Properties Dynamic Simulation of the Flywheel Energy Storage System Model with Speed-Current Double Closed Loop

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Abstract. The random fluctuation of output power of modern distributed power generation system brings many hidden dangers to the safe operation of power grid, and the application of energy storage system is the most effective way to smooth the output power of distributed power generation. Based on the analysis of the structure and charge-discharge dynamic performance of the flywheel energy storage system, the permanent magnet brushless DC motor (PMBLDCM) is proposed as the flywheel motor, and the charging and discharging mathematical model of the flywheel energy storage system based on PMBLDCM is established. Using MATLAB/Simulink, the simulation model of flywheel energy storage system with speed-current double closed Loop is established. The simulation results show that the system can effectively control the flywheel energy storage system to achieve two-way energy conversion, and effectively stabilize power fluctuations.

Introduction

Wind energy is widely used because of its abundant resources and no pollution to the environment [1]. However, the variation of wind speed is volatile, and a small change of wind speed will cause a great change in the output power of wind turbines, which makes wind power generation have many defects in conversion efficiency and stability [2].

At present, adding energy storage devices in wind farms has become an effective way to solve the problem of random fluctuation of wind power [3]. In 2018, Y. Cong, X. Meng, L. Wang and Y. Wang installed battery energy storage devices in wind turbines to suppress power fluctuation [4]. Although battery energy storage technology has been relatively mature at this stage, there are still some problems in the application process, such as high cost, serious environmental pollution and short service life. In the same year, P. Mukherjee and V. V. Rao studied the use of superconducting energy storage systems to smooth power fluctuations in power systems containing wind power [5]. However, there are some shortcomings, such as the critical temperature of superconducting materials to be improved, high cost, complex equipment and immature supporting technology.

Because of its long life, more cycles, high energy density, pollution-free, and good dynamic performance, flywheel energy storage system is selected as energy storage device, permanent magnet brushless DC motor is selected as flywheel motor. By using MATLAB/Simulink, the double closed-loop control system of flywheel energy storage system based on permanent magnet brushless DC motor is constructed, the charging and discharging states of the flywheel energy storage system are simulated. Through the analysis of simulation results, the correctness and validity of the model and the control method are verified.
The Principle and Structure of Flywheel Energy Storage System

Composition and Energy Storage of Flywheel Energy Storage System

The structure of the flywheel energy storage system is shown in Fig. 1 [6].

![Figure 1. Structure of the FES system.](image)

The energy stored in the flywheel is proportional to the moment of inertia of the flywheel and the square of its rotation speed. To improve the energy storage of the flywheel, increasing the speed of the flywheel is more effective than increasing the moment of inertia of the flywheel.

Working Principle of Flywheel Energy Storage System

Flywheel energy storage system is an energy storage device for electromechanical energy conversion. The schematic diagram of the charging and discharging process is shown in Fig. 2 [7].

![Figure 2. Schematic diagram of the FES system.](image)

Mathematical and Simulation Model of Flywheel Energy Storage System with Speed and Current Double Closed-loop Control

Mathematical Model of Permanent Magnet BLDCM in Flywheel Energy Storage System

The mathematical model of permanent magnet brushless DC motor is established directly in Cartesian coordinate system. It is assumed that the air gap permeance of the motor is uniform and the effect of leakage flux is neglected. The voltage equation of three-phase stator winding is established as follows:

\[
\begin{bmatrix}
U_a \\
U_b \\
U_c
\end{bmatrix} =
\begin{bmatrix}
R_s & 0 & 0 \\
0 & R_s & 0 \\
0 & 0 & R_s
\end{bmatrix}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} +
\begin{bmatrix}
L_{sa} & M_{sb} & M_{sc} \\
M_{ba} & L_{bb} & M_{bc} \\
M_{ca} & M_{cb} & L_{cc}
\end{bmatrix}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} +
\frac{d}{dt}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} +
\begin{bmatrix}
E_a \\
E_b \\
E_c
\end{bmatrix} +
\begin{bmatrix}
U_a \\
U_b \\
U_c
\end{bmatrix}
\]

(1)
In the formula, $U_a$, $U_b$, $U_c$ and $U_n$ are the terminal voltage and common node voltage of the three-phase stator winding; $I_a$, $I_b$ and $I_c$ are the current of the three-phase stator winding; $E_a$, $E_b$ and $E_c$ are the back EMF of the three-phase stator winding; $R_a$, $R_b$ and $R_c$ are the resistance of the three-phase stator winding; $L_{aa}$, $L_{bb}$ and $L_{cc}$ are the self-inductance of the three-phase stator winding; $M_{ab}$, $M_{ac}$, $M_{bc}$, $M_{ba}$, $M_{ca}$ and $M_{cb}$ are the mutual inductance of each two-phase stator winding.

The common node voltage is:

$$U_n = \frac{U_a + U_b + U_c}{3}$$

(2)

During the operation of the motor, the expression of electromagnetic torque is as follows:

$$T_e = \frac{E_a I_a + E_b I_b + E_c I_c}{w}$$

(3)

During the charging process, the mechanical motion equation of the motor is:

$$T_e - T_L - f_w = J \frac{dw}{dt}$$

(4)

In the discharge process, the mechanical motion equation of the motor is:

$$T_e - T_L - f_w = -J \frac{dw}{dt}$$

(5)

In the formula, $T_e$ and $T_L$ are electromagnetic torque and load torque respectively; $J$ is the moment of inertia of the rotor; $f$ is the damping coefficient; $w$ is the mechanical angular speed of the rotor.

Simulation Model of Double Closed Loop Control System of Speed and Current for Flywheel Energy Storage System

Mathematical Model and Transfer Function of Flywheel Energy Storage System Based on Double Closed-loop Control of Speed and Current

Using the above established mathematical model, the simulation model of flywheel energy storage system based on permanent magnet brushless DC motor is built in the simulation software MATLAB/Simulink. The charging and discharging process of flywheel energy storage system with double closed-loop control of speed and current is simulated. The principle block diagram of the control system is shown in Fig. 3.

![Figure 3. Block diagram of the double closed-loop control system of the FES system.](image)

The control process is as follows: the $n_{error}$ is obtained by comparing the given speed $n_{ref}$ with the feedback speed $n$, and the $i_{error}$ is output by the speed controller. The error current $i_{error}$ is obtained by comparing the given speed $n_{ref}$ with the feedback current. $i_{error}$ is used as the input of current controller, and the output is driven by thyristor trigger device of power switch through pulse width modulation circuit and electronic commutation circuit. In the whole system, the outer ring is the speed loop, which can stabilize the output speed when the wind speed changes or load disturbance occurs. The inner ring is a current loop, which can effectively prevent the overcharge and discharge caused by the flywheel speed changing too fast by limiting the output current.
System Module Building

According to the mathematical model of flywheel energy storage given above, the system module is built. Fig. 4 is shown.

![System Module Diagram](image)

**Figure 4.** The simulation model of the double closed-loop control system of the brushless DC motor.

Simulation Results of Flywheel Energy Storage System with Speed Current Double Closed Loop Control

Simulation Analysis of Charging Process of Flywheel Energy Storage System

The parameters of the flywheel motor are as follows: rated voltage \( U = 500 \text{V} \), rated speed \( n = 300 \text{r/min} \), pole of Pairs \( P = 4 \), stator winding resistance per phase \( R = 2.875 \Omega \), stator winding self-inductance per phase \( L = 8.5 \times 10^{-3} \text{H} \), damping coefficient \( B = 1 \times 10^{-2} \text{N}\cdot\text{m}\cdot\text{s/\text{rad}} \), moment of inertia \( J = 0.0008 \text{kg}\cdot\text{m}^2 \). At the beginning of the simulation, the motor starts from no-load, the load torque changes from 0N. m to 15N. M. and the simulation time is 0.2s. After entering the steady state, the simulation results are shown in Fig. 5 to Fig. 6.

![Charging Process Diagram](image)

**Figure 5.** The flywheel waveform of charging mode.
Figure 6. The motor output torque waveform of charging mode.

When the flywheel is in charge mode, it can be seen from the simulation curve in Fig. 5 that the charging process of the flywheel is only 0.06s, and the energy stored by the flywheel can reach the maximum value in a short time, and the charging process is completed. Fig. 6 is a simulation result of electromagnetic torque of electromotor. From the figure, it can be seen that the motor's torque fluctuates in a short time after starting. After 0.02s, the motor achieves the required torque and keeps the torque curve stable.

Simulation Analysis of Discharge Process of Flywheel Energy Storage System

Compared with the charging process of the flywheel system, the load torque changes from -15N·m to 0N·m, and other parameters remain unchanged. At this time, the motor is in the operation state of the generator and the flywheel is in the discharge state. The simulation results are shown in Fig. 7 to 8.

Figure 7. The flywheel waveform of discharge mode.

Figure 8. The motor output torque waveform of discharge mode.

As shown in Fig. 7, it can be seen that the discharging process of the flywheel is only 0.06s, and the stored energy of the flywheel can be released completely in a short time to complete the discharging process. Fig. 8 is a simulation result of electromagnetic torque of electromotor. It can be seen from the figure that the torque of the motor fluctuates in a short time after operation. After 0.04s, the motor cannot continue to provide energy to the outside world and stop running. At this time, the torque curve remains 0N·m.
Summary
By reasonably choosing permanent magnet brushless DC motor as flywheel motor and analyzing the energy storage mechanism of flywheel energy storage system, the mathematical model of flywheel energy storage system based on permanent magnet brushless DC motor is established. At the same time, the dynamic simulation of charging and discharging process of the system is carried out. The simulation results show that:

1) The simulation results are consistent with the theoretical analysis, which demonstrates the correctness of the model, and shows that the control system can complete the charge and discharge control of the flywheel energy storage system.

2) By using permanent magnet brushless DC motor as flywheel motor, the system has better dynamic characteristics, can effectively control the flywheel energy storage system to achieve bidirectional energy conversion, effectively suppress current, voltage and power fluctuations.

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