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Flywheel application at customer and electrical grid levels: possibilities and problems

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CONTENTS

1.Introduction

The use of energy is always accompanied by large amounts of energy wasted, but with the progress of times and development of science and technology, this problem can be improved by energy storage systems which stored the excess energy until it is needed. Energy storage technologies are widely concerned today because of their potential to play a key role in the transformation to a low-carbon, clean energy future. 'Storage' is a broad category of technologies and applications that can help utilities balance power supply and demand by holding energy for later use, like a bank account for energy. Storage technologies are distinguished primarily by capacity and discharge time(see Pic1)[i].

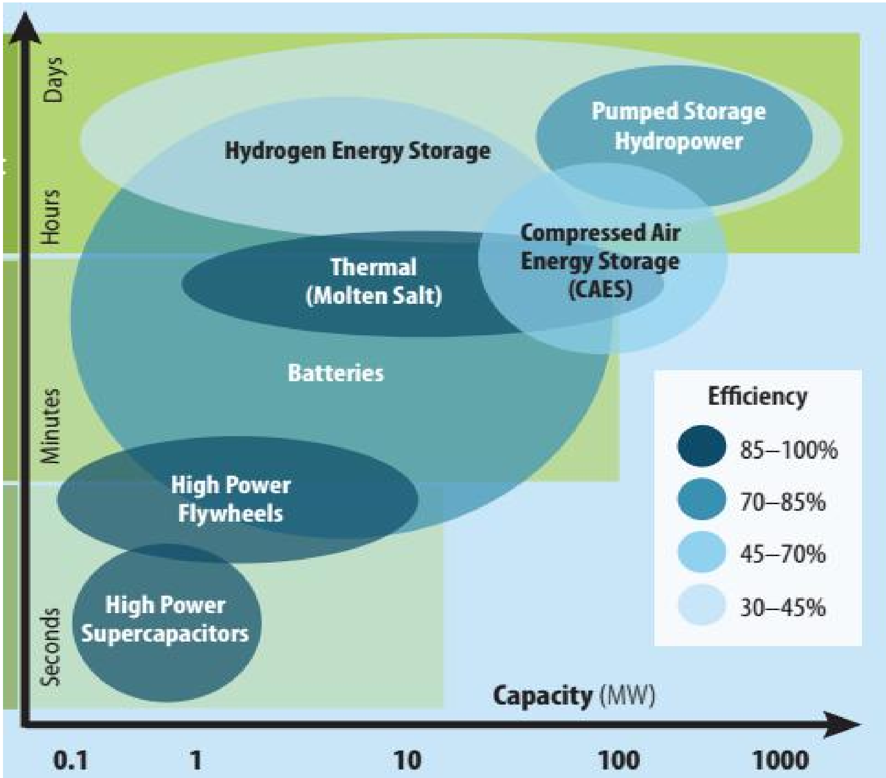


Fig1. storage technology characteristics

The flywheel is one kind of the energy storage systems which is a mechanical device specifically designed to store rotational energy efficiently, and the power can be used later when needed. From Pic1, we can see that the Flywheel has the characteristics of appropriate capacity and appropriate discharge time. Using the high-speed rotating flywheel stores energy is an old topic(Pic2.), but it was not easy to transfer the mechanical energy into other forms of energy with a flywheel, so the applications of the flywheel was very limited in the early twentieth century. In recent decades, transferring energy become comfortable with the innovation of technology, so the applications of the flywheels is more and more extensive. In this paper, the flywheels will be analysis, especially for their applications.

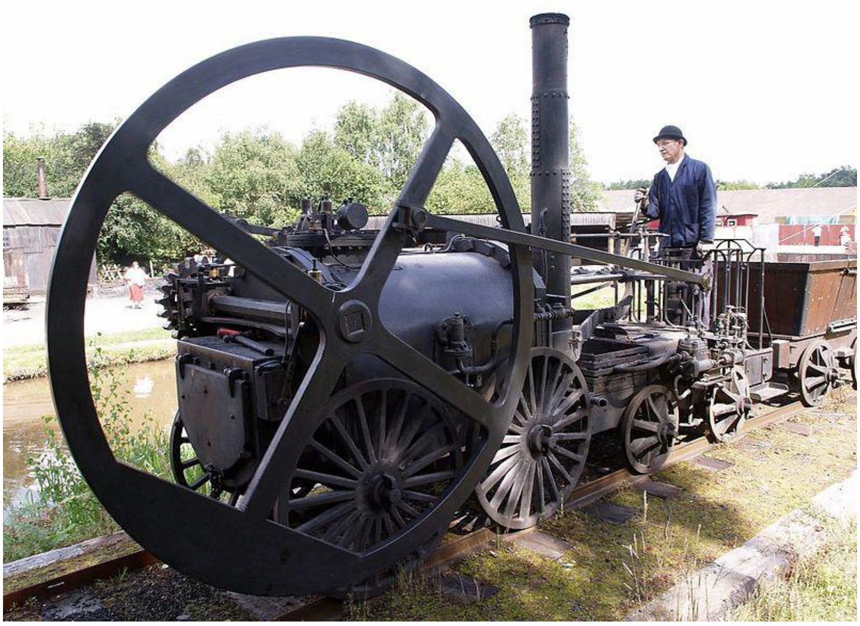


Fig 2. steam locomotive used a flywheel in 1802[ii]

According to flywheel features, it can be used to supply intermittent pulses of energy at power levels that exceed the abilities of its energy source. This is achieved by accumulating energy in the flywheel over a period of time, at a rate that is compatible with the energy source, and then release energy at a much higher rate over a relatively short time when needed. In the field of power grid, the energy stored by flywheels can be used to cope with peak load, can also increase the stability of renewable energy. In the following sections , the application of flywheel at electric grid levels will be explained in detail.

Flywheels are often used to provide continuous power output in systems where the energy source is not continuous. So a flywheel can be used to smooth fast angular velocity fluctuations of the crankshaft in a reciprocating engine, in this case, a crankshaft flywheel stores energy when the torque is exerted on it by a firing piston, and returns energy to the piston to compress a fresh charge of air and fuel. In automotive field, a large quantity of energy is wasted under braking, the flywheel can be used in a system to store the vehicle's kinetic energy under braking for later use under acceleration, this system is called kinetic energy recovery system(KERS, see Pic3). About the specific technology and principle of the flywheel used in automotive field will be illustrated later.

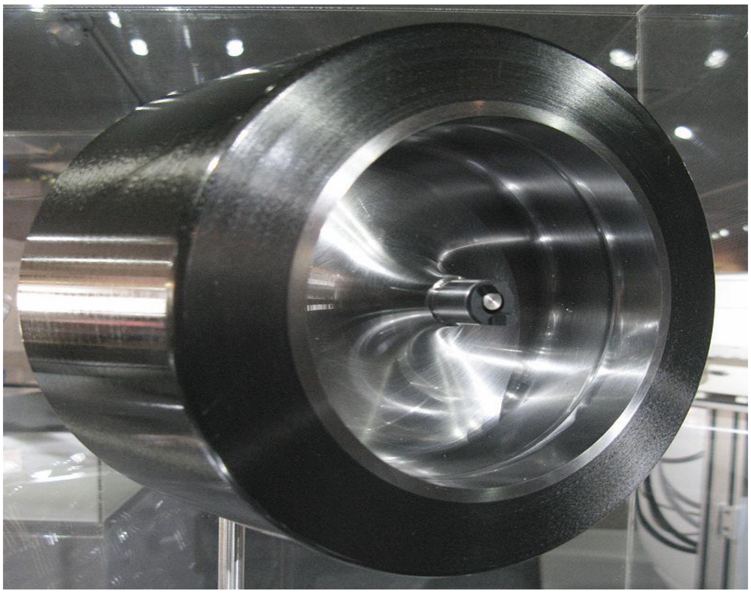


Fig 3. a KERS flywheel[iii]

The flywheel sealed in vacuum can replace the rechargeable battery, it is very suitable for fixed device with the benefits of long life and low cost. It can be full charged or discharged in a few minutes. Flywheel also used primarily by spacecraft for attitude control without using fuel for rockets or other reaction devices and used in medical apparatus and instruments.

The concept of the flywheel battery was put forward in the 90s, it broken through the limitations of chemical batteries, using physical methods to achieve energy storage. We all know that when the flywheel rotates at a certain angular velocity, it has some kinetic energy, then its kinetic energy is converted into electrical energy for storage. High-tech flywheels are used to store energy, much like standard batteries. A flywheel battery system contains a motor driven by the external power supply, the motor driven flywheel high-speed rotation, that is, the power to the flywheel battery "charging" increases the flywheel speed to increase its function. The motor is running in the generator state, the flywheel driven by the external output power to complete the mechanical energy (kinetic energy) to the conversion of electrical energy and then the electrical energy can be stored; afterthat, when the flywheel battery output electricity, the flywheel speed decreased. The flywheel is operating in a vacuum environment, high speed (up to 200000r / min), the use of non-contact magnetic bearing. Allegedly, flywheel batteries can be up to 150W H / kg, the specific power of 5000-10000W / kg, the service life of up to 25 years, 500 million kilometers for electric vehicles.

Today, the flywheel is closely related to our life, the research and development of flywheels never stop, the application of flywheels will more and more widely. Then we will account for the operating principles and key technologies of the flywheels

2.Operating principles and technologies

2.1.The materials of flywheels

The first section gives a brief overview of flywheels, now let’s start with the materials of the flywheel. Flywheels are made from many different materials, the application determines the choice of the material, such as: small flywheels like the ones found in children’s toys are made of lead, old steam engines have cast iron flywheels. More recently, flywheels have been proposed for energy storage and regenerative braking systems for vehicles, some of high-strength steel, some of composites. There appears to be a great diversity of materials in use.

The efficiency of a flywheel is determined by the maximum amount of energy can be stored per unit weight. For the same-sized flywheels, the kinetic energy is proportional to the circumferential stress and their volume:

$$E_k \propto \sigma_t \cdot V$$

Where: E_k is kinetic energy,

σ_t is circumferential stress,

V is volume.

This formula also can write as:

$$E_k \propto \frac{\sigma_t}{\rho} m$$

Where: m is mass,

ρ is density,

$\frac{\sigma_t}{\rho}$ is stress-to-weight ratio, also called the specific tensile strength(unit:[N/m2]/[kg/m^3] or [N•m/kg]).

From the formula we can see that if the flywheel’s stress-to-weight ratio is high, the energy density per unit mass is also high. Since the stress-to-weight ratio is directly influenced by the type of material belonging, so the different materials directly influence the flywheel’s efficiency.

Different materials of flywheels and their comments are showed below:

Material	M_5 (kJ/kg)	Comments
Ceramics	200 – 2000 (compr only)	Brittle and weak in tension, therefore eliminate.
Composites: CFRP	200 – 500	The best performance — a good choice.
Composites: GFRP	100 – 400	Almost as good as CFRP and cheaper.
Beryllium	300	The best metal, but expensive and difficult to work and toxic to machine.
High strength steel	100 – 200	All about equal in performance. Steel and Al-alloys cheaper than Mg and Ti alloys.
High strength Al alloys	100 – 200	
High strength Mg alloys	100 – 200	
Ti alloys	100 – 200	
Lead alloys	3	High density makes these a good (and traditional) selection when performance is velocity-limited, not strength limited.
Cast iron	8 – 10	

Table 1. comments of different materials

Through information research, the different materials' strength-density relation as shown below(Pic4):

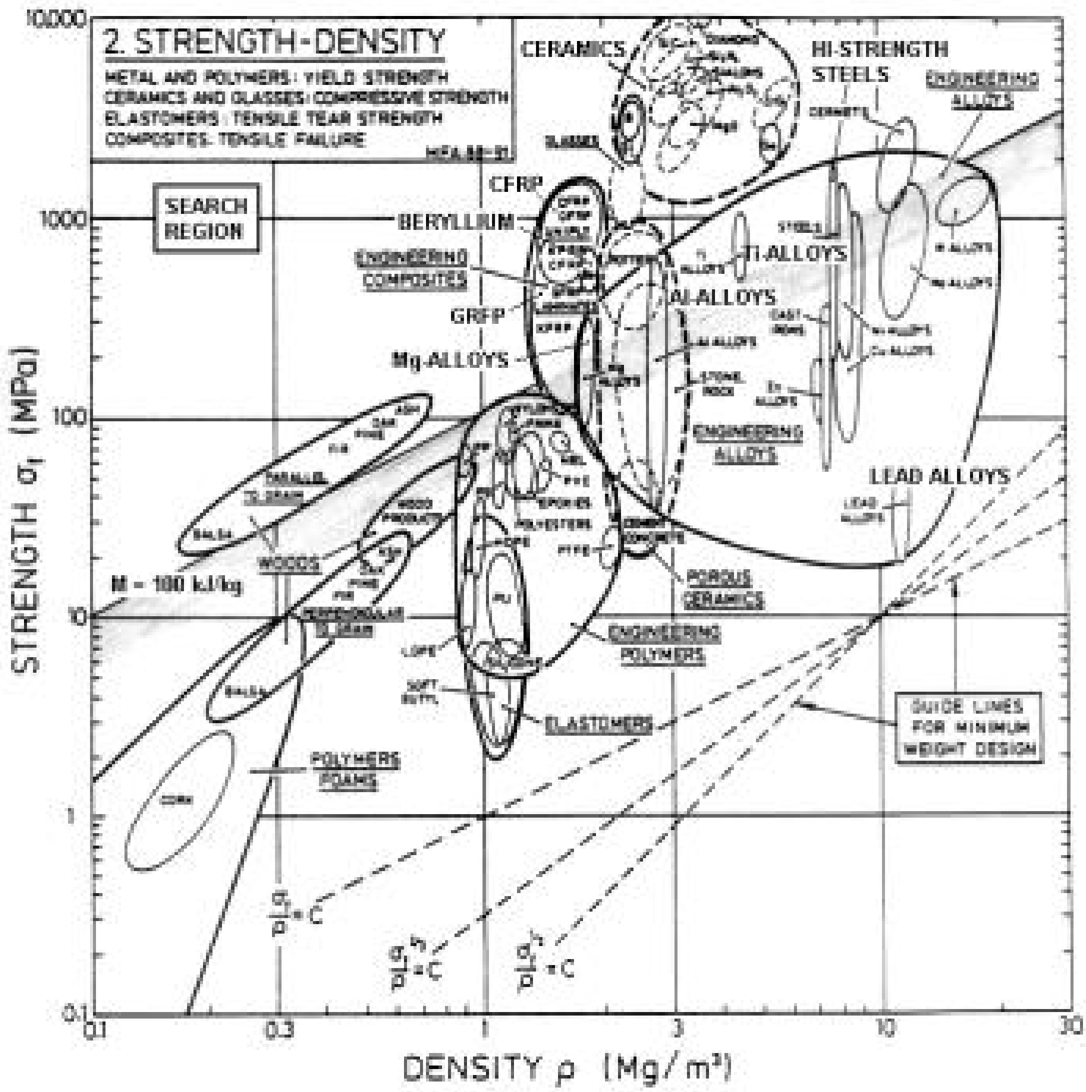


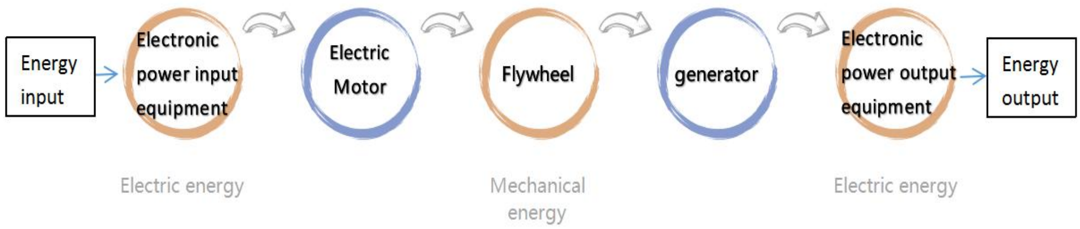
Fig 4. Materials for flywheels[iv]

From this picture, we can get that the Composites and Beryllium are the best choices. Lead and cast iron, traditional for flywheels, are good when performance is limited by rotational velocity, not strength.

According to the above-mentioned analysis, different materials will show the different efficiency. Another important factor of the choice of materials should be considered is the cost. Keeping the above points in mind, Steel for low RPM (few thousands) applications and carbon fiber for higher RPM (>60,000)applications are commonly used. The carbon-fiber flywheel is by far the most efficient; however, it also has the largest radius. In applications (like in an automobile) where the volume is constrained, a carbon-fiber flywheel might not be the best option. Some of them are made of high-strength glass fiber as well. The flywheels are made from different materials will use in different fields, we will discuss the different application fields in detail later.

2.2.The structures of flywheel energy storage systems

In this section we will analysis the structure of the flywheel energy storage (FES) system. The flywheel energy storage system is a method that stores energy in form of rotational kinetic energy by accelerating the flywheel’ s rotor to an extremely high speed. The flywheel energy storage device mainly consists of three core components: flywheel, motor, and power electronics. Its most basic working principle is that the electric energy sent from the outside can be converted into the kinetic energy of the flywheel by the motor. When the outside world needs electric energy, the kinetic energy of the flywheel is converted into electric energy by the generator and output to the external load, while the idle operation requires very little loss. The principle is shown as the following flowchart:



In fact, in order to reduce the loss during idle operation and increase the speed of the flywheel and the efficiency of the flywheel energy storage device, the design of the bearings of the flywheel energy storage device generally uses non-contact magnetic suspension bearing technology. Moreover, both the motor and the flywheel are sealed in a vacuum vessel to reduce windage, and the generator and motor are usually connected together by bearings and flywheels.

When the peripherals power the motor through the power electronic device, the motor is used as a motor, and its function is to accelerate the flywheel and store energy; when the load requires electrical energy, the flywheel applies torque to the motor, which in turn acts as a generator and powers the peripherals through the power electronics; when the flywheel is idle, the entire unit can operate with minimal loss. This way not only can improve efficiency, but also reduce the size of the flywheel, so that the energy storage density of the flywheel is greatly improved. In the entire flywheel energy storage device, the flywheel is undoubtedly the core component, which directly determines the energy storage of the entire device.

The typical structure of a cylinder flywheel showed as following:

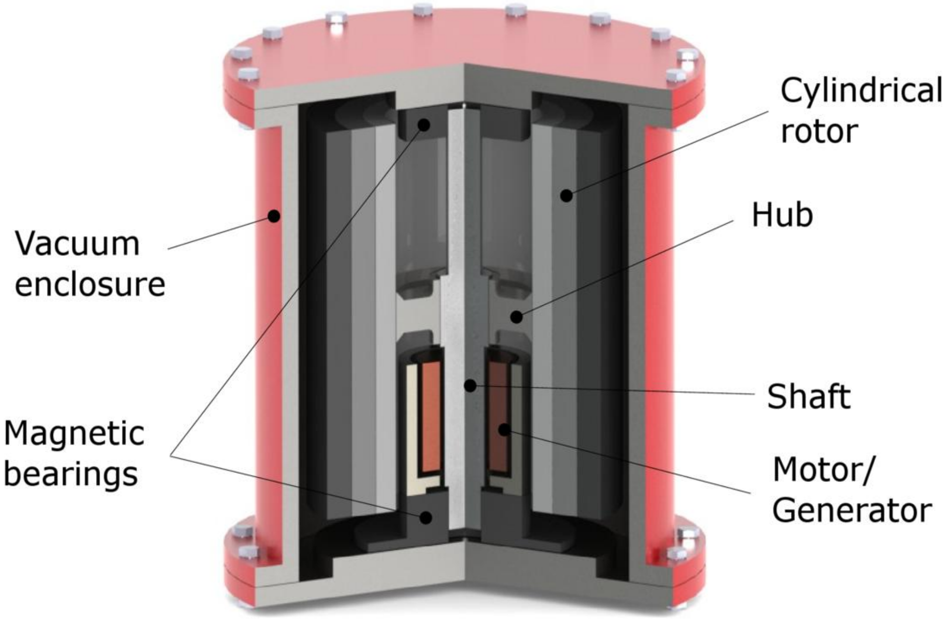


Fig 5.The structure of a cylinder flywheel

A flywheel, in essence is a mechanical battery-simply a mass rotating about an axis. They take an electrical input to accelerate the rotor up to speed by using the built-in motor, and return the electrical energy by using this same motor as a generator. Flywheels are one of the most promising technologies for replacing conventional lead acid batteries as energy storage systems.

A typical flywheel energy storage system consists of a vacuum which to reduce the friction in order to reduce the wind damage, to prevent high-speed rotation of the flywheel safety accidents; inside of the vacuum chamber is equipped with a rotor supported by a bearing and an integrated motor (generator) connected there, too. Flywheel store energy in a rotating mass of steel of composite material. Mechanical inertia is the basis of this storage method. Use of a motor/generator, energy can be cycled(absorbed and then discharged). Increasing surface speed of flywheel, energy storage capacity(kWh) of unit increased.

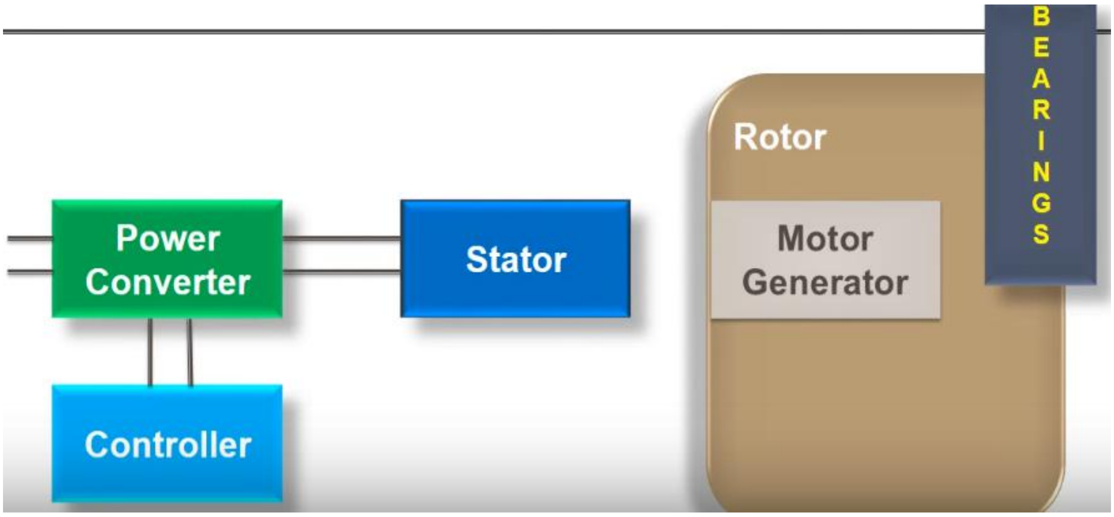


Fig 6. Block diagram

About motor/generator, permanent magnet(PM) machines have the most advantages, including higher efficiency and smaller size when compared with other types of motors of the same power rating. PM also exhibit lower rotor losses and lower winding inductance which make it more suitable for a vacuum operating environment and the rapid energy transfer of flywheel applications. The motor is designed to be operated at high speed for minimize system size.

There are several types of bearings applied these days, including mechanical ball bearing, magnetic bearing, etc. The mechanical bearings generate a large amount of friction loss and need the lubrication as well. For the magnetic bearings, there is no more machenical friction losses and lubrication needed. The three main types of magnetic bearings are passive magnetic bearings(PMB), active magnetic bearings(AMB), and superconduting magnetic bearing(SMB).It is advisable to take the advantage of high-temperature superconductors (HTS) for manufacturing magnetic bearings recently for following reasons:HTS bearings can be as low as 0.1% of the stored energy per hour, while the energy losses of the mechanical and electromechanical bearing are typically 1% to 5%.[vi] HTS bearing is safer and more reliable than the others due to its fairly low operation temperature using liquid nitrogen as a cooling fluid. The superconductivity materials are useful to reduce the electrical dissipation and enlarge the storage of electrical energy. The main limitation is the higher cost.

Most FES systems use current to control the flywheel speed, while equipment that uses mechanical energy directly is being developed. The high-energy FES system uses a rotor made of high-strength carbon fibers and is suspended by a magnetic suspension in which the rotational speed of the rotor can reach 20,000 to 50,000 rpm. This type of flywheel can reach the required speed in minutes - much faster than other forms of energy storage.

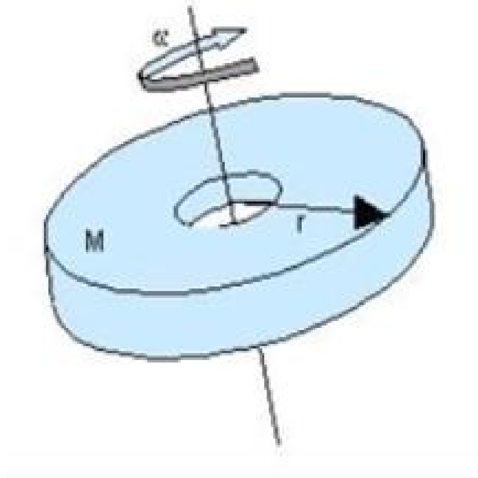
2.3.Operating principles

Flywheels are typically made of steel and rotate on conventional bearings, these are generally limited to a revolution rate of a few thousand RPM high energy density flywheels can be made of carbon fiber composites and employ magnetic bearings, enabling them to revolve at speeds up to 60,000RPM but also with a high cost. Flywheel energy storage is implemented through an electromotor driven the rotor spinning at high speed to convert the electric energy to kinetic energy to be stored, then the flywheel drive the generator to generate power when needed.

The stored energy can be expressed as a formula:

$$E_k = \frac{1}{2} \cdot I \cdot \omega^2$$

Where the I is the moment of inertia and ω is angular velocity.



$$I = \int r^2 dm$$

For most flywheels, the shape is a disc or a cylinder, the corresponding inertia moment is computed as:

$$I = \frac{1}{2} \cdot m \cdot r^2$$

Where **m** is the mass of the rotor and **r** is the outer radius.

The moment of inertia states that the effective mass of a spinning object is not dependent on how much actual mass the spinning object contains. Instead, it is dependent on where the mass is located in relation to the central point that it is rotating around.For example, if spinning at the same speed, a solid flywheel will store less energy than a flywheel of the same mass that has spokes and its weight situated around the rim of the wheel.

So the energy is increased if ω increases or if I increases. And I can be increased by locating as much mass on the outside of the disc(showed in Pic) as possible. But as the speed increases and more mass is located outside of the disc, mechanical limitations are more important.

Now it is necessary to introduce a shape factor K to evaluate its effects. The maximum specific energy and energy density are then given by

$$\frac{E}{m} = K\frac{\sigma_{\max}}{\rho} \quad [J/kg]$$

$$\frac{E}{V} = K\sigma_{\max} \; [J/m3]$$

The above two formula shows that the shape of rotor plays a significant role in determining the stored energy. And the angular velocity is determined by the material strength of the rotor, which is:

$$\sigma_{\max} = \rho r^2 \omega^2$$

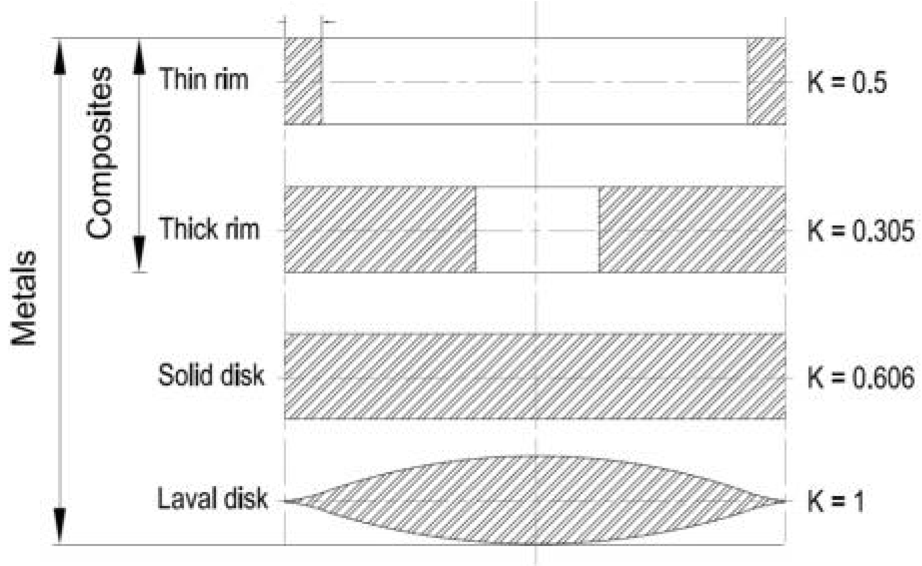


Fig 7. different kinds of the flywheel cross sections

Interesting to look at how a flywheels parameters influence how much energy it can store. These parameters are: mass, radius, speed of rotation (angular velocity). The radius and angular velocity have a far greater impact on energy storage than the mass and since having a higher mass restricts the maximum rotation speed (due to centripetal forces) you are better off having a high speed and light flywheel with high strength to weight ratio (i.e. carbon fiber), than a traditional heavy flywheel.

There are many advantages of flywheel energy storage system: high power density, high energy density, lifetime of the flywheel is almost independent of the depth of the charge and discharge cycle, no periodic maintenance is required, short recharge time, and the flywheel systems are not sensitive to temperature since they are operating in a vacuum containment.

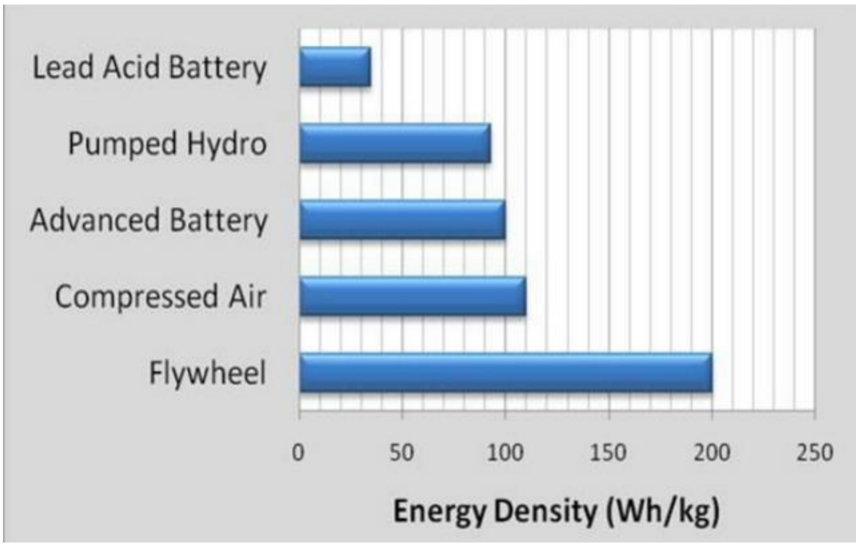


Fig 8. Energy density of flywheel compared with other types energy storage system.

Flywheel applications range from large scale at the electrical grid level, to small scale at the customer level. A high power and capacity is reached by arranging flywheels in banks, rather than by using large machines[vii]. The best and most suitable applications of flywheels fall in the areas of high power for a short duration (e.g., 100 s of kW/10 s of seconds), when frequent charge-discharge cycles are involved. The most common applications are power quality such as frequency and voltage regulation[viii] pulsed power applications for the military, attitude control in space craft, UPS[ix], load levelling, hybrid and electric vehicles, and energy storage applications. As part of energy storage applications, flywheels perform storage applications both at the grid, as well as at the customer level. Next, the applications of flywheel will be described in detail.

3.The application at electrical grid levels

In many countries and regions around the world, the installed proportion of power sources such as wind power and solar energy with volatility continues to increase, and gradually reaches the upper limit of the grid (such as Germany and parts of Japan). Configuring energy storage for smooth output is a necessary condition for further increase in the penetration rate of renewable energy.

As the name implies, the essential function of the energy storage system is the storage of electrical energy, and the charging and discharging work at a specific power at a specific time according to demand. But when people deploy this simple system in different locations of the power system and cooperate with the corresponding control logic, the energy storage system will show great effects, such as[x]:

- Smooth the processing fluctuations of intermittent renewable energy power generation, reduce the impact on the power grid, and improve the penetration rate of clean energy;
- Real-time adjustment of grid operating frequency and voltage, and enhanced stability, reliability and scheduling flexibility of grid operation;
- Smooth output/load curve, realize peak clipping and valley filling in all aspects of power grid, reduce backup capacity construction demand of power generation system, save power investment, and improve equipment utilization rate of transmission and distribution system;
- With the application of distributed power supply, realize miniaturized and miniaturized power system (microgrid);
- Provide protection for completely off-grid electricity in remote areas and special circumstances (such as natural disasters);

Flywheel energy storage system will store energy in high-speed rotating flywheel rotor, with high power density, no environmental pollution, long service life, wide operating temperature range, unlimited number of charge and discharge advantages, so it has been widely used in power quality control and uninterruptible power supply, power system FM, attitude control and energy storage in space satellites, and braking energy recovery in rail transit.

Since 1990, per capita electricity consumption(PCCE) increased by 40% around the globe, there is growing demand for renewable energy with the consumption of non-renewable energy. Although the electricity consumption is so huge, but there are 1.3 billion people still can not get the reliable power even do not have any connection to the grid till today. Based on this environment, more and more renewable energy generation(like solar and wind) is needed to ensure people' s lives which instead of traditional energy. But wind and solar generation are variable and unpredictable, they don' t provide system services i.e. don' t respond instantaneously to provide additional output to compensate for supply/demand deficit. Intermittent is the biggest obstacle of apply the renewable energy.And with the rapid growth of wind power, wind power can be expected to account for the total power ratio will increase rapidly, wind power fluctuations will cause great impact on the power grid, damage the stability of the grid. Consequently grid has less inertia and is less stable. Due to this reasons, we also need to strive to find effective solutions to increase the utilization of electricity. A global movement is afoot to make grids 'smart' .

The first official definition of Smart Grid was provided by the Energy Independence and Security Act of 2007 (EISA-2007), which was approved by the US Congress in January 2007, and signed to law by President George W. Bush in December 2007. Title XIII of this bill provides a description, with ten characteristics, that can be considered a definition for Smart Grid, as follows:
"It is the policy of the United States to support the modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand growth and to achieve each of the following, which together characterize a Smart Grid: (1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid. (2) Dynamic optimization of grid operations and resources, with full cyber-security. (3) Deployment and integration of distributed resources and generation, including renewable resources. (4) Development and incorporation of demand response, demand-side resources, and energy-efficiency resources. (5) Deployment of `smart' technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation. (6) Integration of `smart' appliances and consumer devices. (7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal storage air conditioning. (8) Provision to consumers of timely information and control options. (9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid. (10) Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services."[xi]

The main features of smart grid are reliability, flexibility, efficiency, load adjustment, peak curtailment,

Electric energy storage has the potential to increase reliability, improve stability, and incorporate increased penetration of renewable energy sources. Although renewable energy sources such as wind and solar power are clean and sustainable alternatives to fossil fuel, their natural variability makes them different from past energy sources. In addition, the expansion of grid load requirements has led to increasing line congestion which can result in larger transmission losses and possible line failures[xii][xiii]. In this regard, grid-level energy storage is important to increase penetration of renewable energy sources to mitigate load volatility. The Pic8 shows a simple model of the grid energy storage, the power plant generates the electric power, houses and factories use the power as loads, superfluous power can be stored in the energy storage facility which can release the received superfluous power when the loads need.

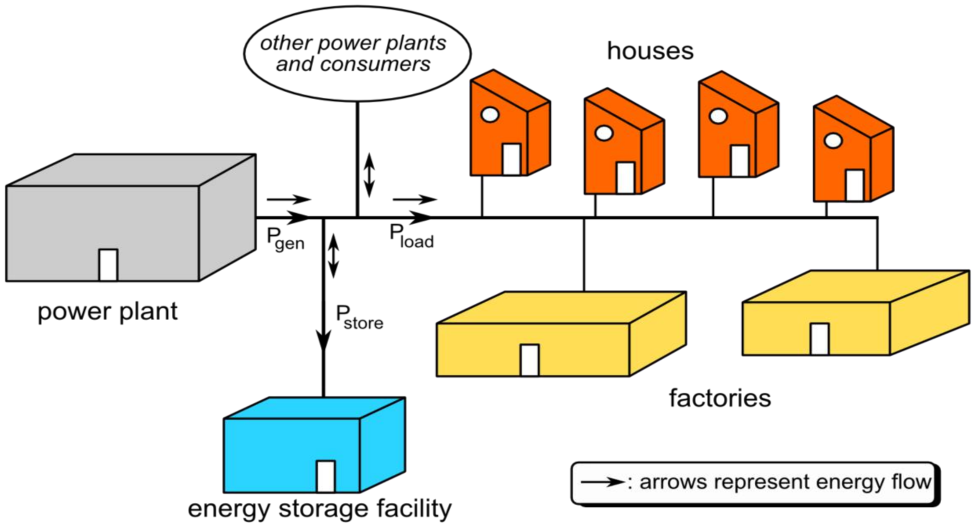


Fig 9. Grid energy storage[xiv]

Energy storage systems have solved the problem to a great extent, they store electricity in their spare time and release energy under peak state. The flywheel energy storage system (FES) is one of the solutions in grid areas and it has become a popular due to its advantages. Flywheel energy storage technology as a grid frequency modulation and short time peak surge, with advantages of suitable for wind power and network adjustment advantages. Advanced flywheels are now used for protecting against interruptions to the national electricity grid. The flywheel provides power during period between the loss of utility supplied power and either the return of utility power or the start of a sufficient back-up power system.

3.1 Principles and application

Flywheel energy storage, which has flexible design configurations between power and delivered energy, is a strong candidate for grid energy storage. Since the flywheel energy storage device has many advantages, it is very suitable for regulating the balance of the grid, especially the larger fluctuations in the wind power grid.

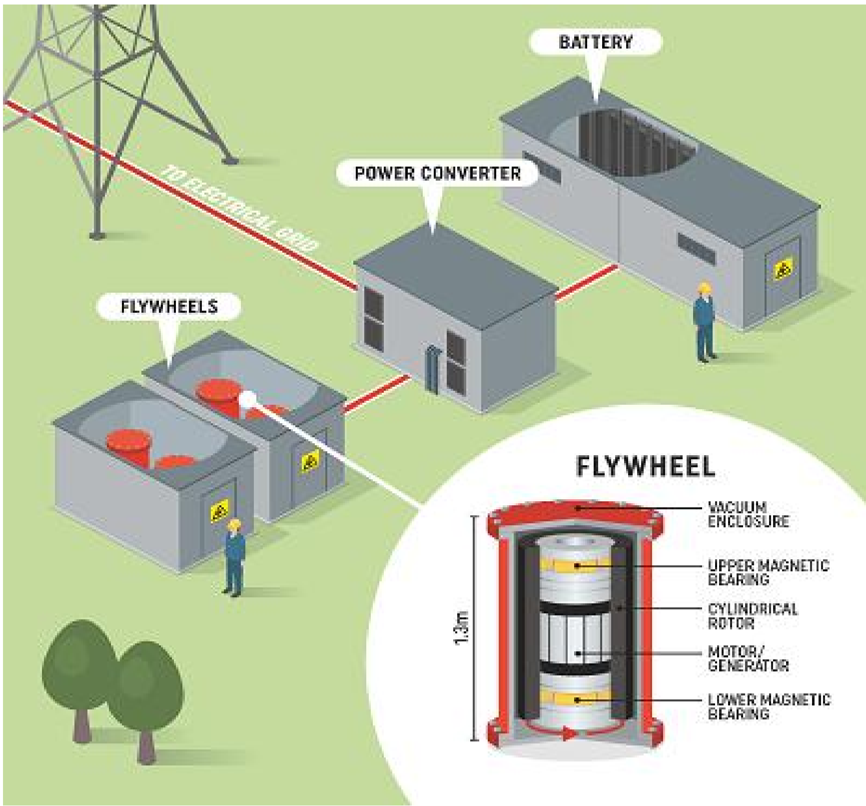


Fig 10. How the flywheel connects to the electricity grid

The most basic working principle of the flywheel energy storage device is that the electric power from the power grid is transferred to the kinetic energy to rotate the flywheel through the motor, after that, the stored kinetic energy is converted into electric energy for the external loads through the generators when the power is not normal or interrupted. As we said previously, Flywheels store energy kinetically by spinning an inertial mass at very high speeds, and electromechanically transfer energy through efficient motor-generators. Flywheels use motor-generators to transfer power and can achieve greater than 90%

efficiency with proper machine design.

Although we have discussed a lot about flywheels, but how it works in electricity grid? When the grid has too much power, the flywheel converts excess electrical energy to kinetic energy and motor can draw electricity to get its rotor spinning. Vacuum enclosure and magnetic bearings allow flywheel to keep spinning without additional power for days, losing very little energy. When the grid needs more power, the flywheel is switched to generate and produces electricity, slowing the wheel back down. Power can also be transferred between the flywheel and battery to keep both at optimum level.

Determining the proper sizing and location in the grid for flywheel energy storage is a complex subject. Since generator sizing can be performed independent of flywheel inertia, power and energy storage needs can be specifically designed for a particular service in the grid. Due to high power capability, flywheels have been demonstrated for frequency regulation and are deemed the most economical energy storage option for power demands less than 30 min. An additional study cited flywheel energy storage as an optimal storage technology for power smoothing and frequency regulation, where high power-to-energy-storage ratios and high charge –discharge frequencies are required. Frictional losses stemming from windage heating and magnetic bearing have impeded the use of flywheels for longer-term load shifting and diurnal energy storage applications. However, reductions in these losses are possible by operating flywheels at vacuum levels below 1 mTorr and optimizing the design of the magnetic bearings. The implementation of superconducting magnetic bearings has been considered as another alternative to further reduce losses.

Flywheel systems are best suited for peak output powers of 100KW to 2MW and for duration of 12 seconds to 60 seconds. The energy is present in the flywheel to provide higher power for a shorter duration, the peak output designed for 125KW for 125Kw for 16 seconds stores enough energy to provide 2MW for 1second.[xv]

3.2 Economic and social benefits

As a mechanical storage means, flywheel energy storage has the following characteristics:

✓ When the power grid receive the adjustment signal, the flywheel energy storage device can respond in a very short time (within 5 milliseconds). Absorbing the excess energy on the power grid at the time of charging and the flywheel speeds up the rotation. In the discharging time, the flywheel is decreasing and releasing the electricity to supplement the lack of power grid. Flywheel energy storage can effectively reduce the instability of wind power.

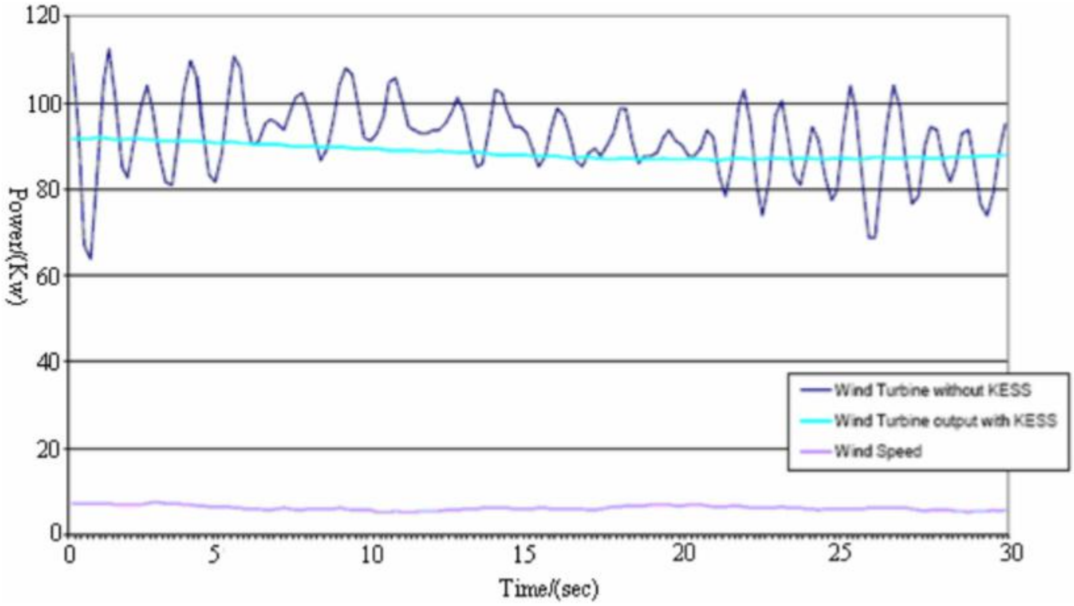


Fig 11. The stabilizing effect of flywheel on power output.

Flywheel energy storage device charging and discharge process is very fast, usually within a few minutes(always in seconds). Compared with the flywheel, the chemical battery does not have the ability to adjust the grid in a short period of time (in seconds) to charge or discharge quickly.

✓ The number of charge and discharge cycles are very large--more than 100 million times. Flywheel energy storage device life is generally more than 10 years without maintenance, some well-designed flywheel energy storage system life can reach more than 20 years. Chemical battery charge and discharge cycle times are far less than the flywheel energy storage device, generally only a few thousand times, and chemical batteries need to replaced every 1 or 2 years usually when they are using for power grid regulation.

✓ Flywheel energy storage is a mechanical and electrical energy storage device without any pollution and greenhouse gas emissions.

Flywheel energy storage technology is now used in many countries, and it has brought many benefits to this countries. Here are some practical examples.

In japan, Fuji Electric installed a 200KW flywheel energy storage system

(UPT KESS) in Dogo Island[xvi], used to reduce the three 600KW De-Wind D4 wind turbine power output fluctuations, with the existing diesel generators, constitute an island power grid.Flywheel energy storage system (UPT KESS) through the dynamic absorption and release of electricity is very effective to improve the wind power grid ratio, and stabilize the grid frequency.

In 2007, seven 320-kilowatt low-load diesel generators and three Vergnet GEV-MP 200-kilowatt wind turbines were used in Coral Bay, Australia[xvii], and a 500-kilovolt flywheel energy storage system was used in conjunction with fans to stabilize wind power output. Flywheel energy storage as an energy buffer which can store too much wind power, and when needed, the release of electricity to the grid. On average, wind power provides more than 90% of Coral Bay's electricity consumption. The flywheel energy storage system greatly provides the permeability of wind power to existing power grids.

Europe' s largest and the UK' s first battery flywheel system will be connected to the Irish and UK grids to help respond to energy demand as part of a new project involving engineers from the University of Sheffield, Schwungrad Energy, Adaptive Balancing Power and Freqcon[xviii]. This project invest €4 million euro, with €2.9 million coming from the EU' s Horizon2020 scheme, will develop an innovative flywheel battery hybrid energy storage system aimed at stabilising pressure on the existing grid infrastructure in Europe.

The application of flywheel in the power grid still has many shortcomings: it can not provide ready backup time; accept the output energy mutation or the overload capacity is poor and there is alot of noise when it is running. Self-discharge rate of the flywheel energy storage system is high, such as stop charging, the energy in a few to several tens of hours will be exhausted. So it is only suitable for some market segments such as high-quality uninterruptible power supply.

4.The application at customer levels

As one kind of new energy storage methods, flywheel energy storage systems have much better advantages than traditional energy storage systems, and it is very consistent with the direction of energy storage technology.

Flywheel applications range from large scale at the electrical grid level, to small scale at the customer level. A high power and capacity is reached by arranging flywheels in banks, rather than by using large machines. The best and most suitable applications of flywheels fall in the areas of high power for a short duration (e.g., 100 s of kW/10 s of seconds), when frequent charge-discharge cycles are involved. The most common applications are power quality such as frequency and voltage regulation, pulsed power applications for the military, attitude control in space craft, UPS[xix], load leveling, hybrid and electric vehicles, and energy storage applications. As part of energy storage applications, flywheels perform storage applications both at the grid, as well as at the customer level.

4.1 Apply in the direction of vehicles

Hybrid systems have been identified as a key technology in order to meet future emission targets for a variety of vehicle applications. In the road car industry,currently only electric hybrid systems are offered to the public. In the bus and truck market both electrical and hydraulic hybrid systems are commercially available.

From the perspective of the development of electric vehicles in the world, energy storage technology is still the bottleneck for the commercialization of electric vehicles. Because of the three main constraints of electric vehicles compared to fuel vehicles: high cost, short driving range and long charging time are directly related to the lack of breakthrough in energy storage technology.

The function of a hybrid system can be achieved with a number of different technologies.

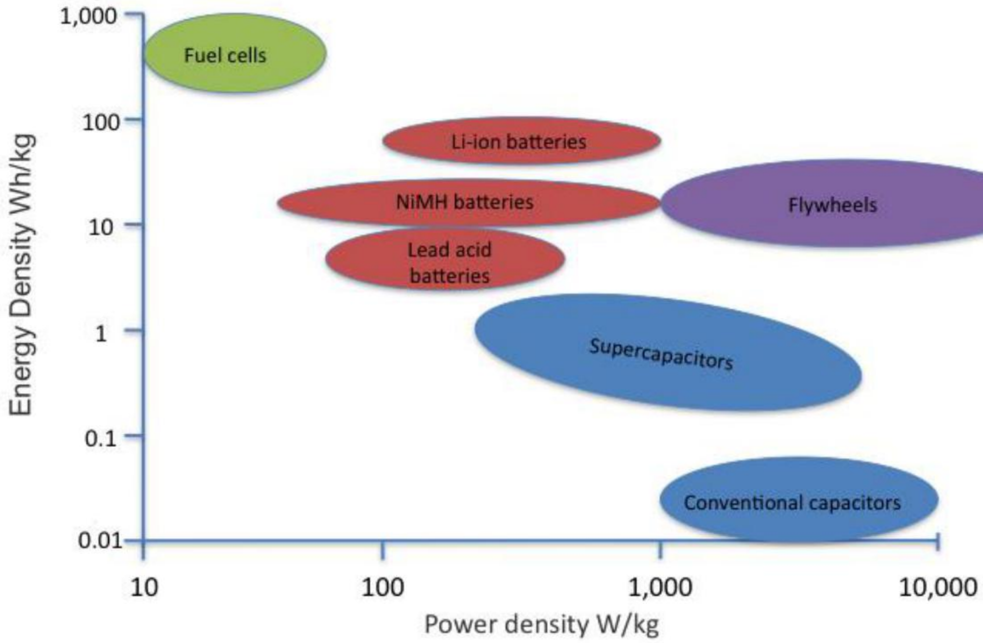


Fig 12. Overview of hybrid technologies[xx]

From the figure we can see that flywheel hybrid systems stand out in this comparison with the potential for a very high power density while still achieving a good energy density.

Despite many setbacks, researchers are still exploring ways to install a flywheel into a hybrid car as an energy storage device.

Fig 13. flywheel energy storage used in vehicle[xxi]

Compared with other energy storage methods, the flywheel system has a longer life cycle (no maintenance cycle), and the full cycle life can reach 10^5 to 10^7 cycles; high energy density (100-130 W • h / kg, or 360-500 kJ / kg) and greater maximum power output; energy efficiency (output energy to input energy) up to 90%. Typical capacities range from 3kwh to 133kwh. System quick charge can be done in 15 minutes, even the energy density of commercial low-cost systems can reach the level of 11W • h / kg or 40kJ / kg.

The energy density of the flywheel system $\frac{\mathrm{E}}{\mathrm{m}}$ depends on the diameter of the rotor and the characteristics of the material(for a single material rotor). The formula can be expressed as:

$$\frac{\mathrm{E}}{\mathrm{m}} = K\left(\frac{\sigma}{\rho}\right)$$

Where K is the coefficient which depends on the diameter of the motor, σ is tensile strength of the material and ρ is density

In terms of energy storage efficiency, the main source of losses in the flywheel system is from the friction in the vacuum chamber. On a high-vacuum racing system, which achieves a peak of 97% and a long-term energy efficiency of 85% when it using a magnetic confinement.

Whenever people turn their wheels with a variety of energies, they also use the flywheel to turn the wheel's rotation into other energy: from the ingot to the steam engine, people use the flywheel to store energy for future use, perhaps in the next second. Now, people are using flywheels to provide energy for hybrid vehicles.

From the physics point of view, the flywheel structure is very simple, and according to the previous description there are two ways to improve the kinetic energy of the flywheel: increasing the weight of the flywheel and increasing the rotational speed of the flywheel.

In the past, the flywheels were very bulky which is used to reserve a large amount of energy (because small flywheels were easily broken at a few thousand revolutions per minute). Such large flywheels could only be used in large spaces, such as the situation of the balance of power grid. In the transportation sector, large flywheels are used on trains extensively, this train-mounted flywheel, which is more than one meter in diameter and weighs over one hundred kilos.For the compact cars, installing a flywheel device will undoubtedly increase the weight and fuel consumption. However,now the large and cumbersome flywheel will be changed. One of the reasons is that carbon fiber that is a new material used to make flywheels in the vehicles field, it is stronger than steel and also very light weight.Flywheels made with this material can rotate sixty thousand revolutions per minute without breaking.

Based on the results of the road test, a hockey-sized flywheel reduced fuel consumption by one-fifth because the flywheel was well designed and made of new materials. Therefore, some industrial observers even predict that flywheel technology will replace electric hybrid technology in the near future.

Flywheel technology and electric hybrid technology have many things in common. When the driver brakes his electric hybrid car such as the Toyota Prius, the car's electric motor is working as a generator that converts the car's mechanical energy into electrical energy stored in the car's battery, when the driver depresses the accelerator , The battery power will be fed into the motor, so that the car began to accelerate again. This is known as the "Regenerative Braking" system. The flywheel device can also act as a temporary energy storage device, and the energy storage effect of the flywheel device is better. The "regenerative braking" system of the hybrid electric vehicle only converts 35% of the energy in the conversion of mechanical energy and electric energy.Dick Elsy claims: "Using flywheel devices, 70% of the energy can be reused" (Dick Elsy is the boss of one British company that works on flywheel energy storage which be named as Torotrak)[xxii]. The flywheel energy storage process is more concise than the regenerative braking systems, first convert mechanical energy into electrical energy that is subsequently converted to chemical energy stored in the battery,The flywheel just transforms one type of mechanical energy into another type of mechanical energy, which consumes less energy. Its service life can be the same as the life of a car, and the flywheel does not contain toxic chemicals that need to be disposed of.

In addition, unlike batteries, flywheel devices do not need to be replaced every few years. Their design life can be the same as the life of a car, and flywheel devices do not contain toxic chemicals that need to be disposed of.

So now, more and more car manufacturers began to pay attention to the flywheel device.

Like other new technologies, high-tech flywheels are first used on F1 cars. In 2009, the International Motor Confederation (FIA) agreed that each team install a kinetic energy recovery system on their participating cars.

People can get the information about the F1 motor sport has also started using environmentally friendly technology if F1 teams installed kinetic energy recovery system. Using kinetic energy recovery systems also making the racing more exciting by improving the speeds of the vehicle in a short time when racers are overtaking or preventing others from overtaking. Some F1 teams use the same battery kinetic energy recovery system as the hybrid electric car, while other F1 teams install the flywheel kinetic energy recovery system into their cars(for example: William's F1 team is using flywheel kinetic energy recovery systems). Because of F1 teams, people began to flywheel device has a new understanding.

Nowadays, flywheel energy storage devices are valued by the people on the one hand, and economically less well-off consumers are having a headache on the soaring oil prices they are seeking to reduce their fuel consumption. On the other hand, the law requires car manufacturers to produce low-emission vehicles.

4.1.1 Flywheel Kinetic Energy Recover System of vehicles

Unlike the flywheels of large passenger cars and train cars, the flywheels mounted on Formula One cars which are manufactured using high technology and new materials. Automotive manufacturers, including Volvo and Jaguar, are experimenting with installing new flywheel equipment into common cars. Derek Crabb is vice president of powertrain engineering at Volvo, he explained that not only technological advances have made flywheel energy storage devices attractive, but also changes in the external economic environment of the automotive industry.

KERS(Kinetic Energy Recovery System) was first used in F1,Ferrari, Renault, BMW and McLaren took the lead in 2009, but Renault and BMW gave up halfway, so that McLaren Mercedes became the first convoy to win the Grand Prix with the KERS system - Hamilton took the championship at the Hungarian Grand Prix. In the Belgian Grand Prix of the same year, Fisichella claimed: "I was quicker than Raikkonen, but I could not keep up with him because of the KERS system."[xxiii]

KERS system has two main forms: flywheel and super capacitor. Here, we only discuss the flywheel kinetic energy recovery system.

Remember those small toy cars you used to play with? You had to either pull them back and let go (pull-back motor) or push forward to get the engine going (friction motor). The friction motor toy used flywheel technology to propel it. The system, known formally as Flywheel Kinetic Energy Recovery System(Flywheel KERS), is fitted to the rear axle. The energy produced from braking causes the flywheel to spin at up to 60000rpm. When the car starts moving again the flywheel's rotation powers the rear wheels.

Now, let's introduce another name: Flybrid(flywheel-based energy recovery systems and associated transmissions), which is purchased by Torotrak Company in early 2014. The Flybrid System is equal to Flywheel Hybrid System(or equal to KERS). Core Flybrid technology relates to design, development, manufacture and the control of high-speed flywheels for using in moving vehicles.

Development of the Flybrid® Kinetic Energy Recovery System (KERS) has been underway for more than 8 years and the technology has grown from its original motorsport roots into a genuine competitor for electric hybrid systems in road cars, buses, trucks and off-highway equipment. The Torotrak Group PLC. has gained experience of running KERS units at very high specific power of over 14 kw/kg, which opens up completely new vehicle powertrain opportunities. It is now reasonable to consider a vehicle that relies entirely on KERS for its driven axle braking and which in all but the most dramatic emergency situation never wastes kinetic energy to heat. With such a vehicle acceleration performance need not be related to its engine capacity or performance. KERS energy release can provide sports car levels of acceleration and the engine can provide long-term power for low emission cruising at constant speeds. Outside the development of the KERS unit itself such vehicles present new challenges in terms of powertrain integration, braking pedal feel and functional safety. A vehicle with this proposed new powertrain architecture can be shown to be capable of impressive performance whilst comfortably meeting the 2025 emissions standards and all at an affordable cost.

Recovering the energy that would otherwise be lost when a vehicle brakes is an extremely effective way to improve fuel economy and reduce emission. As the vehicle slows, kinetic energy is recovered through the KERS clutched transmission (CFT) and stored by accelerating a flywheel. As the vehicle gathers speed, energy is released from the flywheel, via the CFT, back into the driveline. In other words, the flywheel is connected to the vehicle via a special KERS transmission and manipulation of the gear ratio across this transmission achieves control of energy storage and recovery. When the ratio is changed so as to speed up the flywheel energy is stored and when the ratio is changed so as to slow down the flywheel energy is recovered. Using this stored energy to reaccelerate the vehicle in place of energy from the engine reduces engine fuel consumption and CO2 emissions. The most significant reductions in fuel consumption can be achieved in vehicles that are the subject of repeated 'stop-start' cycles.

Alternative KERS usage options include using the stored energy to augment engine power, to enhance vehicle performance.

To transmit the energy from the flywheel to the vehicle the company which named Torotrak has developed its own variable transmission for the Flybrid KERS. The transmission has to be variable as the flywheel speed increases, while the vehicle is slowing down and vice versa. Therefore the ratio between the flywheel speed and the vehicle is constantly changing. To achieve this function, a number of slipping clutches are used. One side of each clutch is connected to the flywheel, the other side of the clutch is connected to the vehicle. The clutches are connected via different ratios between the flywheel and the vehicle.

To store energy a control system decides which clutch to use. It makes its decision based on which of the clutches has the vehicle side of the clutch rotating faster than the flywheel side. If this clutch pack is compressed, then the vehicle side of the clutch is slowed down by the inertia of the flywheel, while the flywheel side is sped up by the kinetic energy of the vehicle. Before the clutch is fully closed the next clutch pack is compressed and the process is repeated. The efficiency of this energy transfer is dependent on the slip speed across the clutch. Usually in this case, on average the efficiency for the full energy transfer in one clutch is around 80%.

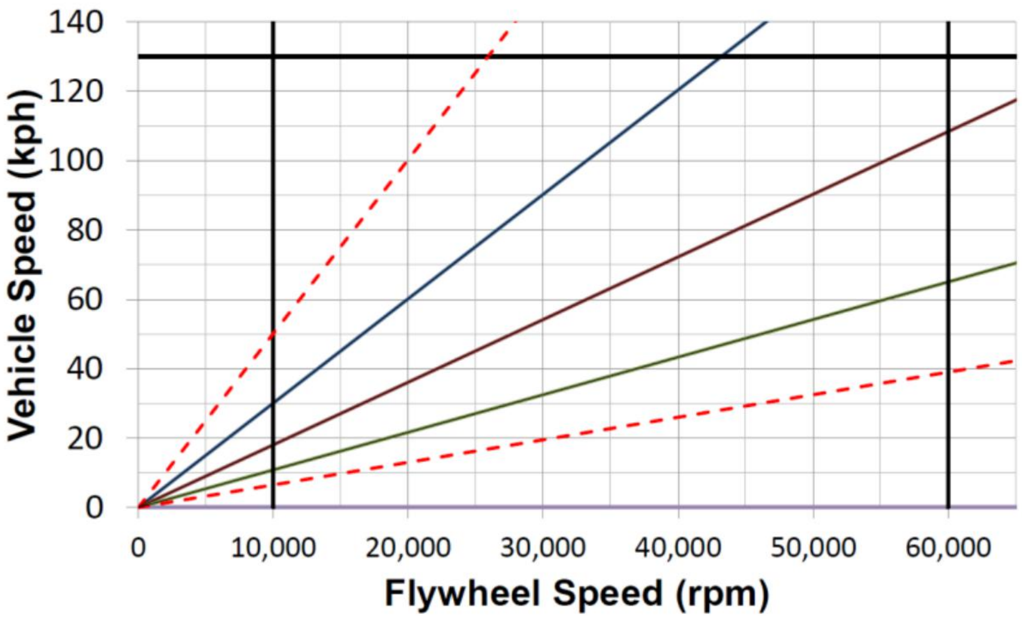


Fig 14. Typical ratio spread for a 3 clutch CFT(Clutched Flywheel Transmission)

The flywheel kinetic energy recovery system was developed and tested by the Williams Test Center (WTC) set up by Williams in 2009 in partnership with Qatar Science & Technology Park, known as the Magnetically Loaded Composite flywheel. This system helped Porsche 911 GT3 R and Audi R18 e-tron won several championships.

For production cars, Volvo hybrid drive is a good example, Volvo was testing a KBS system with a maximum power of 80bhp on the T5 S60. With this system, it can realize the power of a 6-cylinder engine, achieve acceleration of 100 kilometers in 5.5 seconds, and achieve better fuel economy. The S60 is the front drive, the flywheel system is set on the rear wheel drive, when the car slows down, the maximum speed of 60000 revolutions of the flywheel charge, then put energy at start-up.

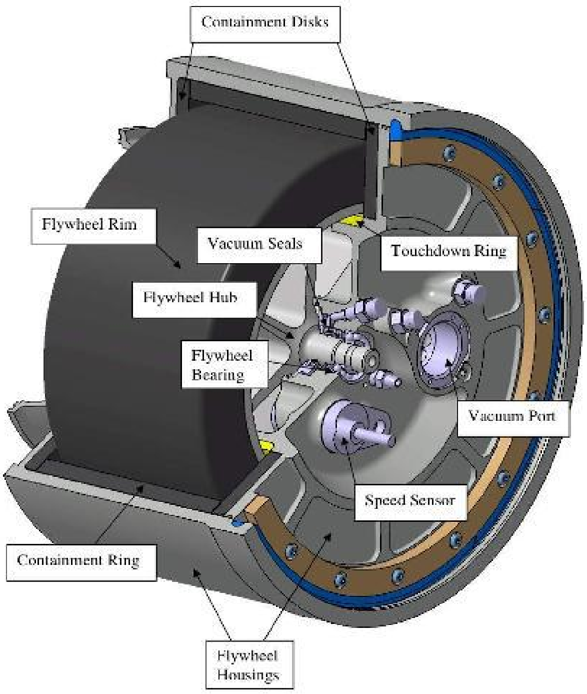


Fig 15. Flywheel module of Flywheel KERS

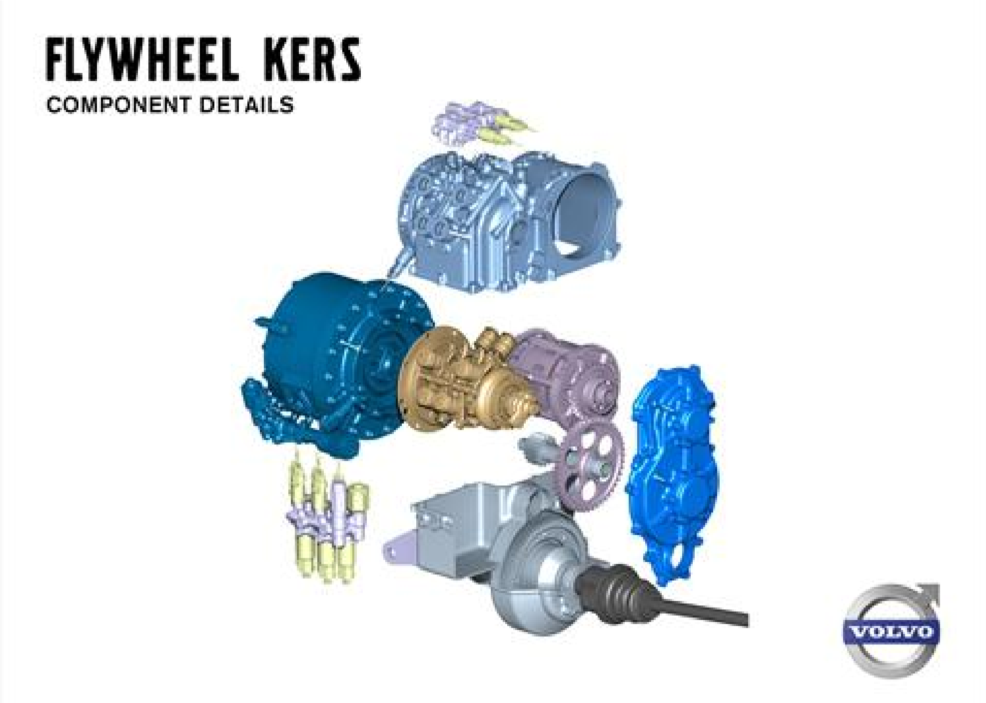


Fig 16. component details of Flywheel KERS

The engine that powers the front wheels is switched off as soon as braking begins. The energy created by the flywheel can then be used to accelerate the vehicle when it starts moving again or to power the vehicle once it reaches cruising speed.

Derek Crabb, vice-president powertrain engineering at volvo, said: "The testing of this experimental system for kinetic energy recovery was carried out during 2012. The results show that this technology combined with a four-cylinder turbo engine has the potential to reduce fuel consumption by up to 25% compared with a six-cylinder turbo engine at a comparable performance level. It makes a car with a four-cylinder engine accelerate like one with a six-cylinder unit, giving the driver an extra 59kW. The flywheel's stored energy is sufficient to power the car for short periods. This has a major impact on fuel consumption."

In the city, Volvo is estimated to save one-fourth of fuel consumption. Since the flywheel is activated by braking, the length of time it spins is limited; therefore the technology is most effective while driving with repeated stops and starts.

Flywheel propulsion assistance was tested in a Volvo 260 in the 1980s and steel flywheels have been evaluated by various manufacturers. However, since steel is heavy and has limited rotational capacity the flywheel Volvo used is made of carbon fibre, weighs about six kilograms and has a diameter of 20cm. The carbon-fibre wheel spins in a vacuum to minimise frictional loss.

Crabb concluded: "The next step will be to evaluate how the technology can be used in upcoming car models."

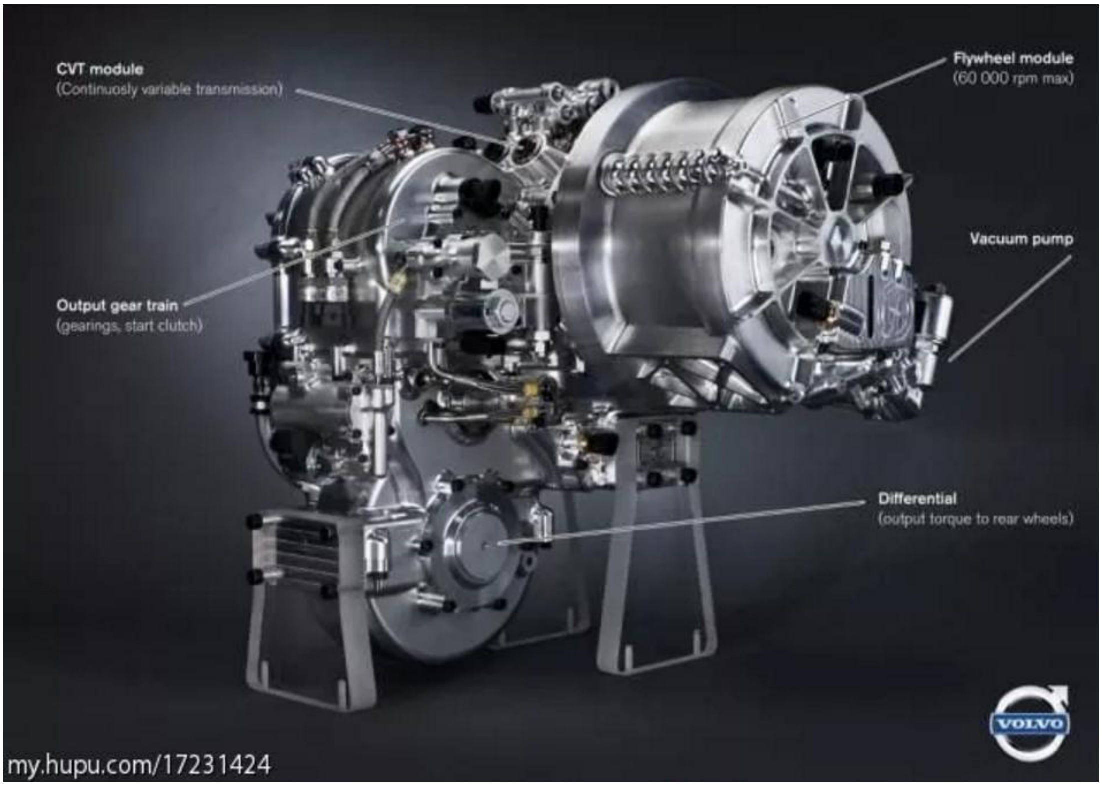


Fig 17. flywheel KERS from VOLVO

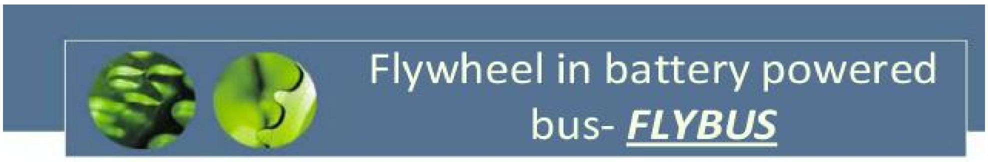
A similar system can also be found on the 918 RSR with a maximum speed of 36,000 rpm. The 918 RSR uses a V8 from the RS Spyder racer, tuned for 563bhp at 10,300rpm . There are two electric motors for the front wheels – they're independently powered to give torque vectoring to improve cornering – and max power is 767bhp when the driver pushes a button to activate the electric motors. It's a six-speed paddleshift transmission for the V8. The electric energy comes from a flywheel in the 'passenger's seat' linked to a motor/generator to turn electric energy into flywheel energy and vice-versa. The flywheel spins to 36,000rpm.

For mass traffic, a consortium called Flybus (Flybus is the first car manufacturer in the world to test a flywheel hybrid system in a public bus.) has put that energy reusing technology into a regular bus. This simple technology takes kinetic energy generated as the vehicle is breaking and winds up a flywheel that feeds energy back into the wheels when acceleration begins again. The flywheel can be wound up to a maximum of 60,000 rounds per minute and can pack some serious emissions-free energy, making both gas powered and electric vehicles Another perk? Hybrid-electric buses can be really expensive, but but engineers believe this hybrid flywheel system could sell for a fraction of the cost.

The engineers involved in the Flybus consortium come from many different companies and call their invention the Optare Solo Midibus. The companies have banded together to use their expertise to execute a single vision in making buses more efficient - Torotrak has provided the transmission, Ricardo provided the flywheel, Allison provides transmission expertise and Optare is a major UK bus and coach company. The project has been partially funded by the UK's Technology Strategy Board.

“The recovery and reuse of kinetic energy during stop-start drive cycles is a priority for bus operators, not just because of the positive impact on emissions but also because it reduces fuel costs and brake wear," says John Fuller, Product Leader for Kinetic Energy Recovery Systems (KERS) at Torotrak. "Electric hybrid systems are expensive, often doubling the transaction cost of a bus. Initial cost estimates suggest that the Flybus system could be available at a fraction of the cost of an electric hybrid, “fuel savings comfortably in excess of 10%.”[xxiv]

The traditional engine is still arranged in the front, responsible for driving the front wheel. When the driver depresses the brake pedal, the front wheels are automatically disconnected from the engine power so that the flywheel kinetic energy recovery system can fully store the kinetic energy, resulting in more rapid acceleration. The system outputs a maximum of 80 horsepower. When the brake pedal is depressed and the flywheel kinetic energy recovery system is activated, the timing of kinetic energy recovery (that is, the freewheeling time of the flywheel) is limited, so that the flywheel kinetic energy recovery system is more suitable for the driving and stopping environment in the city.



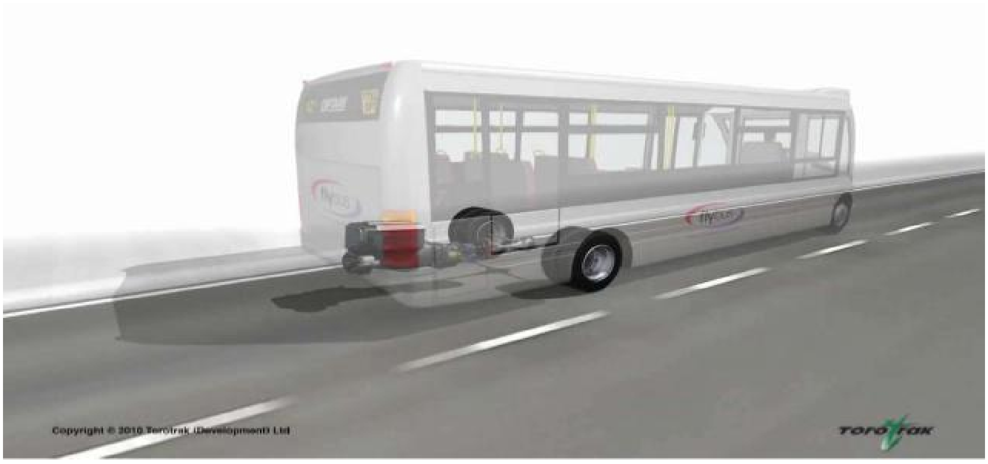


Fig 18. Flybus[xxv]

The flywheel kinetic energy recovery system is a low cost alternative to a conventional hybrid system (which has the expensive battery packs and ECUs) .

Flywheel kinetic energy recovery system also can be used in metros and trains, when they pulled in the station, the energy of the brake can be converted into the flywheel system, then the flywheel outputs the energy later for train acceleration when the train are pulling out the station. This flywheel system can save 20% of the energy consumption for trains or for metros.

4.1.2 Benefits and technical obstacle

The advantage of a mechanical flywheel hybrid system is its superior power density. It enables very compact and light hybrid systems that can be packaged even in the tight constraints of racing cars or road vehicles. The original LMP1 Flybrid KERS systems had a power rating in excess of 100kW and weighed less than 40kg. The limiting factor for performance was clutch durability. The LMP1 system was in theory capable of achieving 250kW with the same hardware that ran on track, but this required either an endurance test with the real hardware or a clutch test rig to be constructed to validate clutch life.

Several of the demonstrator systems that Flybrid produced had flywheels which rotated up to and in some cases in excess of 60,000rpm. These had energy storage capacity in the region of 500 - 600kJ. Flybrid's KERS system for buses rotates at a slightly slower maximum speed to achieve the very long vehicle life and exploits a higher inertia flywheel to achieve a similar storage capacity. With limited design changes and approximately 25% increase in speed, it is feasible to create a flywheel that can store 1MJ. This would have a shorter design life, but would be appropriate for a passenger car application with sufficient validation. Vehicle drivability is determined by the smoothness of torque delivery from the CFTs. For previous racing applications, it has been shown that shifts can be conducted in 30 ms with quick torque response in the region of 50ms[xxvi]. More recent applications with the Flybrid KERS bus application have shown that torque can be delivered smoothly, and the hand over between clutches as ratios are changed is smooth and meets the customers demanding requirements for drivability.

There is a clear direction to reducing CO2 emissions in all regions around the world. For the EU, there is a clear drive to reducing CO2 emissions with a target of 70gCO2/km in 2025(Pic19.). So adding a KERS system is a good solution that will improve performance and can improve emissions further, however most KERS technologies have a relatively low specific power, so to achieve a sensible level of vehicle performance would result in a high additional weight penalty. The flywheel(or flybrid) KERS solution offers a realistic alternative to achieve 2025 emission targets whilst being capable of achieving "sports car" acceleration performance.

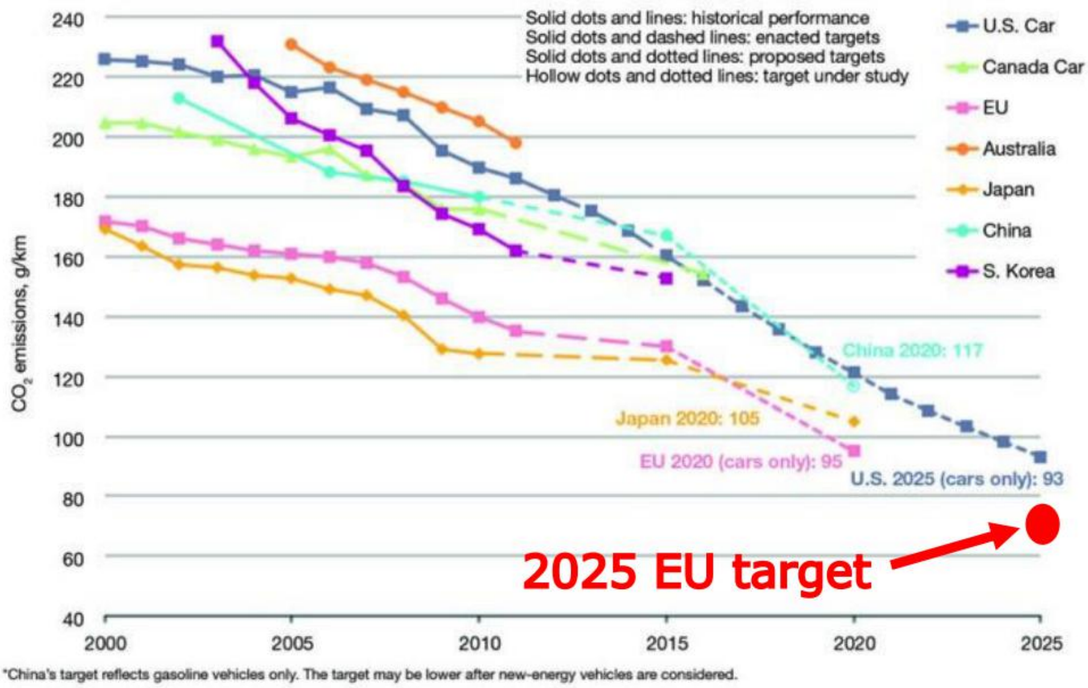


Fig 19. Global CO2 emissions targets

In general, main features of the flywheels applied in automotive field are:

- High System and “Round-Trip” Efficiency – as a purely mechanical system, KERS avoids the inevitable losses that occur when battery-based systems change energy from one form to another (i.e. mechanical to AC, to DC, to chemical), making more energy available for release straight back to the driveline
- High Power Density – KERS is a small system package that is incorporated easily into both cars and commercial vehicles
- Low Weight – Flybrid KERS is typically around 1/3 the weight of a competing battery based electrical hybrid system, with a road car system weighing only around 60kg
- Long System Life – even at high depths of discharge, over a wide temperature range and on severe stop start duty cycles
- Clutched Transmission – KERS uses Flybrid’s own patented clutched transmission (CFT).

Nevertheless, there are still many technical obstacles that flywheel energy storage devices need to overcome. First, when the flywheel reaches 60,000 revolutions per minute, the outer rim of the flywheel rotates at 2000 kilometers per hour, almost twice the speed of sound.At this speed, even carbon fiber materials will become block fragments under air resistance, therefore, the carbon fiber flywheel will only be able to reach 6000 RPM in a vacuum environment. This requires that the flywheel device transfer the mechanical energy of the external air environment to the flywheel in the internal vacuum flywheel chamber, which is still very difficult to achieve.The solution of ‘flywheel power system’ company is to install a rotating seal on the flywheel energy storage device, the seal is not completely sealed, it allows trace air into the flywheel room. In response to the air entering the flywheel chamber, the flywheel energy storage unit is also equipped with a small vacuum pump that draws out impurities when the impurities in the flywheel chamber and reaching a dangerous level. The vacuum pump works just once a day to meet the needs of its work time of 90 seconds. Rather than trying to increase the rotor size and complex vacuum pumps to solve the problem, Richard company made the Kinetic system. The Kinetic system uses a permanent magnet array to place the flywheel completely in a vacuum, a permanent magnet array in the flywheel, and a permanent magnet array in the outer shaft.When the rotating shaft rotates, the magnetic field drives the permanent magnet in the flywheel to rotate, just like the gear rotates.

Another technical problem with flywheel energy storage devices is that the speed of the flywheel is not stable enough. One company uses a variable-speed drive mechanism to solve this problem, which has been used on gearless motors. The transmission mechanism is not fixed connection device, the flywheel and the transmission mechanism is viscous liquid connection, allowing the flywheel’s active parts and follower parts driven at different speeds, but the outputs of the follower and the active parts are consistent of. The power transmission mechanism of this transmission efficiency is high.

Finally, although flywheel kinetic energy recovery systems have many advantages over battery kinetic energy recovery systems, they also have their own shortcomings. The flywheel stores less energy than the battery and can not store large amounts of energy. If the Jaguar sedan only rely on the energy provided by the flywheel, a mile can not run endlessly. However, the flywheel energy storage device can indirectly reduce the fuel consumption of the vehicle by increasing the wheel speed when necessary. In this way, the size of the car engine can be made smaller without reducing the performance of the car, and the engine can consume less fuel. So this shortcoming is not a big problem.By improving flywheel design, R & D personnel break through the technical boundaries, so that the performance of the flywheel device can be more attractive.

Regardless of how fast the flywheel device can rotate, the flywheel can not force the hybrid car out of the market.Regardless of how fast the flywheel unit can rotate, flywheels are not yet able to force the hybrid vehicles out of the market now. But automakers like Volvo are working hard to apply flywheel energy storage to the new models. When these cars are driving on the road, people feel that they are not different from cars that use only fuel. Undoubtedly, those who pay more attention to economic performance may be potential buyers of vehicles equipped with flywheel energy storage devices.

4.2 Apply in the direction of the aviation

One of the most effective ways to increase the efficiency of energy applications is energy management,and because the energy conservation becomes more and more important, energy storage technologies are becoming practical solutions for situations where energy is required to be saved, feasible energy storage methods include flywheels, batteries and ultracapacitors. Flywheels have recently become a promising application of energy storage due to new material and technology improvements.As for the advantages of the flywheel, we have described a lot before, these advantages make flywheel energy storage become the direction of continuous exploration by researchers from all over the world.

4.2.1 Applied on aircraft

The geometry and the material of the flywheel determine the energy density that can be achieved, the flywheel can store a large amount of energy at a relatively small weight, this is one of advantages of the flywheel energy storage system. Similar to flywheel applications in cars, the flywheel energy recovery and storage system on aircraft are also used to recover the energy consumed by wheel brakes. When the aircraft landed, the flywheel is aimed at converting the high landing kinetic energy to useful electrical energy while minimizing temperature and wear of the brake. For a typical aircraft, this system can collect more than half of the dissipated energy at the wheel brakes and converted to electricity.

Bring the landing aircraft to rest need to consume their braking kinetic energy to complete, the kinetic energy of the aircraft at touchdown is given by the expression[xxvii]:

$$E = \frac{1}{2} \cdot [M_1 - M_f] \cdot v^2$$

Where: M_1 is the mass of the aircraft at takeoff;

M_f is the mass of fuel burnt;

v is the velocity of the aircraft at touchdown.

From this equation we can see that the landing kinetic energy depends on the takeoff weight and the flight distance.

Now, let’s analyze the components of the flywheel energy recovery system concretely. The structure image is shown below:

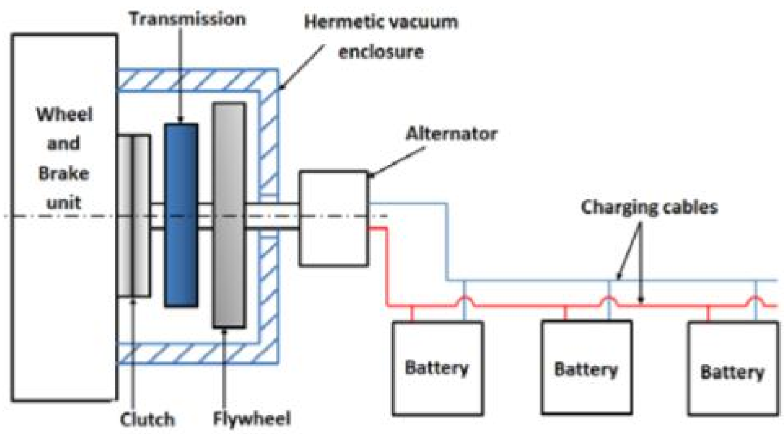


Fig 20. flywheel energy recovery and storage system

the energy recovery system consisting of the wheel and brake unit, the clutch, the transmission mechanism, the flywheel, the charging unit and a set of batteries. The transmission is to give the flywheel an opposite rotational motion to the landing gear wheel, so that the aircraft will slow down and the applied brake pressure is minimum. The motion of the flywheel rotates the alternator to generate the necessary current to charge the batteries to prevent additional weight on the aircraft.

From the fig. 20 we can see that the clutch is connected to the wheel and transfer rotational movement to the flywheel through the transmission system during landing and taxiing. The flywheel is disconnected at takeoff, the power P delivered by the clutch is expressed as

$$P = T \cdot \omega$$

Where T is torque and ω is the angular velocity.

Because the aim of the transmission system is to give the flywheel an opposite rotational motion to the brake wheel, the star configuration was selected for this preliminary study. In the three possible configurations of the epicyclic gear train, the star configuration is the only one that can give the output shaft an opposite rotational motion (the other two are planetary, and solar). Here we use a alphabet G to express the velocity ratio of the transmission system:

$$G = \frac{N_2}{N_1}$$

Where N_1 is the rotation speed of the input shaft;

N_2 is the rotation speed of the output shaft.

Since the output shaft is connected to the flywheel, so the output shaft's angular velocity is that of the flywheel. The recommended reference ratio value is 106.

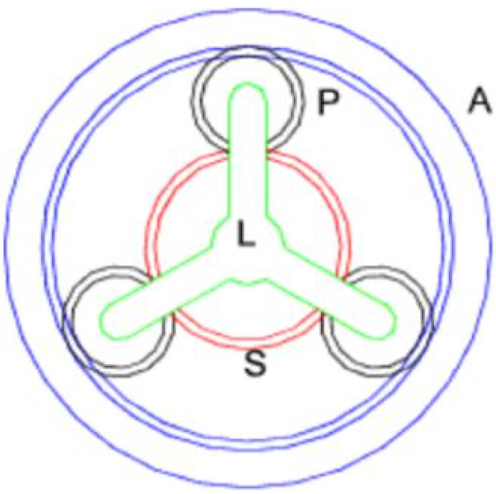


Fig 21. Single Stage Epicyclic Gear Train

In general, flywheel systems cause energy losses mainly due to bearing friction, which makes them less efficient than a battery-based system for storing energy for long periods of time. The combined arrangement of the flywheel and battery system(as shown in the previous figure) is a good solution to the deficiencies of each method.

About energy recovered, parameters for Boeing 777-300ER aircraft in standard flight between St. Louis, MO, US located at 83° 44 ’55″ N, 90° 22’12″ W and Los Angeles, CA, US located at 33° 56’33″ N, 118° 24’29″ W were used in design and testing the analysis.[xxviii] For obtaining the mass of the fuel burnt during the flight, the experimenters analyzed the Bréguet range equation and flight data. Because other deceleration mechanisms of the aircraft, only about 25% of the landing kinetic energy (KE) is dissipated as heat at the wheel brakes. The possible amount of energy that can be collected and stored in the batteries is given by:

$$\text{ES (energy stored)} = 0.25\,\eta_1 \cdot \eta_2 \cdot \text{KE}$$

Where η_1 is flywheel energy collected efficiency;

η_2 is the conversion efficiency.

	Parameter	Value
1	M_1 = MTOW	351,535 kg [17]
2	V_{HW}	38 km/h [15]
3	M_{cr}	0.84 [18]
4	γ	1.4
5	R	287 J/K-mol K
6	T_{cr} at 35,000 ft	218.16 K [19]
7	H_{cr}	30909 km [15]
8	$\Delta W_{lost}/W_1$	0.0152 [15]
9	$\Delta W_{rec}/W_1$	0.001 [15]

Table 2. Parameters and Date used[xxix]

If we using Flywheel Energy Recovery systems instead of traditional energy management systems on Boeing 777 aircraft, it is conservatively estimated that the energy savings per day equivalent to the capacity of a 4.5 MW power plant only in the United States.

Data shows that more than half wasted energy from aircraft brakes can be recovered and made useful via the flywheel system. This will also contribute to increasing the life of the wheel brakes.

4.2.2 Applied on spacecraft

The traditional battery energy storage system has been difficult to meet the overall performance development requirements of the spacecraft due to its inherent shortcomings of low specific energy and low reliability.But with the development of a series of key technologies such as high-performance magnetic bearings, high-strength lightweight composite materials, power electronics technology.It makes it possible for the flywheel energy storage system to replace the current hydrogen power storage system in the spacecraft, just like for automotive and airplanes.

Spacecraft generally uses solar arrays to provide power. Traditional power supply systems use solar arrays, battery packs, power conditioning equipment, power conversion and transmission distribution equipment to perform power generation, storage, control, transmission and distribution functions. As a storage system in spacecraft, the main purpose of the battery pack is to supply power when the spacecraft enters the Earth's shadow zone when the solar array cannot generate electricity or when the required power exceeds the power of the solar array.

With the ever-increasing demands on the performance and power of spacecraft, the characteristics of traditional batteries with lower energy and lower reliability are reflected. For example, if a spacecraft with a storage energy greater than 2000 kW•h and a bus bar voltage higher than 200 V is used, only the weight of the battery core accounts for more than 25% of the weight of the spacecraft when we use a nickel-hydrogen battery(the specific energy is 5-8 W•h/kg, the discharge depth is 30% to 40%, work voltage is 1V), which limits the payload capacity of the spacecraft and the entire system will be expensive to operate, moreover, the reliability of the series connection of a large number of batteries is also significantly reduced. The inherent defects of the battery pack also include: (1) the adaptability of the work is poor; (2) the battery capacity gradually decreases with the increase of the number of charge and discharge cycles, and the service life is limited; (3) it is difficult to accurately estimate the charge and discharge degree of the battery;(4) long charging time.

The above characteristics of the battery restrict the development of the overall performance of modern spacecraft, and these constraints are difficult to make breakthroughs. Therefore, it is necessary to develop a new energy storage system with high specific energy, high efficiency and long life to meet the requirements of spacecraft development, so the application of the flywheel energy storage system is born in time.

In fact, the idea of using flywheels to store energy in spacecraft was proposed in the 1970s. However, at that time, due to the constraints of many key technologies,its potential value was not fully reflected.In recent years, with the breakthrough of a series of key technologies such as magnetic bearings, composite materials, power electronics technology and successful application in many fields, the superiority of the flywheel energy storage system has gradually emerged. Since the early 1980s, the United States has begun the feasibility study of the application of flywheel energy storage systems in the aerospace field. Research shows that the flywheel energy storage system is not only feasible to replace the battery as the energy storage device of the spacecraft, but also finds an important additional function of the flywheel energy storage system: the moment generated by the energy storage flywheel can effectively control the attitude of the spacecraft,that means the flywheel system can simultaneously perform the functions of energy storage and attitude control. In this way, the reaction wheel of the spacecraft for attitude control or the gyro which is used to control the torque can be omitted, so that the weight of the spacecraft can be greatly reduced. Therefore, the effective load can be increased correspondingly, and further increasing the specific energy of the flywheel energy storage system.

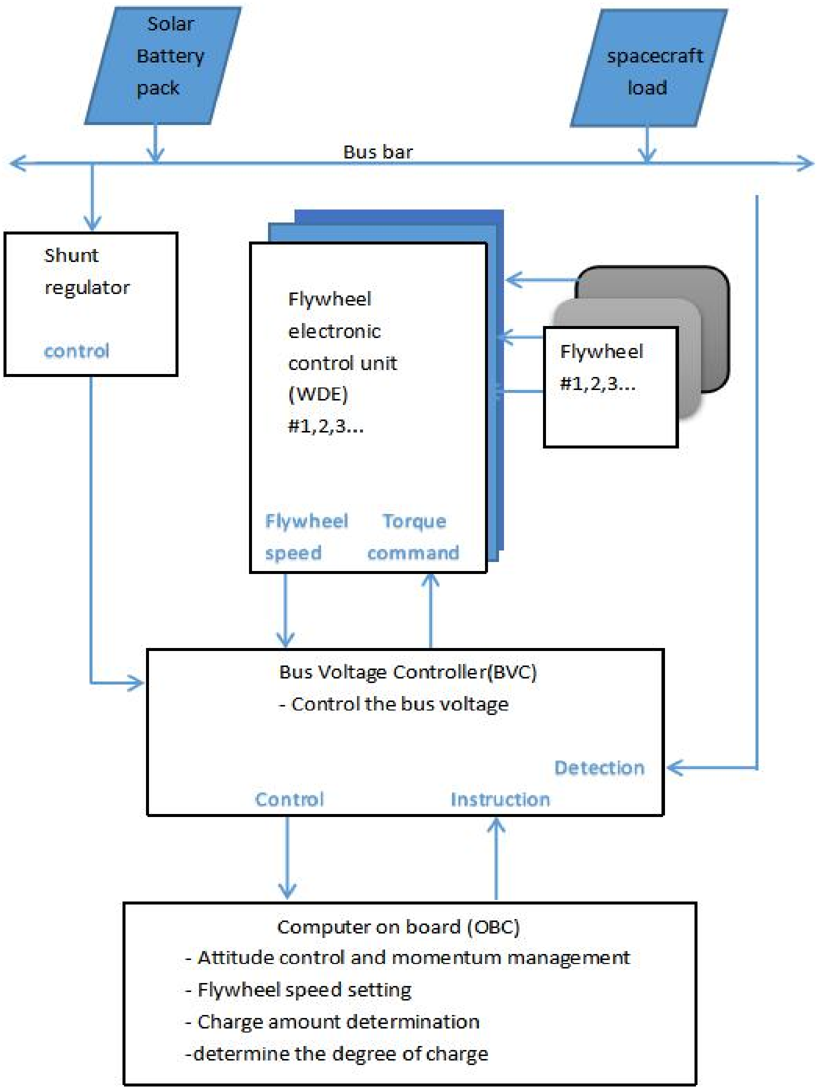
A typical flywheel energy storage system consists of a flywheel assembly and electronic control equipment.

The flywheel assembly includes: high-speed rotor that stores energy,a magnetic bearing system that reduces friction losses, auxiliary mechanical bearings that support launch loads and prevent accidental failure of magnetic bearings, motor generators that convert between mechanical energy and electrical energy, housings that support bearing systems, and vacuum covers for ground performance testing.

Electronic control equipment mainly includes: (1) motor generators and power conversion equipment (control the input and output of the energy of the entire flywheel energy storage system and the distribution, transmission and transformation of the internal power of the flywheel energy storage system).(2) The digital signal processor (for voltage regulation, motor current control, magnetic bearing control, state monitoring of the flywheel energy storage system, and some communication tasks related to spacecraft commands and telemetry).(3) secondary power supply(provides low voltage power to electronic equipment).(4) Magnetic bearing power amplifier.(5) Servo system to realize the exchange between magnetic bearing and mechanical bearing; (6) EMC/EMI filter(suppresses electromagnetic interference to spacecraft power supply).

According to the characteristics of the rotating flywheel itself, if the momentum provided by itself can be used to control the attitude of the spacecraft while storing energy, the weight of the spacecraft can be greatly reduced. The research shows that considering the factors such as the structure, protection strategy and working mode of the flywheel, the weight of the flywheel energy storage system will be reduced by 50% to 70% when replacing the hydrogen battery and reaction wheel or controlling the torque gyro.

From the perspective of storage energy, we can observe an integrated flywheel system can perform energy conversion and power adjustment functions. The perspective of posture control show that it should also have the function of performing posture and steering. It can automatically adjust the imbalance of the motor torque, the mismatch of the rotor's moment of inertia, the different axes of the flywheel components and the external interference. Following flow chart shows the block diagram of the flywheel integrated system:



Each flywheel in the figure connected to the power bus of the aerospace device by a two-way flywheel electronic control unit (WDE). The voltage controller (BVC) senses the voltage and maintains the bus bar voltage stable in the charging mode by controlling the energy flowing through the WDE. The voltage controller supplies the energy converted from the solar array to the spacecraft. The excess energy is delivered to the motor in the flywheel system through the flywheel electronic control unit, which accelerates the rotor to store energy. After the energy storage, the excess energy of the solar array is consumed in the shunt regulator. When the spacecraft enters the shadow zone,the voltage controller changes to the discharge mode,the rotor drives the generator output power. In the whole charge and discharge mode energy storage and attitude control integrated system structure, the computer also controls the rotation speed of each flywheel to complete the attitude control function of the spacecraft through the voltage controller and the flywheel electronic control unit.

The most common construction method is to mount three pairs of counter-rotating flywheels on the gimbal in a space perpendicular to each other. The total energy of the flywheel energy storage system in this configuration is the sum of the kinetic energy of each flywheel, and the net moment of each pair of flywheels is the difference of the moment of two flywheels. If a single flywheel failure occurs, the momentum moment control can be accomplished by another relatively rotating flywheel on the same shaft.

The multi-functional integration of the flywheel energy storage system makes the dynamic analysis of the system very complicated. From the current research situation,we can see it is necessary to further study the uncoordinated inertia of the internal rotor of the flywheel energy storage system, the influence of the difference between the different axes of the flywheel and the relative flywheel speed on the dynamics of the flywheel energy storage system and the impact of the operation of the flywheel energy storage system on the mass distribution dynamics of the entire spacecraft.

4.2.3 Applied on aerospace

Due to the technology and the price of their materials, flywheel energy storage systems are relatively expensive, and their advantages can not be demonstrated in small-scale applications very well. However, in some applications requiring large energy storage devices, the use of chemical batteries is also very expensive, flywheel batteries have been gradually applied, such like space, including satellites, spacecraft, space station, flywheel energy storage system(FESS) as a rechargeable battery can provide twice the power with the same weight of the chemical battery, when they have the same load, flywheel battery can be used 3 to 10 times the chemical battery. And because its speed is measurable and controllable, the FESS is always possible to see how much power is available. NASA has installed 48 flywheel batteries at the space station to jointly provide more than 150 kW of power. Compared to chemical batteries, it can save about 2 million US dollars. As technology advances, the use of flywheels as energy storage systems on aircraft to replace existing chemical batteries has become a trend.

Flywheel energy storage for spacecraft, the combination energy and attitude control system (CEACS) could use the attitude and energy storage tasks at the same moment. The flywheels ' control architecture and its performance has been perfect showed, so it can control the system itself what's the key issue. On the other hand, the main objective of the spacecraft energy management is to prevent excessive charging or discharging operations. Therefore, the maximum and minimum speeds of the flywheel should be limited, but we don' t want to decrease the capability of the energy storage of the system under nominal operation. Further more, the energy requirement must always be fulfilled. But the OBMU is arduous to solve this problem directly, to alleviate this burden, the implementation of an independent speed management strategy becomes desirable. The flywheel energy management strategy also be constrained by the attitude control system (ACS). The control torque required by the ACS shall always be applied constant whatever the flywheels are fully recharged or discharged or at running condition, so the commanded power should be limited in order to ensure the torques are constant. The voltage regulator and the ACS saturation can be used to overcome the energy and attitude constraints.

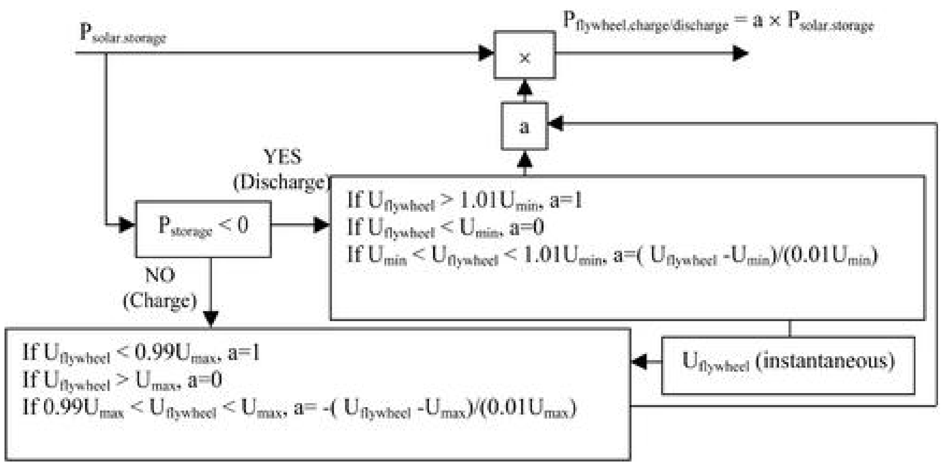


Fig 22. Flywheel energy allocation management

The power profile should be filtered to avoid large flywheel torque variations, which are undesirable for the satellite attitude. The idea is to decrease the impact of the power overshoot. Thus, a filter has to be implemented between the power to the flywheels and the power effectively commanded to the flywheels. The power filtering through a saturation filter could be considered. Hence, the power is only saturated when it reaches a certain threshold. This technique saturates the onboard power (current) overshoots/demands.

In the spacecraft, the traditional flywheel energy storage device is not enough to meet the demand, therefore, more advanced Energy-storing flywheel system with magnetic suspension was developed and applied to the spacecraft.

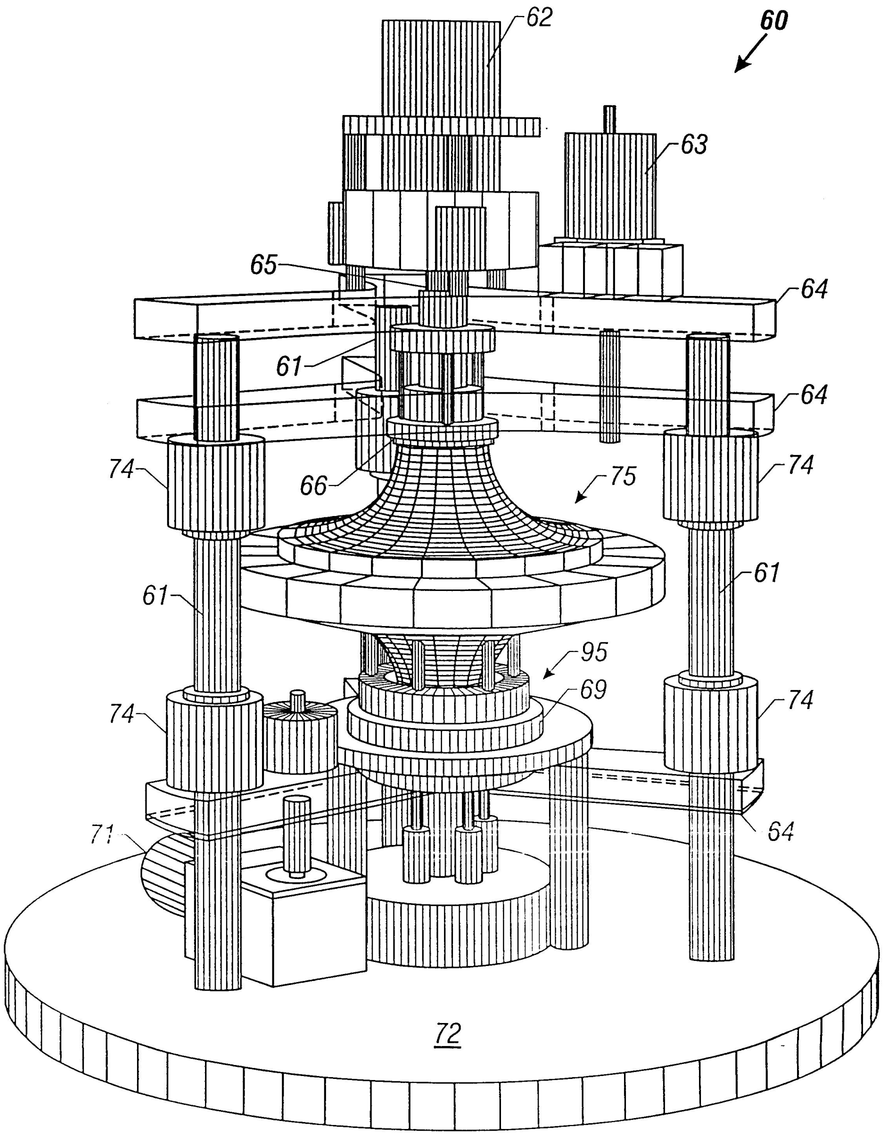


Fig 23.an isometric drawing of flywheel system

As shown in fig23 the flywheel system **60** includes flywheel **75**, motor **62**, stepper motor **63** for the top chamfer, stepper motor **71** for the bottom chamfer, rotor engaging switch **65**, HTS cold stage **66**, support posts **61**, lateral supports **64**, linear bearings **74** which allow movement of lateral supports **64** along support posts **61**, HTS cold stage **69**, cold stage **95**, clutch **68**, back-up bearings 81 and base support plate **72**. Three cold stages **66**, **69** and **95** utilize liquid nitrogen circulated through a closed passage to cool the HTS material.

In the past decade or so, NASA's Green Research Center was studying the use of flywheel batteries on the International Space Station to replace nickel-cadmium batteries. It is planned to use flywheels on low-Earth orbit medium-sized aircraft with energy levels between 1080 and 2520 kJ, then gradually apply them to smaller aircraft smaller than 360 kJ. Finally, the application will be extended to extraterrestrial rovers and some civilian projects.

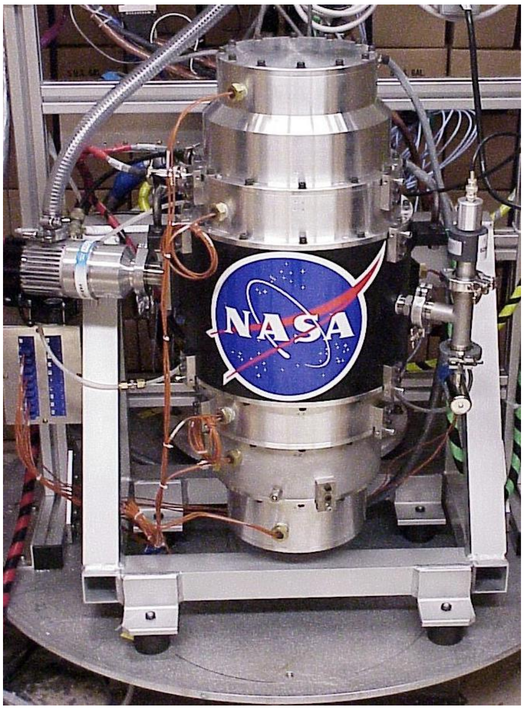


Fig24. Experimental Flywheel: NASA: Public Domain

NASA's flywheel test platform is primarily used to test single-axis control and energy storage systems, and it also will be used to test the prototype of the flywheel energy storage system on the International Space Station. The hardware configuration of the uniaxial test consists of two flywheel modules with parallel axes of rotation. The G2 flywheel designed and engineered by the Green Flywheel Development Group is able to run at 41,000 rpm at a nominal speed faster than previous flywheels with 30% lower running losses. And the rotor temperature increased by only 10 ° C over a nine-hour test period, the highest level of flywheel technology such as rotor composite technology and energy management systems.

The U.S. Air Force Research Laboratory's 'Flywheel Attitude Control and Energy Conversion' project has established a three-DOF space test platform (ASTREX). The ASTREX platform uses magnetic bearings to provide three degrees of freedom for attitude control testing of aircraft, to test both flywheel energy storage and attitude control performance simultaneously, and to study disturbances caused by these two functions of the flywheel.

4.2.4 Applied on satellites

There are various methods for attitude control of satellites in orbital flight, such as spin stabilization and triaxial stability. The long-life satellite's three-axis stability control system uses the flywheel as the main actuator. The flywheel plays a vital role in the satellite steady-state flight attitude control. The flywheel control system can ensure the reliability and long life of the satellite in orbit.

Early satellites used spin to stabilize their posture. Although this method has its superiority, the disadvantages are also obvious, in particular, it cannot meet the requirements of satellite payload high power (large solar cell windsurfing), multi-function, high precision, long life and so on, which limits its use and development. Three-axis attitude control is the most promising control method to meet these requirements.

Active three-axis attitude control system execution components are divided into jet control and flywheel control. Other actuators are basically auxiliary devices, such as magnetic torque devices. The jet control uses the mass of the gas discharged from the thruster to generate the control torque to control the three-axis attitude of the aircraft. The flywheel control uses the angular momentum stored by the flywheel to exchange angular momentum with the aircraft to achieve a stable three-axis attitude. When the flywheel is saturated, it is necessary to use auxiliary jet, magnetic torque or gravity gradient torque unloading. When the flywheel is saturated, it is necessary to use auxiliary jet, magnetic torque or gravity gradient torque unloading.

Compared with the jet control method, the flywheel control method has obvious advantages:

1. Low fuel consumption: Jet control consumes a lot of fuel, and both

non-periodic and periodic disturbances require fuel consumption;The flywheel control mode does not consume any fuel for a periodic disturbance torque with a mean value of zero. Only when the average disturbance torque (unloading) with a non-zero mean is used, some fuel is consumed by means of the jet.If a magnetic torque device is used, the aircraft will not consume any fuel during steady state flight.

2. High control accuracy: The flywheel is capable of producing more precise continuous control torque.Its control accuracy is two orders of magnitude higher than the jet pulse method (0.001°:0.1°), and the attitude error rate is also smaller than that of the jet control.
3. No environmental pollution: Many optical detection instruments are installed on modern satellites, and the gas generated by the jets will have an adverse effect on them; the flywheel control method has no pollution, and provides a good internal working environment for the optical detection instruments of the aircraft.
4. Long life: The life of a jet-controlled aircraft depends first on the quality of the fuel carried during launch, as well as on the sealing performance of the cylinder and piping, and the life of the solenoid valve.The flywheel control method consumes only electrical energy, and the electrical energy can be continuously replenished from the solar cell, making it ideal for long-life work. According to national statistics, the current life situation is: flywheels using ball bearings, life expectancy of 7 ~ 10 years, flywheels using magnetic bearings, life expectancy of 10 ~ 20 years, or even longer.

For the working principle,The working principle of the flywheel is based on the conservation of angular momentum, which can be installed in the satellite star through a bracket or frame. Supposing the angular momentum of the satellite is H, the angular momentum of the flywheel is $\mathrm{H_w}$, and the angular momentum of the system is $H_{\mathrm{T}} = H + H_{\mathrm{W}}$. If the external moment acting on the satellite is M, then:

$$\mathrm{M}=\frac{\mathrm{d}H_t}{\mathrm{d}t}= \frac{\mathrm{dH}}{\mathrm{dt}}-\frac{\mathrm{dH_w}}{\mathrm{dt}} \tag{1}$$

Let the speed of the star coordinate relative to the inertia space be ω_{s}; and take the coordinates attached to the flying engine block, and its rotational speed relative to the coordinates of the star is ω_{c}, then:

$$\frac{\mathrm{dH}}{\mathrm{dt}} = \mathrm{M} - \frac{\mathrm{dH_w}}{\mathrm{dt}} = \mathrm{M} - \frac{\partial \mathrm{H_w}}{\partial \mathrm{t}} - (\omega_{\mathrm{s}} + \omega_c) \times \mathrm{H_w} \tag{2}$$

where: $\frac{\partial \mathrm{H_w}}{\partial \mathrm{t}}$ is the variation of the angular moment;

$(\omega_s + \omega_c) \times H_w$ is the variation in the direction of H_w.

From the equation (2),we can see that whatever the variation of the magnitude or of the direction of the angular moment, the moment of inertia will be generated on the satellite finally.By using this method to change the magnitude and direction of the angular momentum according to a certain law, the purpose of controlling the attitude of the satellite can be achieved.

Flywheel products used in satellites can be divided into:

- Reaction flywheel: The control system uses the reaction torque generated by the flywheel to reverse the acceleration and deceleration, and directly acts on the satellite star to generate the control torque.The reaction flywheel control mode has high control precision and is used by many high-precision satellites.
- Offset Momentum Flywheel: This type of flywheel generally operates at a higher average speed. The control system uses its gyro's fixed axis and reaction torque generated by the speed change to control the attitude of the satellite.This control mode has lower control accuracy than the reactive flywheel control mode and is mainly used for medium precision satellite control systems.
- Control torque gyro and frame flywheel:

5.Overall clarification of the advantages and disadvantages of flywheel applications

The basic working principle of the flywheel and several existing uses have been clarified in the foregoing, and we also know that the flywheel has many advantages that cannot be possessed by chemical and chemical battery storage, such as: the flywheel energy storage system can quickly store and quickly release electrical energy; provides stable output energy in a short time; no need for complex battery management algorithms;the time when the flywheel is recharged is also much shorter than the battery;it can be applied in a wide temperature range and in a variety of environments; the fast response of the flywheel, in the power grid, can provide instantaneous high voltage to compensate for the peak voltage drop of the power;almost no friction loss,low wind resistance; the specific power can reach more than 8kW/kg, which is much higher than the traditional electrochemical energy storage technology; its service life mainly depends on the fatigue life of the flywheel material and the life of the electronic components in the system. The service life of the flywheel energy storage can reach more than 15 years, and the service life is not affected by the depth of charge and discharge; no harmful substances are produced during operation; little maintenance is required during operation;etc..

Although the flywheels have so many advantages,the flywheels still have many disadvantages,such as:

- complexity of durable and low loss bearings.
- mechanical stress and fatigue limits.
- some potentially hazardous failure modes, risk of excessive load on the flywheel and poor accept sudden changes in output energy.
- The energy density is not high enough, and the energy release can only be maintained for a short period of time, usually only a few tens of seconds.The self-discharge rate is high, such as stopping charging, the energy will be exhausted within a few to several tens of hours. Active Power's flywheel energy storage system unit module outputs 250 kW and standby loss is 2.5 kW, so some data say its efficiency is 99%. But this is conditional. This is only efficient if it is used quickly. If self-discharged, the efficiency is greatly reduced. For example, the tens of thousands of high-speed flywheel systems consume around 100 watts, and the 1 kWh system can only sustain 10 hours of self-discharge. Therefore, flywheel energy storage is most suitable

for energy storage needs of high power, short time discharge or frequent charge and discharge.

- Only 15-20 seconds of dynamic fast response.
- Unable to provide accurate backup time.
- Does not have capacity backlash characteristics. Traditional batteries have a capacity back-flush feature that provides short-term secondary power.
- High noise operation. If the flywheel is used as a DC-powered energy medium, the overall impact of noise must be assessed. The noise of the system needs to be considered in conjunction with the installation site.
- Mechanical parts depend on reliability.
- Compared with battery technology, flywheel energy storage is not a mature technology, but it is still in the demonstration application stage and has no advantage in price and cost. Due to the limitations of technology and material prices, the price of flywheel batteries is relatively high, and their advantages are not reflected in small occasions. However, in some places where large energy storage devices are required, the price of using chemical batteries is also very expensive, and the flywheel battery has been gradually applied.

That cannot be ignored even if we have discussed so much. We must continue to study to overcome these shortcomings, so that the flywheel can be widely used to mass produce to reduce the cost of producing flywheels.

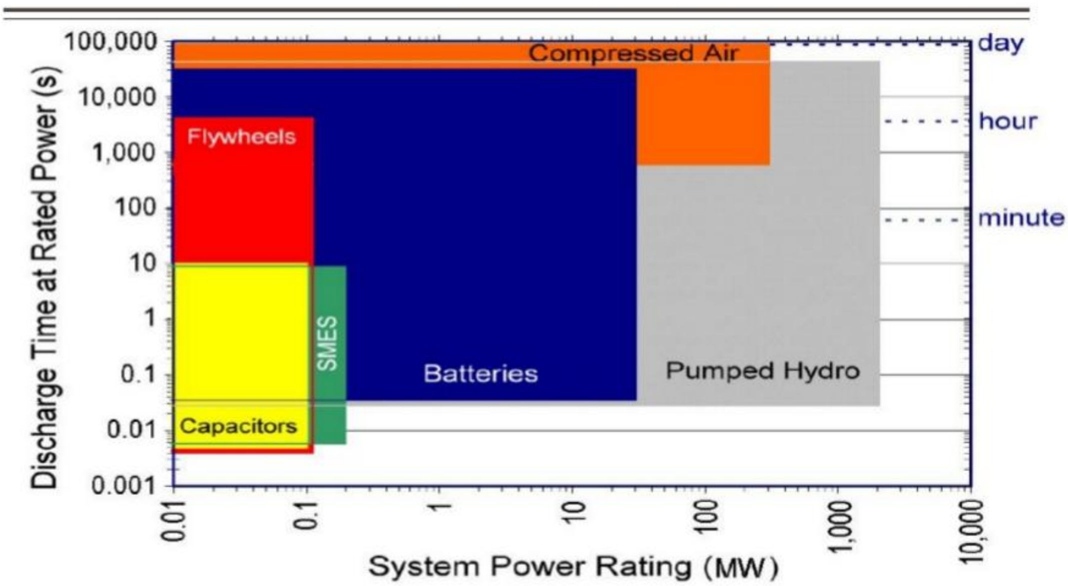


Fig25.System Power Rating vs. Discharging Time at Rated Power of different energy storage systems

6.Conclusion

As the population grows and time passes, the earth's resources are getting closer and closer. The protection of resources and the demand for energy have made new energy sources more and more popular. However, many new environmentally friendly energy sources are timely, so the storage and reuse of energy has become the focus of attention.

Germany, Japan, California and other places have begun to provide subsidies for the deployment of energy storage systems to help the development of the energy storage market. Under some business models, energy storage has gradually become economic. Energy storage and related industries are being pushed from the supporting position to the center of the stage. It can be said that the energy storage industry is like the solar energy in 2004, and the explosive growth is just around the corner.

According to the current public information on the planning and approval progress of urban rail transit in China,it is estimated that the total mileage of urban rail transit operations in China will reach 6,000 kilometers or more in 2020, and the total annual energy consumption will exceed 25 billion kW•h.Take the 333kW flywheel configuration of the current mature GTR flywheel energy storage product as an example. If the calculation is based on 3 sets of 333kW flywheels per kilometer, the total demand of the flywheel is about 18,000 sets. If the flywheel energy storage system equipment successfully implements large-scale applications on the subway,it will save at least 5 billion kW•h of electricity per year. Because the flywheel energy storage system has superior cycle capacity and can be cycled frequently,each set can reduce the emissions of thousands of tons of carbon dioxide per year.In addition,the flywheel energy storage equipment is used in the urban rail transit field, which can save 20%~30% of the electricity expenses every year,and the investment can be recovered within 5 years. Flywheel energy storage equipment has a service life of up to 20 years,which can significantly reduce the cost of urban rail transit operations.

In addition to the uses specifically mentioned in the previous section, the flywheel energy storage system can also be used for military purposes, such as combat vehicles and tanks. In modern combat vehicles, with the increase of new energy loads such as high-power pulse load and electric drive motors, the energy demand for combat vehicles presents a new development trend.In the 1997 Hybrid Combat System Program (CHPS) project initiated by the US military,developed and tested a full-size, 15t hybrid powertrain concept car,shown as the fig25. The vehicle uses a 6X6 chassis and uses a series hybrid drive to develop an integrated diesel turbine generator as the main energy source. The auxiliary power unit uses a MW-class flywheel as the energy storage, load regulation and pulse power source.[xxx]

Fig25. The flywheel is used in combat vehicle

It is foreseeable that along with advances in technology and materials science, flywheel batteries will play an important role in all walks of life in the future. Flywheel energy storage system in addition to the application areas described earlier, but also to the small, low-cost direction(The most likely is the cell phone battery.).

With the advancement of the times and the improvement of technology, the existing shortcomings of the flywheel may be completely solved, and the flywheel will be used in more aspects. And a wide range of applications will expand the market for flywheels, so that production can be more scaled and prices will no longer be high. Maybe one day you will find that flywheel energy storage technology can be seen everywhere in life, let us look forward to it.

Thank you!

References

[i] 《NREL: ENERGY STORAGE》

[ii] https://en.wikipedia.org/wiki/Flywheel

[iii] https://en.wikipedia.org/wiki/Kinetic_energy_recovery_system#/media/File:KERS_flywheel.jpg

[iv] Ashby MF, <On the engineering properties of materials.> *Acta Metall.*, 37 pp 1273–1293, 1989.

[v] File:Example of cylindrical flywheel rotor assembly.png

[vi] J. R. Hull, “Superconducting bearings,” Supercond. Sci. Technol., vol. 13, pp. R1–R15, 2000.

[vii] Vafakhah, B.; Masiala, M.; Salmon, J.; Knight, A. Emulation of flywheel energy storage systems with a PMDC machine. In Proceedings of the 18th IEEE International Conference on Electric Machines, Vilamoura, Algarve, Portugal, 6–9 September 2008; pp. 1–6.

[viii] Whittingham, M.S. History, Evolution, and Future Status of Energy Storage. Proc. IEEE 2012, 100, 1518–1534.

[ix] Pena-Alzola, R.; Sebastián, R.; Quesada, J.; Colmenar, A. Review of Flywheel based Energy Storage Systems. In Proceedings of the 2011 International Conference on Power Engineering, Energy and Electrical Drives, Malaga, Spain, 11–13 May 2011.

[x] 【微控新能源】 https://www.jianshu.com/p/19e838423f29

[xi] ‘smart grid’ from Wikipedia, the free encyclopedia,
https://en.wikipedia.org/wiki/Smart_grid

[xii] A. Nourai, V. Kogan, and C. M. Schafer, “Load leveling reduces T&D line losses,” IEEE Trans. Power Del., vol. 23, no. 4, pp. 2168–2173, Oct. 2008.

[xiii] G. Koeppel, M. Geidl, and G. Anderson, “Value of storage devices in congestion constrained distribution networks,” in Proc. 2004 Int. Conf. Power System Technology, Singapore, Nov. 21–24, 2004.

[xiv] https://en.wikipedia.org/wiki/File:Grid_energy_storage.png

[xv] YouTube: Flywheel Energy Storage System.

[xvi] Richard Baxter. Energy Storage: A Nontechnical Guide. PennWell Corp. 2005.9, 230-231

[xvii] PowerCorp Australia. Project descriptions for Coral Bay and Denham (low load diesel) and Coral Bay and Flores Island (flywheel).

[xviii] Europe’s largest hybrid flywheel battery project to help grid respond to energy demand, from The University Of Sheffield.

[xix] Pena-Alzola, R.; Sebastián, R.; Quesada, J.; Colmenar, A. Review of Flywheel based Energy Storage Systems. In Proceedings of the 2011 International Conference on Power Engineering, Energy and Electrical Drives, Malaga, Spain, 11–13 May 2011.

[xx] <High performance and low CO2 from a Flybrid® mechanical kinetic energy recovery system> A J Deakin, Torotrak Group PLC. UK

[xxi] <飞轮储能系统应用现状及市场简析> which from <储能产业技术联盟>

[xxii] http://www.cheyun.com/content/1893

[xxiii] <WHP Flywheel KERS——威廉姆斯飞轮动能回收系统>
https://bbs.hupu.com/5935674.html

[xxiv]《Flybus: New Hybrid Bus Uses Flywheel Instead of Battery to Store Kinetic Energy》by Brit Liggett

[xxv] <Flywheel as a energy storage device> By: Avinash Sengar.(Enroll.No.-383/10)

[xxvi] Knichel, T. Durable and high torque flywheel based hybrid systems for
commercial vehicles. 11th International CTI Symposium, 2012.

[xxvii] ‘LANDING KINETIC ENERGY OF AIRCRAFTS’ Department of Mechanical Engineering & Energy Processes, Southern Illinois University, Carbondale, IL 62901, USA

[xxviii] A Study on Flywheel Energy Recovery from Aircraft Brakes. ; Michael A. Conteh and Emmanuel C. Nsofor

[xxix] ‘A. Energy recovered’ from [A Study on Flywheel Energy Recovery from Aircraft Brakes.]

[xxx] [现代战斗车辆面临的新课题：如何进行能量体系管理] by zhengwenjunshi