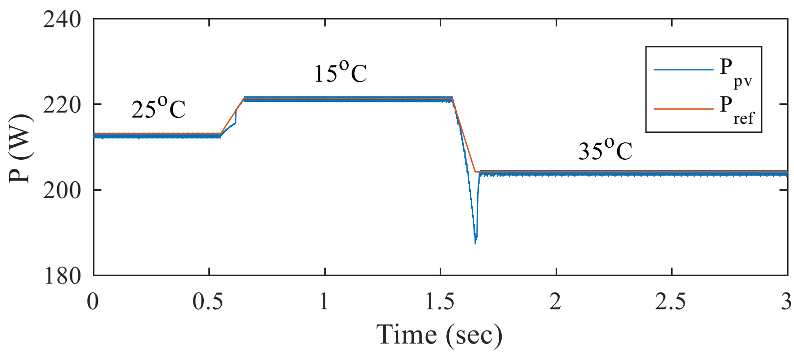


Figure 12. Power variation at 1000 W/m^2 of P&O technique

The circuit in Figure 9 is used for the other MPPT technique, called the incremental conductance. The m-file control code used in the simulation study under the same weather conditions is given in Figure 13. When the code is examined, it is seen that the current and voltage change, and the rate of these changes are checked in the algorithm. Unlike the P&O technique, the algorithm operates by controlling the current and voltage changes instead of power and voltage changes. As a result of operating the control algorithm given in Figure 13, the variations of power drawn from the panel are seen in Figure 14 and Figure 15. When the power outputs obtained at the same temperature and irradiation changes are compared with the P&O technique, it can be understood visually that the results are close to each other. The total produced energy is 447.19 joule at 25^{o}C while 633.84 joule at 1000W/m^{2}.

```
MPPT/MPPT Controller IC *
function D    = IncCond(V, I)
Dinit = 0.39;deltaD = 1e-3;Dmax = 0.9;Dmin = 0.1;
persistent Vold Iold Dold dV dI k Vtop Itop Vort Iort;
if isempty(Vold)
    Vold=0;Iold=0;Dold=Dinit;dV=0;dI=0;k=0;Vtop=0;...
    Itop=0;Vort=0;Iort=0;
end
k=k+1;Vtop=Vtop+V;Itop=Itop+I;
if k==30
    Vort=Vtop/k;Iort=Itop/k;dV= Vort - Vold;
    dI= Iort - Iold;k=0;Vtop=0;Itop=0;
        if dV==0
            if dI==0
                D=Dold;
            else
                if dI>0
                    D=Dold+deltaD;
                else
                    D=Dold-deltaD;
                end
            end
        else
            if dI/dV==-I/V
                D=Dold;
            else
                if dI/dV>-I/V
                    D=Dold-deltaD;
                else
                    D=Dold+deltaD;
                end
            end
        end
else
     D=Dold;
end
 if D >= Dmax || D<= Dmin
     D=Dold;
 end
Dold=D;
Vold=Vort;
Iold=Iort;
end
```

Figure 13. m-file code of IC technique

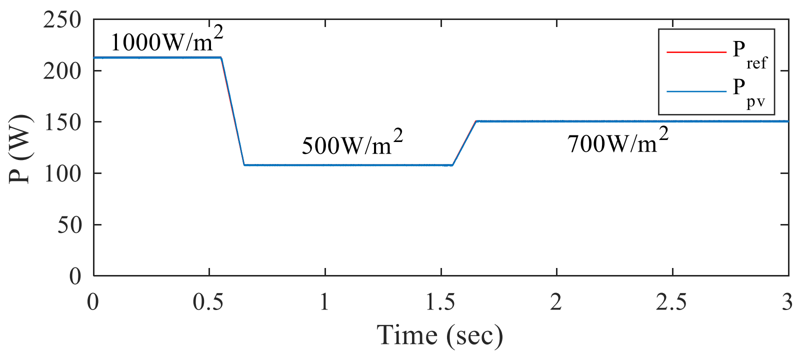


Figure 14. Power variation at 25^{o}C of IC technique

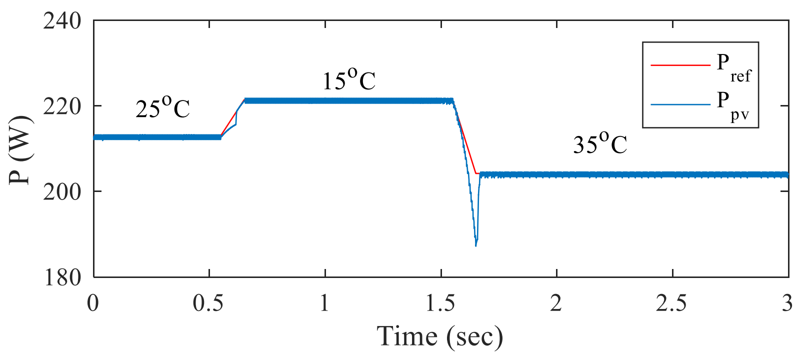


Figure 15. Power variation at 1000W/m^{2} of IC technique

The simulation circuit used in the OCV technique is given in Figure 16. In this technique, a semiconductor switch is used at the panel output in series to make the panel terminals open-circuited for measuring the open circuit voltage. Before the measurement moments, the panel is separated from the system by opening the switch, then the open circuit voltage is measured. The drawn energy from the panel is stored in the battery by the DC-DC boost converter. The m-file code containing the control software of the DC-DC converter is seen in Figure 17. In the simulation circuit in Figure 16, when the sense signal at the input of the MPPT block is on, the 'oc' signal becomes off and the switch separates the panel from the circuit. For a certain period, the measurement signal is on and during this time, the open circuit voltage of the panel is obtained by measuring the panel voltage from terminals. The voltage reference is calculated by multiplying this voltage value with the K_{oc} coefficient. When this measurement interval ends and the sense signal becomes zero, the duty cycle of DC-DC converter is changed to bring the panel output voltage closer to the calculated V_{ref} value. These processes continue periodically. Shortening this measurement period increases the accuracy of the steady state and increases the power interruptions that occur during the measurement moments. As can be seen in the power variations in
Figure 18 and

Figure 19 at each measurement, power generation is zero due to the open circuit of the panel at the measurement moments. For this reason, the panel is disabled during the measuring intervals and system efficiency decreases. Comparing the waveforms shows that temperature change affects the output power negatively more than irradiation change. The output power remains lower than maximum power. Increased measurement period decreases the produced energy.

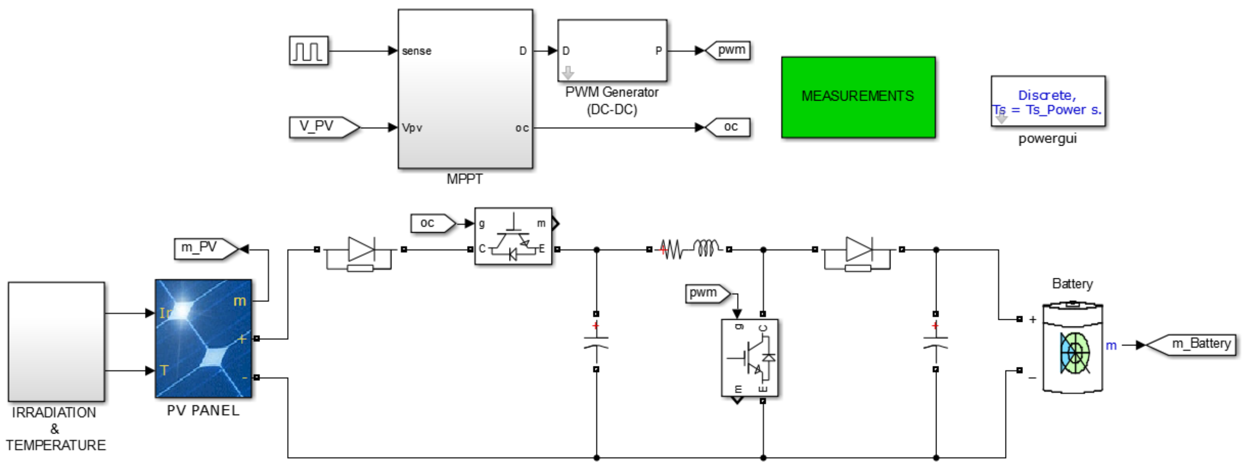
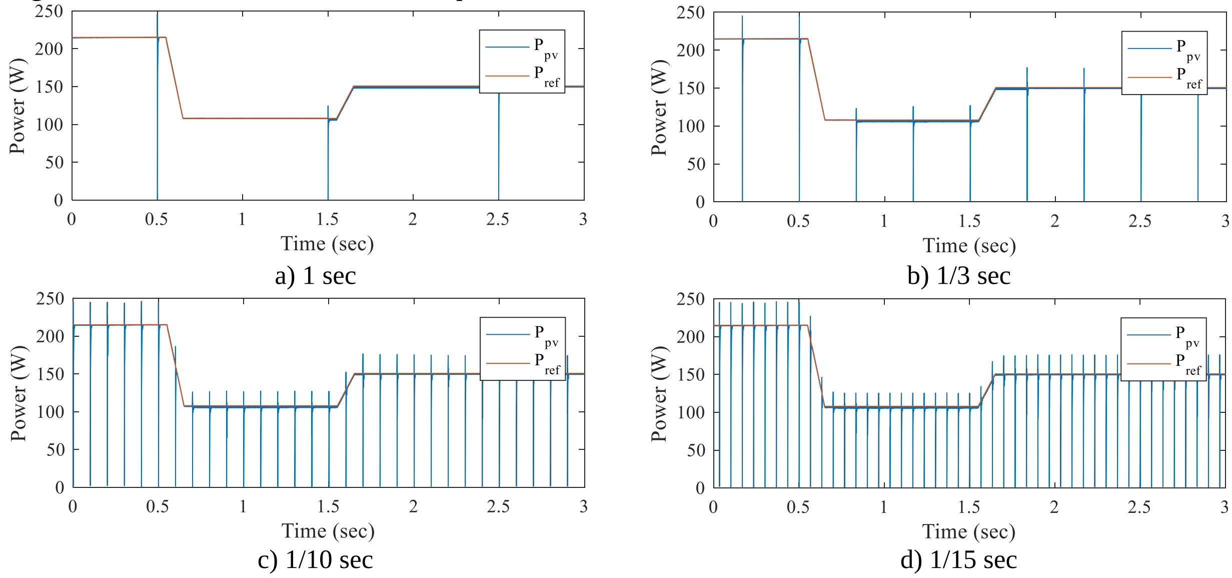


Figure 16. Simulation circuit for OCV technique

```
MPPT/OCV
function [D,oc]  = FOCV(sense, Vpv)
Voc_stc=36.3;
Vmpp_stc=29;
Dinitial=0.3;
deltaD=1e-4;
oc=1;
Koc=Vmpp_stc/Voc_stc;
persistent Dold Vref Verr
if isempty(Dold)
    Dold=Dinitial;
    Vref=Vmpp_stc;
    Verr=0;
end
    if sense==1
        oc=0;
        Voc=Vpv;
        Vref=Koc*Voc;
        D=Dold;
    else
        Verr=Vpv-Vref;
        if Vfark==0
            D=Dold;
        else
            if Verr>0
                if  Verr<0.5
                    D=Dold+deltaD;
                else
                    D=Dold+deltaD;
                end
            else
                if Verr>-0.5
                    D=Dold-deltaD;
                else
                    D=Dold-deltaD;
                end
            end
        end
    end
if D>=0.9 || D<=0.1
D=Dold;
end
Dold=D;
end
```

Figure 17. m-file code of OCV technique



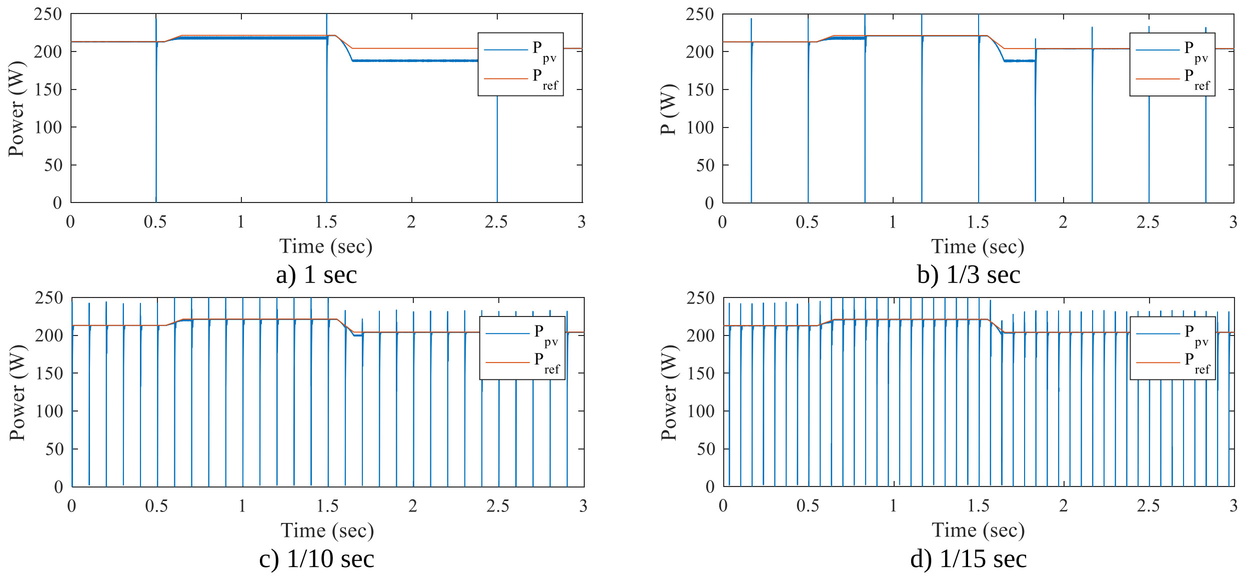
a) 1 sec

b) 1/3 sec

c) 1/10 sec

d) 1/15 sec

Figure 18. Power variations of OCV technique for different measurement periods at 25°C



a) 1 sec

b) 1/3 sec

c) 1/10 sec

d) 1/15 sec

Figure 19. Power variations of OCV technique for different measurement periods at 1000W/m^2

Simulation study of the last technique, short circuit current technique, is carried out in the circuit shown in Figure 20. Unlike the open circuit voltage method, in order to measure the panel short circuit current, there is a parallel-connected semiconductor switch in the circuit and the current is measured by closing the panel short circuit. Unlike the open circuit voltage technique, in order to measure the panel short circuit current, there is a parallel-connected semiconductor switch in the circuit and the current is measured by closing the switch.

Figure 21 shows the m-file code of the short circuit current technique. When the algorithm is examined, similar to the OCV technique, the parallel switch closes when the sense signal is on, and the short circuit current is measured. The current value is produced by multiplying this value with the K_{sc} coefficient. By comparing this current reference and the measured instantaneous current of the panel, the switching signal duty cycle is changed. Figure 22 and Figure 23 shows the drawn power from the PV panel with SCC technique for variable irradiation and temperature. As observed from the waveforms, an interruption occurred in the power due to the drop in the amount of irradiation at constant temperature. In cases where the measurement period is shorter, the generated power increases more rapidly as the new reference value is quickly recalculated. Increasing the measurement period causes a lot of power loss in the irradiation drops in this technique. In the case of increased irradiation, when the new measurement is not taken, the power is produced below the maximum power value and the total amount of energy produced decreases. As seen in Figure 23, power production is not affected much under constant irradiation and variable temperature condition. The maximum power point varies little compared to the change in irradiation. The produced total energy varies in direct proportion to the number of samples taken. When the waveform in Figure 22 and Figure 23 are examined, it is revealed that the SCC technique gives more successful results where the irradiation is constant.

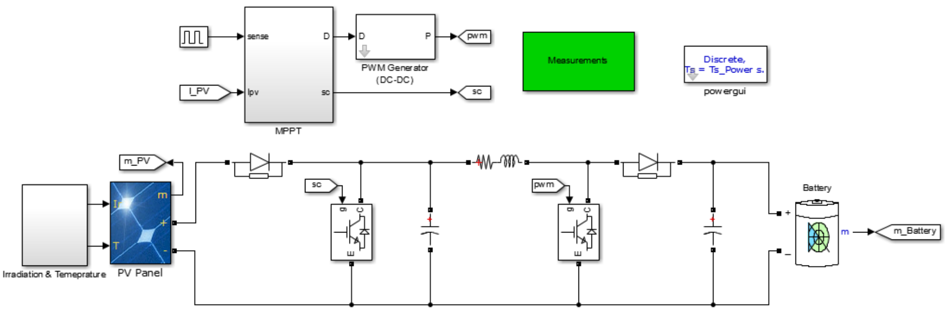


Figure 20. Simulation circuit for SCC technique

MPPT/SCC

```
function [D,sc] = FSCC(olc, Ipv)
Isc_stc=7.84;
Impp_stc=7.35;
Dinitial=0.4;
deltaD=1e-4;
sc=0;
Ksc=Impp_stc/Isc_stc;
persistent Dold Iref Ifark Isc
if isempty(Dold)
    Dold=Dinitial;
    Iref=Impp_stc;
    Ifark=0;
end
    if olc==1
        sc=1;
        Isc=Ipv;
        Iref=Ksc*Isc;
        D=Dold;
    else
        Isc=0;
        Ifark=Ipv-Iref;
        if Ifark==0
            D=Dold;
        else
            if Ifark>0
                    D=Dold-deltaD;
            else
                    D=Dold+deltaD;
            end
        end
    end
if D>=0.99 || D<=0.1
    D=Dold;
end
    Dold=D;
end
```

Figure 21. m-file code of SCC technique

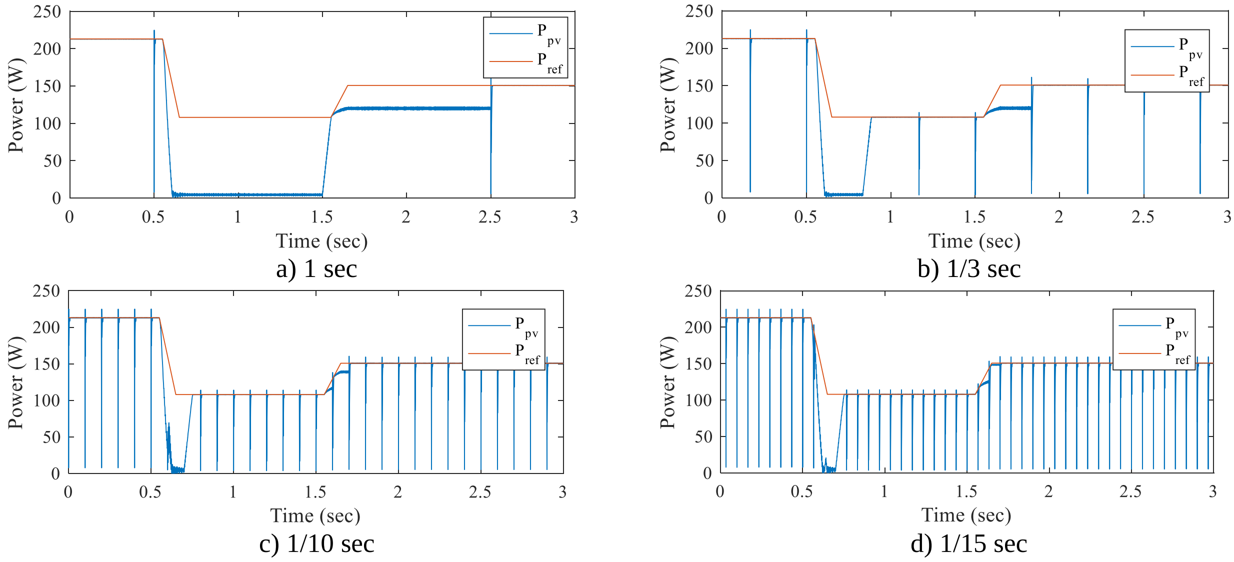


Figure 22. Power variations of SCC technique for different measurement periods at 25°C

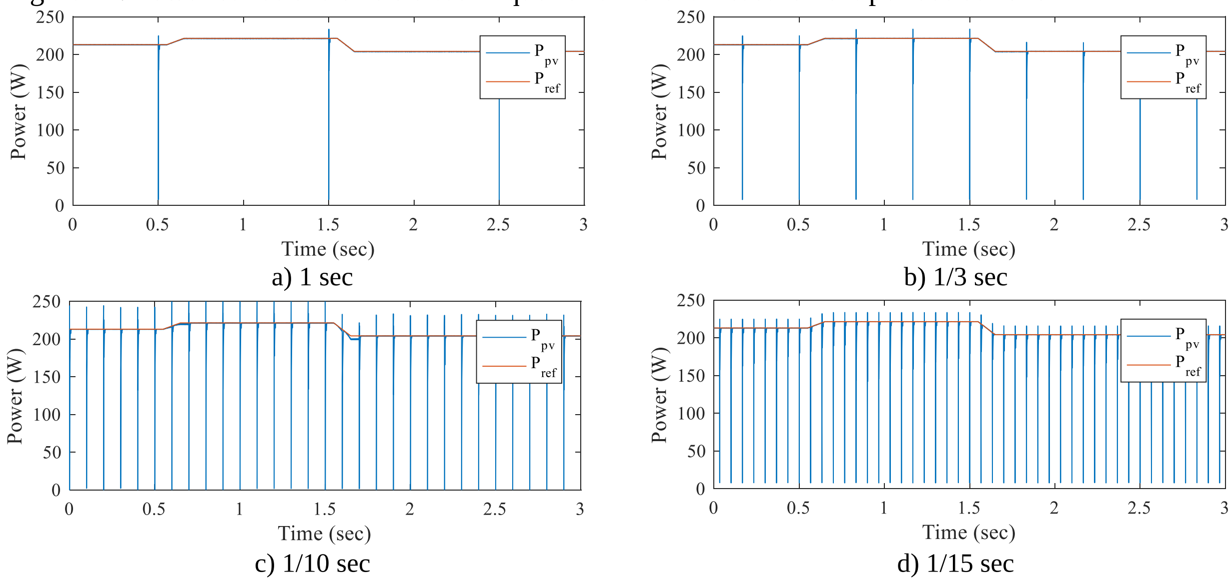


Figure 23. Power variations of SCC technique for different measurement periods at 1000W/m^2

4. Results and Discussion

When the energy obtained from four different MPPT techniques are examined in the 3-second time interval, 177.28 mWh energy is produced in P&O and IC techniques as shown in Table 3 at constant 25^{0}C temperature and 1000 W/m^2 irradiation values. Under the same conditions, lower energy is produced when OCV and SCC techniques are used. In these techniques, when the measurement intervals are applied as 1/15 sec, 1/10 sec, 1/3 sec and 1 sec, 174 mWh, 175.17 mWh, 176.74 mWh and 177.2 mWh are produced respectively in the OCV technique and 174.7 mWh, 175.6 mWh, 176.86 mWh and 177.23 mWh were produced in SCC technique. When the results in Table 4 are analysed, very close results are obtained in both techniques. As the measurement interval increases, the amount of produced energy increases for the same time interval due to the decreasing non-energized time decreases. The produced energy at 25°C and variable irradiation in simulation is 124.2 mWh as seen in Table 5. In the OCV technique, 121.85 mWh, 122.47 mWh, 123.4 mWh and 123.69 mWh energy is produced for 1/15 s, 1/10 s, 1/3 s and 1 s measurement interval, while 117.22 mWh,117.54 mWh, 113 mWh and 88.5 mWh energy are produced in SCC technique. The energy produced in the OCV technique increases with the increase in the measurement period, while the energy produced in the SCC technique decreases. Because the power drops down suddenly with a decrease in irradiation. While the measurement period increases under constant weather conditions, the produced energy decreases in this situation, because the energy remains close to zero until the new measurement point.

The amount of produced energy remains low, as there is a delay in reaching maximum power in the timeframe in which the irradiation increases. For the same measurement intervals, 172.88 mWh, 173.9 mWh, 174.45 mWh and 171.31 mWh energy is produced with a constant radiation of 1000 W/m^2 and variable temperature in OCV technique as given in Table 6. The produced energy decreases when the measurement interval increases to 1 sec. This situation happens because the produced energy remains below the maximum power due to no measurement at the moment of change. Unlike the OCV technique, 173.72 mWh, 174.54 mWh, 175.81 mWh and 176.1 mWh energy is generated in the SCC technique, respectively.

Table 3
Produced energy with P&O and IC

Weather conditions	**P&O (mWh)**	**IC (mWh)**
1000W/m^2 - 25^{o}C	177.28	177.28
1000W/m^2 ve variable temperature	176.07	176.07
25^{o}C ve variable irradiation	124.18	124.2

Table 4
Produced energy at 25^{o}C and 1000W/m^2

Weather conditions	**Measurement interval (sec)**	**OCV (mWh)**	**SCC (mWh)**
25^{o}C - 1000W/m^2	1/15	174	174.7
25^{o}C - 1000W/m^2	1/10	175.17	175.6
25^{o}C - 1000W/m^2	1/3	176.74	176.86
25^{o}C - 1000W/m^2	1	177.2	177.23

Table 5
Produced energy at 25^{o}C and variable irradiation

Weather conditions	**Measurement interval (sec)**	**OCV (mWh)**	**SCC (mWh)**
25^{o}C – variable irradiation	1/15	121.85	117.22
25^{o}C - variable irradiation	1/10	122.47	117.54
25^{o}C - variable irradiation	1/3	123.4	113
25^{o}C - variable irradiation	1	123.69	88.5

Table 6
Produced energy at 1000W/m^2 and variable temperature

Weather conditions	**Measurement interval (sec)**	**OCV (mWh)**	**SCC (mWh)**
1000W/m^2 – variable temperature	1/15	172.88	173.72
1000W/m^2 - variable temperature	1/10	173.9	174.54
1000W/m^2 - variable temperature	1/3	174.45	175.81
1000W/m^2 - variable temperature	1	171.31	176.1

5. Conclusion

In this study, maximum power point tracking techniques used in PV systems called perturb & observe, incremental conductance, short circuit current and open circuit voltage are investigated. A simulation study is performed in Matlab/Simulink to examine these techniques. In the examined system, 215 W photovoltaic panel, a DC-DC boost converter and a battery are used to store the produced energy. MPPT techniques are used in this system in constant temperature and irradiation, variable temperature and variable irradiation conditions, power changes are obtained, and the amount of produced energy is calculated. P&O and IC techniques produce more energy in all ambient conditions. OCV and SCC techniques are tested for different measuring time periods as well as fixed and variable ambient conditions. Both two techniques have very close results under constant conditions. However, under variable conditions, differences occurred in the performance of the two techniques. In variable irradiation conditions, the OCV technique produces more energy than the SCC technique. Although the maximum power point tracking is not fully performed with the increase in the measurement interval, the produced energy increases due to the decrease in losses in the measurement moments. In the SCC technique, the produced energy remains low because the produced power drops down to zero at the decreasing moments of irradiation. Since the new measurement is not performed despite the variable environment in the long measurement period, the maximum amount of energy decreases as the time interval increases. For the variable temperature, this situation changes. The amount of produced energy in the SCC technique varies in direct proportion to the measurement time interval. The reason is that the change in the maximum amount of power versus the temperature change is much less than that of the irradiation change, and consequently the power drawn from the panel does not drops to zero as quickly as in variable irradiation. In the OCV technique, energy production decreases since the new measurement cannot be made within 1-second measurement interval during the change in ambient condition and the reference produced at the previous measurement is followed for a long time.

As a result of the simulation study, P&O and IC lead in terms of maximum power point tracking and energy production performance. It is seen that energy production performance of OCV and SCC techniques decrease depending on the measurement period especially in variable weather conditions while they perform satisfactory results in steady state maximum power point tracking. Although OCV and SCC techniques provide superiority over P&O and IC techniques in terms of algorithm simplicity, additional components should be used for open circuit and short circuit of the panel. Current and voltage sensors are used to perform current and voltage measurements in P&O and IC techniques, while only voltage sensor is used in the OCV technique and only current sensor is used in the SCC technique.

Author Contributions

Evren ISEN: Literature review, simulation study and writing the paper.

Akif SENGUL: Literature review, simulation study.

Conflicts of Interest

The authors declare no conflict of interest.

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