Research of the Model and MPPT Algorithm of solar cells

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Abstract. According to the mathematic model of solar cells, builds its general simulation model based on the S-function designed under the Matlab/Simulink environment. Presents the incremental conductance algorithm based on the optimal gradient to simulate and verify the theories about the maximum power point tracking (MPPT) of photovoltaic power generation. Give the in-depth contrast analysis on the power, output voltage characteristics of photovoltaic power generation, which lays a solid foundation for engineering practice.

Introduction
Solar energy is an inexhaustible and ideal energy of human being. However, there have many uncertain natural conditions which may affect perpendicular incidence of sun to earth. Sunlight is an unpredictable even random energy, so solar cells can’t work at the maximum power point spontaneously. Currently, the power generation efficiency of solar cells is mainly promoted by controlling their output voltage. Literature [1] establishes the simplified model of solar cells, which MPPT algorithm is not given and lack of parameter comparison with actual solar cell model. So it can’t reflect the output characteristic of solar cells accurately; Literature [2] establishes the model according to parameters of solar cells which give linear approximation to non-linear influence of solar radiation intensity and temperature on solar cell arrays and still can’t conform to actual conditions completely, although the model parameters are optimized under different sunlight conditions.

When building the model of solar cells, it must consider the sunlight intensity and ambient temperature to ensure its generality and make it apply to dynamic simulation of various solar cells. Under Matlab/Simulink environment and adopting S-function, this project builds the general model of solar cells based on the DC physical model of solar cells. The computer simulation is conducted by combining with parameters of actual photovoltaic module, so as to reflect the output characteristics of the solar cells accurately. Then, synthesizes the constant voltage method and incremental conductance method based on optimal gradient to make solar cells working rapidly near the maximum power point and resolves the insufficiency of traditional MPPT algorithm with fixed step size.

The Characteristic Analysis and Mathematical Model of Solar Cell
The working principle of solar cells root in photovoltaic effect, namely the charge distribution in object may change and the electromotive force and current are caused when the object suffers sunlight. The equivalent circuit is shown in Fig. 1.
The expression based on the physical principle of solar cell is shown in formula (1) [3]:

$$I = I_{ph} - I_{bk} \exp\left[\frac{q(V + R_I)}{nKT} - 1\right] \frac{V + R_I}{R_{sh}}$$  \hspace{1cm} (1)

**Remark:** $I$ refers to the working current; $V$ refers to the working voltage; $I_{ph}$ refers to the photo-generated current; $I_{bk}$ refers to the saturation current of diode; $q$ refers to the electric charge quantity of electron ($1.6 \times 10^{-19}$ C); $R_s$ refers to the series resistance of solar cell; $n$ refers to the characteristic factor of diode; $K$ refers to the Boltzmann constant ($1.38 \times 10^{-23}$ J/K); $T$ refers to the absolute temperature of solar cell; $R_{sh}$ refers to the parallel resistance of solar cell.

Approximate the current can be obtained by giving the iterative computation to formula (1) with Newton-Laphson method, and then the model can be established. By considering the influences of sunlight intensity and temperature change on solar cell, the general engineering equation, namely formula (2), proved in practice, can be used as the mathematical model of solar cell [4]:

$$I = I_m(1 - C_1(e^{U_m / I_m} - 1)) + DI$$  \hspace{1cm} (2)

In which,

$$C_1 = (1 - I_m / I_{oc}) e^{-\frac{U_m}{I_{oc}}}$$  \hspace{1cm} (3)

$$C_2 = (U_m / U_{oc} - 1) / \ln(1 - I_m / I_{oc})$$  \hspace{1cm} (4)

$$DI = \frac{\alpha \cdot R}{R_{ref} \cdot DT} + \frac{R}{R_{ref} \cdot 1} \cdot I_{oc}$$  \hspace{1cm} (5)

$$DU = -\beta \cdot DT - R_s \cdot DI$$  \hspace{1cm} (6)

$$DT = T - T_{ref}$$  \hspace{1cm} (7)

$$T = T_a - t_c \cdot R$$  \hspace{1cm} (8)

**Remark:** $U_{oc}$ and $I_{oc}$ refer to the open circuit voltage and short circuit current respectively; $U_m$ and $I_m$ refer to the output voltage and current at the maximum power point respectively; $U$ and $I$ refer to the current output voltage and corresponding output current respectively; $R_{ref}$ and $T_{ref}$ refer to the reference values of solar radiation and solar cell temperature respectively and take 1kw/m$^2$ and 25°C as ordinary; $\alpha$ refers to the current-temperature coefficient (Amps/°C) under reference sunlight; $\beta$ refers to the voltage-temperature coefficient (V/°C); $R_s$ refers to the series resistance of photovoltaic module; $T_a$ and $t_c$ refer to the random ambient temperature and temperature coefficient of solar cell modules (degw$^{-1}$m$^2$) respectively.

**The Model Simulation of Solar Cell**

The simulation model of solar cell is presented based on Matlab S-function by combining with formula (8). In which, $R$ and $T$ refer to the current solar radiation intensity and temperature respectively; $U$ refers to the current working voltage of solar cell, and $PV+$ and $PV-$ refer to the positive pole and negative pole respectively. By taking the 250P-24 poly-silicon modules of LDK
solar cells as reference, the simulation parameters can be set as following: the open circuit voltage \( U_{oc} = 44.1 \text{V} \), the short circuit current \( I_{sc} = 8.02 \text{A} \), the maximum power point voltage \( U_m = 35.9 \text{V} \) and the maximum power point current \( I_m = 6.96 \text{A} \).

Suppose that the current sunlight intensity is standard \( R = 1 \text{kw/m}^2 \), and the temperature is \( T = 25^\circ \text{C} \). The simulation results are as following: the output voltage and current at the maximum power point are \( U_m = 35.9 \text{V} \) and \( I_m = 6.95 \text{A} \) respectively, which are basically conform to the parameters of actual module and proved that the model can well reflect the output characteristics of the module selected. Suppose the ambient temperature is \( 25^\circ \text{C} \), the characteristic curves of the output current/voltage and power/voltage under different sunlight intensity \( R \) are shown in Fig. 2.

![Fig. 2 a) I/U characteristic curve b) P/U characteristic curve](image1)

Suppose the standard sunlight intensity \( R \) is \( 1 \text{kw/m}^2 \), the characteristic curves of the output current/voltage and power/voltage under different ambient temperature \( T \) are shown in Fig. 3.

![Fig 3 a) I/U characteristic curve b) P/U characteristic curve](image2)

Research of the MPPT Algorithm

The MPPT algorithms for solar cells used frequently include constant voltage method, perturbation observation method, curve fitting method, single cycle control method, incremental conductance method, the optimal gradient method and so on. The purpose of MPPT for solar cells is to obtain the maximum value of each curve on the P/U characteristic curves shown in figure 2 and figure 3. Literature [5] gives the detailed analysis of the advantages and disadvantages of various MPPT methods; Literature [6] puts forward the mode of single cycle control method combining with perturbation observation; Literature [7] offers the mode of short circuit current proportionality coefficient method combining with perturbation observation; Literature [8] adopts the MPPT method based on secondary interpolation. The constant voltage method ignores the influence of junction temperature on the output voltage of solar cells, and the tracking effect is worse in area with greater temperature difference. The perturbation observation method has the advantages of simple tracking, easy realization, lower accuracy requirements to sensor, simple structure and few perturbation parameters. But the disadvantages are the output power can only vibrate near the maximum power point of solar cells, the tracking step size can’t satisfy the requirements of fast response & high tracking accuracy simultaneously, and the misjudgment will appear under the condition of severe sunlight change. The incremental conductance method is applicable to occasion with rapid change of sunlight intensity, but the realization is relative complex, and it has higher requirements to current sampling sensitivity, microprocessor speed and sensor accuracy. Similarly, the incremental conductance method has the same problem as the perturbation observation method,
which step size is also constant. The overlong step size may lead to aggravate the system oscillation, while the too short step size may make the system in searching phase at low power long time with poor real-time and efficiency. The optimal gradient method is the numerical method for multi-dimensional unconstrained optimal problems based on gradient. As the terminal voltage of solar cells is bounded, the maximum power point searched by applying the gradient will be global origin certainly. Therefore, this project presents the incremental conductance method based on the optimal gradient, which can change the step size dynamically and consider the tracking accuracy & response speed of MPPT simultaneously. The new MPPT algorithm can track the maximum power point of solar cells in real time and resolve the problem of low efficiency because of the improper setting of fixed step size [9].

Suppose that the positive gradient is \( g_k \), the iterative algorithm of gradient method can be defined as:

\[
X_{k+1} = X_k + a_k g_k
\]  

(9)

In which, \( a_k \) is one positive constant, and the maximum value of function searching always faces the direction of the positive gradient \( g_k \).

According to the electrical characteristics of solar cells, ignores the series resistance to express the optimal gradient better, so the relation between the output power \( P \) and the output voltage \( U \) of solar cells can be obtained from formula (2):

\[
P_{PV} = U_i (I_{sc} - I_0 e^{-\frac{qU_{pv}}{AKT}})
\]  

(10)

In which, \( P_{pv} \) is the first-order continuous derivable non-linear function, the output voltage \( U_{o,pv} \) of solar cells is taken as the unique variable, and its related gradient can be calculated:

\[
g_k = g(U_i) = \left. \frac{dP_{pv}}{dU_{o,pv}} \right|_{U_i} \bigg|_{U_{o,pv}=U_i} = (I_{sc} - I_0 e^{-\frac{qU_{pv}}{AKT}} - I_0 \frac{qU_{PV}}{AKT} \frac{e^{-\frac{qU_{PV}}{AKT}}}{U_{o,pv}}) \bigg|_{U_{o,pv}=U_i}
\]  

(11)

Considering the formulas (9) and (11), the iteration arithmetic formula of voltage based on optimal gradient is obtained:

\[
U_{o,PV|k+1} = U_{o,PV|k} + a_k g_k
\]  

(12)

Suppose the the maximum power point voltage of solar cell is \( U_m \), the following formula can be obtained from \( P=UI \):

\[
\frac{dP}{dU} = I + U \frac{dl}{dU}
\]  

(13)

When \( dP/dU>0 \), then \( U< U_m \) and \( dl/dU>-I/U \); when \( dP/dU<0 \), then \( U> U_m \) and \( dl/dU<-I/U \); when \( dP/dU=0 \), then \( U= U_m \) and \( dl/dU=-I/U \). If \( dU=0 \) and \( dl=0 \), it is just the maximum power point, and the working point is not necessary to be adjusted. If \( dU=0 \) and \( dl \neq 0 \), the reference voltage \( U_{o,PV|k} \) shall be adjusted according to the positive and negative of dl. If \( dU \neq 0 \), the working point voltage shall be adjusted according to the relation between \( dl/dU \) and \(-I/U\) to realize the MPPT.

The output voltage of the maximum power of solar cells is about 75% of the open circuit voltage \( U_{oc} \). If the output voltage of solar cells is set to 75% of \( U_{oc} \) directly at the time of system starting, the working point will be near the maximum power point instantly. Then the system could switch to the incremental conductance method based on the optimal gradient for MPPT automatically and it can improve the stable state speed effectively. The flowchart of the MPPT algorithm is shown in Fig. 4.
In which, $|dP_k|<\varepsilon_1$, $|dU_k|<\varepsilon_2$ and $|dI_k|<\varepsilon_3$ mean that they are approximately equal to zero respectively. If $dP_k=dU_k=dI_k=0$ or $\Delta G=G$ is satisfied that the output of solar cells is just at the maximum power point. Otherwise, it shall judge whether the working point voltage according to the relation between $\Delta G$ and $G$. If $dU_k=0$ and $dI_k\neq0$, it shall increase or decrease the working point voltage respectively to reach the maximum power point based on $dI_k>0$ or not.

Obviously, when the working point is located at the left side of the maximum power point, the system shall increase the working point voltage, and decrease the working point voltage conversely. When the working point is close to the maximum power point, it shall be stable in very small range for the extremely small slope and taken as the maximum power point. The simulation model using boost conversion topological structure [10] for MPPT is shown in Fig. 5.

The simulation results on the MPPT algorithm presented in this project can be obtained: when the solar cell temperature is equal to 25°C and the sunlight intensity $R$ increases from 0.9kw/m² to 1kw/m², the P/T and P/V characteristic curves are shown in Fig. 6 and Fig. 7 respectively.
When the sunlight intensity is equal to 1kw/m² and the solar cell temperature $T$ rises from 25°C to 35°C, the $P/T$ and $P/V$ characteristic curves are shown in Fig.8 and Fig.9 respectively.

The following simulation results can be seen from figure 7-9: the maximum power point of the system increases from 221W to 250W along with the increment of sunlight intensity, and it decreases from 250W to 230W along with the increment of temperature, while the system can be stable at the maximum power point from beginning to the end.

Conclusions

Considering the influences of the sunlight intensity and temperature on solar cell, the engineering model of solar cell is presented based on S-function under Matlab/Simulink environment. The consistency verifications are implemented through comparing the I/U and P/U characteristics of the engineering model with the actual solar cells. By aiming at the limitations of the current MPPT algorithms, one new incremental conductance method based on optimal gradient and constant voltage is presented. It can change the step size of MPPT algorithm dynamically based on the optimal gradient, which takes account of the tracking accuracy and response speed of MPPT simultaneously. The new MPPT algorithm can track the maximum power point of solar cells in real time and resolve the problem of low efficiency because of the improper setting of fixed step size verified by the computer simulation based on one boost conversion topological structure.

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