2014

Maximum power point tracking of a solar panel using a DC bus

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ABSTRACT

MAXIMUM POWER POINT TRACKING OF A SOLAR PANEL USING A DC BUS

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Northern Illinois University, 2014
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A system is designed to extract the maximum power from a solar panel using SIMULINK software. The main objective of this thesis is to track the maximum power point from a solar panel by using a DC bus and to notice the changes in the voltage, current and power of the solar panel with the change in the irradiation level. The solar panel is designed by considering the standard current and voltage conditions. A maximum power point tracking algorithm is designed in a MATLAB code and the output gives the track of the maximum power point reached by the system which is given as a feedback to the solar panel by using DC bus and extract the maximum power out of the solar panel. The DC bus used in this system acts as an infinite load which accepts the maximum ranges in order to get the maximum power. For different irradiation levels, there will be a change in the solar panel’s current, power and voltage and the maximum power point as well. These changes in power and current of the solar panel with respect to the voltage are observed by simulation for different irradiation levels, and the maximum power point for different conditions are tracked.

NORTHERN ILLINOIS UNIVERSITY
DE KALB, ILLINOIS

DECEMBER 2014

MAXIMUM POWER POINT TRACKING OF A SOLAR PANEL USING A DC BUS

BY

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A THESIS SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

Thesis Director:
Donlad Zinger

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CHAPTER 1

INTRODUCTION

A circuit is designed in SIMULINK by connecting the main components solar panel with an irradiation variation block, the DC bus and current controller. The solar panel is the heart of the circuit which runs the entire system by giving the power out of it. The solar panel is designed in a subsystem by using the standard current and voltage conditions to give the total voltage and current. Figure 1 is the main circuit which describes the above-mentioned connections. The subsystem of solar panel can be seen in Figure 2, which has an input of irradiance that can be varied.

The output current of the solar panel obtained is given as a feedback to the s-function MPPT (maximum power point) block which is then coded with MPPT algorithm to track the maximum power point at every irradiance level. The output voltage is also given as a feedback to this s-function block as an input. The MPPT algorithm is coded to deal with the conductance conditions. The output of this gives the maximum power point reached by the system at that voltage, current and irradiance levels. This block always accepts the updated values in it at different irradiance and tracks the maximum power point at that level which can be observed in a graph.

This system has a current controller which controls the flow of current all the time. The DC bus acts as an infinite load, which has a probability to accept maximum range of values and helps the system in feeding back the output voltage to the solar panel in order to extract the maximum power from the solar panel. DC bus is very simple to use and reliable as well. There is a capacitor to take care of the storage in the system.

With the change in the irradiation, the changes in the solar panel's current and power with respect to the voltage are observed in the graphs and the point at which the current and power are maximum are noticed. Maximum power point is also tracked by the MPPT (maximum power point tracking) algorithm and observed in the graph at that point of change.

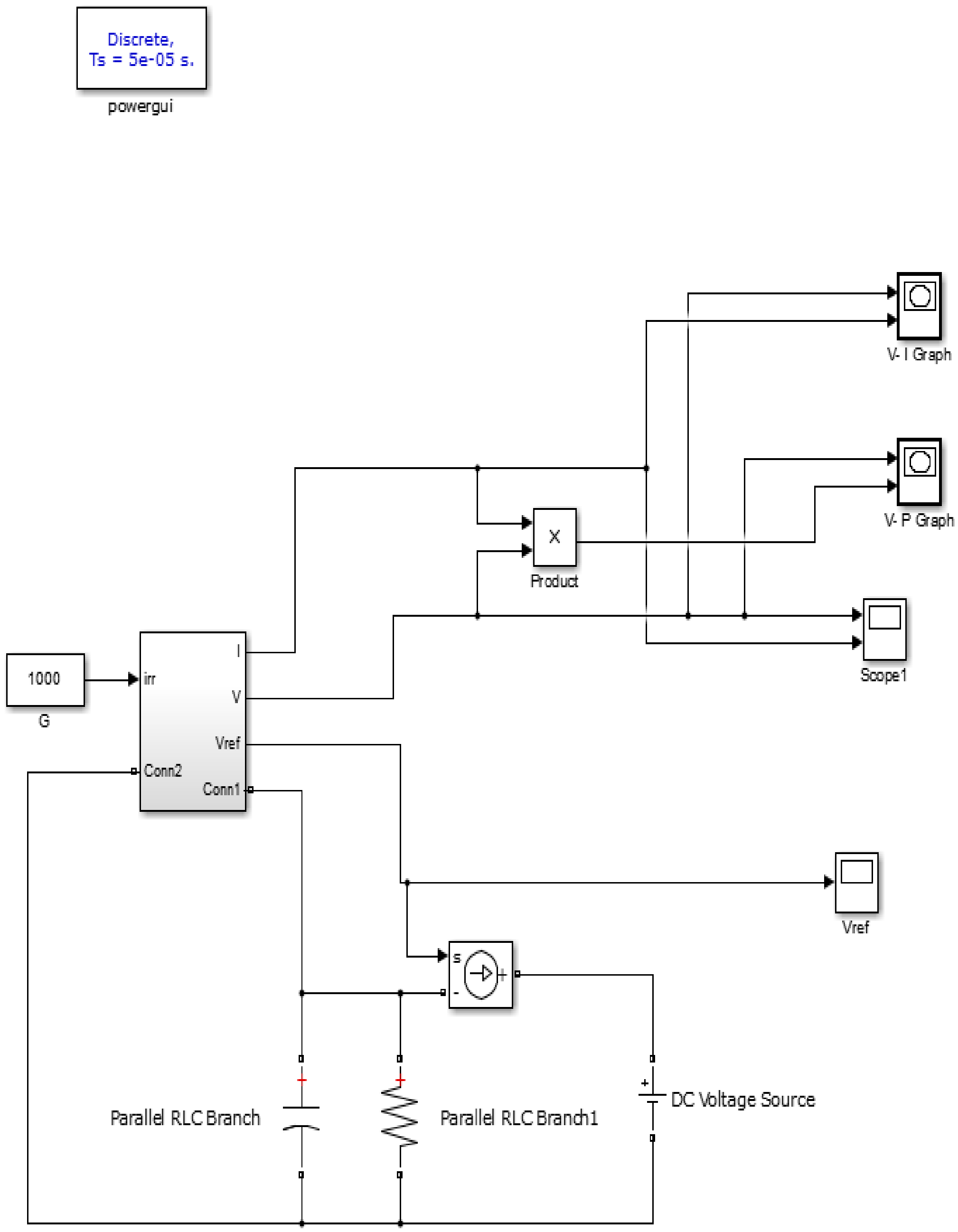


Figure 1. Main circuit of the system.

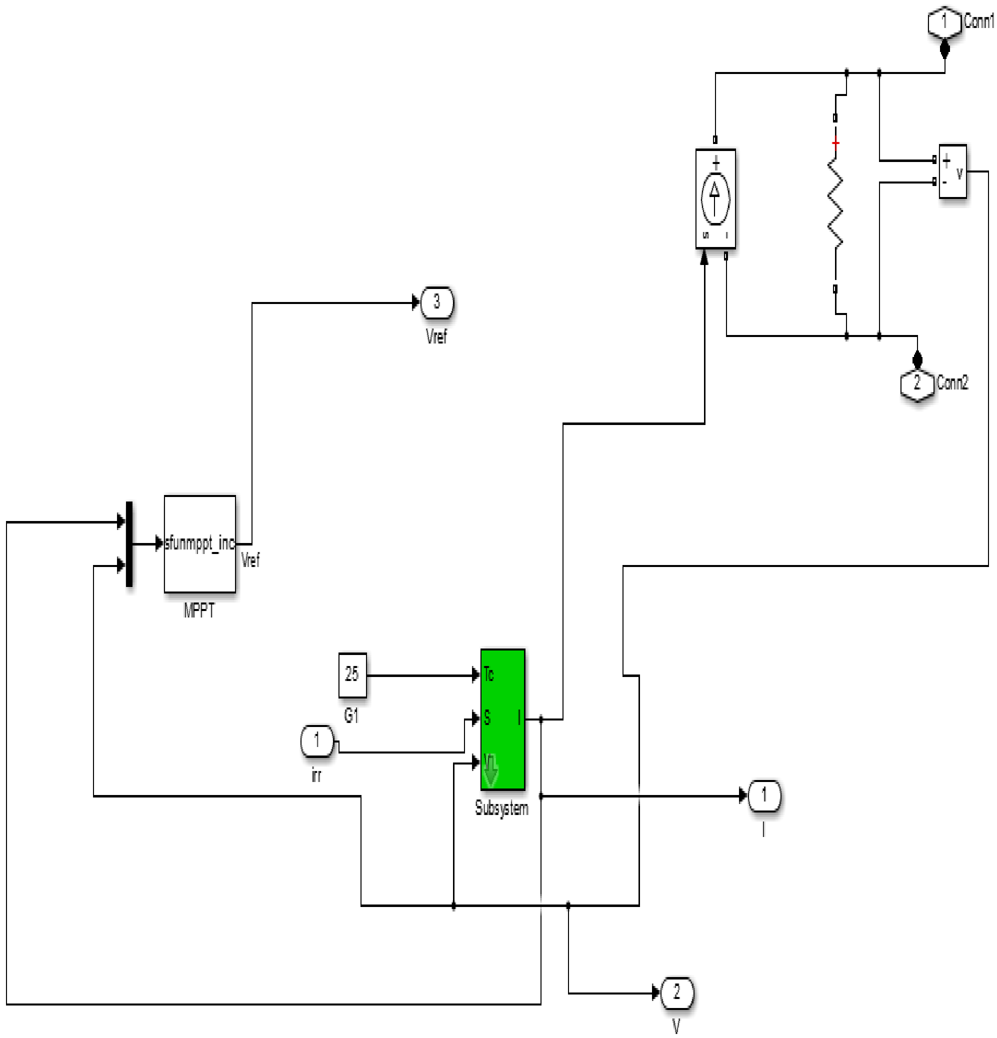


Figure 2. Level 1 of the main circuit.

CHAPTER 2

SOLAR PANEL

A solar panel is a set of photovoltaic modules which are electrically connected and mounted on a supporting structure [1]. A solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in residential and commercial applications. Solar modules use light energy from the sun to generate electricity through the photovoltaic effect. Most solar modules are rigid, but semi-flexible ones are available, based on thin-film cells. The electrical connections are made in either series or parallel to achieve the desired output. We get the voltage when connected in series and current when connected in parallel. The solar cells must be connected not only with one another but also to the rest of the system.

A solar panel presents a nonlinear I-V characteristic curve which represents the change in current with respect to voltage. A mathematical model of solar panel is used to study the maximum power point tracking (MPPT) algorithm and simulation as well. In order to design a solar panel in this system, a set of equations and standard conditions are used to obtain the solar current [2].

The solar irradiance is a measure of the irradiance (power per unit area on the Earth's surface) produced by the sun in the form of electromagnetic radiation. Solar irradiance in a specific area may be measured as insolation [3].

2.1 Designing a Solar Subsystem

A solar subsystem is designed by considering the following current equations. The equation that describes the I-V characteristic of an ideal photovoltaic cell is [4]:

$$I = I_{pv} - I_o \left[\exp\left(\frac{qv}{akt} - 1\right)\right] \quad \rightarrow \text{Equation (1)}$$

where I_{pv} is the photovoltaic current and I_o is the saturation current,

q is the electron charge (1.60217. 10^{-19} C),

K is the Boltzmann constant (1.3806503. 10^{-23}/K),

T is temperature,

a is an ideality constant.

Equation 1 does not represent the total I-V characteristic of a solar array; the observation of the characteristics at the terminals of a solar array requires the extension of this equation.

So, equation 1 can be simplified to:

$$I = I_{pv} - I_o \left[\exp\left(\frac{V + R_S I}{a.\ V_t} - 1\right)\right] \quad \rightarrow \text{Equation 2}$$

where Vt is the thermal voltage with N_s cells connected in series,

$V_t = N_s kT/q$,

Rs is the resistance connected in series and Rp is the parallel resistance.

The characteristic curve of I-V is shown in Figure 3, a current graph with respect to voltage. It has three points, a short circuit (0, I_{sc}), maximum power point (V_{mp}, I_{mp}), and open circuit (V_{oc},0) [5].

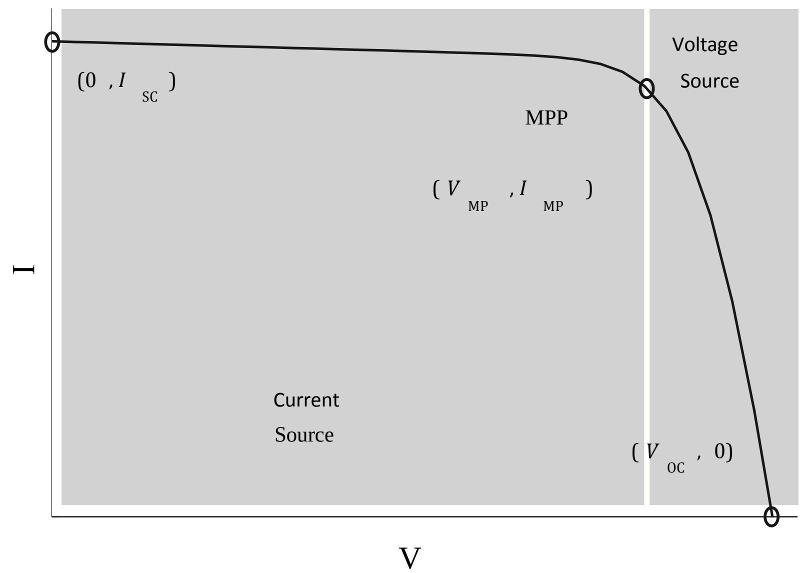


Figure 3. Characteristics of I-V curve [4].

The photovoltaic array gives the standard information about the nominal open-circuit voltage V_{oc}, the nominal short-circuit current $I_{sc,}$, the voltage at the maximum power point V_{mp}, the current at the maximum power point I_{mp}, and the maximum experimental peak output power P_{max}.

This information is always provided with reference to the nominal or standard test conditions (STC) of temperature and solar irradiation. The results of I-V curves for several irradiations are observed in this system. The amount of incident light directly affects the generation of charge carriers and consequently the current generated by the device [5]. The currents of photovoltaic and saturation are represented by equations 3 and 4.

$I_{pv} = (K_t \Delta t + I_{sc}) \frac{G}{G_n}$ → Equation 3, Photovoltaic Current

$\Delta_T = T - T_n$, T and T_n are the actual and nominal temperatures,

G [W/m^2] is the irradiation on the device surface and G_n is the nominal irradiation.

$$I_o = \frac{I_{pv}}{\left[\exp\left(\frac{U_{oc}}{a.\ V_t}-1\right)\right]}$$ → Equation 4, Saturation Current

where $U_{oc} = \Delta t.K_t + V_{ocs}$ → Equation 5

Apart from these, the standard values considered for this system are as follows:

$I_{MP} = 7.61\ A$

V_{MP} = 26.3 V

$P_{max} = 200.143W$

$I_{SC} = 8.21A$

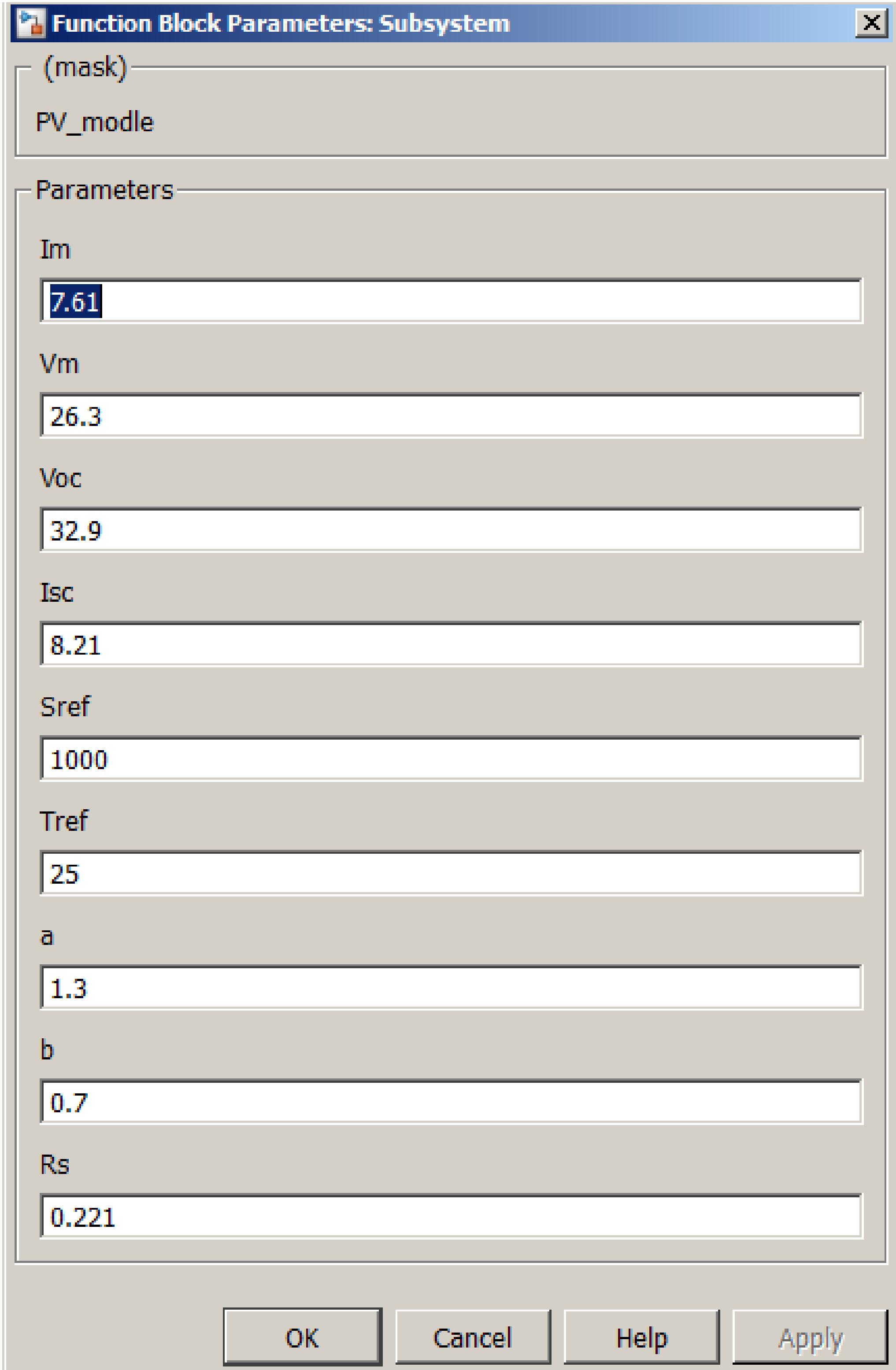
$V_{OC} = 32.9V$

I_o = $9.625.10^{-8}$ A

$I_{PV} = 8.214\ A$

The following block is the one which is used in the SIMULINK to give the conditions.

By applying all these conditions, the total current varied with respect to voltage at different irradiations is shown in the Figure 4.


Function Block Parameters: Subsystem
(mask)
PV_modle
Parameters
Im
7.61
Vm
26.3
Voc
32.9
Isc
8.21
Sref
1000
Tref
25
a
1.3
b
0.7
Rs
0.221
OK
Cancel
Help
Apply

The solar cell I-V curve; a line intersects the knee of the curve where the maximum power point is located (Figure 5).

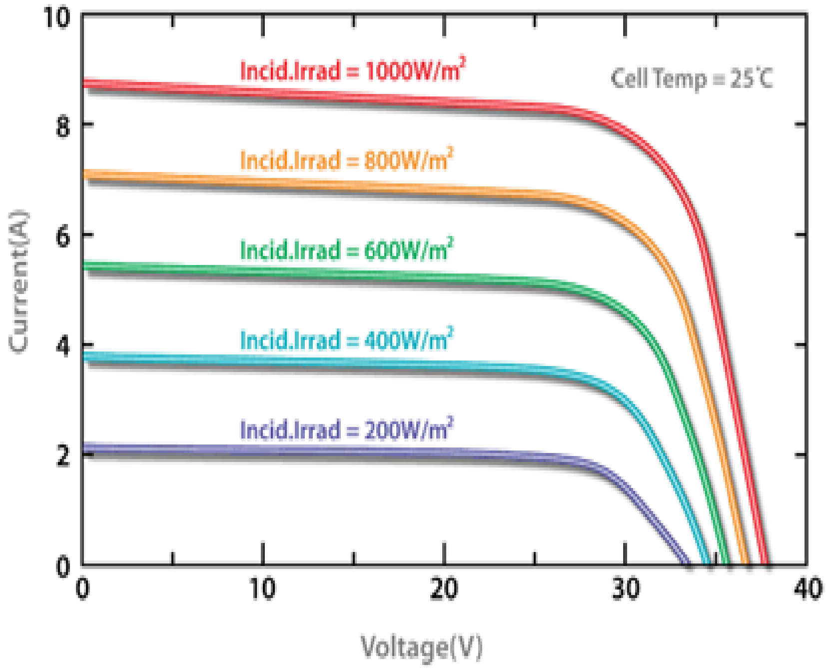


Figure 4. I-V curve for different irradiations [6].

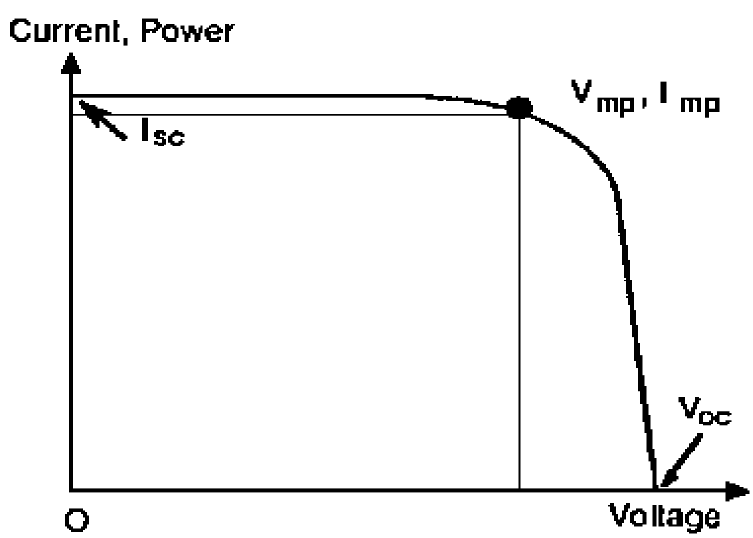


Figure 5. I-V curve describing maximum power point [6].

With the variations of current and voltage, the varied power is plotted with respect to the voltage, shown in Figure 6.

Different powers obtained for different irradiation levels and the maximum power point obtained at that particular level is shown in Figure 7.

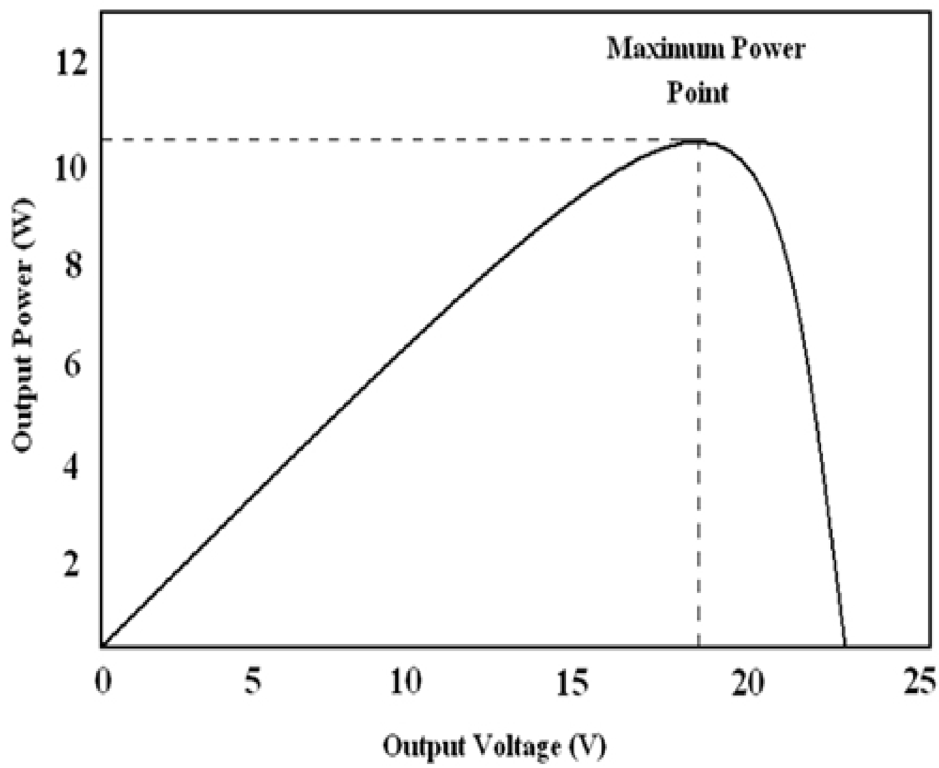


Figure 6. Power voltage (P-V) graph of the solar panel [6].

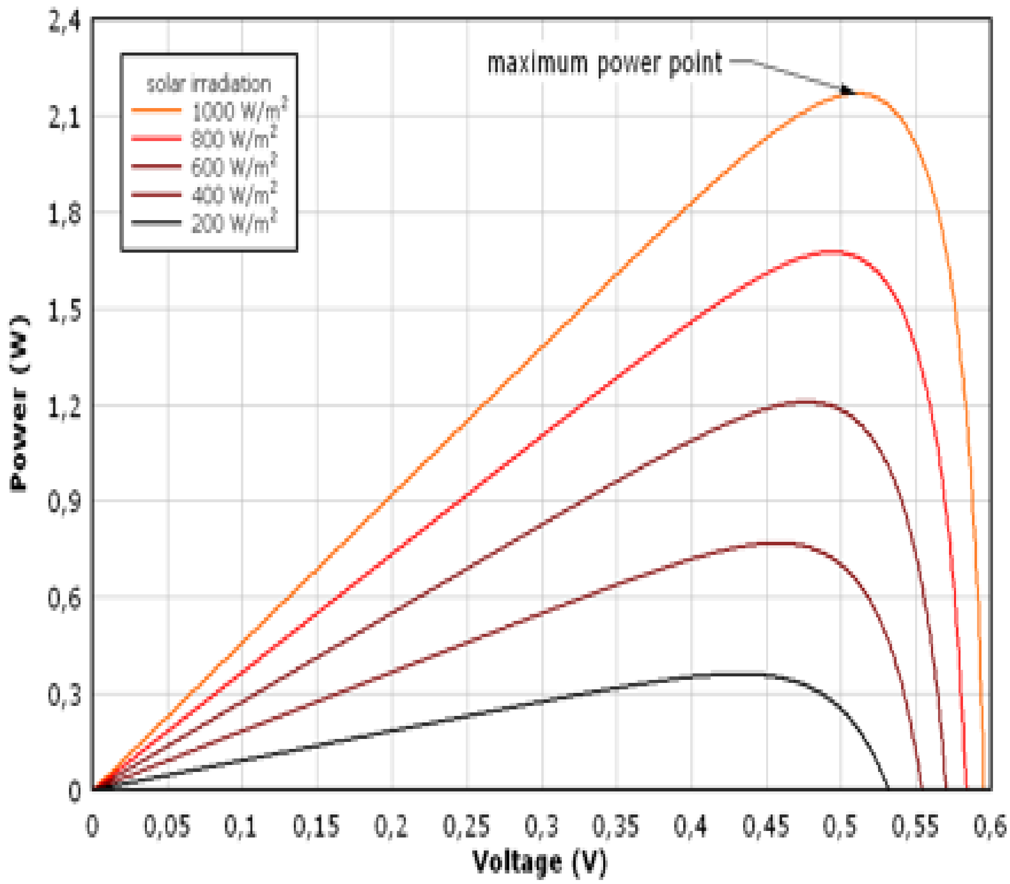


Figure 7. Different powers obtained for different irradiation levels [6].

CHAPTER 3

MAXIMUM POWER POINT TRACKING (MPPT)

For any photovoltaic cell, a particular point where the maximum power is obtained when the current and voltage are maximum is known as maximum power point. Photovoltaic cells have a complex relationship between their operating environment and the maximum power they can produce [6]. A typical solar panel converts only 30 to 40 % of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel.

The MPPT (maximum power point tracking) is an automatic adjustment of the load to achieve the power out of the solar panel, which varies due to factors like weather conditions, temperature and solar irradiation. As the current and voltage have an exponential relationship [7], the maximum power point (MPP) occurs on the knee of the I-V curve where (dP / dV) = 0. It can be said that the characteristic resistance of the solar cell is equal to the load resistance.

3.1 MPPT (Maximum Power Point Tracking) Algorithm

To track the maximum power point for every change in irradiation, s-function MPPT block is designed in MATLAB and connected to the solar panel. This block contains the code which includes the conditions of conductance for different changes in the current. The power delivered from or to a device is optimized where the derivative (graphically, the slope) *dI/dV* of the I-V curve is equal and opposite the *I/V* ratio (where dP/dV=0) is known as the maximum power point (MPP). It is used to maximize module output power [8].

An algorithm used to find the maximum power point is summarized below. This algorithm finds a reference voltage (Vref) used to control the current into the DC bus. The value of Vref is updated based on the relation between changes in current and changes in voltage.

The change in voltage (dV) and the change in current (dI) are observed and coded as:

dV= u(1)- x(1) and

dI= u(2)- x(2), where

u(1) - Present value of the voltage developed

u(2) - Present value of the current

x(1) - Previous voltage and

x(2) – Previous current

The output Vref is termed as x(3); K1 is the step change that should be added or decreased. Vref is updated based on three different cases.

<u>Case 1</u>

If dV=0, i.e., change in the voltage is zero, then the change in the current is also zero and x(3) = Vref. There will be no change in the output and the change in the conductance will be

$\frac{dI}{dV} = \frac{u(2)}{u(1)}$ [8].

Case 2

If dI>0, then Vref= x(3) + K1 . The change in the conductance is $\frac{dI}{dV} > \frac{u(2)}{u(1)}$.

Case 3

If dI<0, then Vref= x(3) – K1. The change in the conductance is $\frac{dI}{dV} < \frac{u(2)}{u(1)}$.

The designed MPPT system has two inputs, solar panel's current and the output voltage [6]. It always updates itself by taking the new reference voltages according to the changes and gives the new track of the power. With the change in the irradiance, there will be a change in the maximum power point based on the changes in the P-V's current and voltage.

The power output of a module varies as a function of the voltage in a way that power generation can be optimized by varying the system voltage to find the maximum power point [9]. This MPPT algorithm gives an output of reference voltage to control the current into the DC bus.

For a particular condition, the maximum power point is obtained from the I-V and P-V graphs; the common voltage at which the power and current is maximum. It can be observed in the Figure 8.

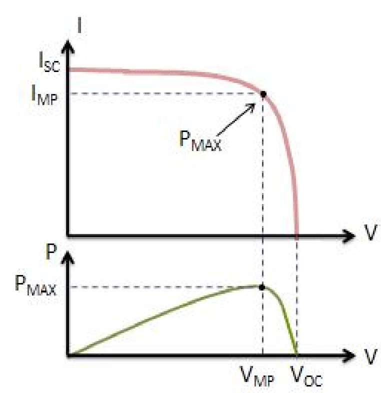


Figure 8. The maximum power point tracked from I-V and P-V graphs [10].

3.2 Description of MATLAB Code

MATLAB is a software package for computation in engineering, science, and applied mathematics. It is mainly used for its simplicity and user friendliness. Help option lets a user to learn the software independently. It has a high advantage due to its fast performance and its huge computation level [11]. SIMULINK is an extension to MATLAB which is used for the construction of a block diagram. A block diagram is simply a graphical representation of a process, which is composed of an input, the system, and an output. However, SIMULINK uses a graphical user interface (GUI) for solving process simulations. It allows the user to easily simulate systems of linear and nonlinear ordinary differential equations. The construction of a model is simplified with click-and-drag mouse operations [11].

SIMULINK includes a comprehensive block library of toolboxes for both linear and nonlinear analyses. Models are hierarchical, which allow using both top-down and bottom-up approaches. As SIMULINK is an integral part of MATLAB, it is easy to switch back and forth during the analysis process and thus the user may take full advantage of features offered in both environments.

The functioning of this software can be done firstly by writing the MPPT code in MATLAB and saving it in an m-file. The SIMULINK design is done by the connections described previously and also by adding the m-file to s-function block in this system. Once the file is saved, it is simulated by running the design and observing the output results in the graphs.

A MATLAB code is designed to generate the maximum power point track at each irradiation level. The system is given the m-file s-functions which can be defined with ordinary differential equations/discrete system equations to use within a Simulink block diagram.

The general form of m-file s-function syntax is:

[SYS, X0,STR,Ts]= Sfunc (T,x,u,flag).

The value returned by the s-function at a given point of time depends on the value of the flag, the current state vector x and also the input u.

X0= Initial state conditions,

STR= State ordering strings,

Ts=Sample time.

After the first output is generated with the initial values, that system generates the outputs and gives the voltage as a feedback and updates the program to get a new output. The previous output acts as an input in the next cycle and it continues to get the maximum power point which is simultaneously observed in a scope. The output will be a reference voltage which is used to control the current into the DC bus.

CHAPTER 4

DC BUS

The DC bus used in this system acts as an infinite load to accept the maximum probable range and extract the maximum power out of the solar panel. The DC bus is used to give the reference voltage generated as a feedback to the solar panel in order to get the maximum power out of it. As the DC bus gives the feedback to the solar panel, the panel updates itself with the new voltage and gives the new I-V and P-V graphs accordingly. During this process there is a lot of current fluctuations in the system. So, a current controller is used to control the flow of currents and give it to the DC bus. A parallel RLC is connected in parallel to the DC bus to manage the power storage. Communication between the panels and the energy management controller allows the optimization of each solar panel operating point to increase the efficiency of the entire system [10]. The strings of the solar panels form an entire data network over the high-voltage power line. It is easy to implement, as it is low cost and occupies less space.

CHAPTER 5

RESULTS

The I-V and P-V curves for different irradiation levels are observed and also the maximum power point of the system is also tracked and observed in a graph. The following results can be observed,

5.1 For an Irradiation of 500 W/m^2

Figure 9 shows the current vs voltage trajectory for the MPPT algorithm with 500 W/m^2. The power curve trajectory for this condition is shown in Figure 10. The voltage and current are individually shown as function of time in Figure 11, while Figure 12 shows the reference value used in the control. Note that the power tends toward its maximum of nearly 100 watts.

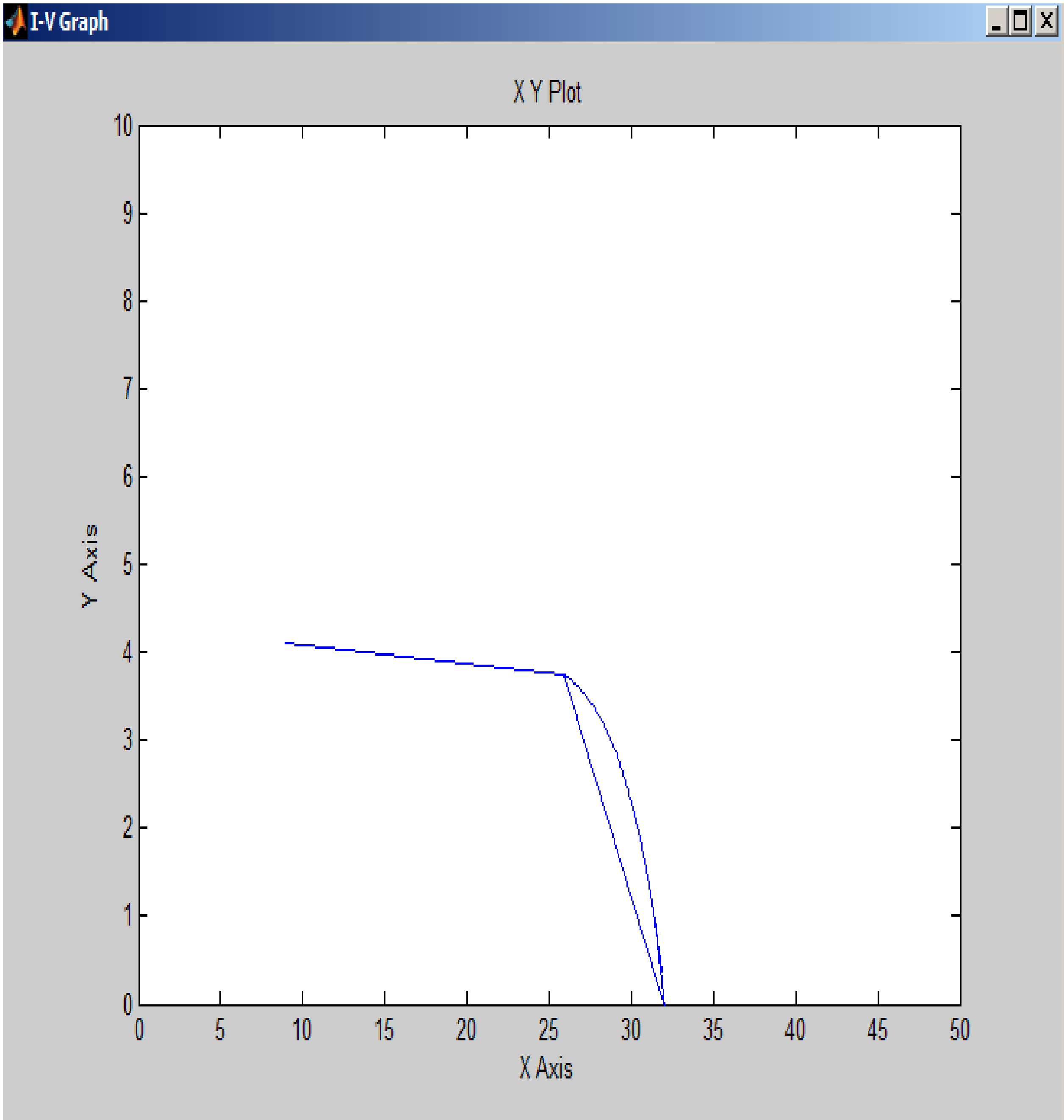


Figure 9. I-V curve for an irradiation of 500 W/m².

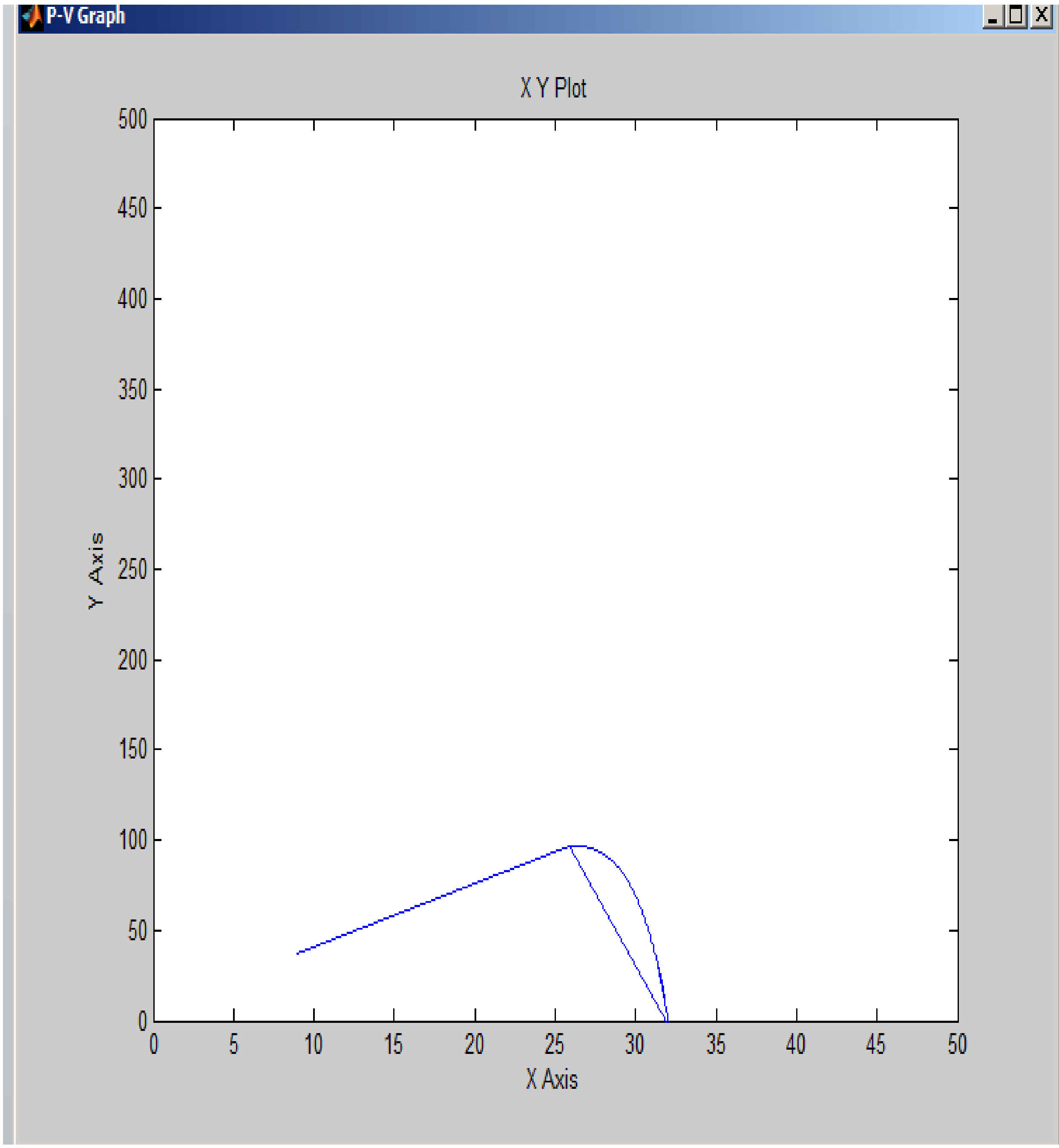


Figure 10. P-V curve for an irradiation of 500 W/m^2.

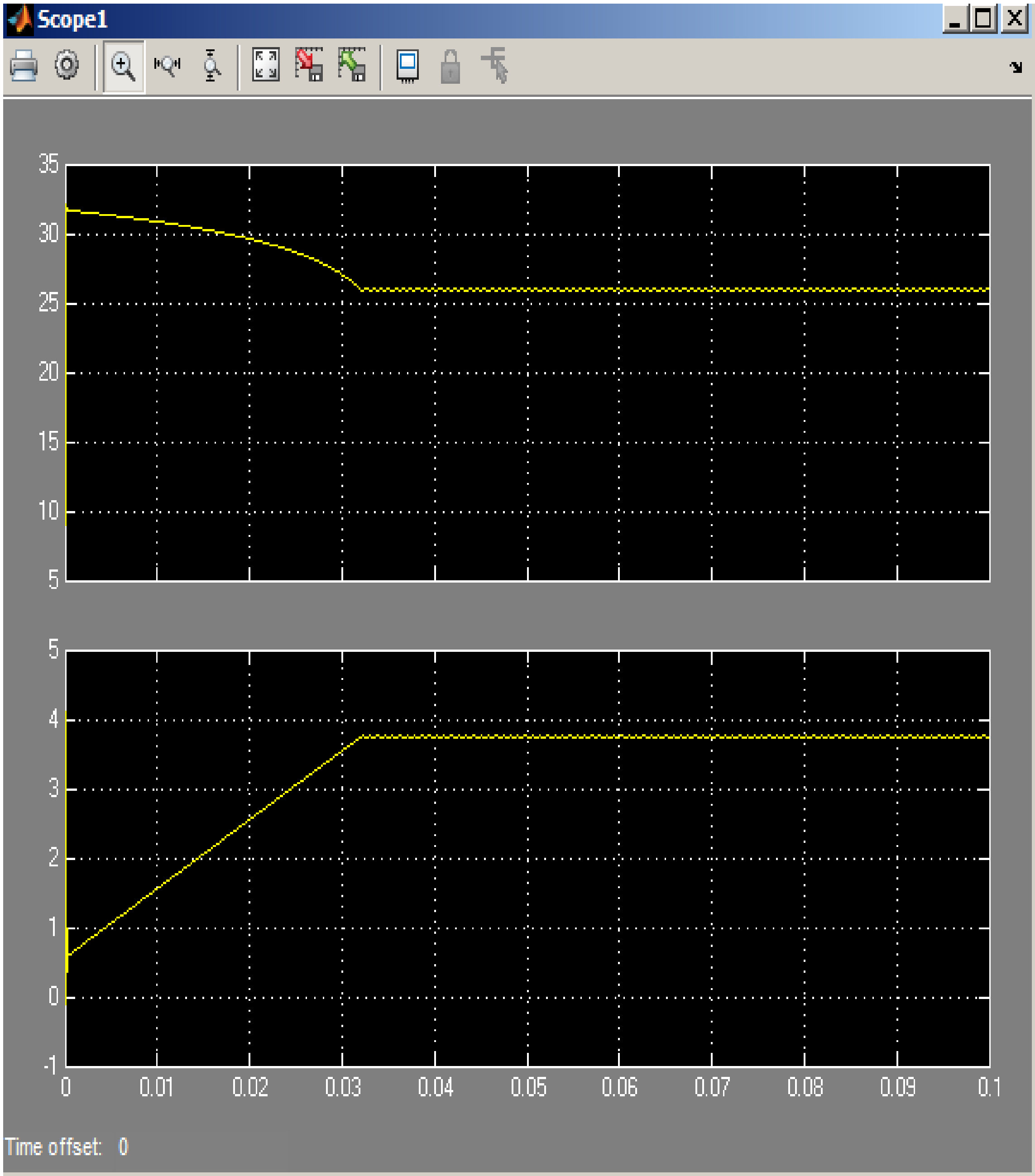


Figure 11 Change in current and voltage with respect to time in a solar panel for $Ir=500\ W/m^2$

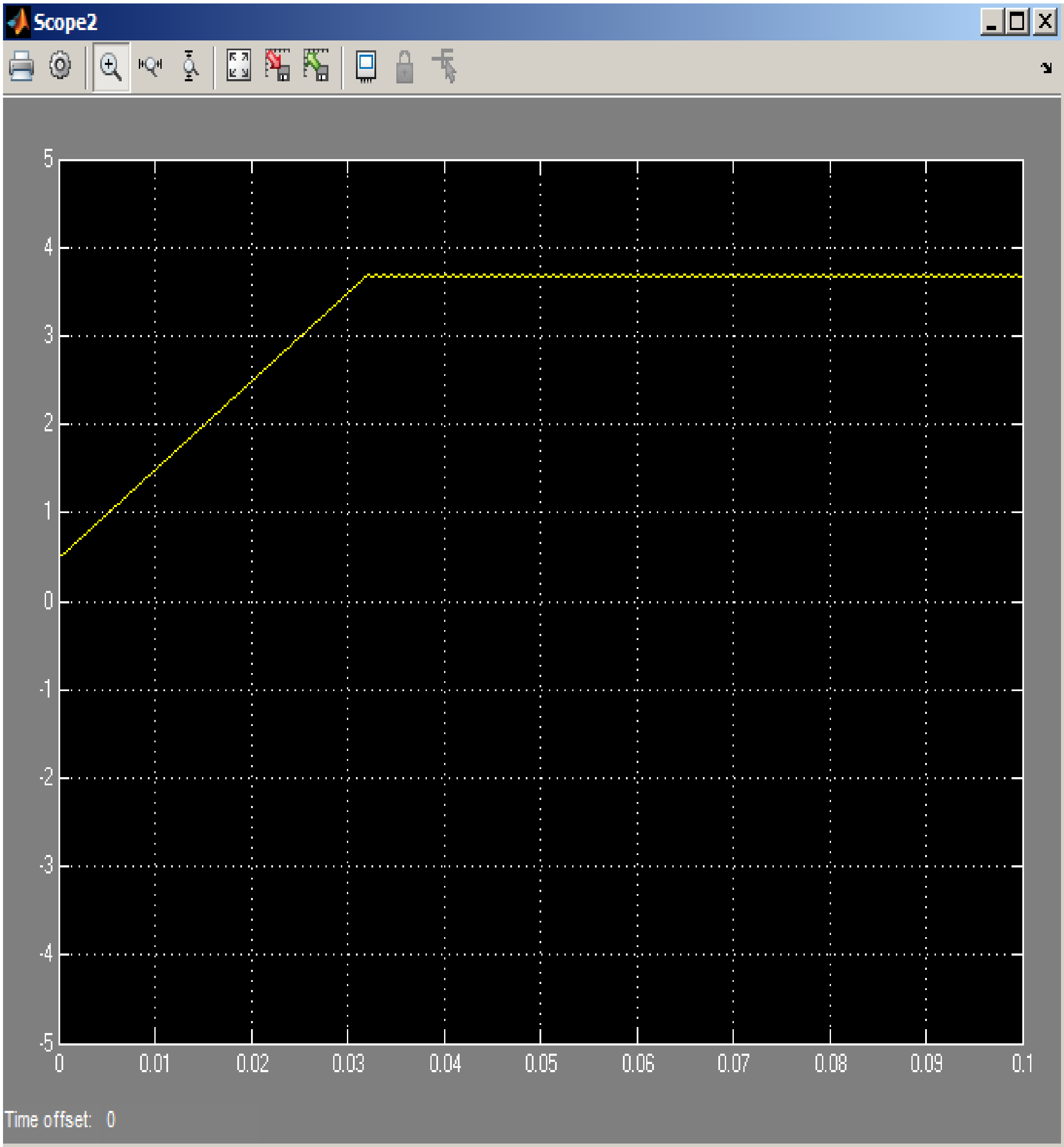


Figure 12. MPPT (maximum power point tracking) for Ir=500 W/m^2.

5.2 For an Irradiation of 800 W/m^2

Figure 13 shows the current vs voltage trajectory for the MPPT algorithm with 800 W/m^2. The power curve trajectory for this condition is shown in Figure 14. The voltage and current are individually shown as function of time in Figure 15, while Figure 16 shows the reference value used in the control. Note that the power tends toward its maximum of nearly 160 watts.

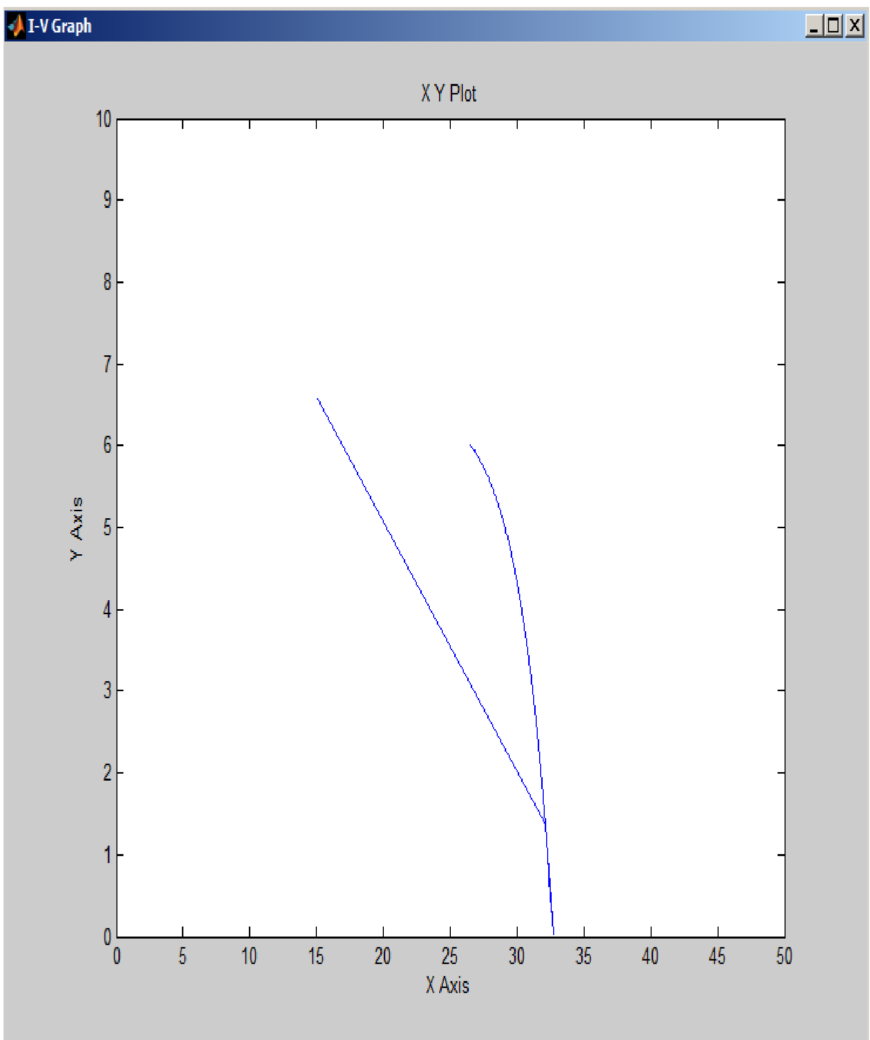


Figure 13. I-V curve for an irradiation of 800 W/m^2.

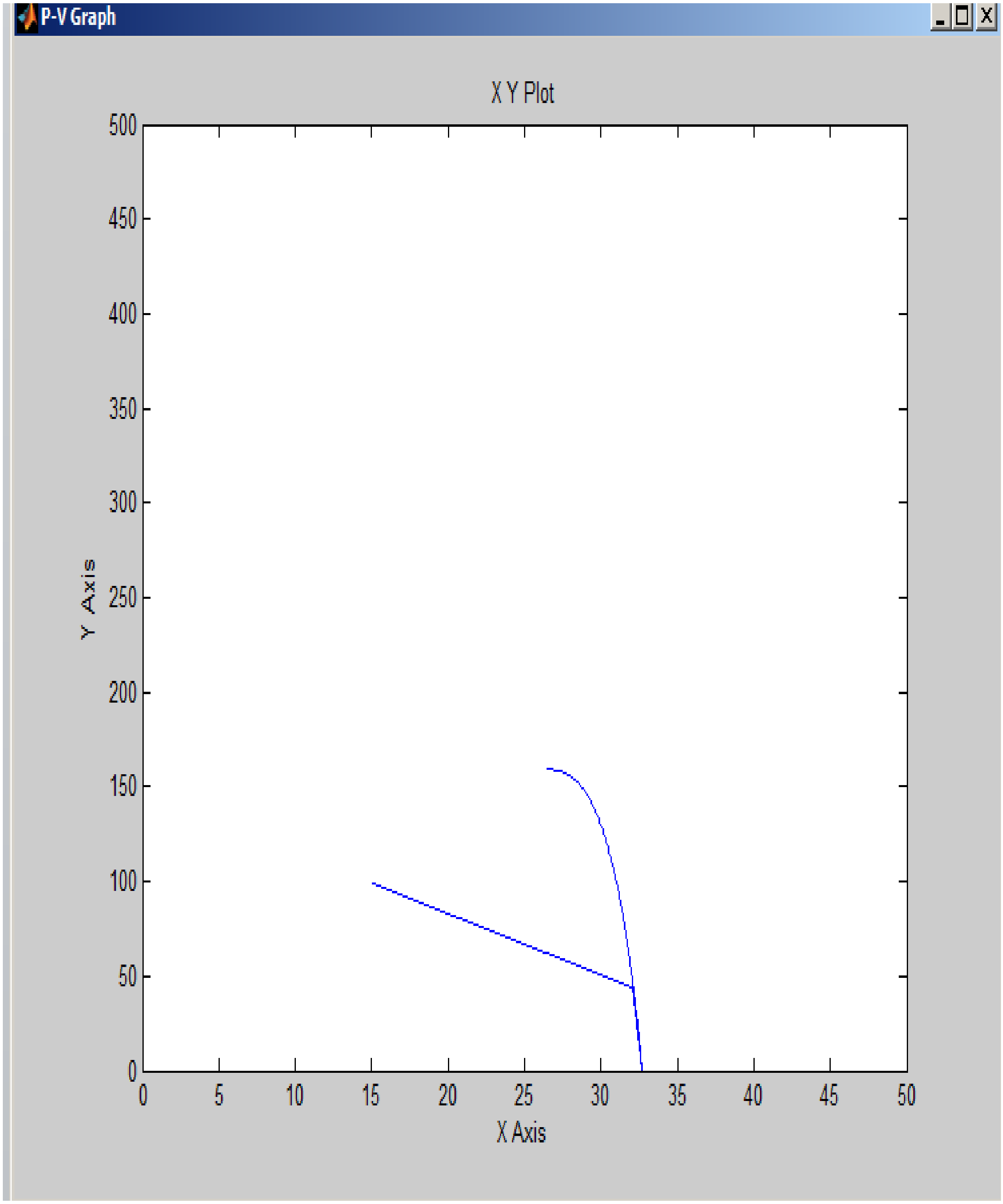


Figure 14. P-V curve for an irradiation of 800 W/m^2.

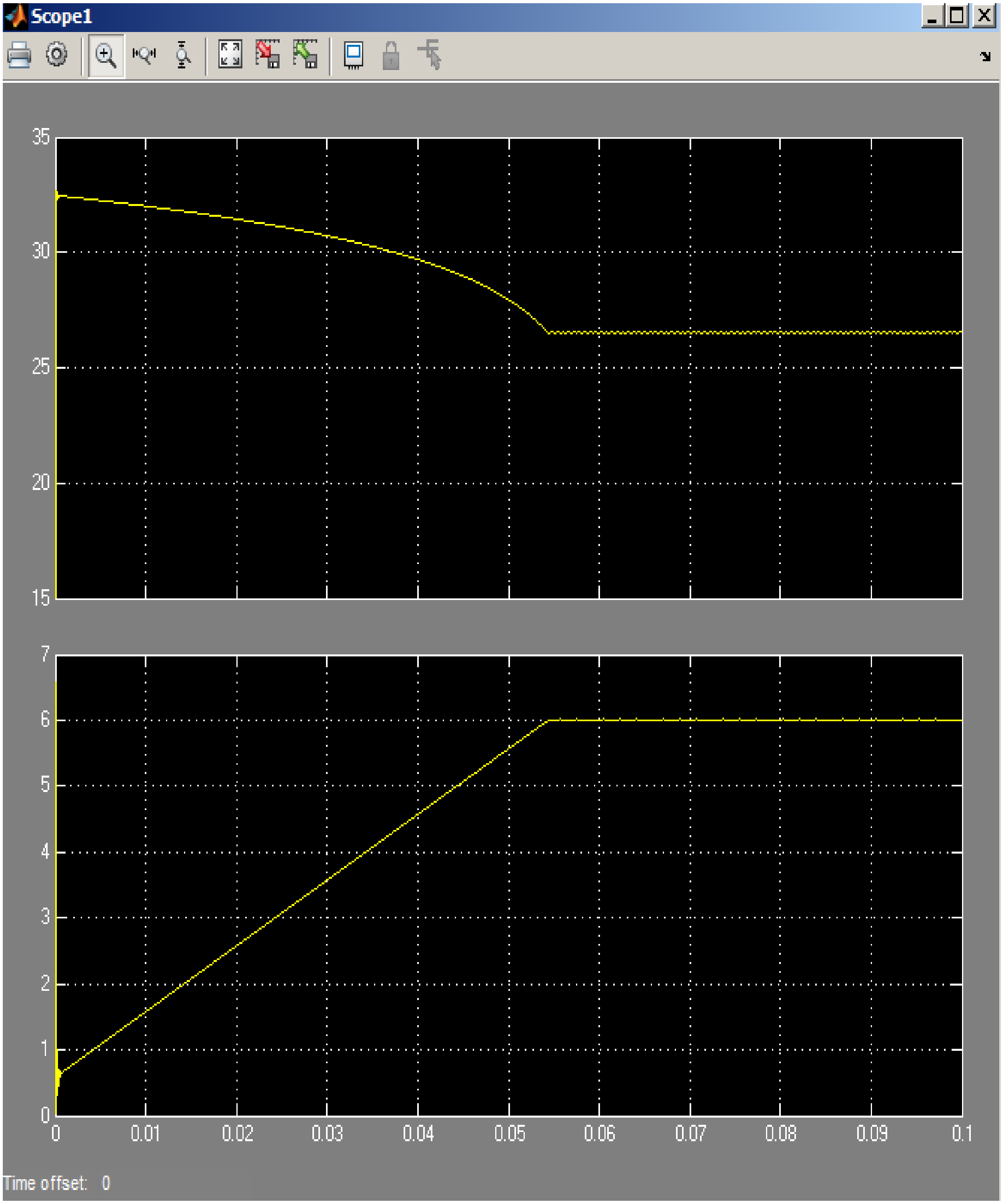


Figure 15. Change in current and voltage with respect to time in a solar panel for Ir=800 W/m^2.

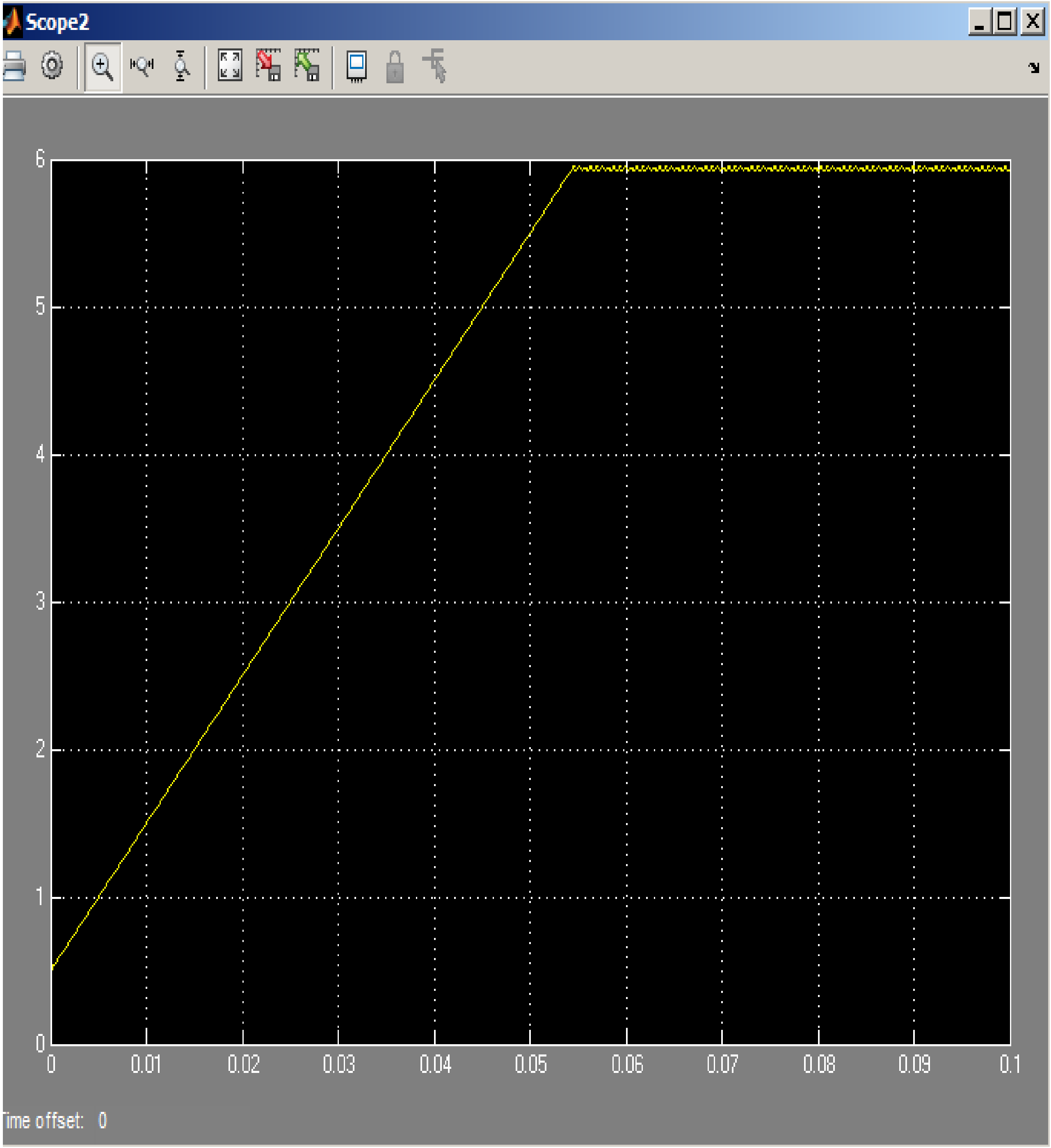


Figure 16. MPPT (maximum power point tracking) for Ir=800 W/m^2.

5.3 For an Irradiation of 1000 W/m^2

Figure 17 shows the current vs voltage trajectory for the MPPT algorithm with 1000 W/m^2. The power curve trajectory for this condition is shown in Figure 18. The voltage and current are individually shown as function of time in Figure 19, while Figure 20 shows the reference value used in the control. Note that the power tends toward its maximum of nearly 200 watts.

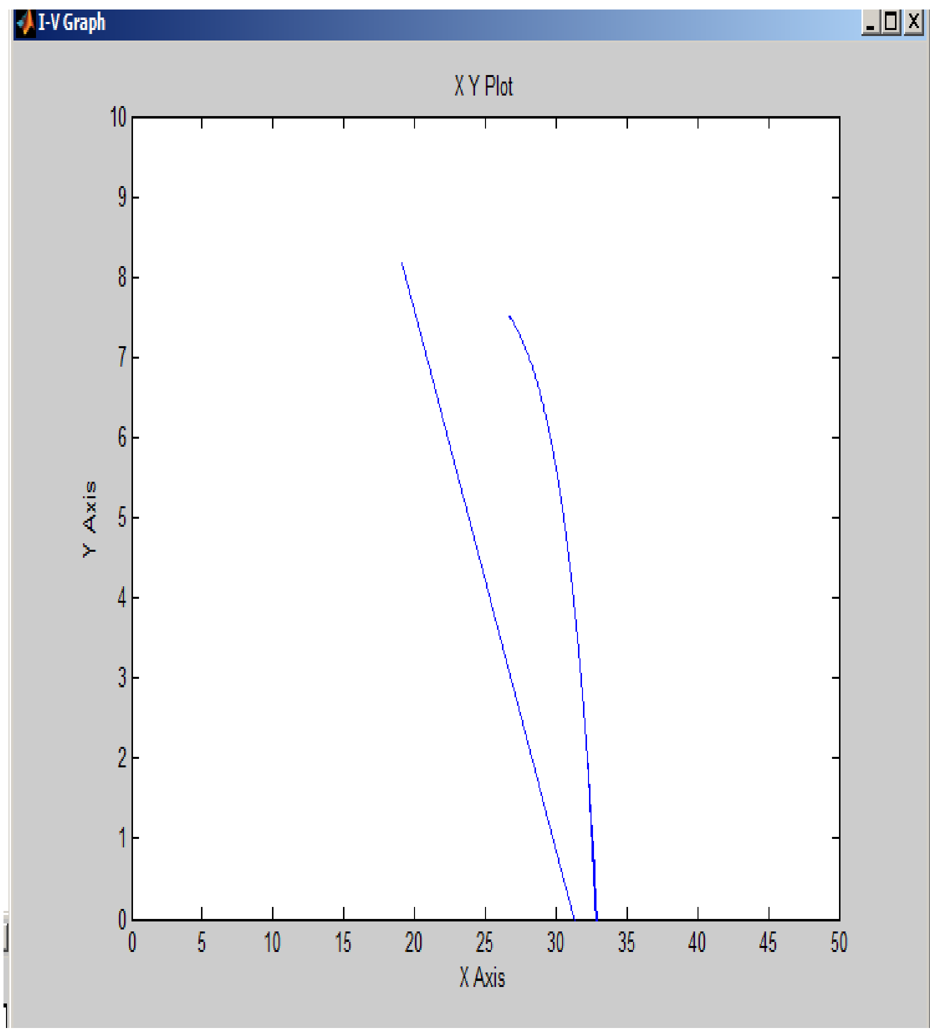


Figure 17. I-V curve for an irradiation of 1000 W/m^2.

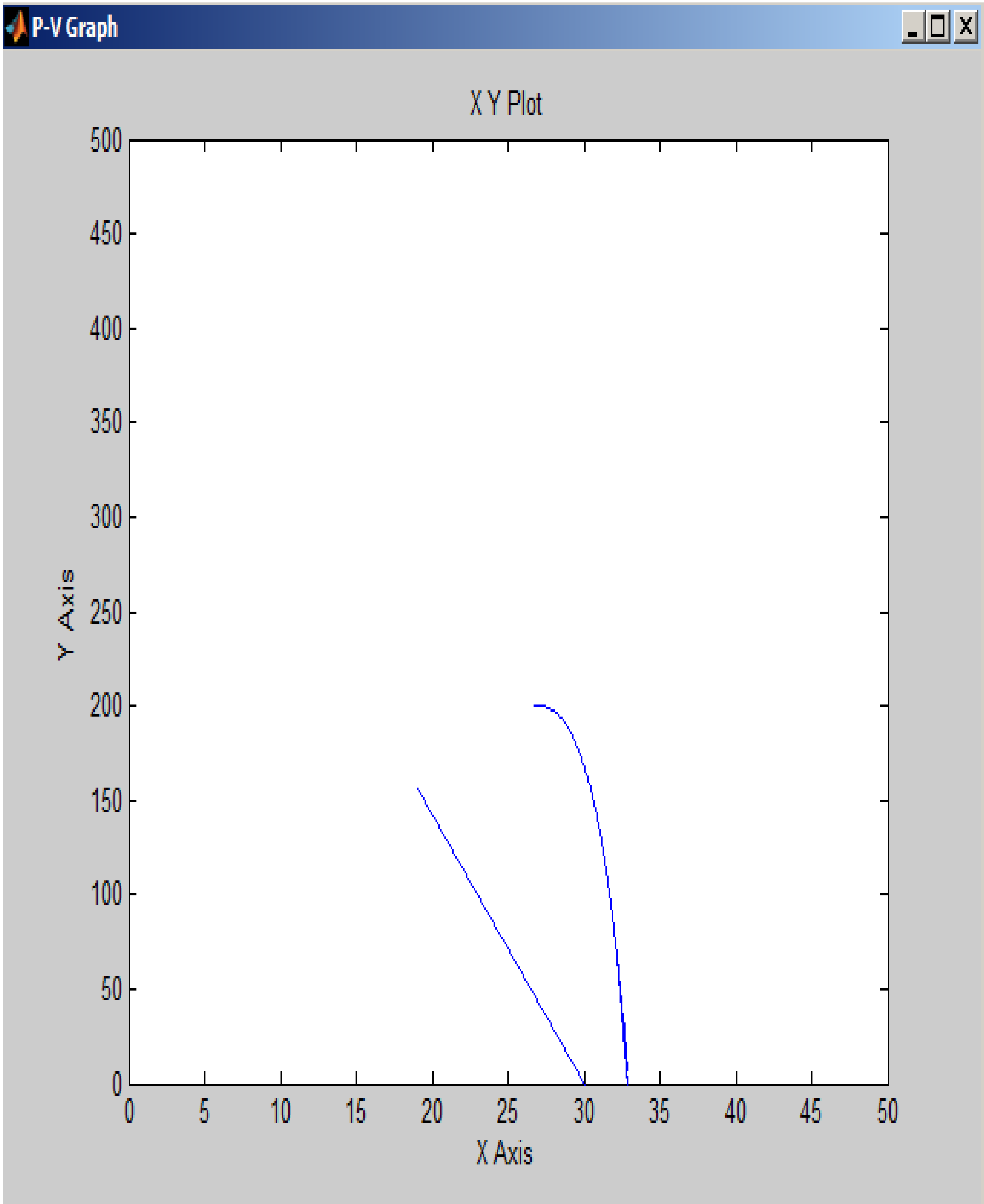


Figure 18. P-V curve for an irradiation of 1000 W/m^2.

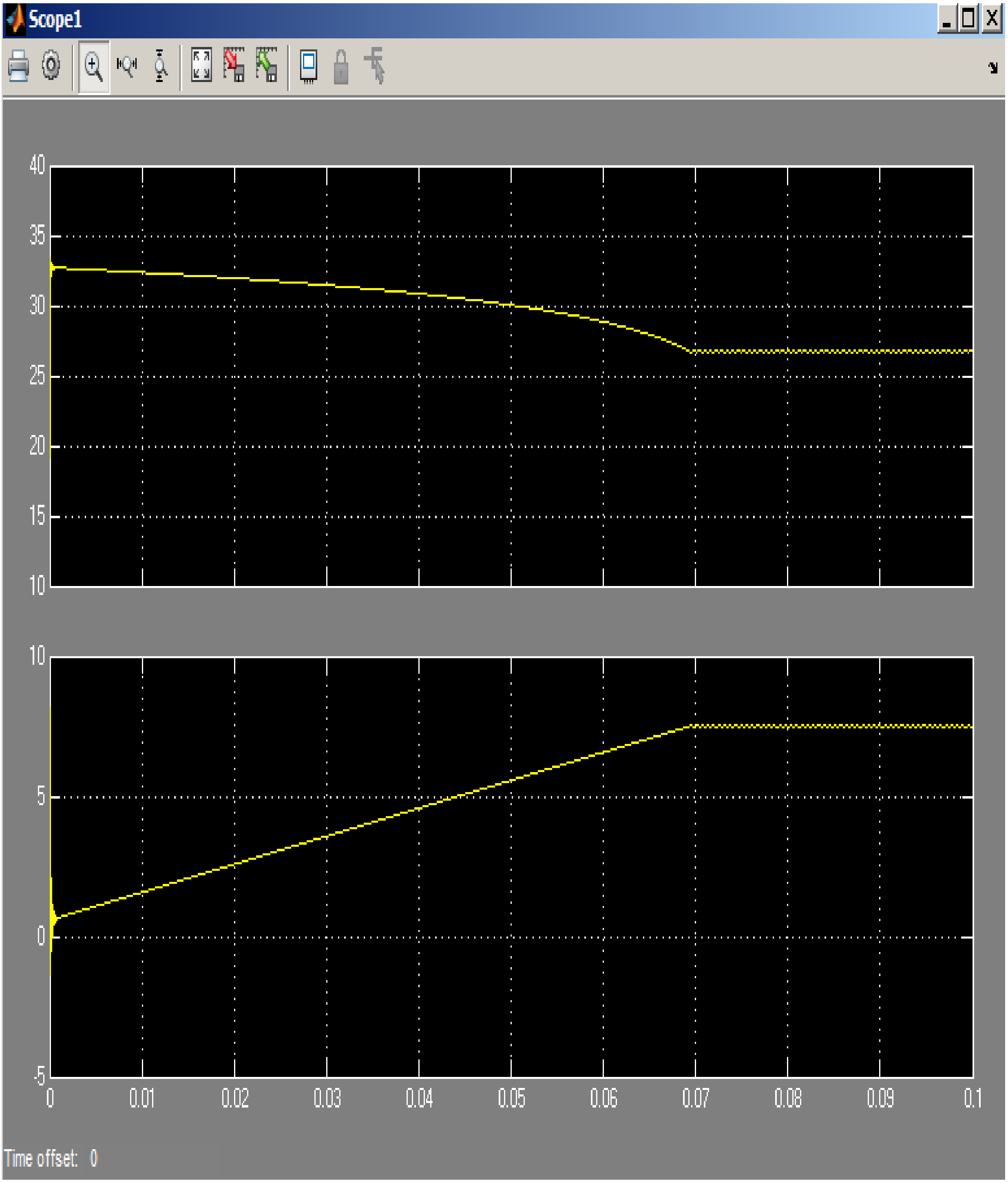


Figure 19. Change in current and voltage with respect to time in a solar panel for Ir=1000 W/m^2.

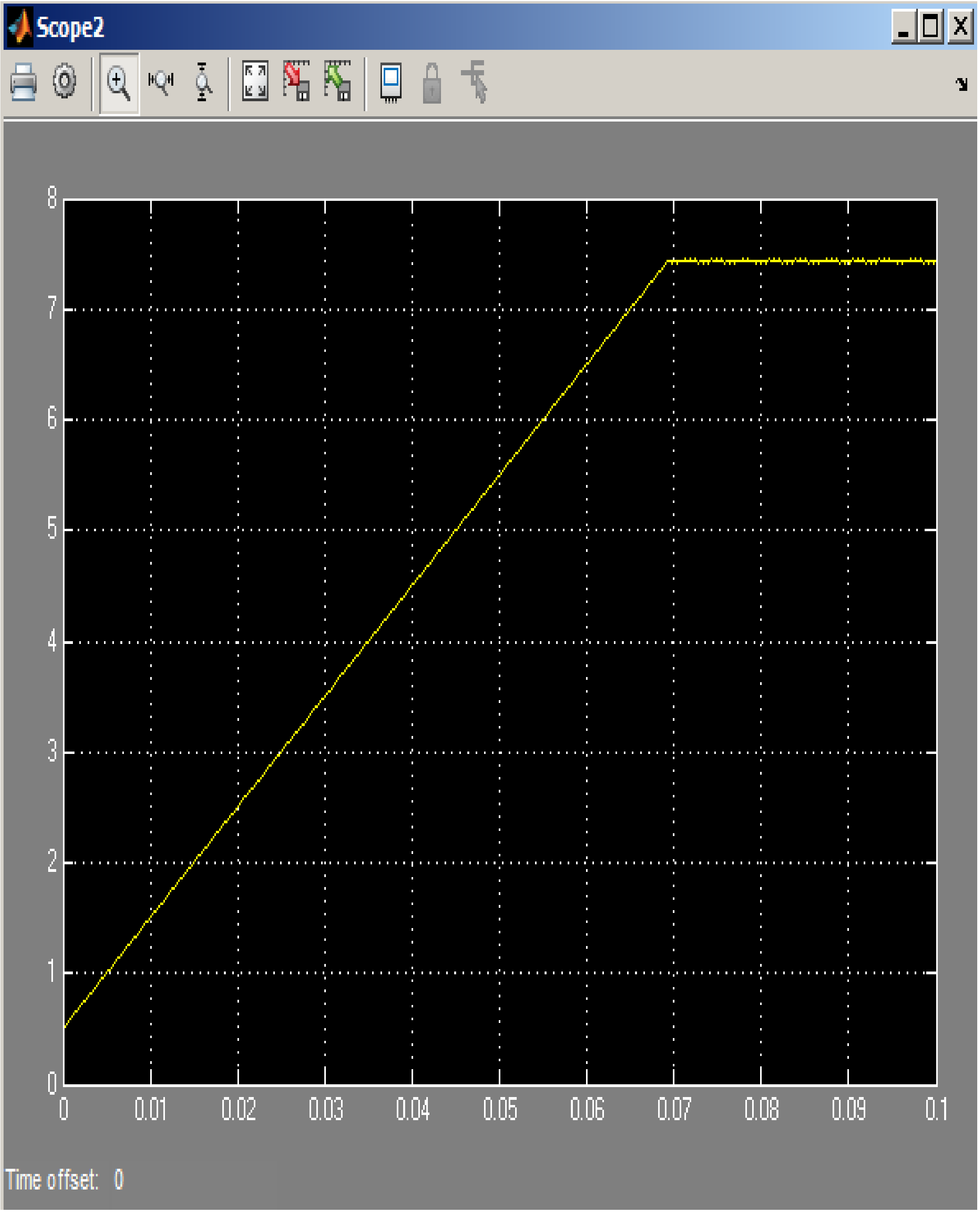


Figure 20. MPPT (maximum power point tracking) for Ir=1000 W/m^2.

5.4 For an Irradiation of 1500 W/m^2

Figure 21 shows the current vs voltage trajectory for the MPPT algorithm with 1500 W/m^2. The power curve trajectory for this condition is shown in Figure 22. The voltage and current are individually shown as function of time in Figure 23, while Figure 24 shows the reference value used in the control. Note that the power tends toward its maximum of nearly 310 watts.

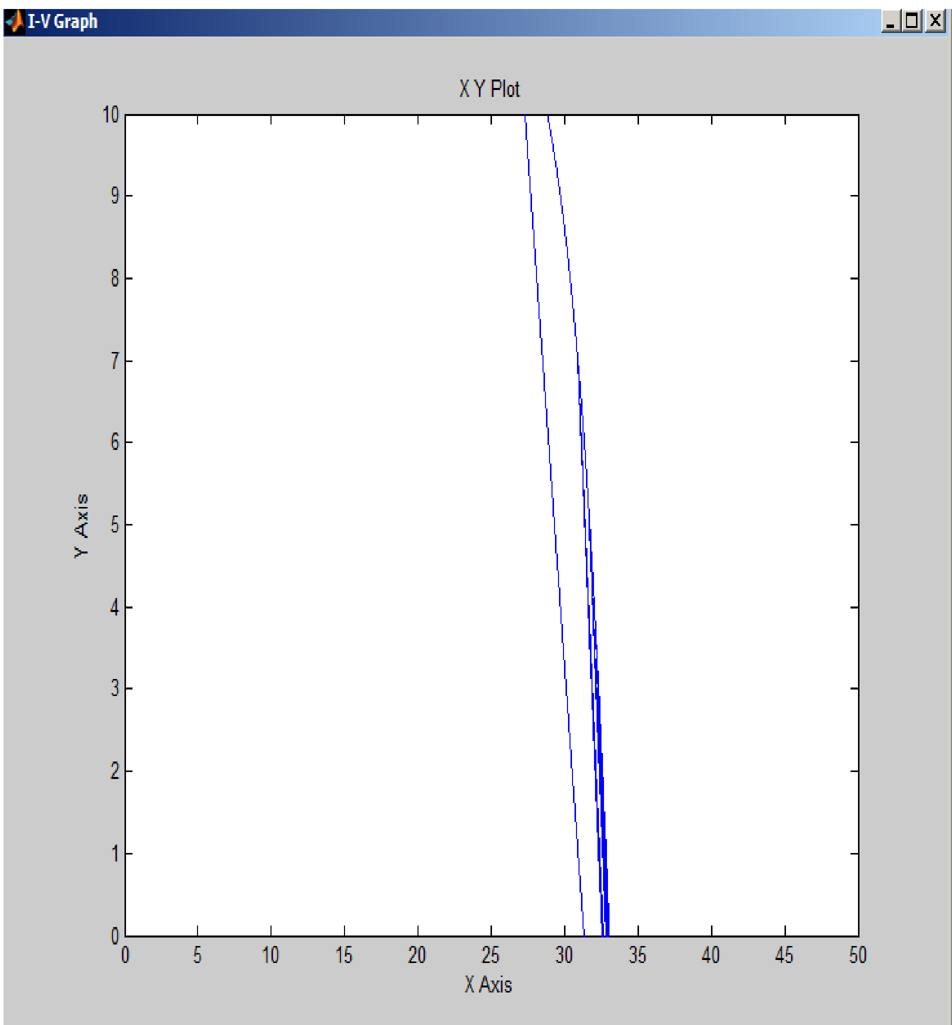


Figure 21. I-V curve for an irradiation of 1500 W/m^2.

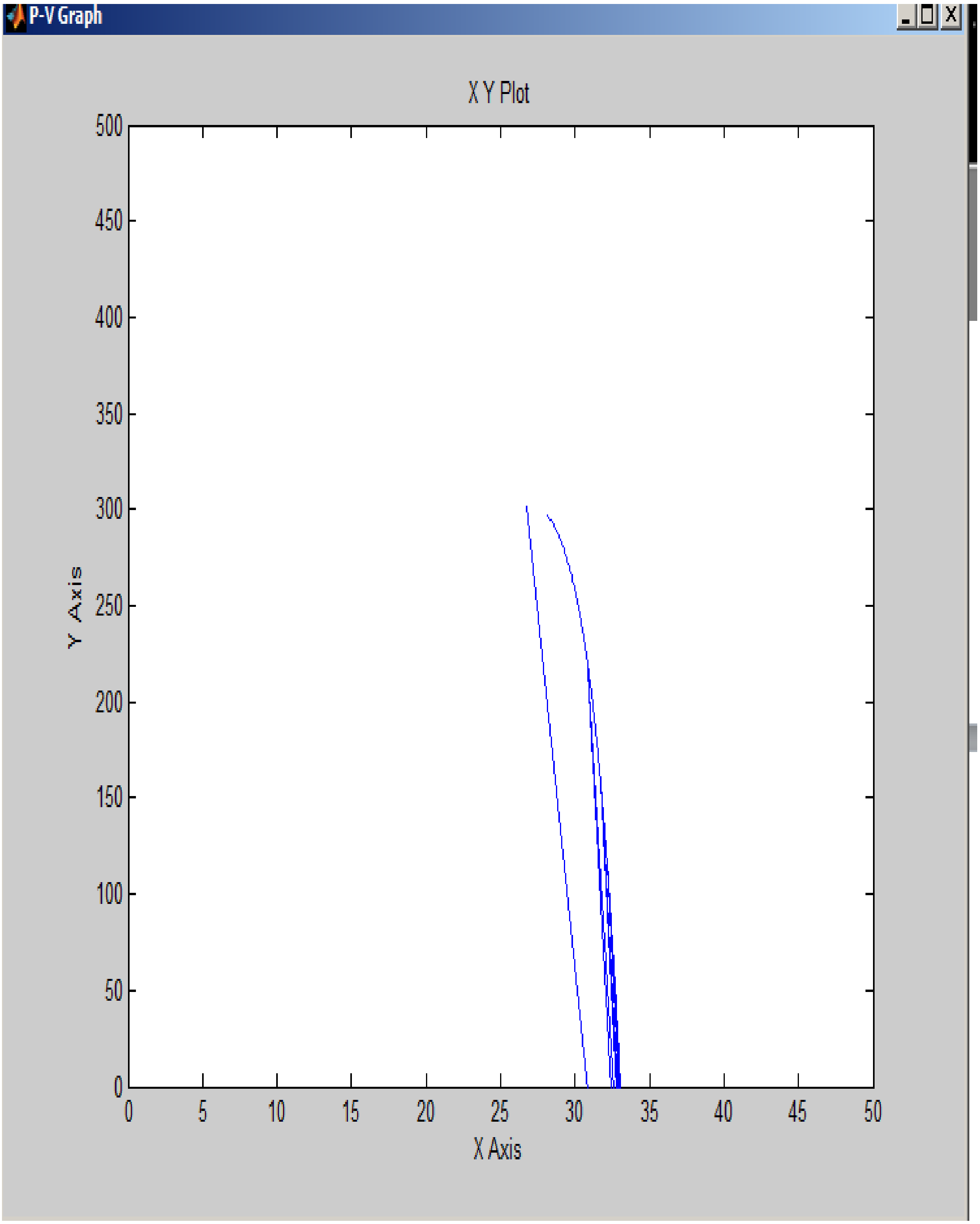


Figure 22. P-V curve for an irradiation of 1500 W/m^2.

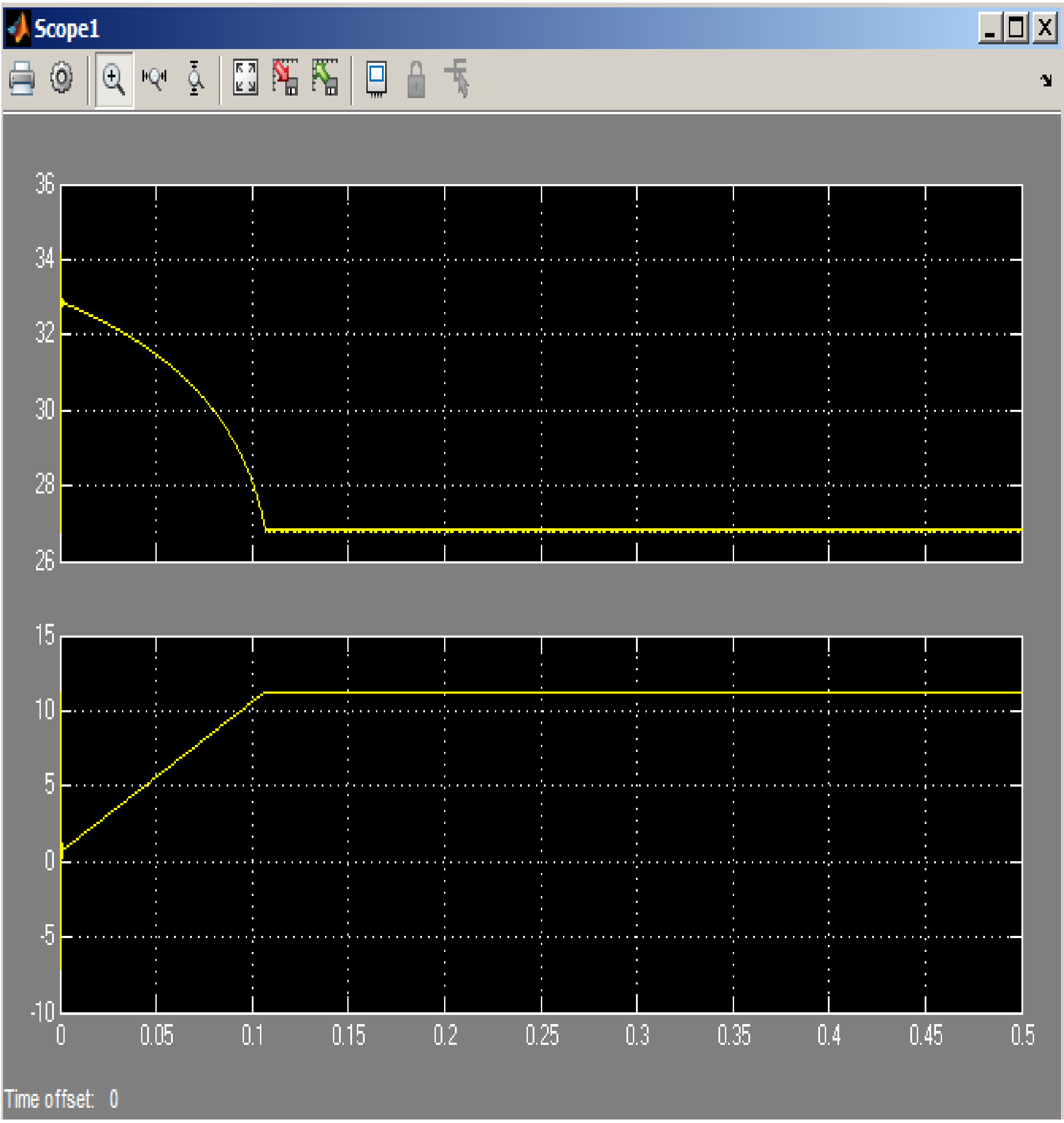


Figure 23. Change in current and voltage with respect to time in a solar panel for Ir=1500 W/m^2.

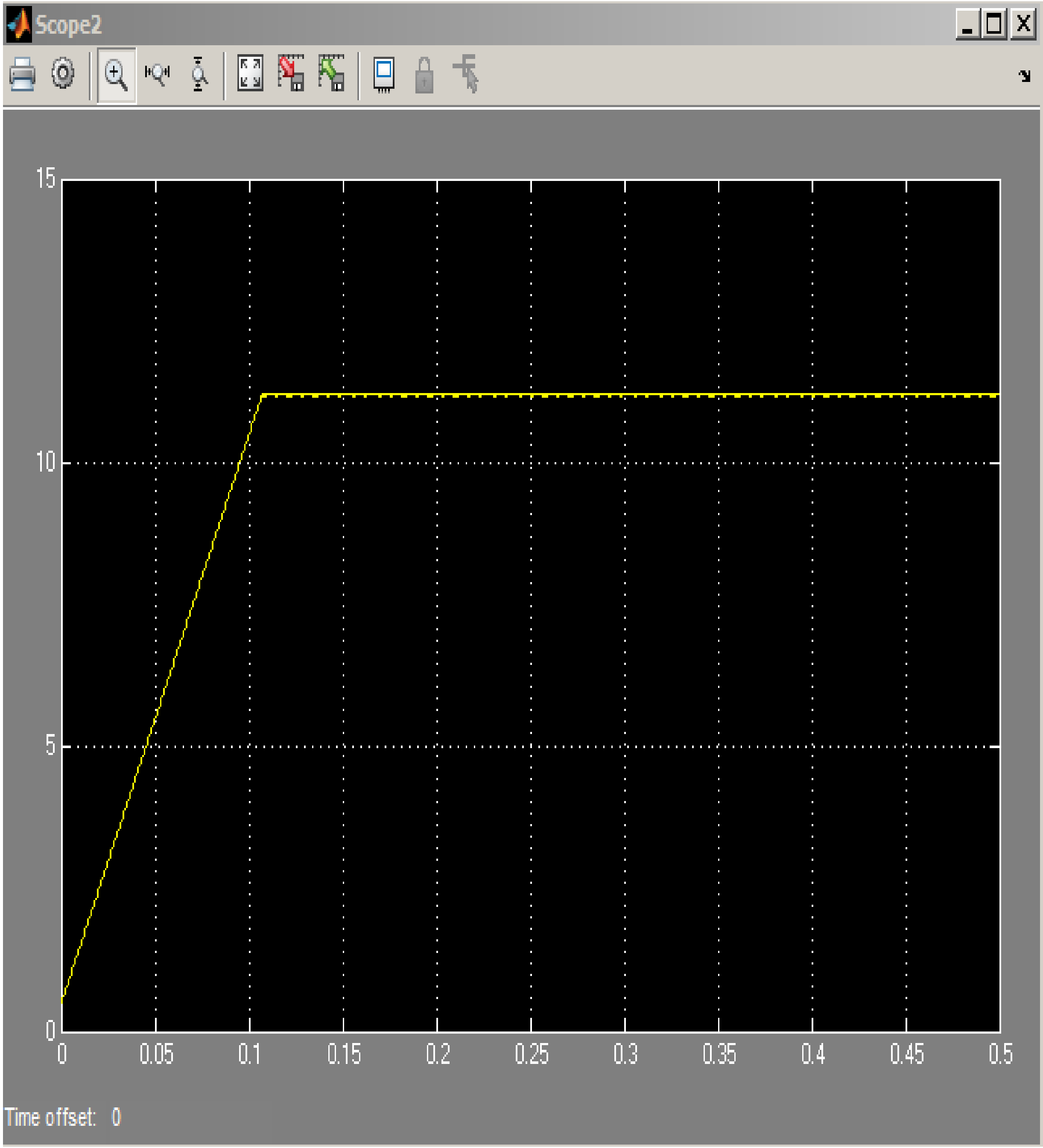


Figure 24. MPPT (maximum power point tracking) for Ir=1500 W/m^2.

5.5 For an Irradiation of 2000 W/m^2

Figure 25 shows the current vs voltage trajectory for the MPPT algorithm with 2000 W/m^2. The power curve trajectory for this condition is shown in Figure 26. The voltage and current are individually shown as function of time in Figure 27, while Figure 28 shows the reference value used in the control. Note that the power tends toward its maximum of nearly 360 watts.

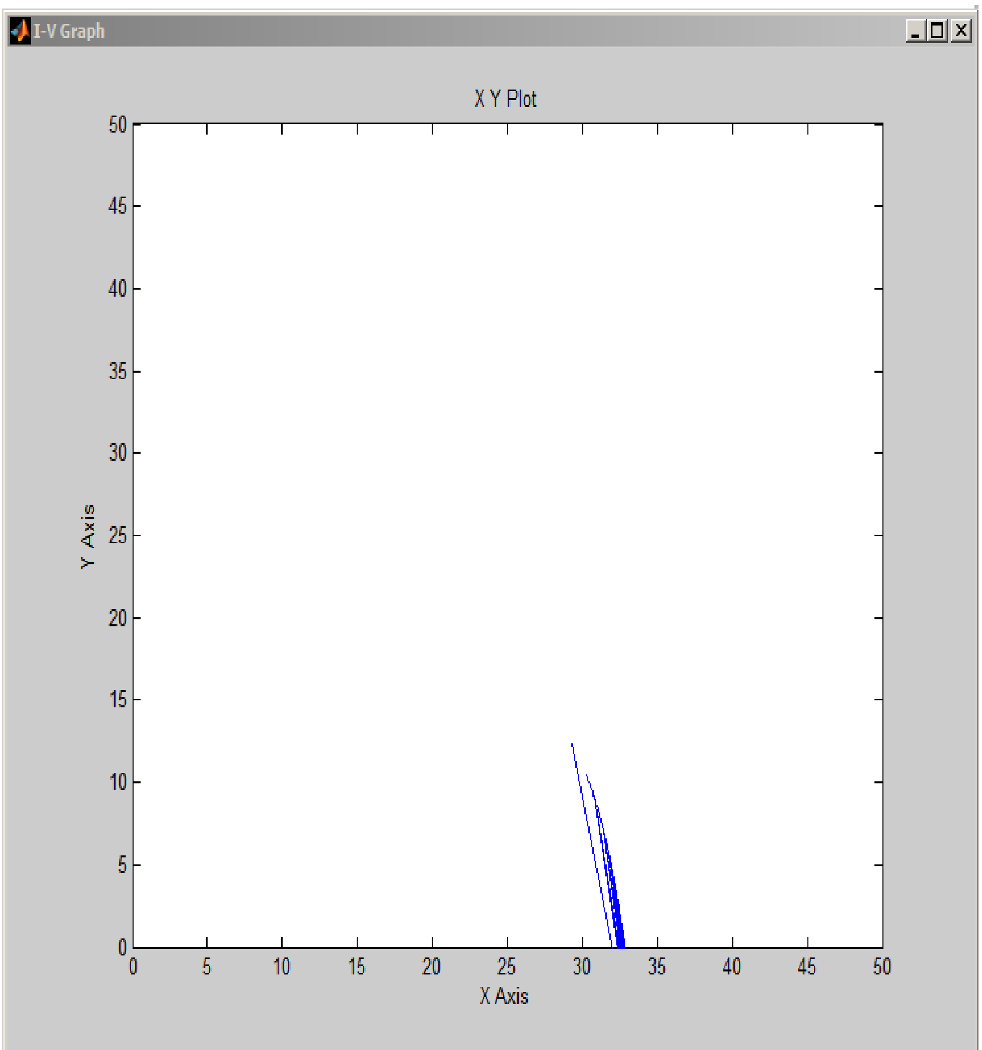


Figure 25. I-V curve for an irradiation of 2000 W/m^2.

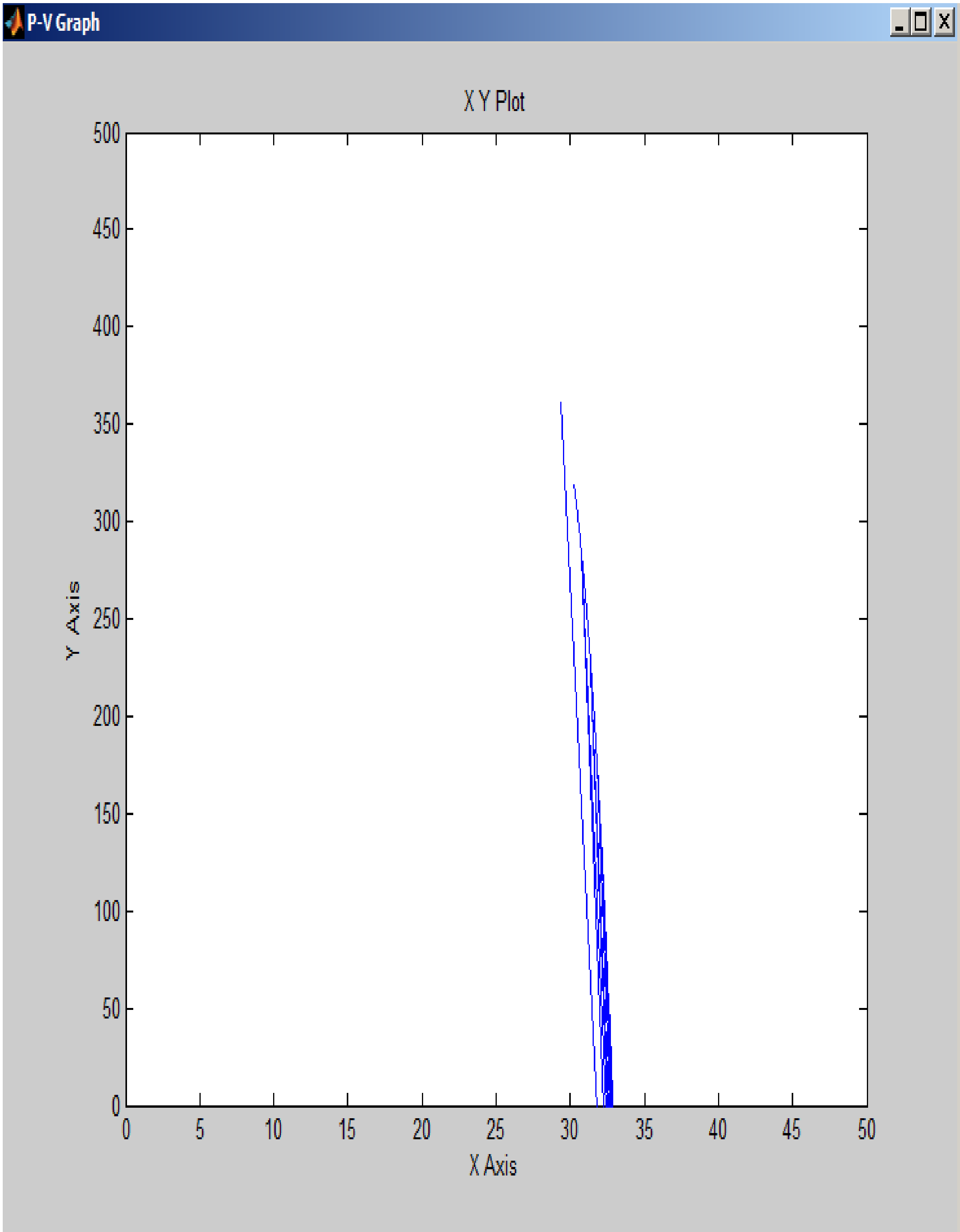


Figure 26. P-V curve for an irradiation of 2000 W/m^2.

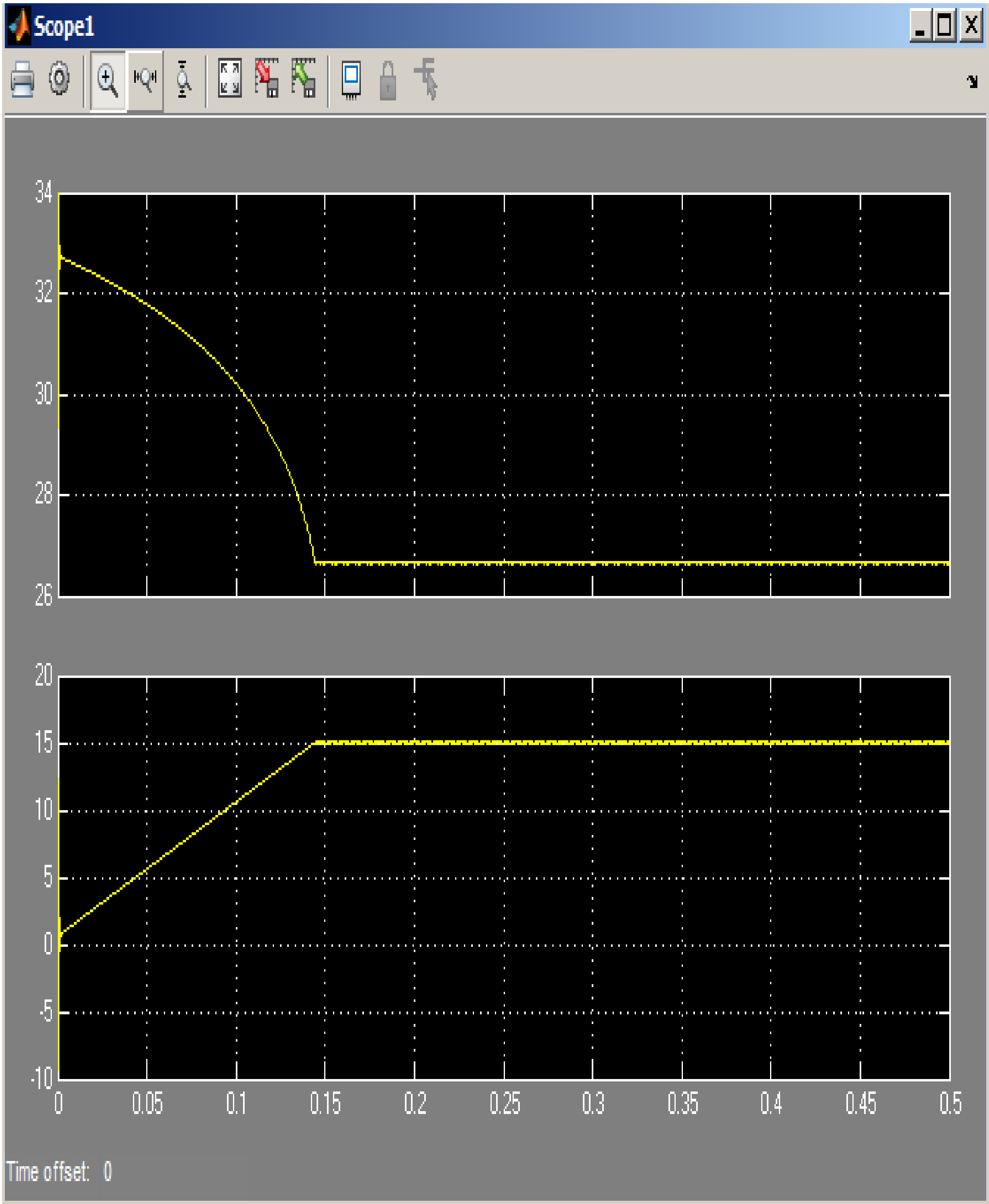


Figure 27. Change in current and voltage with respect to time in a solar panel for Ir=2000 W/m^2.

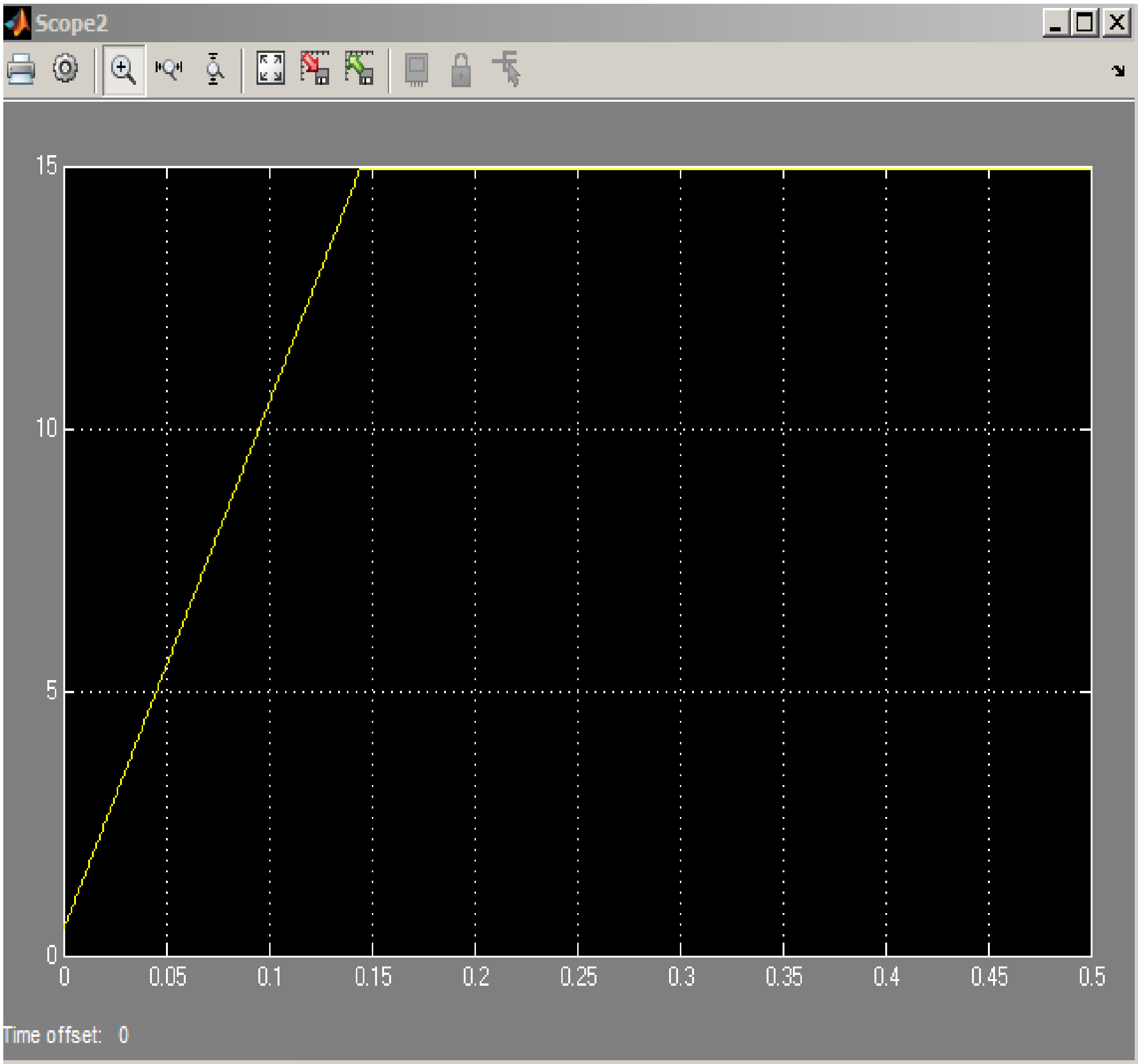


Figure 28. MPPT (maximum power point tracking) for Ir=2000 W/m^2.

5.6 For an Irradiation of 2500 W/m^2

Figure 29 shows the current vs voltage trajectory for the MPPT algorithm with 2500 W/m^2. The power curve trajectory for this condition is shown in Figure 30. The voltage and current are individually shown as function of time in Figure 31, while Figure 32 shows the reference value used in the control. Note that the power tends toward its maximum of nearly 380 watts.

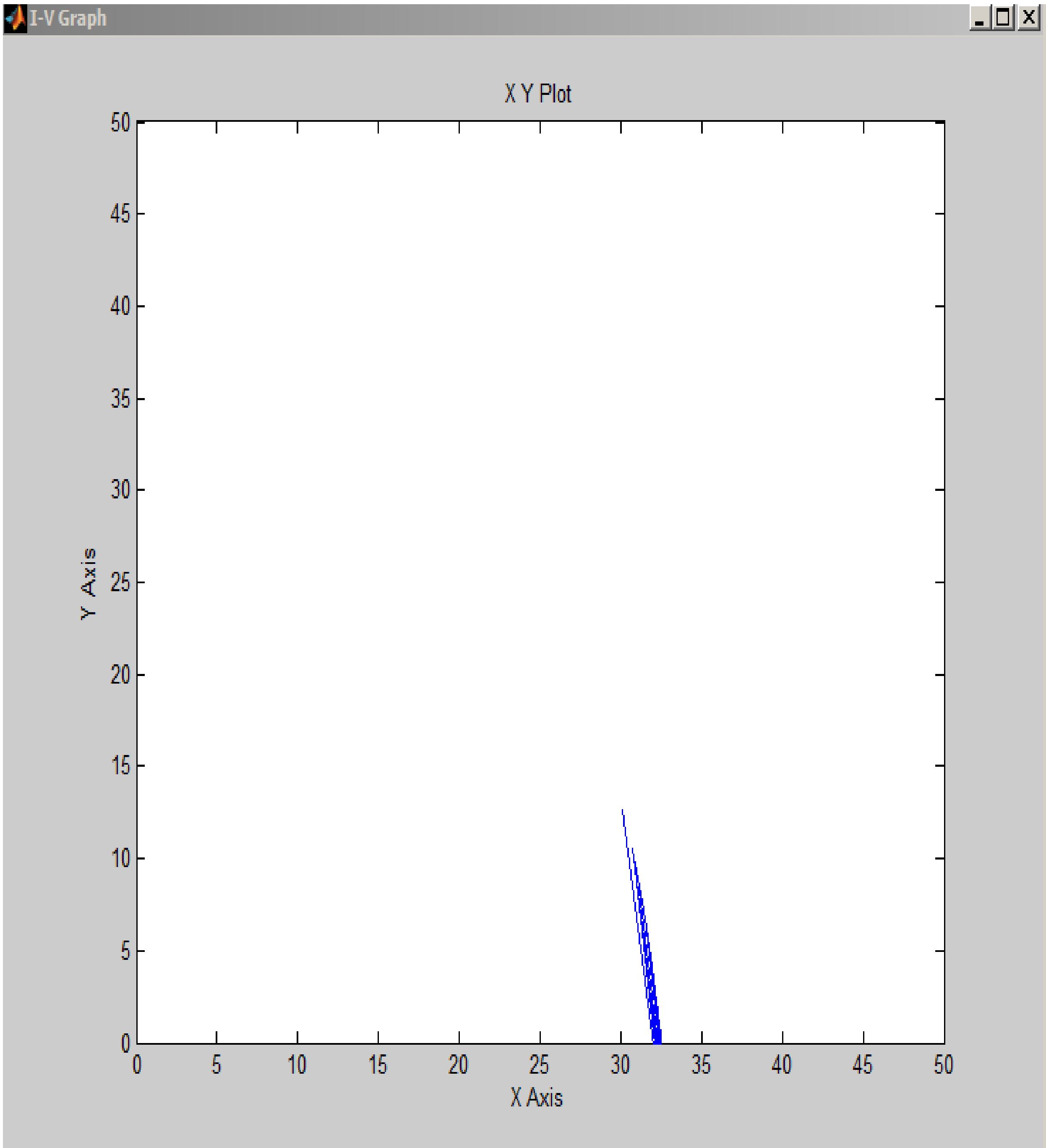


Figure 29. I-V curve for an irradiation of 2500 W/m^2.

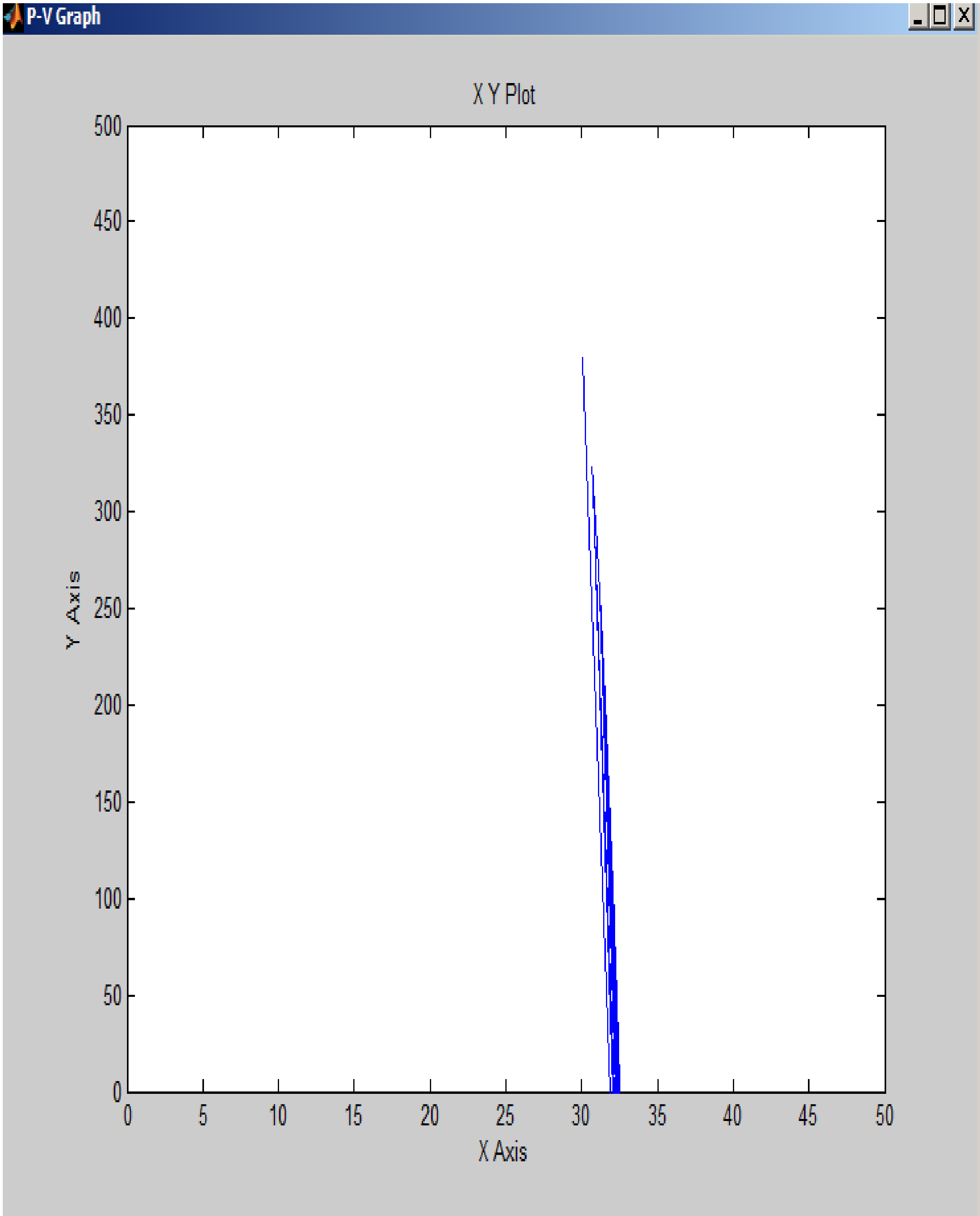


Figure 30. P-V curve for an irradiation of 2500 W/m^2.

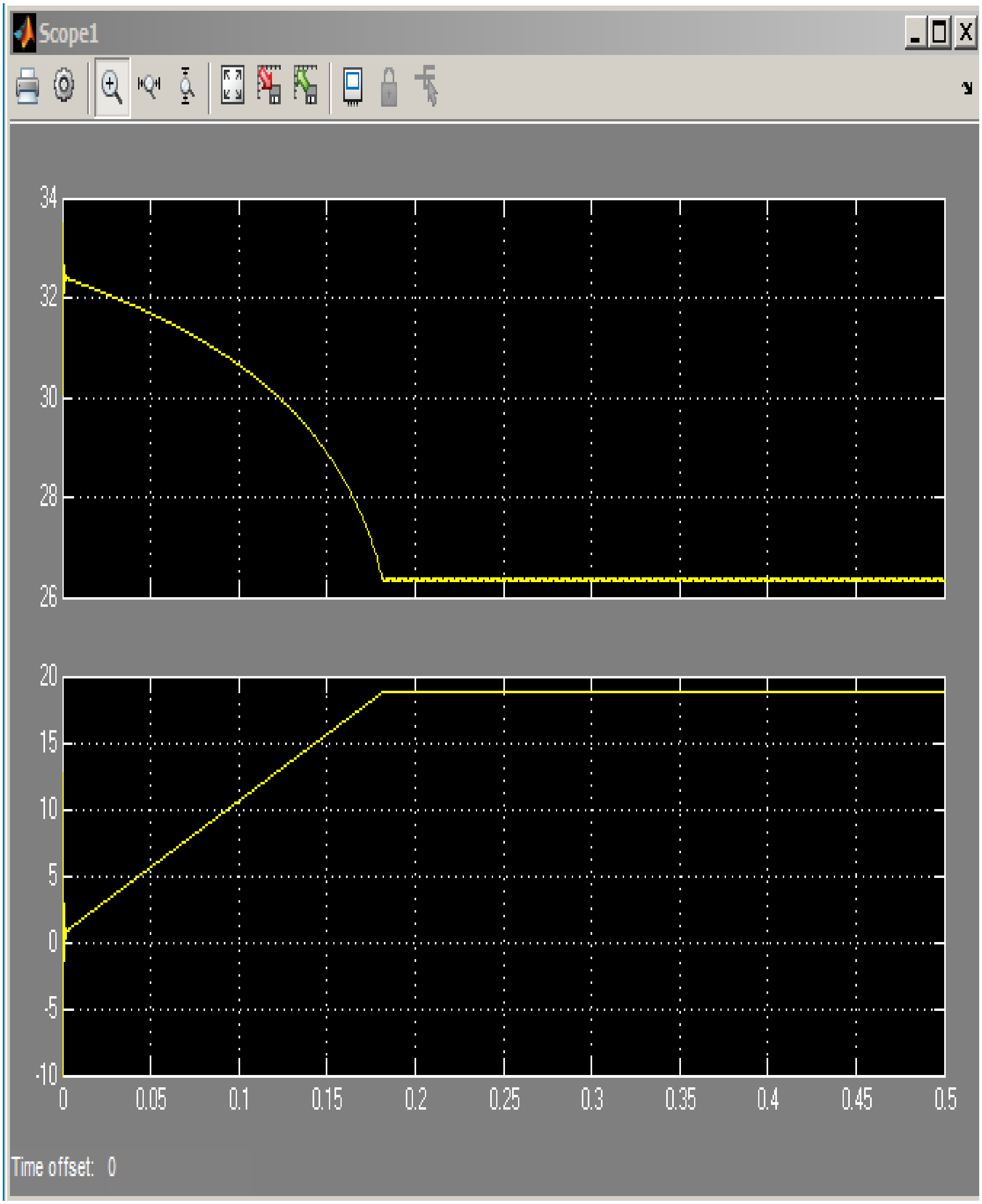


Figure 31. Change in current and voltage with respect to time in a solar panel
For Ir=2500 W/m^2.

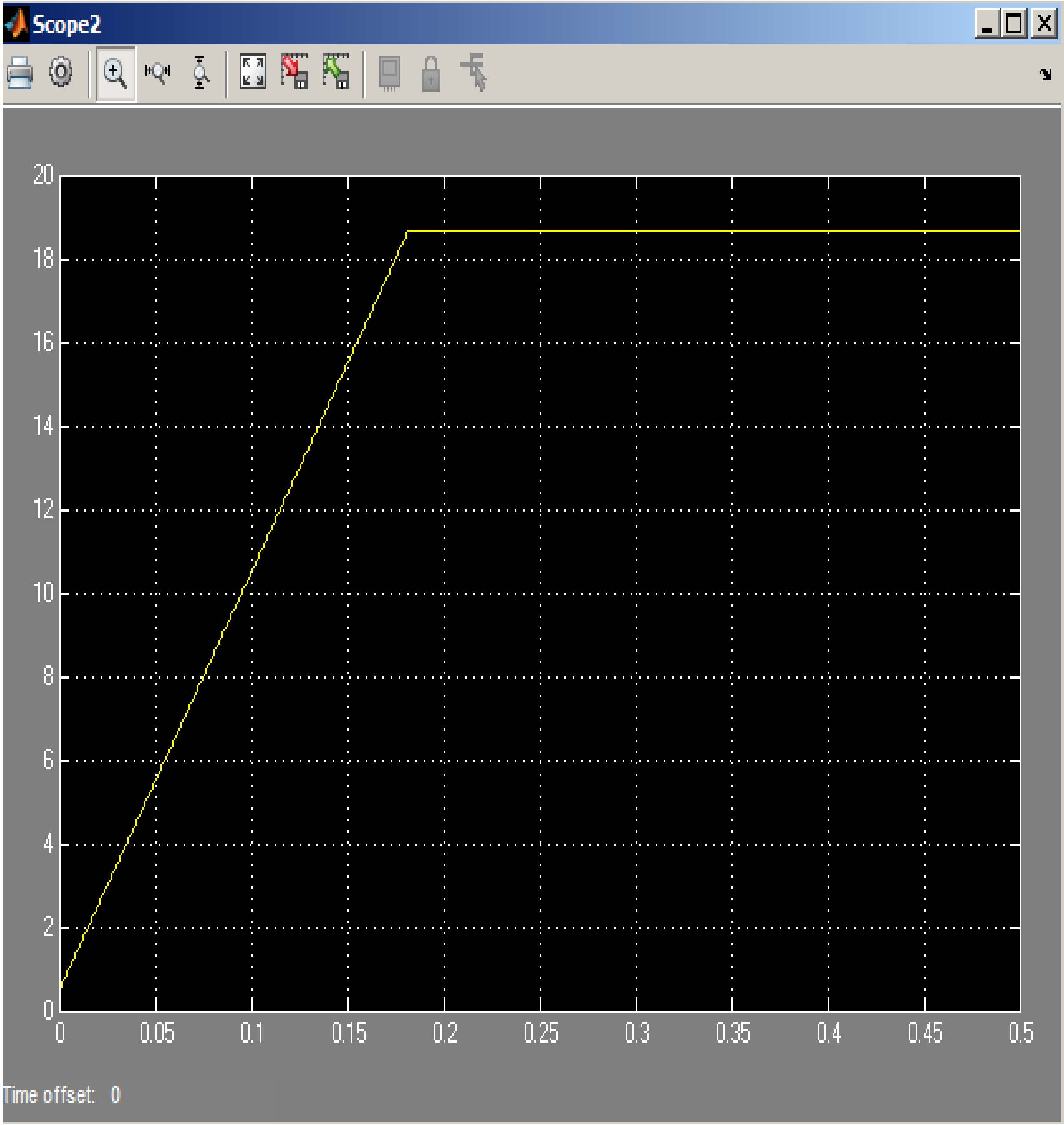


Figure 32. MPPT (maximum power point tracking) for Ir=2500 W/m^2.

5.7. Comparison Table

A comparison of the results is shown in Table 1. This table indicates that the MPPT followed a pattern consistent with the maximum power capable of being delivered at different irradiation levels.

Table 1

Comparison of Results

Irradiance (W/m^2)	**Current (I) Amp**	**Power (P) Watts**	**MPPT**
500	4.1	100	3.8
800	6	160	5.9
1000	7.5	200	7.4
1500	10.2	310	11
2000	11	360	15
2500	13	380	18.5

CHAPTER 6

CONCLUSION

By implementing this system, the maximum power has been extracted from the solar panel and the maximum power point is tracked for different irradiation levels. Output power obtained and the irradiation are directly proportional to each other. The SIMULINK model designed is simulated to get the I-V (Current voltage) curve and P-V(Power voltage) curves obtained for different irradiations, and by the common voltage at which the maximum current and voltage are obtained, the maximum power point has been tracked for that particular irradiation.

Future Work:

We can even extend this system by interfacing it to the grid and deal with the DC to AC current conversions by using an inverter.

REFERENCES

[1] Ayompe, L., Duffey, A., & Conlon, M. (February 2011). "Energy Analysis of a Small-Scale Grid Connected System." *Grid Connected Photovoltaic System*, 816-825.

[2] Takemaro, Y. (1983). "Solar Radiation System." *The Internatinal Journal*, 261.

[3] Brooks, F., & Miller, W. (2005). "Availability of Solar Energy." 30-58.

[4] Georgiey, R., & Boundinoy, H. (2004). "Design of a System With sun Tracking." *Renewable Energy*, 393-400.

[5] Hussein, K., Muta, I., & Hoshino, T. (1995). "Maximum Photovoltaic Power Tracking." *IEEE Publications* (p. 142).

[6] Hohm, D., & Ropp, M. (2003). "Comparative Study of Maximum Power Point Tracking Algorithms." *Progress in Photovoltaics:Research and Applications*, 47-62.

[7] Walker, G. (2001). "Evaluating MPPT Converter Topologies." *Journal of Electrical and Electronics Engineering, Australia*, 35.

[8] Sera, D., Kerekes, T., & Teodorescu, R. (2006). "MPPT Method for Rapidly Changing Environment Conditions." *International Symposium* (p. 200). IEEE Publications.

[9] Manning, J. A. (1999). "Development of a Photovoltaic Array Model." *IEEE Proceedings* (pp. 193-200).

[10] Yeong, C. K., & T-J, L. (2001). "Novel Maximum Power Point Tracking Controller." IEEE Conference 2001. *IEEE Proceedings* (p. 200).

[11] Atlas, I., & Sharaf, A. (2007). “A Photovoltaic Array Simulation Model for MATLAB-SIMULINK GUI Environment.” *International Conference on Clean Power* (pp. 341-345).

APPENDIX

MATLAB CODE

MATLAB CODE

```
function [sys,x0,str,ts] = sfunmppt_inc(t,x,u,flag)
global Vref;
global dV;
global dI;
switch flag,
  case 0,
    [sys,x0,str,ts] = mdlInitializeSizes;
  case 2,
    sys = mdlUpdate(t,x,u);
  case 3,
    sys = mdlOutputs(t,x,u);
  case {1,4,9},
    sys =[];
  otherwise
    error(['unhandled flag = ',num2str(flag)]);
end

function [sys,x0,str,ts] = mdlInitializeSizes
sizes = simsizes;
sizes.NumContStates  = 0;
sizes.NumDiscStates  = 3;
sizes.NumOutputs     = 1;
sizes.NumInputs      = 2;
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 1;
sys = simsizes(sizes);
x0  =[0,0,0.5];
str =[];
ts  =[0.0001 0];

function sys = mdlUpdate(t,x,u)
k1=0.005;
dV=u(1)-x(1);
dI=u(2)-x(2);
if dV==0
    if dI==0
    Vref = x(3);
    elseif dI > 0
    Vref = x(3)+k1;
    elseif  dI < 0
    Vref = x(3)-k1;
    end
else
    if  (dI/dV)  ==(-u(2)/u(1))
```

```
            Vref = x(3);
        elseif (dI/dV) >(-u(2)/u(1))
            Vref = x(3)+k1;
        elseif  (dI/dV) <(-u(2)/u(1))
            Vref = x(3)-k1;
        end
    end

    x(1)=u(1);
    x(2)=u(2);
    x(3)=Vref;
    sys=[x(1),x(2),x(3)];

function sys = mdlOutputs(t,x,u)

sys=x(3);
```