Modeling and control of DC microgrid system based on hydrogen production load

Yingjun Guo¹, Zhe Shi¹, Yajie Guo², Fanyi Deng¹, Hexu Sun¹
¹ Hebei University Of Science & Technology, Shijiazhuang050018, China
² State Grid Hebei Power Supply Branch, Shijiazhuang050000, China
guoyj_hebust@163.com

ABSTRACT: For the intermittent output of wind turbine and photovoltaic power, aiming at the problem of abandoning wind and abandoning light, this paper proposes a DC microgrid system model and control strategy based on hydrogen production load. The DC microgrid system consists of a permanent magnet direct drive wind power system, a photovoltaic power generation system, a buffer energy storage system and an alkaline water electrolysis cell hydrogen production load. The hydrogen production load can adapt to the intermittent fluctuation power supply, make better use of the abandoned wind and light power and be environmentally friendly. Both wind power system and photovoltaic power generation system adopt MPPT control. The battery buffer energy storage device adopts constant voltage charge and discharge control. They are all controlled by their own converters to the DC bus by producing hydrogen to store the unstable electrical energy generated by distributed generation in the DC microgrid. Based on Matlab/Simulink, results show that the system operates flexibly, the control strategy adopted by the system can maintain the stable operation and load of the system under various power fluctuations and different power supply combinations.

1. Introduction

The DC microgrid has a simple control structure, which can improve the quality of power consumption and reduce power loss. With the increase of DC load, the development advantage is obvious, and the output of power depends on climate and geographical location, so energy storage system is needed [1]. The use of hydrogen to store energy is a suitable option, as a fuel can replace almost all fossil fuel applications [2]. The process of preparing hydrogen by using renewable energy sources such as wind and light is pollution-free and can reduce environmental problems. Electrolyzed water hydrogen can be used as a DC load to adapt to unstable power sources such as wind turbine and photovoltaic. At the same time, it’s conducive to solving the problem of abandoned wind and light [3-6].

In recent years, microgrid research combining hydrogen storage systems has been paid attention to in university research. The microgrid system in the literature [7] is an AC microgrid, each unit in the system has to undergo inverter, which will produce a large loss, and the cell is only activated when the system has a power surplus. The PV/SOFC hybrid power generation system proposed in [8] combines photovoltaic power generation with solid oxide fuel cells and electrolyzers. It is an off-grid system, which also uses PV/SOFC to generate electricity, and the remaining electric energy produces hydrogen storage. The literature [9-10] mainly considers the economics of the system, and studies and optimizes the algorithm of the energy storage unit in the system with the goal of cost optimization. In
addition, the literature [11] has studied the modeling and control of the landscape hydrogen integrated energy system.

This paper constructs a DC microgrid system consisting of a permanent magnet direct-drive wind turbine generator, photovoltaic, battery and electrolyzer unit. A control strategy suitable for the system is proposed for the system to operate in two models to achieve stable operation of the system and make full use of distributed power generation.

2. System structure and operation mode
The structure of the DC microgrid system established in this paper is shown in figure 1.

![Figure 1. The structure block diagram of DC microgrid based on hydrogen production load.](image)

When the wind level can meet the requirements of grid connection, close S1, disconnect S2, and control the wind power system converter to connect to the grid. Among them, the PV system and the battery system can also prepare hydrogen when the wind power system is connected to the grid to ensure that the electrolytic tank does not stop at the maximum extent. When the wind level does not meet the grid connection requirements or the power system does not allow wind power to be connected to the grid, disconnect S1, close S2, control the wind power system to access the local DC microgrid, and cooperate with the PV system to supply DC hydrogen load. Therefore, the DC microgrid system in this paper can be divided into two modes of operation.

3. System modeling
3.1. Modeling of photovoltaic systems
The equivalent circuit model of the photovoltaic cell selected in this paper is a single diode type, as shown in figure 2.

![Figure 2. Equivalent circuit model of photovoltaic cell.](image)

Obtain the I-U equation for photovoltaic cells [5]:

\[ I_{pv} = I_{ph} - I_0 \left\{ \exp \left[ \frac{q(U_{pv} + IR)}{nkT} \right] - 1 \right\} \]

(1)

Where: \( I_{pv} \) is the output current of the photovoltaic cell; \( I_0 \) is the saturation current; \( q \) is the electronic constant \(( q = 1.6*10^{-19} \text{ C})\); \( U_{pv} \) is the output voltage of the photovoltaic cell; \( n \) is the diode characteristic fitting coefficient; \( k \) is the Boltzmann constant\(( k = 1.38*10^{-23})\); \( T \) is the absolute ambient temperature.

Take \( I_{ph} \) equal to short-circuit current \( I_{sc} \), open circuit voltage is expressed as \( U_{oc} \). And let \( C_1I_{sc} = I_0 \), \( C_2U_{oc} = nkT / q \), then equation (1) can be simplified as:
Thus, a mathematical model of photovoltaics for engineering can be obtained, $C_1$ and $C_2$ are constants, and since at the maximum power point:

$$\exp\left[\frac{U_m}{C_2U_{oc}}\right] - 1 = \exp\left[\frac{U_m}{C_2U_{oc}}\right]$$

Can be solved:

$$C_1 = \left(1 - \frac{I_m}{I_{oc}}\right) \exp\left[-\frac{U_m}{C_2U_{oc}}\right]$$

$$C_2 = \left(\frac{U_m}{U_{oc}} - 1\right) \left(1 - \frac{I_m}{I_{oc}}\right)^{-1}$$

### 3.2. Modeling of wind turbine systems

In the wind power system, the permanent magnet direct-drive wind turbine includes two parts: a wind turbine as a prime mover and a synchronous generator as a generator. Modeling wind turbines:\[12\]

$$P_m = \frac{1}{2} C_p (\lambda, \beta) \rho A V_w^3$$

Where: $P_m$ is the mechanical power of the output; $\rho$ is the air density; $A$ is the sweeping area of the blade; $V_w$ is the wind speed; $C_p (\lambda, \beta)$ is the fan efficiency; $\lambda$ is the tip speed ratio; $\beta$ is the pitch angle.

The simplified mathematical equations for the voltage, flux linkage and electromagnetic torque of permanent magnet synchronous motor are as follows:\[13\]:

$$u_{sd} = \frac{d\psi_{sd}}{dt} + R_\alpha i_{sd} - \omega \psi_{sq}$$

$$u_{sq} = \frac{d\psi_{sq}}{dt} + R_\alpha i_{sq} + \omega \psi_{sd}$$

$$\psi_{sd} = L_{sd} i_{sd} + \psi_f$$

$$\psi_{sq} = L_{sq} i_{sq}$$

$$T_e = \frac{3}{2} p (\psi_{sd} i_{sq} - \psi_{sq} i_{sd})$$

Where: $u_{sd}$, $u_{sq}$ are generator stator output voltage d, q axis components; $\psi_{sd}$, $\psi_{sq}$ are the d and q axis components of the generator stator flux linkage; $i_{sd}$, $i_{sq}$ are generator stator output current d, q
axis components; $L_{ud}$, $L_{sq}$ are d, q axis electronic coil inductance; $\omega_e$ is the electrical angular velocity; $\psi_f$ is a rotor flux linkage; $R_s$ is the stator resistance; $p$ is the pole number of the motor.

### 3.3 Battery modeling

The equivalent model of the lead-acid battery used in this paper is the general model of the battery. The equivalent circuit is shown in figure 3. It consists of a controllable voltage source connected to the battery internal resistance $R$. Specifically, its mathematical model can be expressed by the following formula \[^{[14]}\]:

$$V_{batt} = E - R \cdot I_{batt}$$

Where $E$ is a controlled voltage source, which can be expressed as:

$$E = E_0 - K \frac{Q}{Q - \int idt} + A \exp\left(-B \int idt\right)$$

Where: $V_{batt}$ is the battery voltage; $E$ is the no-load voltage; $R$ is an internal resistance; $I_{batt}$ is the battery current; $E_0$ is the internal potential; $Q$ is the maximum capacity of the battery; $\int idt$ is the amount of discharge; $K$ is the polarization voltage; $A$ is the exponential region voltage amplitude; $B$ is the reciprocal of the time constant of the exponential region.

### 3.4 Cell modeling

The mathematical model of the electrolyzer used in this paper is based on the experimental experience of the alkaline cell model, which is more suitable for the analysis of the electrical field, including the model of U-I characteristics and the model of hydrogen production rate. The specific description is as follows \[^{[8]}\]:

$$U_{elec,cell} = U_{rev} + \frac{r_1 + r_2 T_{elec}}{A} I_{elec} + k_{elec} \ln\left(\frac{k_{T1} + k_{T2} / T_{elec} + k_{T3} / T_{elec}^2 I_{elec}}{A} + 1\right)$$

Where: $U_{elec,cell}$ is unit voltage; $r_1$ and $r_2$ are ohmic resistance related parameters; $T_{elec}$ is cell temperature; $k_{elec}$, $k_{T1}$, $k_{T2}$, $k_{T3}$ are overvoltage related parameter constants; $A$ is unit electrode area; $I_{elec}$ is output unit current; $U_{rev}$ is reversible open circuit voltage.

Considering the loss of parasitic current in practical applications, the hydrogen production rate can be expressed as follows:

$$q_{H2} = \frac{(I_{elec} / A)^2}{k_{f1} + (I_{elec} / A)^2} - \frac{n I_{elec}}{2F}$$

Where: $k_{f1}$, $k_{f2}$ for current efficiency calculation of related parameters.

### 4. Control of each unit of the system

The control principle is shown in Figure 4. In this system, the wind power system and the photovoltaic system are added to MPPT (Maximum Power Point Tracking) control for making fuller use of energy. The wind power system converter adopts the versatile full-power back-to-back dual PWM topology structure, and the MPPT control is the optimal tip speed ratio method \[^{[15]}\]. The machine side converter control method is dynamic indirect current speed control combined with zero d-axis current control and feedforward decoupling control. The grid side inverter adopts grid-based voltage vector control with feedforward decoupling \[^{[16,17]}\]. The photovoltaic system interface converter adopts Boost chopper, and the MPPT control is variable step disturbance observation method. As the energy storage unit of the system, the battery can maintain the DC bus voltage within the specified range and maintain the normal operation of the system when the power fluctuates continuously. The interface converter is a bidirectional DC/DC converter, which adopts a constant voltage charging (discharging) electric
control strategy\cite{18}. The electrolysis cell can be regarded as a voltage-sensitive nonlinear DC load as an electric device, and the hydrogen gas obtained through the electrolysis cell can be applied in various fields. In addition, fuel cells can convert hydrogen into secondary energy to provide stable power output, which is an important development direction for hydrogen utilization in the future.

5. System simulation verification
The main parameters of the module are shown in Tables 1~4.

5.1. Grid-connected operation mode
In the network mode, when the electrical parameters including voltage, frequency, phase, etc. of the direct drive fan meet the requirements of grid connection, the grid-connected switch in the converter is closed by the converter control system. The direct drive fan is connected to the grid for power generation. At this time, the photovoltaic system in the system is more adaptable due to the output form of its direct current and the hydrogen production load. In the case of daytime and no cloud layer is completely blocked, the photovoltaic system can cooperate with the energy storage battery for the hydrogen production load operation. Set the initial wind speed to 8m/s, change the wind speed to 12m/s and 10m/s at 0.8s and 1.5s, and change the light intensity from 1000W/m$^2$ to 600W/m$^2$ at 2s. The simulation time is 2.5s. The simulation results are shown in figure 5.

| Table 1. Wind turbine parameters. |
|-----------------------------------|
| Wind turbine | Value | Wind turbine | Value |
| $P_n$/kW | 30 | $V_n$(m/s) | 12 |
| $R$/m | 4 | $\rho$ (kg/m$^3$) | 1.225 |
| $J$(kg·m$^2$) | 12 | $R_s$(Ω) | 0.005 |
| $n_p$ | 8 | L/(mH) | 2 |
Table 2. Wind power grid connection system parameters.

| Parameter            | Inverter section | Value | Grid section | Value |
|----------------------|------------------|-------|--------------|-------|
| $u_{dc}$ (V)         | 800              |       | $U_{abcN}$ (V)| 380   |
| $C$ (μF)             | 5000             |       | $f_N$ (Hz)   | 50    |
| $f_c$ (kHz)          | 10               |       | $L$ (mH)     | 6     |

Table 3. Photovoltaic system parameters.

| Parameter      | PV Value | Parameter      | PV Value | Parameter      | PV Value |
|----------------|----------|----------------|----------|----------------|----------|
| $T_{ref}$ °C   | 25       | $S_{ref}$ W/m² | 1000     | $c/°C^{-1}$    | 0.00288  |
| $I_m$ A        | 59.1     | $U_m$ V        | 437.5    | $N_s$          | 25       |
| $I_{dc}$ A     | 63.3     | $U_{dcN}$ V    | 537.5    | $P_N$/kW       | 30       |

Table 4. Battery parameter.

| Parameter              | Battery Value | DC/DC Value |
|------------------------|---------------|--------------|
| $U_{nom}$ (V)          | 120           |              |
| $C_{nom}$ (Ah)         | 250           |              |
| initialSOC (%)         | 80            |              |

The results show that under this control strategy, the wind power output can track the change of wind speed well, the output voltage is consistent with the grid frequency and phase, and the voltage obtained on the DC side is stable and stable when the wind speed changes. For the FFT spectrum analysis of the output grid-connected current after inverter control, the total harmonic distortion rate of the grid-connected current is 0.91%, which is less than 5% of the grid-connected national standard. When the power consumption of the photovoltaic system is reduced at 2s, the battery is changed from the charging mode to the discharging mode to complement the power shortage of the photovoltaic system.

5.2. Off-grid hydrogen production mode

In this mode, the wind power system is integrated into the DC microgrid through the intermediate DC link of the converter, so that the wind power and PV power work together as the power source of the microgrid, and the battery unit as a buffer for energy storage to maintain the stability of the DC bus voltage. Set the simulation time to 2.5s, the initial wind speed is 8m/s, change the wind speed to 12m/s and 10m/s at 0.8s and 1.5s, and change the light from 1000W/m² to 600W/m² at 2s. The result is shown in figure 6.

The simulation results show that the bus voltage of the battery can be stabilized when the wind speed and light intensity conditions change, figure 6 (e) and (f) are the hydrogen production rate waveforms of the load in the system including the battery energy storage device and the energy storage device. It can be seen that the hydrogen production load can stabilize the hydrogen production when the energy storage device is buffered, and the intermittent energy source of the DC microgrid can be better utilized.
Figure 5. Photovoltaic hydrogen production simulation results in grid-connected mode.
6. Conclusion
In this paper, a DC microgrid structure including wind turbine unit, PV unit, battery unit and electrolyzer unit is constructed. The unit is modeled and a suitable control strategy is proposed. And through the simulation results of Matlab/Simulink, it is concluded that the stable three-phase AC power is output in the grid-connected mode and the complete decoupling can be operated under high power factor, and the photovoltaic and energy storage systems can simultaneously prepare hydrogen. In the off-grid hydrogen production mode, the micro-source and the energy storage system can maintain the stability of the bus voltage and the stable operation of the hydrogen production load. However, although the system output power and bus voltage cannot be stabilized when the energy storage system is out of operation, it can also be used to prepare hydrogen if it meets the hydrogen production working conditions. This system operates in a flexible manner and makes better use of the intermittent energy of the DC microgrid.

Acknowledgment
This work is supported by Hebei 'Project Titan' Innovation and Entrepreneurship project fund, Hebei Science and Technology Department project which code 16214510D and Hebei Education Department project which code QN2017313 and QN2016109.

References
[1] Yun yang Research on control strategy of photovoltaic DC microgrid based on hybrid energy storage 2016 Xiamen University
[2] He Du, Hong Lv, Daijun Yang Research progress in simulation of wind solar hybrid power generation system 2017 Chinese Journal of Power Sources 43 173-5
[3] Fengxian Luo Current situation of hydrogen production from renewable energy in the world 2017 Sino-Global Energy 22 25-32
[4] Torreglosa J P, Garcia P, Fernández L M, Jurado F Energy dispatching based on predictive controller of an off-grid wind turbine/photovoltaic/hydrogen/battery hybrid system 2015 Renewable Energy 74 326-36
[5] Trifkovic M, Sheikhzadeh M, Nigim K, Daoutidis P Modeling and Control of a Renewable Hybrid Energy System With Hydrogen Storage 2014 IEEE Transactions on Control Systems Technology 22 169-79

[6] Trifkovic M, Sheikhzadeh M, Nigim K, Daoutidis P Hierarchical control of a renewable hybrid energy system 2012 51st IEEE Conf. on Decision and Control (Hawaii) pp 6376-81

[7] Mengzhu Qin, Guoyue Zhang, Donglian Qi Modeling and Simulation of wind energy hydrogen coupling system 2016 Electronic Technology 8

[8] Wei Guo Modeling and performance simulation of hybrid power system based on PV/SOFC 2014 Shandong University

[9] Pengfei Liu Research on optimal allocation and energy management of integrated power supply system for wind and hydrogen storage 2017 Zhejiang University

[10] Weiqiang Dong Configuration and battery management of wind solar hybrid power system 2017 Zhejiang University

[11] Guowei Cai, Long Peng, Lingguo Kong Power coordinated control of hybrid photovoltaic power generation system 2017 Automation of Electric Power Systems 41 109-16

[12] Shuhua Bai Application of wind solar combined independent power generation system 2007 Chongqing University

[13] Lei Xiao Research on low voltage ride through technology of direct drive permanent magnet wind power generation system 2009 Hunan University

[14] Tremblay O, Dessaint L A, Dekkiche A I. A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles 2007 Vehicle Power and Propulsion Conference (Beijing) pp 284-9

[15] Bin Wu, Sanmin Wei 2012 Power conversion and control of wind power generation system (China: China Machine Press)

[16] Danyang Zhao Coordinated control of wind and solar storage DC microgrid 2015 Southwest Jiaotong University

[17] Wei Cheng Dynamic modeling of photovoltaic and wind power generation systems 2012 Zhejiang University

[18] Fernandez L M, Garcia P, Garcia CA, Torreglosa JP, Jurado F Comparison of control schemes for a fuel cell hybrid tramway integrating two dc/dc converters 2010 International Journal of Hydrogen Energy 35 5731-44