

Research Article

Review of Magnetic Flywheel Energy Storage Systems

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Abstract: This study studies an overview of magnetic flywheel energy storage system. Energy storage is an integral part of any critical power system, as this stored energy is used to offset interruptions in the power delivered system from either a utility or an on-site generator. Magnetic flywheel as mechanical batteries using composite rotor, magnetic support bearings as well as power electronics to store electrical energy to replace stone wheel and chemical batteries has resulted in high power and energy densities. Traditionally, capacitors are used for short term storage (μs -ms) and filtering, chemical batteries are used for intermediate storage (min-h) and diesel fuel is used for long-term storage (h-days). Electricity generated from renewable sources, which has shown remarkable growth worldwide, can rarely provide immediate response to demand as these sources do not deliver regular supply easily adjustable to consumption needs. Thus, the growth of this decentralization production means greater network load stability problems and requires energy storage, generally using lead acid batteries as a potential solution. Finally the integration of all subsystems optimally of the magnetic flywheel system has resulted in a mechanical battery which can supply more efficient, reliable and uninterrupted power to meet the ever increasing demand of industrial machinery and automobiles.

Keywords: Energy storage, generator, magnetic flywheel energy storage system, magnetic support bearing, mechanical batteries

INTRODUCTION

Flywheel existed well over 100 years ago as a stone wheel which was attached to an axle was solely to store kinetic energy and smoothes the operation of a reciprocating engine during its cycle of operation by maintaining a constant speed of rotation.

But recent development in technology has led to a more complex form of energy storage system that consists of more complex integrated power electronics components. The choice of using flywheel as an Uninterrupted Power Supply storage (UPS) system has been well established well over half a century ago by more extensive research activities that have gone on in countries such as the USA, German, Switzerland, China, Japan, as well as institutional laboratories across the world. More recent research into magnetic bearing and power electronics system makes magnetic flywheel a more obvious choice and substitute for much industrial storage application.

The advanced research into power electronics ensures those magnetic flywheels are able to operate at high power density and energy when compared to conventional chemical batteries of the same size.

The used of magnetic bearing offers low frictional and internal energy losses when used as a storage

system for a very long period. Current research activities in many advanced countries and laboratories have led to many breakthroughs in flywheel energy storage technology. These research adopted evolved around a complete approach and has led to the integration of all subsystems been optimally integrated, the end positive achievement is a level of sophistication that has resulted in a mechanical battery that can draw electrical power from a grid acting as a motor which accelerate a rotor at a very high speed and then discharges this electrical power output upon demand by switching the motor into a generator mode.

Magnetic flywheel energy storage system consists of miniaturized control systems, health hazards control and safety control measures for detecting early bearing failure. Recent rotor designs have usable energy densities of about 50 to 95 whrs/kg. US flywheels current research system in the 21st century has focused on the development of an integrated flywheel energy system with the ultimate goal of optimizing each of the subsystem, with the primarily focused on the use of Lower Earth Orbit (LEO). In the focus, many hundreds of fiber composite rotors of high tensile strength graphite are been designed using Finite Element Analysis (FEA).

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Most Flywheel Energy storage (FEA) system use electricity to accelerate and decelerate the rotor but devices that uses mechanical energy are being developed (Stodola, 1927). Advanced flywheel system have rotors made of high strength carbon filament, suspended by magnetic bearings and spinning at speeds from 20,000 to over 60,000 rpm in a vacuum enclosure (Castelvechi, 2007).

In summary magnetic bearing used in energy storage system have extremely high power and high energy densities with no anticipated fall of deep load under repetitive charge and discharge cycles. Ultimately magnetic bearings when used in supporting flywheel rotors results in low frictional resistance in rotor operations resulting in a very low internal energy losses during long period thereby increasing the performance characteristic and efficiency of the energy storage system. So this study seeks to review the various magnetic flywheel energy storage systems, their parts and how they function.

LITERATURE REVIEW

Mechanical flywheels originated well over 100 years ago had the basic function of ensuring that industrial and automotive machines run smoothly from cycle to cycle.

Dr. A. Stodola in 1917 (Stodola, 1927) had a first real breakthrough in translating a book into English entitled analysis of flywheel rotor shapes and rotational stress analysis came as relieve. In the industrial revolution, James Watt contributed to the development of the flywheel in the steam engine and his contemporary James Pickard used a flywheel combined with a crank to transform reciprocating motion into rotary motion. The principle of flywheel is found in the Neolithic Spindle and the potter wheel (Castelvechi, 2007).

The flywheel as a general mechanical device is for equalizing the speed of rotation, according to the America Medievalist Lynn White, recorded in the *De diversibus artibus* (on various arts) of the German artisan. The ophilus Presbyter (ca 1070-1125) who records applying the device in several of his machines (White Jr, 1975, 1964). Flywheel energy storage system after emergence in 1917 existed as a heavy wheel that was used to store kinetic energy and smoothens the operation of reciprocating engines until in the early stages of 1970s when flywheel energy storage system was proposed as a main source of storing energy for stationery machinery as well as for electrical power alternatives for industrial applications.

The discovery of magnetic bearing for the application of flywheel energy storage system in the 1980s showed that the flywheel that were mechanically built had many high attributes when compared with chemical batteries for many industrial applications. The potential of using fiber composite materials in rotor as

well as magnetic bearing started to appear in the research industry about half a century ago due to extensive laboratory research analysis. Recent advanced research has led to tremendous improvement in flywheel energy storage technology.

METHODOLOGY

Related technologies: Flywheels are often used to provide continuous energy in systems where energy source is discontinuous. In such cases, the flywheel stores energy when the energy source is not applying to it. For example, a flywheel is used to maintain constant angular velocity of the crankshaft in a reciprocating engine (Hillier, 1993). In this case, the flywheel which is mounted on the crankshaft stores energy when torque is exerted on it by a firing piston and releases energy to its mechanical loads when no piston is exerting torque on it, other cases of the this examples are friction motors, which uses flywheel to power devices such as toy cars.

A flywheel may also be used to supply intermittent pulses of energy at transfer rates that exceeds the abilities of its energy source, or when such pulses would disrupt the energy supply, this is achieved by accumulating stored energy in the flywheel over a period of time, at a rate that is compatible with the energy source and then releasing that energy at a much higher rate over a relatively short time. For example flywheels are used in riveting machines to store energy from the motor and release it during its operation.

Example of a typical flywheel energy storage device used in industrial machinery is shown in Fig. 1.

Magnetic levitation (automobiles): Magnetic Levitation has been around for so many years, but with advances in technology it has become part of everyday life. The main emphasis for Magnetic Levitation is for ground transportation. Maglev is an advanced mode of surface high speed transportation whereby a vehicle gliding above a guide way is suspended, guided and propelled by magnetic forces.

Flywheel-powered buses known as grobus were used in Yverdon Switzerland and there are ongoing researches to make flywheel systems that are smaller, lighter and have a greater capacity. It is hoped that flywheel systems can replace chemical batteries for mobile applications, such as electric vehicles. Flywheels have also been proposed for use in Continuously Variable Transmission (CVT).

Rosen motors developed a gas turbine powered series hybrid automotive power train using a 55,000 rpm flywheel to provide burst of acceleration which the small gas turbine engine could not provide. The flywheel also stored energy through regenerative braking system; the flywheel was composed of a titanium hub with a carbon fiber cylinder and was

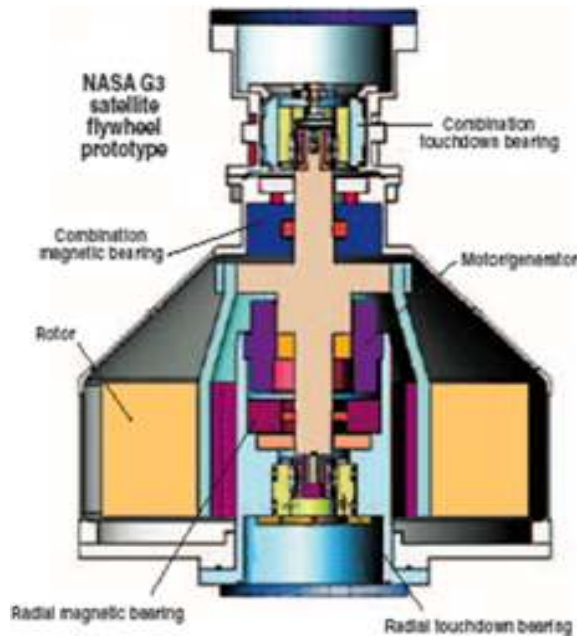


Fig. 1: Magnetic flywheel module

gimbal mounted to minimize adverse gyroscopic effect on vehicle handling.

Rail vehicle: Flywheel system has also been used in small electric locomotives. Maglev train is a high-speed ground transportation vehicle levitated above a track called guide way and propelled by magnetic fields. Magnetic Levitation train technology can be used for urban travel at relatively low speeds (<100 km/h, or less than 62 mph), a short distance maglev shuttle operated for 11 years from 1984-1995 in Japan. Worldwide interest is in high-speed maglev system. Train speed of 552 km/h (343 mph) have been demonstrated by a full size maglev vehicle in Japan, while in German a maglev train has run at 450 km/h (280 mph).

Types of levitation: Two different approaches to magnetic levitation train systems have been developed.

Electromagnetic suspension: In Germany engineers are building an Electromagnet Suspension (EMS) system in which electromagnets are attached to the train's undercarriage and are directed up towards the guide way, which levitates train called Trans rapid. In this system the bottom of the train wraps around a steel guide way. Electromagnets that are attached to the trains undercarriage are directed up towards the guide way, which levitates the train about one-third of an inch (1 cm) keeping the train levitated even when it is not moving, other guidance magnets embedded in the train body keep it stable during travel. Germany has

demonstrated that the Trans rapid maglev train can reach 300 mph with people on board.

Electrodynamics Suspension (EDS): Japanese engineers are developing a competing version of maglev trains that use an Electrodynamic Suspension (EDS) system, which is based on repelling force of magnets and not the attracting force. The key difference between the Japanese and the German maglev train is that Japanese train use super-cooled superconducting electromagnets. These electromagnets can conduct electricity even after the power has been shut off. In the EDS system, which uses standard electromagnets, the coil only conducts electricity when a power supply is present. By chilling the coils at frigid temperatures, Japan's system saves more Energy compared with the Germany's (EMS) system.

Wind turbines: Wind turbines are used to generate electricity from the kinetic power of the wind; historically they are more frequently used as a mechanical device to turn machinery. There exist two main kinds of wind generator, those with vertical axis and those with a horizontal axis. To ensure wind turbine that are big in size work in a better manner a new kind of airflow technology may be soon introduced. Apart from other aspect, it will focus on efficiency of blades used in the wind turbine. The technology will help in increasing the efficiency of these turbines under various conditions.

Renewable energy production and demand growth is gaining momentum in many ways across the world. There is booming demand of wind power today and all wind energy equipment manufacturers are gearing up to meet the demand and take advantage of it. Wind power capacity growth will be reaching 447 GWi the next 5 years and by the end of the year 2014, Asia will lead the world in installed wind capacity. Enercon is amongst the other manufacturers who are focusing on 3 mv-glass wind turbines based on E-82/2.0 without increasing the component sizes.

Uninterruptible power supply: Flywheel power storage systems in productions as of 2001 have storage capacities comparable to batteries and faster discharge rates. They are mainly used to provide load leveling for large battery systems, such as an uninterruptible power supply for data centers as they save considerable amount of space compared to battery systems.

Flywheel maintenance in general run about one-half the cost of traditional battery ups system. The only maintenance is a basic annual preventive maintenance routine and replacing the bearing every 5 to 10 years, which takes about 4 h. Newer flywheel systems completely levitate the spinning mass using

maintenance-free magnetic bearing, thus eliminating mechanical bearing maintenance and failures.

PHYSICAL ATTRIBUTES

Compared with other ways to store electricity, FES systems have long lifetimes (lasting decades with little or no maintenance (Castelvechi, 2007), full-cycle lifetimes quoted for flywheels range from in excess of 10^5 , up to 10^7 , cycles of use) (Bitterly, 1998), high energy density (100-130 Wh/kg, or 360-500 kJ/kg) (Bitterly, 1998; Gabrys, 2001) and large maximum power output. The energy efficiency (ratio of energy out per energy in) of flywheels can be as high as 90%. Typical capacities range from 3 to 133 kWh (Castelvechi, 2007). Rapid charging of a system occurs in less than 15 min (Vere, 2008). The high energy densities often cited with flywheels can be a little misleading as commercial systems built have much lower energy density, for example 11 Wh/kg, or 40 kJ/kg (Technik GmbH, 2010).

Energy density: The maximum energy density of a flywheel rotor is mainly dependent on two factors, the first being the rotor's geometry and the second being the properties of the material being used. For single-material, isotropic rotors this relationship can be expressed as (White Jr, 1975):

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

where, the variables are defined as follows:

- E : Kinetic energy of the rotor (J)
- m : The rotor's mass (kg)
- K : The rotor's geometric shape factor (dimensionless)
- σ : The tensile strength of the material (Pa)
- ρ : The material's density (kg/m^3)

The highest possible value for the shape factor of a flywheel rotor, is $K = 1$, which can only be achieved by the theoretical constant-stress disc geometry (Giancarlo, 1985). A constant-thickness disc geometry has a shape factor of $K = 0.606$, while for a rod of constant thickness the value is $K = 0.333$. A thin cylinder has a shape factor of $K = 0.5$.

For energy storage purposes, materials with high strength and low density are desirable. For this reason, composite materials are frequently being used in advanced flywheels. The strength-to-density ratio of a material can be expressed in the units (Wh/kg) and values greater than 400 Wh/kg can be achieved by certain composite materials.

Several modern flywheel rotors are made from composite materials. Examples include the Smart

Energy 25 flywheel from Beacon Power Corporation and the Power Thru flywheel from Phillips Service Industries.

For these rotors, the relationship between material properties, geometry and energy density can be expressed by using a weighted-average approach (Technik GmbH, 2010).

One of the primary limits to flywheel design is the tensile strength of the material used for the rotor. Generally speaking, the stronger the disc, the faster it may be spun and the more energy the system can store.

When the tensile strength of a composite flywheel's outer binding cover is exceeded the binding cover will fracture, followed by the wheel shattering as the outer wheel compression is lost around the entire circumference, releasing all of its stored energy at once; this is commonly referred to as "flywheel explosion" since wheel fragments can reach kinetic energy comparable to that of a bullet. Composite materials that are wound and glued in layers tend to disintegrate quickly, first into small-diameter filaments that entangle and slow each other and then into red-hot powder, instead of large chunks of high-velocity shrapnel as can occur with a cast metal flywheel.

Energy storage efficiency: An additional limitation for some flywheel types is energy storage time. Flywheel energy storage systems using mechanical bearings can lose 20 to 50% of their energy in 2 h (Ransburg, 2008). Much of the friction responsible for this energy loss results from the flywheel changing orientation due to the rotation of the earth (a concept similar to a Foucault pendulum). This change in orientation is resisted by the gyroscopic forces exerted by the flywheel's angular momentum, thus exerting a force against the mechanical bearings. This force increases friction. This can be avoided by aligning the flywheel's axis of rotation parallel to that of the earth's axis of rotation.

Conversely, flywheels with Magnetic bearings and high vacuum can maintain 97% mechanical efficiency and 85% round trip efficiency.

Design of a maglev flywheel: A maglev flywheel energy storage system was designed to verify the theories which have been mentioned before. And here is the design process.

Structure design: The axial length of the system is 700 mm; max diameter is 420 mm; rated speed is 20, 000 rpm; energy density is 8.29 wh/kg which is 36% higher than NASA-G2 (McLallin, 2001). 3D model and the cutaway view of the maglev flywheel energy storage system are shown as Fig. 2 and 3.

The rotational inertia of the flywheel is $J = \frac{1}{2} m (r_o^2 + r_i^2)$; mass is $m = \pi \rho h (r_o^2 - r_i^2)$.

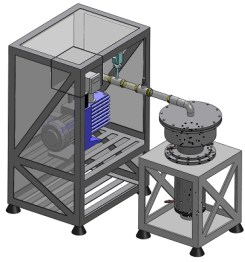


Fig. 2: 3D model of the maglev flywheel energy storage system



Fig. 4: 3D model of radial AMB

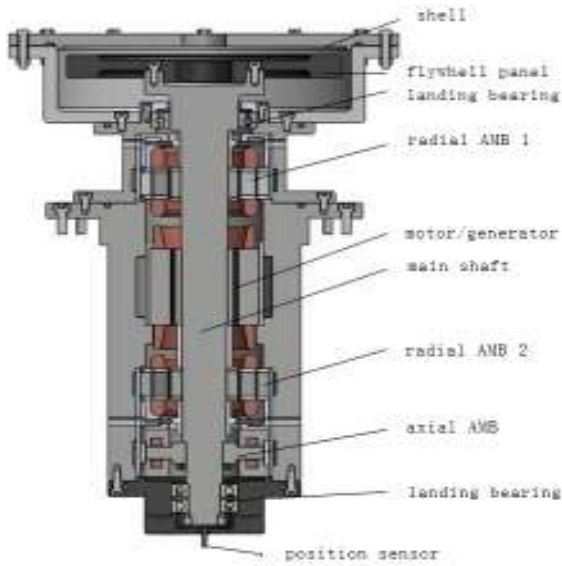


Fig. 3: Cutaway view of the maglev flywheel energy storage system

where, h means the thickness of flywheel panel, r_o , r_i means the internal and external radius of flywheel panel, ω is the revolving speed of flywheel panel. So, the energy which this flywheel can host should be as follow:

$$\begin{aligned}
 E &= \frac{1}{2} J\omega^2 = \frac{1}{4} m(r_o^2 + r_i^2)\omega^2 \\
 &= \frac{1}{4} \pi\rho h(r_o^2 - r_i^2)(r_o^2 + r_i^2)\omega^2 \\
 &= \frac{1}{4} \pi\rho h\omega^2 r_o^2(1 - (\frac{r_i}{r_o})^4) \\
 &= \frac{1}{4} \pi\rho h\omega^2 r_o^2(1 - k^4)
 \end{aligned} \tag{1}$$

where, $k = r_i/r_o$. It is obvious that E is not only relating to ω and material, but also relating to h , r_o and r_i . Energy storage density of the flywheel is:

$$u = \frac{E}{m} = \frac{1}{4}(r_o^2 + r_i^2)\omega^2 = \frac{1}{4}r_o^2\omega^2(1 + k^2) \tag{2}$$

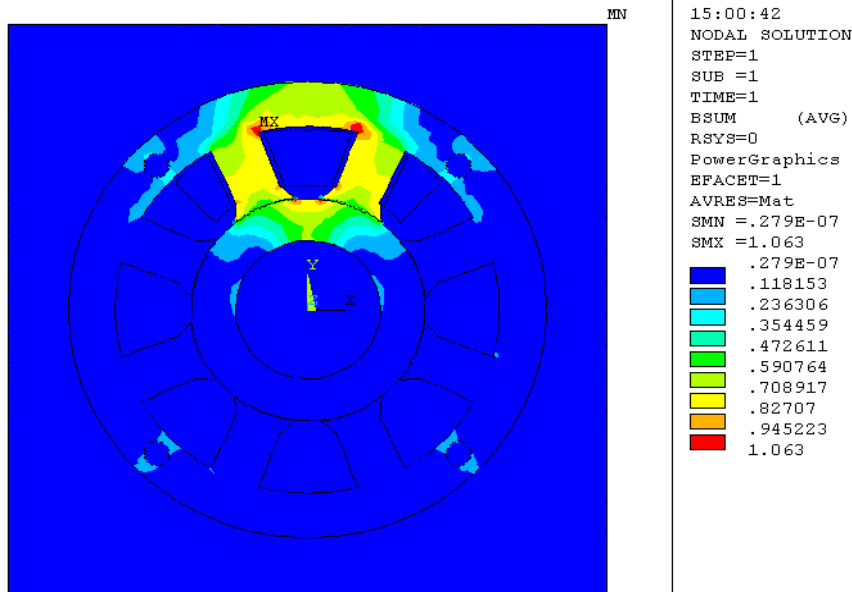


Fig. 5: Node magnetic flux density contour chart



Fig. 6: 3D model of axial AMB

It can be concluded from (1) and (2) that the bigger k is, the bigger u will be. However, the bigger k is, the less E will be. So, an appropriate k is needed to optimize the design. According to the design experience of Maglev Laboratory WHUT, the best k should be 0.4. At this moment, E will be as big as 97.4% as the maximum point and u will be as big as 93.7% as the maximum point.

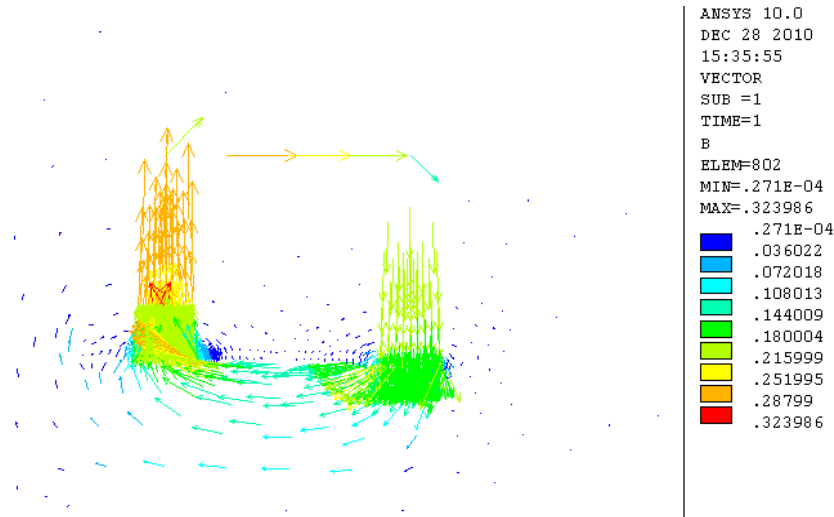


Fig. 7: Magnetic flux density vector of axial AMB

Table 1: Parameters of radial AMB

Working parameters		Dimension parameter	
Work air gap (mm)	0.3	Coil slot cross-sectional area (mm ²)	372
Maximum axial force (N)	260	Stator coil groove bottom diameter (mm)	148
Bias current (A)	1.5	Stator external diameter (mm)	148
Maximum magnetic induction (T)	1.2	Column width (mm)	15
Turns per coil	192	Column height (mm)	17
Air gap cross-sectional area A (mm ²)	245	Stator thickness (mm)	20

According to the above parameters and the formula: $F_{max} = \frac{B_{max}^2 bt \cos \alpha}{\mu_0}$, $F_{max} = 260N$

Table 2: Parameters of axial AMB

Working parameters		Dimension parameters	
Work air gap (mm)	0.30	Coil slot cross-sectional area (mm ²)	190
Maximum axial force (N)	300	Stator coil slot internal diameter (mm)	90
Bias current (A)	2	Stator coil slot external diameter (mm)	112
Equilibrium position control current (A)	0.29	Stator external diameter (mm)	128
Maximum magnetic induction (T)	1.00	Coil cavity depth (mm)	18
Turns per coil	120	Stator thickness (mm)	20



Fig. 8: Maglev flywheel

Radial AMB design: Here we chose 8 poles structure to design the radial AMB. The 3D model of it is shown in Fig. 4, the node magnetic flux density contour chart is shown in Fig. 5 and the parameters are shown in Table 1.

Axial AMB design: The 3D model of axial AMB is shown in Fig. 6, the magnetic flux density vector is shown in Fig. 7 and the parameters are shown in Table 2.

After design, here comes the fabrication part. Figure 8 shows the real maglev flywheel after manufacturing.

CONCLUSION

Flywheels powered vehicles known as grobuses which were used in most of advanced countries such as Switzerland as well as the ongoing research in advanced laboratories to make flywheel systems smaller, lighter, as well as cheaper with a greater capacity.

It is hoped that flywheel systems can replace chemical lead batteries for most mobile application such as electric vehicles.

Proposed flywheel systems would eliminate the disadvantage of convectional chemical batteries such as low capacity, long recharge times.

Technological advancement in the 21st century has proven that magnetic flywheel energy storage system could surpass convectional lead chemical batteries for much industrial machinery because of the use of composite fiber material in the design of the rotor which has resulted in low frictional and internal energy losses ultimately resulting in high power output.

The integration of all the subsystems optimally has resulted in a mechanical battery which can deliver high power and energy densities upon demand.

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