Simulation and contrast study on flywheel energy storage control strategy for dynamic stabilization of power fluctuation in power grid

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Abstract. Flywheel Energy Storage System can not only effectively reduce the impact of energy fluctuation on the power grid, but also fully improve the utilization of distributed energy system because of its characteristics of energy storage and rapid charging. In this study, permanent magnet brushless DC motor is selected as flywheel motor for wind power system. The mathematical model of flywheel energy storage system in rectangular coordinate system is established. The double closed-loop simulation model of speed and current of flywheel energy storage system is built by using MATLAB/Simulink. In order to improve the control performance of flywheel energy storage system, three different control strategies, PID control, sliding mode variable structure control and ADRC control, were used to simulate the charging and discharging dynamic process of FESS. Considering the particularity of flywheel energy storage system as a limited energy storage unit, the controller parameters of three traditional control modes are adjusted effectively on the premise of keeping the parameters of the flywheel motor unchanged. The simulation results are compared from rotation rate and torque, and the advantages and disadvantages of three control strategies and the dynamic performance of flywheel energy storage system under different control strategies are analyzed.

1. Introduction
As the fastest growing part of the energy industry, renewable energy and distributed power generation have received extensive attention [1]. When the capacity of wind turbines in power system exceeds a certain proportion, random fluctuation of wind power will easily cause frequency fluctuation of power system, which will increase the burden of frequency modulation, voltage regulation, operation and dispatch of power system, and affect the safe and stable operation of power system [2-5]. Among many energy storage technologies, flywheel energy storage technology is widely used because of its unique advantages [6-8].

At present, the flywheel energy storage device is applied in distributed generation and renewable energy generation system [9]. Therefore, how to describe, measure and calculate the energy state of the system in real time, and how to better control the rapid energy exchange between renewable energy and energy storage system is particularly important [10],[11]. Different control strategies have different characteristics, and different control strategies have different effects on the system [12],[13].
Therefore, it is necessary to compare and analyze the application effects of several advanced control technologies in the flywheel energy storage system in order to optimize the selection of control strategies according to the different needs of the system [14].

Double closed-loop control is selected as the control mode of flywheel energy storage system. A double closed-loop control system of flywheel energy storage system based on permanent magnet brushless DC motor is constructed by using MATLAB/Simulink. Through the comparative analysis of the existing control strategies, it is found that the three control strategies, PID control, sliding mode variable structure control and ADRC control, can not only meet the requirements of the above control systems, but also effectively stabilize the voltage of the system, at the same time, can quickly balance the system energy and accurately reflect the dynamic performance of the system. In this paper, the flywheel energy storage system is modeled and simulated. The dynamic response characteristics of load fluctuation are compared when three different control strategies are adopted. Mathematical and simulation model of flywheel energy storage system with double closed loop control of speed and current.

2. The establishment of the speed and current double closed loop control system model

2.1. Establishment of mathematical model

In this study, the mathematical model of permanent magnet brushless DC motor is established directly in Cartesian coordinate system. It is assumed that the three-phase windings of the motor are completely symmetrical, with a space difference of 120 degrees electric angle, and the stator windings are 60 degrees phase band full-distance concentrated windings with star connection. The air gap permeance of the motor is uniform, and the effects of leakage flux and magnetic circuit saturation are neglected, and the effects on hysteresis loss and eddy current loss are neglected.

The voltage equation of three-phase stator winding established by this method:

\[
\begin{bmatrix}
U_a \\
U_b \\
U_c 
\end{bmatrix} = \begin{bmatrix}
0 & 0 & I_a \\
0 & 0 & I_b \\
0 & 0 & I_c 
\end{bmatrix} + \begin{bmatrix}
L_{aa} & M_{ab} & M_{ac} \\
M_{ba} & L_{bb} & M_{bc} \\
M_{ca} & M_{cb} & L_{cc} 
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_c 
\end{bmatrix} + \begin{bmatrix}
E_a \\
E_b \\
E_c 
\end{bmatrix} + \begin{bmatrix}
U_a \\
U_b \\
U_c 
\end{bmatrix} 
\]

(1)

In the formula: \(U_a, U_b, U_c\) and \(U_n\) are the End Voltage and Common Node Voltage of Stator Three-phase Winding, \(I_a, I_b, I_c\) are Current of Stator Three-phase Winding, \(E_a, E_b, E_c\) are Back EMF of Stator Three-phase Winding. \(R_a, R_b, R_c\) are Resistance of Stator Three-phase Winding. \(L_{aa}, L_{bb}, L_{cc}\) are Self-inductance of three-phase stator windings. \(M_{ab}, M_{ac}, M_{ba}, M_{bc}, M_{ca}, M_{cb}\) are Mutual inductance between stator windings of each two phases.

Common node voltage:

\[
U_n = \frac{U_a + U_b + U_c}{3} - \frac{E_a + E_b + E_c}{3} 
\]

(2)

The expression of electromagnetic torque in the process of motor operation:

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

(3)

Mechanical motion equation of motor during charging:

\[
T_e - T_L - f w = J \frac{dw}{dt} 
\]

(4)

Mechanical Motion Equation of Motor in Discharge Process:

\[
T_e - T_L - f w = -J \frac{dw}{dt} 
\]

(5)

In the formula: \(T_e, T_L\) are Electromagnetic Torque and Load Torque, \(J\) is Rotating inertia of rotor, \(f\) is Damping coefficient, \(w\) is Mechanical angular velocity of rotor.
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2.2. Establishment of simulation model

2.2.1. Simulation model and transfer function. The closed-loop control has a feedback link, which can greatly improve the accuracy of the system and has a shorter response time. The controller of the system will be affected by the output of the controlled object to form one or more closed-loops. It is suitable for systems that require high response time and stability. Therefore, the simulation module of the flywheel energy storage system is built in MATLAB/Simulink by using the mathematical model established above, and the charging process of the flywheel energy storage system is simulated by using the module built to verify the correctness of the mathematical model and the double closed-loop control system. The control system schematic diagram is shown in Figure 1.

![Figure 1. Block diagram of the double closed-loop control system of the FES system.](image)

The Control principle: By comparing the given speed $n_{\text{ref}}$ with the feedback speed $n$, the comparative result $n_{\text{error}}$ is obtained through the control of the controller. The current $i_{\text{ref}}$ generated by the speed controller is given as the current and compared with the feedback current $i$. Then the error current $i_{\text{error}}$ is controlled by the current controller. The output is fed to magnet brushless DC motor through pulse width modulation, electronic commutation and power switch. In the control system, the speed loop is used as the outer loop, which can stabilize the output speed when the wind speed changes or load disturbance occurs. The current loop is used as the inner loop. In the stable operation system, the current loop can be adjusted with the speed loop at any time. At the same time, by limiting the output current, the current loop can effectively prevent the overcharge and discharge caused by the flywheel speed change too fast. In this study, a complete flywheel energy storage system model is built by encapsulating the flywheel motor and the external circuit into several subsystem modules, and then combining the various sub-modules. In this way, the internal parameters of the encapsulated module can be easily changed in the simulation process, and the readability is strong.

2.2.2. Construction of general simulation module. In this study, three control strategies, PID, sliding mode variable structure and ADRC, are used to simulate the charging process of flywheel energy storage system. For the whole system, different control strategies only have different simulation modules of speed controller and current controller. The simulation models of rectifier, three-phase inverter bridge and logic commutation are fixed. Therefore, according to the mathematical model of flywheel energy storage given above, the construction of several general simulation sub-modules in the flywheel energy storage system is given at first.

Figures 2 to 4 are shown.
In Figure 2, the rectifier is composed of six phase pulse generator modules, three-phase AC power supply module and three-phase rectifier bridge module. The given value of three-phase AC power supply is 380V and the frequency is 50Hz. The phase pulse module is composed of Pulse Generator, which is connected to the gate of Universal Bridge module of three-phase rectifier bridge. Phase voltage input and trigger pulse input of three-phase AC power supply are used as input terminals of three-phase rectifier bridge respectively. As the output terminal of three-phase rectifier bridge, DC voltage directly supplies power to three-phase bridge inverters.

In Figure 3, three-phase bridge inverters are built using IGBT/Diode modules. The output end of the rectifier serves as the input. The output three-phase voltage signal is supplied to the permanent magnet brushless DC motor, and the gate signal of six power switches is provided by the logic commutation module.

In Figure 4, the logical commutation module is composed of three-phase Hall position signal and PWM signal output from the control module. The output signal V1-V6 is used to control the on-off of power switches in three-phase inverters.

3. Performance comparison of three control strategies
Good operation stability and tracking ability of control signal are two important requirements of flywheel energy storage system. In this study, the flywheel energy storage system with double closed-loop control of speed and current is simulated with three control strategies, namely, PID control, sliding mode variable structure control and self-disturbance rejection control. The effects of different control strategies on the dynamic performance of the system are compared.
3.1. PID control strategy

In the actual control system, the specific form of the PID controller can be selected according to the characteristics of the controlled object, the change of load and the control requirements. In the control system of this study, the proportional-integral control method is adopted.

In the simulation process, the parameters of permanent magnet brushless DC motor are as follows: Rated voltage \( U = 500\text{V} \), Rated speed \( n = 3000\text{r/min} \), Polar logarithm \( P = 4 \), Stator winding resistance per phase \( R = 2.875\Omega \), Stator self-inductance per phase winding \( L = 8.5 \times 10^{-3}\text{H} \), Damping coefficient \( B = 1 \times 10^{-3}\text{N·m·s/rad} \), Moment of inertia \( J = 0.0008\text{kg·m}^2 \). The simulation start motor starts from no-load, the load torque changes from 0 N·m to 15 N·m and the simulation time is 0.2s. As shown in Figures 5 and 6, the simulation waveforms of speed and torque under PI control strategy are presented.

From the waveforms of rotational speed and torque in Figures 5 and 6, it can be seen that PI controller has good fast tracking ability and anti-interference ability. Therefore, the speed can quickly reach the given value, but there is a large overshoot.

3.2. Sliding mode variable structure control strategy

Sliding mode variable structure control is a special non-linear control strategy. The most important advantage of the control strategy is its robustness, relatively simple design and implementation and insensitive to the internal winding commutation and external load changes or disturbances [15].

Based on the above theoretical analysis of sliding mode variable structure control, the parameters of PM brushless DC motor in flywheel energy storage system are simulated by using MATLAB/Simulink software, which are the same as those in PI control. The simulation waveforms are shown in Figure 7 and Figure 8.

From the waveforms of rotational speed and torque in Figures 7 and 8, it can be seen that the flywheel energy storage system can be controlled by sliding mode variable structure and the rotational speed can quickly reach the given value without too much overshoot which can better restrain the external interference.
3.3. ADRC control strategy

Active disturbance rejection control (ADRC) realizes the prediction and automatic compensation of disturbance by detecting the system model and load disturbance and utilizing the input and output data of the controlled object [16]. Therefore, we can see that its greatest feature is that it does not need the precise mathematical model of the controlled object.

Based on the theoretical analysis of ADRC, the system is simulated by using MATLAB/Simulink software. The motor parameters of the system are the same as those of PI control. The simulation waveforms are shown in Figures 9 and 10.

![Figure 9. The speed waveform of the FES system under ADRC control strategy.](image)

![Figure 10. The output electromagnetic torque waveform of the motor under ADRC control strategy.](image)

From the waveforms in figures 9 and 10, it can be seen that the speed waveform becomes more stable and the torque fluctuation is not obvious when the ADRC is used to adjust the permanent magnet brushless DC motor, which can achieve no overshoot and has strong robustness.

4. Discussion on the performance of three control strategies

From Table 1, it can be seen that the simulation experiment of flywheel energy storage system using PID control strategy takes a long time to reach the stationary value and has obvious overshoot. The simulation experiment of flywheel energy storage system with sliding mode variable structure control strategy needs a short time to reach the steady-state value and less overshoot. The application of ADRC control strategy in flywheel energy storage system can keep the actual control value consistent with the set value in a short time. It has the advantages of fast response, low speed and small torque ripple. More importantly, the control strategy is used to control the system. It can achieve no overshoot, has good dynamic performance, has strong adaptability and robustness.

| Control strategy | Stationary time (s) | Is there overshoot | Fluctuation range (r/min) | Fluctuation range (N·m) |
|------------------|---------------------|--------------------|---------------------------|------------------------|
| PID              | 0.06                | Yes                | 800                       | 10                     |
| SMVSC            | 0.05                | Yes                | 100                       | 31                     |
| ADRC             | 0.03                | No                 | 0                         | 35                     |

5. Conclusions

The three control strategies of PID, sliding mode variable structure and ADRC are introduced into the control of flywheel energy storage system, which mainly controls the speed and current of flywheel motor. Through theoretical research and comparison of simulation results of speed and torque, the following conclusions are drawn:

The effect of adjusting the speed-current double closed-loop control with different control strategies is discussed. The simulation results show that the system can effectively suppress the power fluctuation of power grid. In the flywheel energy storage system, PID control is adopted. The simulation system is simple in structure, but the response time of the system is long and there is
obvious overshoot. Flywheel energy storage system is controlled by sliding mode variable structure control strategy. The simulation results show that the simulation system based on the control strategy runs stably and reliably, has strong anti-interference ability and good adaptability and robustness. The ADRC control strategy is applied to the flywheel energy storage system. The simulation results show that the control system can detect the disturbance of the system in real time, and the torque ripple is small and there is no overshoot. At the same time, the conclusions can provide a theoretical basis for the reasonable selection of relevant control strategies for distributed generation system under different load disturbances.

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