Survey of Research on Charging Operation Control Strategy of Flywheel Energy Storage System

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Abstract

This paper introduces the composition and working principle of flywheel energy storage system, and summarizes the charging control strategy of flywheel energy storage System. Among them, the control strategy of flywheel energy storage system of charging operation is divided into vector control strategy, compound control strategy and intelligent control strategy. On this basis, the characteristics of the charging operation control strategy of flywheel energy storage system and the problems existing in control operation are analyzed, and finally the summarization and prospect are made.

Keywords

Flywheel energy storage system, Charging, Control strategy.

1. Introduction

In recent years, with the discovery of new materials and the development of power electronics technology, flywheel energy storage systems have been successfully applied in electric vehicles, power system peaking, satellite attitude control, wind power generation, UPS and other fields[1-2]. Among various energy storage methods, flywheel energy storage has the advantages of high energy storage efficiency, high density, unlimited number of charge and discharge times, long life, and fast response. The flywheel energy storage system can not only improve the energy efficiency of new energy generation, but also improve the output power quality in the new energy generation system. The operating state of the flywheel energy storage system includes charge up energy storage, discharge deceleration energy release and energy retention.

The control of the flywheel charging system is mainly to control the flywheel motor. At present, the flywheel motors mainly include asynchronous motors, permanent magnet brushless DC motors and permanent magnet synchronous motors[3]. This article divides according to the charging operation control principle, summarizes and summarizes its operation process control strategy, mainly divides into three kinds of vector control, compound control and intelligent control strategy.

2. The Composition and Working Principle of Flywheel Energy Storage System

Flywheel energy storage system, also known as flywheel battery, its basic structure is composed of flywheel, bearing, motor/generator, power electronic control device, vacuum chamber and other five components[4]. An energy storage system is a device that stores energy in the form of kinetic energy using a high-speed rotating flywheel. It has three operating modes, namely charge mode, hold mode, and discharge mode. The charging mode refers to that the flywheel rotor absorbs energy from the outside and causes the flywheel speed to increase, and the energy is stored in the form of kinetic energy. Discharge mode refers to that the flywheel rotor transfers the kinetic energy to the generator, and the generator converts the kinetic energy into electric energy, and outputs electric current and voltage suitable for the electric equipment through the electric power control device to realize the conversion from mechanical energy to electric energy. Holding mode means that when the speed of the flywheel reaches a predetermined value, it will neither absorb energy nor output energy, as shown in Fig. 1.

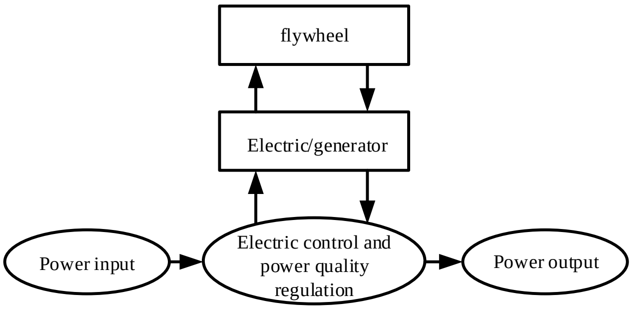

Fig.1 Flywheel energy storage system working principle diagram

The energy stored in the form of kinetic energy by a high-speed rotating flywheel can be expressed as[5]

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

In the formula, v is the flywheel edge shallow velocity; m is the flywheel mass; J is the rotational inertia of the flywheel; ω is the angular velocity of the flywheel. The formula for the inertia of the flywheel is

$$J = \frac{1}{2}mr^2 \tag{2}$$

In the formula, r is the radius of rotation of the flywheel.

3. Vector Control Strategy

At present, in the flywheel energy storage operation control, there are two common methods of motor control, direct torque control and vector control[6]. Direct torque control has the advantage of rapid dynamic response, but there is a large pulsation; vector control technology is more mature, steady-state, dynamic performance is good, and application is more extensive. At present, vector control methods mainly include $i_d = 0$ control, $\cos\varphi = 1$ control, maximum torque and current ratio control, weak magnetic control, and maximum output power control. Among them, $i_d = 0$ control and weak magnetic control are the most widely used in flywheel energy storage charge control.

3.1 Id =0 Vector Control

$i_d = 0$ Vector control Compared with other vector control methods, it has the advantages of simple control system and good constancy.

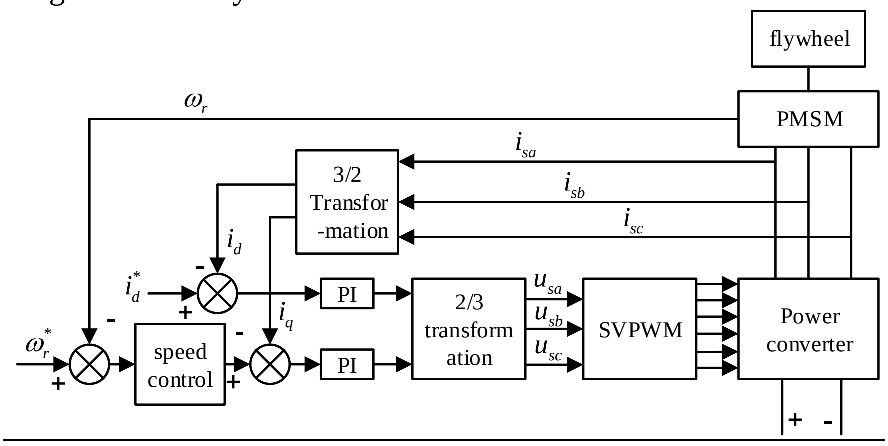

Fig.2 $i_d = 0$ charging vector control principle

In [7], $i_d = 0$ vector control strategy was adopted. By decomposing the d and q axes of the stator current of the flywheel motor and controlling i_d equal to 0, the q axis current can be controlled to control the charging current of the flywheel battery to ensure the charging of the flywheel battery.

Quickness and stability. However, the vector control of $i_d = 0$ needs vector control with complicated coordinate transformation, and it depends on the speed and displacement sensors, and has a large dependence on motor speed and displacement parameters[8]. The principle of charging vector control is shown in Fig. 2.

Considering the instability of rotational speed and displacement in $i_d = 0$ vector control, a MRAS method based on current model is used in [9]. The motor stator current measured by sensor is used as the reference model of the model reference adaptive system, the current model calculated by the stator voltage is used as the adjustable model, and the PI controller is used in the control unit. This method can accurately obtain motor speed and rotor position in FESS from inertial operation to charge and discharge mode, and realize the rapidity and reliability of system state switching.

3.2 Weak Magnetic Control

When using the $i_d = 0$ vector control strategy to control its permanent magnet synchronous motor, the maximum speed of the flywheel motor is quickly limited due to the constraints of the maximum output voltage of the inverter and the maximum current condition of the motor, affecting the maximum storage energy of the flywheel. In response to this problem, the literature [10] uses weak magnetic control. When the motor speed is above the base speed, the stator current of the control motor runs along the intersection of the voltage limit circle and the current limit circle, which not only broadens the speed range but also ensures that the motor has a larger output torque.

The literature [11] compensates for the problem that the negative i_d compensates the weak magnetic control at high speed. It is proposed that the PMSM uses a complex vector current regulator to compensate the weak magnetic control at negative i_d to further improve the stability.

The literature [12] introduced the over-modulation technology to enable the PMSM output performance to reach an optimal state during field-weakening control and improve the carrying capacity of the motor during high-speed operation. The algorithm has good real-time performance and is simple and easy to implement.

4. Compound Control Strategy

The composite control strategy is mainly based on the control strategy of phase division according to the change of speed in the flywheel speed-up energy storage process. With the switching of the working state of the flywheel energy storage system, the energy flows between the flywheel and the load grid. In order to control the flywheel charging operation well, the control method used changes as the speed changes.

In the whole process of energy storage, only a single constant torque control strategy was adopted in [13]. The control is simple and easy to operate, but the energy conversion efficiency of the system is low, and it is difficult to make full use of the energy. The control strategy is not combined with the flywheel operation mode and lacks the flexibility of independent control.

In order to meet the characteristics of low speed response and large starting torque of flywheel, a compound control strategy of low speed constant torque and high speed constant power was adopted in literature [14]. When the motor speed is lower than the rated speed, the constant torque control is adopted, and the $i_d = 0$ control and the maximum torque current ratio control in the vector control theory are generally used. When the motor speed is higher than the rated speed, the constant power control is adopted. If the motor speed is lower than the reference speed, the motor terminal voltage can meet the speed regulation requirements. When the speed is above the reference speed, it is necessary to avoid the limitation of the back electromotive force on the current growth. In order to ensure that the motor still has a large torque when it is running at a high speed, constant power operation is required. This control strategy improves the energy conversion efficiency and better adapts to the working state of the flywheel energy storage.

On the basis of [14], a charging control strategy of improved composite control is proposed in [15]. The charging operation of flywheel is divided into four stages: the starting stage of flywheel, the constant torque running when the speed of motor is higher than the base speed; The motor runs at constant power between the lowest working speed and the highest working speed, and maintains the flywheel operation with small power after reaching the maximum operating speed. This strategy is not only more suitable for flywheel operation mode, but also faster to switch from constant torque control to constant power control. The block diagram of the charge control strategy for improved composite control is shown in Fig. 3.

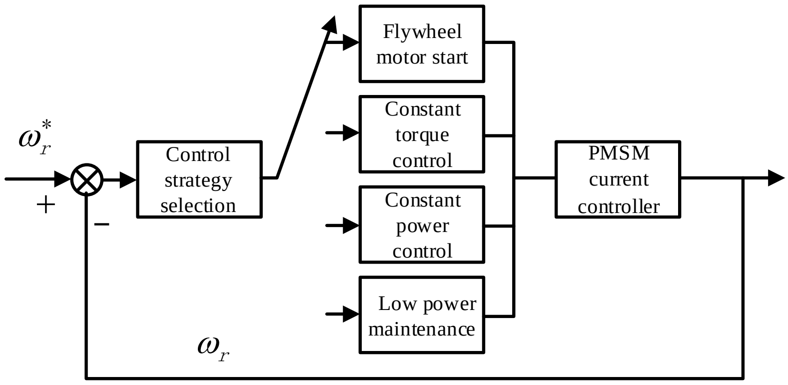

Fig.3 Improved composite control charging control strategy

In [16], a new compound control strategy was adopted. In order to generate a large initial starting moment, constant power current limiting startup was adopted in the start-up phase, and fuzzy control was used in the speed control stage to balance the speed and accuracy. When the speed reached the steady state, In order to improve the steady-state precision, PI control is adopted. This intelligent algorithm can not only track the optimal charging curve of flywheel speed, but also improve the dynamic stability of the controlled object. Furthermore, the speed and accuracy of the flywheel charging process are further improved. The literature [17] draws on the control strategy of [16], uses constant power control during the speed regulation phase, and in addition to simplifying the control process, it also realizes the effect of reducing the unbalanced magnetic tension on the stability of the rotor.

The traditional compound control maintains the maximum constant torque control until the motor reaches its minimum operating speed, which easily causes the motor to generate heat and is not conducive to the safe operation of the system. Based on the characteristics of energy bidirectional flow in flywheel energy storage system, a new control strategy of flywheel energy storage system based on bidirectional DC/DC is presented in [18], that is, charging constant current，constant voltage and PI compound control strategy. This control strategy not only greatly simplifies the structure of the circuit, but also meets the requirements of the flywheel charging, and can control the speed of the motor more flexibly according to the characteristics of the motor.

5. Intelligent Control Strategy

During the flywheel charging operation, the inertia of the load is large and the speed response is slow. It is a nonlinear time-varying system. Due to the use of traditional PI control parameters fixed, the motor response speed is slow, the waveform fluctuation is large and the control effect is not good when the motor parameters are subjected to external disturbance. Therefore, the intelligent control method is commonly used in common control. The main form is based on the use of PI controller, combined with fuzzy control algorithm, BP neural network algorithm, particle sub-group algorithm and other intelligent algorithms, design the controller or optimize the parameters of the PID controller to achieve good control of the speed.

The traditional PID control adopts a double closed-loop control structure. By designing a PID controller of a speed loop and a current loop, the design is simple, but the current phase lag is obvious.

In [19], the speed outer loop is controlled by a conventional PID module, and the current inner loop adopts three-phase current hysteresis loop tracking to control the motor rotation at a given speed. Its structure is simple, its current lag is not obvious, but the tracking speed effect is not good. The literature [20] considers the current loop transfer function under the flywheel energy storage delay. Based on this, a bandwidth-based current loop PI parameter design method is proposed. It adopts a new reduced-order model and optimizes parameters to better solve the problem of current phase lag when the input frequency is high in the charging process. However, due to the large rotational inertia of the flywheel energy storage system, the speed change under this control strategy is still very slow.

5.1 Fuzzy PID Control

In order to improve the traditional PID parameters and obtain the desired ideal control effect, multiple intelligent control algorithms are combined to design the controller. Fuzzy control is an intelligent control method that is not based on the exact mathematical model of the controlled object. It has the advantages of fast control speed, good robustness, and so on. Based on the rough modulation of PID controller, the fuzzy algorithm is introduced into the design of the flywheel energy storage controller. The ideal control result is obtained through fuzzy rule inference. The speed response can be improved and the robustness is good.

In [21], a flywheel charging control system based on fuzzy adaptive PID control was proposed. The fuzzy adaptive PID controller was designed using a general speed and current double closed loop control structure. The fuzzy inference is made according to the deviation of velocity signal and the rate of variation of deviation. Compared with the traditional PID control, it realizes the automatic adjustment of the PID parameters, improves the dynamic performance of the system and improves the robustness. However, its fuzzy control rules are based on the experience of experts or operators, with certain uncertainty, lack of support in theory, difficult to achieve in practical operation, with a certain steady state error. The fuzzy adaptive controller structure is shown in Fig. 4.

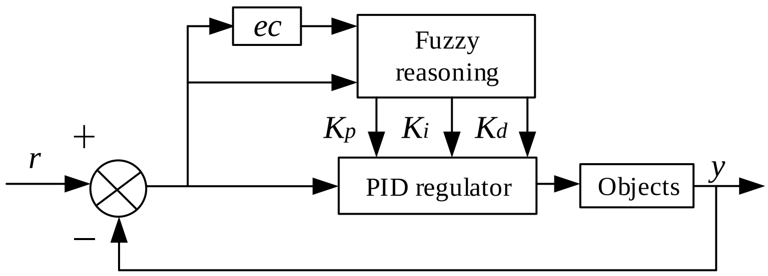

Fig.4 Fuzzy adaptive PID controller structure

In [22], a parameter optimization method for PID based on parameter self-tuning fuzzy control was proposed, but on the basis of this method, double fuzzy control was used to realize the optimization of control parameters. Compared with the literature [21], the proposed fuzzy control method has more advantages in terms of overshoot and adjustment time.

In [23], a fuzzy-PI compound control was adopted. Although the paste controller was directly used in the speed control of the flywheel, it was switched to PI control in the range of small deviation. In this way, the advantages of fuzzy controller for nonlinear time-varying systems and time-delay systems are not only brought into full play, but also the steady-state errors which are difficult to solve by fuzzy control are eliminated. It can not only obtain good dynamic performance, but also achieve no static error of the speed regulation system.

5.2 Artificial Neural Network Control

The speed response of fuzzy control is fast and the robustness is good. However, the theoretical problems of stability and robustness of fuzzy control have not been completely solved, and the design of fuzzy controller is not systematic, so it is impossible to define control objectives. This limits the application of fuzzy controller. The artificial neural network control strategy is a basic model-independent control, which has good adaptability to time-varying and nonlinear objects. The neural network control does not depend on the exact mathematical model of the controlled object, and the adaptive robustness is strong, but the accuracy is poor. The conventional PID controller has simple structure and high precision, but the adaptive robustness is poor[24].

In [25], the BP neural network and the neural network learning algorithm with variable learning rate are combined to design a BP-PID controller, which combines the neural network and the PID controller, and its advantages complement each other. Because the learning rate adaptively adjusts with the error of convergence process, the designed controller has the characteristic of adjustable parameters, and improves the speed of dynamic response. The BP-PID controller structure is shown in Fig. 5.

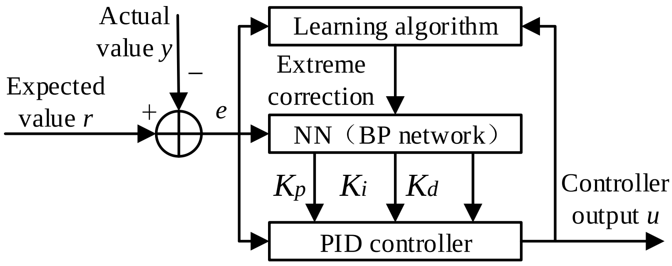

Fig.5 BP-PID controller structure diagram

In [26], the neural network algorithm is improved, the quadratic performance index is introduced, the incremental weighted average algorithm and the PSD algorithm are introduced, the stability and anti-interference ability of the system are increased, and the dynamic performance of the system is shown. In [27], a neuron adaptive PID control algorithm based on rotational speed and current double closed loop control system is proposed, which is used for charge and discharge control of flywheel energy storage unit, and the smooth output of active power of the system is realized. The stability of power output quality operation is improved. In [28], in the combined system of wind power generation and flywheel energy storage, the fuzzy neural network control algorithm is used to realize the automatic adjustment of the DC bus voltage and achieve the purpose of stabilizing the DC bus voltage of the system.

5.3 Particle Swarm Control

The neural network control does not need to know the mathematical model of the controlled object. It can understand the system structure through its own learning and thus generate the optimal control parameters. Its environmental change has strong adaptability and can get better control effect. However, this algorithm requires offline and on-line system identification, which requires a large amount of calculation and is complex to implement[20].

The particle swarm optimization (PSO) algorithm proposed by Kennedy and Eberhart et al. in 1995 is a new type of stochastic optimization intelligence algorithm[29]. However, the traditional PSO algorithm has the disadvantages of low efficiency, easy to fall into local extremes, and prematureness of algorithms. In order to overcome these drawbacks, literature [30] proposes an improved PSO (IPSO) algorithm for these disadvantages. By introducing chaotic initialization, adding chaotic disturbances in iterations, and adaptively adjusting the inertia weight coefficients, the FESS PI controller parameters are optimized. However, in the application, it is found that if there is no restriction on the update of the location, the new location may appear unsatisfactory, causing the convergence speed to slow down. The position update restriction is easy to think of using a similar speed update limit method. Although this position update method is simple, it can easily cause the IPSO algorithm to jump out of the current local optimal solution range, leading to a local optimal solution.

To better limit location updating, the literature [31] introduced the idea of simulated annealing on the basis of [30]. Considering the active and reactive PI controller parameters of the flywheel energy storage system, the objective function of the ITAE index of active power and voltage deviation is taken as the objective function, and an improved intelligent particle swarm optimization algorithm is used to optimize the parameters of the PI controller. It can not only limit the location update, but also can jump out of the local optimal solution. Compared with the traditional PID control algorithm, it obviously has higher efficiency.

6. Summary and Prospects

At present, the mainstream of motor charging control in flywheel energy storage system is vector control, which is the traditional control strategy. The technology of permanent magnet synchronous motor using vector control is more mature, and the control results are satisfactory. The intelligent algorithm control strategy introduced in this paper is not only used by one algorithm alone, but also used by several intelligent algorithms. However, because of the complexity of the synthesis algorithm, the requirement of the chip is too high. There are still some difficulties in the implementation of hardware, which need to be further improved. In addition, there are some control technologies that are worth paying attention to. In order to increase the efficiency of the system, reduce the energy loss, and reduce the size, the motors in flywheel energy storage systems mostly use permanent magnet synchronous motors[32]. However, in the permanent magnet synchronous motor control, in addition to the traditional vector control, the position and speed of the rotor are required to be measured by the sensor. Therefore, various sensorless technologies are widely used in the control of the permanent magnet synchronous motor[33].

Based on the analysis and summarization of current domestic and foreign research results, this paper summarizes the different principles and characteristics of flywheel energy storage system control strategies and provides references for the research and application of flywheel energy storage systems.

Acknowledgements

The Artificial Intelligence Key Laboratory of Sichuan Province Foundation (2015RYY01, 2017RYY02), Sichuan University of Science and Engineering Talent Introduction Project (2017RCL53) and Sichuan University of Science and Engineering Postgraduate Innovation Fund Project (y2017033).

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