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Analysis and Method Overview of Photovoltaic Cell MPPT Technology

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Abstract: This chapter mainly analyzes the principle of photovoltaic cell MPPT technology and various tracking algorithms, and compares and analyzes the three traditional classical tracking algorithms, perturbation observation method, incremental conductance method, constant voltage method, etc., as well as various improved algorithms evolved on their basis. At the same time, it also analyzes the intelligent control methods based on soft computing that have been studied more in recent years. For example, various intelligent control methods based on neural network control and fuzzy control. The advantages and disadvantages of the above methods are compared and analyzed. According to the shortcomings of these methods, the author puts forward his own improvement strategy, and verifies the superiority of the improved method by comparing and analyzing the improved method with the traditional method.

Keywords: Photovoltaic Power Generation; Maximum Power Tracking; Power Prediction; Disturbance Observation Method; There is no Oscillation in the Steady State.

1. Introduction

According to the analysis of the output characteristic curve of the photovoltaic cell above, it can be seen that there will be a maximum power point of the photovoltaic cell when the external light temperature [1] [2] [3] e is kept unchanged, and each maximum power point corresponds to the corresponding output voltage value of the photovoltaic cell Um. When the photovoltaic cell works at the maximum power point voltage Um, the photovoltaic cell will output the maximum power under the environmental state. Under different temperatures and illumination, the photovoltaic cell has different maximum power points, that is, corresponding to different Um. When the temperature and solar irradiation change, the state of the photovoltaic system must be changed and the working voltage of the battery must be adjusted to keep the system at the maximum power point, so as to improve the power generation efficiency.

According to the system equivalent structure of the photovoltaic cell, the circuit of the photovoltaic system can be simplified as the circuit shown in Figure 1, which consists of the photovoltaic cell and the external load RL, where the photovoltaic cell is composed of the ideal voltage source Ui and its internal resistance Ri in series.

Under this circuit, the output power Po of the photovoltaic cell is:

$$P_o = I^2 R_o = \left(\frac{U_i}{R_i + R_o} \right)^2 \times R_o \tag{1}$$

Under the condition that the environment is unchanged, Ri and Ui are unchanged, and the derivative of power Po with respect to Ro can be obtained:

$$\frac{dP_o}{dR_o} = {U_i}^2 \times \frac{R_i - R_o}{(R_i + R_o)^3} \tag{2}$$

When $\frac{dP_o}{dR_o}$=0, that is, when, Po takes its maximum value. That is, when the external load is equal to the internal resistance of the battery, the output power Po of the battery reaches the maximum value. The essence of MPPT technology is to adjust the size of the external load according to the environmental conditions, so that the value of the external load is equal to the internal resistance of the battery [1], so as to ensure that the battery has been working at the maximum power point [1], and output as much power as possible. In reality, since the connected external load value is generally uncontrollable, a DC-DC circuit is added between the load and the photovoltaic cell to adjust the equivalent load value by controlling the DC-DC duty cycle d. As shown in Figure 2,

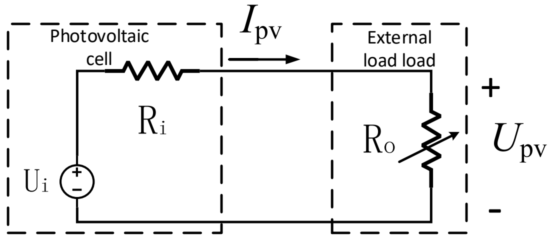

Fig 1. Equivalent circuit diagram of photovoltaic cell power output

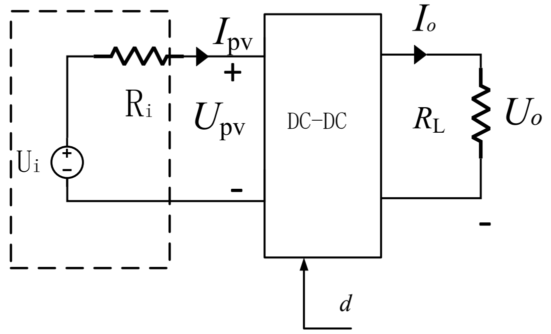

Fig 2. Equivalent circuit of PV system with DC-DC converter added

The DC-DC circuit variable voltage ratio is:

$$M(d) = \frac{U_o}{U_{pv}} = d \tag{3}$$

In the ideal state, there is no power loss of the converter, and according to the principle of power conservation, the power emitted by the photovoltaic cell acts completely on the load RL, then there is

$$P_{pv} = I_{pv} \times U_{pv} = U_o \times I_o \tag{4}$$

From (2-3) and (2-4), it can be deduced that the equivalent external load of the PV cell with the addition of the converter is R_{eq}

$$R_{eq} = \frac{U_{pv}}{I_{pv}} = \frac{U_o / M(d)}{I_o M(d)} = M(d)^2 R_o \tag{5}$$

It can be seen from Equation (5) that the equivalent external load of the photovoltaic cell after the converter is added is a function of d and R_o, that is, the size of the external equivalent load Req can be controlled by adjusting the duty cycle d to make it equal to the internal resistance Ri of the photovoltaic cell, so as to ensure that the photovoltaic cell works at the maximum power point.

2. MPPT Method is Commonly Used for Analysis

Common MPPT methods can be divided into the following four categories. The first category is perturbation-based methods, such as Perturb and Observe (P&O) and Variable step size perturbation method. The second category is admittance-based methods, such as Incremental Conductance, INC. The third category is model-based Methods, such as Model Predictive Control, which is commonly used by weather and system model-based predictive control. The fourth category is Artificial Intelligence Methods. Such as Fuzzy Logic Control (FLC), artificial neural network, particle swarm optimization algorithm, ant colony algorithm, bat algorithm, and hybrid particle swarm optimization algorithm, etc. [3].

2.1. The Perturbation-based Approach

1) Disturbance observation method

Disturbance observation method is one of the most commonly used and simple MPPT methods, which realizes the tracking of the maximum power point by periodically changing the operating point of the photovoltaic system, that is, applying small power disturbance to the photovoltaic array, and then observing the change of power. As shown in Figure 3, at the beginning, the photovoltaic system is set at an initial operating point, usually according to the preset initial voltage or power value. On the basis of the current operating point, a small power disturbance is applied to the photovoltaic array, that is, the voltage value is increased or decreased by a small step. After the disturbance, the output power of the photovoltaic array is measured, and the output power value is obtained by multiplying the current and voltage, and then the measured power is compared with the previous power. If the power increases, the operating point will continue to change in the direction of the disturbance. If the power decreases, the operating point is changed in reverse. In this way, the continuous comparison and adjustment gradually approach the maximum power point. When the power does not change or there is a small change, the stable working point is reached, and the system will continue to remain at this working point to achieve maximum power tracking [4]. The advantage of disturbance observation method is that the algorithm is simple and easy to implement, but its disadvantage is also obvious. In steady state, due to the existence of fixed disturbance step size, it will fluctuate back and forth near the MPP point, which makes it difficult to guarantee the speed and accuracy of tracking the maximum power point at the same time.

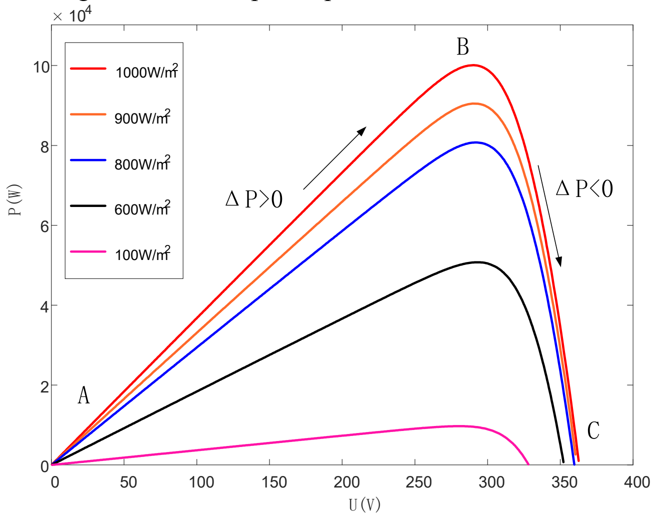

Fig 3. P-U characteristic curve of photovoltaic cell under different light

The algorithm flow of the disturbance observation method is shown in Figure 4. The flow chart is the disturbance observation method with fixed step size. Given the appropriate disturbance step size ΔU, the system can work near the maximum power point by continuously performing the algorithm.

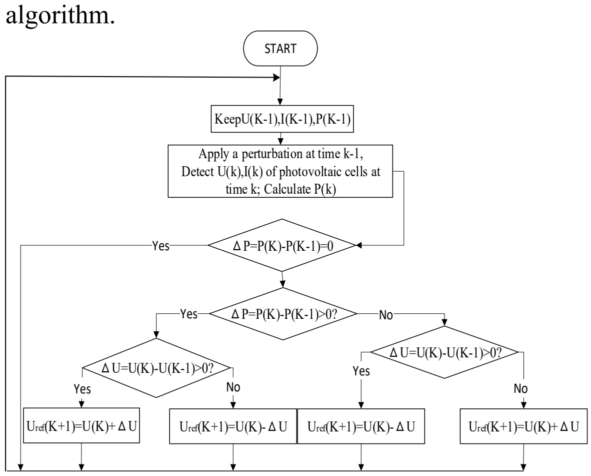

Fig 4. Flow chart of MPPT algorithm for disturbance observation (P & O)

2) Variable step size disturbance observation method

Due to the disturbance near the maximum power oscillation of problems existing in the method of observation, then a series of scholars put forward the disturbance observation variable step length, the introduction of all kinds of variable step size factor, such as the *ΔP* as a variable step length factor, introduced the step length of the |*ΔP*|*|*ΔU*|, |ΔP| will decrease with the of MPP point near, In this way, the disturbance is carried out with a large step length when it is far from the maximum power point, and the disturbance is adjusted with a small step length when it is close to the maximum power point. In this way, the problem of coordination between tracking speed and accuracy is solved. As shown in Figure 3, if the photovoltaic system works in segment A-B and is close to end A, it is far away from the maximum power point B, then A larger disturbance step will be used for tracking to improve the tracking speed. On the contrary, if the system is detected to be working near point B, the disturbance tracking will be carried out in small steps to reduce the shock near the steady-state MPP point.

The algorithm flow is shown in Figure 5

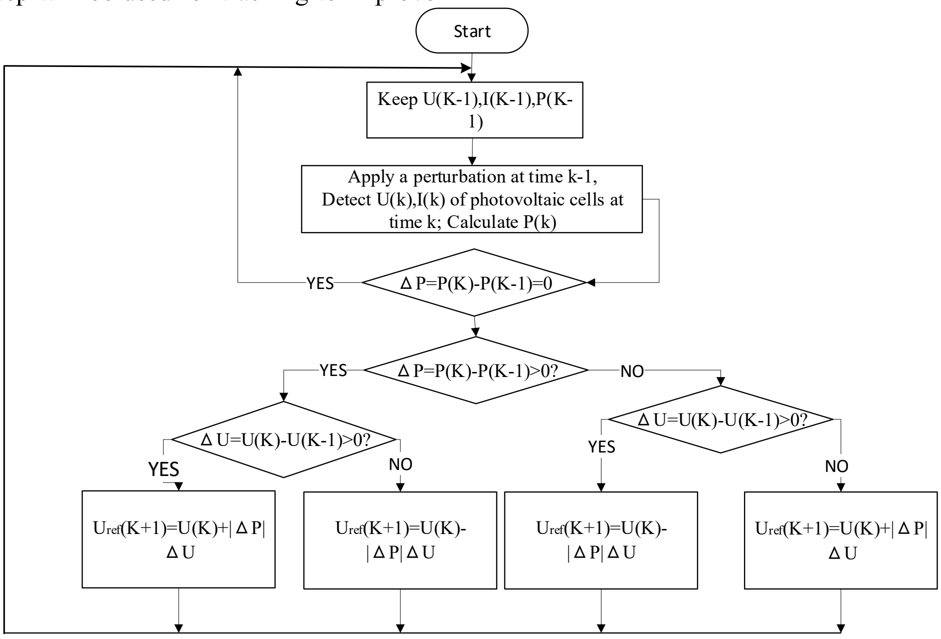

Fig 5. Flowchart of variable step size disturbance observation method

2.2. The Admittance Based Approach

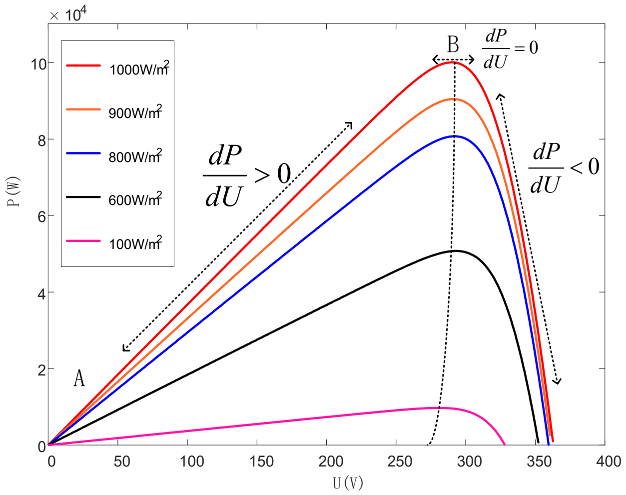

Fig 6. MPPT schematic diagram of increment conductance method

Incremental conductance method (INC) is a MPPT control algorithm by comparing the ratio of instantaneous immittance and immittance change rate of photovoltaic cells. The PV system is initialized as an initial operating point, which is usually set according to a preset initial voltage or power value. Based on the current and voltage measurements, the admittance change rate (slope) of the current and voltage is calculated. Comparing the current admittance change rate with zero, a very small value is often taken to approximately replace zero in practical engineering. In the P-V test curve shown in Figure 4, if the admittance change rate *dP/dU* is zero, it means that the current operating point is near the maximum power point and the current operating point is maintained; If the admittance change rate is positive, it indicates that the PV system has not yet reached the maximum power point and is in the stage A-B, so the operating point needs to be adjusted in the direction of higher voltage. If the admittance change rate dP/dU is negative, it indicates that the PV system has exceeded the maximum power point and is in the stage B-C, so the operating point needs to be adjusted in the direction of lower voltage. According to the positive and negative situation of admittance change rate, the working point is continuously adjusted [5].

The output power of photovoltaic cells is expressed as:

$$P = UI \tag{6}$$

With respect to the derivative of U on both sides of Equation (6), we obtain:

$$\frac{dP}{dU} = \frac{d(UI)}{dU} = I + U\frac{dI}{dU} = 0 \tag{7}$$

$$\frac{dI}{dU} = -\frac{I}{U} \tag{8}$$

According to the working principle of the incremental conductance method in Figure 6, when the external light and temperature conditions are stable, the following judgments can be made:

1) If the operating point of the photovoltaic cell is located on the left side of the MPP, $\frac{dP}{dU} > 0$, Equivalent to the $\frac{dI}{dU} > -\frac{I}{U}$,or $dU = 0$, $dI > 0$,According to the judgment, the positive direction of the disturbance voltage should be applied.

2) If the operating point of the photovoltaic cell is located to the right of the MPP, $\frac{dP}{dU} < 0$,Equivalent to the $\frac{dI}{dU} < -\frac{I}{U}$,or $dU = 0$, $dI < 0$,According to the

judgment, the disturbance voltage in the negative direction should be applied.

3) If the operating point of the photovoltaic cell is located near the MPP, $\frac{dP}{dU}=0$, or $\frac{dP}{dU}<\sigma$,(σ is a small number), it is judged that the voltage should be maintained at the voltage at this time.

The flow chart of the incremental conductance method is as follows:

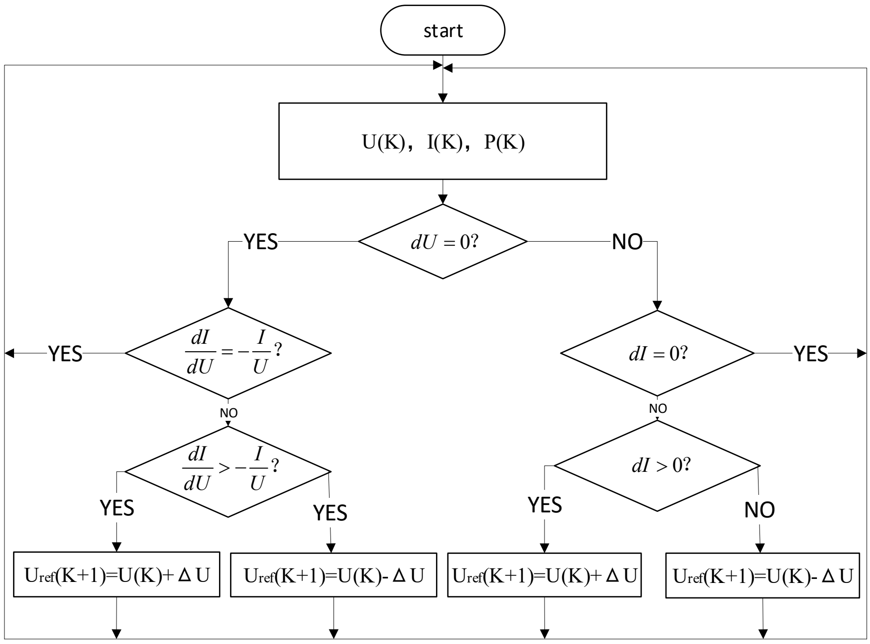

Fig 7. Algorithm flow chart of incremental conductance method

It can be seen from the above process that the advantages of incremental conductance method are obvious. It can achieve non-shock tracking in steady state, reduce the shock loss of the system, respond quickly and have high tracking accuracy. However, due to the division method involved, the measurement of instantaneous immittance and immittance change rate, the calculation performance of hardware is relatively high, and the algorithm is also difficult to implement. Problems such as local shadowing may fall into local optimum.

2.3. Model-based Approach

1) Photovoltaic system model predictive control method

The model predictive control method uses the mathematical model of the photovoltaic system to predict the power and adjust the operating point according to the prediction results. Usually, mathematical models of photovoltaic systems take into account factors such as light, temperature, and battery characteristics to predict the power output of the system. Maximum power point tracking is achieved by continuously predicting and adjusting the operating point to make the predicted power close to the maximum power. Its advantage is that it can use accurate system model for prediction, so it can achieve high MPPT accuracy in the case of more accurate system model modeling. The disadvantage is that the implementation of model predictive control method requires computing power, so as to carry out real-time power prediction and adjustment, requires accurate system parameters and environmental conditions, and has high requirements for modeling and parameter setting. To realize this method, it needs to be integrated with the weather prediction system, and it has high requirements on the accuracy and timeliness of weather prediction data. If there are errors or delays in weather forecast data, the effect of MPPT may be affected.

2) Constant pressure method

Constant voltage control method: a simple method that takes advantage of the fact that the voltage at the end of the photovoltaic cell is basically constant when the maximum power point of the photovoltaic cell changes, and controls the switching converter at the back end of the photovoltaic cell to keep the voltage at the end of the photovoltaic cell constant, so that the load power can approximately reach the maximum output power of the photovoltaic cell. In a short period of time, the output characteristics of photovoltaic cells can be divided into two cases: the temperature is basically unchanged and the light intensity can change instantaneously; The light intensity is basically unchanged while the temperature can change instantaneously [6]. When the light intensity changes within a small range and the temperature remains unchanged, the maximum power point is approximately distributed on an approximately vertical line as shown in Figure 8, so a vertical line can be used instead, that is, the voltage at the end of the photovoltaic cell is kept constant at Um1. Similarly, in the case of a small temperature change range, the maximum power point voltage also remains almost around the same voltage, as shown in Figure 9.

The constant voltage method is a relatively simple MPPT method, which does not require complex algorithms and sensors, and is easy to implement. It is suitable for many different types of photovoltaic systems and controllers, including single photovoltaic cells, photovoltaic arrays, etc., and has the advantages of good versatility and low cost. The disadvantage is that the output voltage of the PV system is usually maintained at a constant value, which cannot be adjusted in real time according to parameters such as real-time light intensity and temperature. Therefore, the optimal MPPT tracking may not be achieved when the light intensity changes rapidly or the PV cell temperature changes greatly.

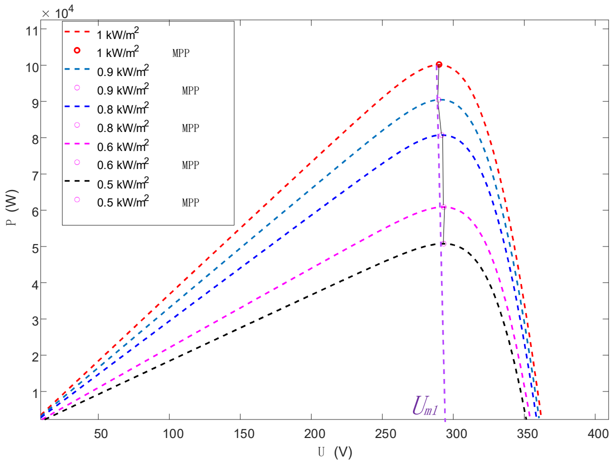

Fig 8. mpp points under different light intensity conditions

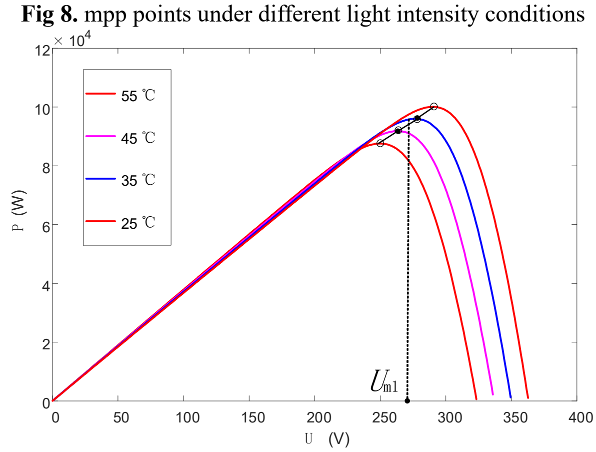

Fig 9. mpp points at different temperatures

2.4. Artificial Intelligence Approach

1) Fuzzy control method

The concept of fuzzy logic is based on the use of professional knowledge to design fuzzy logic controller, using the experience of experts as logic instructions, mainly including the following processes: variable definition, fuzzification, knowledge base, reasoning decision, defuzzification. Fuzzification is the transformation of traditional input values into fuzzy sets, that is, deterministic inputs into fuzzy membership values. The knowledge base is the experience of experts and consists of a large number of fuzzy rules that describe the relationship between inputs and outputs. The reasoning decision is to calculate the output fuzzy set according to the input fuzzy set through the fuzzy rules in the fuzzy rule base. Defuzzification is the conversion of fuzzy output into specific control instructions or operations, and techniques such as weighted average and center method are usually used to calculate the actual value of fuzzy output [8] [9] [10]. The principle of fuzzy method is shown in Figure 10.

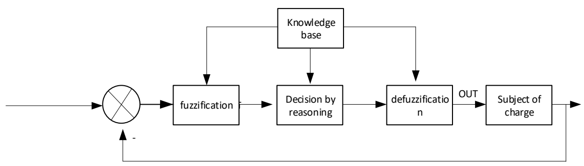

Fig 10. Block diagram of fuzzy control method

The advantage of fuzzy control is that fuzzy control is suitable for dealing with complex, uncertain or fuzzy control problems. For example, in the application of fuzzy control in MPPT, the slope *E(k)* of P-V curve and the derivative *dE(k)* of slope are usually taken as input variables, as shown in Equation 9, 10:

$$E(k) = \frac{p(k) - p(k-1)}{u(k) - u(k-1)} \tag{9}$$

$$dE(k) = E(k) - E(k-1) \tag{10}$$

p(k), *u(k)*, *p(k-1)*, *u(k-1)* are the power and voltage of the photovoltaic cell at the current moment and the power and voltage at the previous moment respectively; The output variable is the change of the disturbance duty cycle dU. The fuzzy variables *E(k), dE(k)* and *dU* are classified by setting the fuzzy language, which can be roughly divided into seven levels: *NB* (negative large), *NM* (negative medium), *NS* (negative small), *ZO* (zero), *PS* (positive small), *PM* (median) and *PB* (positive large), and the corresponding membership degree is set. Typical membership function distribution graph includes trigonometric function, trapezoidal function and so on. Figure 11 shows the distribution diagram of triangular membership function:

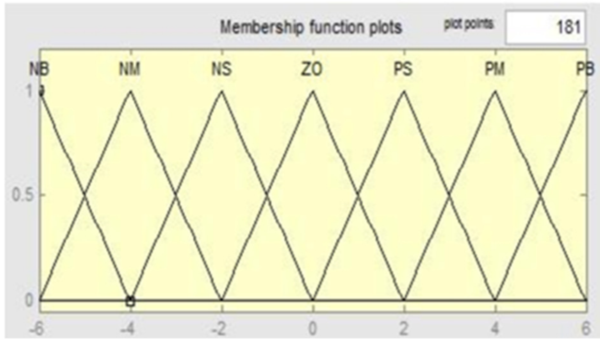

Fig 11. Distribution of triangular membership functions

According to the relationship between the position of the maximum power point and *E(k)* and *dE(k)*, there are the following basic fuzzy rules:

(1) If *E(k)*>0, *dE(k)*<0, Then the current output voltage is less than the maximum power point voltage and is in the approaching state, and the direction of output duty cycle disturbance should be kept unchanged.

(2) If *E(k)*>0, *dE(k)*>0, The current output voltage is less than the maximum power point voltage and is far away. In this case, the output voltage should be increased and the output duty cycle should be reduced.

(3) If *E*(k)<0, *CE*(k)>0, If the current output voltage is greater than the maximum power point voltage and is in the state of approaching, the direction of output duty cycle perturbation should be kept unchanged.

(4) If *E*(k) <0, *CE*(k)<0, If the current output voltage is greater than the maximum power point voltage and is far away, the output voltage should be reduced and the output duty cycle should be increased.

Establish detailed fuzzy rules based on the above basic principles, as shown in Table 1. The fuzzy quantity of *dU* is derived according to the decision part, and the variable can be processed by the defuzzer to obtain the accurate quantity that the actual system can accept, and used for the later controlled object, so as to control the system to track to the maximum power point.

The fuzzy control has good robustness to the change of system parameters and noise, and the control system can still maintain relatively stable performance even when the parameters are changed or the input is noisy. It does not rely on complex mathematical models and calculations, but the design of an appropriate fuzzy rule base is the key to fuzzy control, which needs to be based on expert knowledge and experience. If the rules are not properly designed, the control effect may be poor.

Table 1. Fuzzy control rules

EdE	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	ZO
NM	PB	PB	PM	PS	PS	ZO	NM
NS	PB	PM	PS	PS	ZO	NS	NM
ZO	PB	PM	PS	ZO	NS	NM	NB
PS	PM	PS	ZO	NS	NS	NM	NB
PM	PS	ZO	NS	NM	NM	NB	NB
PB	ZO	NS	NM	NB	NB	NB	NB

2) Neural network control method

Neural network algorithm is a network system that simulates the information transmission mode of neurons in the brain and is connected to each other according to a certain topology structure. The main characteristics are that it does not rely on the system model to achieve control and has strong nonlinear fitting ability. At present, it is widely used in photovoltaic irradiation prediction, photovoltaic model, parameter identification, photovoltaic system selection, photovoltaic structure optimization and photovoltaic MPPT strategy [7][8][9]. It is often used in MPPT for neural network algorithms such as RBF neural network algorithm. Figure 11 shows the framework of RBF neural network:

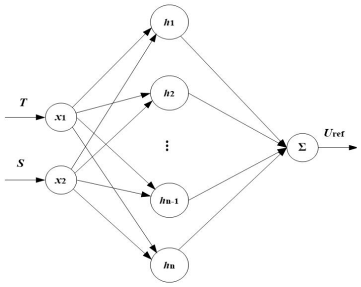

Fig 12. RBF neural network structure diagram

RBF neural network has a simple structure, can approximate non-sexual functions with arbitrary accuracy, and has global search ability. Its structure is input layer, hidden layer and output layer. The mapping relationship between the input layer and the hidden layer is determined by the function center of the selected RBF, and the output layer is the linear weighting of the hidden layer. The node function *h(x)* of the hidden layer is Gaussian function. The illumination intensity *S* and temperature *T* are taken as input layer, and the reference voltage *Uref* of the maximum power point is taken as output layer. The specific relationship is as follows:

$$U_{ref} = \sum_{j=1}^{n} w_j \cdot h_j \tag{11}$$

$$h_j = \exp[\frac{\left\| x - c_j \right\|}{2b_j^{\ 2}}] \tag{12}$$

$$x = [T, S]^T \tag{13}$$

Where w_j -- the weight vector of the JTH node in the hidden layer; c_j -- neural network center vector of the JTH node in the hidden layer; b_j -- width of Gaussian basis function of the JTH node of the hidden layer; X-neural network input variable; U_{ref} - neural network output variable; The output variable U_{ref} is obtained after a certain number of iterations. The advantage of RBF neural network is that it has strong generalization ability and is good at analyzing complex nonlinear systems. The disadvantage is that its calculation results are highly dependent on the collected sample data, and the unstable sample will lead to the reduction of calculation accuracy.

3. The Perturbation based Approach

The control algorithm of MPPT has many forms, and its ultimate purpose is to eliminate all kinds of interference and speed up. Faster and more stable to find the maximum power tracking point, and can achieve real-time tracking. Each algorithm has advantages and disadvantages in the right ring. The use of appropriate algorithm, which needs to consider the characteristics of the algorithm itself, stability and reliability.

There are many measurement standards of MPPT algorithm, such as the complexity of the algorithm, if the algorithm research is more complex, high requirements, greatly increase the cost, but usually more accurate, has a great impact on the final results, and for the accuracy of the algorithm, the difficulty of operation and the difficulty of parameter adjustment are the criteria to distinguish the complexity of the algorithm; Secondly, for the efficiency of MPPT control algorithm, if the output power efficiency of MPPT algorithm is low, then the advantages of MPPT algorithm will not be played; Then there is the problem of anti-interference. When adjusting the parameters during the operation of the MPPT algorithm, the deviation of the overall output efficiency will occur because of the external environmental conditions or load problems, which will lead to the misjudgment of the system. If the system cannot respond quickly to the adverse situation, it will lead to greater accidents. The change of the working characteristics of photovoltaic cells with the MPPT algorithm should also be taken into account. How to judge the maximum power point more quickly and accurately according to the working characteristics of photovoltaic cells is one of the directions of current research. Therefore, it can be known from the above that a safe, stable and efficient MPPT control algorithm should be relatively simple to operate, and can better improve the operation efficiency, and have good anti-interference and response characteristics when the system is disturbed.

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