CHAPTER 7
FLYWHEELS

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Abstract

Flywheels have been used to store energy from ancient times, through the industrial revolution, to a broad range of applications today. In their modern form, flywheel energy storage systems are standalone machines that absorb or provide electricity to an application. Flywheels are best suited for applications that require high power, a large number of charge discharge cycles, and extremely long calendar life. This chapter discusses flywheel technology, safety considerations and the nature of flywheel system cost. The chapter reports that trackside applications in transit systems represent a large potential opportunity where flywheels have demonstrable advantages with respect to competing energy storage technology.

Key Terms

Arbitrage, cylinder, Electromagnetic Aircraft Launch Systems (EMALS), flywheel, frequency-regulation, independent system operator (ISO), power quality (PQ), rotor, rubber-tired gantry crane, stabilization, stress, uninterruptible power supplies (UPS), voltage regulation

1. Introduction

For thousands of years, some form of flywheel technology has been used to smooth the flow of energy in rotating machinery from small, hand-held devices to the largest engines [1]. Flywheels store kinetic energy (the energy of motion) in a rotating mass which historically were connected to a rotating machine such as a mill or steam engine. In contrast, modern flywheel systems employ a rotor spinning at high speed in an evacuated enclosure that is charged and discharged electrically. Standalone flywheel systems store electrical energy for a range of pulsed power, power management, and military applications. Today, the global flywheel energy storage market is estimated to be $264M/year [2].

Flywheel rotors have been built in a wide range of shapes. The oldest configurations were simple stone disks. Beginning with the industrial revolution, “wagon wheel” iron and steel rims (weighing from a few pounds to tens of tons) were used in a variety of stationary machines. High strength, mass-produced metal rotors are found in modern industrial equipment. These rotors are generally disk-like with a geometry tailored for the requirements of the application.

Over the past 50 years of the development of flywheel energy storage systems, numerous unusual configurations have been explored. These include straight fibers oriented along the diameter (“brush” rotors), tapered rotors such as the constant stress Stodola hub, and many others. After much experimentation the two most cost-effective and widely used rotor configurations were determined to be: 1) solid metal disks or cylinders, and 2) thick-walled hollow cylinders constructed from carbon and glass composite materials.

During charging, a motor or other source of rotating power applies accelerating torque to the flywheel in the direction of rotation, increasing the rotor to a higher speed. Discharge is accomplished by using a generator or other sink of rotating power to apply a braking torque that decelerates the flywheel. When used in engines or industrial equipment, flywheels damp out speed variations caused by a pulsed motive source such as a large stationary steam engine (such as the Corliss Centennial Engine shown in Figure 1). In this application, the speed of the flywheel varies only slightly between pulses and relatively little energy is stored in the rotor. For example, the massive rotor of the Corliss Centennial Engine stored a total of just 5 kWh at maximum operating speed.

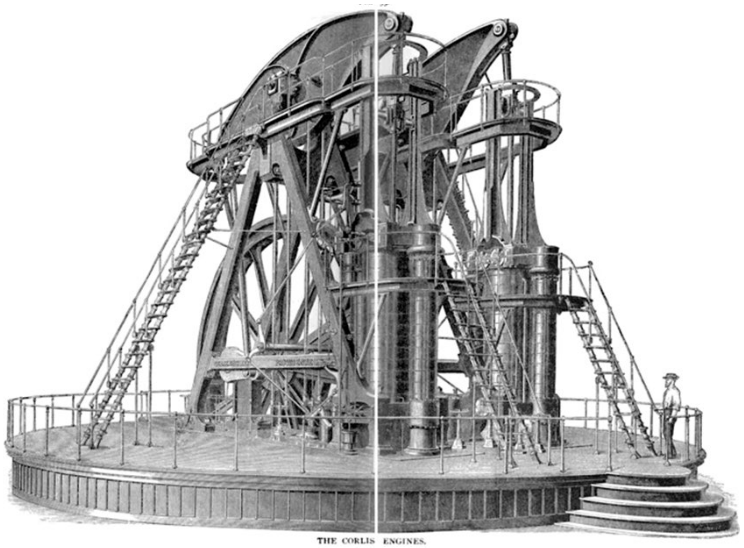

Figure 1. Corliss Centennial engine [3]

A standalone flywheel developed expressly for energy storage will experience much longer charge and discharge intervals and may be operated over a speed range of greater than 2:1 between charged and discharged states. This type of flywheel system may store more than 100 times more energy than the much larger industrial scale flywheels of the past. Due to its operation over a large speed range, a much greater fraction of the total stored energy is available for use.

The flywheel energy storage systems discussed in this chapter have a number of defining attributes:

- Standalone – Housed in an enclosure separate from the application it powers
- Electrically connected to the application – The system sinks and sources electrical energy, and the mechanical nature of the device is not relevant to the application
- Extremely long calendar life – Flywheel rotors can be designed with indefinite rotor life
- Extremely high cycle life – Flywheel systems can offer an effectively unlimited number of cycles (greater than 10^7)
- Power and energy ratings are not inherently coupled – Through independent sizing of the motor/generator (power) and rotor inertia (energy), flywheels in use today have discharge times varying by several orders of magnitude

An instructive example of the modern standalone flywheel system is shown in Figure 2 (blue cylinders). In this example a facility storing energy in flywheels has a capacity to source or sink 20 MW for 15 minutes. The facility uses 200 flywheel units each storing 25 kWh of extractable energy, charging or discharging at up to 100 kW. Each unit employs a 2,000 lb carbon/glass composite rotor spinning in a vacuum with a surface speed of up to 600 m/s. The units are mounted below grade.

Figure 2. Modern flywheel technology—20 MW flywheel frequency regulation plant (courtesy Beacon Power, LLC)

2. State of Current Technology

2.1. Technical Description

Flywheels store kinetic energy in a spinning mass, called a rotor. A flywheel system charges by receiving energy electrically, converting electricity into kinetic energy using a motor, accelerating the rotor. A flywheel discharges by operating the motor as a generator that decelerates the rotor while returning electrical power to the application.

Modern flywheel systems designed to current standards such as UL9540 attain safe operation by ensuring that the likelihood of rotor failure is at least as low as the likelihood of failure for industrial equipment with a comparable hazard, such as pressure vessels. This is achieved through rotor design margin [4]. High speed flywheel systems, where rotor surface speed exceeds 100 m/s, are generally operated in a vacuum or a reduced pressure enclosure to mitigate drag losses. See Figure 3.

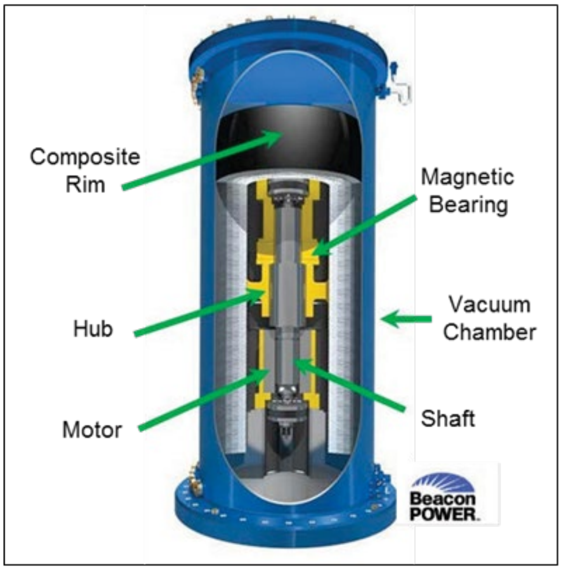

Figure 3. Integrated flywheel system package cutaway diagram (courtesy Beacon Power) [5]

High-power flywheel systems can often deliver their energy and recharge in seconds, if adequate recharging power is available. Bidirectional power conversion facilitates this two-way action [6].

Flywheels generally exhibit excellent cycle life in comparison with other energy storage systems. By designing within the fatigue limits of the rotor material, indefinite cycle life is attainable. Flywheel developers rarely forecast a life of less than 1 million cycles.

Avoidance of rotor failure is the one of two essential elements in ensuring safe flywheel operation. The more than 100-year history of documented flywheel failures, from the cast iron wheels of the 1800s to the carbon composite rims of today, amply demonstrates that practical containment of even a relatively small 5 kWh rotor failure is prohibitively expensive, requiring a containment structure many times more massive than the rotor itself. In light of this history, the assertion that flywheel safety can be attained practically through containment is uninformed. The single most important element of flywheel safety is ensuring that the likelihood of flywheel rotor failure is acceptably low. Once rotor structural integrity is assured, a secondary consideration must be met regarding restraint of a spinning rotor in the event of a bearing failure [3].

In contrast to many other energy storage technologies, flywheel systems have few adverse environmental impacts. Hazardous materials are generally not found in flywheel construction. The machines operate without emissions [4].

Flywheel systems in service today demonstrate millisecond response times, energy storage up to 700 kWh per rotor, power output of up to 500 MW per rotor, and decades of service life. The flywheels summarized here have generally been deployed in stationary applications. However, noteworthy mobile applications include flywheels in Electromagnetic Aircraft Launch Systems (EMALS), rubber-tired gantry cranes, as well as powering cars in top-tier motorsports including Le Mans series racing. All applications except for EMALS and rotary UPS use a vertical spin axis to simplify rotodynamic response and reduce forces and losses associated with the radial bearings.

Although flywheels have power densities many times that of batteries—meaning they require much less space to source or sink a comparable amount of power—the energy density compared to batteries is relatively low.

Because flywheel systems are fast-responding and efficient, they are effective at providing independent system operator (ISO) frequency-regulation services and system benefits such as avoiding the cycling of large fossil power systems and lowering CO_2 emissions. Spindle Grid Regulation, LLC (formerly Beacon Power), has employed megawatt-scale flywheel plants with cumulative capacities of 20 MWs to support the frequency-regulation market needs of ISOs [7].

Some entities are considering using flywheels as an energy storage medium for their applications such as inrush control, voltage regulation, and stabilization in substations for light rail, trolley, and wind-generation stabilization. However, the majority of products currently being marketed by national and international companies are targeted for power quality (PQ) applications.

Another high-value application in PQ is short-term bridging through power disturbances or from one power source to an alternate source [4].

In summary, the applications proposed for stationary, grid connected flywheel energy storage are the following:

- Power quality/regulation
- UPS
- Grid frequency-regulation services

2.2. Rotor Design

The kinetic energy of a rotating object is given by:

$$E = \frac{1}{2}\, I\, \omega^2$$

where E is kinetic energy, I is moment of inertia, and ω is angular velocity. While many rotor shapes have been explored, nearly all flywheels in use are built as solid or hollow cylinders. For a disk or solid cylinder, the moment of inertia is given by:

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

where m is the mass of the rotor and r is its outer radius. For a thin-walled hollow cylinder, mass is concentrated at the periphery and the moment of inertia is given by:

$$I = m r^2$$

The maximum speed at which a flywheel may operate is limited by the strength of the rotor material. The stress experienced by the rotor must remain below the strength of the rotor material with a suitable safety margin. For a uniform disk or solid cylinder, the maximum stress occurs at the center and has a value given by:

$$\sigma_{max} = \frac{1}{8}\, \rho\, r^2\, \omega^2\, (3 + \nu)$$

where σ_{max} is maximum stress, ρ is the density of the rotor material, and ν is the Poisson's ratio of the rotor material. Stress in a rotating, thin-walled cylinder is given by:

$$\sigma_\theta = \rho\, r^2\, \omega^2$$

where σ_θ is the stress in the circumferential direction. The surface speed of a flywheel is given by $V = r\, \omega$ and the specific energy, or energy per unit mass, of a flywheel rotor can be expressed as:

$$\frac{E}{m} = K\, V^2$$

where K is a shape factor with a value of 0.5 for a thin-walled cylinder and 0.25 for a disk. Flywheel rotors will often be designed to operate at the highest surface speed allowed by the rotor material. High performance carbon composite rotors have a maximum operating surface speed in the range of (500-1,000) m s^{-1}, while high performance steel rotors have a maximum operating surface speed in the range of (200-400) m s^{-1}.

Specific energy may also be expressed in terms of rotor material properties:

$$\frac{E}{m} = K_s \frac{\sigma}{\rho}$$

where K_s is a second shape factor with a value 0.5 for a thin-walled cylinder and 0.606 for a disk with a Poisson's ratio of 0.3. This equation reveals that a light, strong material such as a carbon composite stores considerably more energy per unit mass than a heavy strong material such as high strength steel, and that a disk stores more energy per unit mass than a hollow cylinder with the same strength.

2.3. Current Implementation

Flywheels are viable for certain applications when two conditions are met. First, the flywheel must represent a more cost-effective solution than competing forms of energy storage. Second, a market must exist so that the deployment of a flywheel system results in an economic return.

Flywheels are in use globally across various applications, as shown in Table 2. As the table suggests, flywheels are primarily used for high power, short duration, high cycle life applications. Uninterruptible Power Supplies (UPS) are an outlier. There are currently no commercially viable applications for so-called "long duration" flywheels designed for energy arbitrage.

Table 1. Flywheel applications

Grid-Connected Power Management	Installed Applications
Frequency Regulation	Flywheels are used to provide frequency regulation services at two 20-MW facilities.
Pulsed Power	
Electromagnetic Aircraft Launch System	80-MW flywheel alternators launch aircraft from aircraft carriers.
Fusion Power Source	Two 700 kWh flywheels provide 1,000 MW of power to the Joint European Taurus fusion facility.
Roller Coaster Launch	Flywheels provide *MW output for 2 seconds at intervals of 1 minute to launch an amusement park ride.
Industrial and Commercial Power Management	
Transit	Flywheels produced by Calnetix and URENCO have demonstrated trackside energy recovery for transit systems.
Mining	The Usibili mine in Healy, Alaska, uses a 40-ton flywheel to smooth the demand for electricity from a 6-MW dragline.
Materials Handling	Flywheels recover energy and reduce emissions from raising and lowering loads with rubber-tired gantry cranes at container terminals.
Uninterruptible Power Supplies	
Uninterruptible Power Supplies	Rotary UPS and flywheel-based ride-through systems have been an enduring element of the global UPS market.

The power and discharge durations provided by a variety of existing, operating flywheel installations are shown in Figure 4.

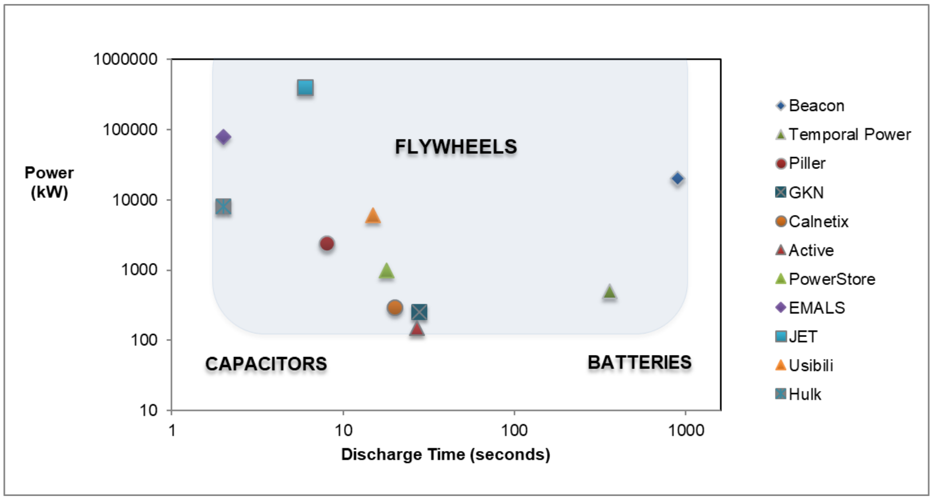

Figure 4. Power and discharge durations for flywheel installations

2.4. Cost and Comparison with Other Technologies

Flywheel system costs are divided among a number of subsystems including the rotor, bearings, power electronics, and the balance of system. The total cost of a flywheel system comprises three scalable cost centers:

1. **Elements that scale with stored energy**—For a particular geometry and rotor material, rotor weight and cost scale with stored energy. Components and subsystems that scale with rotor weight include the bearings, the housing, and structural hardware.
2. **Elements that scale with power**—For a flywheel system with an integral motor/generator, elements that scale with power include the motor itself, the motor drive, and electrical equipment.
3. **Balance of System**—Includes the vacuum pump, sensors, telemetry, diagnostics, controls, and other components required for operation of the flywheel that do not scale with energy or power.

The cost for a complete flywheel system may be expressed as:

$$C = A * Power + B * Energy + C_{BOS}$$

Elements that scale with power, A, have a cost expressed in \$/kW, elements that scale with stored energy, B, have a cost expressed in \$/kWh, and balance of system costs, C_{BOS} have units of dollars.

Flywheel systems in service today have costs spread across all three cost centers. There appears to be no reported instance of an existing system where the cost of the rotor exceeds 20% of the cost of the system. Consequently, in contrast to batteries, it is not valid to scale flywheel system cost on the basis of \$/kWh absent a consideration of the composition of flywheel system cost.

The incremental cost of per unit of stored energy is calculable for rotor materials. To reflect the high-cycling capability of flywheels, it is important to allow for a 50% reduction in strength typical in steel subjected to 10^6 cycles. Table 1 gives an approximation of the incremental cost of rotor material for high-cycle flywheel applications.

The first column refers to the yield strength of various grades of steel when new. The carbon composite values are based on filament wound construction using 4800 MPa (700,000 psi) fiber with 65% fiber fraction and proven safety factors for high cycle life. It is important to recognize that this metric applies only to the incremental cost of increasing the mass of a rotor to store more energy. This metric does not reflect other costs such as the motor, bearings, and the housing that are generally greater than the cost of the rotor itself. The third column indicates the mass of a steel flywheel rotor relative to a carbon composite rotor storing the same energy when both are designed for a life of 10^6 cycles. A heavier rotor requires higher capacity bearings and a heavier, more costly housing. Therefore, not only does a carbon composite rotor have lower incremental cost per unit of stored energy, the balance of systems costs can be reduced as well.

Table 2. Flywheel rotor material cost per unit stored energy

Material	$/(kWh)	Mass/(kWh)
Carbon Composite	$1,200	1
1800 MPa (260,000 psi) steel	$1,800	7x
1100 MPa (160,000 psi) steel	$2,000	12x
600 MPA (90,000 psi) steel	$4,000	24x

3. Challenges

The single overarching challenge facing flywheel technology is the higher cost of a flywheel solution relative to the cost of many competing solutions. Flywheels are a mature technology with a long history. The constituent materials and components such as high strength steel and composite, motors, power electronics, vacuum systems etc. are also highly mature. As a result, the underlying cost of a flywheel system is reasonably straightforward to forecast once a detailed design is established. Cost trends do not favor flywheels. There is no “Moore’s Law” for large mechanical systems. There is no path to drive cost out of a flywheel system that can follow the accelerating downward price trends for batteries.

The challenge within this application space is market acceptance. For example, the trackside application is well understood–there are thousands of potential installations, a significant number of successful demonstrations have been deployed, and value propositions paid back within a couple of years are sound. Despite this technical success, a market for trackside flywheels has not developed. Until effective business models for the deployment of flywheels are developed, they will remain a niche technology solution.

4. Opportunities

Flywheels are a competitive energy storage and power management solution for stationary applications requiring an extremely long calendar and cycle life. The single largest untapped opportunity is transit system energy recovery.

Currently 190 metro systems operate in 54 countries around the world. These systems comprise 9,477 stations and over 11,800 km of track. Many systems have recently been or are currently being extended. In addition, more than 30 new metro rail systems are currently under construction, nearly all of which are in Asia. This massive expansion has received relatively little notice in the United States [1].

Trackside energy storage captures energy lost during braking and allows for heavier and longer trains without increasing transmission or distribution line capacity. To mitigate voltage sag or increase transit system capacity in an existing system without using energy storage, a new substation would need to be installed. Flywheel energy storage installed at a transit station would provide the same mitigation of voltage sag as a new substation but in a small footprint with no new utility feed and at a much lower cost. Given the high rate of charge-discharge cycles, flywheels are particularly well suited for this application.

Using energy storage to recover energy lost in braking reduces metro rail electricity consumption on the order of 10%. Energy cost savings of \$50K to \$90K per station per year have been forecast. When installed in regions where the utility tariff structure includes demand charges, additional savings of \$75K to \$250K per station per year are attainable. In studies and tests to date, trackside storage sized to provide 1-3 MW of launch power or energy recovery per station is an effective rating for the metro rail application.

Presently, a 2 MW flywheel system produced by Vycon is installed in the Los Angles Metro Red Line at the Westlake/MacArthur Park station. The machines are similar to the ones used in the RTG application. From 2000 through 2004, flywheel systems developed by URENCO were demonstrated at trackside installations in New York, London, Paris, and Lyon.

5. Concluding Remarks

Mechanically connected flywheels have long been a component of any machine where reciprocating movement is transformed into rotation, thus ensuring their continued use. As electrically connected energy storage systems, flywheels compete with batteries and ultracapacitors based on cost (where cost is evaluated over the life of a system). Batteries, having attained production costs below \$100/kWh, are more economically competitive than flywheels in lower power and limited cycle life applications. However, applications requiring millions of charge-discharge cycles and a calendar life of decades will continue to benefit from flywheels as battery cycle life remains significantly lower.

Cost reduction is the most important objective in the development of any type of energy storage. The extent to which the use of flywheels will increase or decrease depends on trends in cost reduction for flywheels and for the competing technologies. Cost drivers for flywheel systems are dispersed over several subsystems including the rotor, bearings, power electronics, and the balance of system. Flywheels are not deployed in numbers sufficient to drive down the cost of these subsystems through high volume manufacturing. However, flywheels will benefit as other industries drive both increasing performance and declining cost in several key areas.

Rotor material performance has a geometric impact on the cost of a flywheel system and is one key area where declining costs may be realized. While steel, carbon composites, and glass composites are all mature and improvements in performance or cost are unlikely, the development of potentially transformative materials (perhaps carbon nanotube composite) may significantly increase strength and stiffness over existing composites. If available, the use of such a material in a flywheel would not only substantially improve the energy per unit mass of the rotor but would also lead to much smaller and less costly bearings and housings.

Improved performance and lower cost of power electronics for electric vehicles translate directly into improved performance and lower cost of the flywheel motor drive and the active magnetic bearing. Prompted by the accelerating use of electric powertrains, motor drive power electronics costs for electric vehicles have dropped dramatically over the last decade and are approaching $5/kW.

Given the increasing need in areas where flywheels are already in use combined with performance and cost trends in the underlying technology, flywheels should remain a competitive energy storage solution for the foreseeable future [8].

Donald Bender is a principal member of the technical staff at Sandia National Laboratories in Livermore, California where he is the system quality lead for the W87-1 program. Mr. Bender has more than 20 years of flywheel engineering experience, first as a mechanical engineering group leader at Lawrence Livermore National Laboratory and subsequently as chief technology officer of AFS Trinity Power Corporation. Mr. Bender received his BSME and MSME degrees in mechanical engineering from the Massachusetts Institute of Technology in 1979 and 1983.

References

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[1] D. Bender "Flywheels" SAND2015-3976, Sandia National Laboratories, May 2015.

[2] "Flywheel Energy Storage Market Size, Share & Trends Analysis Report By Application (UPS, Distributed Energy Generation, Transport, Data Centers), By Region, And Segment Forecasts, 2019–2025" Grand View Research, Flywheel Energy Storage Market Size, Industry Report, 2019–2023.

[3] United States Centennial Commission, F. A. Walker, Ed., International Exhibition, 1876, Reports and Awards Group XV, Lippincott, Philadelphia, 1877.

[4] UL9540 Standard for Energy Storage Systems and Equipment, Underwriters Laboratories, 2016.

[5] D. Bender, "Recommended Practices for the Safe Design and Operation of Flywheels," SAND2015-10759, Sandia National Laboratories, 2015.

[6] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, EPRI ID 1001834, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington, DC, 2003. L.D. Mears, H.L. Gotschall - Technology Insights; T. Key, Kamath - EPRI PEAC Corporation.

[7] Inage, Shin-ichi "Prospects for Large-Scale Energy Storage in Decarbonised Power Grids" International Energy Agency, Paris, France, 2009.

[8] *World Scientific Handbook of Energy*, Editor: Gerald S. Crawly, ISBN-13:978-9814343510, World Scientific Publishing Company, 2015.