Modeling of Photovoltaic System in the Large Ocean-going Ship Based on Simulink

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ABSTRACT

Main purpose of this paper is to establish a precise mathematical model of solar photovoltaic array in the ship. Firstly analyzed performance parameters of solar PV power generation system in the “COSCO TengFei ship” and gave principle model of PV cell monomer. Then, the practical engineering mathematics model was proposed for PV cell module. The mathematical model of the PV cell array was established. Finally, this paper compared and analyzed the simulation results and the data from ship, drew the conclusion that the accuracy of the simulation model was verified. So this mathematical model can be used to characteristic research that PV power generation system parallel with power station system in the ship, for example maximum power point tracking, active filter, reactive power compensation, etc.

Key words: ship; photovoltaic (PV) cell array; engineering mathematical model;

INTRODUCTION

In November 2012, the project “Application technology research of solar energy on the larger-going ship” is established by National ministry of industry and information technology. The total capacity is 143.1 kW in the “COSCO TengFei Ship”. This system have two operation mode, PV system off-grid mode, grid-connected mode[1].

THEORETICAL MODEL OF PV CELL

When the semiconductor is in the light, State of charge distribution in a semiconductor is changed. This change produces electromotive force and current, it is called a kind of energy conversion effect[2]. Circuit diagram is shown in Figure 1:
The current formula of PV cell is written from Figure 1:

\[ I = I_{ph} - I_d - I_{sh} \]  \hspace{1cm} (1)

\[ I_{ph} = \frac{I_{sc} S}{1000} + C_t (T - T_{ref}) \]  \hspace{1cm} (2)

\[ I_d = I_0 \left\{ \exp \left[ \frac{q(V + IR_s)}{nKT} \right] - 1 \right\} \]  \hspace{1cm} (3)

\[ I_{sh} = \frac{(V' + IR_s)}{R_{sh}} \]  \hspace{1cm} (4)

Thereinto: \( S \) — Light intensity, \( W / m^2 \); \( T \) — Surface temperature of PV, \( \degree C \); \( T_{ref} \) — Reference temperature, 25 \( \degree C \); \( C_t \) — Temperature coefficient, \( \degree C \); \( I_{sc} \) — Short circuit current; \( I_0 \) — Reverse saturation current; \( q \) — Quantity of charge, \( 1.69 \times 10^{-19} \) C; \( n \) — Diode emission coefficient; \( K \) — Boltzmann constant, \( 1.38 \times 10^{-23} \) J / K;

The formula (2), (3), (4) into (1), it is the expression of output current of PV:

\[ I = I_{sc} \frac{S}{1000} + C_t (T - T_{ref}) - I \left\{ \exp \left[ \frac{q(V + IR_s)}{nKT} \right] - 1 \right\} - \frac{(V' + IR_s)}{R_{sh}} \] \hspace{1cm} (5)

Theoretical model of PV cell is very accurate, but formula(5) is a transcendental equation. It is difficult to deduce the analytic solution of I. The practical value is not very big in the PV cells monomer modeling application[3].

**ENGINEERING MATHEMATICAL MODEL OF PV MODULE**

PV array is series and parallel connections of PV modules. According to the standard conditions of the manufacturer( S=1000W/m², T=25°C) the test parameters of solar panel, \( I_{sc}, V_{oc}, I_m, V_m \), In order to establish mathematical model of engineering, on the basis of the formula (1) two approximation are done[4]:

1. Due to the \( R_{sh} \) is very big, So ignore the item \( (V + R_s I) / R_{sh} \).
2. The \( R_s \) is far less than the positive resistance of the diode, So \( I_{sc}=I_{ph} \).

Based on the above assumptions, the engineering mathematics model of PV module is put forward, formula(6), (7), (8).

\[ I = I_{sc} \frac{S}{1000} + C_1 (T - T_{ref}) - I \left\{ \exp \left[ \frac{q(V + IR_s)}{nKT} \right] - 1 \right\} - \frac{(V' + IR_s)}{R_{sh}} \] \hspace{1cm} (5)

\[ I_{ph} = \frac{I_{sc} S}{1000} + C_t (T - T_{ref}) \] \hspace{1cm} (2)

\[ I_d = I_0 \left\{ \exp \left[ \frac{q(V + IR_s)}{nKT} \right] - 1 \right\} \] \hspace{1cm} (3)

\[ I_{sh} = \frac{(V' + IR_s)}{R_{sh}} \] \hspace{1cm} (4)

\[ I = I_{sc} \frac{S}{1000} + C_1 (T - T_{ref}) \left[ \exp \left( \frac{V'}{C_2 V_{oc}} \right) - 1 \right] \] \hspace{1cm} (6)

\[ C_1 = \left( 1 - \frac{I_m}{I_{sc}} \right) \exp \left( \frac{-V_m}{C_2 V_{oc}} \right) \] \hspace{1cm} (7)

\[ C_2 = \frac{V_m}{V_{oc}} \left[ \ln \left( 1 - \frac{I_m}{I_{sc}} \right) \right]^{-1} \] \hspace{1cm} (8)
MATHEMATICAL MODEL OF SOLAR PV ARRAY IN THE SHIP

PV modules which are installed in the “COSCO TengFei Ship” are produced by YingLi green energy company. Rated voltage is 31.0V, Rated current is 8.55A, Open circuit voltage is 39.0V, Short circuit current is 8.93A. There are 540 solar panels in the ship. It is divided into three arrays. The arrangement of PV array is shown in Figure 2.

According to formula(6) and Figure 2. engineering mathematics model equation (9) can be established:

\[ I = mI_{sc} - mC_{1}I_{sc} \left[ \exp \left( \frac{V}{nC_{2}V_{oc}} \right) - 1 \right] \]  
(9)

\[ T = T_{air} + K \times S \]  
(10)

\[ \Delta T = T - T_{ref} \]  
(11)

\[ \Delta S = \frac{S}{S_{ref}} - 1 \]  
(12)

\[ I'_{sc} = I_{sc} \times \frac{S}{S_{ref}} (1 + a \Delta T) \]  
(13)

\[ V'_{oc} = V_{oc} (1 - c \Delta T) (1 + b \Delta S) \]  
(14)

\[ I'_{m} = I_{m} \times \frac{S}{S_{ref}} (1 + a \Delta T) \]  
(15)

\[ V'_{m} = V_{m} (1 - c \Delta T) (1 + b \Delta S) \]  
(16)
Thereinto: \( m=18, n=10 \); Under standard conditions, \( S_{\text{ref}}=1000\, \text{W/m}^2, T_{\text{ref}}=25\, ^\circ\text{C} \). Formula (9) is established. When the light intensity \( S(\text{W/m}^2) \) and battery temperature \( T(\circ\text{C}) \) are not reference value, it must be consider that the environment condition influence on the PV cell characteristics \cite{7}. \( I_{\text{sc}}, V_{\text{ooc}}, I_{m}^{'}, V_{m}^{'} \) are calculated according to \( I_{\text{sc}}, V_{\text{ooc}}, I_{m}, V_{m} \). In the formula: \( K \) is temperature coefficient of PV cell when the solar radiation intensity changes, Using the typical values \( 0.3\, \circ\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1} \); \( \Delta T \) is difference between the actual battery temperature and reference battery temperature, \( \circ\text{C} \); \( a, b, c \) are constant, recommended value: \( a=0.0025/\circ\text{C}, b=0.5/\circ\text{C}, c=0.00288/\circ\text{C} \) \cite{6}. As we know that influence of light intensity and battery temperature is nonlinear to electrical characteristics of PV array. So we make the linear approximation to Formula (9) - (16).

**SIMULATION MODEL AND OUTPUT CHARACTERISTIC**

Based on the equivalent circuit diagram 1 of PV cells and formula (9) - (16), the simulation module is set up in SIMULINK \cite{7}, As shown in Figure 3. when the environment temperature is \( 25\, ^\circ\text{C} \), then samples of the simulation model through changing the load resistance, so get the output characteristics I - U curve and P-U curve of PV cells under different light intensity, As shown in Figure 4 and Figure 5.

Maintain a constant light intensity \( S=1000\, \text{W/m}^2 \), then samples of the simulation model through changing the load resistance, so get the output characteristics I - U curve of PV cells under different temperature, As shown in Figure 6.

![Figure 5. P-U characteristic curve of PV cells array under different light intensity.](image1)

![Figure 6. I-U characteristic curve of PV cells array under different temperature.](image2)
CONCLUSIONS

By analyzing the working principle of solar PV cells, Engineering mathematics model of PV cells array is put forward, The simulation mathematical model is set up in Simulink, model is simulated Under the condition of different illumination intensity and different temperature. The simulation data were compared with the measured data, So we can draw a conclusion that Engineering mathematics model of PV cells array is accurate, it provide theoretical and technical support for design and performance analysis parallel operation.

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