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ABSTRACT
In order to realize the cyclic utilization for the regenerative braking energy of a metro, a high-speed flywheel array based on high power density and long life is adopted. First, a regenerative energy braking system with a flywheel array is constructed. In order to achieve stable operation and high dynamic response of the flywheel, a control strategy based on voltage threshold is proposed. At the same time, a simulation model of starting and braking of the metro with a high-speed flywheel array is built in MATLAB/Simulink, and the relevant simulation verification is completed. Finally, in order to further verify the effectiveness of the proposed strategy, a GTR flywheel array with a total capacity of 1 MW was installed in a domestic traction station, and field application tests were carried out. The results show that the proposed control strategy can effectively realize the cyclic utilization for regenerative braking energy.

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I. INTRODUCTION
The energy storage technology is used to store the regenerative braking energy of the metro in the storage elements through PWM (Pulse Width Modulation) converter. According to the different energy storage components, the type of regenerative braking energy storage can be divided into battery energy storage, supercapacitor energy storage, and flywheel energy storage. The battery energy storage has the advantages of high energy density and long life, and the technology is relatively mature. However, the charging current of the battery has some limitations, and it cannot absorb a large amount of regenerative braking energy in short time. References 2–4 proposed the regenerative energy utilization system of the metro based on supercapacitors. Although supercapacitor energy storage has the advantages of short-term high-power charging and discharging capacity and long circular life, it still has the problems of series voltage equalization and a large voltage fluctuation range. The flywheel energy storage system has high energy density and long life, which is more suitable for short-term and high-power applications.5–9

At present, there is little research on coordinated control of the flywheel energy storage system. Reference 10 studied the process of energy exchange between two flywheel energy storage units connected in parallel after charging certain energy, but it did not further study the control method of charging and discharging two flywheels at the same time. Reference 11 proposed a consistent power coordination strategy for flywheel arrays, which can achieve power allocation for flywheel arrays. Reference 12 designed the charging and discharging control strategy and safety control strategy of the flywheel energy storage array. The master-slave control mode is adopted to achieve the smooth output of active power of a wind farm. Beacon Power’s on-board flywheel energy storage system matrix contains 10 flywheel DC buses connected in parallel with the maximum output power of 2.5 MW. Its discharge control strategy...
adopts the average distribution strategy. Three kinds of flywheel array discharge control strategies were proposed by the Institute of Electrical Engineering, Chinese Academy of Sciences, and the discharge control strategy of a flywheel array based on residual energy distribution was proposed by Tsinghua University. However, there is no general control strategy for parallel flywheel arrays of metro DC buses. Flywheel regenerative braking energy utilization technology is still in theoretical research in China. The first flywheel energy storage device developed by Dun Shi Magnetic Energy Technology Company in China has passed the inspection and certification of the National Railway Product Quality Supervision and Inspection Center and can be used for regenerative braking energy utilization.

In this paper, a high-speed flywheel array with high power density and long life is used to utilize the regenerative braking energy of the metro. When a metro is braked, the regenerative braking energy is converted to the kinetic energy storage of the flywheel, and the speed of flywheel increases. When the metro starts, the energy storage motor releases energy and the speed of the flywheel decreases. By installing a high-speed flywheel array in the DC traction grid and utilizing regenerative braking energy, it is an effective method to realize energy saving.

First, the regenerative braking energy utilization system of the metro based on a high-speed flywheel array is designed, and the control strategy of the high-speed flywheel array is designed, and the control strategy of the high-speed flywheel array based on voltage threshold is designed. A traction braking simulation model of the metro based on the high-speed flywheel energy storage system is built in MATLAB/Simulink. Finally, the energy-saving data of the high-speed flywheel array are analyzed in a metro traction station in China.

II. DESIGN OF REGENERATIVE BRAKING ENERGY UTILIZATION SYSTEM FOR METRO BASED ON FLYWHEEL ENERGY STORAGE

Figure 1 is the schematic diagram of the regenerative braking energy utilization system for the metro based on the flywheel energy storage system. The 12-pulse rectifier is used to convert the voltage from the AC medium grid to the DC grid. The flywheel energy storage system can realize the energy flow of electric energy and kinetic energy through a bidirectional converter. When the regenerative braking energy of a metro is not absorbed by the other metro, the bidirectional converter controls the flywheel motor to operate as a motor, driving the flywheel to rotate at high speed, so the regenerative braking energy is stored in the form of kinetic energy. When the metro starts, the bidirectional converter controls the flywheel motor to operate as a generator, driving the flywheel to decelerate and rotate, so the energy is transmitted to the DC traction grid.

The energy flow chart of the regenerative braking energy utilization system of the metro based on a flywheel energy storage system is shown in Fig. 2.

The kinetic energy $E_f$ of the flywheel at high speed is shown in the following equation:

$$ E_f = \frac{1}{2} J_f \omega_f^2, \quad (1) $$

where the moment of inertia of the flywheel is $J_f$ and the angular speed of the flywheel is $\omega_f$.

Assuming that the initial speed of the flywheel is $\omega_0$, the minimum speed is $\omega_{\text{min}}$, and the maximum speed is $\omega_{\text{max}}$, the stored energy is shown in Eq. (2) when the flywheel runs at the actual speed $\omega_1$,

$$ W_f = \frac{1}{2} J_f (\omega_0^2 - \omega_1^2). \quad (2) $$

FIG. 1. Schematic diagram of the regenerative braking energy utilization system of the metro based on a flywheel energy storage system.
III. CONTROL STRATEGY OF HIGH SPEED FLYWHEEL ARRAY BASED ON VOLTAGE THRESHOLD

Metro has high running density, which can easily bring large capacity regenerative braking energy when multimetros are braking in the same traction grid. When multimetros are starting, it needs large energy. The flywheel array with parallel DC buses can utilize the regenerative braking energy of the metro.

Figure 3 is the schematic diagram of charge and discharge of the flywheel energy storage system based on voltage threshold, in which the no-load voltage of the DC traction grid is \(U_0\), the minimum allowable voltage of the DC traction grid is \(U_1\), the starting voltage corresponding to full power discharge is \(U_2\), the starting voltage corresponding to full power charging is \(U_3\), and the maximum allowable voltage of the DC traction grid is \(U_4\). The change in equivalent resistance and the real-time change in the equivalent current source during starting or braking of the metro may cause the voltage fluctuation of the traction grid. The voltage of the DC traction grid rises when the metro brakes, and the voltage of the DC traction grid decreases when the metro starts.

1. When the metro brakes, the DC traction grid voltage rises. At this time, \(U_{dc} > U_0 + \Delta U\), the flywheel energy storage system is in the charging zone, which absorbs the braking energy of the metro and converts it into kinetic energy.

2. When the metro starts, the voltage of the DC traction grid decreases. At this time, \(U_{dc} < U_0 - \Delta U\), the flywheel energy storage system is in the discharge area. The flywheel energy storage system releases kinetic energy to supplement the traction power of the metro and stabilizes the DC traction grid voltage.

3. When the DC traction grid voltage is applied as \(U_0 - \Delta U < U_{dc} < U_0 + \Delta U\), the flywheel energy storage system maintains the speed instruction, which is defined as the critical range.

The flywheel energy storage array is composed of three flywheel energy storage systems connected in parallel with DC bus. Three flywheel devices cooperate to control charging and discharging power to maintain the voltage stability of the DC traction grid. Using the voltage threshold control strategy, the DC bus voltage of each flywheel system is sampled and the sampling voltage is converted to the corresponding charging and discharging power values according to the bus voltage-power curve. The control strategy for a single flywheel is shown in Fig. 4.

By sampling the DC bus voltage of the traction grid in real time according to the power charge-discharge curve shown in Fig. 3, the charging power command \(P_{cha}\) or discharge power \(P_{discha}\) can be obtained, which can be judged whether the power command exceeds the maximum charging and discharging power amplitude of the current control cycle of a single flywheel. If it exceeds the amplitude, the limiting operation can be done. Through the power-current instruction conversion unit, the control current instruction is obtained, and the error subtracted from the actual current sampling value is controlled by the double closed-loop current and rotational speed. Finally, the real-time driving signal is obtained to realize the flywheel rotation and achieve the purpose of real-time regulating the charging and discharging power of the flywheel energy storage device.

IV. SIMULATION ANALYSIS OF STARTING AND BRAKING OF METRO BASED ON FLYWHEEL

A simulation model of starting and braking of the metro based on a flywheel is built in MATLAB/Simulink. In the 0–1.10 s stage, the flywheel does not participate in the work. In the 1.10–2.0 s stage, the flywheel participates in the start and brake process of the metro. Set \(U_0 = 820\text{ V}, \Delta U = 20\text{ V}, U_1 = 600\text{ V}, \) and \(U_4 = 900\text{ V}\).

In the 0–0.20 s stage, the metro is in the stopping state. In the 0.20–0.49 s stage, the metro is in the starting state, the starting time is 0.29 s. In the 0.49–0.76 s stage, the metro is in the idle state. In the 0.76–0.90 s stage, the metro is in the braking state, and the braking time is 0.14 s. In the 0.90–1.10 s stage, the metro is in the stopping state. In the 1.10–1.39 s stage, the metro is in the starting state, and the starting time is 0.29 s. In the 1.39–1.66 s stage, the metro is in the idle state. In the 1.66–1.80 s stage, the metro is in the braking state, and the braking time is 0.14 s. In the 1.80–2.0 s stage, the metro is in the stopping state.

The speed simulation result of the metro when the flywheel energy storage system is not involved in the work is shown in Fig. 5(a). The speed simulation result of the metro when the flywheel energy storage system participates in the work is shown in Fig. 5(b). When the metro is in the idle state, the speed of the metro is maintained at 30 km/h. While the metro is in the stopping state, the speed is maintained at 0 km/h. In the process of starting and braking stages, the speed of the metro is stable and its dynamic performance is good.
The speed simulation result of the metro (a) when the flywheel energy storage system is not involved in the work and (b) when the flywheel energy storage system is involved in the work.

The simulation result of DC traction grid voltage when the flywheel energy storage system is not working for the traction system is shown in Fig. 6(a). When the metro is starting, the DC traction grid voltage obviously drops to 710 V. With the end of the metro starting process and on entering the idle stage, the DC traction grid voltage gradually recovers. When the metro brakes, the DC traction grid fluctuates and the voltage exceeds 850 V.
FIG. 7. The simulation result of DC traction grid power: (a) when the flywheel energy storage system is not working for the traction system and (b) when the flywheel energy storage system is working for the traction system.

FIG. 8. The simulation speed result of the flywheel motor (a) when the flywheel energy storage system is not working for the traction system and (b) when the flywheel energy storage system is working for the traction system.
The simulation result of DC traction grid voltage when the flywheel energy storage system is working for the traction system is shown in Fig. 6(b). When the metro brakes and the voltage of the DC traction grid exceeds 800 V, the flywheel energy storage system is charged. Although the DC traction grid voltage fluctuates, the fluctuation range is small, which is about 840 V.

When the flywheel energy storage system is not working for the traction system, the simulation result of starting and braking power of the metro is shown in Fig. 7(a). For the 4M2T marshalling metro, there are four traction inverters, which control 16 traction asynchronous motors. When the metro starts, the traction asynchronous motor absorbs energy from the DC traction grid. When the metro brakes, the traction asynchronous motor releases energy to the DC traction grid.

When the flywheel energy storage system is working for the traction system, the simulation result of starting and braking power of the metro is shown in Fig. 7(b). When the metro brakes, the flywheel energy storage system is charged, and the regenerative braking energy is stored in the flywheel energy storage system. When the metro starts, the flywheel energy storage system is discharged and releases energy for the start of the metro.

In the 0–1.10 s stage, the simulation result of flywheel speed is shown in Fig. 8(a). It can be seen that in the 0–0.20 s stage, the speed of the flywheel accelerates, and the flywheel energy storage system is in the precharging state. The initial speed of the flywheel is given to 15 000 r/min. In the 0.20–1.10 s stage, the flywheel speed is maintained at 15 000 r/min, and the flywheel energy storage system is in the critical state. In the 1.10–2.0 s stage, the simulation result of flywheel speed is shown in Fig. 8(b). It can be seen that in the 1.115–1.39 s stage, the flywheel accelerates, the flywheel energy storage system is in the charge state, and the final speed of the flywheel is set at 12 500 r/min. In the 1.39–1.41 s stage, the metro is in the idle stage, the voltage of the DC traction grid is about 770 V, and the speed is maintained at 13 500 r/min. In the 1.41–1.66 s stage, the flywheel speed is maintained at 15 000 r/min.

V. EXPERIMENTAL VERIFICATION AND ENERGY-WAVING POWER ANALYSIS

A. Deployment of a metro project based on GTR high speed flywheel array

In order to verify the utilization effect of the flywheel energy storage array on the regenerative braking energy of the metro, a 1 MW regenerative energy utilization system consisting of three GTR flywheel devices (333 kW) was tested in a metro traction station to replace the existing resistance regenerative braking absorption device.

The main components and parameters of the GTR flywheel energy storage system are as follows: carbon fiber composite rotor, high speed and high efficiency permanent magnet motor, passive magnetic bearing, needle spherical spiral groove bearing, vacuum...
chamber, and shell. The maximum energy storage is 13.6 MJ, and the maximum power is 333 kW.

Figure 9 is a schematic diagram of the connection of a high-speed flywheel array at a metro traction station. Three flywheel devices are connected to the DC traction grid. Figure 10 is the actual installation and operating scene picture.

B. Energy saving data statistics

The 1 MW high-speed flywheel array energy storage system is installed in the metro traction station. The total energy-saving amount of the flywheel array energy storage system is collected. Figure 11 shows the statistics of energy-saving data on the spot.

According to the 11-h energy-saving statistics, the maximum energy-saving amount is about 81 kW and the whole day operation time is 18 h, the daily energy saving is about 1332 kwh. The annual energy saving is about 486 180 kWh. Through the analysis of annual energy saving, it can be seen that the high-speed flywheel array can greatly reduce the metro operation electricity charges.

VI. CONCLUSION

In this paper, a regenerative braking energy utilization system based on a high-speed flywheel array is designed, and the control strategy of the flywheel array based on voltage threshold is designed. At the same time, a simulation model of starting and braking of the metro based on a high-speed flywheel energy storage system is built in MATLAB/Simulink. The simulation results are analyzed and compared, which show that the flywheel energy storage system can utilize the regenerative braking energy of the metro. Finally, three GTR flywheel devices with 333 kW are installed in a metro traction station in China to form a 1 MW regenerative energy utilization system, which is verified by the experimental results. The field experimental results show that the GTR flywheel energy storage device has high performance power response characteristics and can effectively cyclic utilize the regenerative braking energy of the metro.

The high-speed flywheel array regenerative energy cyclic utilization system replaces the existing resistance regenerative braking absorption mode, which not only can realize the first practical application of the flywheel array in regenerative braking energy utilization of the metro in China but also can achieve certain energy-saving effects with certain application value.

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FIG. 11. Energy-saving data statistical map.