

# Comparative Research on MPPT Methods of Photovoltaic Cells

**Liu Hai<sup>1,2</sup>, Zhang Aqiang<sup>2</sup>, Song Yong<sup>2</sup>, Du Qingfu<sup>2</sup>,  
Han Jitian<sup>1</sup>**

*1 School of Energy and Power Engineering, Shandong University, Jinan, 250061, China*

*2 School of Mechanical, Electrical & Information Engineering,  
Shandong University at Weihai, Weihai, 264209, China*

Corresponding author is Han Jitian

## Abstract

In this paper, different methods were used to track the maximum power point of output power of photovoltaic cells (PV) by MATLAB/Simulink. First of all, the PV and Boost circuit models were built. The output change of voltage and current could be detected when light intensity was changed. Secondly, four circuits of Maximum Power Point Tracking (MPPT) of PV were designed. The four methods are perturbation and observation method, Incremental conductance method, fuzzy control method and neural network method. Then, all the models were built and simulated. According to simulation results, the maximum output power changed with light intensity differently. In the end, a comparative study of the maximum power output waveform of various methods was made. The experimental results show that using neural network method can complete MPPT more quickly and more accurately. Keywords: PHOTOVOLTAIC CELLS, MPPT, MATLAB/SIMULINK, COMPARATIVE RESEARCH, RESULT ANALYSIS.

## 1. Introduction

With the exhaustion of fossil energy and the increasing environment problems, it is imminent to seek an energy that is sufficient and easy to use. As a free and renewable energy, the solar energy is more and more popular. Based on the photovoltaic effect, the PV can directly convert solar energy into electrical energy to be used by people and can alleviate the energy crisis. The photovoltaic cells system has been noted by many countries and regions as one of the first elements which saves primary energy and reduces greenhouse gas emissions<sup>[1]</sup>. It is a well-established technology with high efficiency and very low pollutant emissions. It achieves small installation space, low maintenance and long life service. The system can allow a wide range of operating conditions to match electric end-user requirements.

However the operation and control of photovoltaic cells systems are facing a stringent challenge to

keep the efficiency and stability of the system<sup>[2]</sup>. The low conversion rate and high cost seriously hinder the development of PV<sup>[3]</sup>. The major breakthrough has not been made in the effective solutions for optimal dispatch and control strategy of photovoltaic cells systems<sup>[4]</sup>. On the other hand, the existence of the uncertainty in the supply available from renewable generators has caused severe difficulty for the control and optimization of the system<sup>[5-6]</sup>. The photovoltaic cells system is a very complicated nonlinear system with time-varying. Therefore, it is very necessary to make researching on maximum power point tracking(MPPT) deeply<sup>[7]</sup>.

A PV simulation model based on MATLAB/Simulink was established in this paper. According to mathematical model of PV, The whole simulation model combined PV, Boost circuit and MPPT is built. Different tracking approaches are applied at different operating units realize MPPT, and advantages and

disadvantages of each method are obtained through simulation results. Experimental results show that the effect of neural network is best. Through theoretical analysis, the results of the combining of fuzzy control and incremental conductance method will be better. The simulation systems verify the validity of the MPPT algorithm and the control strategy. MPPT can effectively improve electric efficiency of PV.

## 2. Simulation of PV Model and Principle of MPPT

The equivalent circuit of PV is shown in Figure 1.

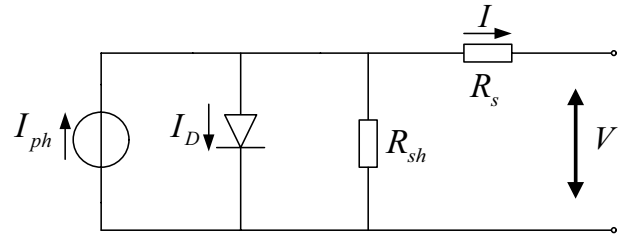


Figure 1. Equivalent circuit of PV

The output characteristic of PV is described as equation (1).

$$I = I_{ph} - I_D \left\{ \exp \left[ q(V + IR_s) / (AkT) \right] - 1 \right\} - (V + IR_s) / R_{sh} \quad (1)$$

where  $I$  is output current of PV,  $V$  is output voltage,  $I_{ph}$  is photocurrent,  $I_D$  is saturation current of diode,  $q$  is charge of electron,  $R_s$  is the series resistor,  $R_{sh}$  is the parallel resistor,  $A$  is characteristic factor of diode,  $k$  is Boltzmann constant and  $T$  is temperature of PV.

Manufacturers of PV generally provide parameters as follows<sup>[8]</sup>:  $I_{scs}$ , the short circuit current;  $V_{os}$ , the open circuit voltage;  $I_{ms}$ , output current of the maximum power point;  $V_{ms}$ , output voltage of the maximum power point;  $P_{ms}$ , output power of the maximum power point. All these parameters are measured in standard conditions (the light intensity,  $S = 1000W / m^2$ ; the temperature,  $25^\circ C$ ). This paper designs a practical engineering mathematical model of PV by using the software MATLAB/Simulink.

The related equations of model of single-crystal silicon PV are shown as follows<sup>[9]</sup>:

$$I = I_{sc} \left\{ 1 - C_1 \left[ \exp(V / (C_2 V_{oc})) - 1 \right] \right\} \quad (2)$$

At the maximum power point

$$\exp(V_m / (C_2 V_{oc})) - 1 \approx \exp(V_m / (C_2 V_{oc}))$$

Get  $C_1$  and  $C_2$

$$C_1 = (1 - I_m / I_{sc}) \exp(-V_m / (C_2 V_{oc})) \quad (3)$$

$$C_2 = (V_m / V_{oc} - 1) / \ln(1 - I_m / I_{sc}) \quad (4)$$

where

$$I_{sc} = I_{scs} S(1 + a\Delta T) / S_{ref} \quad (5)$$

$$V_{oc} = V_{os} (1 - c\Delta T)(1 + b\Delta S) \quad (6)$$

$$I_m = I_{ms} S(1 + a\Delta T) / S_{ref} \quad (7)$$

$$V_m = V_{ms} (1 - c\Delta T)(1 + b\Delta S) \quad (8)$$

$$\Delta T = T - T_{ref} \quad (9)$$

$$\Delta S = S / S_{ref} - 1 \quad (10)$$

$$T = T_{air} + kS \quad (11)$$

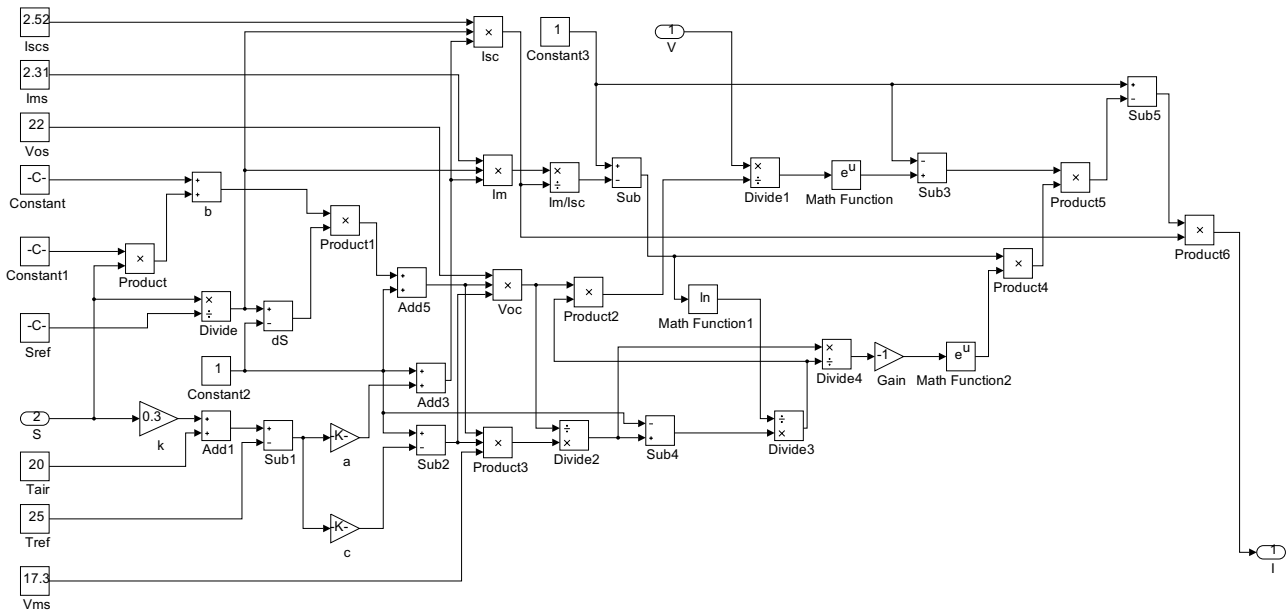
where  $I_{sc}$  is the short circuit current,  $C_1$  and  $C_2$  are correction coefficients,  $V_{oc}$  is the open circuit voltage,  $S$  is light intensity,  $a$  is the temperature coefficient of current change under the reference light intensity,  $S_{ref}$  is the reference light intensity,  $I_m$  and  $V_m$  are the current and voltage of maximum power point,  $c$  is the temperature coefficient of voltage change under the reference light intensity,  $T_{ref}$  is the reference cell temperature,  $T$  is cell temperature,  $\Delta S$  is the relative variation of light intensity,  $k$  is temperature coefficient of PV when the solar radiosity changes and  $T_{air}$  is the environment temperature.

According to the model equations above, the dynamic simulation model of PV by MATLAB/Simulink is built as shown in Figure 2. The model parameters are obtained as follows:  $V_{os} = 22V$ ;  $I_{scs} = 2.52A$ ;  $I_{ms} = 2.31A$ ;  $V_{ms} = 17.3V$ ;  $a = 0.0025A / ^\circ C$ ;  $c = 0.00288V / ^\circ C$ ;  $T_{air} = 20^\circ C$ ;  $k = 0.3^\circ C m^2 / W$ .  $b$  is used by optimized parameters value<sup>[10]</sup>:  $b = -0.1949 + 7.056 \times 10^{-4} \times S$ .

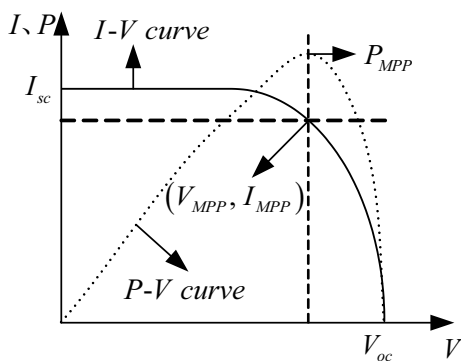
The electrical characteristic curve of PV is unimodal function and as shown in Figure 3.

In this picture,  $P$  is the output power of PV,  $V_{MPP}$  and  $I_{MPP}$  are voltage and current at the maximum output power point.

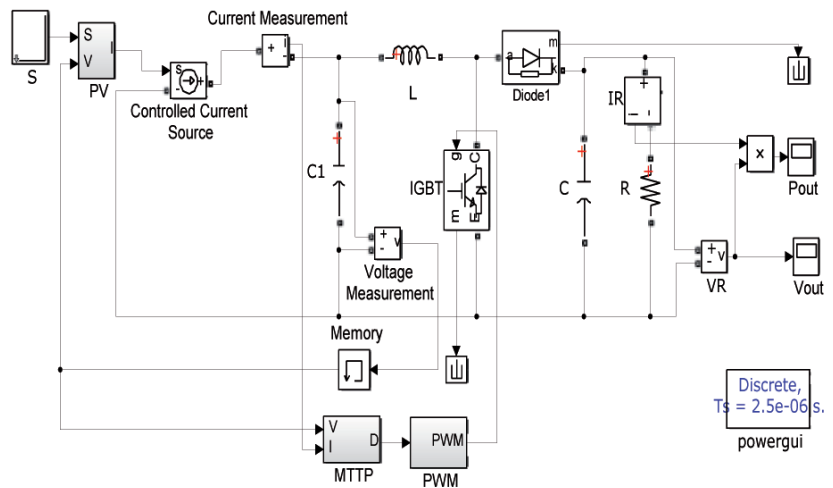
For a linear circuit, when the internal resistance of the power supply is equal to the load resistance, the power supply exports the maximum power. So a DC/DC converter can be added between PV and load, making the load resistance changing with output resistance of PV, then complete the MPPT. The output power of PV is low, so the Boost converter circuit is used to achieve the MPPT<sup>[10]</sup>. The whole simulation model of MPPT of PV is shown as Figure 4.



**Figure 2.** Dynamic simulation model of PV



**Figure 3.** Electrical characteristics of PV



**Figure 4.** Simulation model of MPPT of PV

In Figure 4, PV module is the photovoltaic cell module; MPPT is the maximum power point tracker; PWM is pulse width modulator and is shown in Figure 5;  $C_1$  and  $C$  are input and output capacity of the Boost conversion circuit;  $R$  is load resistance. A pulse signal is generated by pulse width modulation (PWM) to drive the power devices of the Boost converter, so that the output power of PV gradually reached the maximum power.

### 3. Comparative Study on Methods of MPPT

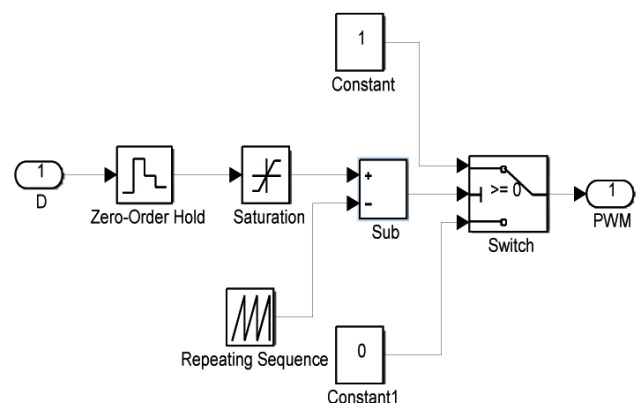
#### 3.1. Perturbation and Observation Method

The flow chart of perturbation and observation method is shown as Figure 6[11].

Figure 7 is the MPPT control simulation model based on perturbation and observation method.

#### 3.2. Incremental Conductance Method

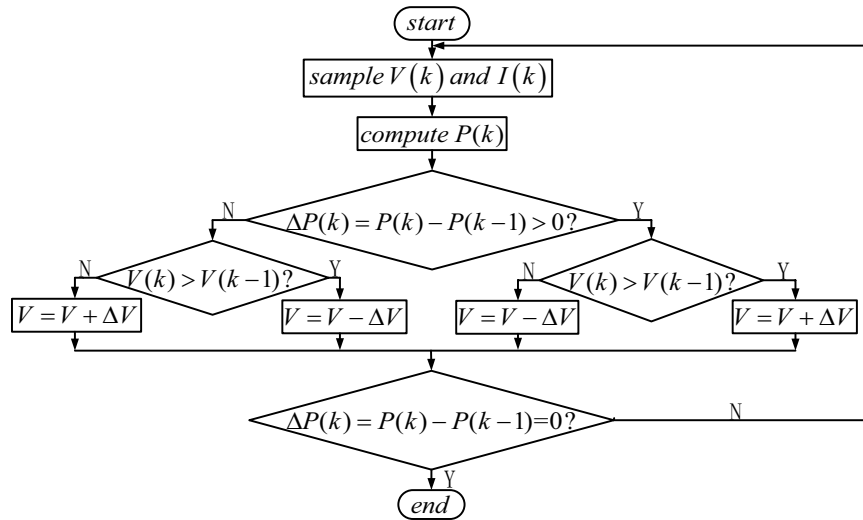
As is shown in the P-V characteristic curve of PV in Figure 8, we can make the system wor-



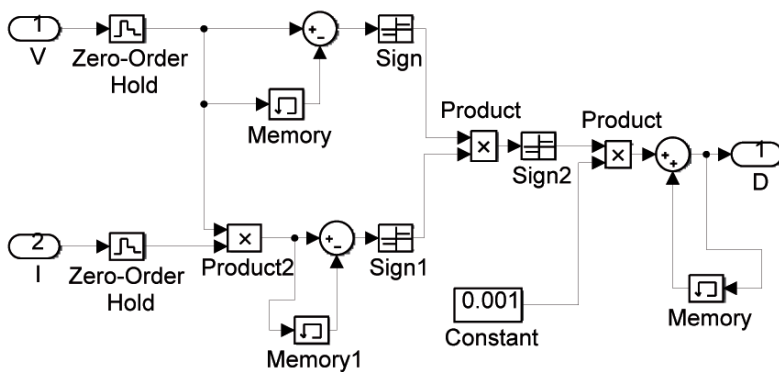
**Figure 5.** Model of PWM

king in the maximum power point by adjusting the voltage.

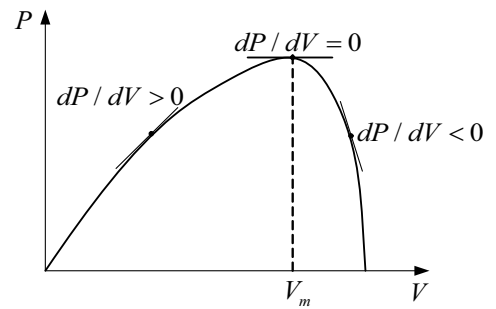
Supposed that output power of PV is  $P$ , output voltage is  $V$ , and output current is  $I$ , and voltage of



**Figure 6.** Flow chart of perturbation and observation method



**Figure 7.** Simulation model of MPPT based on perturbation and observation method



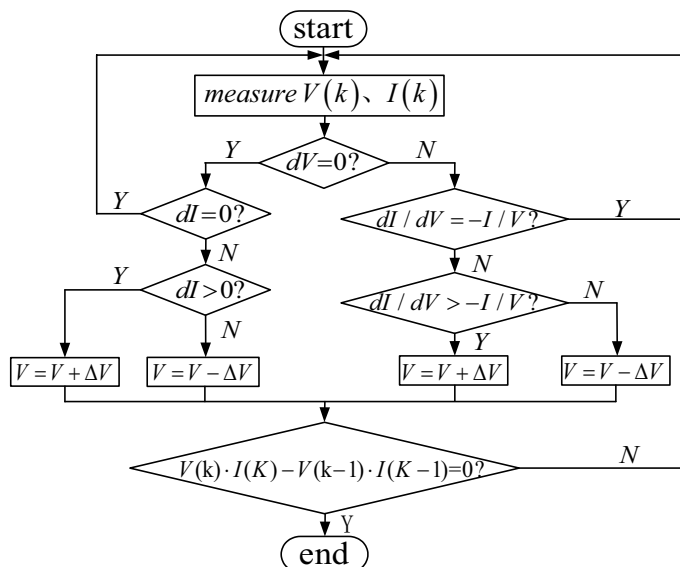
**Figure 8.** P-V Characteristic curve of PV

the maximum power point is  $V_m$  [12]. Then the flow chart of MPPT control is shown in Figure 9.

Figure 10 is the simulation model of MPPT control based on incremental conductance method.

### 3.3. Fuzzy Control Method

This paper uses two-dimensional fuzzy controller and it determines that input variables are power variation  $e(n)$  at  $n$  time and the duty cycle step  $a(n-1)$  at



**Figure 9.** Flow chart of incremental conductance method

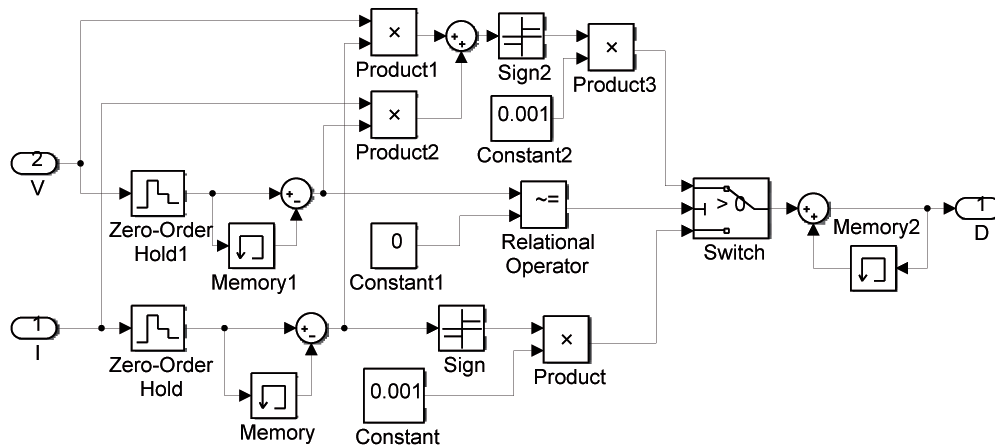


Figure 10. Simulation model of MPPT based on incremental conductance method.

$n - 1$  time, and output variable is the duty cycle step  $a(n)$  at  $n$  time.  $E(n)$  is the value corresponding to  $e(n)$  in the field of fuzzy set. The structure of fuzzy control is shown in Figure 11[13].

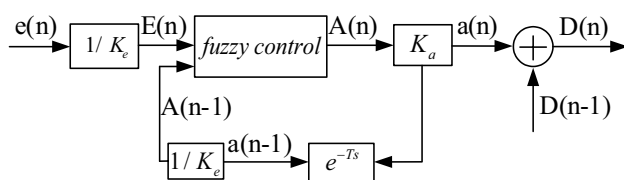


Figure 11. Structure of fuzzy control

$E(n)$  is defined as eight fuzzy subsets, and its range is  $[-3,3]$ .  $A(n)$  and  $A(n - 1)$  are defined as six fuzzy subsets, and their ranges are  $[-1.5,1.5]$  and  $[-3,3]$ . Fuzzy sets are as follows<sup>[14]</sup>:

$E(n) = \{NB, NM, NS, NO, PO, PS, PM, PB\}$ ;

$A(n) = \{NB, NM, NS, PS, PM, PB\}$ ;

$A(n-1) = \{NB, NM, NS, PS, PM, PB\}$ .

where NB, NM, NS, NO, PO, PS, PM, PB respectively represents high negative, moderate negative, small negative, negative zero, positive zero, small positive, moderate positive, large positive. This paper uses triangle membership function, and the membership function of  $e(n)$ ,  $a(n - 1)$  and  $a(n)$  are shown in Figure 12.

Using the reasoning method of Mamdani, according to the basic principle of fuzzy control rules, the table of fuzzy control rules is obtained as Table 1.

According to the conditions above, use the fuzzy control toolbox in MATLAB to edit fuzzy controller.

Import the file mohu4.fis generated from fuzzy controller into the fuzzy control module in Simulink. Get the MPPT control simulation model based on fuzzy control as in Figure 13.

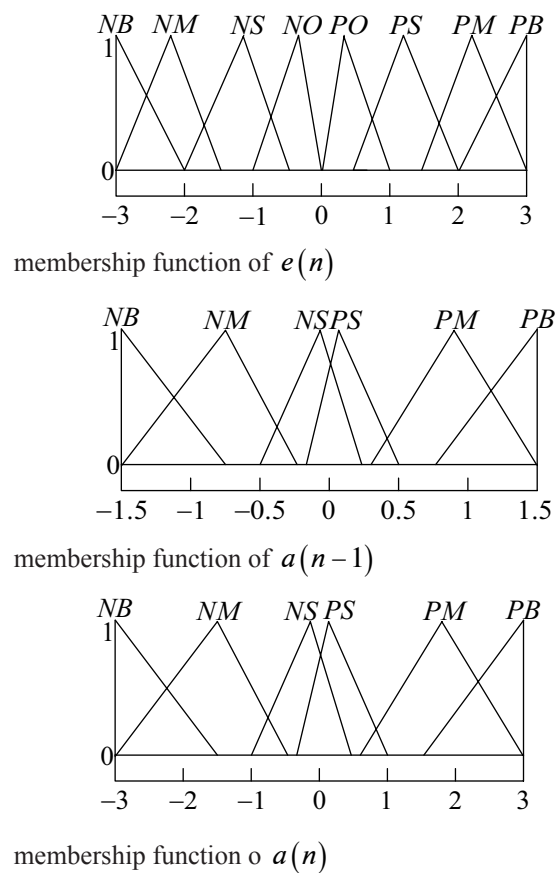


Figure 12. Membership function of  $e(n)$ ,  $a(n - 1)$  and  $a(n)$

Table 1 Table of fuzzy control rules

$A(n) \backslash A(n-1)$	$E(n)$	NB	NM	NS	NO	PO	PS	PM	PB
NB		PB	PM	PS	PS	NM	NM	NB	NB
NM		PB	PB	PM	PS	NM	NM	NB	NB
NS		PB	PB	PM	PS	NS	NS	NS	NM
PS		NM	NS	NS	NS	PS	PM	PB	PB
PM		NB	NB	NM	NM	PS	PM	PB	PB
PB		NB	NB	NM	NM	PS	PS	PM	PB

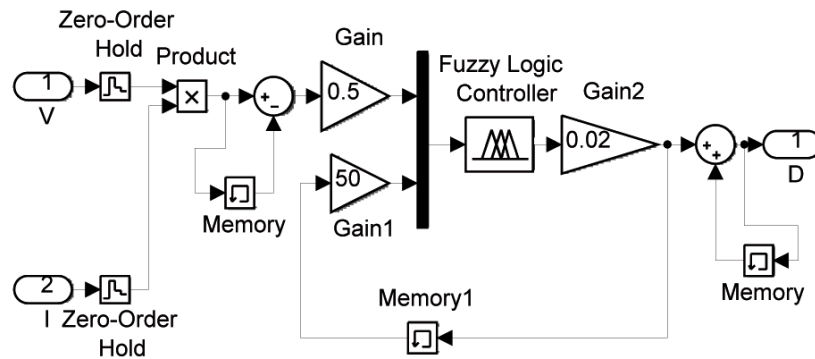


Figure 13. Simulation model of MPPT based on fuzzy control.

### 3.4. BP Neural Network Method

Back Propagation (BP) neural network is a multi-layer neural network based on the error back propagation algorithm, with at least one hidden layer and fully connected mode is adopted between layers. Because the network uses specific BP algorithm, it is called as BP neural network<sup>[3]</sup>. Assuming that the number of neurons in input layer is  $M$ , the number of neurons in hidden layer is  $I$ , and the number of neurons in output layer is  $J$ . Then the network structure is as shown in Figure 14<sup>[15]</sup>.

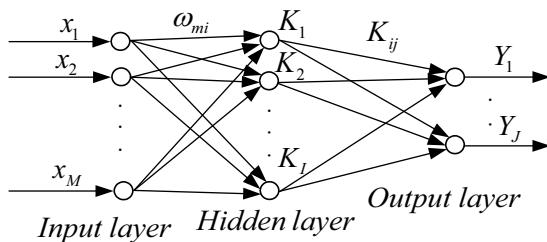


Figure 14. Structure of three-layer neural network

According to BP algorithm, flow chart of BP neural network algorithm as is shown in Figure 15<sup>[16]</sup>.

This paper designs a BP neural network model based on MPPT of PV. The input is light intensity, and the target vector is the maximum power of PV in the neural network. Through test and comparison, the number of hidden layer is determined as five.

The target vector of maximum power of PV is obtained by Newton Iteration method and stored in matrix P1. Using the neural network toolbox in MATLAB, design BP neural network, and programs are as follows:

```
P=0:1:1000;T=P;net=newff(P,T,5);net.trainParam.Fcn='traingd'; net.trainParam.goal=0.001; net=train(net,P,T); Y=sim(net, P);
```

After training, it generates a neural network module which can be applied to Simulink. The model of MPPT control based on neural network is shown as Figure 16.

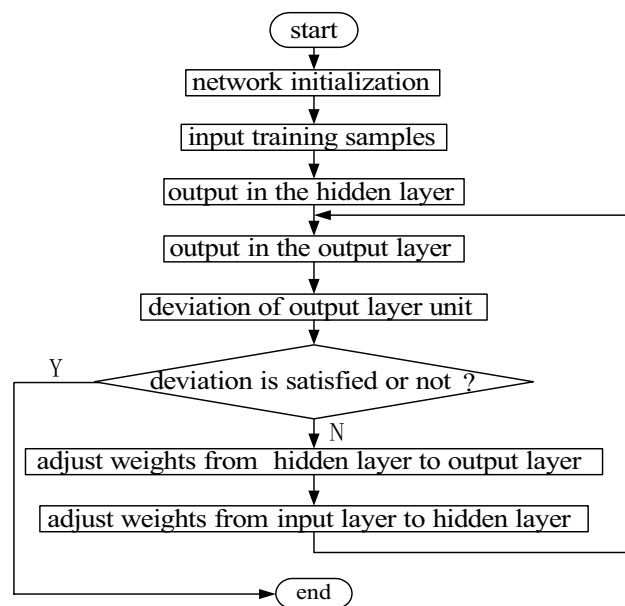


Figure 15. Flow chart of BP neural network

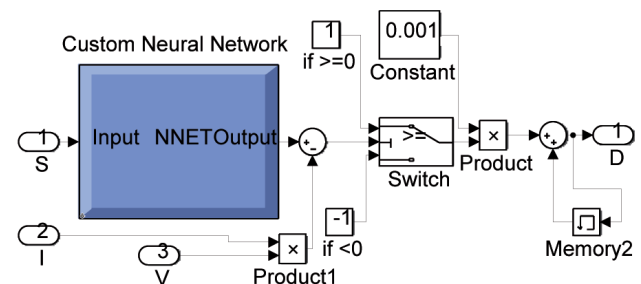


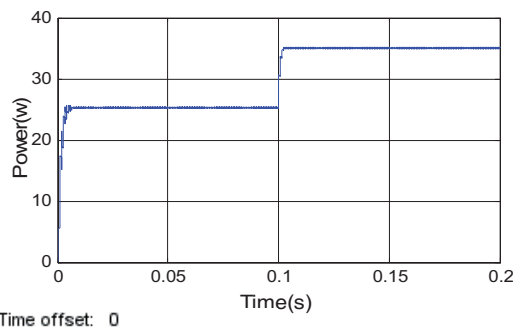
Figure 16. BP MPPT control model of neural network

### 4. Analysis on Simulation Results

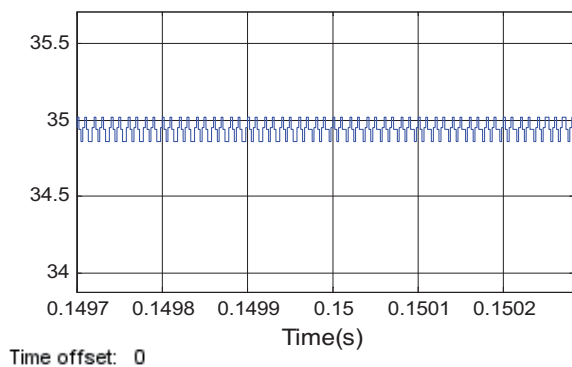
In this paper, as shown in Figure 1, the temperature is 25°C, and the light intensity turns into 950 W/m<sup>2</sup> from 750 W/m<sup>2</sup> at 0.1 second. In the Boost circuit, the value of  $L$  is 220μH,  $C_1$  is 50μF,  $C$  is 60μF and  $R$  is 12.8Ω. The sampling period is set to 0.00001s. Using the algorithm ode23tb(stiff/TR-BDF2) with variable step size, the maximum and minimum step size, the initial step size and the absolute error is set to auto, and the relative error is set



to  $1e-3$ , and then simulate it. The simulation result of each method of MPPT is shown as Figure 17 to 20.

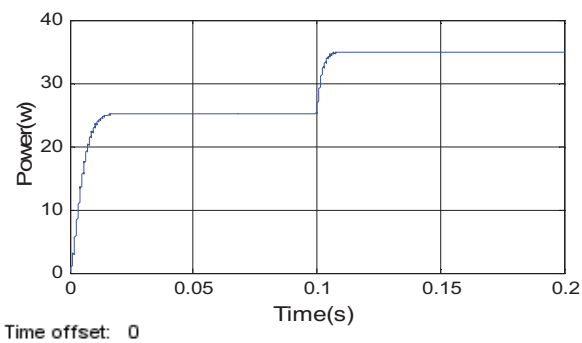


(a) Output power

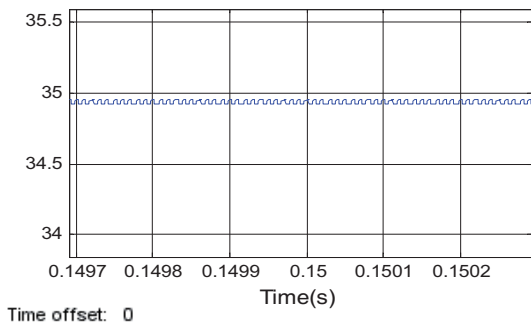


(b) Local amplification of output power

**Figure 17.** Simulation results of perturbation and observation method.

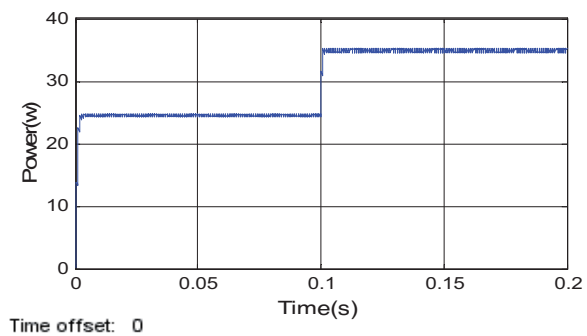


(a) Output power

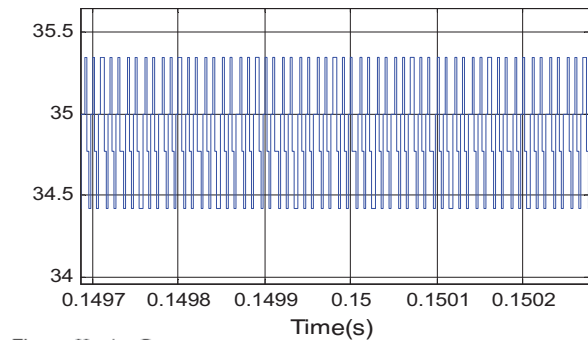


(b) Local amplification of output power

**Figure 18.** Simulation results of incremental conductance method.

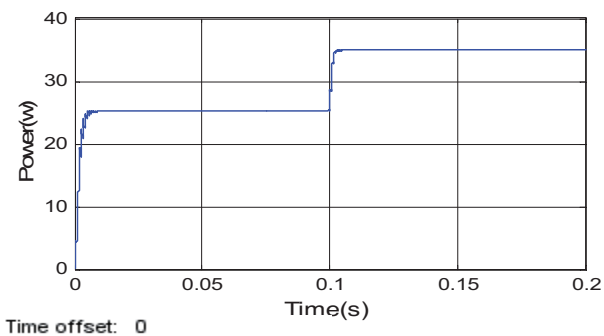


(a) Output power

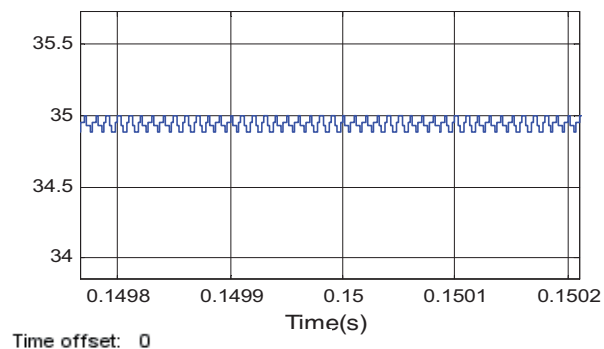


(b) Local amplification of output power

**Figure 19.** Simulation results of fuzzy control method



(a) Output power



(b) Local amplification of output power

**Figure 20.** Simulation results of neural network method

Comparing results of each method of MPPT, the advantages and disadvantages are shown as in Table 2. Table 2 shows that each method has superiorities. Suitable method can be chosen to realize MPPT to reduce power loss to the best. In addition, according to the characteristics of various methods, MPPT can be realized more accurately and fast through complementary advantages.

**Table 2.** Comparison of MPPT methods

	advantages	disadvantages
Perturbation and observation	less parameters, easy to implement, fast tracking	Easy to produce oscillations , bigger power loss, can not take both accuracy and response speed into account
Incremental conductance	Weak oscillation, small power loss	Slow response speed , complex structure
Fuzzy control	Fast response , easy to cooperate with other methods to achieve fast and accurate tracking of maximum power	Strong oscillation , bigger power loss
Neural network	Fast response , weaker oscillation , smaller power loss	Need to get training samples , complex design

through simulation results. It shows that the effect of neural network is best. Through theoretical analysis, the results of the combining of fuzzy control and incremental conductance method will be better.

## Acknowledgments

This work is supported by the National Natural Science Foundation of China (No. 61473174, 61105100, 51376110).

## References

1. Angrisani G, Roselli C, Sasso M. Distributed microtrigeneration systems. *Progress in Energy and Combustion Science*, 2012, 38(4): 502–521.
2. Pepermansa G, Driesenb J, Haeseldonckxc D, et al. Distributed generation: definition, benefits and issues. *Energy Policy*, 2005, 33(6): 787–798.
3. X.F. Han, Research of photovoltaic MPPT composite control based on neural network and fuzzy control. Nanchang Aeronautical University, 2013.
4. Abdollahia G, Meratizaman M. Multi-objective approach in thermoenviromomic optimization of a small-scale distributed CCHP system with risk analysis. *Energy and Buildings*, 2011, 43(11): 3144–3153.
5. Guerrero J M, Blaabjerg F, Zhelev T, et al. Distributed generation: toward a new energy

## 5. Conclusions

MPPT can effectively improve electric efficiency of PV. According to mathematical model of PV, this paper builds a PV simulation model by MATLAB/Simulink. The whole simulation model combined PV, Boost circuit and MPPT is built. Four different methods are used to realize MPPT, and advantages and disadvantages of each method are obtained

- paradigm. *IEEE Industrial Electronics Magazine*, 2010, 4(1): 52–64.
6. Chicco G, Mancarella P Distributed multi-generation: A comprehensive view. *Renewable and Sustainable Energy Reviews*, 2009, 13(3): 535–551.
7. JIAO Yang, SONG Qiang, LIU Wenhua. Control strategy of grid-connected photovoltaic generation system based on modified MPPT method. *Electric Power Automation Equipment*, 2010, 30(12): 92–96.
8. H.L. Tao, Y. Xia & N. Zhang. Photovoltaic cell simulation and model application. *Industrial Control Computer*, 2011.
9. J.Y. Gao, X.H. Gong, F.L. Wang, B. Dong & C. Di, Simulation research on photovoltaic cell Based on Matlab/Simulink. *Power Grid and Clean Energy*, 2013, 29(3), pp. 1–2.
10. VIOREL B, Dynamic model of a complex system including PV cells, Electric Battery, Electrical Motor and Water Pump. *Energy*, 2003, 28(12), pp. 1165–1181.
11. Q. Tang, Maximum power tracking control of photovoltaic power generation system. Shanxi University, 2011.
12. L.G. Liu, Study on the system of maximum power tracking control of photovoltaic power generation. Yanshan University, 2011.
13. J. Chen & J. Hui, MPPT of photovoltaic power generation technology based on fuzzy control



- strategy. Modern electronic technology, 2009, (06).
14. D.S. Lai, Maximum power tracking control based on fuzzy control. The Electronic World, 2011.
15. M. Chen, The neural network and the example. Tsinghua University press: Beijing, 2013, PP. 79-81.
16. L.X. Wang, Comparative study of maximum power point tracking photovoltaic based on BP and RBF neural network. Shantou University, 2010.



## Guidance Technology of Horizontal Curved Flight for Short Range Aircraft with Inertial Navigation

**Wang Yan, Cai Jifei, Zhang Yang, Li Guang**

*Beijing Institute of Graphic Communication, Beijing, 102600, China*

Corresponding author is Wang Yan

### Abstract

For short-range aircraft with inertial navigation (called “fire and forget”), its flying time is short. Besides, the guidance technology is critical in initial introduction. Through mathematical modeling of the guidance technology in initial introduction, the guidance mechanism of aircraft’s horizontal curve flight was studied in the work. Besides, simulations for flight control were conducted under different initial conditions. Results showed that it was feasible to imagine the line of sight to target in initial introduction. Furthermore, simulation results also provided critical technical basis for the comprehensive evaluation of aircraft’s overall scheme and further study of aircraft system. Keywords: AIRCRAFT; SHOULDER-TYPE SOFT FIRING; INERTIAL GUIDANCE; FLIGHT PATH SIMULATION; GUIDANCE IN INTRODUCTION

### 1. Introduction

For short-range aircraft with inertial navigation, called “fire and forget”, its flying time is several seconds, with a flight distance of only hundreds of meters. Fig.(1) showed the launching process of shoulder-type aircraft with soft firing system. Once the target was found, shooter would activate the launching and controlling equipment. In the target tracking, the angular rate of line of sight to target was recorded by

the launching and controlling equipment. Then, the average angular acceleration was calculated based on the 2s data of angular velocity[1][2][3][9][10][20].

Aircraft flight path was divided into straight and curve flight path depending on different projections of aircraft flight path. Straight flight path referred to ideal flight path with straight line on horizontal projection, while curve one to that with curve on horizontal projection. For the launching and controlling