Simulation Study on the Tracking Technology of the Maximal Power Point of the Solar Photovoltaic Based on the Model Predictive Control

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Abstract

The solar photovoltaic battery is a new type of renewable distributed energy's important part of the key research development at home and abroad, but its output power is directly affected by light intensity and temperature, voltage-current characteristics have obvious nonlinear features. Therefore, a new MPPT technology based on model predictive control (MPC) is proposed in this paper, the simulation results show that the method can quickly track the maximum power point under the current environmental conditions, and improve the energy conversion efficiency of the system.

Keywords: Photovoltaic cell; Maximum power point tracking; Solar energy; Matlab/Simulink;

1. Introduction

Currently the survival of humanity is inseparable from the use of energy. Along with the increasing depletion of non-renewable energy, development of renewable energy has become the theme of today's world. Solar energy as a clean and renewable energy attracts the people's attention. That photovoltaic cells convert solar energy into electricity by some way is called as photovoltaic. Because of its affection of environment and the load, and consideration of the input and output characteristics of nonlinear, this paper presents the maximum power point tracking (MPPT) principles and methods, mentions several MPPT method, and compare the advantages and disadvantages of the algorithm .

2. MODELING THE SOLAR CELL

Photovoltaic cell is the device that can convert the sun light into electricity using the photovoltaic effect. The critical element of a photovoltaic cell is a semiconductor diode that P-N junction is exposed to light. The incidence of light on the cell is generates charge carrier that originate an electric current if the cell is short-circuited [1]. Charge are generated when the energy of the incident photon is sufficient to detach the covalent electrons of the semiconductor, and this phenomenon depends on the semiconductor material and the wavelength of the incident light. Basically, the PV phenomenon may be described as the absorption of solar radiation, the generation and transport of free carriers at the p–n junction, and the collection of these electric charges at the terminals of the photovoltaic device [2]. If the terminal of cell is connected with external load, electrons flow through it which is cause of current in the circuit. The commonly accepted solar cell model is a one diode model [3],which is shown in Fig. 1.This Photovoltaic cell model is a nonlinear device and can be represent as a current source model. The output of the current source is directly dependent on the solar irradiance and the ambient temperature. The I-V characteristics of a photovoltaic cell is similar to diodes characteristic, and which is represent by the following equation [2] [3] [4]:

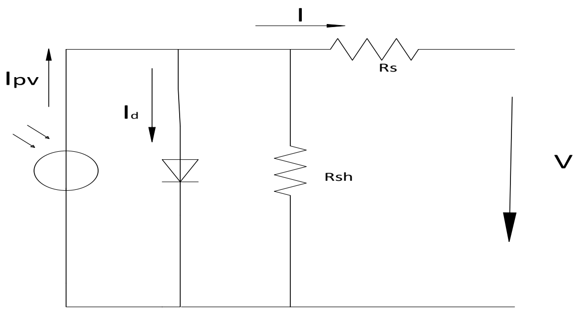

Fig. 1. The circuit diagram of the photovoltaic cell.

$$I = I_{pv,cell} - I_{o,cell}\left(\exp\left(\frac{qV}{aKT}\right) - 1\right) \quad (1)$$

Actually, we care more about photovoltaic arrays, instead of a single cell. In each array, cells connected in parallel increase current and cells connected in series provide greater output voltages. And if there have parallel connection of cells in array, the photovoltaic and saturation current can be expressed as $I_{pv} = N_p I_{pv,cell}, I_o = N_p I_{o,cell}$ .Also the characteristic of photovoltaic arrays can be mathematically described as:

$$I = I_{pv} - I_o\left\{\exp\left(\frac{q(V_o + IR_s)}{aN_s KT}\right) - 1\right\} - \frac{V_o + IR}{R_{sh}} \quad (2)$$

$$I_{pv} = \left(I_{pv,\mathrm{nom}} + K_i \Delta_T\right)\frac{G}{G_{nom}} \quad (3)$$

$$I_o = I_{o,nom}\left(\frac{T_{nom}}{T}\right)^3 \exp\left[\frac{qE_g}{aK}\left(\frac{1}{T_{nom}} - \frac{1}{T}\right)\right] \quad (4)$$

$$I_{pv,nom} = I_{SC}\frac{R_{sh} + R_s}{R_{sh}} \quad (5)$$

$$I_{o,nom} = \frac{I_{SC}}{\exp\left(\frac{V_{OC}}{aV_{t,nom}}\right) - 1} \quad (6)$$

whereand are the output current and voltage of the photovoltaic cell, respectively, is the generated current under a given in solution, is the reverse saturation current, is the charge of an electron (value is), is the Boltzmann's constant (value is), is the ideality factor(usually, and the choice depends on other parameters of the *I-V* model. And here is taken as 1), T is the temperature (in Kelin) of the p-n junction of photovoltaic cell, is the number of photovoltaic cell for each array, is the internal series resistance, is the internal shunt resistance of the photovoltaic cell, is the light-generated current at the nominal situation , is the difference between actual and nominal temperature, is the short circuit current/temperature coefficient, G is the irradiation on the device surface, is the nominal irradiation, is the band gap energy of the semiconductor, and is the thermal voltage of photovoltaic array at the nominal temperature .

The equation (2-2) have a wide application in theoretical analysis of photovoltaic cell. But it is not suitable for engineering application, due to the parameters,, K, and are relative to the solar irradiance and the ambient temperature, and the value of them is hard to determined. Consider that the value of is very small, but is very large. So we can approximately see $(V_o + I_o R_s)/R_{sh}$equal to zero [4]. Also there have other parameters are very important to photovoltaic arrays, such as Open Circuit Voltage, Open Circuit Current , Maximum Power Voltage, Maximum Power Current, and Maximum Power. And the normalized value (work at standard test condition, namely, 25 and $1000\,w/m^2$) of them are provided by manufactures. For example, the Solarex MSX60, a typical 60W photovoltaic module, it parameter as the table 1 described [3].

Table.1.The parameters of the Solarex MSX60 photovoltaic panel

At temperature	**T**	**25**	
Open Circuit Voltage		21.0	V
Short Circuit Current		3.74	A
Maximum Power Voltage		17.1	V
Maximum Power Current		3.5	A
Maximum Power		59.9	W

For the purpose of efficiency and stability, a maximum power point tracker (MPPT) is a power electronic DC-DC converter inserted between the photovoltaic array and its load. By using an intelligent algorithm, it has ability to predict and control the photovoltaic module use the history data of solar irradiance, so it ensure the photovoltaic array always works at its maximum power point as the temperature, insolation and load vary.

3. Maximum Power Point Tracking Algorithms

The operation of photovoltaic array are influenced by solar radiation, temperature and load values. The output power of photovoltaic cell decreasing with the temperature increasing, and increasing with the solar radiation increasing. At a given condition of irradiation and temperature, a photovoltaic cell can work at difference operation point, but there is a unique operation point of the photovoltaic array with maximum output power, that is Maximum power point (MPP). Obviously, it is necessary to take some measure to maintain the photovoltaic array work at MPP, and it also can improve the efficiency of photovoltaic power system. These measures called Maximum Power Point Tracking (MPPT), which draws maximum power from the photovoltaic array regardless of weather or load condition [5]. The principle of maximum power point tracking is through adjusting the load impedance to make the photovoltaic power generation system always work at the near maximum power point, under different environmental condition [6].

Many research papers have produced with various schemes for the MPPT in photovoltaic power generation system. There are many methods of MPPT techniques applied to photovoltaic power system. Such as one cycle control method, feedback voltage and current method, and feedback of power variation with voltage and current [5]. At now the commonly used method about the maximum power point tracking of photovoltaic generation are the constant voltage method (CVT), the perturbation and observation method (P&O) [7], and the incremental conductance method (INC) [8]. Moreover, the fuzzy logic based method could fond in [9] [10] [11]. Among all these methods, due to the poor accuracy, the constant voltage method are not widely applied in industry. And the incremental conductance method (INC) and the perturbation and observation method (P&O) are applied widely. In the next section, we will discuss the two basic MPPT algorithms in detail.

A. Perturbation and Observation method(P&O)

The P&O method maintain the operating point near the maximum power point by a small voltage change ΔV called voltage disturbance signal. At the beginning, it has to measure photovoltaic voltage and current at the moment atmosphere condition, and to calculate the output power P_1. And then periodically increasing (or decreasing) the photovoltaic array voltage, that is $V_2 = V_1 + \Delta V$, and also to calculate the output power P_2.The photovoltaic power P_1 and P_2 are compared, if P_2 is more than P_1, then the perturbation is correct otherwise it should be reversed. This method has major drawback are occasional deviation from the maximum due to its inability to relate the change in the photovoltaic array power to the change in the atmospheric condition. [9]. Moreover, when the MPP is reached, the P&O method will oscillate around it in case of constant or slowly varying atmospheric condition. In order to avoid these, the value of ΔV is very small. The simulation result of this method will be analysis in the next section.

B. Incremental Conductance method (INC)

According to the $\mathrm{P-V}$ characteristic curve, when a photovoltaic array work at maximum power point the slope of $\mathrm{P-V}$ curve is zero, namely $\frac{dv}{dp} = 0$. These relation can further be written as following:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} \quad (7)$$

Namely

$$\frac{dI}{dV} = -\frac{I}{V} \qquad (8)$$

The control strategy of the incremental conductance algorithms can be written in the following simple equations:

$\frac{dI}{dV} > -\frac{I}{V}$, that is $\frac{dI}{dV} > 0$, means $V < V_{\max}$, then $V = V + \Delta V$;

$\frac{dI}{dV} < -\frac{I}{V}$, that is $\frac{dI}{dV} < 0$, means $V > V_{\max}$, then $V = V - \Delta V$;

$\frac{dI}{dV} = -\frac{I}{V}$, that is $\frac{dP}{dV} = 0$, means the photovoltaic array work at maximum power point, and then $V = V$.

Hence, the photovoltaic cell terminal voltage can be adjusted relative to the maximum power point voltage by measuring the incremental (dI/dV) and instantaneous array conductance (I/V) and make use of the mentioned control strategy. In practical application, the incremental are approximated as: $\mathrm{dI} = \mathrm{I} - I_{bef}$ and $\mathrm{dV} = \mathrm{V} - V_{bef}$. Where I_{bef}, V_{bef} are the last time measured value of current and voltage. This method can compare directly the photovoltaic array conductance. It has better track of any changes either in load or photocurrent rather than the perturbation and observation method, but this way of tracking still has some oscillation which cannot be avoided. Also the simulation result of the incremental conductance algorithms will be discussed in next section.

4. Model Predictive Control based Maximum Power Point Tracking

As mentioned above, conventional methods to track the maximum power point the result are not as good as expected, most of them have oscillation and cannot be avoided. We want the output power of photovoltaic array is stable and smooth without oscillation, or the oscillation is small that can be ignored. It is needful to find a new way of tracking to improve the stability of the output power and the conversion efficiency of photovoltaic array. And this paper we consider a model predictive control based MPPT technique applied to photovoltaic module.

Model predictive control (MPC) is widely applied in industrial control with several advantages over the conventional control technique. The main characteristic of model predictive control is predicting the future behavior of the desired control variables until a predefined horizon in time based on the present data of input or output. Also this control variables will be optimized by minimizing a cost function to obtain a satisfying control performance of overall system.

This paper we consider a islanded operation photovoltaic generation system as controlled member, which main consist of a photovoltaic array, a DC-DC boost converter, and a MPC controller as shown in Fig.2.

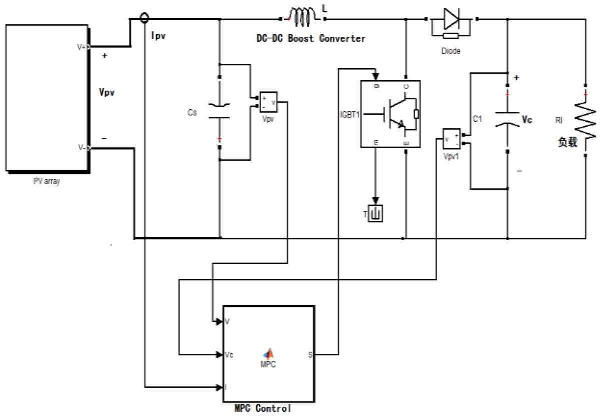

Fig. 2. Control block diagram of overall islanded photovoltaic system configuration implementing MPC based MPPT technique

The photovoltaic array generates electric power directly from solar radiation. And then the power is delivered to DC load through a DC-DC boost converter, whose switch (IGBT) is operated by the MPC controller. The MPC controller applied a model predictive control based maximum power point tracking algorithm. And the states of switch are controlled by the output (S) of MPC controller. Due to the switch have two basic states (open and close) there have two equivalent circuits to represent the DC-DC boost converter to analyze.

When the switch is considered as open, the equivalent circuits of the boost converter shown as Fig.3. And we use the following equations to describe the operation of boost converter.

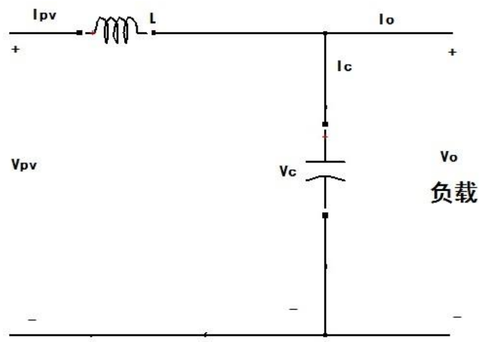

Fig. 3. Equivalent circuits for boost converter when the switch is open (S=0)

$$L\frac{dI_{pv}}{dt}=V_{pv}-V_C \quad (9)$$

$$C\frac{dV_C}{dt}=I_{pv}-\frac{V_C}{R} \quad (10)$$

The Euler approximation is then used to obtain the discrete model of the system:

$$I_{pv}(k+1)=\frac{T_s}{L}V_{pv}(k)-\frac{T_s}{L}V_C(k)+I_{pv}(k) \quad (11)$$

$$V_C(k+1)=\frac{1}{C}I_{pv}(k)-\frac{1}{RC}V_C(k)+V_C(k) \quad (12)$$

$$V_{pv}(k+1)=\frac{L}{T_s}\left(I_{pv}(k+1)-I_{pv}(k)\right)+V_C(k) \quad (13)$$

When the switch is closed, the equivalent circuits of the boost converter shown as Fig.4.and the equations as following:

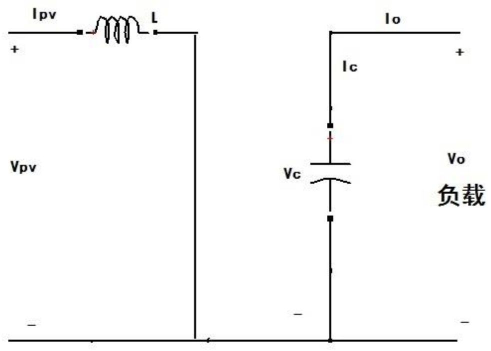

Fig. 4. Equivalent circuits for boost converter when the switch is open (S=1)

$$V_{pv}=L\frac{dI_{pv}}{dt} \quad (14)$$

$$\frac{dV_C}{dt}=-\frac{1}{RC}V_C \quad (15)$$

The discrete model of the system as following:

$$I_{pv}(k+1)=\frac{T_s}{L}V_{pv}(k)+I_{pv}(k) \quad (16)$$

$$V_C(k+1)=\left(1-\frac{T_s}{RC}\right)V_C(k) \quad (17)$$

$$V_{pv}(k+1)=\frac{L}{T_s}\left(I_{pv}(k+1)-I_{pv}(k)\right) \quad (18)$$

Where T_s is sampling frequency, make use of the equation (11), (12), (13) or (16), (17), (18), the behavior of the controlled variableI_{pv}, $V_{pv}$and$V_c$can be predicted for the next sampling instant. And we can utilize the predicted value of this control variables to distinguish whether the photovoltaic array work at the maximum power point. All of this variable estimated and optimized based on the evaluation of a cost function. In this paper, the cost function can be expressed as:

$$J=\left|I_{pv}(k+1)+V_{pv}(k+1)\frac{I_{pv}(k+1)-I_{pv}(k)}{V_{pv}(k+1)-V_{pv}(k)}\right|_{S=0,1} \quad (19)$$

For each sampling sequence the cost function is calculated twice for each switching states. And the cost function for each switch states are compared to determine the control actions for the following time instant. Fig.5.depicts the process of the model predictive control based MPPT control scheme.

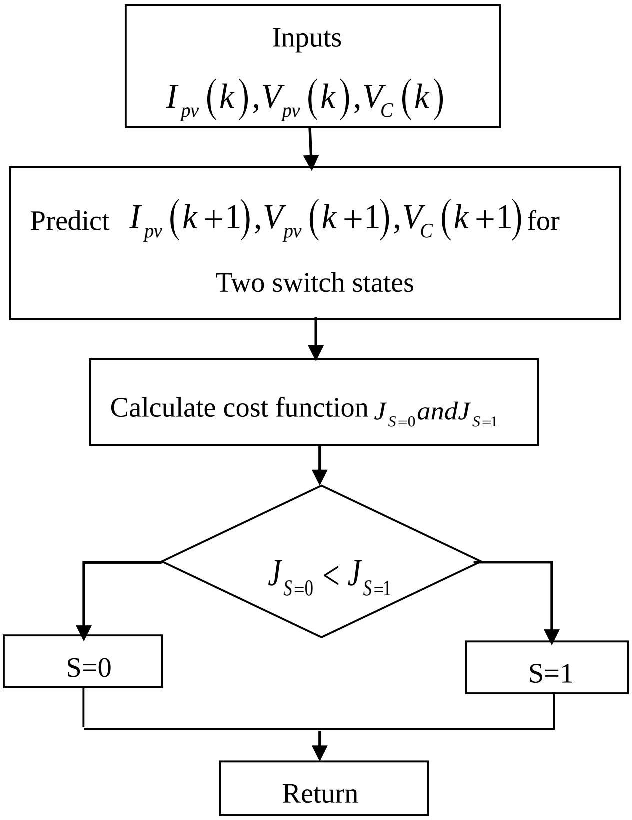

Fig. 5. Flow chart of MPC based MPPT controller

5. Simulation and Result

According to the mathematical model of the solar photovoltaic module described above, build a mathematical model of solar photovoltaic cells in the Matalab/Simulink environment. Simulation were designed based on IMC and MPC described above. In the simulation process of Solar photovoltaic cells, assuming the ambient temperature is maintained at 25 degrees, just considering the changes of the solar illumination and that three time points were given light $700w/m^2$,$900w/m^2$and $1000w/m^2$.In the simulation , simulate the mutations of the light intensity at different moments with three step signal observe and compare the maximum power output tracking situation in the current environment conditions with the use of solar photovoltaic cells under the control of MPC and INC. The simulation results are shown in the following figure.

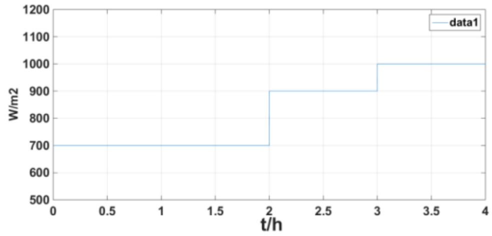

Fig. 6. light changing after time

The initial value of light was 700, at the second the light increases by 200, at the third second the light changed into 1000, and the changes of the moments are mutations. Change of the light is shown in Figure 6.

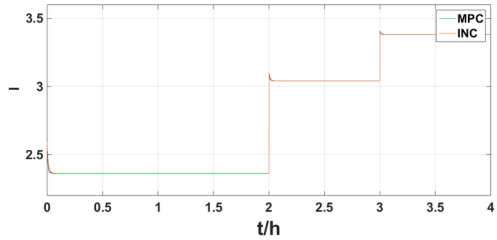

Fig. 7. current changing after time

Output current is shown in Figure 7, since the output of photovoltaic solar cells is directly proportional to the light intensity of the sun, when the sunlight changes, the current of the photovoltaic cell can quickly track changes of the light; since the influence of an external circuit device received by the output current, there is no difference in the use of MPC and lower INC to control the current, and all changes after the light steeply.

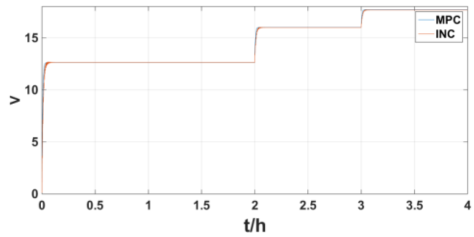

Fig. 8. voltage changing after time

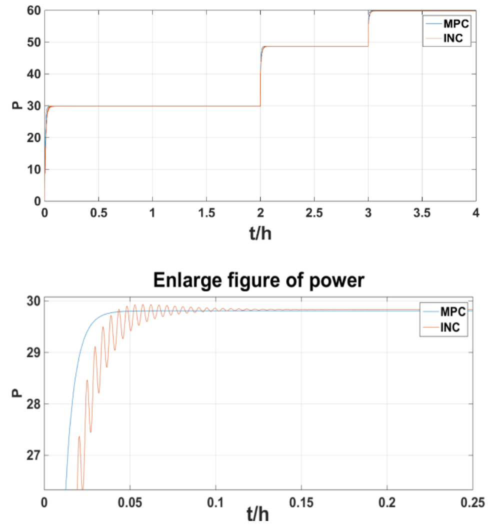

Fig. 9. output power

Output voltage and power as respectively shown in figure 9 and figure 9.shown as the right figure, when the light intensity changes, whether it is the use of MPC or INC to output voltage and power, they are able to follow the changes in light intensity. But the MPC control system is no shock, and the tracking speed is significantly faster than the INC.it is more obviously in the output power. In order to clearly demonstrate the dynamic process of system output under two different control methods, amplified the dynamics process of the change of the power amplification. From the enlarged graph, MPC track the maximum power relatively stable and the method of INC has severe shock that the effect is less good than predicted.

This paper analyzes principle when solar photovoltaic cells work, and relationship between output of current, voltage and power. Under certain light intensity and ambient temperature, the output of power and operating voltage is obviously nonlinear. It is difficult to operate at the maximum outputting point of power. Therefore, in order to improve the conversion rate of solar energy, solar photovoltaic cells designed the predictive control based on the maximum power point tracking technology. According to the solar photovoltaic cell model, predict the output power of the PV array in the current environment, control full-controlled device in the converter circuit, Regulate the operating voltage of the solar cell to operate at maximum power point. The simulation shows that this method can quickly adjust the solar cell operating voltage and track the maximum power point fast, at the same time overcome the shock and other issues brought by the classic disturbance observer and incremental admittance MPPT technology. The accuracy and speed of tracking maximum power point have improved significantly.

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