A Novel Hybrid Energy Storage Strategy Based on Flywheel and Lead-acid Battery in Wind Power Generation System

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Abstract

In this paper, based on expounding the basic structure and operating principle of the flywheel energy storage system, the maximum energy storage and energy efficiency of the flywheel batteries are analyzed. Research data shows that there is still a part of the energy left after the flywheel energy storage system doing the effective energy output. In the premise to save this part of energy for purpose, the way of combining the flywheel battery with lead-acid battery is proposed to put forward a new hybrid energy storage system. At last, the structure of the new hybrid energy storage system is designed for non-grid and grid wind power generation system.

Keywords: *flywheel energy storage, lead-acid batteries, hybrid energy storage, wind power.*

1. Introduction

In recent years, energy has become one of the major problems to be solved in the world. Compared with the continuous development of new energy, efficient use of existing energy comes into people's vision gradually. Following closely, the problems in the store and mode conversion of electrical energy become the hot research ones in the field of energy.

Currently, there are a variety of ways to save electrical energy. But if we have them classified from the energy storage mechanism, they can be divided into three types:

1) Electrochemical energy storage: such as a wide variety of chemical batteries;

2) Electric energy storage: such as super capacitor energy storage and superconducting magnetic energy storage;

3) Mechanical energy storage: such as compressed air energy storage, flywheel energy storage and pumped storage.

There are four kinds of energy storage technology with industrial significance in these storage methods. They are pumped storage, compressed air energy storage, superconducting magnetic energy storage and flywheel energy storage [1].

Table 1. Performance Comparison between the Various forms of Energy Storage

Project	Flywheel Energy Storage	Chemical batteries	Gas turbine	Pumped storage	Compressed air energy storage	SMES
Efficiency(%)	～90	～70	～50	～60	<50	～90
Energy storage	high	middle	>30MW	high	High	high
Modularity	yes	yes	no	no	No	no
Cycle life	unlimited	several hundred	several thousand	several thousand	several thousand	unlimited
Charge and	minute	hour	non	hour	Hour	hour

discharge time						
Location Availability	extremely high	middle	middle	low	Low	extremely low
Environmental Impact	good	large	large	extremely large	Extremely Large	very good
Consequences of the accident	low	middle	middle	high	Middle	high
Usability	used	used	used	used	Used	development

It can be seen from Tab. 1 that flywheel energy storage technology has the advantages of long service life, high power density, high energy storage density, nearly no limits of number of charge and discharge times, convenient installation and maintenance, charging and discharging quickly, without geographical limits and the nearest placed dispersedly. This is more advantageous than the use of other energy storage means [2].

In fact, the theory of flywheel energy storage was suggested as early as 100 years ago. But it could not enter into commercial application stage until 1990s with the constant breakthroughs in technology. The major technological breakthroughs include three aspects. First the appearance of high-strength carbon fiber composite materials (tensile strength as high as 8.27GPa) increased the kinetic energy of the mass storage unit greatly. Second the research of maglev technology and HTS technology had the rapid progress. It could make the friction loss and wind loss of the flywheel rotor be reduced to a minimum limit. Third the new progress in power electronics technology such as the breakthrough of motor/generator and power conversion technology provided exchange between kinetic energy and electric energy of flywheel energy storage with advanced means [3].

There are wide range of applications for flywheel energy storage. It is applicable to the field with high power, high frequency applications and short working time. Such as UPS, the power system peaking load, wind power generation, solar generator and so on [4].

2. Working Principle of Flywheel Energy Storage System

2.1. The Composition of Flywheel Battery

A typical flywheel energy storage system is generally composed of three main, two controllers and a few of accessories: ① Flywheel energy storage; ② Integrated drive motor/generator; ③ Magnetic bearing system; ④ Magnetic bearing controller and motor speed controller; ⑤ Accessories (landing bearings, cooling system, display instrument, vacuum equipment, security container and so on).
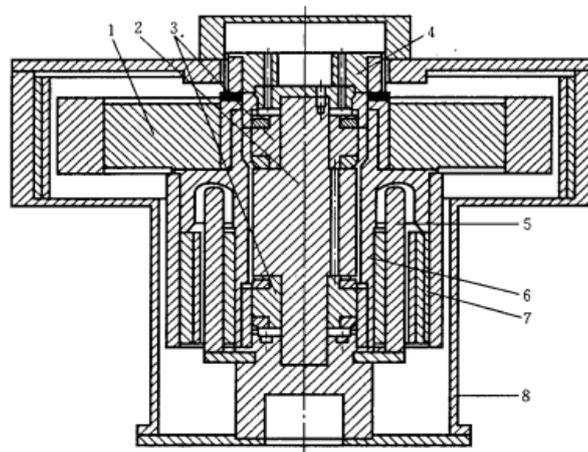

Figure 1. Structure Diagram of Flywheel Batteries

Figure 1 shows the structure diagram of a kind of flywheel batteries. 1 is flywheel; 2 is stator of radial magnetic bearing; 3 is radial magnetic bearing; 4 is axial magnetic bearing; 5 is motor stator containing cooling water; 6 is the motor rotor inside; 7 is the motor rotor outside; 8 is vacuum shell.

2.2. Flywheel Rotor

Flywheel rotor is the most important component in the flywheel battery structure. The storage and conversion of the whole system is completely relying on the kinetic energy produced by flywheel rotation.

The energy absorbed and released by a rotating flywheel rotor is:

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

E is the stored energy; J is moment of inertia of flywheel rotor, $kg.m^{-2}$; ω is angular speed of flywheel, $rad.s^{-1}$.

The maximum energy can be stored by the flywheel is:

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

ω_{max} is maximum angular speed of flywheel, ω_{min} is minimum angular speed of flywheel.

From Eqs. (1) and (2), it shows it is possible to increase storage capacity of flywheel batteries by increasing the moment of inertia of flywheel rotor and improving the speed of the flywheel.

While increasing the kinetic energy by improving the speed of the flywheel, the flywheel will be broken by the centrifugal force for speeds exceeding a certain value due to the limited strength of flywheel materials [5].

Energy storage density is an important index for characterizing the performance comparison of the energy storage device.

$$e = \frac{E}{m} = \frac{2.72 K_s \sigma}{\rho} \tag{3}$$

In the formula:
e——energy storage density of flywheel, Wh/kg;
K_S——shape coefficient of flywheel;
ρ——the proportion of the material, kg/cm^3;
σ——allowable stress of material, MPa.

3. Energy Conversion Scheme of Flywheel Energy Storage System

3.1. Energy Conversion Principle of Flywheel Energy Storage System

Flywheel in the flywheel energy storage system is an electromechanical energy conversion device. The energy conversion is mainly achieved through the motor and power electronics control equipment. The motor speed formula can be represented by the following formula.

$$n = \frac{60 f}{p} \tag{4}$$

where
n——the speed of the motor;
f——the frequency of the power supply;
p——the pole number of motor.

From the formula (4) it is possible to achieve the purpose of changing the speed of the motor through changing the frequency of the power supply. First make the three-phase AC power supply into the DC power supply through the rectifier. Second make the DC power supply into the AC power supply whose voltage and frequency can be controlled for the motor through the inverter. Then the purpose is achieved to improve the speed of motor by increasing the frequency [6].

Flywheel makes the transmission and control energy relying on bi-directional inverter as the electromechanical energy conversion device in flywheel energy storage system. When the system is being charged, the power input from the outside is converted from DC to AC through the inverter to drive the flywheel motor making the flywheel rotating in order to converts electrical energy into mechanical energy for storage; When the system is being discharged, the high speed rotating flywheel rotates the generator to convert mechanical energy of the flywheel into electrical energy and the electrical energy will be transformed into various frequency and voltage levels power required by external load through the rectifier. The workflow of flywheel energy storage system is shown in Figure 2 [7].
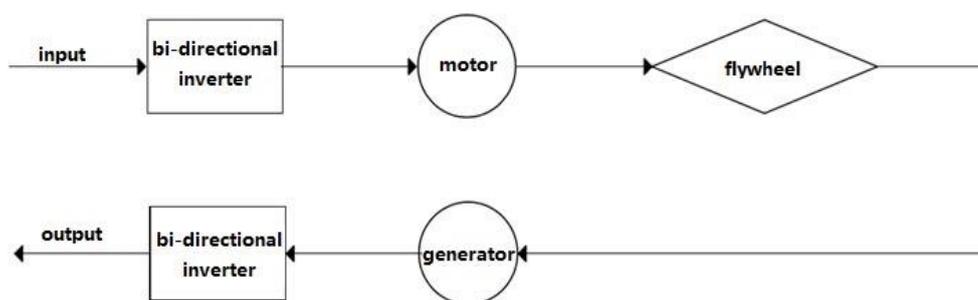

Figure 2. The Workflow of Flywheel Energy Storage System

Flywheel battery energy conversion is mainly realized by frequency controlled regulating system. Its frequency controlled regulating system should meet the following requirements.

1) It can regulate the speed of the motor effectively and make the motor speed up smoothly.

2) It can reliably convert the mechanical energy stored in the flywheel into electrical energy through the generator.

3) It can keep the power in the constant frequency and constant voltage state to delivery to the electric equipment.

4) It can ensure the power flow between AC and DC able to be bidirectional controlled. Then the rectification and inverter are achieved.

3.2. Analysis of Flywheel Battery Energy Conversion System

Flywheel batteries not only convert electrical energy into mechanical energy for storing in a flywheel but also convert mechanical energy into electrical energy for external electrical equipment. Traditional frequency changing speed device often works in the way of AC-DC-AC. It converts the AC power into the DC power, and then it converts the DC power into the AC power whose voltage and frequency can be controlled to drive motor. We can not use traditional frequency changing speed device as flywheel battery energy conversion equipment because it can not achieve two-way flow of energy [8].

The functions "charge" and "discharge" of the flywheel are achieved by PWM converter in this system. Its work principle is shown in Figure 3. The PWM converter can

achieve two-way flow of energy because it can work in two states of rectifying and inverting.

When the flywheel battery is in the charging state, the $1^{\#}$ PWM converter works in the state of rectifying to rectify AC power into DC power and the $2^{\#}$ PWM converter works in the state of inverting to convert DC power into AC power whose voltage and frequency can be controlled to drive permanent magnet motor with flywheel battery inside. The motor drives the flywheel rotate faster to convert electrical energy into mechanical energy for storage.

When the flywheel battery is in the discharging state, the flywheel rotating at high speed drives the motor make power while converting the mechanical energy into electrical energy. The $2^{\#}$ PWM converter works in the state of rectifying and the $1^{\#}$ PWM converter works in the state of inverting to convert DC power supply into alternating AC power for electrical equipment.
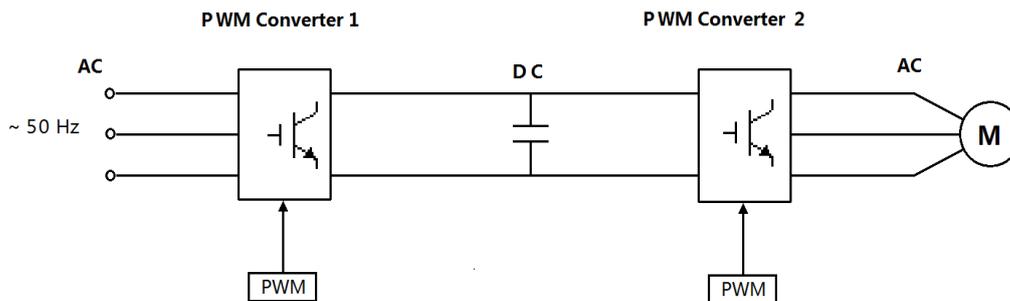

Figure 3. Working Principle of PWM Converter Mode

The PWM converter can achieve two-way flow of energy. The flywheel battery with it can both work as the energy storage device and be used to regulate the electric energy quality.

3.3. Energy Output Interval

By the formula (2) we can see that flywheel energy storage system can not make the one hundred percent feedback energy in the energy output stage and energy efficient feedback interval is running on the flywheel with high speed rotation zone. Because with the decline of the flywheel speed, a large range of fluctuation will appear in the frequency and voltage of feedback current. As shown in Figure 4, the feedback voltage value may be less than the voltage on the bus capacitors C1, so that flywheel energy storage system cannot make effectively energy output. If making the discharge in the non control rectification after the decrease of voltage bus values, this will make the DC bus voltage instability. Then this will affect the characteristics of grid-connected inverter and damage output performance of inverter. There are two schemes to deal with this situation.

1) Plus a boost circuit in the main circuit.

2) Make the motor operation in regenerative braking state by controlling the converter to convert mechanical energy of the flywheel into electrical energy to maintain the DC link voltage constant. The essence of this method is to make the inductance of the motor as the boosting circuit of the inductor to omit the hardware of booster circuit. This can improve the system stability [9].

Despite there are two schemes which can improve the system, the effective feedback area of flywheel energy storage system probably stops when the flywheel speed drops to 50%. The remaining energy is difficult to use effectively [10].
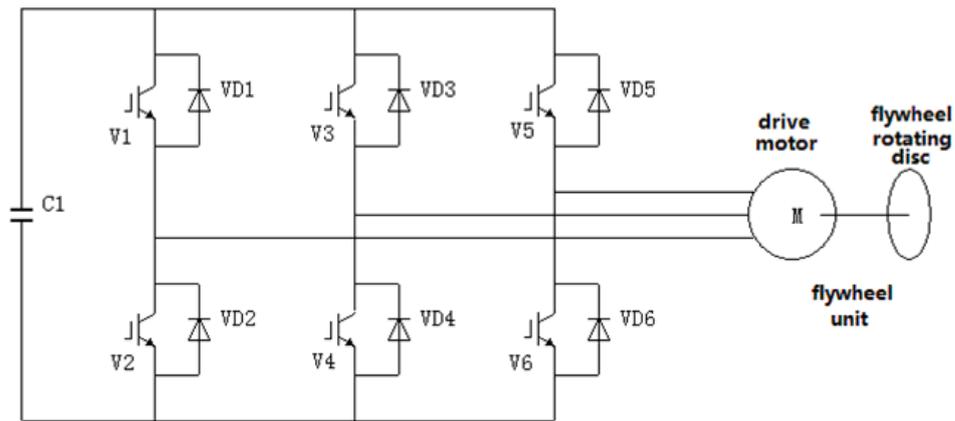
Figure 4. The Main Circuit Topology of Flywheel Energy Storage System

3.4. Energy Loss

There are three modes charging, discharging and load operation in the application process of flywheel energy storage system. The energy loss of energy storage system is divided into two parts, energy loss of the flywheel motor system and energy loss of the auxiliary system. While the energy loss of flywheel system is divided into three parts: wind loss, electricity loss and bearing loss.

Due to the birth of magnetic bearings and vacuum environment, they make the wind damage and bearing loss of flywheel greatly reduced. But flywheel energy storage system has its own disadvantages, because of its high self discharge rate, such as after charging, energy will be depleted in a few hours. Therefore in order to keep the energy of flywheel energy storage system, it is necessary to provide a continuous power supply for its charging.

3.5. Energy Efficiency of Charge and Discharge

The definition of charging efficiency is the ratio of the kinetic energy Ed to the income electric energy E_t of engine control system when the rotational speed (r/min) of flywheel (moment of inertia, J) increases from n_b to n_t at the end of charging process.

$$\eta_c = \frac{E_d}{E_t} \tag{5}$$

$$E_d = \frac{1}{1800}\pi^2 J(n_t^2 - n_b^2) \tag{6}$$

The definition of discharging efficiency is the ratio of the electric energy coming from the system (negative useful work) to the kinetic energy of flywheel when the rotational speed of flywheel decreases from n_b to n_t at the end of discharging process.

$$\eta_d = \frac{W_1}{E_d} \tag{7}$$

The definition of charge discharge efficiency is the ratio of the output energy (negative useful work) to the input energy.

$$\eta_E = \frac{W_1}{E_i} \tag{8}$$

According to the literature [11], most energy loss is the motor loss and control loss in the charge and discharge processes of flywheel energy storage system while the wind loss and bearing loss are only a small part of the loss.

4. Novel Hybrid Energy Storage System Consisted of Flywheel Batteries and Lead-acid Batteries

In order to smooth power fluctuation of wind power generation system and reduce the influence of random fluctuation of wind power on power system, it is possible to add the energy storage device in wind power generation system [12]. When the wind power increases suddenly, the energy storage device can store the excess energy. When the wind power decreases so that it can not meet the load demand, the energy storage device will release the stored energy to achieve constant power output of wind power generation system. This is the main purpose of the energy storage system equipped.

4.1. Rationality of Novel Hybrid Energy Storage System

4.1.1. From the Point of Flywheel Battery View

From Table 1 it can be seen flywheel battery and lead-acid battery has the same feature of work location selection flexibility. This primary feature makes the combination of flywheel batteries and lead-acid batteries possible and then it means novel hybrid energy storage system also has the feature of work location selection flexibility to be convenient for application.

Table 2. The Performance Comparison between Flywheel Battery and Lead-acid Battery

Type of energy storage	Specific capacity/ (Wh/kg)	Specific power/ (W/kg)	Discharge duration	Cost/ ($/kW/yr)	Life/times （80% depth of discharge）	Response time	Operating temperature
Flywheel	40~230	>5×10^3	15s~15min	40~80	104~6×10^4	<1s	-40℃~+50℃
Lead acid battery	35~50	75~300	1min~ a few hours	25	2×10^2~5×10^3	<10s	10℃~30℃

According to Table 2, the flywheel battery and lead-acid battery has certain functional complementarity. First, the response time of flywheel battery is sooner which makes a very important role in the protection of electric power system safety. But the discharge time of flywheel batteries is short, only 15s~15min, not enough to meet the demand of long time energy supply. And the effective feedback area of flywheel energy storage system probably stops when the flywheel speed drops to 50%. The remaining energy is difficult to use effectively [13].

In the novel hybrid energy storage system consisted of flywheel batteries and lead-acid batteries, when energy demanded is less than the maximum energy storage of flywheel battery, the flywheel battery supplies the energy output completely. When energy demanded is more than the maximum energy storage of flywheel battery, the flywheel battery will supply energy output until the flywheel speeds down to the lowest effective speed, and then the lead-acid battery does the subsequent energy output. At the same time, when the flywheel gets its lowest effective speed, lead-acid battery will provide a continuous power to maintain its current speed. Then when once again charging for the flywheel, electric machinery implements the energy supply to it based on the lowest effective speed. So the energy is saved which makes the flywheel from a standstill to the lowest effective speed.

Eq. 1 shows that the power of flywheel is proportional to the square of its rotational speed. In addition, based on the recent research, the minimum efficient speed of flywheel generally is 50% of the maximum speed.

$$E_{max} = \frac{1}{2} J \omega_{max}^2 \tag{9}$$

$$E_{min} = \frac{1}{2} J \omega_{min}^2 \tag{10}$$

$$\omega_{min}^2 = \frac{1}{4} \omega_{max}^2 \tag{11}$$

According to the formula (9) (10) (11), we can see that when the flywheel gets its lowest effective speed, its energy left is still about 1/4 of the energy contained by the flywheel in its highest speed. If the formula (2) (9) (10) (11) linked, it is not difficult to find when the flywheel is reduced to the lowest effective speed, the energy left is equivalent to 1/3 of the maximum energy stored by the flywheel. From this it can be seen, if the energy left can be retained in flywheel with lowest effective speed, this will save a sizable portion of energy at the time of once again charging for the flywheel.

Due to the development of vacuum technology and superconducting maglev technology, the wind loss and bearing loss have become very little. And only a small amount of electricity is required to maintain the operation status of the flywheel.

4.1.2. From the Point of Lead-acid Battery View

Compared with the flywheel battery, lead-acid battery has the advantages of long continuous discharge time, a high degree of technological maturity, low cost construction and so on.

But lead-acid battery has two shortcomings which are difficult to make up.

(1) Lead-acid battery life is short and the charge and discharge time of it is less than the flywheel.

(2) The response time of lead-acid battery is longer, cannot promptly in response to the changes in the power system [14].

There are many applications of lead-acid battery in distributed power generations. For wind and solar photovoltaic, the output power of their power generation unit has characteristic of random and intermittent. And the change of the load is also stochastic. This brings great challenges to the stable operation of micro grid. In order to maintain internal balance of micro grid instantaneous energy in micro grid, energy storage systems often require to absorb (output) large power. Frequent large power charge and discharge and depth of discharge will cause the phenomena that the temperature of lead-acid battery rises, the active substances on positive and negative plates fall off and so on. These will seriously affect the battery life by resulting in the accumulation of loss of battery capacity and making the battery capacity rapid decline in short time.

It makes an effective combination of the flywheel battery and the lead-acid battery to form a new energy storage system. When the load changes, flywheel battery output power to respond rapidly to power demand while reserving reaction time for lead-acid battery at first, then the lead-acid battery makes the power compensation for payload after a certain delay. If the power required to compensate the load is less than the maximum energy storage of flywheel battery, the flywheel battery will supply the energy output completely to reduce the times of battery charge and discharge in order to extend lead-acid battery life.

4.2. Application of Novel Hybrid Energy Storage System in Wind Power Generation System

4.2.1. Application in Non Grid Connected Wind Power Generation System

Output power of wind turbine become DC to which meet requirements of inverter input through rectifier circuit and boost chopper. DC is transformed to AC after conversion for load. Flywheel energy storage system is connected in parallel with DC line of grid-side by energy conversion device. So, the transfer of energy can be bidirectional. Lead-acid battery system is connected in parallel with generation-side of wind power by energy conversion device to make the transfer of energy be bidirectional. When the flywheel gets the lowest effective speed, the lead-acid battery provides power to the load while supplying the flywheel an additional continuous current to maintain its rotation. Structure of no-grid wind power generation system adopting novel hybrid energy storage system is shown in Figure 5.
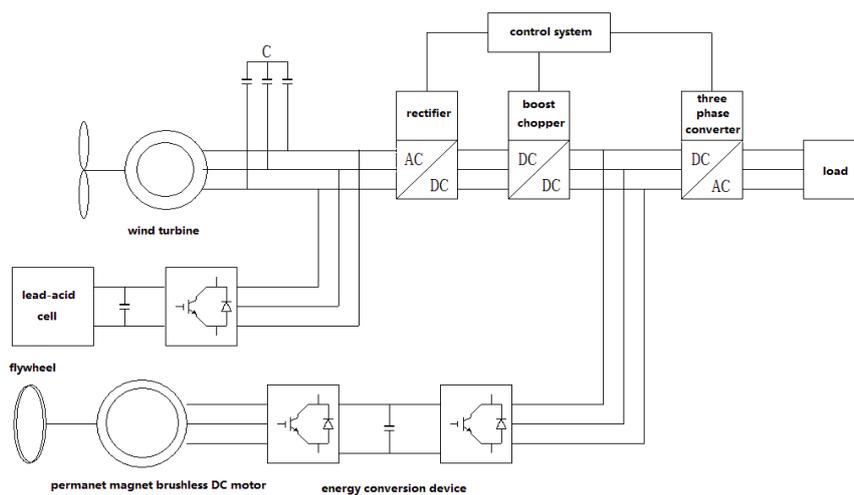

Figure 5. Structure of No-grid Wind Power Generation System Adopting Novel Hybrid Energy Storage System

4.2.2. Application in Grid Connected Wind Power Generation System

Output power of grid wind turbine will disturb grid for a little time, voltage and power in grid is difficult to be controlled and predicted. Grid wind power is random source for grid. That will bring electric energy quality down. The application of novel hybrid energy storage system is made. It is consisted of flywheel batteries and lead-acid batteries in grid connected wind power generation system. It can take advantage of its characteristic the rapid response power and two-way adjustment ability to make fast comprehensive compensation for active and reactive power outputted by grid connected wind power system in order to reduce the impact of the output power fluctuation of wind power station to power grid. Structure of the grid connected power system adopting novel hybrid energy storage system is shown in Figure 6 [15].
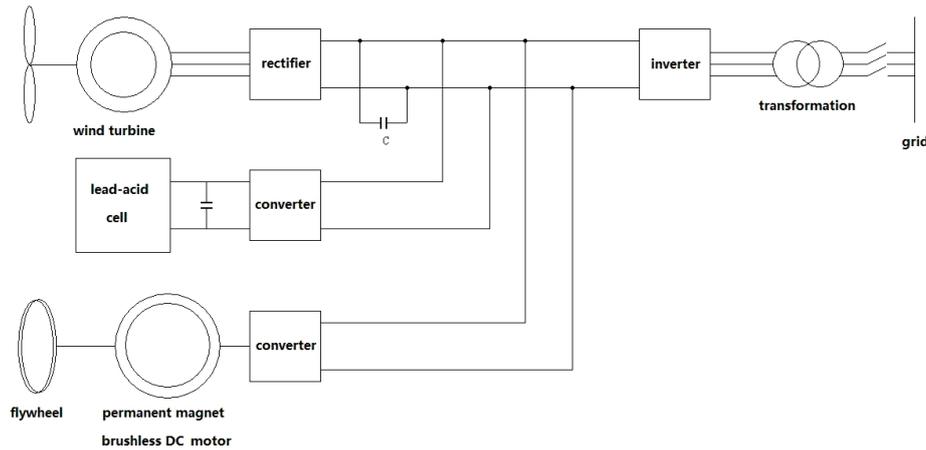
Figure 6. Structure of the Grid Connected Power System Adopting Novel Hybrid Energy Storage System

5. Conclusion

At first this paper introduces the working principle of flywheel energy storage system with doing a comprehensive exposition on the maximum number of stored energy, energy storage density and the workflow of energy storage system. Then the data shows there is still part of energy left in the flywheel when the flywheel finishes conducting effective energy output after researching on the use of flywheel energy storage system energy efficiency. Based on the purpose of saving this part of energy, comparing the flywheel batteries with lead-acid batteries, it shows they can make up the short board. So the scheme is proposed which makes a novel hybrid energy storage system consisted of flywheel batteries and lead-acid batteries. Compared with the simple flywheel energy storage system, the new kind of energy storage system has longer continuous discharge time and saves energy which makes the flywheel from a standstill to the lowest effective speed. Compared with the simple lead-acid energy storage system, it responds to the change of system power more quickly and reserves reaction time for lead-acid battery while reducing the times of battery charge and discharge in order to extend lead-acid battery life. Finally, this paper gives the structure of grid and non-grid connected wind power system adopting novel hybrid energy storage system. The simulation analysis will be done to this operation structure and the further verification will be made on the correctness of the hybrid energy storage system.

Acknowledgements

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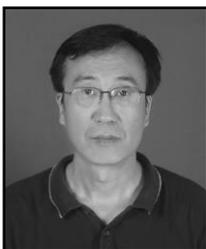
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