MPPT-based Photovoltaic Power Generation Techniques

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Abstract. A Matlab/Simulink photovoltaic array model and a MPTT controller simulation model are built after making clear the principles and characteristics of photovoltaic power generation. The conductance increment method for photovoltaic power generation is utilized for the maximum power point tracking. The fuzzy control technique is applied to improve the control accuracy, reduce fluctuation of the output power of photovoltaic cells and achieve the optimum control of maximum power point tracking. This is of great significance for enhancing the photoelectric conversion efficiency.

Introduction

Currently solar energy is one of the rapidly growing new energy sources. Many countries in the world are doing research on photovoltaic (PV) power generation technologies and the PV industry has become part of the new energy industries. In 2017, the new increase of installed capacity of PV power generation in China is 53 million kW, which means a year-on-year increase of more than 50% and hits a record high for five consecutive years. It is estimated that the proportion of PV power generation in the world’s electricity production will be around 1% in 2020 and 25% in 2050\textsuperscript{[1,2]}. To improve the efficiency of independent PV power generation systems, the key technique is the Maximum Power Point Tracking (MPPT). MPPT algorithms mainly include: constant voltage, perturb and observe, conductance increment, fuzzy control, neutral networks, genetic algorithm and new algorithms formed by combination of the aforesaid algorithms. The essence of these algorithms is to ensure that the solar battery operates at the maximum power point by controlling the operating voltage. With the development of modern control theories, the theory of artificial intelligence is applied in the field of industrial control. Fuzzy control, neural networks and genetic algorithm of PV power generation systems are intelligent algorithms\textsuperscript{[3-5]}. In this paper, the MPTT-based conductance increment method and the fuzzy control technique are employed to reduce the fluctuation of power output and obtain higher energy conversion efficiency, which is important for the ease of energy crisis and the environmental protection.

Working Principle and Characteristics of Solar battery

A solar battery is a semiconductor device that can directly convert the solar radiant energy into the electrical energy. The photovoltaic effect refers to the effect of voltage generated at \textit{P-N} junction by the solar battery through absorbing a certain amount of solar radiant energy after exposure to sunlight. Its principle is shown in Fig.1. In the figure, $h$ denotes the Planck constant, $v$ is the electromagnetic radiation frequency, $hv$ represents the photon energy, $E_F$ means the Fermi level, and $E_g$ is the band gap energy. The solar battery works in three processes: (1) it absorbs the photon energy when exposed to sunlight, and if $hv \geq E_g$, photons will excite non-equilibrium electron-hole pairs; (2) acted by the built-in electric field pointing from \textit{N} region to \textit{P} region, non-equilibrium electron-hole pairs move...
from the generation region to the built-in electric field region by diffusion or drifting; (3) the separation of non-equilibrium electron-hole pairs occurs in the built-in electric field and finally generates a photo-electromotive force in a different direction with that in the built-in electric field.

**Solar battery Characteristics and Model**

A photovoltaic cell is a device that converts light energy into electrical energy. Its basic working principle is the photovoltaic effect. The output of photovoltaic cells is non-linear and largely influenced by external environmental factors such as light intensity and temperature. The equivalent model of the photovoltaic cell is shown in Fig.2. The photovoltaic cell is equivalent to a current source and a diode in parallel, plus a parallel resistance and a series resistance.

The mathematical model of photovoltaic cell:

\[ I_{pv} = I_{ph} - I_d - I_{sh} \]  

(1)

Here: \( I_{pv} \) is the output current for the photovoltaic cell; \( I_{ph} \) is the photo-generated current; \( I_d \) is the current flowing through the parallel diode; \( I_{sh} \) is the current flowing through the parallel resistor \( R_{sh} \) of the photovoltaic cell. The current \( I_d \) flowing through the diode is related to the reverse saturation current of the diode as follows:

\[ I_d = I_0 \left\{ \exp \left[ \frac{q(U_{pv} + I_{pv}R_s)}{nKT} \right] - 1 \right\} \]  

(2)

Here: \( q \) is the electronic charge constant; \( U_{pv} \) is the voltage at both load ends of the photovoltaic cell output; \( R_s \) is the series internal resistance of the photovoltaic cell; \( U_{pv} + I_{pv}R_s \) is the voltage at both ends of the diode; \( n \) is the diode factor; \( K \) is the Boltzmann constant; \( T \) is the Kelvin temperature.

In order to facilitate the derivation of the mathematical model of photovoltaic cell, according to the circuit of Fig.1, the current of the parallel resistance and the output current of photovoltaic cell can be obtained. The two intermediate quantities \( C_1 \) and \( C_2 \) are introduced, \( C_1I_{pv} = I_0, \ C_2 = nKT/q \).

\( I_{sc} \) is the short-circuit current of photovoltaic cell. To simplify the calculation, assume that \( I_{sc} \approx I_{ph} \).

The current \( I_{sh} \) flowing through the parallel resistance is much smaller than the photo-generated current \( I_{ph} \), which can be ignored. The series resistance \( R_s \) and its voltage can be ignored because they are too small. The output current of photovoltaic cell is:

\[ I_{pv} = I_{sc} \left\{ 1 - C_1 \left[ \exp \left( \frac{U_{pv}}{C_2U_{oc}} \right) \right] - 1 \right\} \]  

(3)
Here: $U_{oc}$ is the open circuit voltage of photovoltaic cell. A solar battery is a device that converts light energy into electrical energy through the “photovoltaic” effect. It is composed of single solar cells. A single solar cell is generally sized $4 \sim 100cm^2$ with the operating voltage of around $0.45 \sim 0.5V$ and the operating current of around $20 \sim 25mA$.

In order to generate electrical energy, a solar battery must satisfy the following conditions: (1) exposure to sunlight; (2) ability to form stable electron-hole pairs when photons are injected into the semiconductor; (3) an electrostatic field, under the action of which the electron-hole pairs after separation can be concentrated to the two poles to form a photo-generated electric field; (4) a load is applied between the two poles to form a certain amount of current, thereby obtaining electric energy. If the two poles are shorted by wires, a current proportional to the sunlight can be formed, which is the short-circuit current; when the wire is disconnected, the potential difference of the electrons and holes entering the two poles is the open circuit voltage. A number of solar cells are connected in series and in parallel and packaged into a module, which may generate the certain voltage and current for use in PV power generation systems [6,7].

Simulink Simulation of Off-Grid Photovoltaic Array Power Generation System

An off-grid photovoltaic power generation system generally consists of photovoltaic array, DC/DC converter, lead-acid battery pack, inverter and load. Because there is no parallel connection with the power grid, the battery pack is required to store the excess power generated by the photovoltaic array. When there is no sunlight or insufficient light, the battery discharge complements the load supply. The basic PV power generation system includes solar panels, DC-DC converter circuit, MPPT controller, PWM pulse generator and load. The MPPT controller collects the current and voltage outputted by PV cells, calculates the amount of voltage or duty cycle that needs to be adjusted and sends it to the PWM signal generating circuit to output a corresponding pulse control chopper circuit.

The photovoltaic array is the basic component of the solar photovoltaic power generation system. Its $I-V$ and $P-V$ characteristics have nonlinear relations because of the influence by solar light intensity, battery temperature and battery $PN$ junction parameters. Given that the output voltage and current of a single photovoltaic cell are small, in order to achieve the desired output characteristics, single photovoltaic cells are typically combined in series and parallel to form a photovoltaic array. The photovoltaic array is composed of a number of photovoltaic cell modules in series and in parallel, and each photovoltaic cell module comprises a number of photovoltaic cells in series and in parallel. The currently utilized photovoltaic cell models mainly include physical equivalent models and engineering practical models [7-9]. The physical equivalent models are built according as the physical characteristics of photovoltaic cells, mainly including single exponential model and double-exponential model. The single exponential model means that the equivalent circuit of PV cell contains a diode. This type of model is suitable for the modeling of crystalline silicon photovoltaic cells; the single exponential model can also be appropriately simplified as needed. The engineering practical models utilize the technical parameters provided by the photovoltaic cell supplier, such as: short-circuit current of photovoltaic cell $I_{sc}$, open circuit voltage of photovoltaic cell $V_{oc}$, maximum power point current $I_m$, maximum power point voltage $V_m$ and maximum power $P_m$, etc., and the photo-generated current value $I_{phc}$ is determined by the following equation:

$$I_{phc} = \left[ I_{scr} + C_{Tc} \left( T_{cell} - T_{ref} \right) \right] \frac{G}{G_{ref}}$$  \hspace{1cm} (4)

Here: $I_{scr}$ is the short-circuit current of photovoltaic cell measured under reference conditions; $T_{cell}$ is the absolute temperature of photovoltaic cell; $G$ is the light intensity; $C_{Tc}$ is the temperature coefficient of short-circuit current of photovoltaic cell (A/K); the reference conditions are $T_{cell} = 298K$ and $G = 1000W/m^2$, and the power of the load resistance is:
\[
P_0 = I^2R_0 = R_0 \left( \frac{U_i}{R_i + R_0} \right)^2
\]

(5)

Find the derivative of Eq.(5). The output power becomes largest when \( R_0 = R_i \) and the derivative is 0. Therefore, by adjusting the external resistance, the maximum power can be obtained. When the influencing factors remain unchanged, such as sunlight and temperature, the PV cell can be regarded as a power source with constant internal resistance. The chopper circuit can change the load characteristics of the external circuit to obtain the maximum output power of photovoltaic cell.

The boost chopper circuit in Fig.3 is used. Its basic working principle is when \( V \) is open, the output voltage \( u_i \) of the power source \( E \) charges to the inductance, with the charge current \( i_l \). No current flows through the diode \( VD \). The load \( R \) is charged by the capacitance \( C \). Assume that \( C \) is large enough, the voltage at both ends of the load keeps at \( u_0 \). Set the on-state time of one switching cycle as \( t_{on} \), then the energy accumulated in the inductance in the on-state time is \( u_i l_i t_{on} \); when \( V \) is closed, the current on the inductance \( L \) cannot abruptly change. The diode \( VD \) is conducting and the inductance \( L \) supplies energy to the load and charges the capacitance \( C \). Set the off-state time of one switching cycle as \( t_{off} \), the energy released by the inductance in one off-state time is \( (u_0 - u_i) l_i t_{off} \). When the boost chopper circuit runs in a steady state, the energy absorbed and released by the inductance \( L \) is equal in one cycle, then we have \( u_i l_i t_{on} = (u_0 - u_i) l_i t_{off} \), which can be converted into:

\[
u_0 = u_i / (1 - D)
\]

where: \( D \) is the duty cycle, \( D = t_{on} / (t_{on} + t_{off}) \). The duty cycle is greater than 0 and less than 1, then the voltage at the output load end is raised. The capacitance keeps the load end voltage in the on-state and the inductance \( L \) raises the load-end voltage in the off-state, so the average value of the output voltage increases and realizes the effect of boosting voltage. From the perspective of tracking the maximum power of photovoltaic cell, the DC-DC converter circuit changes the output voltage and the output current, thereby changing the output impedance. When the output impedance matches the internal resistance, the photovoltaic cell operates at the maximum power point and achieves the effect of tracking the maximum power.

Fig.3 Boost chopper circuit

The simulation model of the photovoltaic power generation system is shown in Fig.4, where the inductance \( L = 10mH \), the capacitance \( C = 300mF \) and load resistance \( R = 10\Omega \). A correlation analysis is made for the output characteristic curves of the photovoltaic array obtained by simulation. The maximum power tracking of the photovoltaic array is realized based on the conductance increment method and the boost chopper circuit design. The photovoltaic array of the PV power generation system can convert the light energy into DC electrical energy, which is converted to be AC power through the boost circuit controlled by the MPPT controller and passing the DC/AC photovoltaic inverter controlled by the control strategy. The power is supplied through filter and isolation transformer.
In order to test \( I-V \) and \( P-V \) characteristics of the photovoltaic array, the voltage increases continuously due to the charging of photovoltaic cell, and the terminal voltage of photovoltaic cell also constantly increases, so that the characteristic curve of the photovoltaic power generation system of the photovoltaic array can be obtained. The maximum power and the maximum power point voltage of the photovoltaic array can also be obtained through this circuit. The parameters and simulation conditions of the photovoltaic array are set as follows: (1) the number of series and parallel modules in the photovoltaic array \( N_{sr} = 1, N_{pl} = 1 \) and the number of series and parallel photovoltaic cells in each battery module \( N_{csr} = 100, N_{cpl} = 2 \); the temperature input remaining unchanged at 25\(^\circ\)C, the light intensity is taken as \( G = 1000 \text{W/m}^2, 800 \text{W/m}^2, 600 \text{W/m}^2 \) and \( 400 \text{W/m}^2 \), respectively. The simulation results are the curves in Fig.5. The curve in Fig.5(a) shows that when the light intensity and the temperature of photovoltaic cell are constant, the current remains constant over a certain voltage range and the output power increases as the voltage increases; but when the voltage reaches a certain value, the current decreases as the voltage increases, and the output power reaches its maximum at a certain voltage value and then decreases as the voltage increases. In addition, Fig.5(b) indicates that: when the temperature is constant, the maximum output current and the maximum output power of the photovoltaic cell are positively correlated with the light intensity, that is, the greater the light intensity, the higher the maximum output current and the maximum output power of the photovoltaic cell.

**Output Maximum Power Tracking Technique of Photovoltaic Array**

The voltage and current of the photovoltaic array have a nonlinear relation, which can influence the output power of the photovoltaic array under different light intensities, temperatures or the factors of component aging and optoelectronic materials. The \( P-V \) characteristic curve in Fig.5 shows that each working curve has only one maximum power point, which is the optimal operating point of the photovoltaic array. Therefore, in order to make full use of the solar energy, a control strategy is required to enable the maximum power absorbed from the photovoltaic array in various working environments, that is to say, the so-called maximum power point tracking (MPPT). Currently the most commonly used MPPT algorithms include constant voltage tracking, power signal feedback,
perturb and observe, duty cycle perturbation, conductance increment method and other artificial intelligence algorithms [10-12]. In this paper, the conductance increment method is used to track the maximum power point.

**Conductance Increment Principle and MPPT Algorithm**

The MPPT process is essentially an optimization process that controls the photovoltaic array voltage for controlling output of the maximum power. The $P-V$ characteristic curve of the output power of photovoltaic array indicates the maximum output power and the maximum power point voltage of photovoltaic cell. In the figure, when the photovoltaic array operates on the left side of $U_{\text{max}}$, the active output of photovoltaic cells increases as the photovoltaic array voltage increases; when the photovoltaic array operates on the right side of $U_{\text{max}}$, the active output of photovoltaic cells decreases as the photovoltaic array voltage increases.

The MPPT control is realized by adopting the conductance increment method. In the conductance increment method, the derivative of the photovoltaic cell output curve $\frac{dP}{dU}$ at the maximum power point is 0, so the following conclusions can be drawn: (1) when $\frac{dP}{dU} = 0$, the operating point is at the maximum power point; (2) when $\frac{dP}{dU} > 0$, the operating point is on the left side of the maximum power point; (3) when $\frac{dP}{dU} < 0$, the operating point is on the right side of the maximum power point. The value of $\frac{dP}{dU}$ is approximated by subtracting the value obtained at the previous sampling time from the value of the current sampling time, that is, replaced by $\frac{\Delta P}{\Delta U}$. Change of the operating point voltage requires the change of the duty cycle $D$ of the boost chopper circuit, which means that the control quantity output by the MPPT algorithm is the duty cycle change $\Delta D$ and that the larger the duty cycle, the larger the output voltage. In the conductance increment method, the positivity and negativity of the ratio of power change to voltage change are used to judge the position of the operating point, and then determine the direction of voltage change. Since both multiplication and division have the same like-sign property, the multiplication is utilized for judgment. The flow chart of the conductance increment method is shown in Fig.6.

![Fig.6 Flow chart of conductance increment method](image)

**Maximum Power Tracking Control Technique**

In order to output the maximum power of the photovoltaic array, the terminal voltage of the photovoltaic array must be controlled at the maximum power point voltage. The maximum power point tracking can be realized in two parts: (1) sampling the output voltage and current of the
photovoltaic array and using the conductance increment method to obtain the reference voltage value \( V_{in\_ref} \) of the maximum power point; (2) using the boost chopper circuit to control the output terminal voltage of the photovoltaic array to track the reference voltage value \( V_{in\_ref} \) at the maximum power point. The output terminal voltage of the boost chopper circuit can remain constant by the controller design. Therefore, the input terminal voltage can be changed by adjusting the duty cycle, and the output power of photovoltaic array can be controlled by controlling the terminal voltage of photovoltaic cell. To reduce the fluctuation of the photovoltaic cell terminal voltage, a capacitance \( C_1 \) is added at the output terminal of the basic boost chopper circuit, as shown in Fig.7. Under the same conditions, the fuzzy control based MPPT conductance increment algorithm for PV power generation has a better maximum power tracking effect and can quickly re-track to the maximum power point in the case of sudden change of sunlight. The improved algorithm can output more stable power at the maximum power point.

Charging Control Method and Energy Management

In an independent PV power generation system, the energy storage is a crucial part of the system. In the battery energy management, residual capacity prediction and charging control are core contents. The conventional charging methods include constant voltage charging and constant current charging. Because the characteristics of battery are not considered, the charging characteristic curve of the battery is not conformed and the overcharging and gassing is easily caused and results in a short battery life and a low charging efficiency. The PWM charging mode protects the battery to a certain extent, reduces the amount of gassing and can adjust the charging current of battery by controlling the duty cycle, thereby improving the charging efficiency.

Currently in terms of residual capacity estimation, the State of Charge (SOC) is widely applied at home and abroad to indicate the residual capacity of battery \([13, 14]\). Based on the stage charging strategy of battery, combined with the characteristics of the PV system, in line with the maximum power tracking control of photovoltaic array, a charging method is proposed by integrating the maximum power tracing charging with the stage charging. The maximum power tracking charging analyzes the output characteristics of photovoltaic power generation and adjusts its operating point so that the output power is maintained at the maximum state. This process is called the maximum power tracking. If batteries are charged by this method, the PV charging control system efficiency can be improved to achieve the full utilization of the solar power generation energy \([15, 16]\). The charging control method is the core of the independent photovoltaic power generation system controller and it has a direct bearing on the service life of battery in the independent photovoltaic power generation system and the working efficiency of the system.

Conclusions

In this paper, the equivalent circuit and mathematical model of photovoltaic cell are studied. Based on the MPPT conductance increment control algorithm of photovoltaic power generation, the
simulation model of a photovoltaic power generation system is built in Matlab/Simulink. The input quantity is the change of output voltage and output power of photovoltaic cell. The output quantity is the adjustment to the duty cycle of the boost chopper circuit. The results indicate that the fuzzy control algorithm of conductance increment control can track the maximum power in a real time manner under different external conditions. The step size can be gradually reduced when approaching the maximum power point through software, and finally the duty cycle is stabilized at a fixed value. This can reduce the fluctuation of the photovoltaic cell output power and obtains higher photoelectric conversion efficiency.

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