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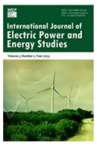

Research on Energy Storage Flywheel Motor Drive Control Technology

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ABSTRACT

Currently there is a way to use for energy storage: batteries for chemical energy storage, super for electric field energy storage, and flywheel batteries for mechanical energy storage. Flywheel energy storage has the advantages of high energy storage density, high efficiency, short charging time, no pollution, wide applicability, no noise, long service life, easy maintenance and continuous operation. Recently the most promising and competitive new energy storage technology - flywheel energy storage technology, relative to other forms of energy storage, by domestic and foreign experts unanimously optimistic. This paper will focus on the composition and operation principle of flywheel energy storage system, the classification of drive control strategy, charging control strategy, discharge control strategy and other aspects.

KEYWORDS

Energy Storage Flywheel Motor; Flywheel Energy Storage; Drive Control.

1. INTRODUCTION

There are three main forms of energy storage technology: electrochemical energy storage, mechanical energy storage, and electromagnetic storage. Among them, mechanical energy storage is pumped storage, compressed air energy storage, flywheel energy storage and other a kind of storage, the electrical energy into mechanical energy. Electrochemical energy storage, which is mainly applied to battery energy storage, is one of the most mature energy storage technologies, which is a way to convert electrical energy into chemical energy and store it. Electromagnetic energy storage is a way that electrical energy can be converted into magnetic energy and stored, including supercapacitor energy storage (ermalery) and superconducting magnetic energy storage (ermalery). The operational control of the flywheel energy storage system essentially controls the large inertia servo motor (ServiceMachine). In charging mode, the system drives the flywheel motor to rotate rapidly through an electronic inverter, which is realized by externally supplied electrical energy. It achieves and maintains stable high-speed rotation, at which time the flywheel device converts the externally inputted electrical energy into flywheel kinetic energy and stores it, realizing the conversion of electrical energy into mechanical energy and storing it. When the flywheel energy storage system delivers power to the load, the flywheel power machine will play the role of a generator and is powered by the flywheel body which is driven by the flywheel wheel body to rotate itself at high speed. When supplying power to the load, the flywheel motor drives the flywheel to rotate rapidly as a generator, and utilizes the electronic rectifier and inverter components to convert the kinetic energy lost by the flywheel motor into electrical energy when rotating, and then outputs a stable voltage and current again to complete the conversion of power into electrical energy for the flywheel device to provide electrical energy to the load. Both of these methods require the flywheel motor to operate properly, thus the flywheel motor is the core component for energy conversion in the flywheel energy storage system. One of the key steps in realizing flywheel energy storage is to effectively control the flywheel energy storage system, which needs to include effective control of the dual motors and management of energy. The flywheel energy storage system not only improves the efficiency of electrical energy generation using new energy sources, but also the quality of the flywheel energy storage system for the new energy generation system that outputs electrical energy. Relative to other energy storage methods, flywheel energy storage is characterized by high energy storage density, high discharge power, fast charging and discharging, long service life, and no environmental pollution[1]. This shows a broad prospect. At present, researchers have applied this technology in the fields of electric vehicles[2], wind power generation [3] and UPS[4].

2. COMPONENTS AND WORKING PRINCIPLE OF FLYWHEEL ENERGY STORAGE SYSTEM

2.1. Composition of Flywheel Energy Storage System

The components of a typical flywheel energy storage system including motor, flywheel, bearings, vacuum chamber and power electronic converter are shown below.

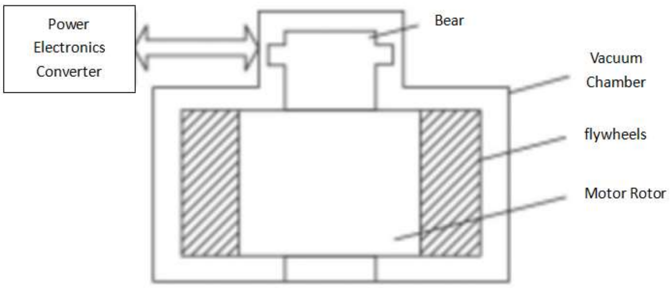

Fig. 1 Construction instructions for the flywheel energy storage system

According to Fig. 1, what shows the mutual conversion of electrical and mechanical energy is the rotation between the motor rotor and the flywheel. In this case, the flywheel is usually made of super-strong glass fiber (or carbon fiber, etc.) compounded with epoxy resin, which is required to have great inertia, stress resistance and deformation capability[5]. There are currently four types to choose from, namely electromagnetic levitation, permanent magnetic levitation, mechanical bearings and superconducting magnetic levitation. The bearings of the flywheel energy storage system play a role in supporting the flywheel and maintaining its dynamic balance. The flywheel is placed in a vacuum environment to minimize drag and prevent accidents. As a key component of electromechanical energy conversion, the motor needs to have high efficiency operation capability, both electric and power generation states, and a high speed, so permanent magnet synchronous motor is an alternative with a wide range of applications.

2.2. Energy Conversion Principle of Flywheel Energy Storage System

The operation status of flywheel energy storage system includes three aspects: acceleration energy storage, deceleration energy release and energy maintenance. The flywheel energy storage system motor is used as a motor that receives electrical energy during acceleration energy storage control. Fig. 2 shows the main circuit structure of the flywheel energy storage system. When the energy storage system is in the boost energy storage state, the energy flows through the three-phase uncontrolled rectifier bridge to the DC bus, thus providing the DC voltage to the inverter (dcvoltage). Then, according to the charging control algorithm, the DC power is converted through the three-phase inverter into AC power (Transference) used to drive the motor to increase its speed. When the flywheel energy storage system decelerates to release energy, in order to maintain a stable output voltage, its motor works with rectification technology to convert the output AC power to DC power for use as a three-phase generator. The DC power generated can now be used either for DC loads or can be fed back to the grid through an inverter. In Fig. 2, KT is a relay that prevents the motor from feeding energy back to the grid by controlling its switching state during the energy holding process.

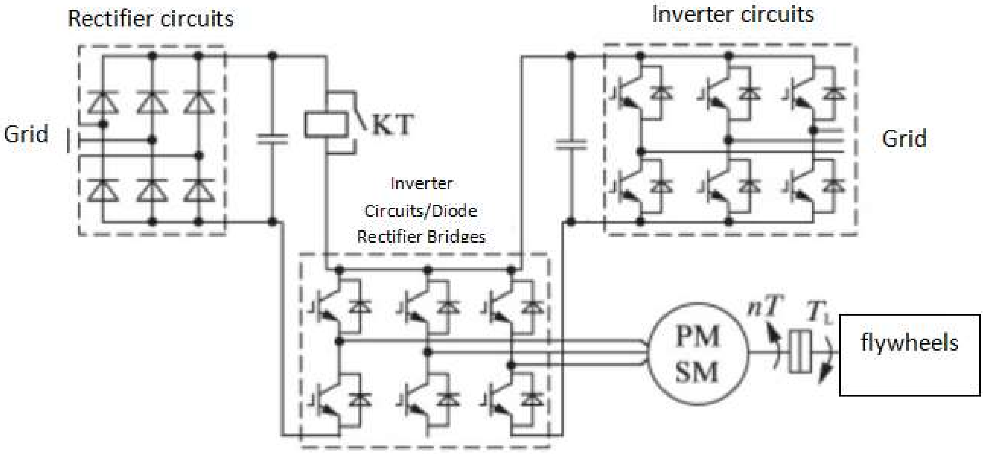

Fig. 2 Main circuit topology for flywheel energy storage system

3. CLASSIFICATION OF TRAVEL CONTROL STRATEGIES FOR FLYWHEEL ENERGY STORAGE SYSTEMS

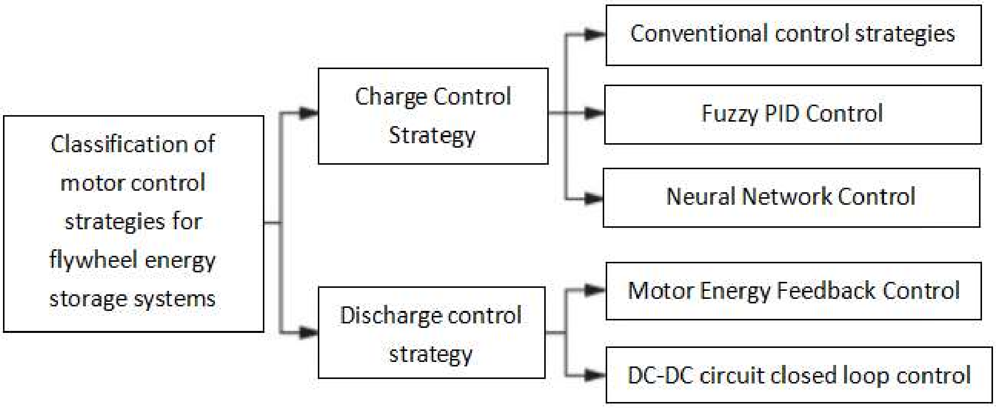

Fig. 3 Control strategies for flywheel energy storage systems with categorized schematics

A variety of control strategies for flywheel energy storage systems have been published in domestic and international studies with different categorization methods. The flywheel motor charging and discharging control strategies are categorized from the perspective of power electronic control technology, and the classification results are shown in Fig. 3. According to the description in Fig. 3, the control strategies can be classified into two types according to the direction of energy flow, one is charging and the other is discharging[6]. The charging control strategy including traditional control, fuzzy PID control and neural network control three ways. The discharge control strategy can be divided into two types: one is to use closed-loop control in combination with an additional DC-DC chopper circuit, and the other is to utilize the energy feedback from the motor for control. With the continuous progress of control theory, in addition to the conventional PI double closed-loop control method, the closed-loop control method based on the DC-DC chopper circuit has also appeared, i.e., the discharge control strategy of the flywheel energy storage system with the help of nonlinear control theory.

4. CHARGING CONTROL STRATEGY OF FLYWHEEL ENERGY STORAGE SYSTEM

4.1. Traditional Control Strategy

The traditional control strategy is a composite control strategy, which uses constant torque and constant power on the vector control idea. The flywheel energy storage system has three operating states according to the different control objectives, which are accelerated charging, decelerated discharging, and energy maintenance to ensure the energy flow between the flywheel and the grid. It can be expressed in terms of the momentum of the flywheel as it rotates:

$$E=\frac{1}{2}J\omega^2$$

Where: J---rotating body inertia;

ω---rotating angular velocity.

In general, it is necessary to increase the total amount of energy stored in the system by increasing the moment of inertia and maximum speed of the rotating body. According to literature [5], a 20 kWh multilayer cylindrical flywheel weighing 172.6 kg and reaching a maximum speed of 46,344 rpm was developed at the University of Maryland, USA. This implies that a control system with a comprehensive control strategy is necessary.

The equations of motion of an electric drag system show that the electromagnetic torque Te of the motor is proportional to the load torque Tl and the rate of change of angular velocity dω/dt. The size of the electromagnetic moment determines the size of the angular acceleration of the flywheel rotation. Due to the heat generated by the motor, the rated torque rather than the maximum torque is selected for acceleration and deceleration control according to the recommendation in Ref. [6] to ensure the stable operation of the motor energy storage device. References [7-9] In order to improve the response speed of the system and help the motor reach the set speed quickly, a compound control strategy is proposed by combining the low-speed constant torque and high-speed constant power control methods. The relationship between constant torque control and constant power control for permanent magnet synchronous machine in terms of energy storage time and power are [7]

$$t_p : t_T = \frac{3}{4}\frac{J\omega_{max}}{T_{max}} : \frac{1}{2}\frac{J\omega_{max}}{T_{max}} = 3:2$$

$$P_p : P_{T_{max}} = \frac{T_{max}\omega_{max}}{2} : T_{max}\omega_{max} = 1:2$$

Where: ω_{max}---Motor representing maximum angular speed;

T_{max}---Indicates maximum electromagnetic torque;

t_P, t_T, P_P, P_{Tmax}---The time and power required to accelerate the motor to the maximum speed in constant power and constant torque control mode.

Maximum torque-current ratio control (ID = 0) is often used to achieve constant torque control when the motor speed is below the rated speed, usually using vector control theory. ID = 0 control based on the maximum torque to current ratio is described in more detail in the literature[10-11]. When the motor operates above the rated speed, the output of the current regulator needs to be advanced in phase in order to ensure high-speed constant power operation, so the weak magnetic speed control method should be used[8].

The control block diagram of the flywheel energy storage system driven by a DC brushless motor is shown in Fig. 4[9]. In Fig. 4, the target current I_{ref} is obtained by dividing the given torque T_{ref} by the torque coefficient K. The target current I_{ref} is then compared with the feedback phase current I_{ph}. The PWM voltage is then regulated by a PI regulator. When the motor speed ω_n is greater than the rated speed ω_n, the occupied air ratio d can exceed the maximum air ratio d_{max}, and then the proportional regulator p should be used. Brushless DC motors can be advanced up to 60 degrees, the duty cycle of the PWM wave can be calculated according to the algorithm for the pre-implementation of the conduction angle and the detection of the rotor position for the purpose of controlling the inverter and the brushless DC motor.

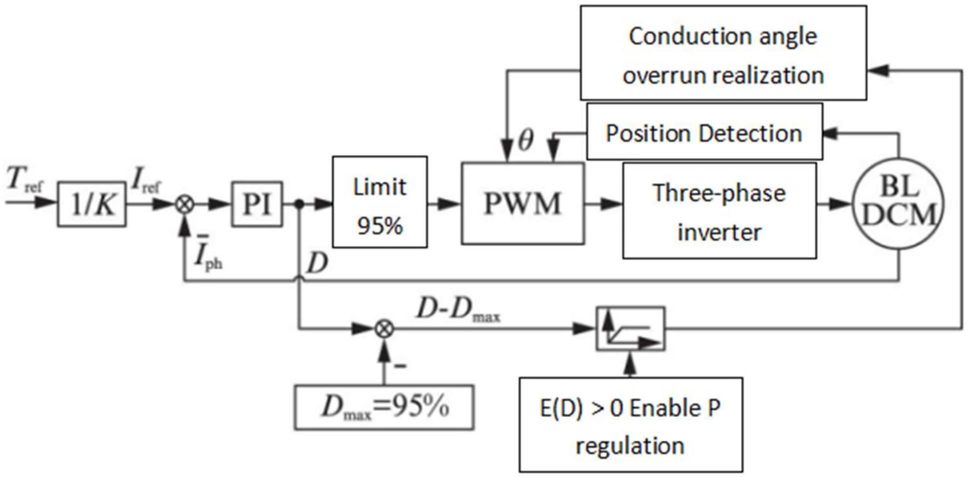

Fig. 4 Flywheel energy storage system control block diagram

4.2. Fuzzy PID Control Strategy

The flywheel energy storage system with complex structure and more uncertain parameters is a nonlinear system, so it needs a specially designed control strategy to meet its special requirements. The charging and discharging processes of the system are modeled in Literature [2] and [12], respectively, and their control block diagrams are shown in Fig. 5, where a fuzzy PID hybrid control method is used. The input variables of the fuzzy control algorithm are the speed error E and its differential term de/dt. The fuzzy PID hybrid control block diagram in Fig. 5 is suitable for the case where the speed error is large because the fuzzy control has less influence on the nonlinearities and uncertain parameters of the system. When the system is in the dynamic process stage, when the speed error E exceeds the set error E0, fuzzy control can be considered to improve the system performance. When the speed error reaches an hour, in order to make the flywheel speed follow the set value, a PI regulator can be used to eliminate the static error. In Fig. 5, the fuzzy controller is an important part of the fuzzy control system, while the fuzzy parameter self-tuning PID controller is a method of combining the fuzzy control with the traditional PID controller by using the fuzzy logic way of thinking to continuously optimize the control system. Parameters KP, KI, and KD are parameterized according to the deviation value and deviation change rate[13].

References [14] and [15] integrate fuzzy control with neural network control, adjust the PID parameters through the self-organization and self-learning function of individual neurons, and use fuzzy adaptive control to adjust the gain K of individual neurons. The shortcomings of PID in time-varying nature are effectively compensated, so that the charging process of the flywheel rotor is more rapid, stable and tough, and the maneuvering performance is significantly improved compared with that of a single maneuvering strategy[14].

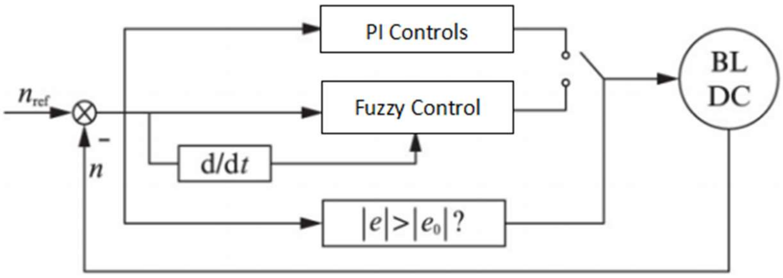

Fig. 5 Block diagram of hybrid fuzzy-PID control

4.3. Artificial Neural Network Control Strategy

Unlike the previously mentioned control methods, the artificial neural network control strategy is basically a control method for time-varying and nonlinear control objects, such as flywheel energy storage systems, which is independent of the model. Since the error back propagation neural network (BP algorithm) solves problems such as heteroskedasticity that cannot be handled by simple perceptual machines, the BP model has been widely used and has become one of the important models in neural networks [13].

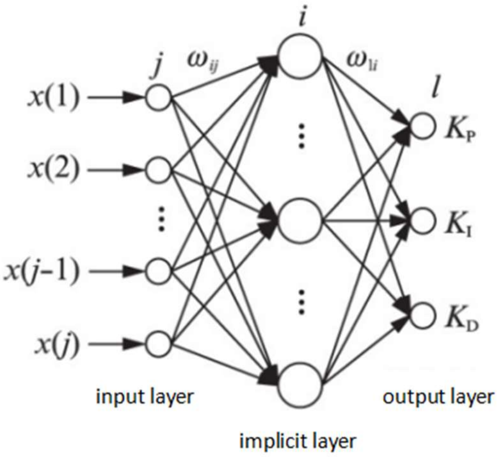

Fig. 6 BP neural network structure

Ref. [16] A BP neural network control technique is used in a flywheel energy storage system, where the reference values of the motor speed, the actual output value and the error are used as the input parameters of the BP network. The following statement is made after the reorganization: the input layer accepts the system state quantities, the output layer generates the PID parameters according to the three-layer BP network structure shown in Fig. 6, and ω_{IJ} and ω_{LI} denote the weight coefficients of the implicit layer and the output layer, respectively.

Literature [17] The proposed BP neural network structure in Fig. 6 is optimized by introducing the secondary performance index, the control increment weighted average (WA) improvement algorithm, and the PSD algorithm. While demonstrating excellent dynamic performance, the system stability and anti-interference ability are enhanced.

5. DISCHARGE CONTROL STRATEGY FOR FLYWHEEL ENERGY STORAGE SYSTEM

5.1. Closed-loop Control Strategy with Additional DC-DC Chopper Circuits

Closed-loop control strategy with additional DC-DC chopper circuit the motor operates as a generator when the flywheel decelerates to release energy. As the energy is released, the rotational speed decreases, causing the DC bus voltage at the output of the IGBT to drop gradually, so the output voltage of the IGBT needs to be stabilized by a DC-DC chopper circuit. The discharge circuit is mainly composed of two parts: the rectifier circuit and the bidirectional direct current (DC-DC) circuit. The topology is shown in Fig. 7 [18].

When the motor is generating power, the kinetic energy is converted into electrical energy, which is fed into the DC bus through the inverter circuit via the continuity diode and the bidirectional DC-DC converter. The whole process is an uncontrolled shunt poop bridge. The voltage of the bus is regulated high to maintain a smooth condition. Literature [19] Using the topology shown in Fig. 7, two voltage outputs, low and high voltage, are successfully realized for battery and traction machine power supply.

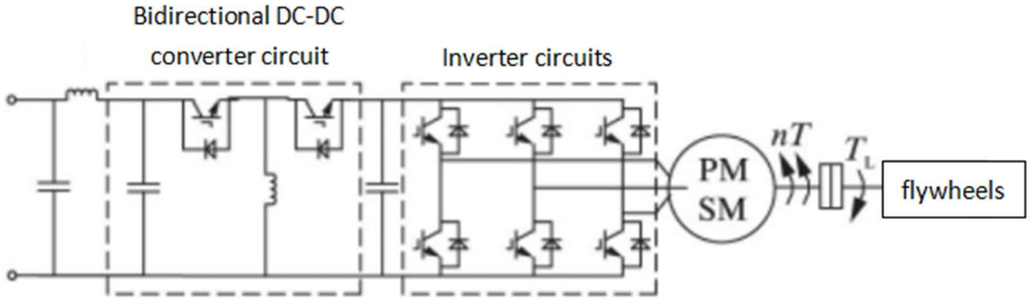

Fig. 7 Topology of rectifier circuit and bidirectional DC-DC circuit

The DC-DC conversion circuit in Literature [18], including the rectifier circuit in Fig. 7 and the bidirectional DC circuit topology, is designed with bidirectional boosting. When the system output is discharged at constant voltage, it meets the requirements of frequency conversion to drive high-speed motors, stabilizes the fixed speed and reduces the speed. Reference [20] only discusses BOOST circuits with low cost, simple structure and easy control. The studies cited in Refs. [21] and [22] indicate that an innovative DC-DC circuit design is able to achieve higher power output while adapting to a wider range of voltages than conventional solutions. The applicability of the circuit is enhanced. Reference [18] A single-cycle inductor-averaged current double-closed-circuit control strategy is used to maintain a constant output voltage of the flywheel energy storage power supply. A schematic of the voltage-current double closed-circuit control is shown in Fig. 8. In Fig. 8, the voltage feedback serves to maintain the stability of the output voltage even when the output voltage or load changes. This mechanism outputs the voltage according to the setting of the PI regulator. Therefore, the maximum output current of the voltage regulator has a direct impact on the performance of the next PI controller, which always follows the voltage loop in steady state and responds quickly to external disturbances. It also prevents the flywheel from dropping too fast during discharge, drawing too much current and releasing too much energy.

In fact, the DC-DC converter circuit is a kind of circuit with nonlinear characteristics, and some researchers have introduced nonlinear control theory into it in order to control it more efficiently, and the study shows that the system has a good performance in static performance and dynamic performance. Dual-loop serial nonlinear control for flywheel energy storage system discharge is proposed on the basis of voltage-current dual PI control[23]; development of flywheel battery discharge stabilization system is based on smooth mode control[24]. Applying the differential geometry theory of nonlinear systems, a decaying control rate is obtained to achieve an asymptotically stabilized BOOST converter control system when the input fluctuation is large and is experimentally confirmed to be effective. The system still shows good stability [25].

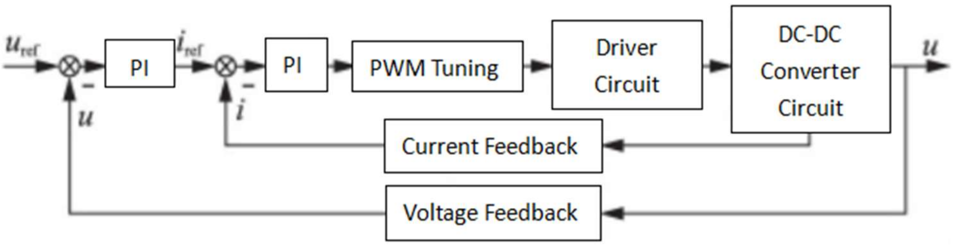

Fig. 8 Voltage-current double closed-loop control principle diagram

5.2. Control Strategy Utilizing Motor Inductor Boost Chopper

The motor feedback braking method is a cost-saving and efficient way of discharging the motor without adding any power electronic devices by using this control method. According to the rotor position signal of the permanent magnet DC brushless motor, the corresponding power switching tubes are turned on according to a specific rule, so that the motor current is in the same phase with the reverse electric current and the braking torque is generated, so as to achieve the function of energy feedback to the motor. In the process of energy feedback to the motor[26-28], we can adjust the duty cycle of the power switching tubes in a PWM cycle to make the DC voltage output constant with the help of the motor inductor boost principle[28]. This is a control strategy with a motor inductor clipper.

A new modulation strategy for the problem of uneven heating and torque pulsation of power devices is proposed for the half-bridge modulation strategy in the feedback braking of a brushless DC motor and successfully applied in a high-speed flywheel energy storage system. The phase current waveform is effectively improved and the motor torque pulsation is significantly reduced[26].

Using a permanent magnet synchronous motor, under the condition that the motor phase voltage is less than the counterpotential and the stator current flows from a high potential, the stator current vector is made to be in the III quaternion by controlling the transverse-axis current, which is in the opposite phase of the motor counterpotential, thus realizing the conversion of flywheel machinery (FlyingMachine) to electric energy[29].

6. CONCLUSION

At present, the traditional vector control strategy is commonly applied to the motor charging control of flywheel energy storage system, especially the vector control application of permanent magnet synchronous motor technology has achieved remarkable maturity and satisfactory control effect. The motor control technology without speed inductor has been developing rapidly for the requirements of cost and reliability, especially for flywheel energy storage system, the motor control technology is more prominent. Due to its more complex algorithm, which requires the chip to have a high processing speed and is not simple to realize, it still needs to be further improved, and there are certain challenges in the realization of fuzzy control and neural network control. By analyzing and synthesizing the research results at home and abroad, the various principles and characteristics of the control strategy of flywheel energy storage system are summarized, which provides a reference for the further research and application of flywheel energy storage system.

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