

Research on the Control Strategy of Maximum Energy Utilization and Disordered Disturbance Suppression in Distributed Generation System

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Abstract. The ultimate goal of distributed renewable energy control is to minimize disorder disturbance to the power grid while ensuring maximum energy utilization. Taking wind power as an example, a coupling system using flywheel energy storage system to balance the output variables of wind power system was proposed while using hill climb searching (HCS) to maximize the utilization of wind energy. These methods can obtain stable DC output voltage. In the case of wind speed variation, as a limited capacity energy pool structure, flywheel energy storage system can ensure the maximum utilization of wind energy. Based on fully utilization of wind energy resources, the rapid and comprehensive compensation of wind power output can effectively smooth the output voltage of grid-connected wind power system, thus achieving the purpose of improving the power quality of grid-connected wind power system.

1. Introduction

With the progress and maturity of technology, renewable energy power generation has become the most promising way of power generation because of its flexible mode, high reliability of local power supply and low investment [1]. However, due to the random and disordered disturbance of the power generation mode, it has many adverse consequences in the process of joint operation with the large power grid [2]. It is mainly manifested in the following aspects:

- 1) Power quality of power grid is seriously threatened.
- 2) It is not easy to dispatch power system and difficult to configure relay protection devices [3], etc.

To make full use of wind energy resources, it is inevitable to confront disordered disturbance caused by wind energy fluctuation of power grid. In this way, not only the stability of grid-connected power can't be guaranteed, but also great hidden trouble is generated to the safe operation of power grid [4]. At present, adding energy storage device into wind farm has become an effective way to solve the problem of random fluctuation of wind power [5]. With the reasonable and effective control



strategies that solve the conflicts between wind power utilization rate and grid stability, it is available to make fully use of wind energy [6].

Previous researchers have conducted extensive studies on the application of energy storage technology in wind power generation. H. HaiPing and others installed battery energy storage devices in wind turbines to suppress power fluctuations [7]. Although battery energy storage technology is relatively mature, there are still some problems in the application process, such as high cost, serious environmental pollution, short service life. S. M. Said, A.Selim and others studied the suppression of power fluctuation in power system with wind power by using superconducting energy storage system [8]. However, superconducting materials have some disadvantages, such as high critical temperature, high cost, complex equipment and immature supporting technology. After comparison and analysis, flywheel energy storage system is taken as the energy pool of finite energy temporary storage, which has the characteristics of long life, many cycles, high energy density, no pollution and good dynamic performance.

Based on the strategy of maximum wind energy capture and control, a system which couples flywheel energy storage system and direct-drive permanent magnet wind turbine into power grid is proposed. In this system, firstly, the power generated by wind turbines passes through three-phase uncontrollable rectifier circuit and DC-DC boost chopper circuit in turn. Then, the unstable power generated by wind turbines is transformed into stable AC power which can be connected to the grid through inverters. Finally, the real-time control and tracking of the grid is realized. It can be seen from the simulation results that the flywheel energy storage system can effectively suppress the small random disorder disturbance to the grid caused by wind speed fluctuation and other factors in a short time.

2. Principle of flywheel energy storage system for suppressing power fluctuation

Figure 1 is the structure diagram of the flywheel energy storage unit connected to the grid-connected direct-drive wind power generation system as a buffer device. The wind turbine is connected to the power grid through back-to-back PWM converter.

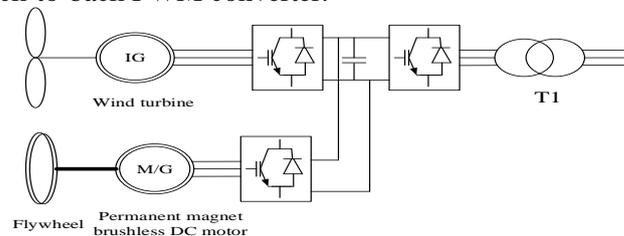


Figure 1. Structure chart of direct-drive permanent magnet wind power system based on flywheel energy storage

3. Confirmation of grid-connected structure of flywheel energy storage system and optimization of control strategy

Good operation stability and tracking ability of control signal are two important requirements of flywheel energy storage system. When the system is disturbed, in order to make the system run normally and reach the instruction value timely and accurately, it is necessary to apply a good control strategy to the flywheel system to improve the robustness of the whole system.

3.1. Grid-connected structure and working principle of flywheel energy storage system

Figure 2 is the main circuit diagram of the flywheel energy storage system connected to the grid. It is mainly composed of flywheel, permanent magnet brushless dc motor, flywheel side converter and dc side capacitance.

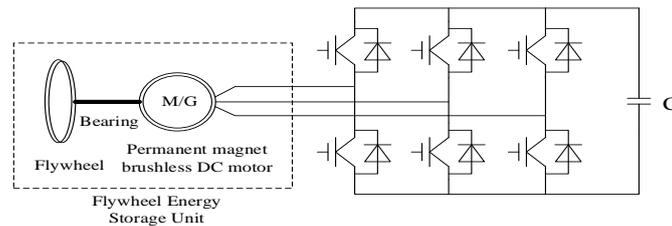


Figure 2. The main circuit of flywheel energy storage system connected to grid

3.2. Selection of control strategy

3.2.1. *DC link constant voltage control.* The DC part voltage and the stator current of the permanent magnet brushless DC motor are controlled by voltage-current double closed-loop control. The principle is shown in Figure 3.

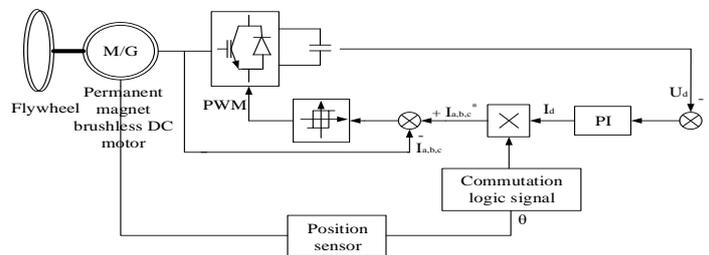


Figure 3. The control principle diagram of DC link voltage

After comparing the actual voltage U_d of the DC link with the reference voltage U_d^* , the reference current i_d of the DC side of the flywheel energy storage unit is obtained by PI regulator. The reference values $i_{a,b,c}^*$ of stator three-phase currents are obtained by multiplying the signal θ of each phase winding which is obtained by position sensor of permanent magnet brushless DC motor. After comparing with the actual three-phase stator currents, the hysteresis controller generates PWM to control the switching action of the converter, which achieves the purpose of controlling the voltage stability of the DC link, and realizes its tracking of the reference voltage value.

3.2.2. *Maximum wind energy tracking control.* Due to the uncertainty of wind speed change, it is particularly important to adopt maximum power tracking strategy in wind power generation system in order to improve the utilization rate of wind energy. The mechanical power P that can be output by a wind turbine with a rotation radius of R can be expressed as:

$$P = \frac{1}{2} \rho \pi R^2 C_p v^3 \quad (1)$$

In the formula, ρ is the air density. $1/2\pi R^2$ is the area swept by the wind turbine. C_p is the wind energy utilization coefficient of the wind turbine. v is the wind speed.

When the pitch angle β is constant, the wind energy utilization coefficient C_p of wind turbine is a function of the tip speed ratio λ , i.e. $C_p=f(\lambda)$. λ can be expressed as:

$$\lambda = \frac{wR}{v} \quad (2)$$

In the formula, w is the mechanical angular velocity of wind turbine rotation.

There is one point of λ_m in the process of the change of C_p with λ , which maximized C_p , i.e. C_{pmax} . The λ_m is called the optimal tip speed ratio, and the corresponding maximum output mechanical power is:

$$P_{max} = \frac{1}{2} \rho \pi R^2 C_{pmax} v^3 \quad (3)$$

In the actual wind power generation system, with the constant change of wind speed, the wind turbine operates in variable speed and its output power also changes. However, there must be an optimal speed to maximize the output mechanical power of the wind turbine. It is necessary to adjust the speed of the wind turbine in time when the wind speed changes to ensure that the wind turbine operates at the optimal tip speed ratio and achieve the maximum power tracking.

This article adopts maximum power tracking control algorithm based on hill climb searching (HCS). The specific control mode is that when the wind turbine runs at rated wind speed, the speed of the wind turbine can be adjusted by controlling the reference value of the output current of the wind turbine. The output power of the wind turbine is realized by controlling the inductance current in the boost chopper circuit. Through calculation, the signal of inductance current in the boost chopper circuit is determined so that the actual current can track its change and control the output power of the generator. In this way, the speed of the controller can be controlled under the condition of the optimal tip speed ratio and achieve the maximum power control.

4. Establishment and control of equivalent circuit for flywheel energy storage system

4.1. Grid-connected equivalent circuit diagram of flywheel energy storage system

According to the system structure diagram of Figure 1, the equivalent circuit of flywheel energy storage system integrated into power grid as shown in Figure 4 can be obtained.

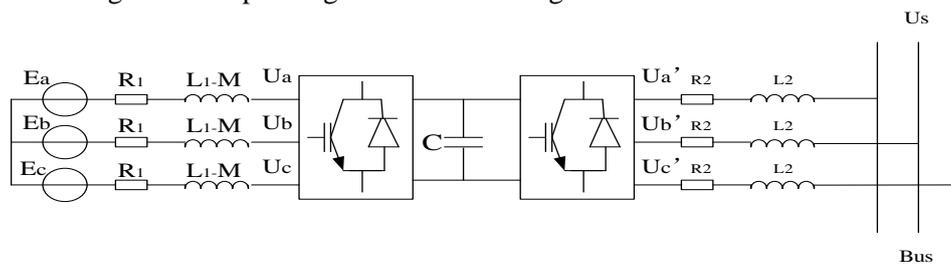


Figure 4. The equivalent circuit of flywheel energy storage system connected to grid

In the figure, E_a , E_b , and E_c are three-phase induction electromotive forces of permanent magnet brushless DC motor. U_a , U_b , and U_c are the terminal voltages of three-phase winding of motor stator. U_a' , U_b' , and U_c' are the terminal voltages of the grid side inverters. R_1 , R_2 are the connection resistances of motor winding resistance and grid side converter. L_1 , L_2 are inductances of motor winding and connection inductance of grid side converter. M is the mutual inductance between the two-phase windings of the motor stator.

4.2. Control of motor side controller

Space vector control of rotor field is adopted for direct-drive permanent magnet wind turbine. In this way, the dq coordinate system rotates at the same speed and the d -axis lags behind the q -axis by 90° . By defining the flux direction of the rotor permanent magnet as the d -axis direction, the stator equation of the motor can be established as follows:

$$\begin{cases} u_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} - w_s L_s i_{sq} \\ u_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + w_s \frac{di_{sq}}{dt} + w_s L_s i_{sd} + w_s \Psi \end{cases} \quad (4)$$

In the formula, u_{sd} , u_{sq} are d and q axis voltages of generator stator winding. i_{sd} , i_{sq} are d and q axis currents of generator stator. L_s , R_s are inductance and resistance of generator stator winding respectively. w_s is synchronous angular velocity. Ψ is the permanent magnet flux linkage of the rotor.

Because the permanent magnet motor provides excitation current, the d -axis current component can be set to 0, i.e. $i_d = 0$. Then the electromagnetic torque equation of permanent magnet synchronous generator can be simplified as follows:

$$T_e = 1.5n_p i_{sq} \Psi \quad (5)$$

In the formula, n_p is the number of pole-pairs of permanent magnet synchronous generator.

Formula (5) shows that the electromagnetic torque is only related to the q -axis current component. When the stator winding loss is neglected, the electromagnetic power generated by the q -axis current is the active power of the motor side converter, that is:

$$P = T_e w \quad (6)$$

In the formula, P is the active power output by the motor side converter. T_e is the electromagnetic torque of the motor. w is the angular speed of the motor. It can be seen from the formula that the accurate adjustment of the active power output or absorption of the motor can be realized by controlling the electromagnetic torque of the motor.

4.3. Control of power grid side controller

In the dq synchronous rotation reference system, it is assumed that d -axis lags behind q -axis, and the vector direction of grid voltage u_g locates d -axis, that is, the component of grid voltage on q -axis is 0, Then the voltage equation of the grid side converter can be written as follows:

$$\begin{cases} u_d - u_{gd} = -Ri_d - L \frac{di_d}{dt} - wLi_q \\ u_q - u_{gq} = -Ri_q - L \frac{di_q}{dt} - wLi_d \end{cases} \quad (7)$$

In the formula, u_d , u_q are the d and q axis components of the control voltage of the grid side converter. u_{gd} , u_{gq} are d and q axis components of grid side converter voltage. i_d , i_q are d and q axis components of the grid side converter current.

Because of $u_{gq}=0$, the active and reactive power of the grid side converter can be obtained as follows:

$$\begin{cases} P = 1.5u_{gd}i_d \\ Q = 1.5u_{gd}i_q \end{cases} \quad (8)$$

Formula (8) shows that the active power P and reactive power Q of the grid side converter can be controlled by d and q axis component i_d and i_q of the currents of the grid side converter. The closed-loop PI control of i_d and i_q is carried out.

4.4. Control strategy of flywheel energy storage system

The principle of coupling the flywheel energy storage device to the DC side of the grid-connected direct-drive permanent magnet generator is shown in Figure 5.

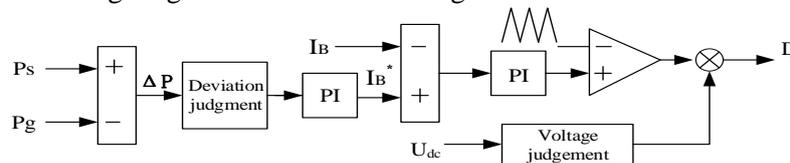


Figure 5. FESS control principle of DC part

When there is a deviation ΔP in the active power flowing through the DC-side converter, the given charge/discharge current I_B^* of the flywheel energy storage system can be obtained through PI controller after judging the deviation. Comparing the actual current values I_B of other flywheel energy storage systems, and then through the role of PI controller, the duty cycle D will be generated. The flywheel side converter is switched to control the charging and discharging of the flywheel system. When $I_B > 0$, the flywheel accelerated rotation and was in charge state. When $I_B < 0$, the flywheel decelerated rotation and was in discharge state. The flywheel system does not work when ΔP and the voltage of DC part fluctuates within the allowable range, at this time, $D=0$. When ΔP changes beyond

the set range, the flywheel energy storage system is integrated into the coupling system by controlling the duty cycle D to assist the wind power system to transmit electricity to the grid.

5. Simulation analysis of flywheel energy storage system for suppressing wind power fluctuation in maximum energy utilization

The article used Matlab/Simulink simulation software to simulate the direct-drive permanent magnet synchronous generator added to flywheel energy storage system. The simulation parameters of the system are as follows: The number of pole-pairs of wind turbine is $P=32$. The stator winding resistance is 7Ω . Stator inductance is 3mH . The stator winding of wind turbine energy storage system is 0.0028Ω . The stator inductance is $8.5\text{e-}3\text{H}$. The permanent magnetic flux is 0.175Wb . The moment of inertia is $J=0.0008\text{kg}\cdot\text{m}^2$. The equivalent resistance and inductance of grid-side inverters are $R=0.05\Omega$, $L=0.039\text{H}$ respectively.

The active power and reactive power of the wind generator adding the flywheel energy storage system before and after are obtained as shown in Figures 6 and 7. The voltage waveform of the connection point between wind power generation system and power grid adding flywheel energy storage system before and after are shown in Figure 8.

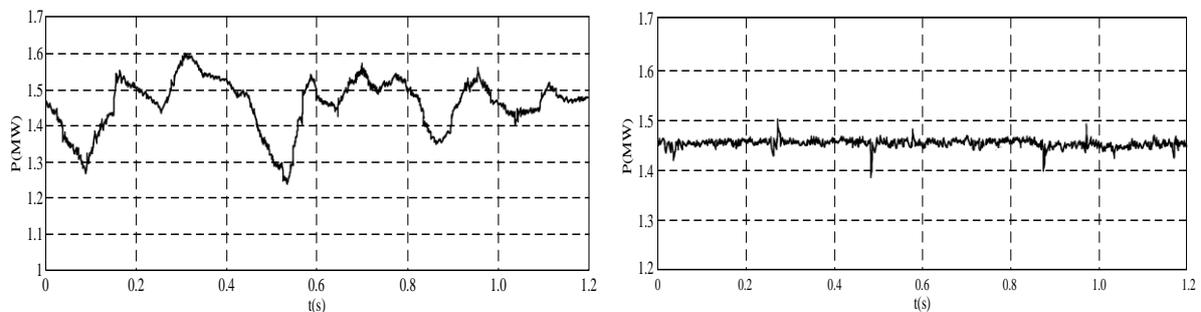


Figure 6. Wind generator active output power waveform without and with flywheel energy storage system

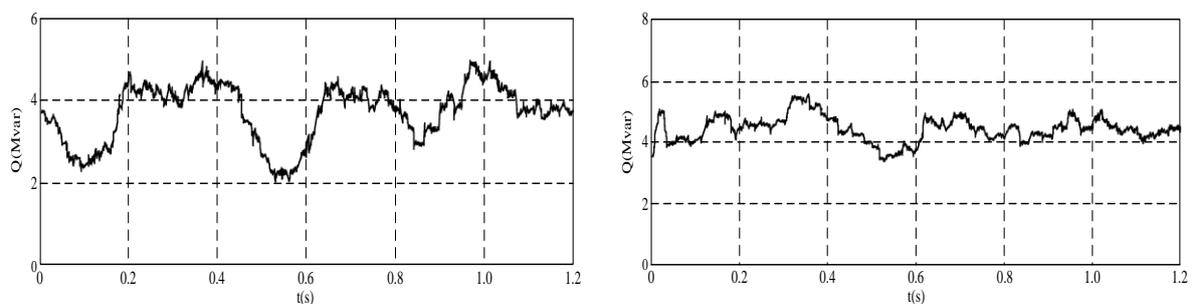


Figure 7. wattless output power waveform of wind generator without and with FESS

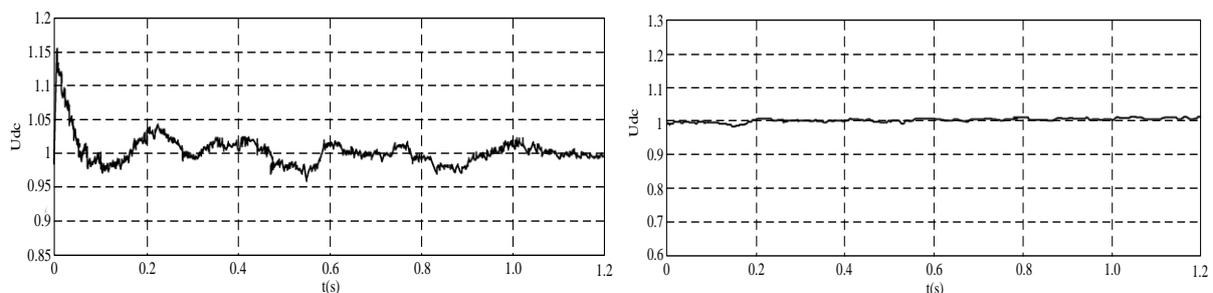


Figure 8. voltage waveform of wind power generation system connecting to the grid without and with FESS

From the simulation results of Figure 6, it can be seen that after connecting to the flywheel energy storage system, the active power injected into the grid by the coupling system is obviously stable. Comparing Figure 7, it can be seen that the flywheel energy storage system can realize fast reactive power compensation for grid-connected wind power system. By comparing Figure 8, it can be seen that by stabilizing the DC bus voltage of the grid-connected coupled system, it can effectively stabilize its given value.

6. Conclusion

This article introduced the flywheel energy storage system into the distributed energy grid-connected generation system with wind power as an example. The simulation model of grid-connected control system of direct-drive wind power generation based on flywheel energy storage system is established. The model is simulated and analyzed. The following conclusions are drawn:

- 1) Flywheel energy storage system has the characteristics of energy storage and rapid charging and discharging. It can effectively suppress random disturbances.
- 2) In the process of continuous fluctuation of wind speed, the maximum wind energy tracking control strategy can be used to enable the flywheel energy storage system to switch dynamically in real time according to the actual situation of wind energy.

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