Control technology and development status of flywheel energy storage system

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Abstract. Flywheel energy storage technology has attracted more and more attention in the energy storage industry due to its high energy density, fast charge and discharge speed, long service life, clean and pollution-free characteristics. It is widely used in uninterruptible power system, grid frequency modulation, energy recovery and reuse and other fields. With the development of flywheel rotor materials, motors, bearings and control technology, flywheel energy storage technology has been greatly developed. Introducing the basic structure of the flywheel energy storage system in the above three applications. Typical charge-discharge control strategies are given for the three sensor-less algorithms of model reference adaptive control, sliding mode observer and extended Kalman filter, which are suitable for flywheel energy storage devices.

Keywords: Flywheel energy storage system, Development status, Key technology, Charge and discharge control.

1 Introduction

During the NPC and CPPCC sessions in 2020, general secretary Xi Jinping made important instructions for China to realize 'Carbon peak in 2030 and Carbon neutral in 2060'. According to statistics, in 2020, China's wind power generation increased by 34.6% year-on-year, and solar power generation increased by 24.1% year-on-year. At the same time, the new equipment capacity of wind power generation increased by 178.7% year-on-year, and the new equipment capacity of solar power generation increased by 81.7% year-on-year [1]. With the increasing proportion of clean energy power generation such as wind power generation and solar power generation, some technical difficulties are gradually exposed. Due to its special form of power generation, it is largely limited to the natural environment, resulting in the instability of its power generation form, it has great obstacles in grid connection. In order to realize efficient grid connection of clean energy power generation, good energy storage technology is very important.

Among many energy storage technologies, flywheel energy storage system (FESS) is prominent for its large capacity, high energy conversion rate, high instantaneous power and

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high energy density. In addition, FESS belongs to mechanical energy storage, so it will not produce pollutants in work, which belongs to a green energy storage technology. At present, in China, most of the application products of FESS are only commercial demonstration, and there is lots of room for improvement in the future.

Various forms of energy storage have different advantages and disadvantages. The specific comparison is shown in Figure 1. The energy efficiency and cycle times of FESS have absolute advantages in the form of energy storage, which are very close to super capacitors and much higher than batteries. FESS also has certain advantages in terms of power ratio, which is similar to super capacitors and compressed air. But in terms of energy ratio, the energy range of FESS is smaller than that of batteries and larger than that of super capacitors [2].

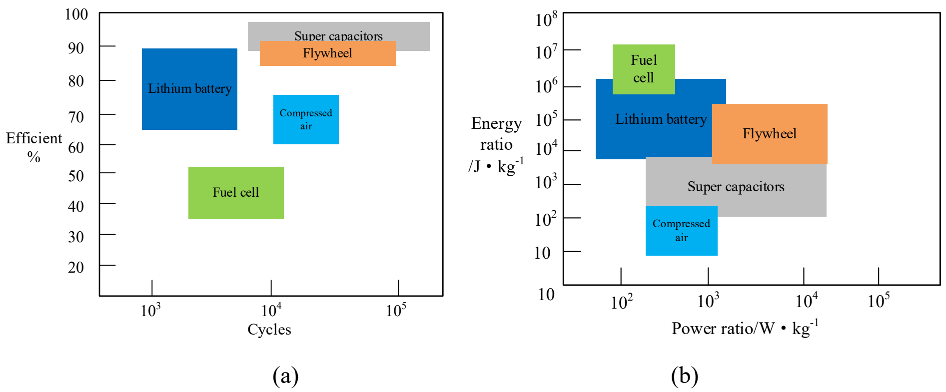

Fig. 1. The comparison of typical energy storage technologies.

2 Structure and working principle of FESS

When FESS works, the motor drives the flywheel to rotate at high speed to store energy. Its energy change is a process of converting electric energy into kinetic energy and then into electric energy. The stored energy of FESS depends on the moment of inertia and speed of flywheel, and the expression of kinetic energy E is:

$$E = \frac{1}{2}J \cdot (\omega_{max} - \omega_{min})^2 \tag{1}$$

Where: J is the moment of inertia, kg·m^2; ω is the angular velocity, rad/s. Usually the $\omega_{max} = 2\omega_{min}$.It can be seen from the above equations that the size of kinetic energy E depends on the moment of inertia and rotational angular velocity of the flywheel. However, when the flywheel reaches a certain speed, the further increase of speed will be greatly limited by the flywheel rotor material. Therefore, the selection of flywheel rotor material has always been a difficult problem. The energy density e of the flywheel is:

$$e = k\frac{\sigma}{\rho} \tag{2}$$

Where: k is the shape coefficient of flywheel; ρ is the density of flywheel material, kg/cm^3; σ is the allowable stress of flywheel material, MPa. It can be seen from the above formula that the smaller the density of flywheel material, the larger the tensile strength. Common flywheel rotor materials include aluminum alloy, steel, glass fiber and carbon fiber. Among them, composite materials such as carbon fiber, with the characteristics of low material density and large allowable stress, have gradually become the first choice for flywheel rotor materials of some high-speed flywheel systems.

The motor that occupies the flywheel system is the main choice. Among them, the utilization rate of asynchronous motor is low due to low operation efficiency and low power factor. Although the reluctance motor has small starting current, large torque and high output efficiency, it needs to be connected with excitation current and is easy to produce voltage spikes. At present, the utilization rate of permanent magnet motor is higher than the first two, mainly due to the characteristics of low rotor loss, large speed variation range and high operation efficiency [3-5]. All motors used in this article are permanent magnet synchronous motors (PMSM).

In addition to the above two points, the supported bearing system also affects the maximum speed of the flywheel. Although the flywheel is in vacuum during operation, it will still produce certain friction loss with the bearing during its rotation. At present, the traditional mechanical bearing is suitable for the flywheel system with low speed because of its high friction and high loss, but low cost. The magnetic bearing uses magnetic force to manage almost no loss operation, and its stability is also very high. The disadvantage is that the cost is high and the structural system is complex. For example, the superconducting magnetic bearing (SMB) developed by Railway Technology Research Institute (RTRI) in Japan supports the flywheel with strong magnetic repulsion force to avoid mechanical loss. SMB has high temperature superconducting (HTS) block in the rotor and HTS coil as the stator. When the HTS block is not excited, it is cooled and then enters the superconducting state. When the HTS coil is excited, a huge magnetic field will be generated around the HTS block, and the shielding current on its surface eliminates the magnetic flux trying to eliminate the magnetic field. Finally, a large magnetic levitation force will be generated between the HTS block and the HTS coil. Because there is no force acting on the radial direction, and because the HTS block and the coil are rotationally symmetrical, the HTS block presents a suspended state without any friction loss. In the internal container, helium is used for cooling, and the pressure is about 10 Pa [6].

Besides the Japan, ATZ in Germany has turning the practical use of HTS for rational and efficient energy consumption since 1992. For instance, ATZ has developed a 5 kWh/250 kW FESS based on the conventional magnetodynamic storage unit of L-3 Magnet-Motor. The flywheel system is extremely compact in design and construction and has a vertical rotation axis. The rotor is a hollow cylinder and is made primarily of a carbon fiber compound. To make the system compact, the motor/generator unit is integrated concentrically in the cylindrical rotor. Figure 2. shows a section of the design principle of the HTS flywheel [7]. Figure 3. shows a structural diagram of a FESS.

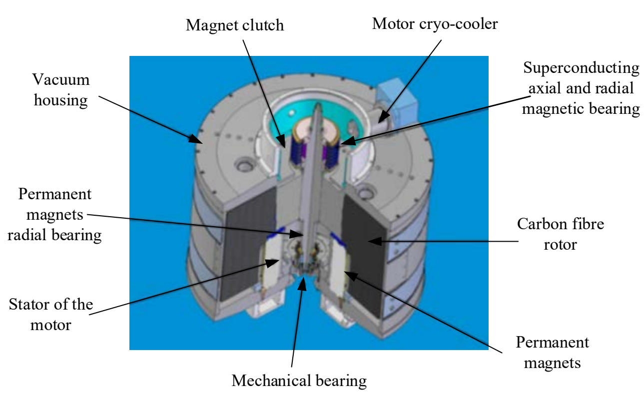

Fig. 2. Outline sketch of the 5 kWh/250 kW HTS FESS.

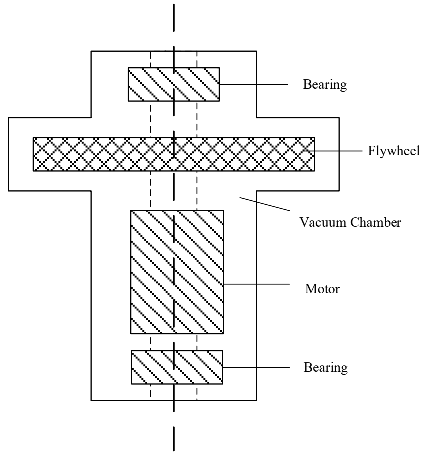

Fig. 3. FESS structure diagram.

The working state of FESS is divided into three types: charging, holding and discharging. Charging: the motor accelerates its rotation under the input of external electric energy. At this time, the direction of motor torque is consistent with that of flywheel, so as to drive the flywheel to accelerate and convert electric energy into kinetic energy for storage. Hold: when the flywheel speed reaches the specified speed, the system maintains the state of high-speed rotation. Because the flywheel is in the vacuum environment, the loss is very small and the speed is basically unchanged. Discharge: when the system receives the discharge command, the high-speed rotating flywheel brake the rotor and uses inertia to drive the motor to generate electricity. The flywheel speed decreases, so as to convert the kinetic energy into electric energy output. In the process of input and output of electric energy, the voltage and frequency are adjusted by power electronic converter [8]. The working principle diagram of the system is shown in Figure 4.

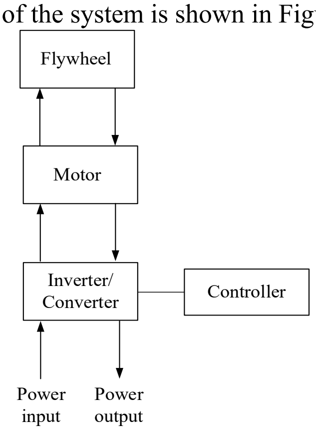

Fig. 4. Working principle diagram of FESS.

3. The development status at home and abroad

Since the 1930s, FESS applied to automobiles has been studied internationally. The first vehicle using flywheel energy storage is called ‘Gyrobus’, which was developed by Oerlikon in Switzerland. The flywheel has a mass of 1500 kg, a diameter of 1.6m and a maximum speed of 3000 rpm [9]. Then it attracted the attention of global scholars. At present, flywheel energy storage is widely used, including UPS, power grid frequency modulation, kinetic energy recovery and recycling, hybrid electric vehicles, etc.

3.1 UPS

Since the 1960s, NASA, development of energy and other institutions in the United States have begun to increase investment and research in flywheel energy storage technology, and long-term funding has made the United States a global leader in flywheel energy storage technology research. Active power, which applies flywheel energy storage technology to UPS, is a leader in the world. The company's HD series and PLUS series reduce the cost by 40% compared with the traditional UPS. Compared with the lead-acid battery, they reduce the operating carbon emission by 40%, reduce the occupied space by 50% and have a service life of up to 20 years. Among them, the FESS power of a single module of PLUSSMS series is about 300 kW, the output voltage can reach 480 V, and the power of PLUSSMS series is between 300 kW and 2400 kW. The storage energy of HD series can reach 10.2 MJ and the power is 625 kW [10]. Figure. 5 shows the UPS structure of FESS of Active Power.

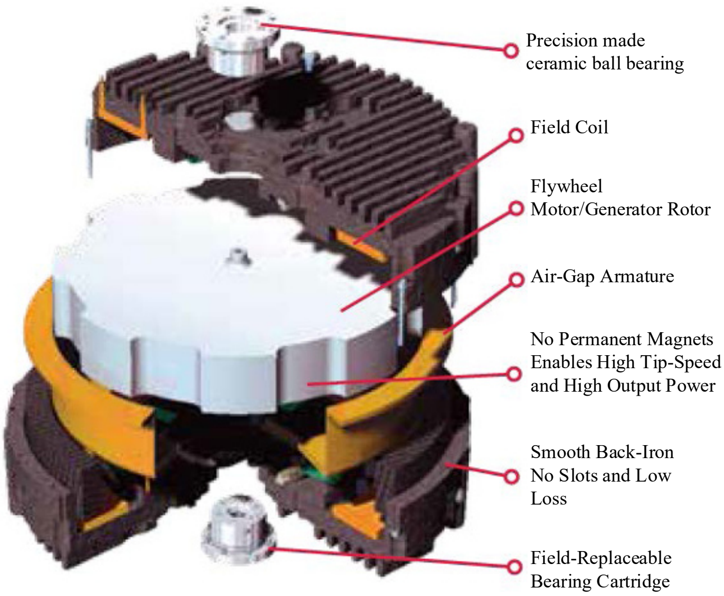

Fig. 5. UPS structure of active power.

PILLER of Germany is the world's largest high-tech company developing UPS. Its rotary dynamic UPS has the advantages of simple and reliable structure, simple maintenance and long service life. PILLER has more than 7000 flywheel energy storage devices and more than 6000 rotary UPS devices up to 3000 kW, serving more than 40 countries. At present, the integration of CPM300 and CPM360 flywheel UPS launched by PILLER has been in a leading position in the world, with working efficiency of 99%, rated power of 300/360 kW, single size of 2450*900*1900 (mm), total power of 2.4 MW and storage energy of 6 MJ, 16.5 MJ and 21 MJ to meet different demands [11].

In addition, there are some application demonstrations of applying flywheel energy storage technology to UPS in China. For example, the EP-100/200 flywheel energy storage UPS independently developed by Erzhong Deyang Power Technology Co., Ltd. has been put into use in the data center of Zhengzhou high tech information park in 2020. The maximum power of EP-200 can reach 200 kW, the flywheel speed is 7200 rpm, the output voltage is 300-540 V_{dc}, the size is 2200*900*1000 (mm) and the mass is 2500 kg [12].

Compared with the traditional UPS that uses battery energy storage, the characteristic of FESS that releases high power in a short period of time is its advantage in the UPS market. Although the initial investment cost of FESS is relatively high, its long service life makes its cost in the entire use process lower than battery energy storage. Therefore, UPS of FESS is already a mature product abroad [13-14].

3.2 Power grid frequency modulation

Enterprises led by Beacon Power in the Unite State have occupied a large share in the commercial market of FESS. Beacon Power applies flywheel energy storage technology to power grid frequency modulation on a large scale. For example, the 20 MW flywheel energy storage power station in Stephenstown and Hazle officially put into operation in 2014 is a 400 model flywheel. Its individual flywheel is about 2 m high, 1m diameter, 1100 kg mass, the maximum rotor speed can reach 16000 rpm, the rated power is 100 kW, and the energy storage capacity is 25 kWh. The latest flywheel single module 500XP has an energy storage capacity of 50 kWh, a power of 500 kW and a peak output of 1 MW/60 s [15]. Figure 6. shows the cutaway of FESS of Beacon Power.

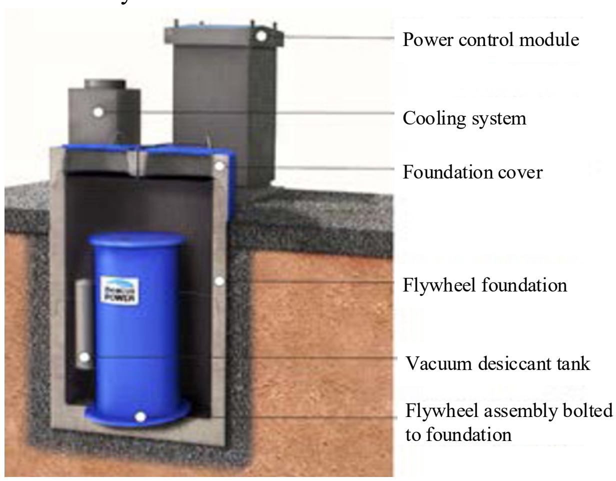

Fig. 6. Cutaway of flywheel in foundation of beacon power.

Meanwhile, Temporal Power in Canada is also very advanced in the field of grid frequency modulation technology of flywheel energy storage. With the strong support of NRSTOR, IESO and hydro one for flywheel energy storage technology, Temporal Power established the first flywheel frequency modulation power station in Canada in 2014, with a total power of 2.5 MW, a single flywheel power of 250 kW and an annual cycle of more than 5200 times. After that, the world's first 20 MW flywheel power station for reactive power compensation of wind farm was commercially operated in Ontario, Canada in 2016, with 10 flywheels, a single flywheel power of 500 kW and an annual cycle of more than 5000 times. Meanwhile, with the support of Aruba, the world's largest island flywheel energy storage power station was officially put into operation in 2018, with a total power of 5 MW, 20 flywheels, a single flywheel power of 250 kW and an annual cycle of more than 3000 times [16].

With the implementation of the " carbon peak and neutrality", clear energy power generation will become the mainstream form, and the problem of fluctuations in the power grid will become more prominent. The discharge time of FESS is at the level of minutes and seconds, which can provide high-quality electric energy and high-frequency frequency modulation [17-18].

3.3 Energy recovery and reuse

Since the 21st century, Occident has used FESS for the recovery and reuse of train braking energy and to provide voltage support for the traction line, so as to help the subway save energy and reduce consumption and improve the stable operation of the train system. In 2001, the 1 MW FESS was installed in Far Rockaway–Mott Avenue station, New York Metro, with 10 flywheels and single flywheel power of 100 kW. The daily average energy saving of the device is about 1300 kWh, and the energy-saving efficiency is about 20.6%. In addition, the 1 MW container composed of five 200 kW flywheel energy storage devices located in the golden line Highland Park of Los Angeles Metro was officially used to provide voltage support for the traction line in 2015. After it is put into use, the minimum value of traction network voltage is about 700 V, whereas before it is not used, it is only 518 V [19].

Japan's NEDO has invested heavily in and supported FESS since the last century. Now, many enterprises including Toshiba, Mitsubishi and Tokyo Electric Power also actively participate in the development of flywheel energy storage technology. At present, the FESS of HTS magnetic bearing developed in Japan has been successfully operated in Komekurayama photovoltaic power plant in 2012. At the same time, the Cryogenic System Laboratory of magnetic levitation system technology department is still studying the application of this system in Railway on the basis of increasing its stored energy. The output power of a single flywheel energy storage device can reach 300 kW, the storage capacity is 10 kWh, and the speed is about 3000 rpm [20-22]. Figure 7. shows the conFigureuration of FESS of NEDO.

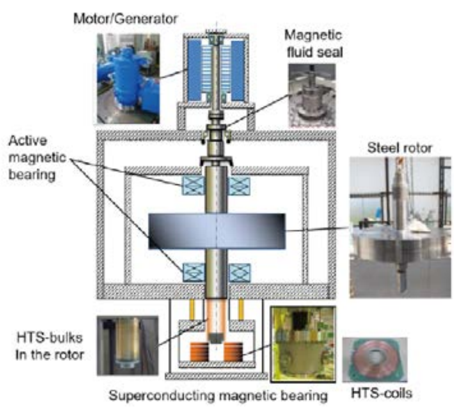

Fig. 7. ConFigureuration of FESS demonstration machine of NEDO.

Domestic Kinetic Traction Systems, Inc. combines the civilian use of URENCO centrifugal technology. After acquiring KTSI of the United States, it introduces the world's leading flywheel energy storage technology into China. Its GTR series flywheel energy storage device has always been excellent in urban rail transit. The GTR-333 FESS developed in 2018 has a rated power of 1 MW and a storage capacity of 11 kWh. It can effectively absorb and reuse braking power in Beijing urban rail transit. It is the first application in the field of subway in China. The average daily energy saving of the device is 1100-1800 kWh, the energy saving ratio can reach more than 20%, and the network voltage fluctuation is controlled at 750-900 V [23-24].

Energy recovery and reuse can not only play a great role in rail transit, but also play a good role in some large lifting machinery. Great achievements have been made in the application of FESS in oil drilling in China. Tsinghua University developed a 1 MW/60 MJ FESS for oil well drilling rig in 2017, with charging power of 100~300 kW, generating power of 500 ~ 1000 kW and available energy of 42 MJ. It has made great contributions to the domestic flywheel energy storage technology in energy recovery and reuse. HHE-FW2550, HHE-FW2503 and HHE-FW3002 FESS developed by Beijing Honghui Energy Development Co, Ltd. are energy type, key power supply and power type respectively, which are mainly used in oil drilling. In 2018, the flywheel energy storage and energy recovery system of oil drilling platform has accomplished deep charge and discharge more than 300 times a day in Karamay, Xinjiang. The flywheel used has a single rated power of 300 kW, a stored energy of 3 kWh and a charge discharge response time of less than 10 ms [25-26].

What's more, FESS even has a far-reaching impact on the research of nuclear fusion energy. On December 4, 2020, China loop 2 M device (HL-2M) generated power for the first time. HL-2M is the largest and most advanced Tokamak device in China, and it is a new generation of advanced magnetic confinement fusion experimental research device in China. The FESS is selected to supply power to the magnetic field coil to generate and maintain the magnetic field, mainly because it has the characteristics of large capacity and short working time, and can reduce the impact on the public power grid. The total capacity of FESS can reach 600 MW, the total energy storage is 5 GJ, and the impulse release energy is about 2.6 GJ. It is the largest FESS in China [27].

From the initial hybrid vehicle, to the rail transit, to the current domestic independent research and development of oil drilling, FESS has shown excellent energy reuse capabilities. In the contemporary era of rapid development of new energy vehicles, car battery management has always been a technical difficulty. With the help of FESS, the endurance of new energy vehicles will be greatly improved.

4 Charging and discharging control strategy of FESS

4.1 Application structure diagram

UPS based on FESS are generally divided into three types: backup type (Figure 8.), online double conversion type (Figure 9.) and online interactive type (Figure 10.). The advantage of online double conversion UPS is that it is not affected by power grid voltage fluctuation. But due to the rectifier transformation of the AC/DC converter also delivers a portion of the current harmonics to the grid, it's working efficiency and reliability are less than the others. The working efficiency of Online Interactive UPS is much higher than that of double conversion system, but its control algorithm is more complex. The backup UPS has the highest working efficiency, but the response speed is not as fast as the online UPS [28].

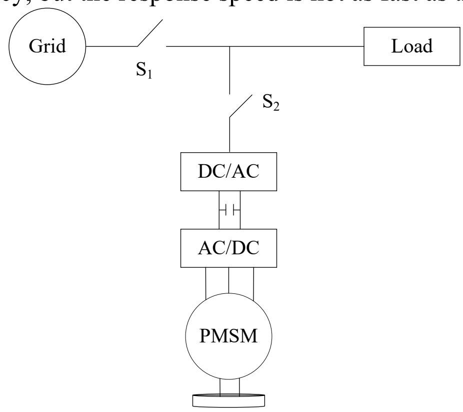

Fig. 8. The Backup Type UPS of FESS.

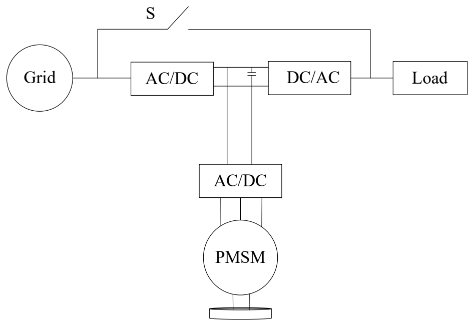

Fig. 9. The Online Double Conversion Type UPS of FESS.

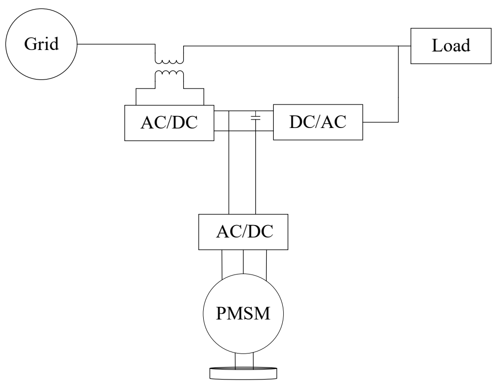

Fig. 10. The Online Interactive Type UPS of FESS.

At present, clean energy power generation has become the second largest power generation form in China, but it is difficult to adjust peak and frequency due to its own power generation instability. The business model of using battery energy storage technology to assist coal-fired units in joint frequency modulation has appeared in Guangdong, Shanxi and Mengxi power grids, and flywheel energy storage is a very suitable power grid frequency modulation battery. Flywheel energy storage assisted frequency modulation of coal-fired units can effectively improve the quality of frequency modulation and ensure the safety of unit operation. Figure 11. shows a structural diagram of FESS participating in power grid frequency modulation [29-30].

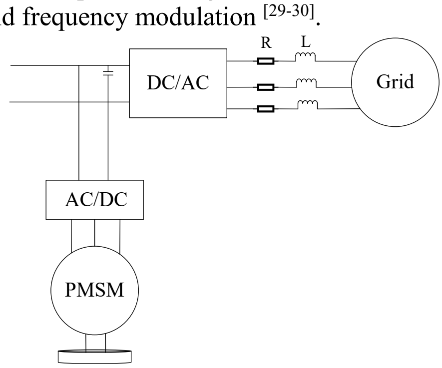

Fig. 11. Grid frequency modulation block diagram based on FESS.

In terms of energy recovery and reuse, from the initial hybrid vehicle to the kinetic energy recovery and utilization of the train, the FESS makes a great contribution to energy conservation. At present, hybrid electric vehicles are still in the demonstration application stage, and the recovery and utilization of train kinetic energy has reached small-scale commercial application. Other energy recovery and utilization, such as oil drilling, are also demonstration applications. Figure 12. shows the control block diagram of hybrid electric vehicle, and Figure 13. shows the block diagram of kinetic energy recovery and reuse by flywheel energy storage in the train [31-34].

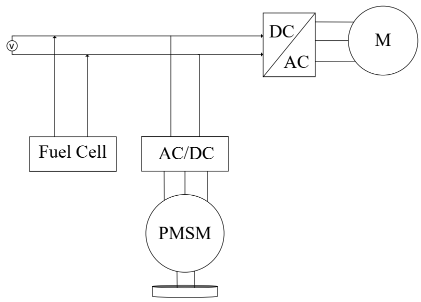

Fig. 12. Hybrid electric vehicle block diagram based on FESS.

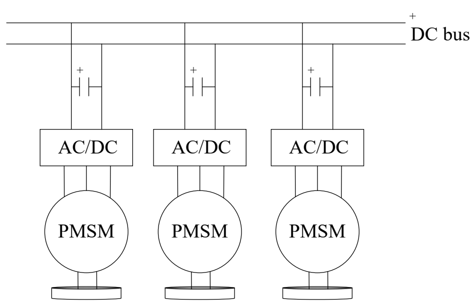

Fig. 13. Energy harvesting block diagram based on FESS.

At present, in the high-speed FESS, permanent magnet synchronous motor is generally used as the driving motor, and vector control technology is used to control the motor operation. The charging control strategy generally adopts speed and current double closed-loop control, and the discharge control strategy generally adopts voltage and current double closed-loop control. When using vector control technology to control the motor, it is necessary to obtain the position and speed of the rotor. However, due to the special structure of the flywheel system, it is impossible to install sensors to measure the position and speed of the rotor, so the sensor-less algorithm will be used. At present, there are many sensor-less algorithms, such as model reference adaptive control, sliding mode variable structure control, extended Kalman filter and so on [35].

From the above structure diagram of UPS, power grid frequency modulation and energy recovery and reuse, it can be seen that the topology diagram of FESS in these three aspects is still different. UPS needs mains power to charge the FESS. Power grid frequency modulation supplies power to the power grid side in the process of grid connection, and energy recovery and reuse is separated from the power grid and supplies power to the load end. For the charge discharge control on the motor side, the topology diagrams under the three sensor-less calculations are basically the same.

3.2 Sensor-less control

Due to the special structure of the flywheel system, it is impossible to install sensors to measure the position and speed of the rotor. Therefore, the sensor-less control for FESS is indispensable.

Model adaptive control system (MRAS) includes a reference model of an actual motor without parameters, an adjustable model with unknown parameters and an adaptive rate to adjust the unknown parameters. The physical meaning of the two models is the same, and the adaptive rate is used to make the unknown parameters in the adjustable model close to the parameters in the reference model. Applying Popov hyperstability theorem in MRAS, firstly, the system can be guaranteed to be asymptotically stable. Secondly, the adaptive rate of unknown parameters can be obtained by Popov inequality, so as to obtain the value of unknown parameters [36-38]. Among them, the adaptive rate is:

$$\widehat{\omega}_e = \left(k_p + \frac{k_i}{s}\right)\left(\frac{L_q}{L_d} i_d^* \hat{\imath}_q - \frac{L_d}{L_q} i_q^* \hat{\imath}_d\right) + \left(\frac{L_d}{L_q} - \frac{L_q}{L_d}\right)\hat{\imath}_d \hat{\imath}_q + \left(\hat{\imath}_q - i_q\right)\frac{\varphi_f}{L_q} \quad (4)$$

where: $\widehat{\omega}_e$ is electrical angular velocity, rad/s; L_q 、 L_d is motor inductance, H; φ_f is Permanent magnet link; k_p and k_i are adaptive parameters.

Figure 14. shows a typical MRAS based flywheel charging and discharging control diagram.

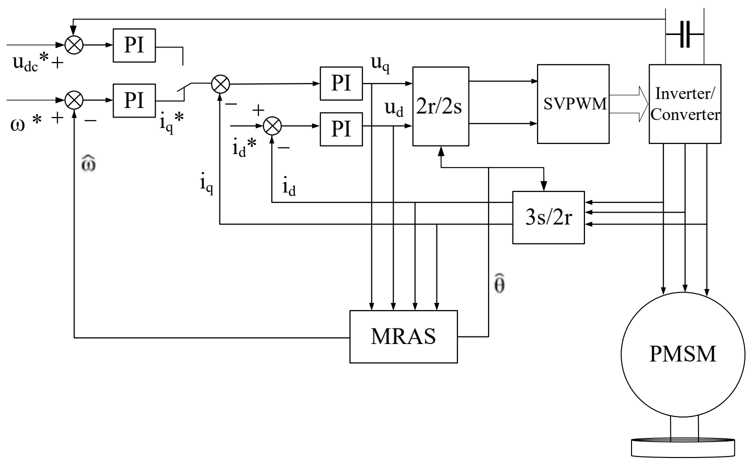

Fig. 14. FESS charging and discharging control block diagram based on MRAS.

Sliding mode observer (SMO) has been paid attention to in many sensor-less systems because of its strong robustness and little influence on it by the change of motor parameters. The main idea is to estimate the back EMF of the motor, then pass through the low-pass filter, and finally calculate the position and angular velocity of the rotor. However, the sign function used in the traditional SMO is discrete, which will cause the chattering of the system. Therefore, most of them will improve SMO, mainly using other functions to replace the symbolic function. For example, the combination of hyperbolic tangent function, sigmoid function, Gaussian error function and saturation function [39-42].

For instance, based on the hyperbolic tangent function, the flywheel position and speed equations can be obtained by SMO is:

$$\hat{\theta} = tan^{-1}\left(-\frac{e_\alpha}{e_\beta}\right) \quad (4)$$

$$\widehat{\omega}_e = \frac{d}{dt}\hat{\theta} \quad (5)$$

where: e_α and e_β are the factor of SMO.

Figure 15. Shows a typical SMO based on flywheel charging and discharging control diagram.

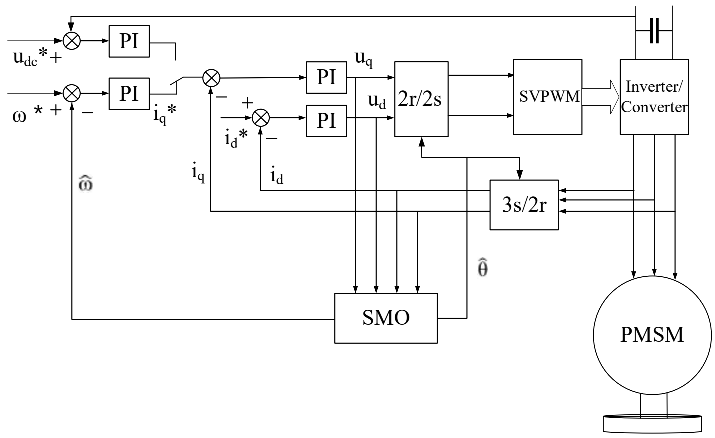

Fig. 15. FESS charging and discharging control block diagram based on SMO.

Extended Kalman filter (EFK) uses statistical principle to estimate rotor position and angular velocity. EFK algorithm has strong suppression ability to system noise and measurement noise. At the same time, it also has good robustness to motor parameters. EFK algorithm is a recursive algorithm, which is divided into prediction stage and correction stage [43-46].

(1) Prediction stage:

Prediction of the state vector is:

$$\tilde{x}(k+1) = A'^{\hat{x}(k)} + B'u(k) \tag{6}$$

The covariance of prediction error is:

$$\tilde{p}(k+1) = G(k+1)\hat{p}(k)G^T(k+1) + Q \tag{7}$$

(2) Correction stage:

The optimal gain matrix equation is:

$$K(k+1) = \tilde{p}(k+1)C^T[C\tilde{p}(k+1)C^T + R]^{-1} \tag{8}$$

Where, R is the observation noise covariance matrix, Q is the process excitation noise covariance matrix, K is the optimal gain matrix, G is the input matrix, p is the filter error, $x = [i_d \quad i_q \quad \omega \quad \theta]^T$, $u = [u_d \quad u_q]^T$, $y = [i_d \quad i_q]^T$,

$$A = \begin{bmatrix} -\frac{R}{L_d} & \omega\frac{L_q}{L_d} & 0 & 0 \\ -\omega\frac{L_d}{L_q} & -\frac{R}{L_q} & -\frac{\varphi_f}{L_q} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}, , A' = e^{AT_m}, B' = B \cdot T_m.$$

Figure 16. Shows a typical EFK based flywheel charging and discharging control diagram.

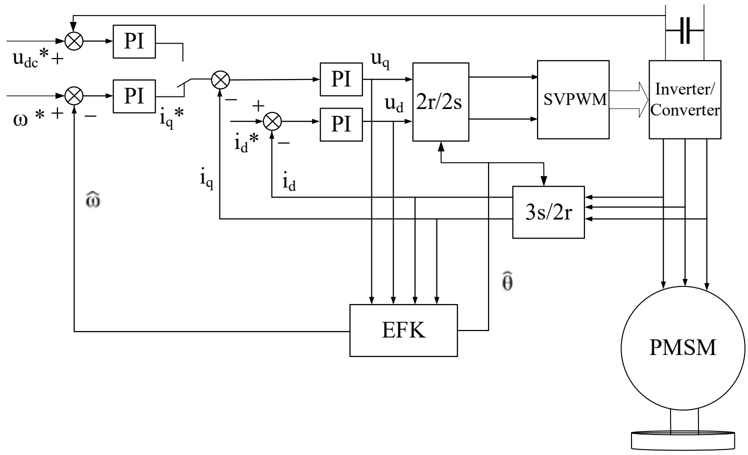

Fig. 16. FESS charging and discharging control block diagram based on EFK.

It can be seen from the above three control methods that the overall control method adopts speed outer loop (or voltage outer loop) and current inner loop control. The difference between the three different sensor-less controls is only in the algorithm itself. The input to the algorithm is i_d, i_q, u_d, u_q, and the output is the estimated rotor speed and position. Among the three algorithms, MRAS is easier to implement in terms of hardware. SMO has a powerful robustness and does not depend on the parameters of the motor. EFK requires a lot of calculations during the design but it has a strong inhibitory capacity to interference. All of them have a wide range of applications in FESS.

5 Conclusion

From the original 'Gyrobus' developed in Switzerland to the present, FESS has been researched for nearly a century, but there is still a lot of room for development. The research contents are mainly flywheel rotor materials in the high-speed field, high-temperature superconducting magnetic bearings, high-speed and high-efficiency motors, and control strategy. Although the basic double closed-loop control strategy and several speed estimation algorithms currently applied to FESS have performed well, there are still certain flaws in the high-speed field, so the optimization of the algorithm will continue.

FESS has potential to achieve substantial breakthroughs in the fields of UPS, grid frequency modulation and energy recovery and reuse in China within five years, which will bring huge benefits to the ‘Carbon peak in 2030 and Carbon neutral in 2060’ economic model.

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