MODELLING AND MEASUREMENT OF A PHOTOVOLTAIC CELL ARRAY MAXIMUM POWER POINT TRACKING SYSTEM FOR GREENHOUSE
/
用于大棚光伏电池矩阵的最大功率点跟踪建模与测量

Liming Wei[1)], Jinxin Luo[1)], Boheng Li[1)], Xiujuan Guo[1)], Bin Li* [1, 2)1]
[1)] Institute of Electrical & Computer, Jilin Jianzhu University, Changchun 130012, P.R. China;
[2)] College of Computer Science and Technology, Jilin University, Changchun 130012, P.R. China
Tel: +86-043184566184; E-mail: 870731919@qq.com
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ABSTRACT

Maximum power point tracking (MPPT) strategy has been performed by experimental simulation and measurement in order to minimize the energy loss for photovoltaic greenhouse projects. Calculations and simulation of power prediction algorithm were carried out for obtaining the suitable parameters and duty cycle of the fuzzy control algorithm, to modulate output power in real-time. Experiments were carried out to evaluate the performance by using simulation and measurement involving corresponding circuits. Results of experiments demonstrate that the proposed method in this paper can achieve quicker response and less power loss than traditional method. The proposed algorithm can be adopted and optimized by carrying out further experiments for increasing the efficiency of solar energy utilization.

摘要

为了使光伏温室项目的能量损失最小化,通过实验仿真和测量来实现最大功率点跟踪策略。研究中采用了功率预测算法和模糊控制算法相结合的方法。为能实时调节输出功率，进行功率预测计算和仿真，得到模糊控制算法的合理参数并输出合适的占空比，以实现功率最大化。并通过对相应电路的仿真和测量，对其性能进行实验评价。实验结果表明，本文提出的方法比传统方法具有更快的响应时间和更小的功耗。为提高太阳能利用效率，本文提出的算法可以通过进一步的实验加以采用和优化。

INTRODUCTION

The development and utilization of photo-voltaic (PV) power generation in agricultural greenhouse is a trend in recent years. The solar energy can provide suitable temperature and environment for crops and it is also a supplement to electricity consumption in agricultural greenhouse *(Maher A., 2016; Dinesh H., 2016; Hassan G.E., 2016)*. For example, the electric quantity required by the ventilation and heating in the greenhouse, the illumination in the shed and the electricity utilization of the crop irrigation can be powered by solar electricity. The distribution of the electric energy obtained by the photo-voltaic power generation is carried out also realizing circular ecological agriculture, with high efficiency of science and technology *(Li C., 2017; Rubio-Aliaga A., 2019; Ju YT., 2019; Jones M., 2015)*.

Photo-voltaic cell is usually composed of photo-voltaic arrays. Since the material of the photo-voltaic cell is generally crystalline silicon, the power generation efficiency can only reach about 18% *(Bechouat M., 2019; Joshi P., 2018)*. This is due to the strong nonlinear characteristics of photo-voltaic cells. The output of photo-voltaic cells is affected by many environmental factors, such as temperature and light intensity. Therefore, the power output is not stable and there is a certain loss of oscillation.

MPPT (Maximum Power Point Tracking) algorithm is applied to achieve less power waste and is widely researched in recent years *(Yilmaza U., 2019; Murtaza AF., 2019)*. MPPT algorithm maintains the power output in the maximum state, which can be applied to solar photo-voltaic array to improve its power generation efficiency.

In this paper, a photo-voltaic power generation system with MPPT device is modeled and is measured to evaluate the performance. Power prediction algorithm and fuzzy control algorithm are adopted in this modelling process. The results have been tested by using corresponding circuits. Based on the proposed methods, less output power wasted can be achieved due to the advantages including fast response time, high efficiency and high robustness.

[1] *Liming Wei, Prof.; Jinxin Luo, Stud.; Boheng Li, Stud.; Xiujuan Guo, Prof.; Bin Li, PhD.*

SYSTEM STRUCTURE AND THEORY

System structure

The functional block diagram of the MPPT adopted PV cell array system and is shown in Figure 1. In this figure, the complete set of photovoltaic power generation system includes PV cell array, Boost converter, MPPT device, DC load, AC load, inverter and battery *(Reddy, J., 2018; Mishra, AK., 2018)*. The photovoltaic cell array receives solar illumination and outputs electrical energy. The output voltage is raised to a certain level by the Boost circuit in order to drive DC load, AC load or charge batteries. The system can also be connected with an inverter to convert DC to AC for supplying AC loads. And the MPPT device is used for monitoring the voltage and current generated by the photovoltaic cell in real time to determine the working point and the maximum power point of the current system. By adopting MPPT algorithm, the MPPT device produces the corresponding adjusting signals. After the pulse modulation process, the switch ratio of the boost converter can be adjusted by the generated PWM signal which is determined by the MPPT algorithm. The internal resistance of photovoltaic cell array can be matched with the load impedance by changing the duty cycle. Thus, the photovoltaic array can always be adjusted in real time to output at the maximum power point.

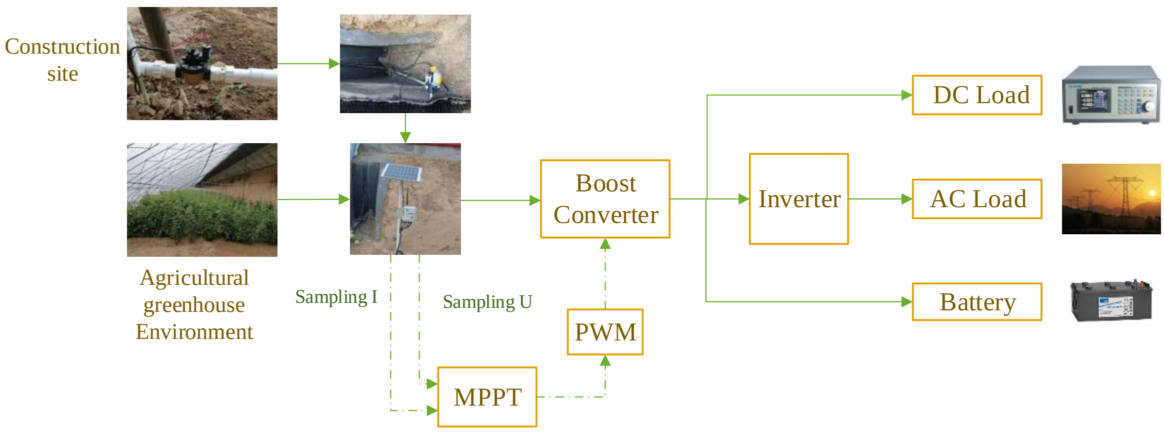

Fig. 1 - Block diagram of the MPPT adopted PV cell array system

MPPT Theory

The MPPT theory is adopted in this PV cell array system, which has features including nonlinear, asymmetry and mono-pole, in order to achieve the target that the output power of the system can be maintained constant at its maximum power as the environment changes. The general MPPT algorithm modes can be divided into three categories, which are direct sampling control mode, indirect approximate control mode and intelligent control mode. Intelligent control mode has been developed rapidly by many researchers in recent years because of highly self-adoption and fast processing speed *(Boutabba T., 2018; Chekired, F., 2011; Nabipour M., 2019)*.

Fuzzy control method is one of intelligent control methods and the applied fuzzy control algorithm is shown in Figure 2 *(Abdourraziq M.A., 2018; Blaifi S.A., 2018; Eltawil M.A., 2013)*. The fuzzy controller has two input ports and the inputs will be processed separately. Then, the operation of fuzzy controller is carried out through the database, the knowledge base and the rule base. The final output is duty cycle and can be shortened as D.

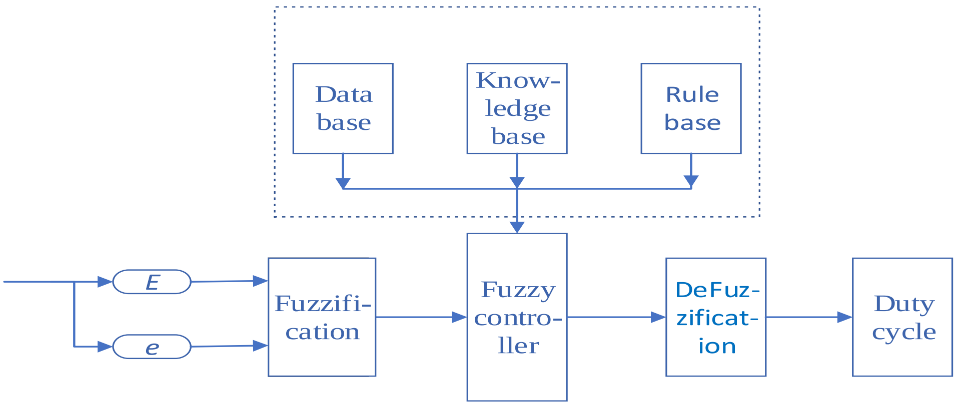

Fig. 2 - Applied Fuzzy control method in the system

Power prediction algorithm is widely adopted in applications involving system misjudgement *(Xie Y., 2013; Osorio, G.J., 2015)*. Misjudgement is generally due to the fact that the samples measured by the system come from different characteristic curves. For instance, the initial voltage and power are U_1 and P_1 as shown in Figure 3. While the voltage is increasing, the raised output power is P_2 according to the initial curve. However, the final output is P_3, which is not equal to the predicted output power of P_2, due to the influence of the environmental change. In this way, the misjudgement is produced. To avoid this misjudgement, sampling of system factors should be added in the process and the predicted power can be obtained by calculation.

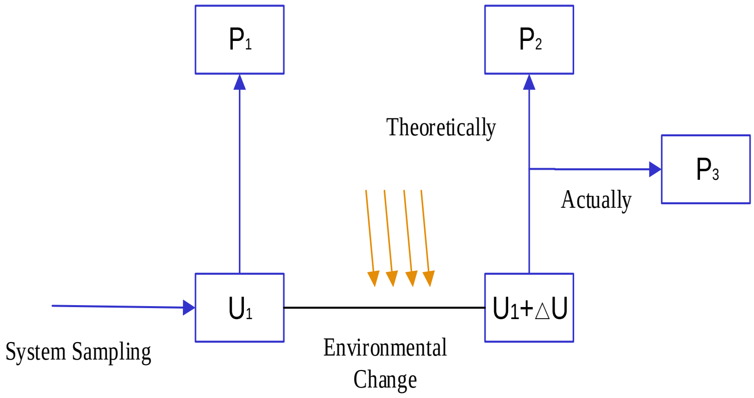

Fig. 3 - Misjudgement analysis diagram for power prediction

In this paper, the power difference obtained by the formula of power prediction method is applied to the fuzzy controller to get D (duty cycle). The combination of the two algorithms can minimize the error of system judgment. Before the fuzzy control calculation, the power prediction process can result in an optimized output power. Therefore, the system can reach maximum power point more quickly by adopting the power prediction and fuzzy control algorithm.

MATERIALS AND METHODS

Simulation of power prediction algorithm

Hypothesis at kT time the output power of photovoltaic cell is $P_{(k)}$. By adding one sample at $(k+1/2)T$ times, the power value can be obtained as Equation (1).

$$P'_{(k)} = 2P_{(k+1/2)} - P_{(k)} \tag{1}$$

Continue the sampling process, the system obtains $P_{(k+1)}$ in the period of time of $(k+1)T$ According to the power prediction theory, $P_{(k+1)}$ is same as $P'_{(k)}$. Therefore, the difference between output power at $(k+1)T$ and at kT is:

$$dP = P'_{(k)} - P_{(k)} = 2[P_{(k+1/2)} - P_{(k)}] \tag{2}$$

Based on the above equations, the relationship between real-time power and predicted power can be calculated by designing a fuzzy controller using Simulink as shown in Figure 4. In this designed module, two input factors are voltage and current of the PV cell array and the power prediction process is performed. The final output is D which is the duty cycle and it will be applied as input to the fuzzy control algorithm.

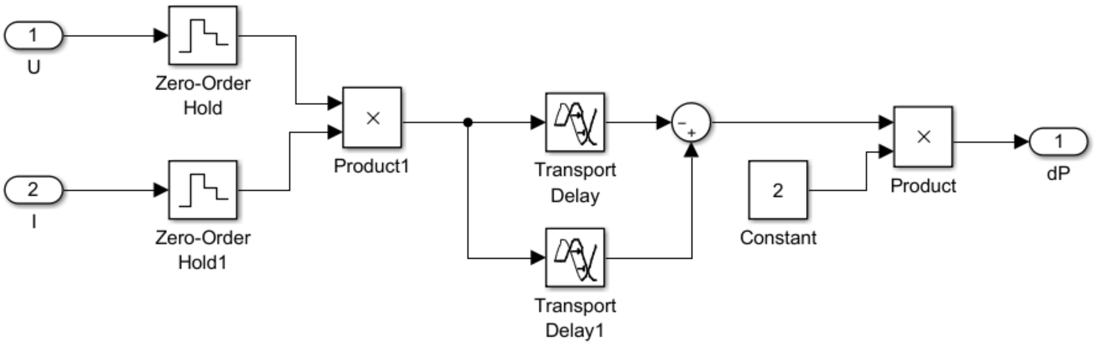

Fig. 4 - Sub-module of the power prediction simulation module

Simulation of fuzzy control algorithm

The fuzzy control algorithm uses the power prediction calculation's output, which is the duty cycle D, as its input. The input of fuzzy control method for power prediction is represented as E_1 and e_1 as shown in Equation (3). The input of the traditional fuzzy control method is represented as E_2 and e_2 as shown in Equation (4).

$$E_1 = \frac{dP}{U_{k+1} - U_k}, \quad e_1 = E_{1(k+1)} - E_{1(k)} \tag{3}$$

$$E_2 = \frac{P_{(k+1)} - P_k}{U_{k+1} - U_k}, \quad e_2 = E_{2(k)} - E_{2(k-1)} \tag{4}$$

The fuzzy subsets of E_1, e_1, E_2, e_2 and D are represented in {NB, NM, NS, Z, PS, PM, PB} as shown in Table 1. In this assembly, NB is Negative Big, NM is negative middle, NS is negative small, Z is zero, PS is positive small, PM is the positive middle, PB is positive big. The fuzzy domain of E_1 and E_2 is [-5, 5], e_1, e_2 and D is [-1, 1]. Fuzzy rules as follows are made by IF A and B then C. The above information is essential for the fuzzy controller and has been filled in the designed module as shown in Figure 5(a).

Table 1

Fuzzy Control Decision Table

E_1、E_2 / e_1、e_2	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PS	NS	NB	NB
NM	PB	PB	PM	PS	NS	NB	NS
NS	PB	PM	PS	PS	NS	NM	NS
Z	PM	PS	PS	Z	NS	NS	NM
PS	PS	PS	Z	NS	NS	NS	NB
PM	PS	PS	Z	NS	NS	NM	NS
PB	Z	Z	Z	NS	NM	NB	NB

Finally, the decision module is obtained by using the above assembly and parameters as shown in Figure 5 (b) and (c). In this simulation module, the temperature is set as 25ºC, the luminous intensity is set as 1000 W/m², and the time duration is 1 s. The obtained coefficient surface is shown in Figure 5 (d) In order to illustrate the performance of this algorithm, the traditional fuzzy control algorithm is compared with the fuzzy control algorithm of power prediction in the experimental results section.

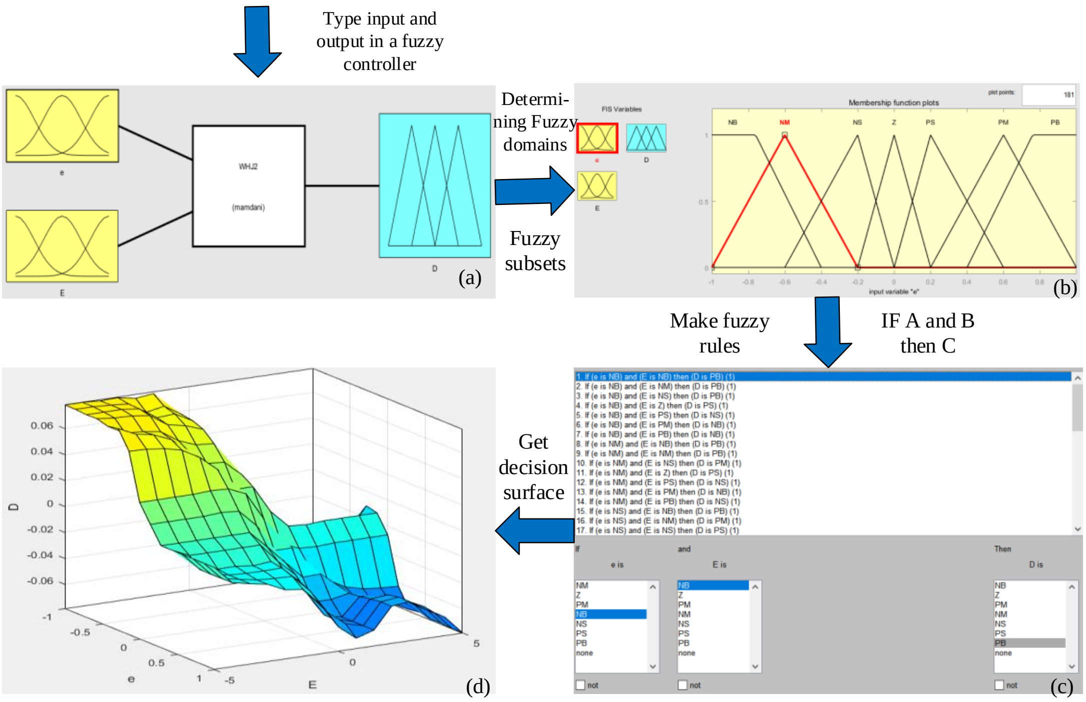

Fig. 5 - Working flowchart of the fuzzy control simulation module

Experimental circuits

The schematic diagram of the proposed MPPT circuit is shown in Figure 6. The output current and voltage of the PV cell array is measured in real time in order to perform the power prediction and fuzzy control algorithm. The current detection circuit converts current to voltage for its following ADC (analog-to-digital converter). And the output voltage of the PV cell array can be measured by the ADC circuit as well. The main controller board has multiple functions including ADC, UART (Universal Asynchronous Receiver/Transmitter), and PWM generation. The output PWM is generated by the main controller board for controlling the working status of the boost circuit. In addition, the power supply voltage for these boards is unified as 5V and is supplied by a low ripple linear power circuit.

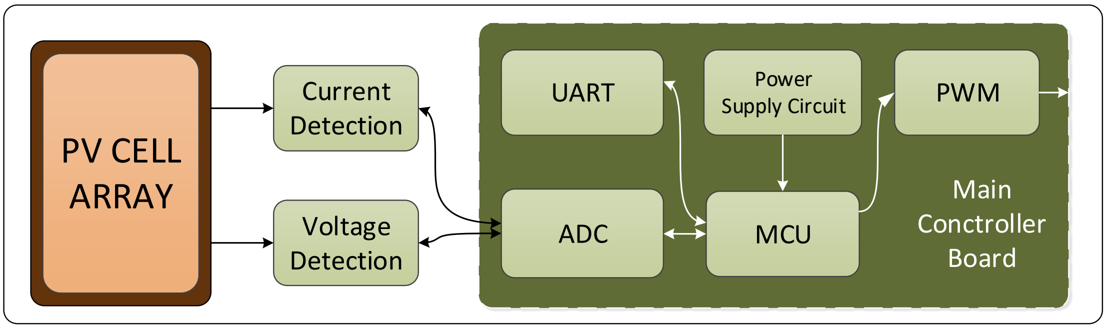

Fig. 6 - Schematic diagram of the MPPT circuit in this system

The applied circuits have been tested separated and are shown in Figure 7. The current detection circuit, which is shown in Figure 7 (a), has a maximum detection range from -5 A to 5 A. It converts current to voltage by using a ratio of 185 mV/A and the output voltage is linked to the ADC input port. The main controller board, which is shown in Figure 7 (b), is a highly integrated circuit with many functions. The main controller chip is STC15W4K56S4 that has 4 KB integrated RAM and 56 KB Flash. It has 8 ADC channels with 10 bit converting accuracy. In addition, the PWM generator is also integrated in this chip which is determined by the adopted algorithm for controlling the boost circuit. The boost converter circuit has a wide range of output voltage from 10V to 120V and is shown in Figure 7 (c). Considering the high output voltage, it also has a numeric display module to show the output voltage to avoid safety issues. The working frequency can be adjusted by the main controller board in order to drive loads or batteries.

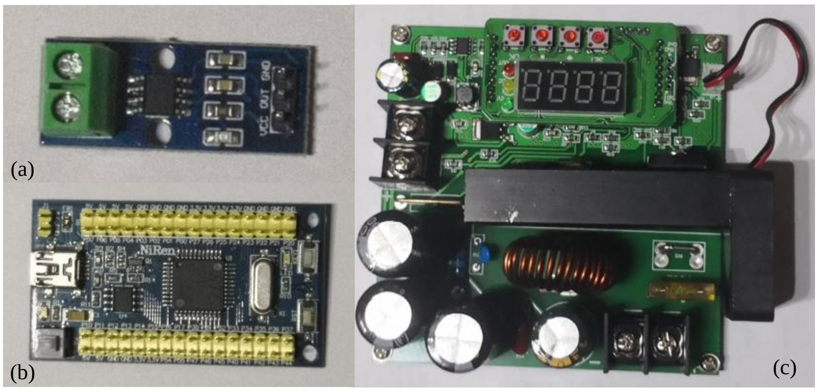

Fig. 7 - Current detection circuit (a), main control board (b) and Boost converter circuit for PV cell array system

RESTULTS AND DISCUSSION

- **Results**

Simulation results

In combination with the condition of the simulation setting in the previous section, the model is established in MATLAB/Simulink and the results are shown in Figure 8. Two curves of the proposed fuzzy control algorithm and the traditional fuzzy algorithm of the power prediction can be obtained as shown in Figure 8. It can be seen that the power prediction combined fuzzy control algorithm reaches MPP at 0.15 s and the traditional fuzzy control algorithm reaches MPP at 0.28 s. This result suggests that PV cell array system adopting the proposed fuzzy control algorithm can reach peak output power quicker and has less power waste comparing with the traditional fuzzy control algorithm.

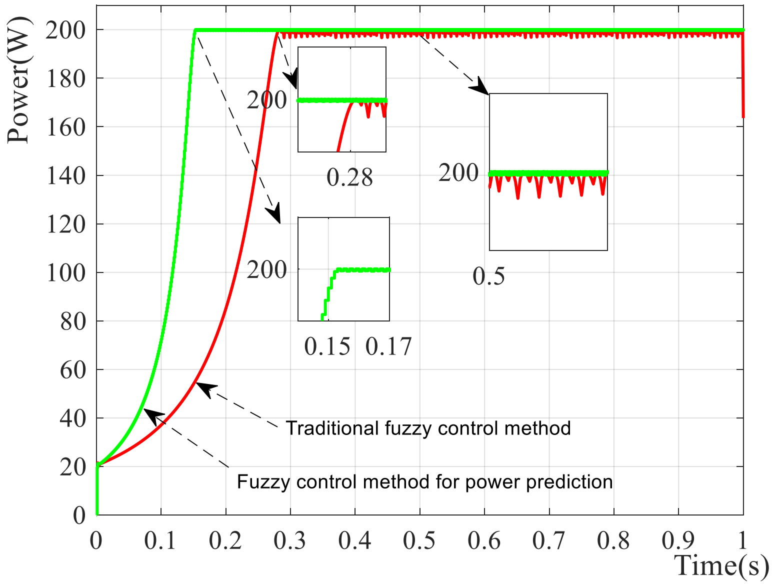

Fig. 8 - Comparison between the proposed and traditional fuzzy control algorithm

Robust test

A robust test of the simulated system adopting fuzzy control algorithm was carried out to investigate its performance in condition of environment factors varies. For instance, the luminous intensity drops from 1000 W/m^2 to 800 W/m^2 and the comparison curves are plotted in Figure 9. It can be seen that the curve of the proposed fuzzy control algorithm has a shorter response time the traditional fuzzy control algorithm. This also results in less power waste suggesting effectiveness of the proposed algorithm.

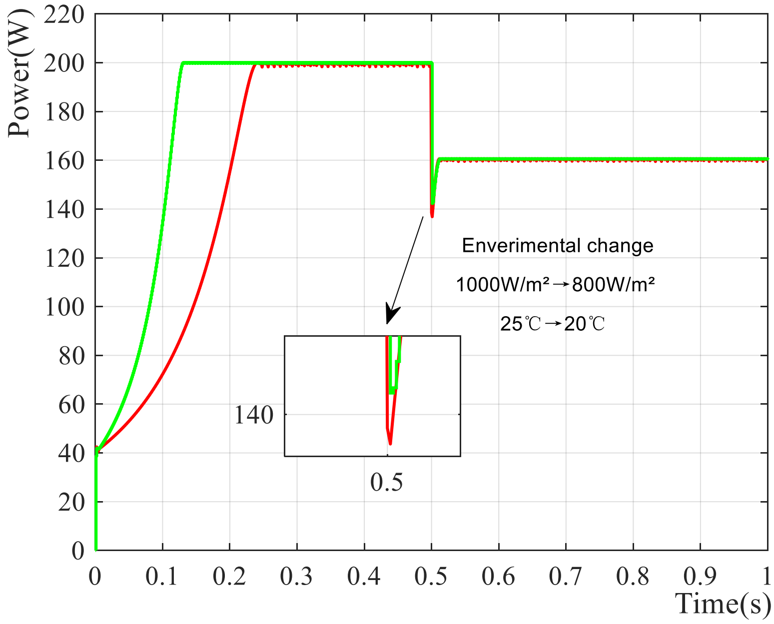

Fig. 9 - Contrast curves under the condition of environmental factors varies

Experimental results

Experiments were carried out to investigate the performance of the proposed algorithm by using the circuits demonstrated in the last section. The measured curves are shown in Figure 10. It can be seen that the red curve, which is the proposed fuzzy control algorithm combined with power prediction method, reaches its peak output voltage quickly when the system was powered on. The response time is much shorter than the black curve, which is the traditional fuzzy control method, though it was optimized to direct output without algorithm control. The experimental measurement shows the effectiveness of the proposed method.

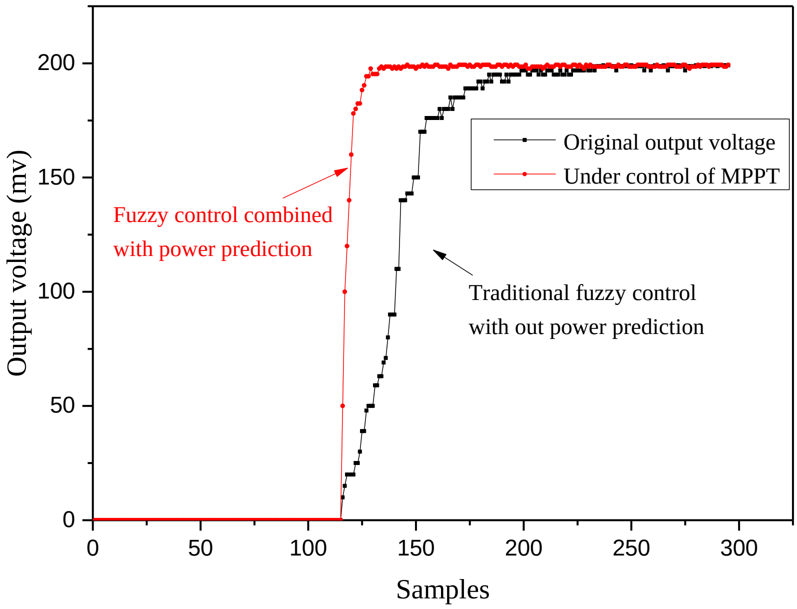

Fig. 10 - Response speed comparison

Discussion

The proposed algorithm has been verified by performing simulation and experimental measurement in above sections. For the agricultural greenhouse photovoltaic project demonstrated in this paper, MPPT algorithm is used to maximize the output power of the system. As shown in Figure 5, the power obtained by the fuzzy control algorithm using power prediction is 199.7~200.1 W, and the power loss is 0.2%. In this way, the proposed algorithm is capable to reduce power loss. The power obtained by using the traditional fuzzy control algorithm is 199.3~199.9W and the power loss is 0.4%. In the case of environmental change in Figure 6, the strain ability of the proposed algorithm is more efficient than the traditional method. In addition, the measured waveform displayed in the oscilloscope also demonstrated the effectiveness of the experiment.

CONCLUSIONS

In this paper, modulation and measurement has been carried out to minimize the energy loss in a photovoltaic cell array system. Fuzzy control algorithm and power prediction algorithm has been adopted and calculated. In this process, models have been established and relative parameters have been obtained experimentally. The duty cycle, which is shorted as D, is obtained by the model of power prediction algorithm and it is essential for the fuzzy control algorithm as its input. The PWM signal can be modified according to the environmental change based on the proposed method. In this way, the output power can reach its peak value quicker than traditional method and the power loss can also be minimized. Therefore, the photovoltaic cell array system can be optimized to generate more electricity. In the future, further experiments will be carried out to optimize the performance of the system in order to increase the efficiency of solar energy utilization.

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REFERENCES

[1] Abdourraziq M.A., Abdourraziq S., Maaroufi M., (2018), Efficiency optimisation of a microcontroller-based PV system employing a single sensor fuzzy-logic controller. *IET Power Electronics*, Vol. 11, pp. 539-547, Rabat/Morocco;

[2] Bechouat M., Sedraoui M., Feraga C.E. et al., (2019). Modeling and fuzzy MPPT controller design for photovoltaic module equipped with a closed-loop cooling system. *Journal of Electronic Materials*. Vol. 48, pp. 5471-5480, Guelma/Algeria;

[3] Blaifi S.A., Moulahoum S., Benkercha R. et al, (2018), M5p model tree based fast fuzzy maximum power point tracker, *Solar Energy*, Vol. 163, pp. 405-424, Medea/ Algeria;

[4] Boutabba T., Drid S., Chrifi-Alaoui L., (2018), A New Implementation of Maximum Power Point Tracking Based on Fuzzy Logic Algorithm for Solar Photovoltaic System, *International Journal of Engineering*, Vol. 31, pp. 580-587, Algeria;

[5] Chekired F., Larbes C., Rekioua D., et al, (2011), Implementation of a MPPT fuzzy controller for photovoltaic systems on FPGA circuit. *Energy Procedia*, Vol. 6, pp.541-549, Alger / Algeria;

[6] Dinesh H., Pearce J.M., (2016), The potential of agrivoltaic systems, *Renewable and Sustainable Energy Reviews*, Vol. 54, pp.299-308, Michigan/U.S.A.;

[7] Eltawil M.A., Zhao Z., (2013), MPPT techniques for photovoltaic applications, *Renewable and Sustainable Energy Reviews*, Vol. 25, pp.793-813, Saudi Arabia;

[8] Hassan G.E., Salah A.H., Fath H. et al., (2016), Optimum operational performance of a new stand-alone agricultural greenhouse with integrated-TPV solar panels. *Solar Energy*, Vol. 136, pp. 303-316, Alexandria/Egypt;

[9] Ju YT., Jin MX., Wang JK., (2019), Research on Optimal Dispatching Strategy for Micro-Energy-Grid of Protected Agriculture, *Applied Sciences-Basel*, Vol. 9, Beijing/China;

[10] Jones M., (2015), Systems modelling and economic analysis of photovoltaic (PV) powered water pumping and brackish water desalination for agriculture, *Dissertations & Theses – Gradworks*, Logan/Utah;

[11] Joshi P., Arora S., (2017), Maximum power point tracking methodologies for solar PV systems – a review. *Renewable and Sustainable Energy Reviews*, Vol. 70, pp.1154-1177, Guelma/ Algeria;

[12] Li C., Wang H., Miao H. et al., (2017), The economic and social performance of integrated photovoltaic and agricultural greenhouses systems: case study in China. *Applied Energy*, Vol. 190, pp.204-212, China;

[13] Murtaza AF., Ahmad R, (2019), Optical isolation mechanism based MPPT for PV array under partial shading condition, *Solar energy*, Vol. 185, pp..516-524, Lahore/Pakistan;

[14] Mishra A.K., Singh B., (2018), Design of solar-powered agriculture pump using new configuration of dual-output buck-boost converter, *IET Renewable Power Generation*, Vol. 12, pp.1640-1650, New Delhi/India;

[15] Maher A., Kamel E., Enrico F. et al., (2016), An intelligent system for the climate control and energy savings in agricultural greenhouses, *Energy Efficiency*, Vol. 6, pp.1241-1255, Tunis/Tunisia;

[16] Nabipour M., Razaz M., Seifossadat S.GH et al., (2019), A new MPPT scheme based on a novel fuzzy approach, *Renewable & Sustainable Energy Reviews*, Vol. 74, pp. 1147-1169, Ahwaz/ Iran;

[17] Osrio G.J., Matias J.C.O., Catalão. J.P.S., (2015), Short-term wind power forecasting using adaptive neuro-fuzzy inference system combined with evolutionary particle swarm optimization, wavelet transform and mutual information, *Renewable Energy*, Vol. 75, pp.301-307, Covilha/Portugal;

[18] Reddy J., Natarajan S., (2018), Control and Analysis of MPPT Techniques for Standalone PV System with High Voltage Gain Interleaved Boost Converter, *Gazi University Journal of Science*, Vol. 31, pp.515-530, Ankala/Turkey;

[19] Rubio-Aliaga A., Molina-Garcia A., Garcia-Cascales M.S. et al., (2019), Net-Metering and Self-Consumption Analysis for Direct PV Groundwater Pumping in Agriculture: *A Spanish Case Study*, Vol. 8, Cartagena/Spain;

[20] Sun C., Wang Y., (2016), Research of kind of variable step size perturbation and observation MPPT based on power prediction, *2016 IEEE International Conference on Mechatronics and Automation*， IEEE. Harbin/China;

[21] Xie Y., Wu Q., Wang Y. et al., (2013), A variable step MPPT optimized algorithm based on power prediction, *Control Conference*, China;

[22] Yilmaza U., Turksoy O., Tekec A., (2019), Improved MPPT method to increase accuracy and speed in photovoltaic systems under variable atmospheric conditions, *Electrical Power and Energy Systems*, Vol. 113, pp.634-651, Turkey.