FPGA-based Adaptive Variable Step MPPT Real Time Simulation for Photovoltaic Systems

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Abstract. In order to obtain more output power, maximum power point tracking (MPPT) control technology is usually designed to track the maximum power of photovoltaic (PV) array. The traditional power disturbance observation method tends to cause power oscillation loss, so an adaptive variable step algorithm is presented to balance the tracking accuracy and speed of PV system. Different from off-line simulation, the overall model is built on FPGA to complete the real time digital realization of MPPT control for PV system. Finally, the model is simulated and verified by ModelSim software. The experimental results show that the system can track the maximum power more quickly and accurately in real time.

1. Introduction
With the exhaustion of traditional energy, PV power generation technology has been developed rapidly. Some high-power solar power stations have been put into operation. However, the PV cell array is vulnerable to ambient temperature, light intensity and other factors, which greatly affect the output power. In order to obtain as much electric energy as possible under different sunshine and temperature conditions, maximum power point tracking (MPPT) control technology has become one of the important subjects to capture the maximum power point.

The output power of PV cell is sensitive to many factors including temperature and light intensity. Considering the nonlinear property of the output power, the PV system should be maintained at the unique maximum power point to improve the efficiency. The fixed-voltage tracking method is proposed in [1], which could not adapt to the characteristic changes of the output of PV array. The traditional perturbation observation method is adopted in [2]. Due to the property of fixed tracking step size of the solver, the tracking accuracy and speed cannot be balanced during the oscillation process. The fuzzy control is presented in [3], but the control rules mostly rely on the subjective experience, so it cannot be applied to all scenarios. Moreover, most variable step tracking methods are based on off-line simulation software such as MATLAB/Simulink[5]. Nevertheless, there is still a gap with the real-time transient simulation, which considers the actual delay condition and so on.

The field programmable gate array (FPGA) can realize the real-time transient simulation of distributed generation system, because of the capabilities of high integration, low power consumption and short development period. Therefore, we present an adaptive variable step perturbation observation method to complete the digital realization of MPPT control system based on FPGA for PV
array.

In this paper: Section 2 presents the equivalent model and MPPT control technology of PV cell. In Section 3, the adaptive variable step algorithm and total model are constructed in quartus II 13.1 software platform. The experimental results are described by Modelsim platform in section 4. Finally, section 5 presents the conclusion of all paper.

2. Implementation principle of MPPT control technology for PV array

2.1. PV cell model

The PV effect of semiconductor is applied to convert solar energy directly into electricity. The equivalent circuit of PV cell is represented by diode equivalent model, which is shown in figure 1.

![Figure 1. Equivalent circuit diagram of PV cell](image)

The formula can be expressed as:

\[
I = I_{LG} - I_0 \exp\left\{ \frac{(U_L + IR_s)q}{nkT} - 1 \right\} \left( \frac{U_L + IR_s}{R_p} \right)
\]

(1)

PV array are usually matched with load impedance by an external power conversion circuit to achieve maximum power output. As shown in figure 2, the PV array is connected with the load resistance by a Buck circuit. The Buck circuit is controlled by the pulse width modulation (PWM) signal generated by FPGA after handling the detected power signal. According to the technical knowledge of power electronics, we can deduce:

\[
R_{pv} = \frac{U_{pv}}{I_{pv}} = \alpha^2 \cdot R
\]

(2)

2.2. MPPT technology based on FPGA for PV array

An adaptive variable step size method is presented in this section, which can automatically change the perturbation step size according to the slope of \( P - \alpha \) characteristic curve during the perturbation process, so as to improve the system optimization efficiency. According to formula (1) and (2), the characteristic curve of PV array between the output power and duty cycle is shown in figure 3.
According to the $P-\alpha$ curve of PV system, the PV system satisfies the following relation:
\[
\begin{align*}
    \frac{dP}{d\alpha} &> 0, \text{The working point is to the left of the } P_{\text{max}} \\
    \frac{dP}{d\alpha} &= 0, \text{The working point is at the point of the } P_{\text{max}} \\
    \frac{dP}{d\alpha} &< 0, \text{The working point is to the right of the } P_{\text{max}}
\end{align*}
\]  
(3)

Based on characteristic curve, the control principle of adaptive variable step MPPT is as follows: when the system is far away from the $P_{\text{max}}$, the large step size can be used to track and improve the tracking speed. As the work point gets closer to $P_{\text{max}}$, the step size of the system gradually decreases, and the smaller step size can be used to track and improve the tracking accuracy, so as to realize adaptive variable step size MPPT control. Based on the above analysis, the tracking step of the MPPT control algorithm is determined by the following formula:
\[
D(n+1) = D(n) \pm k \cdot \left| \frac{dP}{d\alpha} \right|
\]  
(4)

It can be equivalent to the following formula:
\[
D(n+1) = D(n) \pm k \cdot \frac{P_n - P_{\text{max}}}{\alpha_n - \alpha_{\text{opt}}} \quad \text{if} \quad \left| \frac{dP}{d\alpha} \right| < \Delta D_{\text{max}}
\]  
(5)

As shown in figure 4, the FPGA-based MPPT control process can be summarized as: The first step
is to achieve an initial output power by calculating the product of sampled voltage and current value with an initialize duty ratio. The output of the PV cell will be changed by an unexpected external disturbance. And then the output power and duty ratio of the current moment and the previous moment are compared respectively to judge the tracking direction. In this way, the output power at the next moment can be maximized driven by the new corrected control signal. Finally, when the absolute value of the change of output power is less than a certain minimum, the output power reaches the $P_{\text{max}}$ point and the duty ratio signal is stable.

3. The FPGA-based construction of MPPT model

An adaptive variable step MPPT algorithm is designed by using Verilog language, and the digital realization of the control system is completed on Quartus II 13.1 software platform. This design uses the FPGA control chip of cyclone III EP3C80U484C8 series. MPPT control model is divided into three modules: data acquisition module, MPPT control module and PWM generation module.

As depicted in figure 5, the total module works as follows: Firstly, the sampled output voltage and current of the PV array is used to achieve the current power by a multiplier, which is stored into a register for the next comparison. Then, the MPPT control module compares the power difference and duty cycle variation of the current and previous instant, respectively. The trajectory of duty cycle signal at the next moment can be predicted. Finally, the PWM module is driven to produce stable PWM signal wave. The final actual PV system model is presented in figure 6:
4. Experimental results

The frequency of the FPGA crystal vibration selected for the system is 20MHz, and the sampling period of the MPPT control system is 50ns. The PWM signal is generated by comparing duty ratio signal and sawtooth wave signal. The frequency of Buck circuit switch designed is 50kHz, and the sawtooth wave can be generated by a counter. Since the duty cycle varies from 0-1 and the sawtooth wave varies from 1-400, in order to compare and determine the output pulse width, the scale factor in the formula (6) is designed as: \( k = \frac{1}{400} \).

Firstly, the initial value of duty cycle is set as 0.5 (counter value is 200), then a disturbance in the positive direction is given. The overall design module is functionally verified in ModelSim software platform, and some simulation results are intercepted as shown in figure 7.

As shown in figure 7, the moment of the rising edge of the second pulse comes, the power difference and duty cycle variation are calculated as: \( \Delta data2 = 56 > data1 = 22 \), \( \Delta D = 214 - 201 = 13 > 0 \). The disturbance is judged to be positive direction, and the duty cycle is increased to 0.54(\( ddt = 216 \)).

The moment of the rising edge of the third pulse comes, the power difference and duty cycle variation were calculated by: \( data2 = 39 < data1 = 56 \), \( \Delta D = 216 - 214 = 2 > 0 \). At this time, disturbance is judged to be negative direction, and the duty cycle decreases to 0.52(\( ddt = 208 \)). It can be seen that the system can track in real time and react sensitively to the current situation.

5. Conclusion

In this paper, an adaptive variable step MPPT control algorithm based on FPGA for PV cell is designed to capture the maximum output power by constantly adjusting the duty cycle. The tracking speed and accuracy of the system are considered by this method. The oscillation problem of the traditional perturbation method can be restrained to some extent. Each module has its own target division and can be precisely coordinated. The system provides the theoretical basis of simulation for the practical work of PV array.

Acknowledgment

This work is supported by the State Grid Corporation of China Science and Technology Project (No.
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