Power output control method of small power photovoltaic grid connected power generation under complex illumination

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Abstract—Due to the irregular change of lighting conditions, there is a large error in the control of photovoltaic grid connected power output. Therefore, this paper proposes a power output control method for low-power photovoltaic grid-connected power generation considering complex illumination. Based on the analysis of the basic characteristics of photovoltaic grid connected power generation, the output characteristics of photovoltaic array under complex lighting conditions are studied. Combined with its variation characteristics, based on fuzzy control strategy, the output of photovoltaic grid connected energy storage system is adjusted by filter control with variable time constant, and economic operation and stable operation are taken as constraints. The test results show that the design method has a high degree of fit between the control of photovoltaic grid connected power output and the actual results, and the error is within a reasonable range, which is obviously due to the two groups of comparison methods.

1. INTRODUCTION

The traditional primary energy such as coal, oil and natural gas has been used by human beings for a long time, but the energy on our earth is actually very limited and can not be consumed by human beings without limit, and will be exhausted one day [1-2]. There is only one feasible way: vigorously develop new energy. Since the end of last century, countries all over the world have paid more and more attention to the development and utilization of new energy [3-5]. Solar energy is a green and clean alternative energy. However, today's solar photovoltaic power generation still has some defects, such as low efficiency, high power generation cost and high on grid electricity price. These defects lead to the inability of large-scale production of solar photovoltaic power generation and limit its large-scale promotion and utilization, which is greatly constrained in economic benefits [6]. Therefore, taking measures to greatly improve the utilization rate of light energy and reduce the power generation cost is the top priority of photovoltaic power generation research. It is assumed that when the light intensity of the sunlight perpendicular to the surface of the silicon wafer and the temperature of the silicon wafer are constant, the output volt ampere characteristics of the solar cell are theoretically determined for the same photovoltaic module, and there is a maximum power value when the photovoltaic panel is not aged and covered. Therefore, in order to maximize the use of solar energy and reduce the power generation cost, it is necessary to make the photovoltaic cell run near the maximum power output node as far as possible, for example, by adjusting the equivalent impedance of the load. At the same time, it will also affect the stable output of power, and even make the power curve fluctuate seriously. If no measures are taken, the photovoltaic module will enter an unstable working state. Photovoltaic power generation is a new power generation mode that directly converts solar radiation energy into electric
energy by using the photovoltaic effect of solar cell semiconductor materials. However, photovoltaic power generation is random and intermittent, which will affect the quality of power and aggravate the fluctuation of power grid. Equipped with certain energy storage in the light energy system, it can effectively suppress power fluctuation and improve the safety and stability of power grid operation. Therefore, the smooth control of the output power of the optical energy motor unit has become the focus of research.

2. ANALYSIS OF BASIC CHARACTERISTICS OF PHOTOVOLTAIC GRID CONNECTED POWER GENERATION

2.1. Analysis of basic properties of photovoltaic cells

The basic model of photovoltaic cell based on light energy is shown as Figure 1.

According to the equivalent circuit diagram, the KCl current equation can be obtained

\[ I_{pv} = I_{ph} - I_D - I_{sh} \] (1)

among,

\[ I_{ph} = [I_{sc} + K(T - T_{ref})] \frac{S}{S_{ref}} \] (2)

\[ I_D = I_{rs} \left[ \exp \left( \frac{q}{AKT} (U + i_{pv} R_s) \right) - 1 \right] \] (3)

Where \( I_{pv} \) represents the output current of the photovoltaic panel, \( I_{ph} \) represents the photogenerated current, \( I_D \) represents the short-circuit current of the photovoltaic cell, \( U \) represents the external voltage of the photovoltaic cell, \( R_s \) represents the series resistance, \( R_{sh} \) represents the parallel resistance, \( I_{sh} \) represents the forward current of the PN junction, \( I_{sc} \) represents the leakage current of the PN junction, \( i_{pv} \) represents the reverse saturation current of the diode, \( K \) represents the temperature coefficient, \( k \) is the Boltzmann constant (1.38 \times 10^{-23} \text{J/K}), \( q \) represents the charge of electrons (1.6x10^{-19} \text{C}), \( A \) represents the diode characteristic factor, \( T_{ref} \) represents the standard cell temperature, \( T \) represents the photovoltaic cell temperature, \( S_{ref} \) represents the standard light intensity, \( S \) represents the light intensity.

In practical application, it is found that the series resistance \( R_s \) is very small, while the parallel resistance \( R_{sh} \) is very large. Therefore, we can further simplify the analysis of the above formula, so we can obtain the characteristic equation representing the ideal solar cell:

\[ I_{pv} = I_{ph} - I_{rs} \left[ \exp \left( \frac{qU}{AKT} \right) - 1 \right] \] (4)
On this basis, the photovoltaic cell model based on MATLAB / Simulink is constructed.

3. STUDY ON OUTPUT CHARACTERISTICS OF PHOTOVOLTAIC ARRAY UNDER COMPLEX ILLUMINATION

When the illumination is uneven, the illumination intensity of each battery panel is different, and the photovoltaic voltage and current generated are different. The diodes connected in parallel to the battery panel may form a positive voltage and be in the on state, which changes the $I-V$ characteristics and $P-V$ characteristics of the series array.

(1) When the output current of the series array is within $[0, I_{sc}]$, the bypass diode is in the reverse bias state without conduction. The photovoltaic panels $S1$ and $S2$ flow the same current and can output power externally. The voltage of the series array is equal to the sum of the output voltages of $S1$ and $S2$, i.e

$$V = V_{S1} + V_{S2} = \frac{nKT}{q}[(\ln \frac{I_{sc}}{I_0} + 1)] - 2IR_S \quad (5)$$

The current $\max I_{S2} \in (0, I_{sc})$ at the maximum power point of photovoltaic panel $S2$ can be obtained from the output characteristics of photovoltaic cells. When the output current of the series array is within $[0, \max I_{S2}]$, with the increase of the current, the voltage of the photovoltaic panel $S2$ decreases within the interval $[\max V_{S2}, V_{oc}]$, and the output power of the corresponding photovoltaic panel $S1$ and $S2$ increases, resulting in the increase of the output power of the series array, in which the output power of $S2$ increases from 0 to the maximum power $\max P_{S2}$. When the output current of the series array is in $[\max I_{S2}, I_{sc}]$, with the increase of the current, the voltage of the photovoltaic panel $S2$ decreases in the interval $[0, \max V_{S2}]$, and the output power of the photovoltaic panel $S2$ decreases. Therefore, when the output current of the series array is within $[0, I_{S2}]$, the output power of the array is the sum of the output power of photovoltaic panels $S1$ and $S2$. With the increase of current, it first increases and then decreases, reaching a local peak near $\max I_{S2}$.

(2) When the output current $I$ of the series array is within $[I_{S1}, I_{S2}]$, the current generated by the photovoltaic panel $S1$ is greater than the current generated by $S2$, the bypass diode of $S2$ is in the forward bias state and turned on, and the current flowing through is $I - I_{S2}$. In this case, the photovoltaic panel $S1$ outputs power to the outside. The voltage of the series array is equal to the sum of $S1$ and the bypass diode, i.e

$$V = V_{S1} + V_{S2} = \frac{nKT}{q}[(\ln \frac{I_{Ph}}{I_0} + 1)] - IR_S - V_D \quad (6)$$

Thus, the series array in $[I_{S1}, I_{S2}]$, series array output voltage and photovoltaic cell $S1$ voltage difference diode on-voltage drop, their output characteristics are basically the same. The maximum power point of photovoltaic cell $S1$ is within this range, so the series array has a peak power point in this range.

4. RESEARCH ON POWER OUTPUT CONTROL OF PHOTOVOLTAIC GRID-CONNECTED GENERATION

4.1. Smooth output control of energy storage system

The power fluctuation of smooth renewable energy is mainly divided into short time power fluctuation and long time power fluctuation, and the time scale of short time fluctuation is generally S-class. Long-term power fluctuation time scale for the general min level, generally applied to renewable energy and
load short-term power mismatch between the following analysis of photovoltaic grid-connected smooth output control.

4.1.1 Filtering control of variable time constant
Because of the dynamic change of illumination condition, the fixed filter can not meet the output requirement. Therefore, the variable time constant is added in this paper, and the filter time constant is adjusted at the same time to keep the SOC of the energy storage system in a certain range, so as to achieve the goal of smoothing the output and taking into account the life of the storage battery. The control structure is shown in Figure 2.

\[ \text{Adjust the time constant } T \text{ according to SOC} \]

Figure 2. Filter control structure of variable time constant

Among them, \( T_s \) is the filtering time constant, according to the principle of system filtering function, the output power of energy storage system is proportional to the time constant \( T_s \). Therefore, when the SOC of energy storage battery is high, the charging power of energy storage system can be reduced by decreasing the time constant \( T_s \), which can effectively prevent the SOC from exceeding the upper limit. Similarly, when the energy storage battery is in the low position and the battery is in the state of discharge compensation, reducing the time constant \( T_s \) can effectively prevent the SOC from exceeding the lower limit.

4.2 Control constraints
On the basis of the above, but also on the photovoltaic grid-connected power output control constraints, this paper mainly from the following two aspects.

4.2.1 Photovoltaic grid-connected economic operation
In the process of battery operation, large charging and discharging current and over charging and over discharging will affect the battery life, so it is necessary to make the battery work in a certain bound range. To this end, we must first control the current and voltage.

(1) Current constraint conditions, when the charging and discharging current of the battery exceeds the limit, the service life of the battery will be affected.

\[ I_{sc} < \max I_{sc} \quad (7) \]

(2) Voltage constraints, when the battery voltage is lower or higher than a certain value will affect the battery life.

\[ V_{\min} < V < V_{\max} \quad (8) \]

Among them, \( V_{\min} \) and \( V_{\max} \) represent the minimum and maximum of the charging and discharging voltage of the battery respectively.

(3) SOC constraints for storage batteries: the storage batteries must be operated between the minimum and maximum SOC values, and the service life of the storage batteries will be affected if they exceed the limits.
Under the condition of economic operation, the control strategy of energy storage system searches for fuzzy rules according to the SOC status of storage battery, PV power forecast value, load forecast value and $P_e$ exchange status of current PV power interconnection line, and achieves the control of battery charging and discharging to achieve the goal of economic operation. The fuzzy rules table is shown in Table 1.

| $P_e$ | SOC | $P_{pv}$ |
|---|---|---|
| $+$ | $[0, SOC_{min}]$ | $[0,0.25]$ | $[0.25,0.50]$ | $[0.50,0.75]$ | $[0.75,1.00]$ |
| $+$ | $[SOC_{min}, SOC_{max}]$ | $[0,0.25]$ | $[0.25,0.50]$ | $[0.50,0.75]$ | $[0.75,1.00]$ |
| $-$ | $[0, SOC_{min}]$ | $[0,0.25]$ | $[0.25,0.50]$ | $[0.50,0.75]$ | $[0.75,1.00]$ |
| $-$ | $[SOC_{min}, SOC_{max}]$ | $[0,0.25]$ | $[0.25,0.50]$ | $[0.50,0.75]$ | $[0.75,1.00]$ |

In the table, $P_e$ for "+$" means positive power status: photovoltaic grid-connected to the distribution network to sell electricity; For "-$" means negative power status: means photovoltaic grid-connected distribution network to buy electricity.

4.2.2 Photovoltaic grid-connected stable operation
On the premise of guaranteeing the service life of the battery, the fuzzy control of the storage battery is designed according to the power fluctuation and the continuous power supply capacity of the system. Based on the current SOC status of the battery, the predicted photovoltaic power and the predicted load value, the system can run stably by querying the fuzzy rule table. The fuzzy rules table is shown in Table 2.

| SOC | $P_{pv}$ |
|---|---|
| $[0, SOC_{min}]$ | $[0,0.25]$ |
| $[SOC_{min}, SOC_{max}]$ | $[0.25,0.50]$ |
| $[SOC_{min}, SOC_{max}]$ | $[0.50,0.75]$ |
| $[SOC_{high}, SOC_{max}]$ | $[0.75,1.00]$ |

On this basis, to ensure the reliability of the control.

4.3. Fuzzy control output
On the basis of the above, the output of defuzzy control is the process of converting the fuzzy quantity of fuzzy inference and decision output into the definite control quantity, which corresponds to the fuzzy quantity of the system. According to the symmetry of the output fuzzy set in this paper, the output defuzzy quantity is obtained by weighted average method. The calculation formula is shown in formula (10).

$$P^* = \sum_{i=1}^{n} \mu(P_i)P_i / \sum_{i=1}^{n} \mu(P_i)$$ (10)
In the equation, \( P_i \) and \( \mu(P) \) represent the center of mass and the value of membership function of symmetric membership function respectively. The actual control quantity can be obtained by solving \( P^* \) according to the above formula and multiplying by the corresponding scale factor.

5. SIMULATION OF POWER CONTROL FOR PHOTOVOLTAIC POWER STATION

5.1. Experimental environment design

Using Matlab/Simulink to build 20 photovoltaic power plant models and active power control models with the rated power of 1MW, and through the simulation of the photovoltaic power plant output power control to verify the distribution strategy proposed in this paper, the control model is shown in Figure 3, in simulation, it is assumed that each photovoltaic inverter is in normal state.

5.2. Test results

The output power of photovoltaic power station is set to 12 MW, 11 MW, 10 MW, 9 MW, 8 MW, 9 MW, 10 MW and 11 MW respectively at different time periods. The output power curve of photovoltaic power station is shown in Figure 5 by using the method proposed in literature [8] and literature [9] as a comparison.

As can be seen from the figure 4, the set power of the photovoltaic power plant is lower than the predicted power of the photovoltaic power plant. When the set value is constant, the actual output power of the PV plant can ensure the stable output of the set power. When the set power is changed, the PV plant can complete the tracking of the new set power in a short time.

6. CONCLUSION

With the rapid development of solar photovoltaic power generation technology in the world, more and more large scale photovoltaic power plants begin to be connected to the power grid, and the stability of
the power grid caused by this problem is becoming more and more serious. In order to improve the stability and dispatchability of output power of photovoltaic power station and promote the acceptance of large scale photovoltaic power station, this paper studies the control strategy. The simulation results show that the active power control method studied in this paper can meet the requirements of active power control of photovoltaic power plants.

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