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Research on Grid-Connected Photovoltaic System Based on Improved Algorithm

***Abstract**. In order to simulate and predict the behaviors of the real photovoltaic system, this paper develops a grid-connected photovoltaic simulation system with maximum power point tracking (MPPT) function using MATLAB software. An engineering model for the photovoltaic (PV) cell is first established and then combined with the models of an MPPT controller and a DC-DC converter. This paper uses an improved algorithm in the MPPT controller by comparing with the commonly-used algorithms. A DC-AC inverter using double closed loop control method is used to track the grid characteristics. The simulation results show that the system not only achieves the maximum power point tracking function quickly but also modulates the outputs of the inverter into sine waveforms accompanied with fewer ripples. And the power factor is close to 1*

***Streszczenie**. W artykule zaproponowano symulację połączonego sieciowo system fotowoltaicznego z funkcja śledzenia maksymalnej mocy. Zaproponowano model inżynierski w MATLABie złożony ze sterownika i przekształtnika. Przekształtnik DC-AC wykorzystuje podwójną zamkniętą pętlę sterowania. (**Badania połączonego w sieć systemu fotowoltaicznego z ulepszonym algorytmem sterowania**)*

Keywords: photovoltaic cell; MPPT; inverter; grid-connected photovoltaic system
Słowa kluczowe: system fotowoltaiczny, przekształtnik, sieć.

Introduction

In recent years, with the growing crisis of traditional energy, research and applications of renewable energy, especially for the photovoltaic power generation, have aroused incremental public attention. The outputs of the photovoltaic (or solar) cell are nonlinear, so in order to obtain the maximum power, we need to track and control them. And to decide which control algorithm to capture the maximum power point (MPP) is the focus of this study. By analyzing the topological structure of the grid-connected photovoltaic system, we know that the control is more complicated for the single-stage grid-connected photovolta-
ic system not only to achieve the outputs of the inverter, which can track the grid voltage fast and stably but also to achieve the maximum power point tracking and so on. Considering this point of view, this paper decides to use the double-stage grid-connected photovoltaic system.

Single-phase double-stage grid-connected photovoltaic system

Fig.1 shows the main circuit structure of this system. The DC/DC converter consisting of L_1、VT_1、D_1、C_1 forms the boost precircuit. It will achieve two main functions. First, it matches the output voltage of the solar cells with the DC input voltage of the inverter; second, it detects the outputs of the solar cells continuously to change the duty ratio in order to achieve maximum power point tracking. The inverse system is a single-phase full-bridge inverse circuit composed of four IGBTs. D_2-D_5 are the fly-wheel diodes. In this part, the inverse controller changes on-off switch of the full-bridge circuit by tracking the characteristics of the grid voltage in order to achieve synchronization with the grid. This double-stage structure makes the control method simple and reliable.

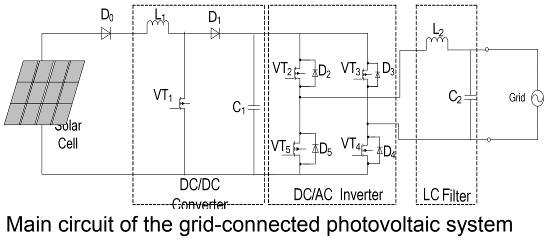

Fig.1 Main circuit of the grid-connected photovoltaic system

Model of the photovoltaic cell

Considering many parameters in the equation based on the physical characteristics of the solar (or PV) cell [1], which are associated with the environmental temperature and solar irradiance, confirmed difficultly and applied inconveniently in engineering, this paper uses the engineering model of the PV cell proposed in the literature [2]. The model is expressed as:

$$I = I_{sc}\{1 - A[e^{(U-DU)/BU_{oc}} - 1]\} + DI \quad (1)$$

With: $A = (1 - I_m / I_{sc})e^{-U_m / BU_{oc}}$, $DT = T - T_{ref}$

$B = (U_m / U_{oc} - 1)\ln(1 - I_m / I_{sc})$, $DU = -\beta \cdot (DT) + R_s \cdot (DI)$

$DI = \alpha \cdot (DT) \cdot R / R_{ref} + (R / R_{ref} - 1) \cdot I_{sc}$

where I, U – the output current and voltage of the solar module, I_{sc} – the short-circuit current of the solar module, U_{oc} – the open-circuit voltage of it, I_m, U_m – the current and voltage at the MPP, R_{ref}, T_{ref} – the reference solar irradiance and temperature of the solar module, α – the temperature coefficient of the short-circuit current, β – the temperature coefficient of the open-circuit voltage, R_s – the internal series resistance.

Fig.2 shows the simulation structure of the model in MATLAB/Simulink according to the equation (1).

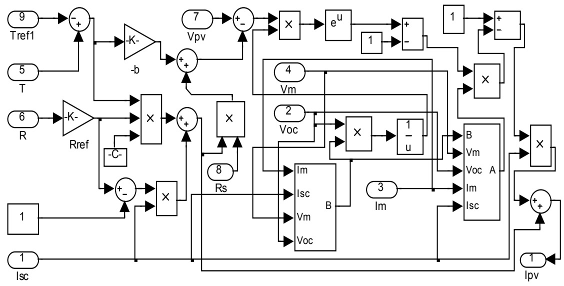

Fig.2 Structure of the photovoltaic cell in MATLAB/Simulink

Encapsulating the above simulation model with the program can get a more realistic appearance shown in Fig.3, than that in literature [3].

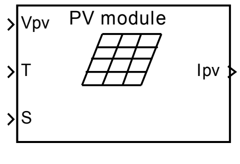

Fig.3 Hardcover model of the photovoltaic cell in MATLAB/Simulink

This model, using the electrical parameters, such as the PV voltage (V_{pv}), solar irradiance (S) and environmental temperature (*T*) as the inputs, yields the PV current (I_{pv}). So we can get I-U property and P-U property easily. There are some cell parameters provided by the manufacturers who produce the solar cells inside the encapsulation. The parameter-setting interface is similar to that in literature [3].

Control strategy and results of MPPT based on boost circuit

It can be known that the output characteristics of the photovoltaic cell are nonlinear through the simulation of the model above. As illustrated in Fig.4, it shows the simulation results of the I-U property under the given different conditions.

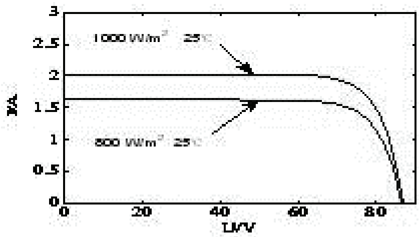

Fig.4 I-U property of the photovoltaic cell

Therefore, the photovoltaic system needs to achieve maximum power point tracking, so that it can output maximum power, especially when the external environment changes. Maximum power point tracking (MPPT) is an essential process of self-optimization [4].

In this paper, boost circuit is used to achieve the function of MPPT according to the advantages and disadvantages in the boost and buck circuit [5].

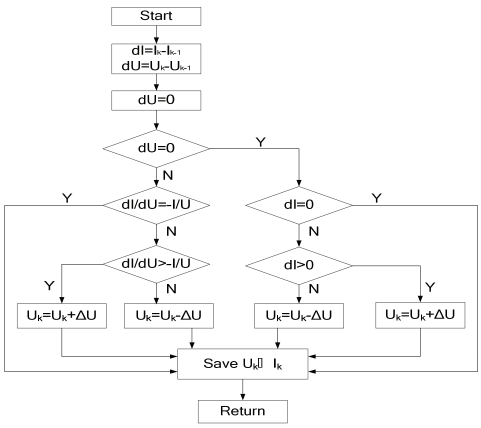

Fig.5 Flow chart of the incremental conductance method

A. ***A kind of commonly-used control strategy of MPPT***

This paper introduces the incremental conductance method widely used in MPPT control methods. From P-U, the property of the solar cell, we know $dP/dU = 0$ at MPP. So according to $P = U \cdot I$, we have the following equation when taking the derivative of it and looking on I as the function of U:

(2) $$\frac{dP}{dU} = I + U\frac{dI}{dU} = 0$$

Rearranging equation (2) yields the following equation:

(3) $$\frac{dI}{dU} = -\frac{I}{U}$$

Therefore, we can achieve MPPT by comparing dI/dU with $-I/U$. Fig.5 is its flow chart. It's noteworthy that the variation of the voltage at the end of the flow chart is realized by changing the duty ratio of the DC/DC converter.

B. ***Simulation results of the incremental conductance method in the boost circuit***

Fig.6 shows the simulation diagram achieving MPPT function in MATLAB/Simulink.

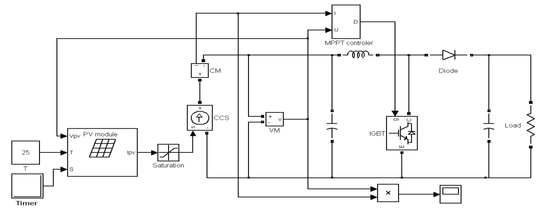

Fig.6 The simulation diagram of MPPT based on the boost circuit

First, according to Fig.3, we can simulate the relationship between P and U in the following cases: the irradiance, S, is initially set to change from 400W/m^2 to 600W/m^2 at the simulation time of 2 sec; Temperature: 25℃; Load: 20Ω. The simulation result is shown in Fig.7. We can see the value of the maximum power point (MPP) in this figure.

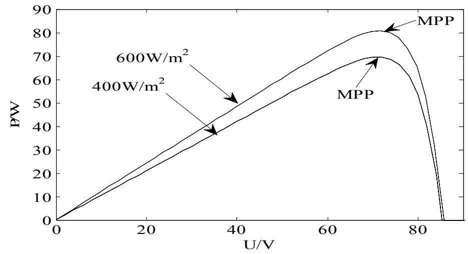

Fig.7 P-U property of the solar cell under the given conditions

Fig.8 shows the simulation result of this method under the given conditions. In order to see the subtle changes of output power from the solar cells clearly, the simulation result is enlarged at around the time of 2 sec.

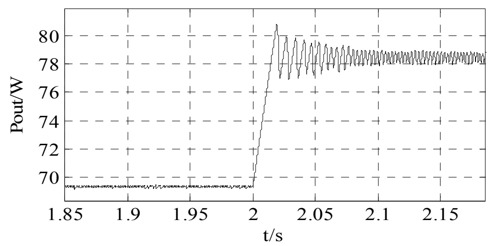

Fig.8 Simulation result based on the incremental conductance method

It can be seen from Fig.8 that the output power oscillates around a constant value in the case of fixed ΔU or step. The constant value mentioned above is the value of MPP in fact. But it doesn't output the stable power. Therefore we need some improved algorithms to abate this oscillation [6].

C. ***An improved algorithm***

Perturbation and observation method and incremental conductance method commonly used in MPPT algorithms all change the duty ratio of the DC/DC converter by detecting the output voltage and current of the solar cells to get the maximum power. The parameters to be measured in the perturbation and observation method are fewer and the control is simple. But the perturbation step is fixed when looking for the maximum power point, so it may oscillate near the MPP and produce loss. Although incremental conductance method applies to the environmental mutation, its control is more complicated and the tracking speed near MPP relates to ΔU. It is verified in Fig.8. If ΔU is not proper, it will affect the efficiency of power generation. In fact, the perturbation step of the above two methods is fixed.

This paper adopts the perturbation and observation method with a variable step which uses the duty ratio of the

DC/DC converter as the control object to improve the efficiency of the system rapidly. It will automatically adjust the duty ratio according to the changes of the output power of solar cells. Fig.9 shows the relation curve between the output power of solar cell and the duty ratio [7].

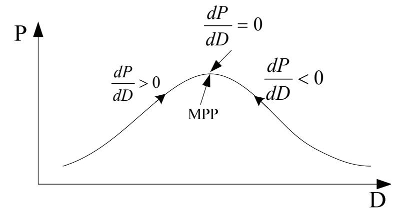

Fig.9 P-D relationship

The basic idea of the perturbation and observation method with a variable step is that choose a big step when the output power is away from MPP to make the output power close to the value of MPP quickly. When the power is close to MPP, choose a small step to make the output close to MPP stably.

It can be seen from Fig.9 that the value of $\left|dP/dD\right|$ will gradually reduce to zero only near MPP, so we can construct a real-time step:

$$a_{(k+1)} = \varepsilon \frac{\left|\Delta P\right|}{a_{(k)}} \tag{4}$$

where ε – the proportional factor, ΔP – the variation of power, $a_{(k+1)}$ – the variation of step.

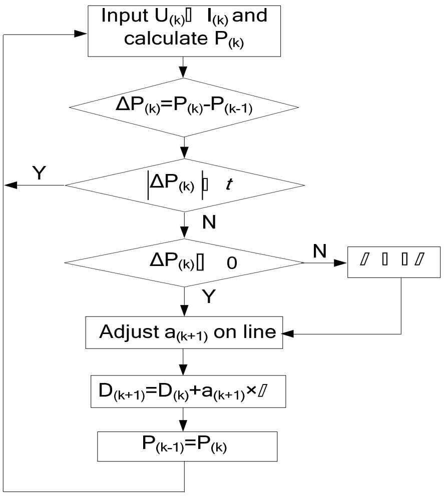

Fig.10 Flow chart of the perturbation and observation method with a variable step

According to the flow chart in Fig.10, the first thing to do when using this method is to detect the output voltage and current of the solar cells and then calculate the current output power. Compare it with the previous power. If the difference is smaller than the given value, t, the current output power of the solar cells is thought to be the maximum value, or it's away from MPP. Then judge the direction of power. η is the sign bit of the step. Its value is 1 or -1. If the difference is greater than zero, the perturbation is in accordance with original direction and η is 1; if it's smaller than zero, the perturbation will be in an opposite direction and η is -1. ε reflects the flexibility of the system. The greater the value is, the more sensitive the on-line regulator will be.

D. *Simulation results of this improved algorithm*

This improved algorithm is used in the same simulation cases with the incremental conductance method. Before simulating this improved algorithm, the perturbation with a fixed step based on this algorithm is simulated first in order to give the differences between them. Fig.11 shows the simulation result of perturbation with a fixed step.

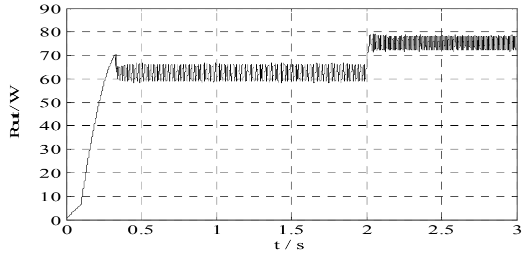

Fig.11 Simulation curve of the system when the step is 0.04

The output power oscillates up and down when using a fixed step. But the maximum value of the output power isn't the value of MPP in Fig.7. Compare Fig.8 with Fig.11, we can see that the output using incremental conductance method is more stable than that using the perturbation method with a fixed step. Fig.12 gives the simulation result by using the control method with a variable step. According to Fig.7, it can be seen clearly that using this method can track the maximum power point exactly. Compare it with Fig.8 and Fig.11; it is obviously that the oscillation disappears when using this improved method. In addition, it can track the maximum power point quickly, especially when the external environment changes suddenly.

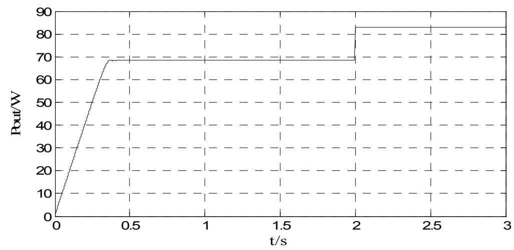

Fig.12 Simulation curve of the system with a variable step

From the simulation results mentioned above, we may reasonably arrive at the conclusion that the controller based on this improved method achieves the MPPT function perfectly, especially when the environment changes, so it's correct.

Control strategy of grid-connected system

According to the requirements for control method of the inverter in the grid-connected system, this paper uses the double closed loop control method. Its diagram is shown in Fig.13.

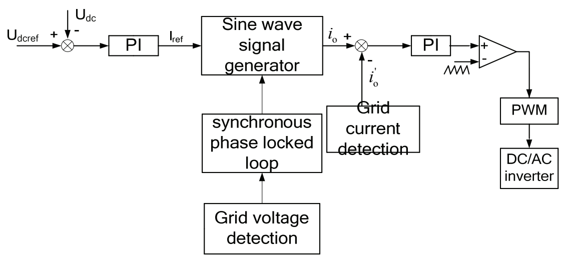

Fig.13 Double closed loop control of the voltage and current

The outer DC voltage control loop is to keep the input DC voltage of the inverter stable, and the inner grid current control loop is to ensure that the output current of the inverter has the same frequency and phase as the grid voltage. Outer voltage is a given calculated value. The feedback value is the DC bus voltage generated by MPPT. Give the difference between the given value and the feedback value, and then output the difference by using PI control. As a result, we can get I_{ref}. Look on it as the given amplitude for the inner current loop. Next, let I_{ref} multiplied by the discrete sine value and look on the result, i_o, as the discrete reference value of the inner current loop. Fig.14 shows the process how to build the model of the discrete sine value in MATLAB/Simulink.

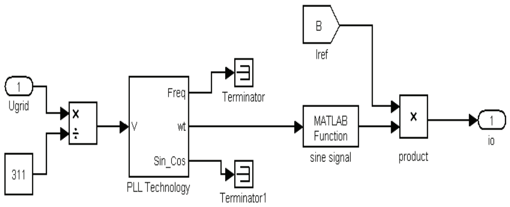

Fig.14 Model of the discrete reference value in MATLAB/Simulink

Compare i_o with the output current of the inverter which is also the grid current, and it will generate an error signal, which is controlled by PI regulator next. By comparing the signal from PI regulator with triangular carrier, we can get PWM to control the output of the inverter.

Simulation results of the whole system

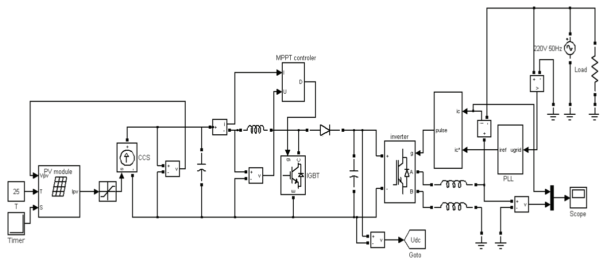

Fig.15 The simulation diagram of the grid-connected photovoltaic system with MPPT

In Fig.15, the simulation is made to illustrate the response of the whole system for different temperature or solar irradiance levels for a duration of 5 sec. For this purpose, the irradiance is initially set to change from 800W/m^2 to 1000 W/m^2 at the simulation time of 2.5 sec and the temperature is set to be constant as 25℃. Outputs of the PV arrays change obviously at this time. MPPT controller detects the changes continuously and then tracks the maximum power point at once. After a very shot while, the controller achieves MPPT function. The output results of the PV arrays are shown in Fig16.

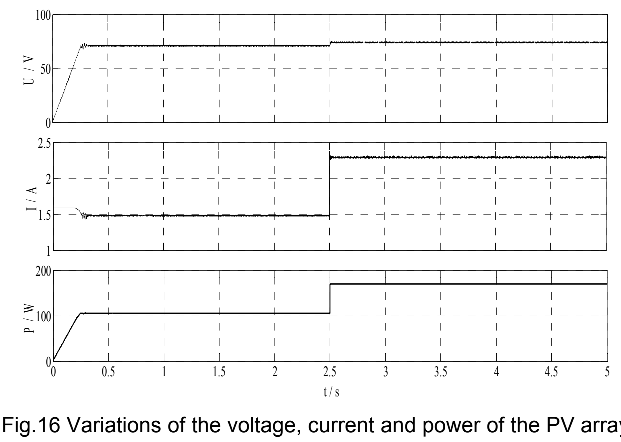

Fig.16 Variations of the voltage, current and power of the PV arrays as the solar irradiance level increases

We can see that the output current of the inverter also increases in Fig.17 due to the ambient changes. And then it keeps stable in order to keep the input voltage stable after 2.5 sec which could be seen easily in the amplified simulation environment. The current also has the same frequency and phase as the grid voltage all the time and the output voltage has the same peak value and phase as the grid voltage.

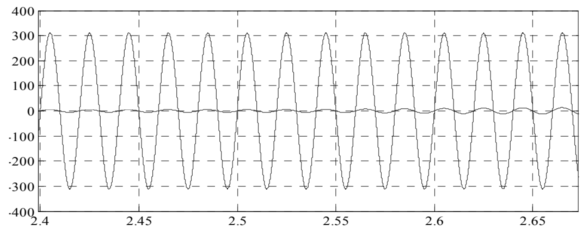

Fig.17 The output voltage and current of the inverter

Summaries

This paper established a model for the grid-connected photovoltaic system with maximum power point tracking function. In the beginning, the MPPT controller used a traditional control algorithm in the DC-DC converter. But the output power wasn't the maximum value and ideal. An improved algorithm was proposed after that. The simulation result verified the correctness and flexibility of using this algorithm. In order to combine with the grid, a DC-AC inverter using double closed loop control was used in this research. And also we could see from the output results of the inverter that the inverter and its control method satisfied the demands of the grid-connected photovoltaic system, especially when the irradiance increased. The output current could also track the grid quickly at that moment. PLL technique used in the inverse circuit ensured the tracking accuracy for the output current of the inverter. The simulation results were sine waves and had fewer ripples. This system would show its feasibility in practice.

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