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Research on the Electrical Characteristics of Photovoltaic Arrays and Corresponding MPPT Simulation

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Abstract: Photovoltaic cells, as the primary part of a solar photovoltaic system, are a nonlinear DC power supply related to multiple parameters. The demand of increasing the generating efficiency of photovoltaic cells requires having a good understanding of their electrical characteristics. In this study, the mathematical and physical model of the photovoltaic cells was built by the means of Matlab and Simulink based on the internal principles and equivalent circuits of the photovoltaic cells. After the simulation of such practical and versatile model, it's found that the nonlinear P-V and I-V characteristics of the photovoltaic cells, with the change of sunlight intensity and temperature, could be accurately reflected by this high simulation precision model. Furthermore, the Maximum Power Point Tracking method was proposed using the logical formula dP/dI=0 of the maximum power point of photovoltaic cells. This method can simply and fast implement the tracking for the maximum power point. *Copyright © 2013 IFSA.*

Keywords: Photovoltaic cell, Electrical characteristic, Maximum power point tracking.

1. Introduction

Solar photovoltaic systems have earned more attention with the aggravation of the world's energy crisis, and the solar energy is a kind of clean energy which is pollution-free, noiseless, widely distributed and without region limit. Therefore, the solar photovoltaic technology, compared to other new energy technologies, is a renewable energy technology for sustainable development. The critical part of a solar photovoltaic system is the photovoltaic array whose generating efficiency has an effect on the stability and feasibility of the entire system. Nevertheless, affected by sunlight intensity, temperature and raw materials, etc., the electrical characteristics of the photovoltaic array assume nonlinearity. The voltage across the photovoltaic array varies with the change of sunlight intensity and ambient temperature, and so is its output power. In other words, the photovoltaic cells provide unstable power supply. MPPT (Maximum Power Point Tracking) is a process of adjusting the operating point of the photovoltaic cells in real time to keep it near the maximum power point for the purpose of improving the overall efficiency of the solar photovoltaic system [1-2].

Currently, there are many MPPT algorithms for photovoltaic cells, such as the voltage feedback method, power feedback method, perturbation and observation method, incremental conductance method and actual measurement method. All these methods take voltage as the reference value to perform adjustment in order to track and control the maximum power point of a solar photovoltaic system. However, there are some shortcomings unavoidably like complexity and rapidity owing to the nonlinear relationship between P and V. The disturbance attributed to these shortcomings inevitably causes power fluctuations and consequently generates extra losses. As a result, this study presents a straight-line approximation method based on many MPPT methods to avoid such shortcomings. This MPPT method is simple, easy to track and relatively accurate [3-4].

The mathematical simulation model of the photovoltaic array in the early research was built to reduce cost. The dynamic simulation of the photovoltaic array was implemented using this simulation platform, which is beneficial to fully study the characteristics of the photovoltaic array. In addition, it can either increase the utilization efficiency of the photovoltaic cells or shorten the research cycle of the solar photovoltaic system considerably.

2. Establishment of the Photovoltaic Cell Models

2.1. Mathematical-physical Model of a Single Photovoltaic Cell

A photovoltaic cell is a device directly converting light energy into electric energy through the photovoltaic effect. When a photovoltaic cell exposed to sunlight connects to a load, the photo current flows through the load and creates terminal voltage at the both ends of the load. At this time, an equivalent circuit model can be used for the current working status of the photovoltaic cell. Fig. 1 shows the photovoltaic cell can be considered as an ideal current source that stably generates the photo current I_{ph}[5].

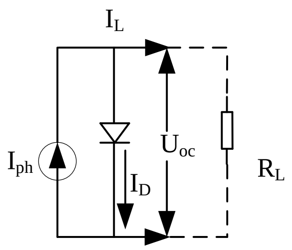

Fig. 1. Ideal equivalent circuit of the photovoltaic cell.

Considering the effects of the photovoltaic cell resistance on the photovoltaic cell's properties, the actual equivalent circuit is shown in Fig. 2. R_s is the series resistance composed of the internal resistance of silicon wafers and electrode resistance. It primarily consists of body resistance, surface resistance, electrode conductor resistance, and the contact resistance between electrodes and silicon surface. R_{sh} is bypass resistance resulting from the unclean edges of silicon wafers and inherent defects. The circuit models can help to have an insight into the working principle and electrical characteristics of the photovoltaic cell.

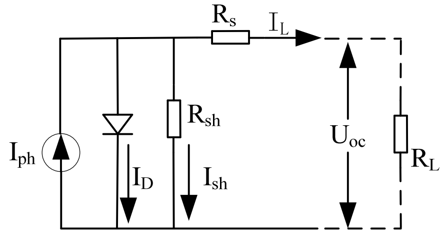

Fig. 2. Actual equivalent circuit of the photovoltaic cell.

According to the equivalent circuits in Figs. 1 and 2, the equations of output characteristics variables of the photovoltaic cell can be given as:

$$I_D = I_0[\exp(\frac{qU_D}{AkT})-1] \quad (1)$$

$$I_L = I_{ph} - I_0[\exp(\frac{q(U_{oc}+I_L R_s)}{AkT})-1] - \frac{U_D}{R_{sh}} \quad (2)$$

$$I_{sc} = I_{ph} - I_D - \frac{U_D}{R_{sh}} - \frac{U_D}{R_s}, \quad (3)$$

where

$$I_{ph} = I_{sc}[1+a(T-298)]\frac{G}{1000} \quad (4)$$

$$I_0 = I_{or}[\frac{T}{T_r}]\exp[\frac{qE_G}{Bk}(\frac{1}{T_r}-\frac{1}{T})] \quad (5)$$

The parallel resistance R_{sh} can be ignored, since it can generally reach several thousand ohms and its current value is far less than the photo current's. So we can simplify the output characteristic equation of the photovoltaic cell as:

$$I_L = I_{ph} - I_0[\exp(\frac{q(U_{oc}+I_L R_s)}{AkT})-1] \quad (6)$$

In case of the short circuit of the external load, U_{oc} = 0, all the photovoltaic current I_{ph} flows into the shorted external load, and the short circuit current I_{sc} is almost equal to the photo current, $I_{ph} = I_{sc}$. In case of the open circuit, I = 0, all the photo current flows through the diode D, and the open circuit voltage is:

$$U_{oc} = \frac{AKT}{q}\ln(\frac{I_{ph}}{I_0}+1) \quad (7)$$

According to Equation (7), the short circuit current I_{sc} varies with the change of temperature and sunlight intensity and is proportional to the sunlight intensity, when the output current and voltage of the photovoltaic cell are affected by these external factors. At the same time, the open circuit voltage is also tightly related to the above two factors [6], as shown in Equation (8), (see Table 1) is the parameters of any of the above formula.

$$U_{oc} = U_{ocs}[1 + b(T - T_r)] \tag{8}$$

Table 1. Parameter list of the equivalent circuit of the photovoltaic cell.

Parameter	Description	Type
I_o	The reverse saturation current of the photovoltaic cell	Variables
T	The temperature of the photovoltaic cell	Constant
K	Boltzmann constant	Constant (1.38×10^{-23} J/K)
G	Sunlight intensity	Variables
q	Electron charge	Constant (1.6×10^{-19} C)
I_{or}	The reverse saturation current of the diode	Constant
T_r	Reference temperature under standard test conditions	Constant (298 K)
E_G	The band gap of the semiconductor material	Constant
a	Short circuit current temperature coefficient	Constant
A, B	The curve constant of the P-N junction	Constant (from 1 to 5)
b	Open circuit voltage temperature coefficient	Constant

2.2. Establishment of the Photovoltaic Array Model

A silicon photo cell has the open circuit voltage of 0.45–0.6 V and the short circuit current density of 20–25 mA/m^2. However, instead of a photovoltaic cell which is rarely used individually in actual lives, the form of many series-parallel photovoltaic cells is the common selection. These photovoltaic cells form a photovoltaic module, with a certain degree of impact and corrosion resistance, which increases the voltage through series connection and the current through parallel connection to provide a load with the larger power. Based on the fact that the series-parallel combination of photovoltaic cells can provide the expected DC voltage or current, the output characteristic equation of the photovoltaic cell module group can be obtained as:

$$I_L = n_p I_{ph} - n_p I_o \left\{ \exp\left[\frac{q(U_{oc} + I_L R_s)}{n_s AkT} \right] - 1 \right\}, \tag{9}$$

where n_p is the parallel connection number of the photovoltaic cells in the module group; n_s is the series connection number of the photovoltaic cells in the module group.

3. Electrical Characteristic Simulation and Analysis for the Photovoltaic Cells

Based on the above mathematical equivalent model, the physical mechanism-based mathematical simulation model of the photovoltaic array is directly built based on the existing math operations by means of Simulink in the Matlab environment [7-8]. We set the photovoltaic array parameters in the above model for simulation based on the technical parameters of the 60 W photovoltaic cell panel of our laboratory (see Table 2).

Table 2. Electrical specification parameters of XMT-U60 panel (1000 W/m ^{2}, 25 °C).

Maximum power (W)	60
Maximum working voltage (V)	18 V
Maximum working currency (A)	3.3
Open circuit voltage (V)	22.5
Short circuit current (A)	3.5
Photovoltaic cell number	36 (4)
Short circuit current temperature coefficient	0.065 /°C
Open circuit voltage temperature coefficient	-2.23 mV/°C

When the sunlight intensity is 1000 W/m^2, the I-V and P-V curves of the photovoltaic array are obtained through measurement at 5 °C, 25 °C and 50 °C. The results are shown in Figs. 3 and 4, respectively.

At the fixed temperature of 25 °C, the I-V and P-V curves of the photovoltaic array are obtained through measurement with the sunlight intensity of 1000 W/m^2, 800 W/m^2 and 600 W/m^2. The results are shown in Figs. 5 and 6.

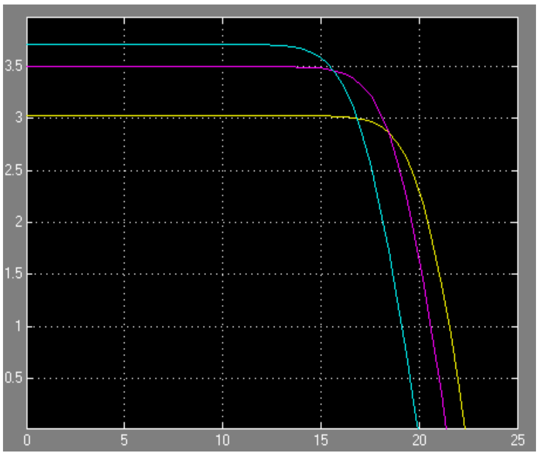

Fig. 3. Photovoltaic array I-V curve based on the change of temperature.

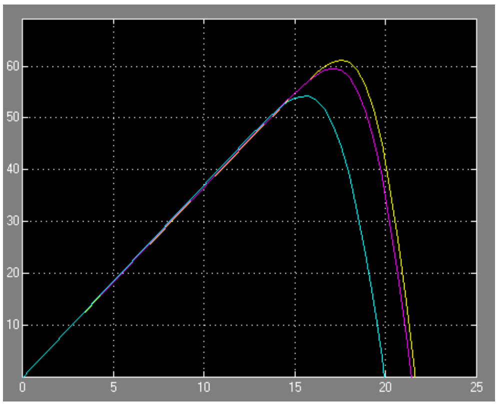

Fig. 4. Photovoltaic array P-V curve based on the change of temperature.

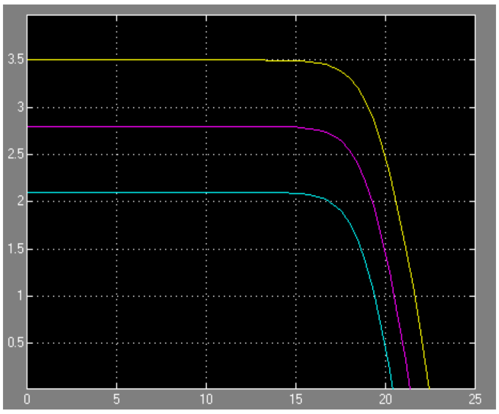

Fig. 5. Photovoltaic array I-V curve based on the change of sunlight intensity.

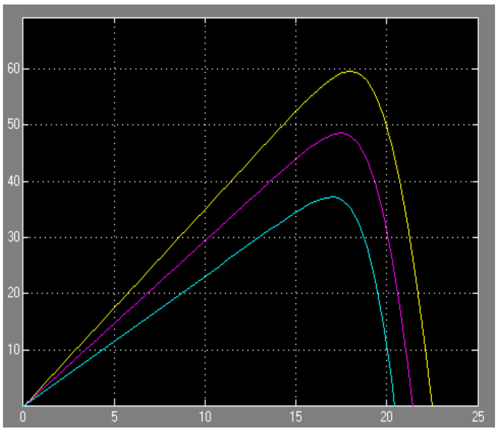

Fig. 6. Photovoltaic array P-V curve based on the change of sunlight intensity.

Figs. 3, 4 indicates that the short circuit current I_{sc} of the photovoltaic array slightly increases but the open circuit voltage U_{oc} rapidly decreases with the temperature rise at the fixed sunlight intensity, which leads to the general coastdown of output power of the photovoltaic array. Fig. 5, 6 indicates that the open circuit voltage U_{oc} of the photovoltaic array slightly changes and the short circuit current I_{sc} obviously increases at the fixed ambient temperature when the sunlight intensity rises, which leads to the increase of the maximum output power. It can be seen that the working environment temperature and sunlight intensity are the critical factors affecting the output characteristics of the photovoltaic array. However, the frequent change of the temperature and sunlight intensity may cause the photovoltaic array to fail in providing adequate energy to the load and even zero voltage which induces application losses. As a result, the MPPT method is capable of seeking the best operating point of a photovoltaic array by controlling an external load to avoid these disadvantages wherever possible and obtain optimum power.

4. MPPT Algorithm Simulation of the Photovoltaic Array

The fundamental concept of the straight line approximation method is to make use of the logical formula dP/dI=0. A straight line is applied for approximating the maximum power points under different sunlight intensity at a certain temperature. Only if controlling the output current to be on this straight line, MPPT can be easily implemented [9].

For the abovementioned equivalent model of the photovoltaic array, if n_s=36 and n_p=1, and in addition the equivalent series resistance is not ignored, Equation (9) can be rewritten as:

$$V = \frac{36kTA}{q}\ln[\frac{(I_{ph}+I_0-I)}{I_0}] - IR_s \qquad (10)$$

Then based on Equation (9) and (10), we can obtain:

$$P = IV = \frac{36kTA}{q} I \ln[\frac{(I_{ph}+I_0-I)}{I_0}] - I^2 R_s \qquad (11)$$

Because the maximum power point is required to satisfy *dP/dI*=0, the differential of I is performed with Equation (11) and we make it equal to zero:

$$\frac{36kTA}{q}\ln[\frac{(I_{ph}+I_0-I)}{I_0} - \frac{I}{I_{ph}+I_0-I}] - 2IR_s = 0 \qquad (12)$$

Based on Equation (10), (11), and (12), the relationship of the output power P_1 and the output current I_1 at the maximum power point can be obtained as:

$$P_1 = \frac{36kTA}{q} I_1 \ln[\frac{36kTAI_1^2}{(P_1 - I_1^2 R_s) I_0}] - I_1^2 R_s \qquad (13)$$

Finally, based on the above algorithms, we acquire the P_1-I_1 curve, as shown in Fig. 7, by solving Equation (10-13) with Matlab. It can be seen from the figure that there is a linear relationship between the maximum power point and the output current under different sunlight intensity at the same temperature [10-11].

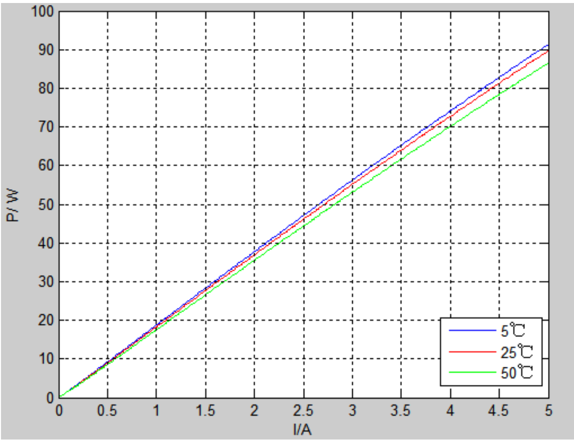

Fig. 7. Relationship of the maximum power point and the output current.

5. Conclusion

The mathematical expression of output I-V characteristics of the photovoltaic array composed of series-parallel photovoltaic cells is solved based on the equivalent circuit model of the photovoltaic cells. The simulation experiment results show the nonlinear P-V and I-V characteristics of photovoltaic cells with the change of sunlight intensity and temperature, and the photovoltaic cells output is a random and unstable power supply system. When the photovoltaic cells are used, their output characteristics often substantially change under the effects of load states, sunshine amount and ambient temperature, etc. The short circuit current is almost proportional to the sunshine amount, and the open circuit voltage is greatly affected by the temperature change. Therefore, the output power has a great change, in other words, the maximum power point is changing. In this study, new algorithms were used to deduce the approximate linear relationship of the maximum power point and the output current, and the MPPT control algorithm, based on current control, was proposed. The MPPT method, simple, easy to track and relatively accurate, is suitable for the simulation studies of complex solar photovoltaic systems.

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