A Hybrid Energy Storage System Controlled by Two Degree-of-Freedom PID for Wind Power Generations

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Abstract. In order to make the unstable three-phase power output of wind turbine can charge the lithium battery pack steadily through the control of topology circuit and controller, a hybrid energy storage system controlled by two degree-of-freedom (DoF) PID is proposed to realize stable charging of lithium battery pack in this paper. The circuit combines the control circuit, the detection circuit and the protection circuit to achieve normal charging of the lithium battery pack. The system model composed of each module is built and simulated by MATLAB/Simulink software. The simulation results show that when the unstable three-phase voltage of wind turbine varies in the range of 0.4V-400V, the hybrid energy storage system keeps the charge current of the lithium battery group within the range of the normal range of the 2.5A-3.5A. And the system can effectively charge the lithium battery pack with the unstable three-phase power output of wind turbine.

1. Introduction

Because of the intermittent and unstable characteristics of wind resources, the wind power has random volatility which is difficult to avoid. When the wind turbine charges lithium batteries, the unstable current will inevitably affect the life of lithium battery pack and even cause charging safety accidents. Therefore, it is necessary to use the appropriate adjustment system to improve the charging characteristics of the unstable three-phase power of the wind turbine to the lithium battery pack, which can realize the stable charging of the lithium battery pack.

Based on the energy buffering and closed-loop feedback technology and the piecewise linear method, a capacitor buffering dual-parameter control energy storage strategy for off-grid wind power system was proposed and simulated in MATLAB/Simulink [1]. A Fractional order fuzzy PID controller to control the frequency and power of an hybrid power system was proposed and the controller used the quasi-oppositional harmony search algorithm to improve performance of system [2]. A hybrid operation strategy for wind power systems with battery energy storage systems was proposed [3]. The strategy uses active power tracking for maximum power point tracking and adjusts short-term frequency response based on dynamic discharge control.

An adaptive fuzzy PID controller that allows the wind turbine to always output at maximum power was proposed [4]. However, this controller requires a lot of human experience, and the model accuracy needs to be verified.

Corresponding controllers and control strategies for different hybrid energy storage systems. Their performance has been verified by simulation [5-7].

The hybrid energy storage system of Fala capacitor+ lithium battery pack is used to build a hybrid energy storage system model in MATLAB/Simulink and simulate it in this paper. The simulation results show that the system can effectively realize the stable charging of lithium battery pack by unstable three-phase electricity output from wind turbines.
2. Topology Design of Rectifying Circuit and Chopper Circuit

2.1. Topology Design of Rectifier Circuit
In order to convert the unstable three-phase power output from the wind turbine to DC output, we use a three-phase bridge rectifier circuit to convert the three-phase power into a pulsating DC. The Q1-Q6 is uncontrollable two-stage tube, as shown in Figure 1. Assuming the three-phase voltage of the wind turbine is $U_2$, the maximum value of the average output voltage of the rectifier circuit at no load is $2.45U_2$.

![Figure 1. Rectifying and filtering circuit.](image1)

2.2. Topology Design of Chopper Circuit
DC chopper circuit is a commonly used DC-DC conversion circuit, which is divided into three types: boost-buck circuit, boost circuit and buck circuit. The maximum cut-off voltage of the whole lithium battery pack is 25.6V, because this paper aims at eight lithium batteries with a voltage of 3.2V. Due to the instability of the wind speed, the DC voltage of the output voltage of the wind turbine may be higher than 25.6V after the rectifier filter, and may be lower than 25.6V. Therefore, this paper chooses the boost-buck circuit to get the charge voltage of the lithium battery group. As shown in Figure 2.

![Figure 2. Boost-buck chopper circuit.](image2)

The chopper circuit controls the conduction time of the MOSFET tube by controlling the duty cycle of the PWM, thus controlling the output voltage $U_{out}$ of the circuit. The value of the output voltage is as shown in Formula 1.

$$U_{out} = \frac{D}{1-D}U_{in}, \quad (1)$$

where $D$ is the duty cycle, $U_{in}$ is the input voltage, and $U_{out}$ is the output voltage.

2.3. Design of DC-DC Voltage Controller
Due to the instability of the wind speed, the three-phase power output by the wind turbine is not stable after rectification and filtering, which leads to the fluctuation of the charge current of the lithium battery pack, which will have an adverse effect on the charging time and the cycle life of the lithium battery pack. Therefore, in order to keep the output current constant, this paper adds a DC-DC voltage controller to the circuit. By collecting the output voltage $U_{out}$ of the boost-buck chopper circuit, the controller compares the $U_{out}$ with the preset reference voltage $U_{ref}$, and the controller takes the difference $E_{error}$ of the two as the input, and outputs the control signal through PID control. The control signal is usually represented as a certain duty ratio. The two degree of freedom PID DC-DC voltage controller MATLAB/Simulink model is built, as shown Figure 3. And the control signal output as shown in Formula 2.

$$D=K_p(bU_{ref}-U_{out})+K_i\sum_{z=1}^{1/T_s}(U_{ref}-U_{out})+K_D\frac{N}{1+NT_s}+(cU_{ref}-U_{out})+FF. \quad (2)$$

where $D$ is the control signal, expressed as a duty cycle. $K_p$ is the proportional gain. $K_i$ is the integral gain. $K_d$ is the differential gain. $N$ is the filter coefficient. $T_s$ is the sample time. $U_{ref}$ is the reference
voltage. $U_{\text{out}}$ is the measured voltage. $FF$ is the feed forward input.

**Figure 3.** Basic principle block diagram of DC-DC voltage controller.

### 3. Design of Hybrid Energy Storage System for Super Capacitor and Lithium Battery Pack

Design of control strategy for hybrid energy storage control system. The power output fluctuation of wind turbines can be controlled by using the flexible charging and discharging capacity of capacitors. The specific control strategy is shown in Figure 4.

**Figure 4.** Flow chart of control strategy for hybrid energy storage control system.

### 4. Model Simulation and Analysis of Simulation Results

In order to simulate the unstable three-phase power produced by the wind turbine, the Three-Phase Programmable Voltage Source module in MATLAB/Simulink is used to program the three-phase power. The initial voltage of Fala capacitor is set to 0.5V. In the process of simulation, CC-charge shows the output current after the three-phase electricity is rectified and chopped circuit. The I-charge represents the charging current of the lithium battery pack, and U-c indicates the voltage at both ends of the Fala capacitor. The unsteady three-phase power output of the wind turbine simulated by the
system is shown in Figure 5.

![Figure 5. Unstable three-phase voltage simulated by system.](image)

![Figure 6. The currents changing](image)  ![Figure 7. Fala capacitance voltage changing](image)

From Figure 6-Figure 7, we can see that when the CC-charge is less than the threshold 1.5A, the charge current I-charge of the lithium battery pack is 0. Fala capacitance is in charge state. When CC-charge is greater than 1.5A and less than 2.5A, the Faraday capacitor is in discharge state. Fala capacitor completes charging compensation for lithium battery pack. When the CC-charge is greater than the threshold 2.5A and less than 3.5A, the circuit of the Fala capacitor is open. I-charge is consistent with CC-charge. From Figure 8-Figure 9, we can see that the SOC and terminal voltages of the lithium ion batteries have increased steadily under the regulation of the hybrid energy storage system. The reason why the voltage curve increases at 1 second is due to a large increase in the phase voltage in one second, and the phase voltage increases from 0.4V to 12.62V at a moment. Because the voltage rise is instantaneous, the DC-DC controller needs time to respond to it.
5. Conclusion

Through the above theoretical analysis and MATLAB/Simulink simulation, the wind energy storage system can better realize the stable charging of the unstable three-phase power of the wind turbine to the lithium battery pack. When the system adopts the constant current charging mode and the CC-charger is less than 1.5A, the Fala capacitor is in the charge state and stores the energy, and the charge current of the lithium battery pack is 0. When the CC-charger is greater than or equal to 1.5A and less than 2.5A, the Faraday capacitor is in a discharge state and the lithium battery pack is compensated for charging. When the CC-charger is greater than or equal to 2.5A and less than 3.5A, the system can charge the lithium battery pack normally. When the CC-charger is greater than or equal to 3.5A and less than 4A, the Faraday capacitor is charged and dynamically stored to absorb part of the power. When the CC-charger is greater than or equal to 4A and the output voltage of the rectifier circuit is greater than 567V, the system stops charging the lithium battery pack.
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