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

Yangxin Zhang [a], Hao Wu [b], Xingxing Dong [c], Ruikai Ye [d]

School of Automation & Information Engineering, Sichuan University of Science & Engineering, Zigong 643000, China;

[a]laputazyx@163.com, [b]11305076@qq.com, [c]domewatson@126.com, [d]pokagic@163.com

Abstract

This paper introduces the composition and working principle of flywheel energy storage system, and summarizes the discharge control strategy of flywheel energy storage System. In this paper, the control strategy of the flywheel energy storage system of the discharge operation is broadly divided into the motor feedback modulation control strategy and the control strategy of the additional DC circuit; On this basis, the characteristics of discharge operation control strategy of flywheel energy storage system and the problems in control operation are analyzed, and finally, the paper summarizes and forecasts.

Keywords

Flywheel energy storage system, Discharging, Control strategy.

1. Introduction

With the development of society and the deterioration of the environment, the traditional energy is increasingly scarce, which greatly promotes the development of new energy technology. However, the new energy such as wind energy, solar power generation and other widespread intermittence, volatility and other issues. Flywheel energy storage system can not only improve the utilization rate of new energy generation, but also improve the output power quality in the new energy generation system. Compared with other energy storage methods, flywheel energy storage has the characteristics of high energy storage density, high discharge power, fast charging and discharging speed, long service life, as well as environmental friendly and pollution-free, and has a bright future[1]. At present, researchers have applied it to the fields of electric vehicle[2], wind power generation[3], UPS[4] and so on.

In this paper, according to the principle and structure of discharge operation control, the operation process control strategies are summarized, mainly from the motor feedback modulation and additional DC-DC converter control strategies are classified and summarized.

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

The flywheel energy storage system, also known as the flywheel battery, is a device that uses high-speed rotating flywheels to store energy in the form of kinetic energy. Its basic structure is composed of five components such as flywheel, bearing, motor/generator, power electronic control device and vacuum chamber[5]. 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.

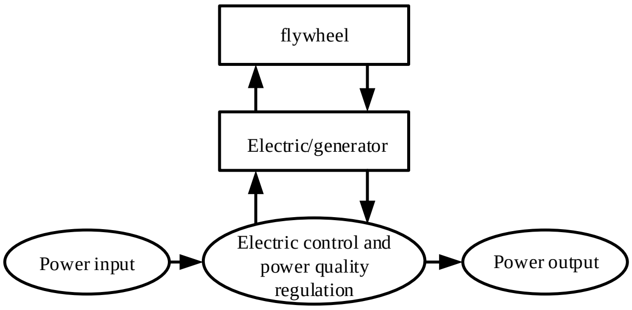

Fig. 1 Flywheel energy storage system working principle diagram

The energy stored in the form of kinetic energy by a high-speed rotating flywheel can be expressed as[6]

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

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. Discharge Control Framework for Flywheel Energy Storage System

When the flywheel is in the discharge state, the motor operates as a generator. As the energy is released, the speed will gradually decrease, resulting in a gradual decrease in the DC bus voltage at the IGBT output[7]. Therefore, in the flywheel energy storage discharge operation, the first requirement is to keep the DC bus voltage output from the power conversion circuit constant and realize energy feedback. At this time, the output DC power can be supplied to the DC load, or can be fed back to the grid after the inverter.

In the discharge operation of flywheel energy storage system, the motor current and DC side current are reversed. The double closed loop control structure of DC bus voltage outer loop and motor current inner loop is commonly used. As shown in Fig. 2.

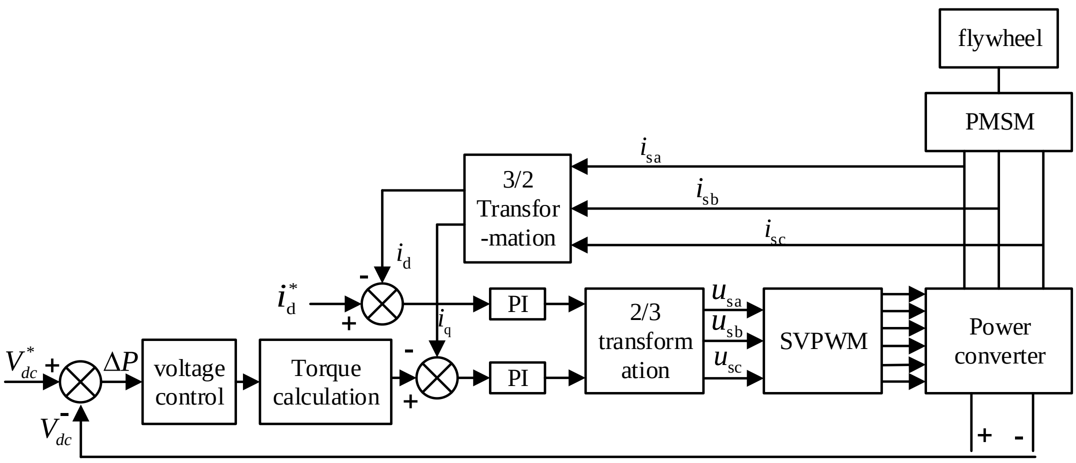

Fig. 2 Schematic diagram of discharge operation control principle

4. Motor Feedback Modulation Control Strategy

Electric energy conversion circuit is the pivot of flywheel energy storage system. It drives the motor based on power electronic switching device to realize the mutual conversion of electric energy and mechanical energy, and provides interface to the external system. IGBT in switching device is used in flywheel energy storage system with its high switching frequency and simple driving circuit[8]. The flywheel energy storage motor conversion circuit is a three-phase bridge circuit composed of fully controlled devices, as shown in Fig. 3. It can be used as a bidirectional PWM converter to meet the functional requirements of flywheel converter circuit to achieve bidirectional flow of energy.

The motor feedback braking mode is a cost-effective discharge mode. This control method does not require any additional power electronics, and can be directly applied to the main circuit topology of FIG. The feedback braking of permanent magnet brushless DC motor (BLDCM) usually has two modes: half-bridge modulation mode and full-bridge modulation mode. The latter has a switching loss of 1 times more than that of the former[7].

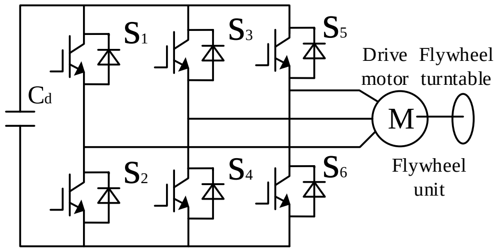

Fig. 3 Flywheel energy storage system power conversion main circuit topology

The literature [9] [10] uses the working mode of motor feedback braking, and gives the equivalent circuit of the energy feedback braking of the flywheel unit, as shown in Fig. 4. The DC loop voltage can be maintained stable by adjusting the step-up effect of the inductance of the motor, and then the DC/AC inverter can supply AC power to the load by controlling, that is, in a PWM cycle, constant DC voltage can be output by changing the duty cycle of the power switch.

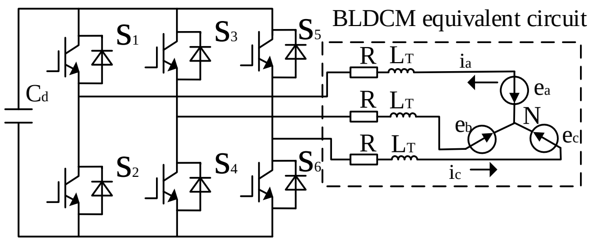

Fig. 4 Equivalent circuit of flywheel unit energy feedback braking

The motor feedback brake half-bridge modulation mode can reduce the rate of change of current during commutation, which will result in large torque ripple, and uneven heating of the upper and lower bridge power devices is not conducive to long-term stable operation. Literature [11] proposed a "new six-shot PWM" modulation method, which realizes that the inverter still has only one power device switching action at any time in one cycle. It better solves the problem of torque ripple caused by uneven heating of the power device and slow construction flow rate, and the method does not need to increase the power device, and the implementation is easy and the applicability is strong.

In [12], the permanent magnet synchronous motor is used, and the regenerative braking principle of the motor is used to control the electric energy conversion circuit to reverse the cross shaft current and the motor back EMF, so that the phase voltage of the motor phase lags behind the back EMF, and the amplitude is smaller than the back EMF. Finally, the stator current flows from the high potential to the low potential, and the mechanical energy of the flywheel is output to the electric energy.

Literature [13] proposed a discharge strategy, which achieves global linearization by incorporating speed into the algorithm of the voltage controller and combining the DC bus voltage design controller.

It better solves the problem that the frequency and amplitude of the output AC voltage continuously decrease during the discharge process, which ensures the stability of the discharge operation process.

In [14], the required electromagnetic torque and the given current are calculated by using the motor speed obtained by MRAS speedless observation. This value can be used for vector control to realize the discharge control of FESS. This method can better maintain the voltage constant, and at the same time ensure the fast and reliable state switching of the flywheel energy storage system.

5. Control Strategy of Additional DC-DC Converter Circuit

DC-DC converter is the core of switching power supply, which can convert one DC power supply into another with different output characteristics. The basic means of the DC-DC converter is to turn on and off the switching device, so that the load line with the filter is connected to the DC power supply for a while, and then disconnected, and another level of DC voltage is obtained on the load[15]. Due to the characteristics of the flywheel, the most widely used in the flywheel energy storage system is the DC-DC converter without isolation transformer, among which the Buck-Boost application is the most common.

During the discharge operation, the mechanical energy of the system is converted into electric energy, and the motor speed decreases, causing the voltage at the motor terminal to gradually decrease. Therefore, considering the Boost boost circuit before the load, the control strategy of the additional DC-DC conversion circuit can be proposed.

The literature [16] [17] proposed the circuit topology of the flywheel energy storage system that introduces the boost circuit, as shown in Fig. 5. By controlling the closing of the switch SB, the boosting circuit can be operated in both short-circuited and unregulated states, and finally the control voltage rises to the set DC bus voltage value.

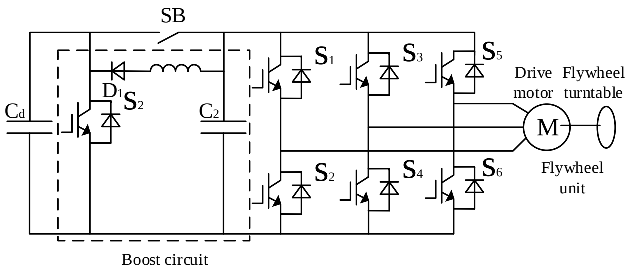

Fig. 5 Main circuit topology of flywheel energy storage system with boost circuit

The introduction of the booster circuit makes the control of the main circuit topology simple, but causes the flywheel unit to be completely out of control, the current wave difference, the torque ripple is large, and the hardware cost is increased, and the reliability is lowered. The literature [18][19][20] uses a flywheel motor conversion circuit with a bidirectional buck-boost link as shown in Fig. 6. The bidirectional buck-boost circuit outside the dotted wire frame is controlled by DC chopper to adjust the average phase voltage of the stator, and then DC/DC boost chopper is applied to the DC voltage obtained by PWM rectification to output DC voltage which meets the requirements.

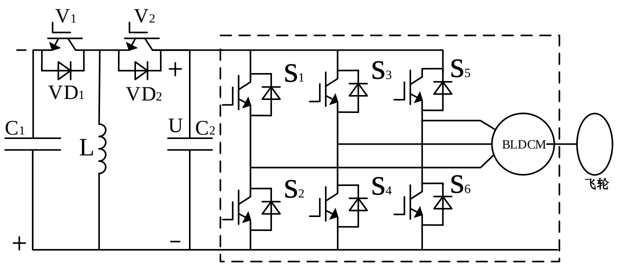

Fig. 6 Conversion circuit of permanent magnet brushless DC motor with bidirectional buck-boost

Reference [21] proposes a simplified DC-DC conversion circuit that uses a bidirectional buck-boost design to remove V1 of Figure 6, leaving only the freewheeling diode VD1. When the motor is running in the state of power generation, the energy will be converted from kinetic energy to electrical energy. The uncontrollable rectifier bridge and bidirectional DC-DC converter are formed by the diodes in the inverter circuit to inject energy into the DC bus, and the constant voltage of the DC bus is achieved.

A novel DC-DC circuit is proposed in [22] and [23] respectively. In [22], the inverter circuit, the storage capacitor and the DC-DC converter in the rectified state together constitute the energy feedback main circuit, which widens the system voltage regulation range and improves the power capacity. The DC-DC converter module in [23] uses Cuk chopper circuit, which makes the circuit simpler and easier to implement.

In [24], a two-degree-of-freedom PI control strategy based on bidirectional DC/DC is proposed, which not only improves the instability of single-degree-of-freedom control, but also has better resistance to load interference and target value following.

In order to deal with the nonlinear characteristics of the Buck-Boost converter, the literature [25] proposed the double-loop cascade nonlinear control of the flywheel energy storage system based on the additional bidirectional DC-DC converter. The voltage outer loop adopts a robust sliding mode variable structure and increases the current limiting link. This method ensures smooth and safe discharge operation, and improves dynamic characteristics such as output voltage regulation time and overshoot compared to dual-loop PI control.

The literature [26] improved the sliding mode observer in the literature [25], and presented a charging and discharging control method for the flywheel energy storage system based on the improved sliding mode observer. It switches to the synovial variable structure control at a certain set value of the rotational speed, which better solves the problem that the estimated angle of the sliding mode observer is deviated when the flywheel motor runs at high speed.

6. Summary and Prospects

This paper analyzes the discharge operation process of the flywheel energy storage system and summarizes its control strategy. At present, the discharge operation control of the flywheel energy storage system is the control hub for the power conversion circuit during the discharge process. The research on this aspect is also the most comprehensive. For the energy feedback of PMSM, considering that the DC-side capacitor voltage is related to the injected active power, it is necessary to control the output power of PMSM to the DC-side according to the change of capacitor voltage to stabilize DC voltage. Since the DC-DC converter circuit is a nonlinear circuit, researchers have applied nonlinear control theory to it for better control[7]. The control of the flywheel energy storage system based on the artificial intelligence method will bring revolutionary changes to the field of flywheel control.

Acknowledgements

The Artificial Intelligence Key Laboratory of Sichuan Province Foundation (2015RYY01), Sichuan University of Science and Engineering Postgraduate Innovation Fund Project (B20306167, y2017033, y2017032).

References

[1] Q.S. Zhang: Research on the Control Strategies of the Flywheel Energy Storage System(MS. Beijing Jiaotong University, China 2012), p.01.

[2] X.X. Fu, X. Xie: The Control Strategy of Flywheel Battery for Electric Vehicles. IEEE International Conference on Control and Automation (Guangzhou, China, May 30-June 1, 2007), p. 492-496.

[3] G.O. Cimuca,C.Saudemont and B.Robyns, et al. Control and Performance Evaluation of a Flywheel Energy-Storage System Associated to a Variable-Speed Wind Generator. IEEE Transactions on Industrial Electronics. Vol. 53(2006) No. 4, p. 1074-1085.
[4] J.D. Park, C. Kalev and H.F. Hofmann: Control of High-Speed Solid-Rotor Synchronous Reluctance Motor/Generator for Flywheel-Based Uninterruptible Power Supplies, IEEE Transactions on Industrial Electronics. Vol. 55 (2008) No. 8, p. 3038-3046.
[5] X.B. Zhang, J.W. Chu, H.L. Li, et al. Key technologies of flywheel energy storage systems and current development status, Energy Storage Science & Technology. Vol. 04 (2015) No. 1, p. 55-60.
[6] R.Okou, A.B. Sebitosi, P. Pillay: Flywheel rotor manufacture for rural energy storage in sub-Saharan Africa, Energy. Vol. 36 (2011) No. 10, p. 6138-6145.
[7] Y.A. Chen, H.Y. Chen, J.H. Zhou, et al. Drive Control Strategy of Flywheel Energy Storage System, Electric Machines & Control Application. Vol. 42 (2015) No. 04, p. 16-20.
[8] Z. Tan, Y.L. Li: Development of flywheel energy storage system control platform based on dual-DSP, Power System Protection & Control. Vol. 40 (2012) No. 11, p. 127-132.
[9] X.J. Jiang, D.Q. Zhu, P.L. Huang, et al. Research on a Permanent Magnet Synchronous Motor Drive System for Electric Vehicle, Electric Machines & Control. (1997) No. 04, p. 208-214.
[10] X.S. Li: Research of Flywheel Energy Storage System on Motor and Generator Controlling Technology(MS. North China Electric Power University, China 2007).
[11] Y.Q. Huang, X.J. Jiang, A.R. Qiu. Energy feedback control for flywheel energy storage system, Journal of Tsinghua University. Vol. 48 (2008) No. 07, p. 1085-1088.
[12] L. Zhou, Z.P. Qi. Modeling and Simulation of Flywheel Energy Storage Unit for Voltage Sag in Distribution Network, Power System Technology. Vol. 33 (2009) No. 19, p. 152-158.
[13] X. Zhang, J. Yang. A Robust Flywheel Energy Storage System Discharge Strategy for Wide Speed Range Operation, IEEE Transactions on Industrial Electronics. Vol. PP (2017) No. 99, p. 1-1.
[14] W. Guo, Y. Wang, N. Li: Control Strategy for Flywheel Energy Storage System with Permanent Magnet Synchronous Machine, Journal of Xian Jiaotong University. Vol. 48 (2014) No. 10, p. 60-65.
[15] F. Lin, X. Du: MATLAB simulation of power electronics application technology (China Electric Power Press, China 2009).
[16] B.J. Li, Z.X. Wang, D.G. Wu. Simulation Research on Charging and Discharging of Flywheel Energy Storage System, Industrial Control Computer. Vol. 24(2011) No. 12, p. 107-109.
[17] R.S. Weissbach, G.G. Karady, R.G. Farmer. A combined uninterruptible power supply and dynamic voltage compensator using a flywheel energy storage system, IEEE Transactions on Power Delivery. Vol. 16(2015) No. 02, p. 265-270.
[18] X.J. Dai, X.Z. Zhang, X.J. Jiang, et al. Flywheel energy storage technology in Tsinghua University, Energy Storage Science & Technology. Vol. 01(2012) No. 01, p. 64-68.
[19] Z. Tan: Research on Drive Control System for Flywheel Energy Storage(MS. Tianjin University, China 2012).
[20] J.P. Ruan, L.B. Yu. Study on Generator Operation Control for Flywheel Energy Storage System, Northeast Electric Power Technology. Vol. 28(2007) No. 11, p. 13-16.
[21] J. Sun: Method for controlling constant-voltage discharging of energy storage system of flywheel (MS. Tianjin University, China 2011).
[22] R.J. He: Research on control system and energy feedback technology of flywheel energy storage(MS. Donghua University, China 2004).
[23] J.F. Wang, S.D. Zhao, C.W.Zhao, et al. Design of flywheel battery discharge system and its simulation with Simulink, Chinese Journal of Power Sources. Vol. 38(2014) No. 09, p. 1695-1697.

[24] Y.X. Ou, S.S. Fan, X.L.Tang. Research on Flywheel Energy Storage System Control Strategy Based on Bidirectional DC/DC, Electrotechnics Electric. (2016) No. 4, p. 12-16.
[25] N. Wang, Y.L. Li, W.Y. Zhang, et al. A Nonlinear Control Algorithm for Flywheel Energy Storage Systems in Dischar. Vol. 33 (2013) No. 19, p. 1-7.
[26] W.J. Liu, L. Zhou, X.S. Tang, et al. Research on FESS Control Based on the Improved Sliding-mode Observer, Proceedings of the Csee. Vol. 34 (2014) No. 01, p. 71-78.