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Original Article

Flywheel Energy Storage Systems and their Applications: A Review

N. Z. Nkomo[1], A. A. Alugongo[2]

[1,2]Department of Industrial Engineering and Operations Management & Mechanical Engineering, Vaal University of Technology, Vanderbijlpark, South Africa.

[1]Corresponding Author : nkosilathin@vut.ac.za

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Abstract *- This study gives a critical review of flywheel energy storage systems and their feasibility in various applications. Flywheel energy storage systems have gained increased popularity as a method of environmentally friendly energy storage. Fly wheels store energy in mechanical rotational energy to be then converted into the required power form when required. Energy storage is a vital component of any power system, as the stored energy can be used to offset inconsistencies in the power delivery system. The energy crisis, mainly in developing countries, has had an adverse effect on various sectors, resulting in a resort to various energy storage systems to cater for the outages that are experienced. Solar systems have been the preferred backup system to use. However, the high cost of purchase and maintenance of solar batteries has been a major hindrance. Flywheel energy storage systems are suitable and economical when frequent charge and discharge cycles are required. Furthermore, flywheel batteries have high power density and a low environmental footprint. Various techniques are being employed to improve the efficiency of the flywheel, including the use of composite materials. Application areas of flywheel technology will be discussed in this review paper in fields such as electric vehicles, storage systems for solar and wind generation as well as in uninterrupted power supply systems.*

Keywords *- Energy storage systems, Flywheel, Mechanical batteries, Renewable energy.*

1. Introduction

Energy is an essential part of any modern society and is essential for its development. There is extremely high energy demand in today's 4th industrial revolution. The increase in energy demand and its impact on the environment has led to increasing dependence on renewable energy. Energy storage is imperative in any grid system, and it works as an energy buffer that can alleviate imbalances between energy production and consumption [1]. The use of renewable energy is gaining significant traction in electricity supply due to the limited quantity of fossil fuels available. Furthermore, research has shown beyond doubt that fossil fuels are harmful to the environment. In attempts to reduce environmental impact this has led to significant amounts of research in renewable energy. However, most of the renewable energy sources from wind and solar tend to be intermittent, with some need for energy storage systems to buffer these fluctuations in power generation. If an effective storage system is coupled to intermittent renewable energy, the power supply can be consistent and this will add considerable value to the system and make it sustainable [2]. There are a number of energy storage systems in use, such as Pumped Hydro Storage (PHS) [3], Compressed Air Energy Storage (CAES) [4], Battery Energy Storage (BES) [5], Capacitor Storage (CS) [6], Super Capacitor Energy Storage (SCES) [7], Thermal Energy Storage (TES) [8], Hydrogen Storage System (HSS) [9] and Flywheel Energy Storage System (FESS) [10] Energy storage devices can be grouped into four classes which are electrical based, electrochemical based, thermal, and mechanical systems. Currently, the most widely used energy storage system is the chemical battery. However, chemical batteries have several shortcomings, such as high cost, low thermal reliability, short life cycles and high maintenance costs. Furthermore, chemical batteries cannot provide high power in a short time and are unsuitable for applications where rapid discharge and charging occur frequently. Disposal of chemical batteries creates water and air pollution. As the batteries corrode, chemicals soak and contaminate groundwater and surface water. About 4% of landfill waste includes e-waste, often containing batteries [11] Flywheel Energy Storage Systems (FESS) is a sustainable energy storage source as it is environmentally friendly, can sustain infinite charge/discharge cycles and has a high power-to-weight ratio in comparison to chemical batteries [12]. A flywheel is a mechanical battery that is made up of a spinning mass around an axis. The flywheel works through the principle of storing energy in the form of kinetic rotational energy [13]. The flywheel has existed for thousands of years, and a typical example is the potter's wheel, which uses a flywheel system to preserve energy under its own inertia [14] The flywheel is also used considerably in reciprocating engines as the torque is intermittent. The flywheel can be used to smooth out the discontinuous energy source [15]. FESS is generally supported by active magnetic bearing (AMB) systems due to their low friction [16] Flywheels have been used traditionally to smoothen out fluctuations in irregular drive mechanics. However, flywheel systems are gaining traction due to advancements in the technology of magnetic bearings, the material of flywheel and drive systems [2]. Flywheels are now a possible technology for power storage systems for fixed or mobile installations. FESS have numerous advantages, such as high power density, high energy density, no capacity degradation, ease of measurement of state of charge, don't require periodic maintenance and have short recharge times [17]. Furthermore, flywheels are environmentally friendly as they contain no chemicals and are a scalable technology [16]. A shortcoming of FESS is its high self-discharge rate, with losses in the region of 5-20% per hour [18, 19]. FESS systems can be combined with renewable energy due to their fast response time, making them suitable for uninterrupted power to the grid.

The energy storage systems in use have limited cycles of storage and have an impact on the environment, such as lithium battery energy storage. The mining of lithium and the manufacture of the battery has an environmental impact. Therefore, there is a need for a more environmentally friendly energy storage mechanism that also has a lower carbon footprint, such as FESS technology. FESS has a significant advantage over lithium energy storage and other chemical batteries in that it has a fast charge and discharge rate, low maintenance, high energy storage density and minimal environmental pollution. Furthermore, the use of FESS technology gives a battery that is capable of thousands of cycles without degradation in the depth, rate or frequency of charge cycles, unlike chemical batteries.

The objective of this article is to give a review of the FESS technology, its application, and future trends. The paper will give insight into how FESS works and will highlight investigations that have been done into FES technology to improve its efficiency.

2. Working Principle

A FESS system works by storing up charge in the form of kinetic energy. The flywheel system is enclosed in a vacuum containment to reduce friction. The kinetic energy is transferred to the flywheel through external drives, which may be mechanical or electrical in nature. The amount of energy that can be collected in a flywheel system is directly proportional to the moment of inertia and the square of its angular velocity, as shown in equation 1.

$$E_k = \frac{1}{2} I \omega^2 \qquad (1)$$

Where E_k is the flywheel energy, I represent the moment of inertia, and ω is the flywheel angular velocity. The moment of inertia is dependent on two variables which are the flywheel mass and diameter, as shown in equation 2.

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

Where m is the mass of the flywheel, therefore, from equations (1) and (2), to increase the energy storage of the flywheel, the mass, size, and speed of rotation must increase. However, the material of the flywheel governs the highest possible speed of the flywheel. The moment of inertia of a flywheel is calculated as a function of its shape. In steel solid cylinder flywheel rotors, the inertia is calculated as shown in equation 3.

$$I = \frac{1}{2} r^4 \pi \alpha \mathrm{P} \qquad (3)$$

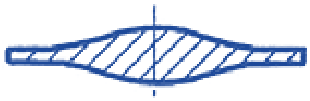
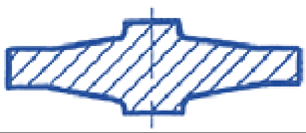
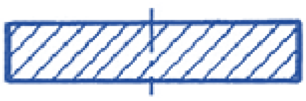
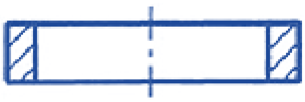
Where $\boldsymbol{\alpha}$ is the length of the cylinder, and p is the density of the cylinder material. The maximum energy density in relation to the volume and mass is as shown in equations 4 and 5, respectively.

$$e_v = K_\sigma \qquad (4)$$

$$e_m = {}^{K\sigma}/_{p} \qquad (5)$$

In equations 4 and 5, e_v and e_m represent the kinetic energy per unit volume. K represents the flywheel shape factor, σ represents the maximum stress, and p is density. The flywheel can take several shapes, such as constant stress disk, conical disk, constant thickness (pierced and unpierced) disk, disk with rim and thin rim, as shown in. The shape of the flywheel influences its shape factor.

Table 1. Showing shape factor (K) for various planar geometries of flywheels [17, 2]

Shape of flywheel	**Cross-Sectional shape**	**Shape factor (K)**
Disc		1.000
Modified constant stress disc		0.931
Conical disc		0.806
Flat unpierced disc		0.606
Thin firm		0.500
Rim with web		0.400

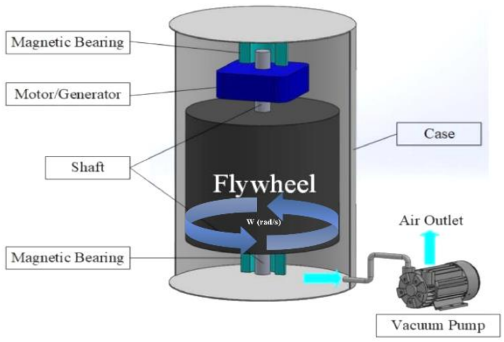


Fig. 1 Flywheel design [20]

3. Components of FESS

The FESS typical components are the spinning rotor, bearings, dual-function motor/generator, power electronic unit and housing unit, as shown in Fig. *1*. Flywheels are broadly classified into two types, namely low speed (<10 000 rpm) and high speed (<100 000 rpm). The low-speed FESS typically use heavy materials such as steel, whereas the high-speed FESS normally use lighter composite materials. Composite flywheels allow for much higher density than conventional steel-based flywheels due to their low density and high mechanical strength properties [21].

4. Materials of the Flywheel

The flywheel rotor is the main component of the FESS and is the rotating disc that is responsible for storing the kinetic energy. Two main kinds of material have been used in flywheel design namely steel and composite materials [22].

4.1. Steel Flywheel

Steel flywheels work best at lower rotational speeds of less than 10000 rpm. Much research into steel flywheels is focused on enhancing the geometry profile using various software modelling tools to improve the energy-carrying density [23].

4.2. Composite Flywheels

Composite flywheels can withstand higher rotational speeds and stress compared to conventional steel flywheels. Furthermore, composite materials are lighter than steel flywheels. This implies that composites can find use in high-speed flywheel systems and can handle speeds up to 100 000 rpm [24, 17, 25]. Composite materials have been traditionally more expensive than steel; however, with advancements in technology and the availability of materials, composites are now cost-competitive.

Research has been carried out by DeTeresa and Grooves (2001) [26] who concluded that carbon fibre-reinforced composites are most suited in flywheel designs for high performance.

5. Bearing Systems

The bearings systems used to support the flywheel rotor must have minimal frictional drag. The options available are the mechanical rolling element and magnetic bearings. The mechanical rolling element bearings are normally lubricated using oils capable of operating in vacuum conditions. Mechanical bearings are suited for low-speed flywheels and tend to have high friction, high energy losses, low operating lifespan and high maintenance costs. On the other hand, magnetic bearings such as the Passive Magnetic Bearing (PMB) and the Active Magnetic Bearing (AMB) operate by levitating around the moving rotor shaft without coming into direct contact with it. Due to their lack of physical contact, these magnetic bearings work well with high-speed flywheels and have low friction and, hence, low energy losses [27, 28].

5.1. Passive Magnetic Bearing (PMB)

Passive Magnetic Bearings (PMBs) are bearings that use permanent magnets to compensate for the weight of the flywheel without the need for any power requirement. Passive magnetic bearings cannot be used as the sole bearing due to Earnshaw's theorem. Earnshaw's theorem states that a collection of point charges cannot be maintained in a stable equilibrium configuration solely by the electrostatic interaction of the charges. Furthermore, PMBs cannot provide a stable suspension in all dimensions and are used only as an auxiliary bearings [29, 30].

5.2. Active Magnetic Bearing (AMB)

Active magnetic bearings require a power source to work. The AMB assist to reduce the vibrations of the rotor [31]. However, Active Magnetic Bearings (AMB) can only be used after careful consideration of the power loss from energizing the system versus the gain obtained.

5.3. Safety and Containment

There is a need for a safety containment system in the case of a failed or runaway flywheel. The FESS failure could originate from crack growth due to material flaws, bearing failure or external shock load, as shown in Table 2. The vacuum chamber acts as the first safety enclosure to prevent rotor debris from flying free. As a contingency, there are barrier systems put in place which include thick steel, concrete chambers and/or underground vaults [17].

Table 2. Typical failure root causes and their failure mode for flywheel systems [32]

Cause	Initial Failure Mode
Flywheel rotor damage is caused by rotational stress due to crack propagation or excessive speed.	Rotor pieces break off and fly off in both tangential and radial directions.
The flywheel shaft or hub is damaged due to torsional stresses, which can be caused by excessive bearing vibrations.	The flywheel rotor loosens and flies off in a radial direction.
Composite flywheel rotor cracks on softening of the resin. This occurs if the vacuum is not sufficient.	Flywheel particles break out in a radial and tangential direction.
External factors to the flywheel, such as earthquakes and penetrations of the flywheel holding chamber.	Damaged flywheel particles are being flung off in radial and tangential directions.

6. FESS Applications

FESS have numerous applications and possible applications, such as Uninterruptable Power Supply (UPS), power smoothing, aircraft and military projects, vehicles, renewable energy storage systems and aircraft carriers. In the subsequent subsections, these applications will be reviewed and presented.

6.1. FESS in Vehicles

FESS can be used as the only source of energy for the propulsion of a vehicle, as was done with Gyro Buses. Gyro buses developed by Oerlikon shown in 2 were used as regular transport in Switzerland from October 1943 and used to ply a 4.5km route between Yverdon-les Bains and Grandson [33]. The bus was also used in Kinshasa in the Democratic Republic of Congo until 1969. The flywheel was made from steel with a mass of 1500 kg and had a vertical rotation axis with an outside diameter of 1.6m. The recharging process took approximately 4 minutes, impacting 150 kW [33]. The generator motor got its power from a three-phase 50 Hz network through bar collectors on the roof of the bus. The motor had a maximum speed of 2900 rpm and a minimum operation speed of 2300 rpm implying 63% of the stored energy was wasted [33]. This bus could attain speeds of 55 km/hr and cover 5 to 6 km between charges.

The flywheel technology at this time was rudimentary; however, the system worked. The flywheel has to be adequately sized to be able to move the vehicle a considerable distance. This type of technology can work for buses that travel set routes within the city. This bus had some disadvantages, which led to its demise with one of those being that the spinning flywheel acts like a huge gyroscope which resists change in orientation. This could also be an advantage as this also resulted in a smooth ride.

There is a need for further research into the use of this technology in hybrid vehicles to create cheaper and longer-lasting batteries. The parasitic loses of charging the flywheel can be offset by regenerative braking systems and optimization techniques to reduce fuel consumption. During regenerative braking of the flywheel, the kinetic energy from the automotive can be used to run a generator and return some power to the flywheel system [34].

Fig. 2 Flywheel powered Gyro Bus [35]

FESS technology can be used as a hybrid system in vehicles. The battery lifespan management system in electric vehicles degrades over time due to charging/discharging processes due to stochastic heat and mass transfer. FESS can be integrated into the battery storage system and can improve the battery lifespan [36, 37].

6.2. Renewable Energy and FESS

Wind and solar power generation is becoming a significant power generation medium. However, both these power generation methods fluctuate widely, with wind power depending on wind speed and solar power dependent on the availability of sunshine. There is, therefore, a need to have an energy storage system embedded in the renewable energy system.

Solar photovoltaic power is an environmentally friendly and sustainable energy source that is also economical [38]. However, the irregular nature of the solar irradiance results in unstable power. Hence some form of storage systems must be used with solar systems. A French start-up company Energiestro, has developed FESS for use in residential solar PV systems. The flywheel is made from prestressed concrete, and the idea is for its purpose in rural electrification in developing countries [39].

6.3. Uninterruptible Power System (UPS)

Most available FESS systems find use under UPS applications. The main reason for the use of FESS systems in this application is due to the high-power quality, longer life cycles and low maintenance requirement of the system [16]. Direct Current (DC) FESS can be used almost anywhere that batteries are used in UPS systems.

The flywheel system can provide power during the period the backup generator is firing up. Generally, chemical batteries can supply backup power for much longer than FESS can. However, this must be looked at in perspective in areas where the flywheel would be more suited.

The flywheel could have the advantage of [40]:

- Useful operating span of approximately 20 years, whereas UPS chemical batteries typically last between 3 - 5 years.
- Chemical batteries require a narrow optimum temperature range, whereas flywheels can handle harsher ambient conditions.
- Frequent discharge and charge cycles have very little impact on flywheel life in comparison to chemical batteries.
- Flywheels are compact and can use only about 10 to 20% of the space required by chemical batteries for the same output.
- Flywheels require much less maintenance, hence lowering the operating costs.
- Flywheels do not have to contend with safety issues related to chemicals.

6.4. FESS in Aerospace

Flywheels are finding applications in the aerospace industry as a store of energy as well as to control the orientation of satellites [41]. FESS are important in the space industry as they can substitute hazardous and heavy chemical batteries. FESS technology can be used in small satellites and probes to maned power stations. In power stations, two counter-rotating flywheels are used to counter the net torque and momentum. In addition to energy storage, the flywheel can provide the added functionality of attitude control; these systems are normally referred to by NASA as flywheel-based Integrated Power and Attitude Control Systems (IPACS) [42]. The attractiveness of FESS systems in aerospace has initiated research to use the technology in hybrid mode or as a sole storage system [8, 43].

6.5. Energy Saving in Repetitive Motions

In engineering applications, some of the machine motions are repetitive in nature, such as cranes lifting objects to relocate them to another area. A robotic arm which follows a predetermined path will accelerate and decelerate according to the required speed. It is a possibility that through the regenerative process, the excess energy will be harvested and utilized in the next trajectory of the robotic arm. The flywheel energy storage system can utilize this energy hence improving the efficiency of the operation significantly [44, 45]. Furthermore, the flywheel is suited for repeated charge and discharge cycles with minimal loss in efficiency.

6.6. Military Applications

Flywheel energy storage is finding use in military applications such as charging modules for aircraft electromagnetic launch systems [46]. The flywheel energy storage is a substitute for steam-powered catapults on aircraft carriers. The use of flywheels in this application has the potential for weight reduction.

The US Marine Corps are researching the integration of flywheel energy storage systems to supply power to their base stations through renewable energy sources. This will reduce the dependence on chemical batteries and, ultimately cost of running [47].

7. Future Trends

The future of flywheel energy storage systems is debatable mainly because its success hinges on several factors. The amount of research and funding put into mechanical batteries, such as the FESS over chemical batteries, will determine the development of this technology. The advantages of FESS which include their low cost, high discharge and discharge cycles and reliability, make it attractive. However, it has disadvantages such as the complexity of the design, the need for high speeds and related problems that originate from rotating a huge mass at high speed. There is a need for further research into this technology to improve it.

There is research taking place into various composite flywheel rotors that are lower in cost and can operate at higher speeds safely. There is also a thrust into the use of lighter and environmentally friendly materials [48].

There is significant research being done into the various ways to minimize losses which have an adverse effect on the charge holding capacity. The losses are mechanical and electrical in nature. These two need to be tackled concurrently to produce an efficient FESS.

8. Conclusion

This review paper has presented a review of FESS and its various applications. Energy storage systems are important in creating a buffer for renewable energy sources. Chemical batteries are the preferred method of energy storage; however, this review article shows that FESS technology has several advantages over chemical batteries. Research that is being carried out by FESS, including optimizing the rotor shape and material, has the potential to reduce cost and increase efficiency considerably. FESS systems have been used in a wide range of end uses such as renewable energy, transportation, space and others. There is a need for further research on FESS systems in an interdisciplinary approach that involves electrical, mechanical, and magnetic systems to improve their efficiency.

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