Research on Energy Storage and Hydrogen Production System of Offshore Wind-solar Hybrid Power Generation Based on 3D Finite Element Method

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Abstract. At present, hydrogen, as a fuel, has the characteristics of high efficiency and no pollution, which can replace traditional fossil energy and be used in various fields to a certain extent. Using clean energy such as wind and light to electrolyze water to prepare hydrogen can realize zero pollution in the whole process from hydrogen preparation to use. Such energy conversion and use can reduce air pollution, improve air quality and solve the problem of abandoning wind and light. In this paper, a simulation model is established by using three-dimensional finite element method, and meteorological parameters are input into the model, so as to obtain the power generation, hydrogen production rate and the efficiency of converting solar energy, wind energy and electric energy into hydrogen energy under different capacity configurations of each part of the system. Using the model established in this paper, the parameters of wind and solar energy resources, environmental factors and load power in different regions are input. By changing the battery capacity, observing the battery operation and DC bus output, the battery equipment suitable for the whole system can be selected.

1 Introduction

Offshore wind-solar hybrid power generation system is a renewable clean energy efficient utilization system based on separate wind power generation and photovoltaic power generation systems. Since 1990s, the utilization of renewable energy has developed rapidly, and many countries in the world have taken clean energy as the basis of their energy policies. By 2015, at least 120 countries in the world have formulated various renewable energy promotion policies; At least 32 countries and 5 regions have implemented policies to encourage the use of new energy [1]. From the utilization and development trend of new energy in the world, wind energy, solar energy, biomass energy and fuel cells (mainly in the transportation field) have good development prospects.

Offshore wind-solar hybrid power generation hydrogen production system can be roughly divided into two categories: one is off-grid type, that is, wind and light generate electricity independently, and provide electric energy to electrolyzer for hydrogen production. This type has the advantages of low investment, high flexibility and easy management. The other type is grid-connected. After being inverted by an inverter, the wind turbines and photovoltaic panels are integrated into the power grid, and the electricity of the power grid or the remaining electricity beyond the capacity of the power grid is used to electrolyze water to produce hydrogen [2]. This way can realize energy storage and reduce the impact on the power grid.

Traditional solar and wind power generation systems all use batteries to store energy, which have the characteristics of high efficiency, low energy density, high self-discharge efficiency and unsuitable
for long-term storage. Hydrogen energy has the advantages of high energy density, easy long-term storage and no leakage. The energy storage system for hydrogen production by wind-solar hybrid power generation integrates solar energy and wind energy, thus providing a reliable energy supply system [3-4]. This system makes a good technical reserve for the practical application of hydrogen production and energy storage system in remote areas, weather stations and barracks posts, which has very important practical significance.

2 Wind-solar hybrid energy storage power generation hydrogen production system

The offshore wind-solar hybrid power generation energy storage hydrogen production system is mainly composed of wind turbines, solar photovoltaic batteries, controllers, energy storage devices, inverters, electrolyzers and other parts. The specific process is that the surplus energy is stored in the energy storage device by the DC power supply from the photovoltaic array and the wind turbine generator set through the controller, and then converted into alternating current through the inverter for hydrogen production by electrolysis of water.

2.1 Photovoltaic power generation part

Photovoltaic cell is a semiconductor device that directly converts light energy into electric energy, which generates current and voltage after being irradiated by light. Photovoltaic effect refers to the physical phenomenon that semiconductors under sunlight can generate electromotive force. Structurally speaking, the photovoltaic cell can be regarded as a large-area planar P-N junction, in which the P region is negatively charged and the N region is positively charged [5]. Once exposed to sunlight, conductive carriers, i.e. holes and electrons, will be generated on the P-N junction. Under the action of electrostatic field, the potential in the P region increases and the potential in the N region decreases, thus generating electromotive force at the P-N junction and forming photovoltaic effect. Generally, the current when the P-N junction is short-circuited is called short-circuit current, and the potential difference when the P-N junction is short-circuited is called open-circuit voltage. If the P-N junction is connected with the peripheral circuit, the circuit will always conduct under the illumination condition, and then the P-N junction is equivalent to the power supply, providing power for the peripheral circuit.

2.2 Wind power generation part

The wind power generation system is generally divided into four parts, namely, the wind wheel mechanism, the wind power generation cabin, the foundation of the wind power generation system at the bottom, and the tower on which the wind wheel and the cabin are installed. After the wind turbine generator is started, the captured wind energy is converted into kinetic energy of high-speed rotation of the wind turbine, and the high-speed rotation of the wind wheel drives the mechanical rotating parts to move, so that the rotor of the wind turbine generator rotates to complete the start; With the increase of rotor speed, the stator side of the generator outputs electric energy. To sum up, the main function of wind power generation system is to convert wind energy into mechanical energy, and then convert mechanical energy into electrical energy through wind power generator.

According to the classification of different institutions, there are many kinds of wind turbines, and each has its advantages and disadvantages. Commonly used wind turbines are usually divided into three types [6-7]: Constant speed constant frequency induction generator, variable speed constant frequency doubly-fed asynchronous generator and variable speed constant frequency direct drive permanent magnet synchronous generator. Variable speed constant frequency wind turbine has many advantages, such as easy speed regulation, flexible control method and easy realization, so it is a hot spot of application and research at present.
3 Simulation study on hydrogen production system of offshore wind-solar hybrid power generation with energy storage

3.1 Three-dimensional finite element mathematical model of wind-solar hybrid power generation system

The offshore wind-solar hybrid power generation system is basically a simple superposition of ordinary wind power and photoelectric conversion in the energy collection part, and its mathematical model can also be regarded as a description of the independent operation state of photovoltaic power generation and wind power generation respectively.

3.1.1 Photovoltaic power generation model

Photovoltaic power generation relies on photovoltaic effect of electrical components to directly convert solar energy into direct current energy. When lighting conditions are constant, photovoltaic cells can be regarded as a constant current source. When the external circuit of the photovoltaic cell is connected to the load, the photovoltaic current flowing through the load will form potential at both ends of the load.

\[ I_{ph} = \frac{V_{pv}}{R_{sh}} \]

As shown in fig. 1, in the equivalent circuit of a single photovoltaic cell, the photogenerated current generated by the photovoltaic cell under sunlight radiation is represented by a constant current source \( I_{ph} \); \( I_D \) is the total diffusion current of P-N junction (expressed by the forward current of diode); The series resistance of the battery (used for inherent resistance) is \( R_s \), which is generally between \( 10^{-3} \) ohms and several ohms, mainly including the basic resistance, surface resistance and electrode resistance of the battery; The parallel resistance \( R_{sh} \) represents the resistance caused by the inherent defects of the semiconductor crystal inside the battery in the manufacturing process, and the value of \( R_{sh} \) can reach several thousand ohms, so the current flowing through the parallel resistance is very small and can be ignored.

According to the equivalent circuit of the photovoltaic cell, the volt-ampere characteristic formula of the photovoltaic cell under certain illumination conditions and cell temperature can be derived:

\[
I_{pv} = I_L - I_D = I_L - I_O \left( e^{(V_{pv} + R_s I_{pv}) / (A q k T)} - 1 \right)
\]

In which:
- \( I_{pv} \) —— Output current supplied by photovoltaic cell to load;
- \( I_L \) —— Photogenerated current;
- \( V_{pv} \) —— Output voltage across the load;
- \( I_O \) —— Reverse saturation current of diode;
- \( q \) —— Electron charge, \( q = 1.6 \times 10^{-19} \text{ J/k} \);
- \( A \) —— The ideal constant factor of diode, \( A = 2 \).
**Boltzmann constant**, \( k = 1.38 \times 10^{-23} \, \text{J/K} \);

**Thermodynamic temperature of photovoltaic cell**, unit \( \text{K} \).

The output voltage \( V_{\text{pv}} \) of a single photovoltaic cell is very small, and the single photovoltaic panel used in the actual experiment is composed of 60 pieces \((106\times)\) of small polysilicon in series. In order to achieve the voltage and current values required by the experiment, 40 photovoltaic panels are set in series and parallel to form a photovoltaic array in the photoelectric unit of the system, in which the number of series is \( n_s = 10 \) and the number of parallel is \( n_p = 4 \).

### 3.1.2 Wind power generation model

Wind turbine is a system that collects wind energy and converts it into mechanical energy [8]. The wind acts on the blades of the wind driven generator at a certain speed and angle of attack, which makes the blades rotate and then drives the generator to work. According to the aerodynamic principle of wind power generation, its output power is:

\[
P_t = \frac{1}{2} \rho \pi \lambda C_p(\lambda, \beta) v^3 R^2
\]

(2)

Among them, \( \rho \) ——Air density;

\( v \) ——Undisturbed wind speed;

\( R \) ——Wind turbine blade radius;

\( \lambda \) ——Tip speed ratio, that is, the ratio of the linear velocity at the tip of the wind turbine blade to the wind speed:

\( \beta \) ——Pitch angle;

\( C_p \) ——Wind energy utilization coefficient, that is, the ratio of the mechanical power output by the wind turbine to the wind energy power input into the wind wheel surface. The specific expression of \( C_p(\lambda, \beta) \) is as follows:

\[
C_p(\lambda, \beta) = C_1 \left( \frac{C_2}{\lambda^2} - C_3 \beta - C_4 \right) e^{C_5/\lambda} + C_6 \lambda
\]

(3)

\[
\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} \cdot \frac{0.035}{\beta^3 + 1}
\]

(4)

The blade tip speed ratio \( \lambda \) in formula (4) is the ratio of the blade tip linear velocity to the wind speed of the wind turbine blade, and the calculation formula is:

\[
\lambda = \frac{\omega R}{v} = \frac{2m_w R}{60v}
\]

(5)

In which: \( \omega \) ——Angular velocity of wind turbine rotor rotation;

\( n_s \) ——Fan speed.

In addition, the wind energy utilization coefficient of wind turbine under certain wind speed can be determined according to the relationship table between wind energy utilization coefficient and tip speed ratio provided by wind turbine at factory, and the wind energy utilization coefficient can be calculated by using lookup module in MATLAB/Simulink.

### 3.2 Control strategy of photovoltaic power generation system

In photovoltaic power generation system, with the development of technology, most of them use maximum power point tracking to improve photovoltaic power generation efficiency. As the basis of con-
trol strategy, duty cycle disturbance control is more and more applied [9-10]. The commonly used algorithms are fixed voltage method, incremental conductance method and disturbance observation method. In this paper, the widely used disturbance observation method is used to study the photovoltaic power generation control system [11].

As shown in Figure 2 above, the working principle of the disturbance observation method is to sample the output voltage $U_i$ and current $I_k$ of photovoltaic cells in real time, calculate the output power $P_k = U_i I_k$ at this time, and introduce a small voltage to interfere with the system. The output power $P_{PV}$ is calculated according to the output voltage $U_{PV}$ and the output current $I_{PV}$. The output power before the interference is subtracted from the output power at this time to judge the difference between the two. If the difference is greater than zero, it means that the direction of the interference is correct, and the output voltage of the module continues to increase or decrease in the same direction; If the difference value is less than zero, it means that the interference direction is wrong. Choose the opposite direction to increase or decrease the battery output voltage.

Under the condition of normal illumination and no shadow, this paper uses disturbance observation method and Boost circuit to study MPPT of photovoltaic power generation control system [12-13], and establishes the simulation model of photovoltaic power generation control system under Simulink environment.

3.3 Tracking control of photovoltaic given power
In this system, under the condition that the wind-driven generator does not work, one part of the electric energy generated by the photovoltaic array is provided to the load and the other part is charged to the storage battery by using the principle of energy conservation. The charging current of the battery is equal to the power of the photovoltaic array minus the load power and divided by the DC bus voltage. At this time, the state of charge of the battery should be monitored, and if the battery is full, float charging should be performed. Given the output power of the photovoltaic array, the feedback quantity is calculated by sampling the voltage and current of the photovoltaic array. The output power of photovoltaic array is direct current, and the PI regulator can achieve ideal control effect.
If the battery enters the floating charging state, it is necessary to control the DC bus voltage. PI regulator is also used to make it work at the floating charging state voltage, and its control structure is shown in Figure 3.

![PI regulator control structure diagram](image)

Fig. 3. PV control structure diagram of battery in floating state

In this experiment, the photovoltaic array was replaced by DC power supply, so the maximum power point tracking function could not be realized. The photovoltaic given power tracking control was adopted to provide stable power output for the battery and load. At the same time, monitor the state of charge of the battery to avoid overcharge.

4 Result analysis

4.1 Analysis of power generation under different system configurations

By inputting the capacity of solar photovoltaic power generation 10 kW, wind power generation 5 kW, monthly average solar radiation intensity and monthly average wind speed into the simulation model, the monthly average power generation of solar photovoltaic power generation alone, wind energy power generation alone and solar and wind energy combined power generation can be obtained. The change of monthly average power generation is shown in Figure 4. During the year, the solar photovoltaic power generation increased first and then decreased, reaching the maximum value in May, with the daily power generation reaching the maximum value of about 55 kWh. After May, the daily power generation gradually decreased, reaching the minimum value of about 15 kWh in December.

Wind power generation changes little and gently in a year, reaching the maximum value in April every year, with daily power generation reaching the maximum value of about 15 kWh, and reaching the minimum value of daily power generation of about 5 kWh in December. Wind-solar hybrid power generation reaches its maximum value in May every year, with daily power generation reaching its maximum value of about 70 kWh, and reaching its lowest value in December with daily power generation of about 20 kWh[7].

![Power generation under different system configurations](image)

Fig. 4. Generation diagram under different system configurations
Generally speaking, wind-solar hybrid power generation is complementary to a certain extent, but the trend of wind-solar hybrid power generation is roughly the same as that of solar photovoltaic power generation alone. The application of wind-solar hybrid power generation in Handan area can not reduce the fluctuation between peaks and valleys.

4.2 Comparison between experiment and simulation of hydrogen production system by electrolysis of water

According to Faraday's law, when the current density is constant, the gas production rate will not change. The rated hydrogen production capacity of SPE electrolyzer used in this experiment is 0.2Nm³/h. In this experiment, the independent variable is set as current, and the magnitude of current is changed during the experiment. The correlation between gas production rate and current and voltage value is observed and recorded, and the hydrogen production of electrolyzer and its own voltage change are observed and recorded.

Experimental steps:
1. (1) turn on the power supply and SPE water electrolysis device, set the system working pressure to 2MP, run at constant current for a period of time, and turn on the electronic gas flowmeter.
2. (2) Start the water pump control device to cool the electrolyzer so that the temperature is controlled at 60°C.
3. (3) Change the current, keep other parameters unchanged, run for 30min under each current condition, record the amount of hydrogen produced in this period of time, and calculate the produced gas rate.
4. (4) In the process of changing current, record the change of voltage value of electrolytic cell.
5. (5) Repeat the experiment and record the experimental data.

Table 1. Changes of hydrogen production rate and voltage by electrolysis of water under different current conditions

| Input current (A) | Electrolytic cell voltage (V) | Power (KW) | Hydrogen production (Nm³/h) |
|------------------|-----------------------------|------------|---------------------------|
| 51               | 18.3                        | 0.98       | 0.17                      |
| 63               | 19.5                        | 1.13       | 0.22                      |
| 80               | 21.2                        | 1.69       | 0.36                      |
| 101              | 23.1                        | 2.03       | 0.42                      |
| 118              | 24.5                        | 2.77       | 0.51                      |

In the simulation study of electrolyzer, input the relevant parameters of equipment, change the input current of the system, record the hydrogen production of the system, and compare with the experimental data.

![Fig. 5. Hydrogen production rate by electrolysis of water](image)

It can be found from fig. 5 that the hydrogen production rate of the experiment and the model increases with the increase of the electrified current, showing a positive proportion relationship, and the
results of the two are relatively consistent, and the hydrogen production system model by electrolysis of water has high reliability.

5 Conclusion

The simulation of wind-solar hybrid hydrogen production system can be divided into economical type and technical type. The overall goal is to ensure high-efficiency power generation while maximizing hydrogen production and minimizing system cost. The amount of hydrogen production depends on the power generation and operation efficiency of the system, and the cost of hydrogen production mainly depends on the reasonable matching, design, operation and maintenance of fans, photovoltaic panels, electrolyzers and electrical control equipment. In this paper, taking the development and utilization of light energy and wind energy as the starting point, based on three-dimensional finite element method, an experimental study was carried out on a set of power generation equipment and a set of hydrogen production equipment by electrolysis of water in a miniature wind-solar hybrid hydrogen production system. By referring to the power parameters of large-scale hydrogen compression equipment, the specifications of the hydrogen compressor required by the prototype system were estimated, and the problem of small energy consumption of compressed hydrogen in model calculation was corrected, which improved the accuracy and reliability of the model.

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