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Power Regulation System and Charge-discharge Test Applied in Power Grid Based on the Flywheel Energy Storage Array

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Abstract: Due to a larger intervention application of the wind-photovolatic new energy generation system, the stability and reliability of the main power grid will be greatly affected. One of the most effective methods to improve the quality of the power grid is to add the energy storage euipment. Based in this, according to the energy storage demand of short term and high frequency in the power grid, this paper focuses on a kind of power regulation system based on the flywheel energy storage array. Owing to the advantages of fast response and frequent charge-discharge characteristics, the flywheel system can be used to support and regulate the power grid through the process of the frequency and amplitude modulation. By using the flywheel system, the stability of the power grid can be improved effectively. In this paper, the proposed power regulation system is firstly introduced as well as the working principle of the flywheel energy storage array. On this basis, the key performance indices of the flywheel array are given, and then a kind of charge-discharge test process is provided. Finally, the power experiments by using the actual flywheel system is developed, including the power absorption and feedback electric generation. The experiment results show that the response characteristics, capacity and power of the designed flywheel array can meet the needs of power regulation system applied in the power grid.

Keywords: Power Grid, Flywheel Energy Storage Array, Power Regulation System, Charge-Discharge Test

1. Introduction

In the traditional field of the power grid system, coal-based thermal power generation is the main electricity source with a larger AGC frequency modulation demand. With the rapid development of the new energy forms, the proportion of wind and photovoltaic power or other power generation systems have gradually increased, which present natural randomness, volatility and intermittency. And thus a large-scale applications of the new energy will further increase the contradiction between the power supply and the loads demand, bringing a larger grid uncertainty [1-5]. The most effective way to solve the contradiction is to introduce an advanced energy storage technology between the generation system and the grid side, such as the pumped storage, the flywheel energy storage, compressed air energy storage, super capacitor, chemical battery energy storage, etc.. Among them, the flywheel energy storage system is one of the most promising technologies, which has the advantages of high instantaneous power, fast charge-discharge response, high conversion efficiency, long service life and little environmental pollution [6-12]. Based on this, the flywheel energy storage system will be connected to the grid-connected portal of the new energy generation in real. Due to the rapidity and frequent charge-discharge process of the flywheel, the real-time power regulation and support are carried out to improve the stability and reliabilty of the power grid by cutting peak and filling valley.

For the flywheel energy storage system, some research has been done to introduce the working principle or control strategies of the flywheel system. But few works have been presented to develop the design and application of the flywheel array in the power grid field. In order to meet the demand of short term and frequent energy storage for the power grid, a kind of power regulation system based on the magnetically suspended flywheel array is proposed in this paper. Firstly, the composition and working principle of the flywheel array are introduced, then the power regulation system applied in the power grid is designed. Finally, the real experimental system are developed based on two groups of 50kWh flywheel array and some experiments are carried out to indicate the effectiveness of the proposed system.

2. Working Principle of the Magnetically Suspended Flywheel Energy Storage System

2.1. System Composition

The overall and internal structure of the magnetically suspended flywheel [13-17] is shown in figure 1. The flywheel body is composed of a sealed shell, a three-phase permanent magnet synchronous motor stator and rotor, a high-speed flywheel rotor, up axial and down axial electromagnetic bearings, mechanical working bearings, mechanical protecting bearings and high-voltage vacuum electrodes, etc.. The axial displacement of the flywheel rotor can be measured by the axial displacement sensors, which is used to maintain the axial suspension of the high-speed rotor. The three-phase permanent magnet synchronous motor is considered as the driven mechanism of the flywheel rotor, through the charge-discharge control process to realize the energy conversion. The mechanical protection bearings are used to protect the electromagnetic coils and prevent the falling rotor to damage the electromagnetic bearings. The sealed body is used to fix the internal components of the flywheel with a suitable internal sealing index [18-20].

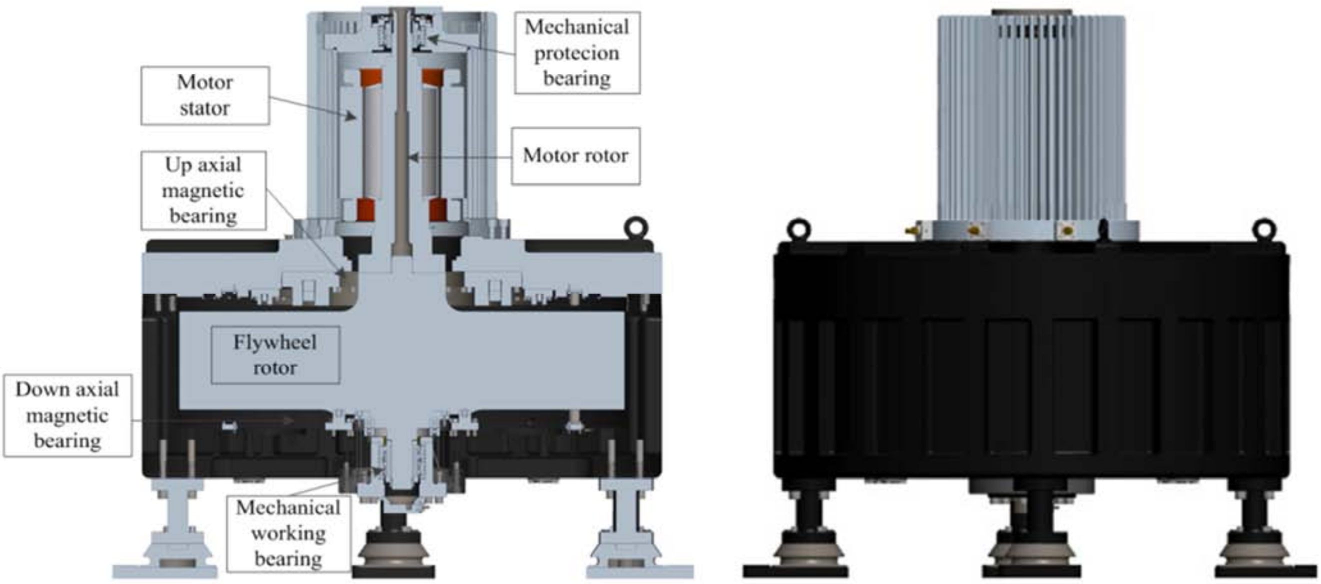


Figure 1. *Structure of the flywheel body.*

2.2. Working Principle

The working principle of the flywheel is shown in figure 2. The control system is composed of flywheel management system, charge-discharge controller, magnetic bearing controller, flywheel converter, current transformer and so on. The external input of the bi-directional converter is DC voltage U_{dc}, and the internal output of the converter is connected to the three-phase permanent magnet synchronous motor. The converter is used to realize the energy conversion between the flywheel kinetic energy and DC electricity. The output control current of the magnetic bearing controller drives the electromagnetic coil to generate electromagnetic force, which is used to absorb and maintain the flywheel rotor suspended. The health management and failure assessment of the operation status are carried out to ensure the safety of flywheel system through the flywheel management system by combing the information of charge-discharge controller, magnetic bearing controller and measurement equipment. When the flywheel is charging, the charge-discharge controller provides the control command, which makes the converter operation as an inverter. And then the electric energy flows from the DC side to the AC motor side. The motor is used to drive the flywheel rotor accelerated and the electric energy is stored in the form of the kinetic energy. When the flywheel is discharging, the charge-discharge controller makes the converter operation as a rectifier, and the motor is used as a generator. During the flywheel decelerated, the kinetic energy is released in the form of DC elecricity energy. The energy conversion routes of the flywheel only go through power electronic device and permanent magnet synchronous motor such that the power response speed is fast (after a few micro seconds, full power can be generated), the conversion efficiency is high, and a frequent charge-discharge of the flywheel can be realized under the state of the magnetic bearing support and the vacuum state (thousands of cycles per day).

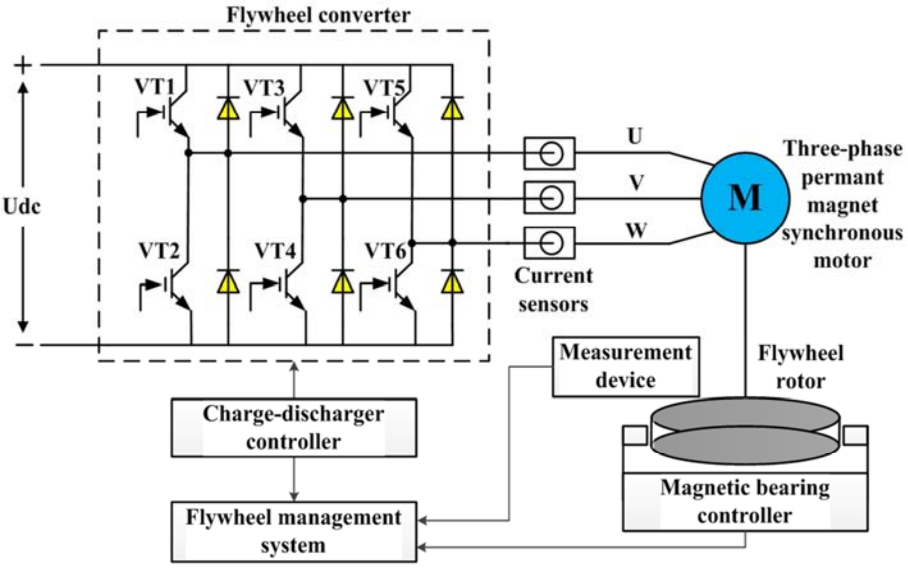


Figure 2. *Working principle of the flywheel system.*

3. Power Regulation System of the Power Grid based on Flywheel Energy Storage Array

3.1. System Topology Structure

As shown in figure 3, the power regulation topology structure of the power grid based on the flywheel energy storage array contains the electric generator (thermal power units, new energy electric generator, etc.), load cells, energy storage converter PCS, flywheel converters, flywheel array, flywheel management system. The flywheel converters and the power grids are connected in parallel to the public AC bus. The AC side of the PCS is connected together with the common bus, while the DC side is connected with the common DC bus of the flywheel converters. The flywheel array is configured in a one-and-many mode, while each flywheel unit is equipped with an independent flywheel converter and each flywheel converter is equipped with an independent flywheel management system (FMS). The whole power regulation system is integrated by using an energy management system (EMS). The traditional industrial ethernet communication interface can be used to control the FMS and the power grid for the EMS.

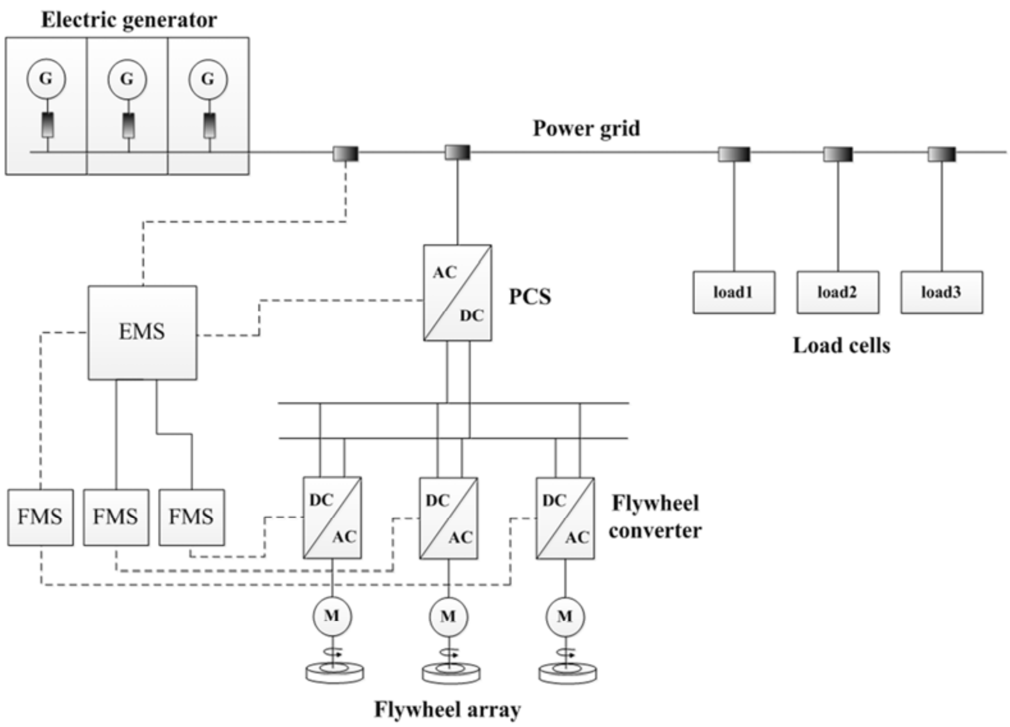


Figure 3. *The power regulation topology structure of the power grid.*

3.2. Power Regulation Principle

As shown in figure 3, the entire power regulation system is divided into two working mode: local and remote. In local mode, the PCS and flywheel converter are controlled by the local touch panels while all data are uploaded to the EMS. In remote mode, both of the PCS and FMS are controlled by the EMS, and the flywheel converter is controlled by the FMS. Taking the remote mode for example, the power modulation principle of the power grid is introduced as below.

3.2.1. Pre-charging Process

After the power grid is normal, the EMS detects the voltage value meets the requirement, and the sends a “start command” to the PCS, while the PCS enters into the standby mode after receiving the start command. At meanwhile, the EMS sends a “start command” to the FMS. After receiving the start command, the FMS firstly sends the “full suspension” command to the magnetic bearing controller to make the flywheel suspension. During that, the FMS continuously detects all of the information of the flywheel, including the vacuum value, temperature values, suspension state and so on.

When everything is normal, a kind of dry I/O is closed to make the PCS switched from the standby mode to the DC stability mode (CV mode). in CV mode, the DC bus voltage is controlled by PCS. After the DC bus voltage is stabilized, the EMS sends the “pre-charging control command” to the FMS. After receiving the command and reference speed, the flywheel will be charged with the programmed power to accelerate and store energy. After reaching the reference speed, the flywheel motor will be drive with a low current to maintain the speed.

3.2.2. Normal Operation Process

After receiving the “permissible discharge” signal, the EMS sends a “shutdown command” to PCS. Then the DC bus voltage will be continuously dropping until the flywheel begins to discharge and stabilize the DC voltage. When the DC voltage is stable, the EMS sends “PQ control command” to PCS. And then the PCS will be switched to PQ operation mode, i.e., power modulation mode. The external AGC equipment provides the adjusted power values, and the EMS sends these values to PCS. Based on this, the PCS can achieve the active power compensation and reactive power elimination. Detaily, when the power grid needs active power compensation, the PCS operates in the +PQ mode. Then PCS absorbs power from the DC side, and the flywheel array begins to discharge to stabilize the DC bus voltage. When the power grid needs active power absorption, the PCS operates in the -PQ mode. Then PCS transfers the electric energy from the grid side to the DC side, and the flywheel array begins to charge to stabilize the DC bus voltage. At meanwhile, when the power grid is cut off, the PCS can automatically operate in the *V/F* off-grid mode. And the flywheel array can provide energy to ensure the uninterrupted power supply for the electric loads.

3.3. Capacity Assignment of Flywheel Array

When designing the flywheel array system, two requirements must be met: the total power and the total storage energy.

According to the total capacity of the electric generator, about 10% energy storage system is typically configured as the power regulation component, such as a 5MW electric generator with a 500kW flywheel energy storage system.

Considering the frequency modulation experience, the flywheel array system is generally required to provide the rated power within 1 to 2 minutes. Then the energy capacity of the 500kW flywheel system should reach to:

$$500 * 2 / 60 = 16.7\text{kWh} \tag{1}$$

It is seen that for a 500kW flywheel array system, the available storaged energy is 16.7kWh. Considering the discharge depth about 75%, the maximum storaged energy capacity of the flywheel array is

$$16.7 / 0.75 = 22.2\text{kWh} \tag{2}$$

The maximum storaged energy capacity of flywheel array is 22.2kWh under the rated power of 500kW and 2min frequency modulation range. According to the flywheel energy formula as follows:

$$E = \frac{1}{2} \times J \times \omega^2 \tag{3}$$

Among them, E is the maximum storaged energy of the flywheel. According to the relationship between the moment of inertia J and the rated speed ω, which can be used to support the design of flywheel body.

3.4. Working Process of Flywheel Array

Generally, the rated power and energy capacity of one flywheel unit can not meet the demand of the power regulating system in the filed of the power grid. To deal with this problem, it is common to combine several flywheel units as an array system in the form of DC parallel operation. For the array control process, a kind of contant-voltage mean-current method can be effective. In this strategy, one flywheel unit is taken as the master to achieve the voltage closed-loop control and other flywheel units are taken as the slavers to receive the power values of the host. The mentioned control block diagram is shown in figure 4.

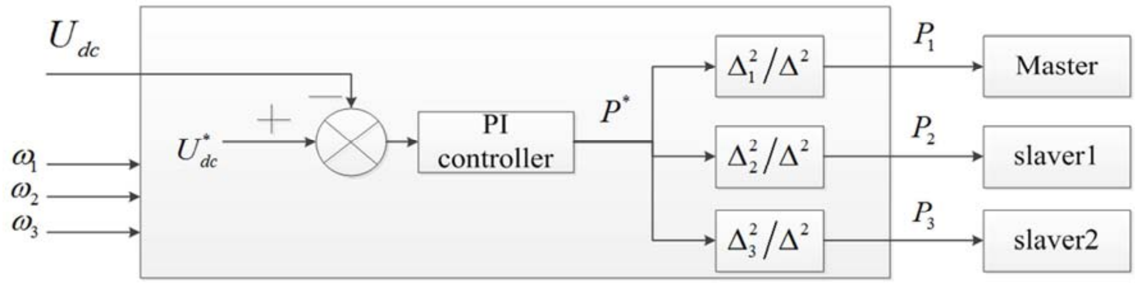


Figure 4. *The control block diagram of flywheel array.*

As shown in figure 5, the master achieves the DC bus voltage closed-loop control. The output of the voltage PI controller is considered as the total expected power of the flywheel array P^*. According to each flywheel speed, a kind of equal time length control method is applied. Based on this, the charge-discharge power of each flywheel is as follows:

$$P_i = P^* \times \frac{\Delta_i^2}{\Delta^2} \tag{4}$$

Among them, P_i and Δ_i are the power and residual energy of the i flywheel unit and Δ is the total residual energy of the flywheel array. By using this control method, the charge-discharge power of the high-speed flywheel is larger than the slow-speed ones. Due to this, the maximum charge-discharge time can be obtained for the flywheel array.

4. Experimental Results

4.1. Experimental Equipment

In this paper, a high-power magnetically suspended flywheel array system developed by Beijing Honghui International Energy Technology Development Co., Ltd. is taken as the experimental object to verify the power regulation system performance. The experimental equipment are shown in figure 5, which contains two flywheel units with each power 250kW and energy 50kWh. The total power of the flywheel array is 500kW and the energy capacity is 100kWh. The parameters of the flywheel unit are shown in Table 1.

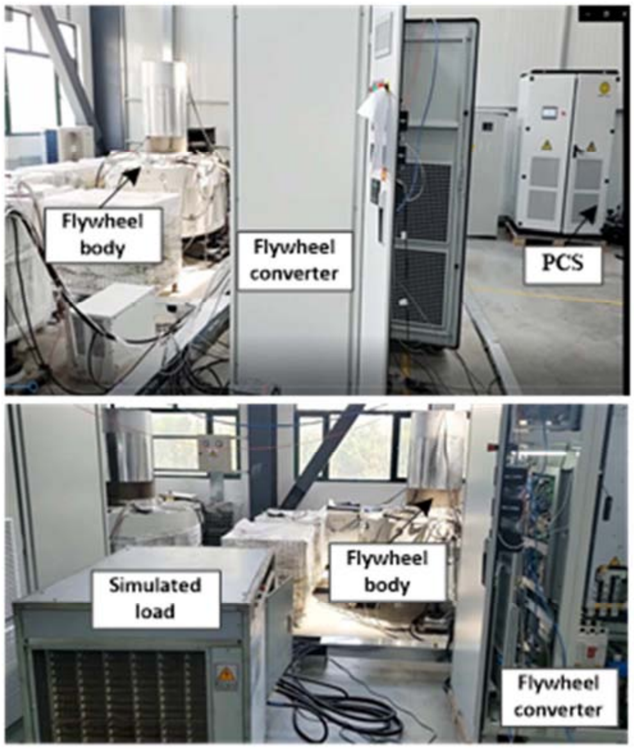


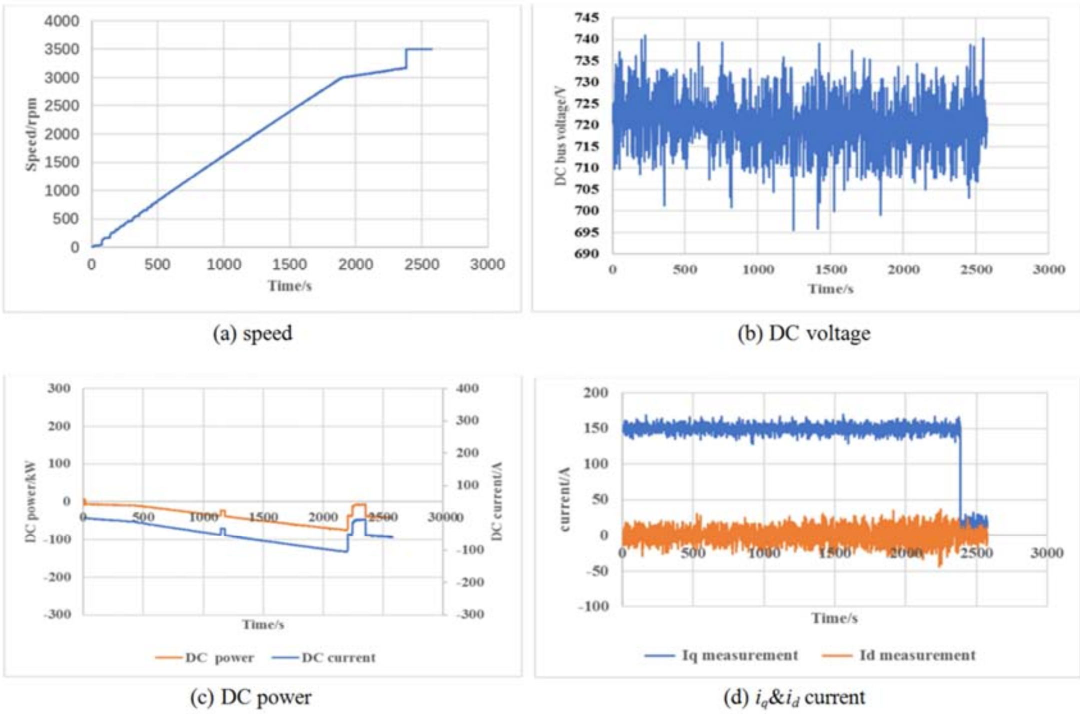
Figure 5. *Experimental equipment.*

Table 1. *Parameters of the Flywheel Unit.*

Number	Parameters of flywheel unit		
	parameter	**index**	**symbol**
1	rated power	250kW	P_N
2	maximum energy	50kWh	E_N
3	working speed	3000~7200rpm	n_N
4	voltage range	0~480V	V_N
5	current range	0~800A	I_N
6	discharge depth	80%	---
7	rotor inertia of moment	641.774kgm^2	J

4.2. CV Mode Experiment

After the flywheel system is powered on, the PCS is operated into the CV mode. And the DC bus voltage is stabilized accurately. The flywheel begins to accelerate in the pre-charging mode. Taking the flywheel unit 1# for example, the curves of speed, DC voltage, DC power and i_q & i_d current are shown in figure 6, respectively.



(a) speed (b) DC voltage

(c) DC power (d) i_q&i_d current

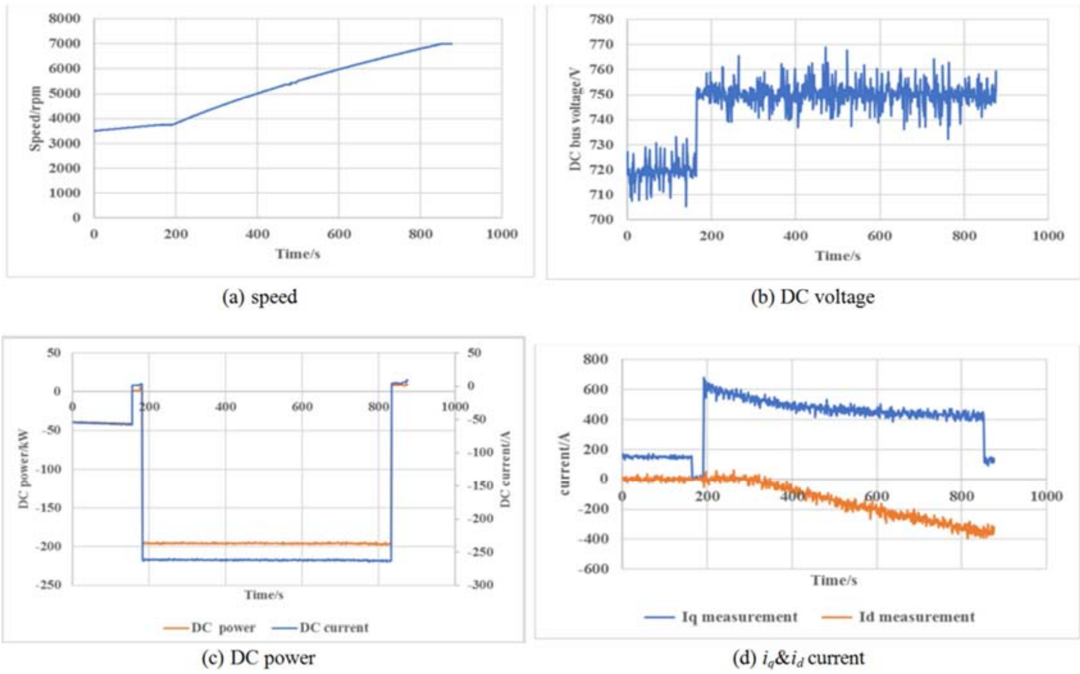
Figure 6. *Experimental curves in CV mode.*

It can be seen that the pre-charging current of the flywheel converter is 150A with the DC power less than 100kW and the DC voltage 720VDC maintained by PCS. The flywheel is accelerated from 0 to 3500rpm taking about 40min. The i_q & i_d current measurement can track the reference values effectively.

4.3. -PQ mode Experiment

After the speed of the flywheel unit 1# has reached to 3500rpm, the PCS is switched into the -PQ mode. And the flywheel begins to charge in order to stabilize the DC voltage. Provided a -200kW power, the curves of speed, DC voltage, DC power and i_q & i_d current are shown in figure 7, respectively.

It can be seen that the real DC power is -200kW with the DC voltage 750VDC maintained by the flywheel converter. The flywheel is accelerated from 3500rpm to 7000rpm taking about 11min. The i_q current measurement can reach to 700A in 3500rpm and 350A in 7000rpm. According to the formula $E = P * t$, the input electric energy is $E = 200 * 11 / 60 = 36.66$kWh, which is larger than the storaged energy.



(a) speed (b) DC voltage

(c) DC power (d) i_q&i_d current

Figure 7. *Experimental curves in -PQ mode.*

4.4. +PQ Mode Experiment

After the speed of the flywheel unit 1# has reached to 7000rpm, the PCS is switched into the +PQ mode. And the flywheel begins to discharge in order to stabilize the DC voltage. Provided a +250kW power, the curves of speed, DC voltage, DC power and i_q & i_d current are shown in figure 8, respectively.

It can be seen that the real DC power is +250kW with the DC voltage 750VDC. The flywheel is decelerated from 7000rpm to 3500rpm taking about 8.2min. The i_q current measurement can reach to 500A in 7000rpm and 1000A in 3500rpm. According to the formula $E = P * t$, the output energy is $E = 250 * 8.2 / 60 =$ 34.1kWh, which is smaller than the storaged energy.

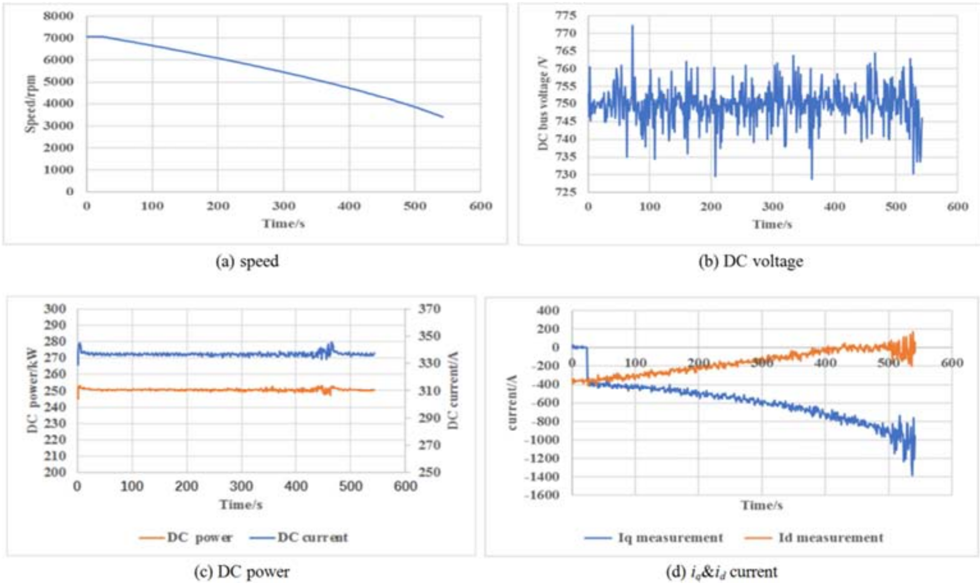


Figure 8. *Experimental curves in +PQ mode.*

4.5. Parallel Experiment of Flywheel Array

Now we take the flywheel unit 1# and 2# to demonstrate the parallel experimental results. After the flywheel unit 1# and 2# have charged over, the PCS is switched into the *V/F* off-grid mode. And the simulated load is powered on with a total capacity of 500kW. Then the flywheel unit 1# and 2# begin to discharge at the same time to stabilize the DC voltage. Provided a +300kW load, the curves of speed, DC voltage, DC power and i_q & i_d current are shown in figure 8, respectively.

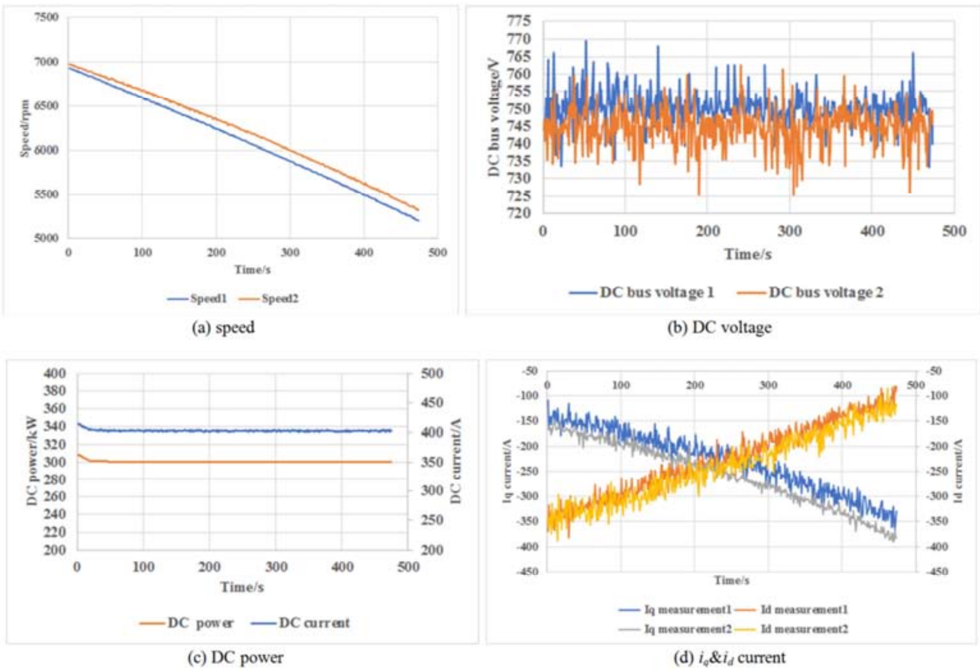


Figure 9. *Experimental curves in parallel mode.*

It can be seen that the real DC power is +300kW with the DC voltage 750VDC. The flywheel unit 2# is decelerated from 7000rpm to 5200rpm, while the flywheel unit 1# is decelerated from 6900rpm to 5300rpm taking about 8min. Based on the equal time length control method, the discharge i_q current of flywheel 2# is larger than that of flywheel 1#, with -170A to -370A and -150 to -350A, respectively.

5. Conclusions

In this paper, the flywheel energy storage array-based power regulation system has been presented in order to improve the stability and reliablity of the power grid. Based on the proposed system composition and control strategy, the flywheel array system has the advantages of fast response and frequent charge-discharge performance so that the short term and high frequency energy storage demands of the power grid can be effectively satisfied. Finally, the real expertimental equipment has been developed and the charge-discharge control tests have been carried on to indicate the effectiveness of the flywheel array system. The experimental results in the CV or PQ working mode with the serial or parallel control structure have provided the charge-discharge control process and performance of the flywheel array system. Through these results, it can be conclued that the flywheel aray system is suitable to improve the stability and electricity quality of the main power grid.

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