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Review

Critical Review of Flywheel Energy Storage System

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Abstract: This review presents a detailed summary of the latest technologies used in flywheel energy storage systems (FESS). This paper covers the types of technologies and systems employed within FESS, the range of materials used in the production of FESS, and the reasons for the use of these materials. Furthermore, this paper provides an overview of the types of uses of FESS, covering vehicles and the transport industry, grid leveling and power storage for domestic and industrial electricity providers, their use in motorsport, and applications for space, satellites, and spacecraft. Different types of machines for flywheel energy storage systems are also discussed. This serves to analyse which implementations reduce the cost of permanent magnet synchronous machines. As well as this, further investigations need to be carried out to determine the ideal temperature range of operation. Induction machines are currently stoutly designed with lower manufacturing cost, making them unsuitable for high-speed operations. Brushless direct current machines, the Homolar machines, and permanent magnet synchronous machines should also be considered for future research activities to improve their performance in a flywheel energy storage system. An active magnetic bearing can also be used alongside mechanical bearings to reduce the control systems' complications, thereby making the entire system cost-effective.

Keywords: flywheel energy storage systems (FESS); spacecraft; renewable energy; transport industry; electricity

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1. Introduction

The severe environmental impact of fossil fuels, used in all aspects of our lives, is a serious threat, as is clear from the resulting health problems and climate change [1,2]. To reduce the severe problems caused by the different fossil fuels, scientists have proposed different solutions, such as waste heat recycling [3,4], developing efficient energy conversion systems that have low or no environmental impact [5–7], transitioning from fossil fuel resources to renewable energy resources [8–10], and, finally, CO_2 capture [11–14]. In the last decade, the renewable energy sources' capacity was exponentially increased, resulting in a critical need for energy conversion/storage systems that can effectively use/store such an increase in energy. Regarding energy conversion devices, fuel cells are efficient devices [15–17] that are fueled by renewable fuels such as biohydrogen [18], biogas [19], or other biomass resources [20,21]; they have high potential to replace conventional energy conversion sysetms in several applications, such as water desalination [22,23], transportation [24–26], aviation [27], and portable applications [28]. The energy storage systems are divided into four categories, i.e., electrical, electrochemical, thermal, and mechanical. Mechanical ones are suitable for large-scale capacities with low environmental impacts compared to the other types. Among the different mechanical energy storage systems, the flywheel energy storage system (FESS) is considered suitable for commercial applications. An FESS, shown in Figure 1, is a spinning mass, composite or steel, secured within a vessel with very low ambient pressure. The reduced pressure within the vessel reduces drag on the spinning mass, thereby maintaining momentum and generating electricity for longer [29]. A flywheel stores energy in a rotating mass, and the kinetic energy produced is stored as rotational energy. The amount of kinetic energy stored depends on the inertia and speed of the rotating mass. In order to eradicate any energy loss due to friction, the flywheel is placed inside a vacuum containment. It is also suspended by bearings so that operation is stable. This results in the flywheel being able to continue spinning without any added power and with very little energy loss. The kinetic energy is transferred in and out of the flywheel by an electrical machine. The electrical device has two modes of operation, namely either a motor or generator. These modes of operation are dependent on the load angle [30–33]. When the machine is acting as a motor, electrical energy is provided to the stator winding. The stator winding is a wire coil built into the motor, which produces a rotating magnetic field when energised. This energy is then converted to torque and applied to the rotor, resulting in it spinning rapidly and gaining kinetic energy. This is used when an excess of energy is being produced from an external source, and, therefore, the flywheel stores the energy [34]. When this stored energy is required, the electrical machine acts as a generator, and the kinetic energy stored in the rotor applies a torque. This is then converted into electrical energy. This causes the wheel to slow back down [30].

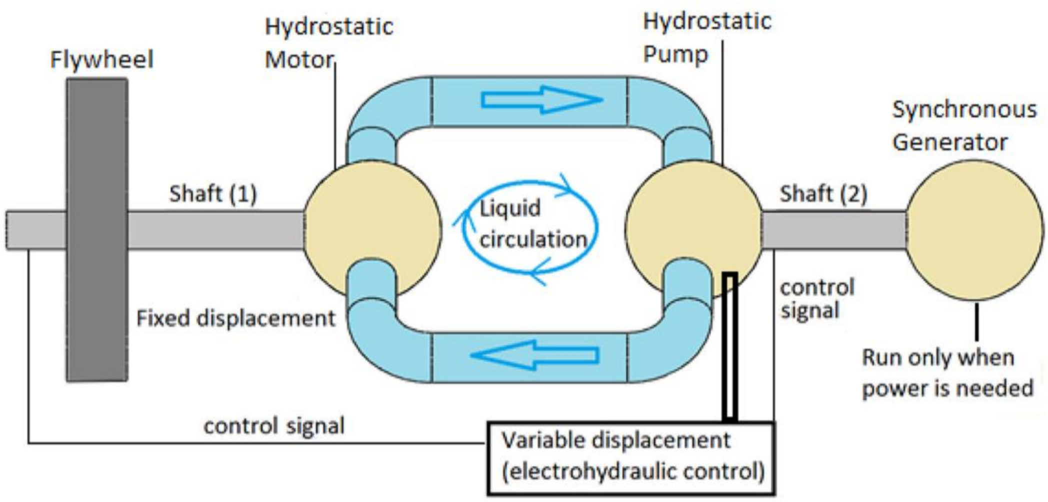


Figure 1. An illustration of a typical FESS, reproduced with permission from Elsevier [29].

One typical use for FESS is to smooth the varying supply of electricity from either a change in the grid supply or renewable systems. Renewable energy generation systems are generally intermittent in their creation and supply of electricity. Flywheels are capable of rectifying the wind oscillations, coupled with improvement in the system frequency, and for solar systems, they can be combined with batteries to enhance the system output as well as extend the battery's operational lifetime. This allows flexibility and control to rely more on renewable sources [31,35]. The flywheel energy storage system (FESS) is one such storage system that is gaining popularity. This is due to the increasing manufacturing capabilities and the growing variety of materials available for use in FESS construction. Better control systems are another important recent breakthrough in the development of FESS [32,36–38]. FESS present a green alternative technology to traditional chemical-based batteries for short-term storage needs [39,40], doing so without hazardous materials and offering very long lifetime (millions of full-depth discharge cycles) [41], ease of production [42,43], use, and decommissioning [44], especially with the current increase in renewable energy applications, as shown in Figure 2.

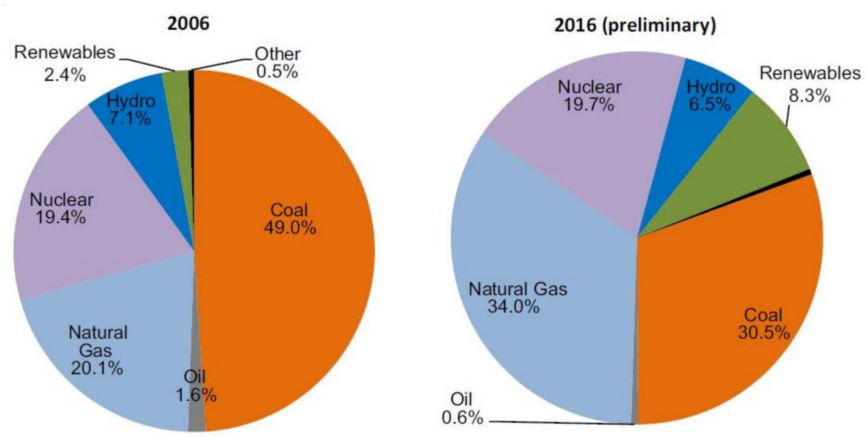


Figure 2. An indication of the increase in renewable energy sources, adapted from [45].

A flywheel's ability to store energy is a well-established phenomenon [46]. Flywheels (FW)/mechanical batteries save excess electrical energy by converting it into motion in a high-speed rotating disk connected to an electric motor. This stored momentum can then be used to regenerate electrical energy when needed [47].

There are already many other ways to store excess energy, as depicted below:

- Pumped hydro storage (PHS);
- Compressed-air energy storage (CAES);
- Battery energy storage (BES);
- Capacitor storage (CS);
- Supercapacitor energy storage (SCES);
- Superconducting magnetic energy storage (SMES);
- Thermal energy storage (TES);
- Hydrogen storage system (HSS);
- Flywheel energy storage system (FESS).

FESS have four main component areas, as shown in Figure 3 below. These are [48]:

1. Machine;
2. Bearing;
3. Rotating mass;
4. Power electronic interface (PEI).

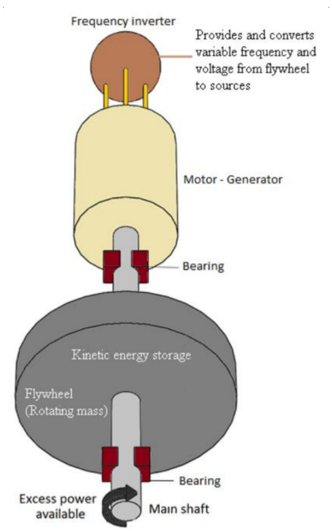


Figure 3. Components of flywheel energy storage system, reproduced with permission from Elsevier [47].

Merits and Demerits of FESS

FESS is gaining much attention from the research community due to the intermittent nature of energy harnessed from renewable sources. The flywheel components are built using environmentally friendly materials. Unlike other storage systems, there is no issue in terms of wear in flywheels; hence, regular maintenance is usually not required. FESS is also developed in the absence of any chemicals. This implies that decommissioning requirements are not needed in flywheel energy storage systems, unlike chemical batteries [48]. Due to industrial development coupled with population growth, the demand for energy continues to increase. Thus, the need for FESS to augment the existing medium of energy generation continues to increase as well. FESS have several advantages and disadvantages, as shown in Table 1. The capital cost of the system is very high due to the need for special materials at high speed, i.e., light mass, and the expensive magnetic bearing in the heavy mass. In general, the FESS needs to have a very balanced system to ensure sufficient mechanical performance.

Table 1. Advantages and disadvantages of the flywheel.

Advantages	Disadvantages	Ref.
• High energy-efficiency • Almost immediate delivery • Strong power • Requires little maintenance • Long service life • Environmentally friendly • Simple and safe • Flexible in the rate of charging and/or discharging	• The need for permanent magnets in the rotor • May require costly cryogenic cooling devices • Cryogenic cooling also reduces the overall energy storage efficiency • Deep discharging cannot be achieved • High capital cost, whether due to the materials' cost for the light rotational mass, i.e., at high rpm, or for the magnetic bearing using heavy rotational masses • High self-discharge rate and low energy density	[29] [47] [48] [49] [50,51]

There are two classifications of speed rating:

- Low speed, less than 10,000 revolutions per minute (rpm);
- High speed, 10,000 to 100,000 rpm.

High-speed FESS is normally restricted by cost, which is normally five times as much as low-speed FESS. The required speeds affect the types of materials (Table 2), size and geometry, and the types of bearings and electrical machines available. However, in the developing industry, they offer the best composites regarding high strength and light weight and the most advanced electronics for power and control FESS, making them a genuine alternative to chemical battery storage systems [29]. FESS can be reused many more times than batteries, and recharging is also quicker [52].

When comparing FESS to batteries, as shown in Table 3, FESS has a higher power output, measured in Watts (W), but cannot store as much energy, Watt-Hours (Wh), for a long period of time. They are presently able to store energy for only a couple of hours. Offering several million discharge cycles, FESS lasts longer. FESS is also lighter, smaller in size, and has a smaller physical footprint. The lifecycle cost for FESS is less than that for batteries [53]. FESS can be used in conjunction with batteries due to FESS being more effective in storing than delivering considerable amounts of energy in a short time. This also increases the batteries' lifetime [54]. FESS can also compete with supercapacitors in short-term storage applications in the seconds to minutes range [46,55–57].

Table 2. Comparison between high-speed flywheel energy storage system (HSFESS) and low-speed flywheel energy storage system (LSFESS).

	LSFESS	HSFESS	
Material for disk	Steel	Composite	Ref.
Electrical machine	Permanent magnet synchronous machine (PMSM), induction machine	Permanent magnet synchronous machine (PMSM)	[58]
Bearing	Mechanical	Magnetic	[59]
Application	Power quality	Traction and aerospace industry	[60]
Cost	Low	High	[60]

Table 3. Comparison between characteristic performance of flywheel and battery [47,49,51,61–64].

Characteristics	Flywheel	Battery
Cycles	100,000 to 10 mil	Up to 20,000 (according to the type)
Energy density (Wh/kg)	130	160
Charging/discharging time	10 s–10 min	Several hours
Self-discharging time	Few hours	5–25 months
Energy conversion	Determined by generator	Chemical process

2. Components of Flywheel Energy Storage System

The flywheel is made up of a disk, an electrical machine, a large capacitor, source converters, and control systems. The main component of the technology, which is the flywheel, has, over the years, supported the smooth running of machines [60]. Steel is the most common material used for flywheels, but recently, the use of composite materials has been encouraged. The main contrast between the steel and composite materials is their rotational stress limitations. The composite flywheels are designed to carry high speeds as well as rotational stress thresholds compared to steel-based ones [65,66]. Therefore, it is recommended that composite materials are used for high-speed flywheels, and steel is used for low-speed flywheels [67,68]. The main challenge with composite materials, however, is the fact that they are very costly.

2.1. Machine

The motor is an electromechanical interface used in FESS. As the machine operates as a motor, the energy is transferred, charged, and stored in the FESS. The machine also operates as a generator when the FESS is discharging. FESS use different types of machines as follows.

- Permanent magnet synchronous machine (PMSM)

This is the most common type due to its excellent efficiency. This type shows less rotor loss due to the rotor flux produced with the permanent magnet. The PMSM shown in Figure 4 is suitable for several applications, but it has a narrow optimum temperature range, and they are also expensive [65,69–71].

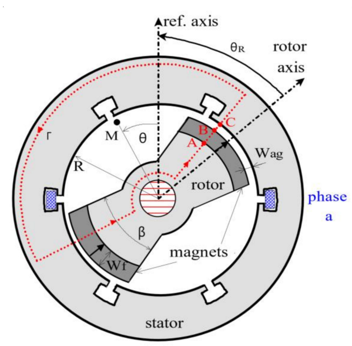


Figure 4. Diagram of permanent magnet synchronous machine (PMSM) for flywheels, adapted from [72].

- Induction Machine (IM)
  - The induction machine shown in Figure 5 should be considered the best all-round choice for high-power installations [73]. They are stoutly constructed, with low build cost, they suit high torque applications, and they are highly reliable [67,74]. They do not suit high-speed applications [75], although double-fed induction machines (DFIM) are in development to overcome this limitation [76,77].

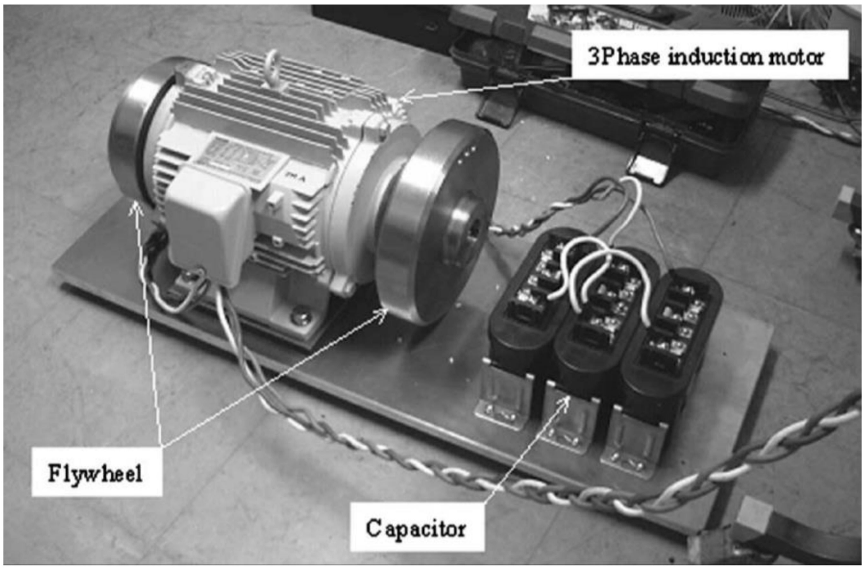


Figure 5. Flywheel energy storage system with an induction motor adapted from [73].

- Brushless direct current machine (BLDCM)
  - A BLDCM as shown in Figure 6 is designed to be a synchronous machine containing a permanent magnet within the rotor and operates a self-controlling function, optimising the stator current by the use of an inverter. High efficiency, large operational speed range, compactness, mechanical stablility, low maintenance, and operation without electromagnetic interference are the main advantages of a brushless direct current machine [78–83].

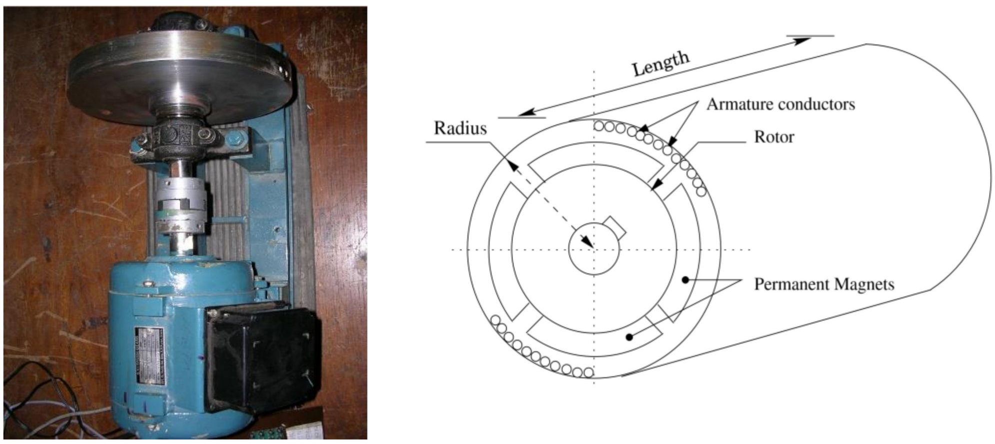


Figure 6. Brushless DC machine with flywheel adopted from [78].

- Switched reluctance machine (SRM)
  - The switched reluctance machine shown in Figure 7 with it's rotor (7(a)) below has a simplified build, and idle losses are low. They can operate in harsh

environments, including at temperatures of 400 °C, still with a wide speed range [84]. Switched reluctance machines similarly are operational even when one or two phases are damaged. An SRM is challenging to control at lower speeds but is easier to control at high speeds than an induction machine [85].

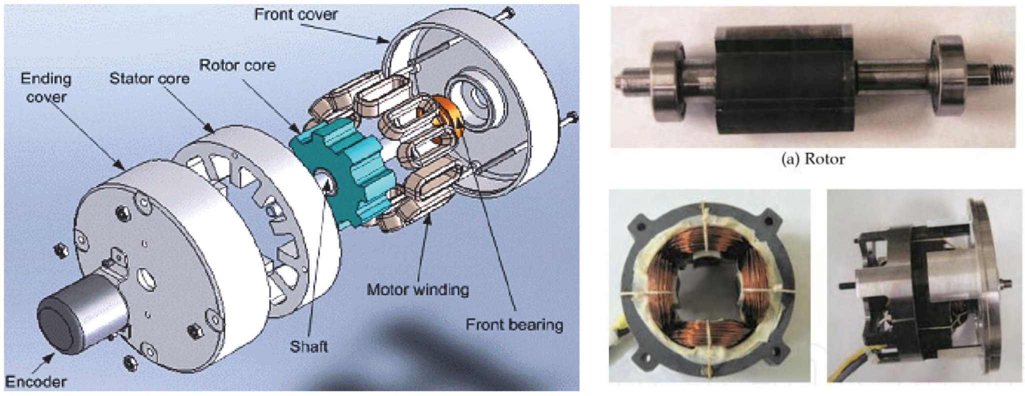


Figure 7. Switched reluctance motor for flywheel adapted from [85].

- Homopolar machine (HM)
    - The HM shown in Figure 8 is also known as the homopolar inductor alternator and also the homopolar synchronous machine [86]. The homopolar machine is well built with low idle losses and suits long-term high-speed applications due to its reliability [87]. There is a reduction in the self-discharge rate using this technology, hence increasing efficiency as well as energy density [88]. This, therefore, reduces the overall cost of this technology. This motor utilises a single winding to generate torque in the absence of permanent magnets [89,90]. They are also ideal for industrial blowers, hole pumps, etc. [91]. Current excitation on the stator side for this type of machine is used with a flywheel [92,93]. During the idling period, magnetisation can be eliminated through the turning down of the current, hence reducing self-discharge losses.

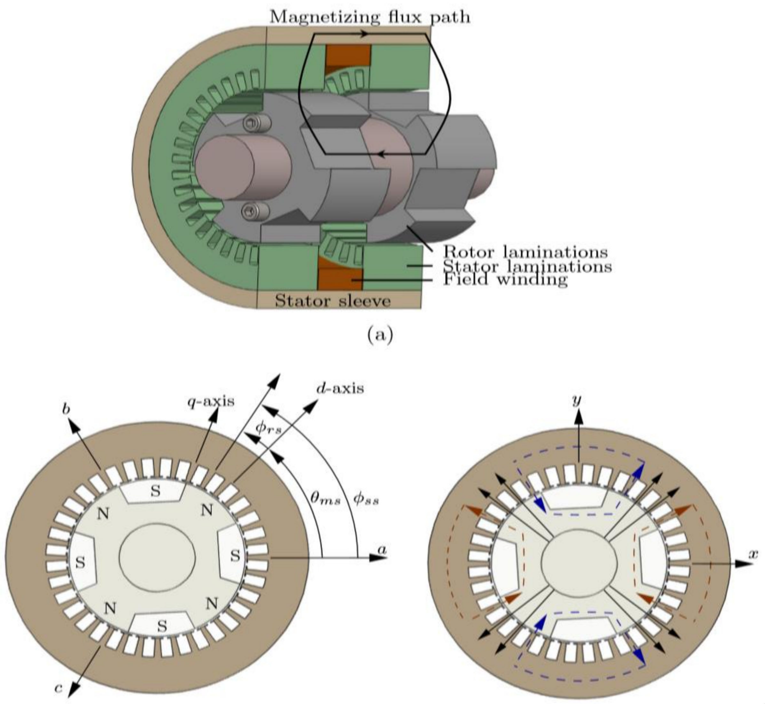


Figure 8. AC homopolar motor, adapted from [94].

- Synchronous Reluctance Machine (SRM)
    - An SRM depicted in Figure 9 is capable of controlling varying torques via two thyristor-controlled components coupled to the stator windings. This allows a dampening effect in the rotating components when used in oscillation mode [95]. Table 4 compares the differences between the switched reluctance machine and synchronous reluctance machine.

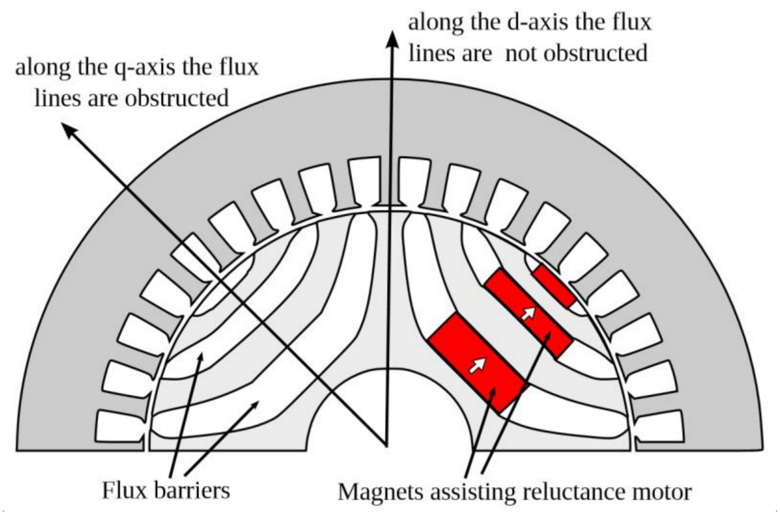
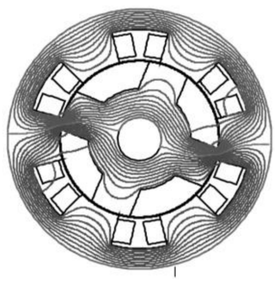
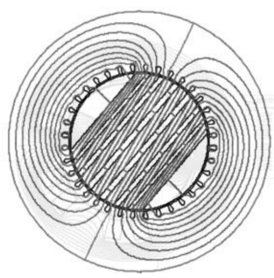


Figure 9. Diagram of a synchronous reluctance motor, adapted from [95].

Table 4. Comparison between switched reluctance machine and synchronous reluctance machine.

	Switched Reluctance Machine	Synchronous Reluctance Machine	
			Ref.
Saliency	Double (Stator and Rotor)	Single (Rotor)	[96]
Sensor	Salient poles (Concentrated coil)	Conventional AC machine	[97]
Rotor	Salient poles	Arrangement of internal flux guides	[98]
Winding	Single tooth winding	Poly phase distributed windings	[99,100]
Excitation	Pulse DC voltage sequence	Balanced sinusoidal currents	[101]
Waveform	Triangular/Trapezoidal	Sinusoidal	[102]
Converter	Asymmetric half bridge	Conventional 3-phase inverter	[103]

2.2. Rotor Bearing

Bearing design is an important part of the FESS process. A poor bearing design will increase friction and losses and will cost more in terms of requiring more maintenance. The first type of bearing used was mechanical bearings; these needed regular lubrication and often failed. The introduction of magnetic bearings changed the validity of FESS as an energy storage device. The main drawback with magnetic bearings is the required sophisticated control system. Magnetic bearings offer low loss, long service life, high speed, high load capacity, and fast response, although FESS has mechanical bearings on standby in the event of failure. FESS use three main types of magnetic bearings as follows:

- Permanent (Passive) magnetic bearing (PMB).

- ○ PMBs are permanent magnets (Figure 10) rather than electromagnetic so therefore are used with other bearing types as they are unable to sufficiently dampen movement on all axes [104]. PMBs offer extremely low losses because of the absence of electromagnetic drag and have low construction and installation costs. They are also used as auxiliary bearings as required [105,106].

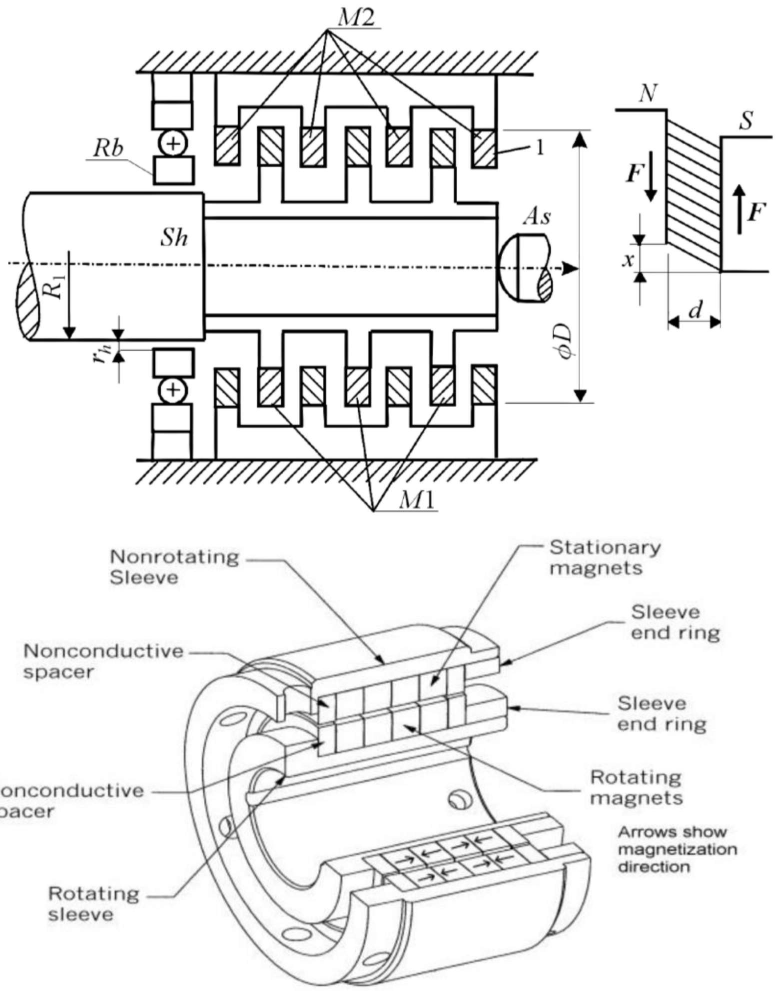


Figure 10. Passive magnetic bearing (PMB), adapted from [107].

- Active magnetic bearing (AMB)
  - ○ Active magnetic bearing (Figure 11) accommodates coils that can adjust the amount of electromagnetic force in the system, thereby reducing vibrations in the rotating mass [108,109]. This is achieved via a feedback system monitoring the shaft position and increasing the stability of the FESS. This suspension and stiffness control increase losses from the power output due to the presence of the control system current. When used in conjunction with mechanical bearings, the complications of the control system can be reduced, making this option more cost-effective, stable, and feasible. However, there is still a need for a complex control system and, therefore, this should not be considered in applications susceptible to electromagnetic interference [110].
- Superconducting magnetic bearing (SMB).
  - ○ SMBs are best for high-speed use, as shown in Figure 12 below. The high speeds generated and the comparatively friction-free environment offer long life and stability. The main disadvantage with SMBs is the need for very low

operating temperatures. Cryogenic cooling is needed to keep the bearings from failing. High-temperature superconductors (HTS) are in use with SMBs to combat this system requirement, and there have been recent attempts to incorporate cryogenic isolation for the SMBs to reduce costs and keep the operating temperatures low, but, at the moment, SMBs and PMBs need to be used at the same time [111,112].

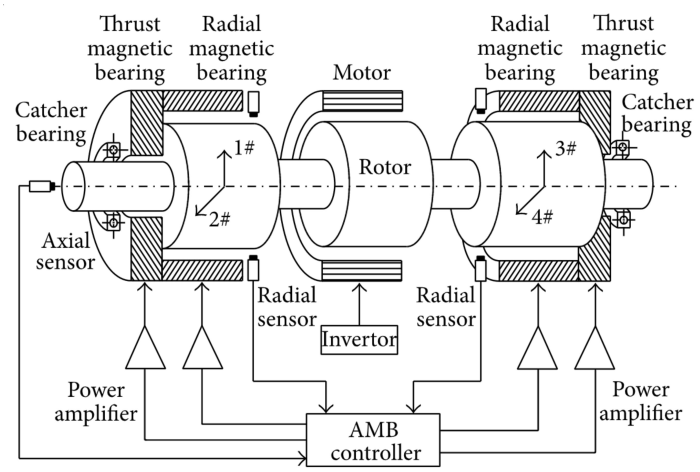


Figure 11. Active magnetic bearing system, adapted from [110].

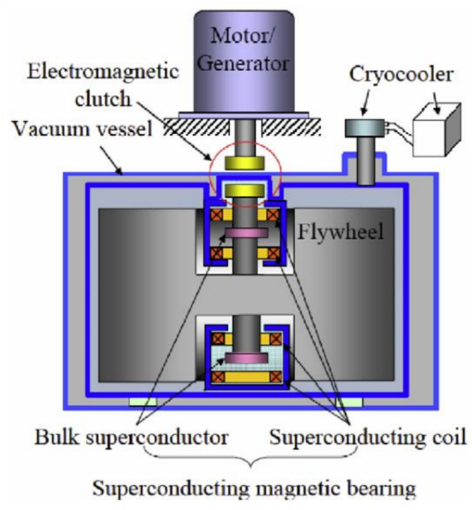


Figure 12. Superconducting magnetic bearing, adapted from [113].

The high-speed rotor and vacuum conditions mean that there is a high pressure placed on the system's suspension bearings [114]. The bearings are used to keep the rotor in place with low friction and provide a support mechanism for the flywheel [59]. Although mechanical bearings have a low initial cost and are simple to implement, there is a huge frictional loss due to the rotor's high rotating speed and the unsuitability of the lubricant for a vacuum environment. This explains why they are rarely used to support the flywheel rotor.

Generally, ball bearings are used in conjunction with magnetic bearings. In addition, ball bearings can also act as catcher bearings and catch the rotor and suspend it if the magnetic bearings fail. Magnetic bearings do not come into contact with the rotor; they have low loss, no wear out, and no lubrication is required [114,115]. However, if active magnetic bearings are used, power is needed to energise them [116,117]. Magnetic bearings use permanent magnets or magnetic fields from current-carrying coils to stabilise the flywheel by supporting its weight [118,119]. There are three types of magnetic bearing systems used: active magnetic bearings (AMB), permanent/passive magnetic bearings (PMB), and superconducting magnetic bearings (SMB) [48,120,121].

- Bearingless machine (BM)
    - A bearingless machine is capable of combining the two independent operations of magnetic suspension and generating torque into a single machine. This approach can be applied to the other types of machine mentioned herein, offering a reduced cost and compact design. BM can be implemented in high-speed FESS [122].

When the electric machine is acting as a motor, it charges the flywheel by accelerating it and drawing electrical energy from the source, storing the energy. When this energy is required, the same machine then acts as a generator, extracting it, thereby slowing down the flywheel. Three common machines used in flywheel energy storage systems are the induction machine (IM), the variable reluctant machine (VRM), and the permanent magnet machine (PM).

For high-power applications, an IM is utilised as it is very rugged, has high torque, and is not expensive. However, some disadvantages associated with the use of IM are its speed limitations, complex control, and high maintenance requirements. IMs are often used in wind turbine applications. Furthermore, the VRM is also robust, has low idling losses, and has a wide speed range. In addition, its control mechanism is easier to use than the IM's. However, it also presents its own drawbacks, such as its low power factor, high torque ripples, and low power density. Due to this, the PM is the most commonly used machine for flywheel energy storage systems. Characteristics such as its higher efficiency, low rotor losses, and high-power density make it a more favourable choice. It is used in high-speed applications extensively because it does not have the speed limitations associated with IMs or the torque ripples, vibrations, or noise of VRMs. However, the disadvantages of PMs include their idling losses, their high cost, and their low tensile strength. To overcome these disadvantages, hybrid PM reluctance machines have been developed [123].

2.3. Containment/Housing

This component provides (Figure 13) the vacuum enclosure, the mounting location for inner components, and it provides containment of the rotor if it fails, protecting external facilities and workers. If a rotor fails, its crack mode depends on the material it is made from. If the flywheel rotor is made from metal, then it is prone to break into larger pieces, which can be predicted as metals are homogeneous isotropic materials [124]. However, rotors made from composite materials tend to break into numerous small fragments [125].

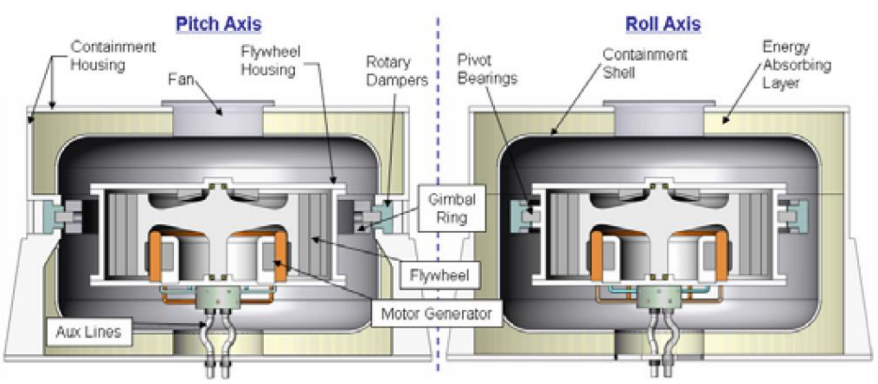


Figure 13. Flywheel containment structure, adapted from [126].

2.4. Power Electronic Interface

It is the improvements in electronics since the 1960s that have led to the feasibility of FESS. FESS would not be possible without the control circuitry [127]. The power electronic interface continues to play a major role in FESS today. The topology—which is the way in which a device networks with devices and, in the case of FESS, grids—is a deciding factor when considering layouts and applications. The most common layout is AC-DC-AC. This is also known as back to back (BTB). In this configuration, the grid connection side supplies an AC supply to the system; it is then converted to DC and then converted to the relevant AC voltage for the machine. See Figure 14 for this layout with a wind turbine.

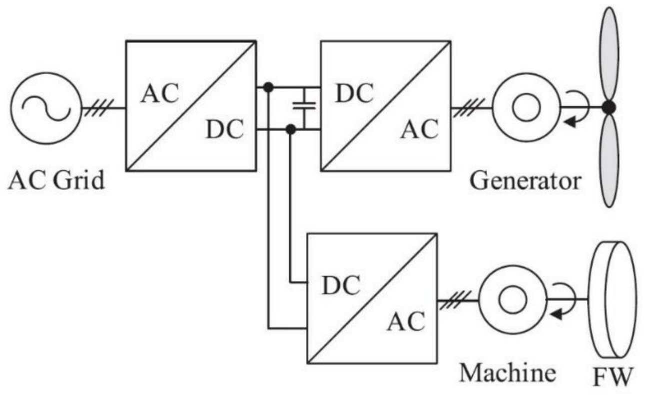


Figure 14. Back to back layout, adapted from [128].

Other topologies include AC-AC, DC-AC, and DC-DC. The system may be used with a DC link in some applications, using a subsidiary DC-AC converter to allow use with an uninterruptable power supply (UPS) [128].

The standard operational process of an FESS is explained as an electrical supply is used to "charge" the flywheel. This "charging" drives the mass in a rotation and converts the electrical supply to kinetic energy. The amount of energy that can be stored depends on the FESS's physical attributes, the mass of the flywheel, the material, and the rated maximum rotational speed. After charging, the energy is stored as kinetic energy and maintained in standby mode by allowing the flywheel to spin for as long as possible, minimising any restrictive forces to the rotation. When the energy is needed, the flywheel can then transfer the kinetic energy back to electrical energy via the machine [128].

Another type of PEI is the AC-AC matrix converter (MC) shown in Figure 15. MC offers the advantage of not needing any system capacitors. This means that there are no capacitor balancing issues. Further advantages include lower weight, smaller volume, and a modest structure. This type of converter was introduced by Gyugi and Pelly [109]. MCs can be direct or indirect. MCs have the disadvantages of having their output gain capped at 86.6%, a high level of total harmonic distortion (THD), and they require a complex control system [129].

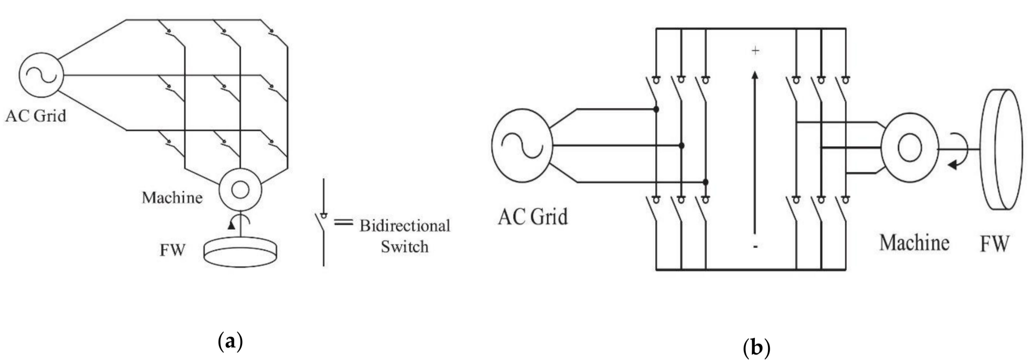


Figure 15. (**a**) Direct matrix converter, (**b**) indirect matrix converter, reproduced with permission from [48].

3. Current Application of FESS

Flywheels can provide an excellent addition to energy-producing systems. This is because energy can be easily input and output depending on how much energy is being produced at a given time. Flywheels may also be used for many different scales of projects but will only be implemented if it is found to be economically feasible for the entire system, i.e., if it will benefit the whole system. FESS can be more efficient than compressed air and thermal energy storage in specific applications. For larger-scale energy applications, FESS is usually only used when other storage methods are not viable. The system is not necessarily new, but recent developments in its internal features have enabled new advancements in its technology to become integrated with current energy-producing projects. Figure 16 shows the various applications of the flywheel energy storage system.

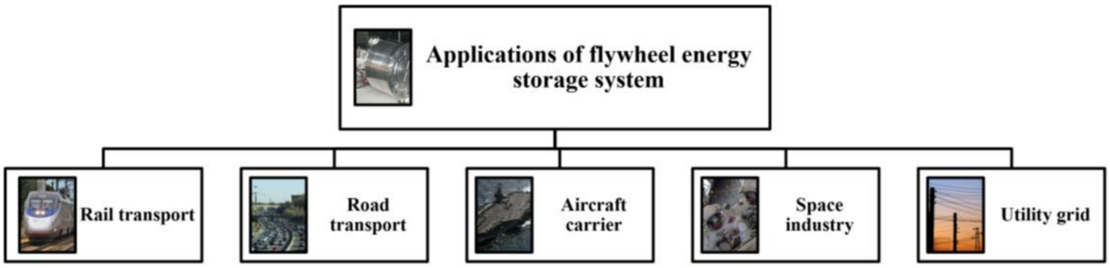


Figure 16. Applications of flywheel energy storage system.

3.1. Application of Flywheel in the Transport Sector

3.1.1. Rail Transport

Energy consumption by light rail transit trains (Figure 17) could be reduced by 31.21% by capturing the braking energy with a flywheel energy storage system. This FESS also has the benefit of having, compared to other storage systems, a better energy capacity by mass and, due to the unlimited charge/discharge cycles, comparatively long life. Low-speed flywheels, more suitable for short-journey trains, are more cost-effective than high-speed flywheels; the cost per kWh is in the hundreds for the former and up to USD 25,000 for the latter. The low-speed rotors are generally composed of steel and can produce 1000s of kWh for short periods, while the high-speed rotors produce kWh by the hundreds but can store tens of kWh hours of energy [35].

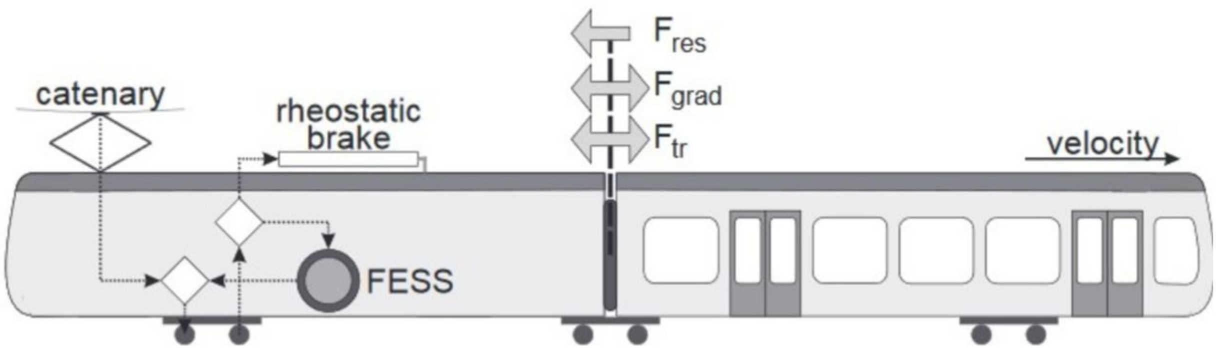


Figure 17. Flywheel energy storage system in rail transport, reproduced with permission from [35].

The heavy-haul locomotives are open to developing a hybrid diesel/electric system that has been in use historically in automotives. Heavy locomotives require consideration of the weight, size, power/energy densities, lifespan, and cost before considering which energy storage system is best. Wang et al. suggest that a flywheel system is installed as a booster unit to the usual locomotive [129]. Flywheels were first designed for use in a stationary position but have, however, lately undergone much research, to the extent that

NASA uses them. To be used in locomotives, they have to be able to withstand shocks from movement. Meinert's (2015) research explains that FESS has several uses within the locomotive industry [130]:

- On-board use in diesel–electric vehicles to store braking energy;
- On-board use in DC systems to raise the recuperation rate;
- Stationary use in DC power supply systems to raise the recuperation rate.

The FESS used have an efficiency of an impressive 95% [130].

In Los Angeles VYCON Inc., flywheels attached to the track recover the once wasted energy from trains as they brake. This recovers 66% of the braking energy, with an energy saving of 20% within 6 months of installation. The trains have traction systems that are AC and DC, all resulting in a monetary saving for each station.

3.1.2. Road Transport

In hybrid automobiles, flywheels, as shown in Figure 18, are used to give extra power to push uphill and, whenever an acceleration boost is required, contributing to fuel conservation, they extend the lifespan of the engine while cutting down on noise and air pollution.

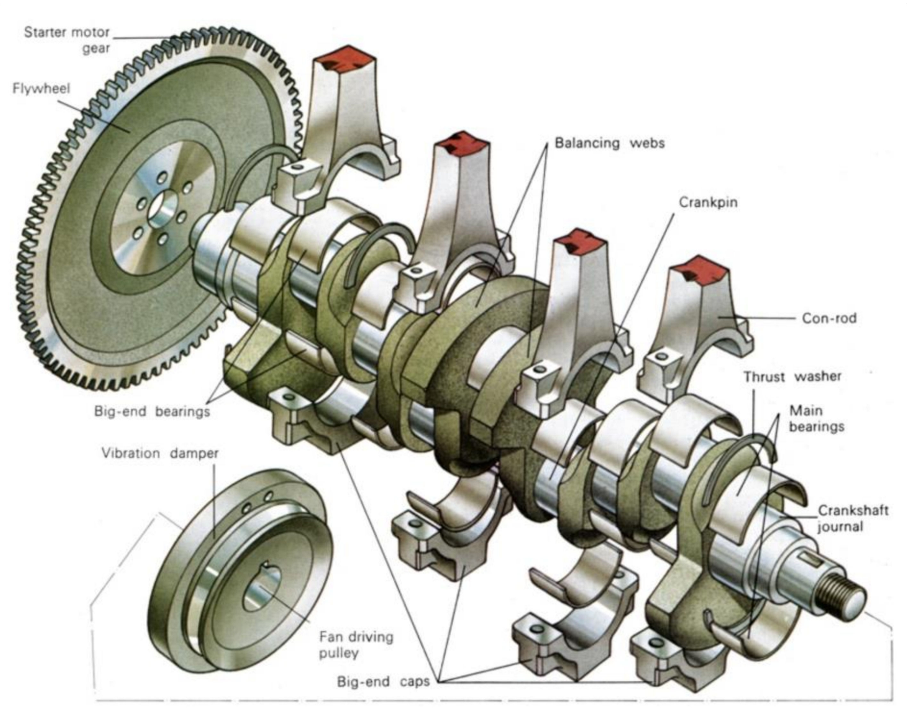


Figure 18. Applications of flywheels in vehicles, adapted from [131].

The S60 sedan from Volvo (Figure 19) has a flywheel system where the energy can be used to power the vehicle. The flywheel provides a 25% reduction in fuel usage due to the engine being cut off by the braking energy. Volvo confirms that applying the flywheel as a kinetic energy recovery system (KERS) during the retardation "braking" resulted in a reduction in fuel consumption by 25%. In such a system, the flywheel uses the braking energy, which is used again when the car starts to move. The Williams Formula 1 Team developed the Gyrodrive, which has been installed in over 200 buses run in Oxford, and these flywheels can rotate up to 36,000 rpm, again, saving 25% fuel.

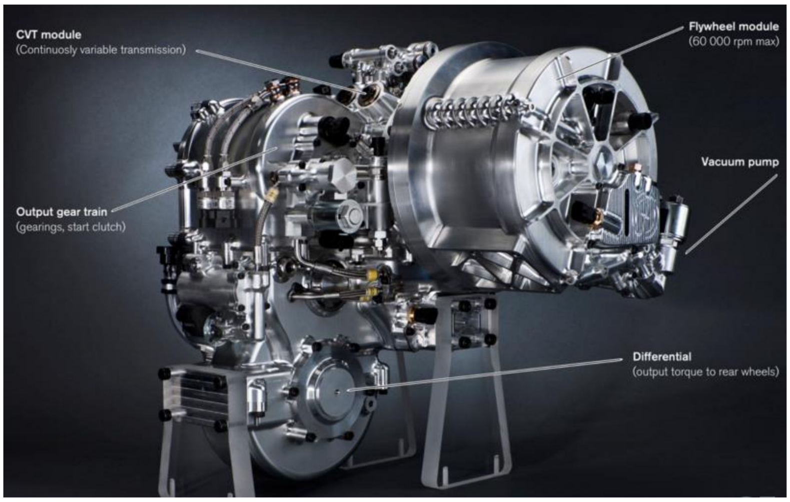


Figure 19. S60 Sedan volvo flywheel, adapted from [132].

3.2. Aircraft Carrier

The USA aircraft carrier Gerald R Ford has an "electromagnetic aircraft launch system" (Doyle); to enable this to work properly, it is fitted with flywheels (Figure 20) to store energy from the ship's engine for quick release when needed to help lift the aircraft. This technology allows 122MJ to be released in 2–3 s and this energy is restored in 45 s. They rotate at 64,000 rpm with a density of 28 kJ/kg [133].

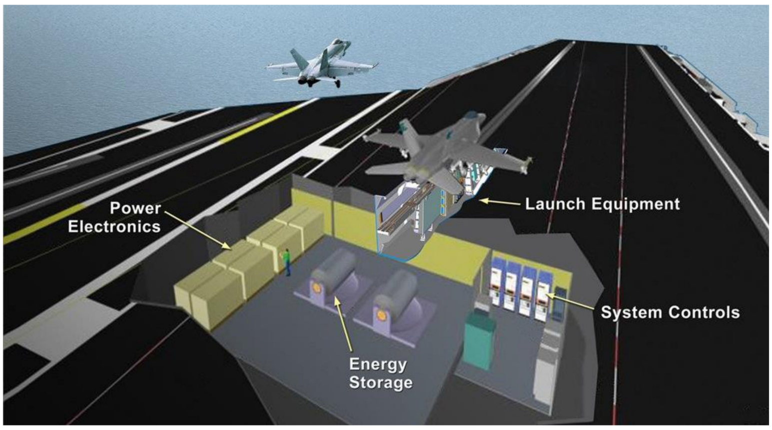


Figure 20. Electromagnetic aircraft launch system, adapted from [133].

3.2.1. Incredible Hulk Roller Coaster

In Orlando Florida, the Incredible Hulk theme ride uses flywheels to capture the energy as the roller coaster falls downwards followed by rapid acceleration. Here, 4500 kg flywheels are used to power the mechanics of the uphill propulsion. The flywheel can discharge 8 MW and recharge at 200 kW [134,135].

3.2.2. Domestic Applications of Flywheels

Similarly, in terms of residential application, the production of a domestic FESS may help to establish a low-carbon future. The excess energy produced by other renewables can be stored and released on-demand, with guaranteed wear and tear over 25 years and an efficiency of 90% [136,137].

3.2.3. Flywheel Application in the Space Industry

Due to the gyroscopic effect, satellites are using FESS because of the quick recharge and high efficiency of the system, but they can also exploit the added advantage of the gyroscopic effect to control the satellite's movement in space. The recent development of power electronics technology, new strong, lightweight materials, and magnetic bearings has raised interest in FESS. They can now outpower chemical batteries. These new developments (Figure 21) were carried out by NASA for energy storage in space [138].

Figure 21. NASA flywheel and mounting bracket, adapted from [138].

3.3. Load Levellers

This type of FESS is used when a highly variable electrical load is installed in a location away from the power plant, or when power lines are not up to a sufficient standard, resulting in oscillations in power delivery. Within this scenario, a load-leveling unit could be installed, which would increase the efficiency of the systems, providing a more uniform and continuous supply of energy [139].

3.4. Emergency Devices

The application of FESS can vary from complex to simple systems. Most existing systems are connected to cooling shafts or lubrication pumps. This is to help the system's operation if any emergency occurs, and backup power is needed for emergency buildings, such as hospital devices, or to ensure the safe slowing down of the mechanism [138].

3.5. Low-Energy Applications

Applications that store small amounts of energy to equalise the machine's motion are considered low-energy storage applications. The majority of FESS used in industries using low energy storage are within this category as the majority will be used from mechanical rotational systems such as friction welding or mechanical press machines [138].

3.6. Utility Grid

With regard to having FESS implemented within the utility grid, recent trials have been carried out by the University of Sheffield, Schwungrad Energie, Adaptive Balancing Power, Freqcon in Ireland, and the Schwungrad Energie Hybrid Flywheel-Battery Facility, as shown in Figure 22 below. The system was to be Europe's and the UK's largest and first FESS connected to the Irish and UK grid. This trial aimed to investigate whether or not the systems would benefit the utility grid [44].

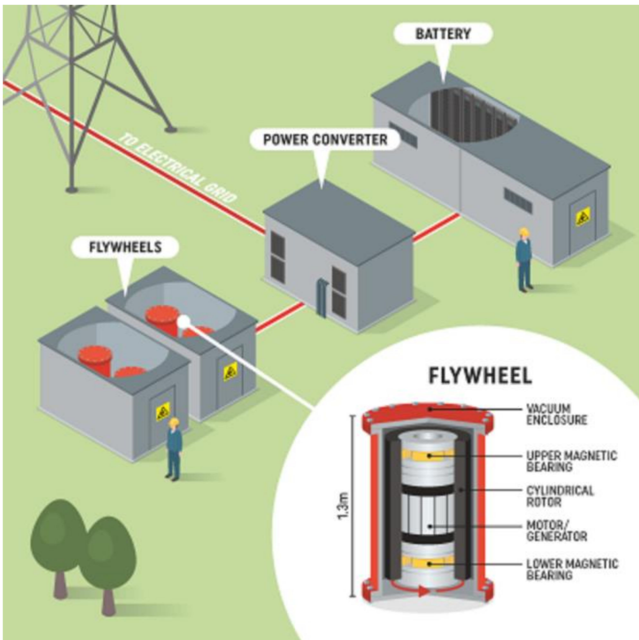


Figure 22. Domestic application of flywheel, adapted from [139].

Due to the demanding oscillatory nature of electricity from the public, the year-long FESS trial demonstrated that it would be very beneficial to have this sort of system connected to the grid. Due to the trial showing much promise, the University of Sheffield decided to go forward and install another FESS at their 2 MW battery facility to provide "20 kWh of energy storage" [139].

3.7. Materials

The flywheel was not a popular choice but has re-emerged lately, with promising applications for storing energy—this is due to massive improvements in the technology and materials used. When the flywheel is weighed up against conventional energy storage systems, it has many advantages, which include high power, availability of output directly in mechanical form, fewer environmental problems, and higher efficiency. Conventional steel-based flywheels have a much lower density than composite material flywheels, being able to have a greater higher density. A report based on a comparison of flywheel properties suggests that using a 70% graphite whisker/epoxy material will yield an improvement of 17.6 over steel, which was thought to be the highest-strength material for a constant stress flywheel rotor [140].

The maximum energy storage of the flywheel can be calculated using Equations (1) to (5).

R = radius

t = thickness

ω = angular velocity

1. The flywheel stores kinetic energy E

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

2. $J = \pi\rho R^4 t/2$ axial mass moment of inertia of the disc and ρ is density; therefore,

$$E = \frac{\pi}{4}\rho R^4 t\omega 2 \tag{2}$$

Mass of disc is $m = \pi R^2 t\rho$

3. Energy per unit of mass is the ratio of the last two equations

$$\frac{E}{m} = \frac{1}{4} R^2 \omega^2 \tag{3}$$

4. Poisson's ratio, v. Stress must not exceed yield strength (σ_y), factor of safety, S.

$$\frac{E}{m} = \left(\frac{2}{S(3+v)} \right) \left(\frac{\sigma_y}{\rho} \right) \tag{4}$$

5. v is roughly 1/3 for solids and is treated as a constant

$$M_s = \frac{\sigma_y}{\rho} \tag{5}$$

M_s units is kJ/kg.
Some materials used for the manufacturing of the rotor are summarised in Table 5.

Table 5. Materials for rotor of FESS [140,141].

Material	Density (kg/m3), ρ	Strength (MPa), σ	Energy Density (MJ/kg)	Cost ($/lb)
Steel (AICI 4340)	7800	1800	0.231	1
Alloy (ALM_nM_g)	2700	600	0.22	3
Titanium ($TiAI_6Zr_5$)	4500	1200	0.27	9
Carbon-fibre composite (S2)	1920	1470	0.766	24.6
Carbon-fibre composite (M30S)	1553	2760	1.777	n/a
(M30S) 1553 2760 1.777 n/a Carbon-fibre composite (T1000G)	1664	3620	2.175	101.8

The material's ability to withstand centrifugal force exerted on it determines the speed of the rotor. This is the ultimate strength of the material. There is a direct relationship between the mass, centrifugal forces, and radius, as well as the speed. The maximum energy per volume and mass is represented as Equations (6) and (7).

$$e_v = K \, \sigma_{\theta,u} \tag{6}$$

$$e_m = K \left(\frac{\sigma_{\theta,u}}{\rho} \right) \tag{7}$$

K is the shape factor, ρ is the density, and $\sigma_{\theta,u}$ is the ultimate tensile strength.

Materials ideal for flywheels must be light in weight. This implies that the density of the material must be lower as well. For higher speeds, the material must also have high tensile strength. These characteristics are common with composite materials, unlike metals with higher weight, but the cost of metal is lower than that of composites. The shape factor K is also a representation of material utilisation. The shapes of flywheels manufactured from composite and metals are depicted in Figure 23.

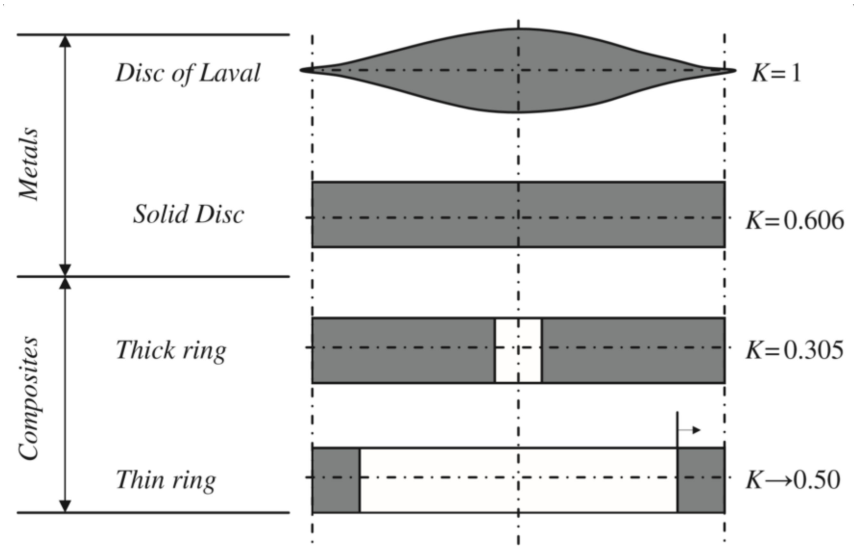


Figure 23. Shapes of FESS composed of composite and metallic materials, reproduced with permission from Elsevier [141].

Commercial Use

Larger-scale companies would be best using composites (carbon fiber-reinforced polymer composites, CFRP) because they are the best performing and also the most affordable. Meanwhile, a smaller company would more than likely use a composite (glass fiber-reinforced polymer composites, GFRP) due to it being almost the same as composite CFRP but cheaper. These smaller companies could use lead alloys and cast iron, but these choices are limited in terms of speed [142]. Table 6 contains information to help in the selection of the most appropriate material.

Table 6. Some selected materials for FESS.

Material	kJ/kg	Comments	Ref.
Ceramics	200–2000	High failure rates so rarely used	[142]
Composites: CFRP	200–500	Most popular, used in a wide range of applications	[142]
Composites: GFRP	100–400	Also widely used. Less range than CFRP but cheaper	[139]
Beryllium	300	High costs and challenging to work with	[140]
High-Strength Steel	100–200	These blends are all equal in strength and applications. Steel and aluminium are less expensive than magnesium and titanium	[141]
High-Strength Al Alloys	100–200		
High-Strength Mg Alloys	100–200		
Ti Alloys	100–200		
Lead Alloys	3	Traditionally used when requiring high density and in low-speed applications	[140]
Cast Alloys	8–10		

4. Design

4.1. Rotor Design

Energy storage technologies are becoming very useful for cases where energy needs to be stored and used later. The most common types of energy storage technologies are batteries and flywheels. Due to some major improvements in technology, the flywheel is a capable application for energy storage. A flywheel energy storage system comprises a vacuum chamber, a motor, a flywheel rotor, a power conversion system, and magnetic bearings. Magnetic bearings usually support the rotor in the flywheel with no contact, but they supply very low frictional losses, the kinetic energy is stored, and also the motor changes mechanical energy to electrical energy and vice versa. The rotor makes use of high speed, high mechanical strength, dynamic properties, and high energy density. The rotor is the main component of the flywheel energy storage system. Recent studies have shown that optimal design and stress analysis are the main priorities associated with the development of flywheel rotors [140].

4.2. The Flywheel Rotor Design Process

This process, shown in Figure 24, consists of the rotor type option, optimum design, requirements analysis, performance evaluation, and general design. The aim is to determine the geometric parameters of a flywheel dependent on a restricting factor; surroundings and influences must be taken into consideration, which includes the general configuration of the flywheel energy storage device, operation speed, material behaviour, the stored energy, rotor dynamics, moment of inertia, structural manufacturability, and flywheel rotor mass [140,141].

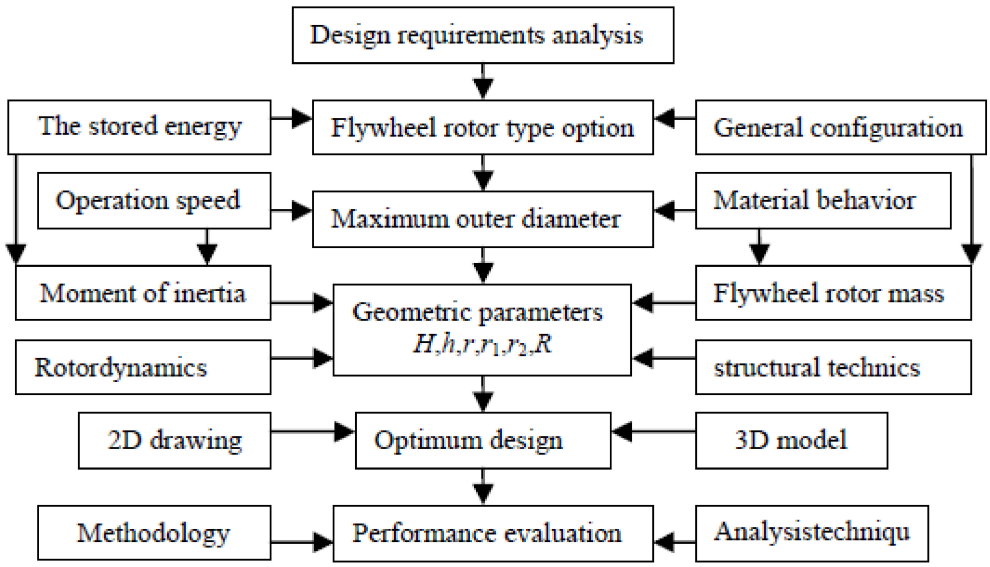


Figure 24. Flywheel rotor design process and its influence factor, reproduced with permission from [143].

4.3. The Stress Analysis

This section gives an example of how a design could be accomplished for a flywheel. The metal flywheel can be grouped into two spokes and a metal rim, as shown in Figure 25. They have a uniform thickness rotating disk. The stress at a particular point in the disk can be in three stages: the radial stress σ_r, tangential stress σ_θ, and axial stress σ_z. This is because the surface of the disk is a free surface in the z direction, $\sigma_z = 0$. For the case of an isotropic material, the radial and tangential stress are stated below in Equations (8) and (9).

$$\sigma_r = \frac{3 + \mu}{8}\rho\omega^2\left(R^2 + r^2 - \frac{R^2 r^2}{r_i^2} - r_i^2\right) \tag{8}$$

$$\sigma_\theta = \frac{3 + \mu}{8}\rho\omega^2\left(R^2 + r^2 + \frac{R^2 r^2}{r_i^2} - \frac{1+3\mu}{3+\mu}\, r_i^2\right) \tag{9}$$

r = inner radius;

R = outer radius, v = poisson's ratio, $\rho = material\ density$, ω = angular velocity and r_i = radius.

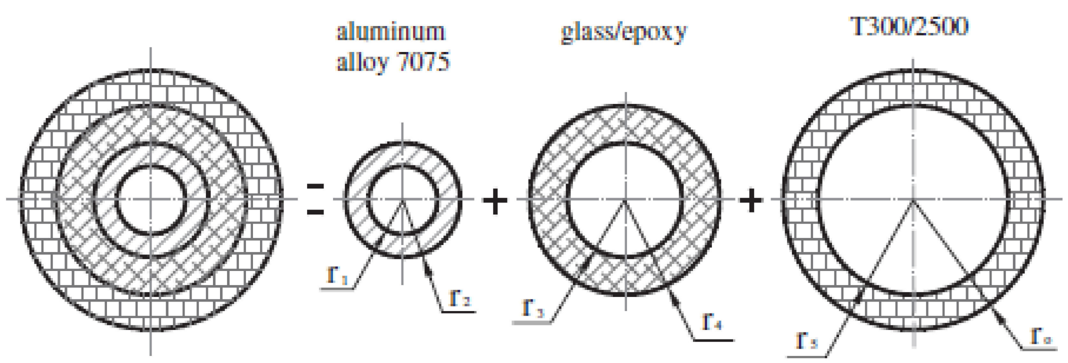


Figure 25. A schematic diagram of hybrid composite flywheel structure, reproduced with permission from Elsevier [144].

4.4. The Failure Criteria Selection

For a composite rim, the failure criteria are Tsai-Wu, Tsai-Hill, Hoffman, and Maximum failure [145]. For isotropic materials, the failure criteria are Tresca, Von Mises, and Tresca Stress. The Tresca criterion is known to be more conventional and can also be used for ductile and isotropic materials. The disk is made of plastic metal. Therefore, the tresca stress criterion is used as a failure criterion. This simply means that failure occurs due to the maximum shear stress in the component being equal to that of the maximum shear stress in a uniaxial tensile test at the yield stress. σ_1 *and* σ_3 are the maximum and minimum principal stresses, and σ is the safe stress.

$$\sigma_1 - \sigma_3 \leq [\sigma] \tag{10}$$

The flywheel in comparison to other typical energy storage systems has a lot of benefits; these benefits are a reduction in environmental issues, high energy/power density, high efficiency, and accessibility of output energy exactly in mechanical form. The flywheels made of composite materials permit high density, unlike the typical steel-based flywheels with low density [70]. Two materials are mainly used to construct flywheel energy storage systems: they are composite materials made up of carbon fiber or graphite and metal materials. A hybrid composite flywheel, shown in Figure 25, operates on a simple concept, which is to place the stiffer and lighter materials in the outer side of the rotor and the softer and heavier materials in the inner side of the rotor. The hybrid composite is made of three layers: the inner layer, which is aluminum alloy 7075; the middle layer is a softer composite of epoxy/glass, and the outer layer is high-strength composite T300/2500 [129,130].

The properties of the three materials in a hybrid composite flywheel are shown in Table 7 (adapted from [140]) below. Figure 26 also shows a multi-rim rotor for FESS. The analytical method for the study of the hybrid composite multi-rim flywheel rotor can be traced back to 1977 [68].

Table 7. Material characteristics of hybrid composite flywheel [68,130,140]

Material Property	T300/2500	Glass/Epoxy	Aluminium Alloy 7075
Density (Kg/m^3)	1600	1800	2800
Long-Trans. Poisson’s Ratio	0.3	0.26	0.3
Longitudinal Young’s Modulus (GPa)	130	38.6	72.5
Transverse Young’s Modulus (GPa)	9	8.27	-
Long Tensile Strength (MPa)	1800	1062	590
Long Compressive Strength (MPa)	1400	610	-
Trans. Tensile Strength (MPa)	80	31	-
Trans. Compressive Strength (MPa)	168	118	-

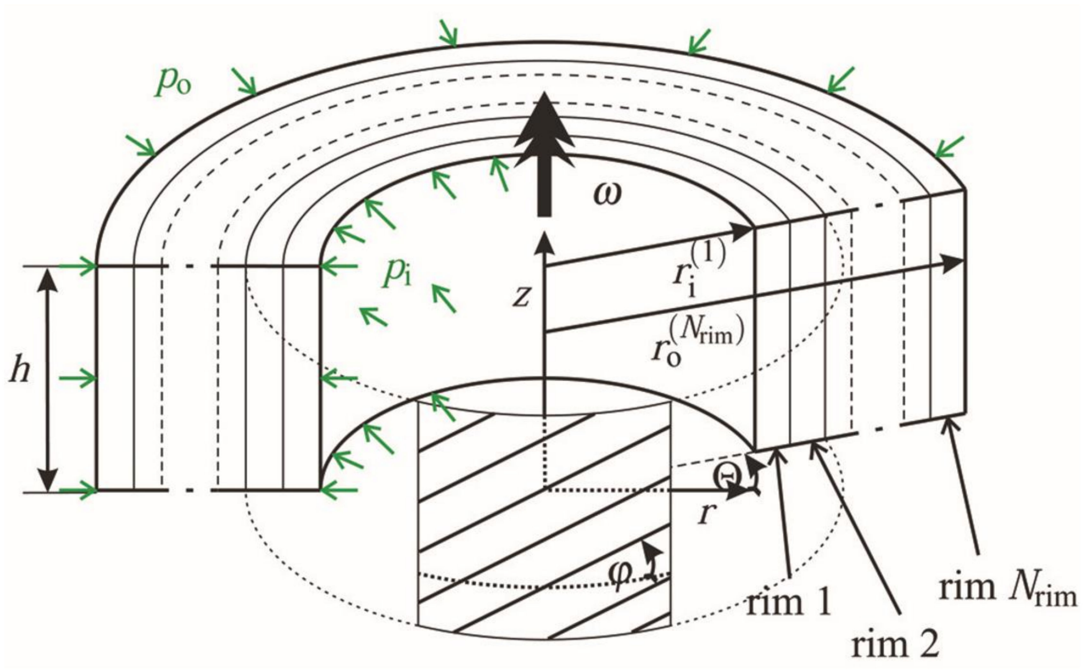


Figure 26. Rotor set up for flywheel, adapted from [146].

These two materials have different specifications and there are different reasons as to why they are both used. In as much as the kinetic energy for both of these materials is similar when they both have constant thickness, composite rotors are known to perform better in relation to specific energy and they also have a lower specific energy than metal rotors, which make use of tensile failure considerations. However, some physical limitations and the impact of materials must be recognised. In some recent studies, an optimised model permitted the application of limitations on the radial stresses, as well as direction-dependent failure modes, which then caused a limit in the attainable specific energy of orthotropic materials such as composites used to make flywheel rotors. In an attempt to improve the performance of flywheels, a study showed that press-fitted multi-rim composite rotors with detailed material series could overtake metal flywheels and single-rim composite flywheels in relation to total energy [109,126]. One of the performance criteria used was energy per cost, and it revealed that two-rim motors presented no meaningful benefit over single-rim motors. With additional developments, the metal flywheel could accomplish optimised stress distribution with the use of differences in the shapes of the rotor. This analysis will make use of a 2D or 3D numerical rotor model. The outcome of exhaustion on the efficient performance of the various types of flywheel rotors over their anticipated lifespan can add to the selection of rotor materials and needs to be reviewed [68,147].

4.5. Overview of Flywheel Mounted on a Rotating System

The application of flywheel energy storage systems in a rotating system comes with several challenges. As explained earlier, the rotor for such a flywheel should be built from a material with high specific strength in order to attain excellent specific energy [148]. This supports the fact that material selection, as discussed earlier, is key in the determination of flywheel for specific application. The material type selected has a direct correlation to the specific energy coupled with the rotor tip speed that can be harnessed from the flywheel. It must, however, be stated that an increase in the tip speed will also imply an increment in parasitic windage loss. Reducing the windage loss will require the rotor to rotate inside a vacuum [149]. The utilisation of a vacuum also comes with its own challenges in terms of vacuum compatibility. The bearing, for instance, should be designed to sustain high speed, higher stiffness, durability, and higher load capacity. Due to these demands, magnetic bearings are often selected for flywheel energy storage applications in spite of the magnetic bearing method being novel. This section will attempt to evaluate flywheel energy storage systems with a specific focus on the ones mounting magnetic bearings.

4.5.1. Bearing Load

In the case of a vehicle, the bearing loads come from the vehicle and the flywheel energy storage itself. Due to the flywheel being fixed in the vehicle, they are exposed to base motion input at the various installation points. Motion at the mount points can be categorised into shock, vibration, and maneuvering. These phenomena are predominantly common when the vehicle hits a pothole, cobblestone pavement, etc. Residual mass imbalance of high-speed rotors is another source of bearing load [149]. Shock, vibration, maneuvering, and imbalance will critically be discussed in subsequent sections. Another key area that will be discussed is gyrodynamics, which is sub-classified under maneuvering. The last few decades have seen several research works carried out to determine vibration and shock loads on vehicles as a result of irregularities on the road. The parameters deduced were presented in terms of power spectral density plots [150]. Power spectral density plots present detailed information on amplitude as well as frequency values of road vibration under varying operating conditions. According to the literature, vibration due to the road decreases rapidly with respect to an increase in frequency. It must be stated that high-frequency vibration can be filtered more easily compared to low-frequency vibration. The flywheel energy storage mount points will normally have a lower frequency, between 0.25 Hz and 25 Hz. Most reported information is for road input at either the road surface or the axle. There is very limited information on the impact of vibration or shock on the chassis of vehicles.

Shock

Shock scenarios occur due to potholes and are characterised by their transient nature. Evaluation of shock from a technical point of view has been presented by several researchers [151,152] in terms of the impulsive aspect. The impact of the shock on the system is influenced by the peak acceleration of the system due to the shock. In the case of vehicles, the shocks created from the road are mitigated with the aid of a suspension. The movement of the flywheel energy storage system mount point due to shock is needed in order to determine the flywheel energy storage bearing loads. Mount point motion is referred to as a transient waveform of displacement. The motion occurring in three orthogonal directions for the mount point is usually stated categorically. The waveform created is dependent on the type as well as the nature of the shock. When carrying out a simulation, the same waveform is utilised at each mount but the longitudinal, lateral, and vertical directions are considered separately. Objects hitting the flywheel housing unit can also create shocks, as can a collision. Most testing in the automotive industry is carried out to ensure that, in the event that a vehicle collides, it can sustain the shocks impacted on it [153].

Vibrations

Variations differ from shocks in terms of the input and response to attain amplitude at a steady state, which is usually required to be maintained for a longer period of time. Activating the vibration source results in transient conditions, which is often considered a major issue as it is dealt with using shock methods. The vibration motion for a flywheel energy storage system can be denoted in terms of spectral density plots of acceleration against frequency. With the aid of information from PSDs, researchers have developed realistic surface terrains suitable for computer simulations for testing mounting hardware performance. Most vehicles are designed so that the tires coupled with the suspension reduce high-frequency loads [153]. It is often recommended that the "Functional equipment shall operate without degradation during and after exposure to vibration as predominant in normal revenue service". Figure 27 captures the specific vibrating spectrum. This is recommended for an area next to the rear end of a bus. It is, however, recommended that operation should continue without any degradation, even after 1000 h of vibration under a nonoperating state.

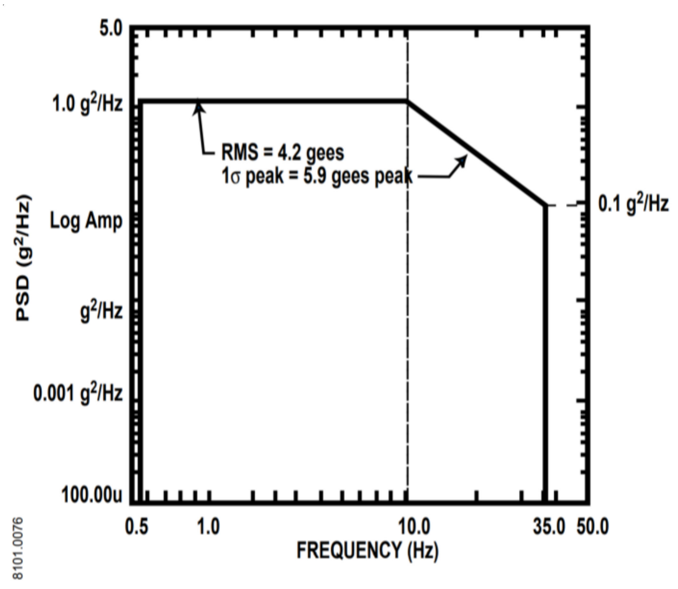


Figure 27. Requirements for vibration spectrum for flywheel at the rear end of a bus, adapted from [153].

Rotating Mass Imbalance

Residual mass imbalance for the flywheel rotor is another source of load for flywheel energy storage system bearings [154]. The magnitudes for the loads are directly related to the rotor imbalance but also correlated to the dynamics for the rotor-bearing system. In flywheel energy storage systems, the flywheel, similarly to high-speed rotors, is designed to be precision-balanced. They are designed such that, after balancing, the flywheel's mass centre is usually within 1.3×10^{-6} m from the centre of rotation. The radial magnetic bearings determine the centre of rotation. Due to this balance level, the bearing loads are often around 89 N or lower, within the flywheel energy storage system's operating speed range. The presence of the magnetic bearing provides the potential to sustain a larger mass imbalance. Should the flywheel energy storage system flywheel rotor fail in holding its precision balance, the magnetic bearing control algorithm can be employed to rebalance the rotor [155,156].

Gyrodynamics

The relatively large angular momentum for the flywheel rotor results in gyroscopic effects. A gyroscopic effect is a vector quantity with both directions as well as magnitude. The angular momentum vector is seen in the direction of the rotational spin axis for a high-speed flywheel rotor, and this usually comes with magnitude. In an attempt to alter the position of the flywheel spin axis, larger torques will be required. It is recommended that the torque emanates from the radial bearings because the flywheel is usually not in contact with anything when in operation. Other authors have explored the gyroscopic effect on flywheels for vehicles [157]. A correlation between the torque needed to change the position of the flywheel axis is very important, as depicted in Equation (11).

$$Torque = P\Omega\dot{\theta} \quad (11)$$

where P = polar moment of inertia of flywheel rotor (kgm^{-2});
Ω = spin speed of flywheel rotor (rad/s);
θ = rate of turn of the flywheel axis (rad/s).

There are instances where the gyroscopic torques are so huge that they impact the movement of a vehicle [158]. This is very common in space vehicles as well as ocean ships. For vehicles, the gyroscopic torque is too small to affect the movement of the car but can be a key source of load on the radial bearings. When the vehicle is designed in such a way that the flywheel is firmly anchored to the bus, the bearing load, in this case, can be ten times the capacity of the radial magnetic bearings. In order to curb the generation of large gyroscopic torques, the position of the flywheel rotors must be isolated from the position of the vehicle chassis. This simply implies that the flywheel must be vertically aligned. This approach ensures that the flywheel is isolated from the vehicle yaw changes. There must also be some component to sustain the flywheel in order to allow it to pitch or roll freely. Figure 28 presents an image showing a mathematical model established to ascertain the interaction between a flywheel and a vehicle. In the figure, a rigid rotating flywheel mass can be seen inside a unit but supported by springs in the pitch coupled with the roll coordinates. The springs can be fixed to the vehicle frame. There is the occurrence of viscous damping, which occurs in parallel to the springs.

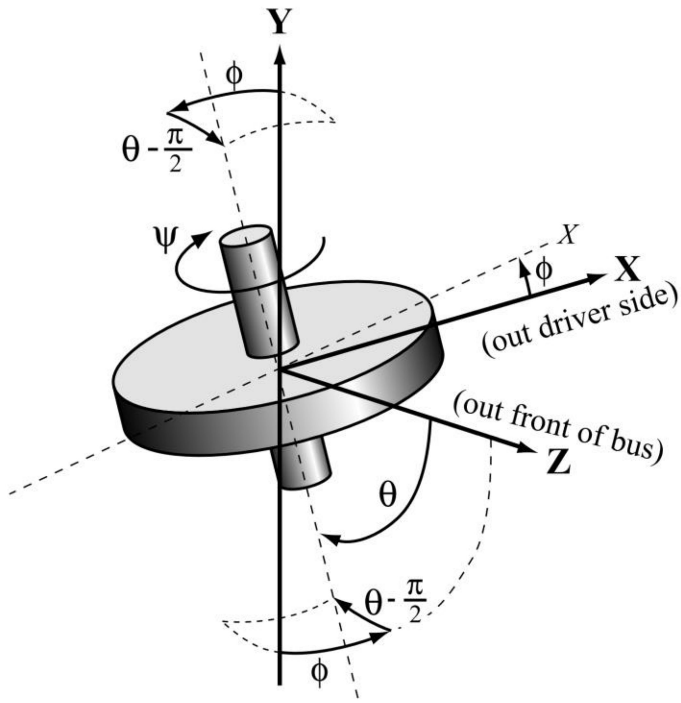


Figure 28. Mathematical model and coordinate systems used to analyze flywheel gyrodynamics, adapted from [159].

In order to dissociate the flywheel and vehicle yaw axes, it is recommended that the flywheel spin axis is kept vertical; hence, the support must not be neutral. A force is therefore needed to keep the flywheel in this vertical orientation. This force can be attained with the aid of springs or sometimes gravity. If the flywheel is not maintained in the equilibrium orientation, it can easily move away from the vertical orientation. It has, however, been reported that, while at operating speed, when the flywheel is not in equilibrium, it can precess about its home orientation in a slow circular orbit in the opposite direction to the flywheel spin. An investigation into the spinning top can be utilised in examining the nature of this motion [160]. The flywheel process when displaced from its equilibrium position should, however, be noted.

Some actions that can lead to displacement of the flywheel from its equilibrium position in the case of the vehicle include:

(i) The vehicle turn in-plane, provided that the flywheel is not in its home orientation in relation to the vehicle;

(ii) Vehicle pitch or roll, subject to whether the flywheel energy storage support uses a spring or damper bolted to the car frame;
(iii) Vehicle lateral acceleration, provided that the support uses a pendulum-type spring;
(iv) Torque on the flywheel energy storage emanating from the flywheel energy storage system motor-generator, provided that the stator's reaction torque vector comes with an element normal to the spin axes of the flywheel;
(v) Torque on the flywheel energy storage systems rotor obtained using bearings, but the beating's stator reaction torque vectors must be normal to the spin axis.

When the flywheel is in its home orientation, it will precess, and this is very common in the operation of flywheels. Precession has many sources and it can accumulate. Using damping on pitch and roll motions can reduce precision to ideal values. It is recommended that damping is sufficient in tandem with the precession inputs to reduce the possibility of going beyond the allowable motion range of the support. Excessive damping can lead to precision.

5. Future Development of FESS

The low-speed flywheel (LSF) has been commercially available for around 30 years, but now, with the demand for renewable energy and advances in materials technology, a great deal of research and development is devoted to flywheel development. There are two ways to increase the amount of energy that a flywheel can store—one is by increasing the rotational speed of the flywheel; the other is to increase the moment of inertia [29]. The maximum speed of a flywheel can be determined by the tensile strength of the rotor. Consequentially, extensive research has been devoted to materials with higher tensile strength to increase the amount of energy stored. The problem with lightweight materials, such as new carbon fiber composite materials, is that they are expensive, and this has hindered the uptake and advancement of flywheel technology [54]. There is a new line of research aimed at developing an intermediate-speed flywheel using the readily available steel material. "A new class of intermediate speed flywheels, benefiting from the low cost of steel materials but a sufficiently high energy density, is also being developed based on the use of laminated steel. This has the potential to offer low cost, but also compact options." [115].

5.1. Application of Flywheel Energy Storage Systems in Renewable Energy Sources

The development of suitable FESS is being researched to improve the overall system stability and energy quality in current solar and wind energy systems. The flywheel can be introduced into a wind farm setup to store excess energy during peak production times, to later be released back into the grid at times when there is no wind. In solar systems, FESS is being introduced to prolong the battery storage life that already exists by using the energy stored in the FESS first, so the batteries' workload should be drastically reduced, thereby improving the battery lifespan [34].

5.2. Application of Flywheel Energy Storage Systems in Military

The use of FESS is being developed for the next generation of combat ships, vehicles, navigation, and weapons due to the instant demand that their on-board electrical applications have. The combination of FESS with batteries will provide the energy needed while extending the life span of the batteries, should they have been used as a singular system.

The US Marine Corps have also integrated an FESS into a microgrid that supplies energy to the base through mainly renewable means. The system is backed up by diesel generators, but it is expected that the FESS will reduce diesel dependency by 40%. "The flywheel storage is intended to decrease the dependency on diesel generators by about 40%." [59].

5.3. Application of Flywheel Energy Storage Systems in Spacecraft

In aerospace, flywheels are being considered as spacecrafts are mainly powered by solar energy. The idea is that FESS will bridge the energy gap when the spacecraft goes into darkness. The advantage of using FESS is that they are lighter than batteries, have a much longer lifecycle, and the reduction in spacecraft mass will reduce spacecraft production costs. The main driver behind the development of FESS seems to be that they will replace batteries or work as a hybrid system with them. The benefits of using FESS are that they are cleaner to produce and that an FESS made of steel is fully recyclable. Comparing all different current and future developments, it is evident that FESS could help to prevent the periodic nature that comes with many energy-producing systems. The FESS can help to maintain constant and stable delivery by allowing excess energy that is produced to be stored in the form of kinetic energy, to later be used when needed. The majority of the references used demonstrate that FESS being tested in a number of locations and industries showed improvements over past systems. These improvements can be seen in the system's efficiency due to the oscillatory demand problems that the grid and transport industries encounter. The stop-and-start problem can be reduced with the excess generation of energy stored in the flywheels, stored later for when demand is higher. With the promising results gathered from all of the tests and trials, significantly more companies are investigating the implementation of FESS in far more complex problems and systems, such as the military and spacecraft applications. Even though it can be seen as a promising invention that allows energy storage, it comes with drawbacks. The system can be costly to manufacture due to the composites and the magnetic bearing system required. As completely efficient systems cannot be currently made, there will still be energy loss in the form of friction and heat. However, even though these problems occur, the FESS will still be a viable option to be installed in many types of energy-producing systems.

6. Conclusions

It seems almost paradoxical that flywheels are well established as an essential tool in human history, yet they are still currently at the very cutting edge of what is technologically possible. From vehicular brake recuperation, to space applications and electricity supply levelling, to rail transport efficiency, the diversity and scope of applications for flywheels are huge. The latest technologies and advancements in the PEI, cryogenically cooled bearings, vacuum chambers, composite materials, machines, and a range of speeds and topologies are all at the forefront of research and development. As energy storage becomes ever more prominent in culture and society, it will become even more valuable. As more and more renewable energy sources are being used, FESS has become a clear and attractive prospect for implementation and further exploration. This is because they are in tune with the required low carbon footprint and are easily recyclable. Excellent efficiency and fuel savings will encourage investment in their development for further use in all types of transport.

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References

1. Elsaid, K.; Kamil, M.; Sayed, E.T.; Abdelkareem, M.A.; Wilberforce, T.; Olabi, A. Environmental impact of desalination technologies: A review. *Sci. Total. Environ.* **2020**, *748*, 141528. [CrossRef]
2. Shehata, N.; Sayed, E.T.; Abdelkareem, M.A. Recent progress in environmentally friendly geopolymers: A review. *Sci. Total. Environ.* **2021**, *762*, 143166. [CrossRef] [PubMed]
3. Zhang, Z.; Zhang, Y.; Sui, X.; Li, W.; Xu, D. Performance of Thermoelectric Power-Generation System for Sufficient Recovery and Reuse of Heat Accumulated at Cold Side of TEG with Water-Cooling Energy Exchange Circuit. *Energies* **2020**, *13*, 5542. [CrossRef]
4. Olabi, A.; Elsaid, K.; Rabaia, M.K.H.; Askalany, A.A.; Abdelkareem, M.A. Waste heat-driven desalination systems: Perspective. *Energy* **2020**, *209*, 118373. [CrossRef]
5. Olabi, A.; Wilberforce, T.; Abdelkareem, M.A. Fuel cell application in the automotive industry and future perspective. *Energy* **2021**, *214*, 118955. [CrossRef]
6. Olabi, A.; Wilberforce, T.; Sayed, E.T.; Elsaid, K.; Abdelkareem, M.A. Prospects of Fuel Cell Combined Heat and Power Systems. *Energies* **2020**, *13*, 4104. [CrossRef]
7. Abdelkareem, M.A.; Elsaid, K.; Wilberforce, T.; Kamil, M.; Sayed, E.T.; Olabi, A. Environmental aspects of fuel cells: A review. *Sci. Total. Environ.* **2021**, *752*, 141803. [CrossRef]
8. Moriarty, P.; Honnery, D. Feasibility of a 100% Global Renewable Energy System. *Energies* **2020**, *13*, 5543. [CrossRef]
9. Gumbarević, S.; Burcar Dunović, I.; Milovanović, B.; Gaši, M. Method for Building Information Modeling Supported Project Control of Nearly Zero-Energy Building Delivery. *Energies* **2020**, *13*, 5519. [CrossRef]
10. Sefidari, H.; Lindblom, B.; Nordin, L.-O.; Wiinikka, H. The Feasibility of Replacing Coal with Biomass in Iron-Ore Pelletizing Plants with Respect to Melt-Induced Slagging. *Energies* **2020**, *13*, 5386. [CrossRef]
11. Wilberforce, T.; Baroutaji, A.; Soudan, B.; Al-Alami, A.H.; Olabi, A.G. Outlook of carbon capture technology and challenges. *Sci. Total. Environ.* **2019**, *657*, 56–72. [CrossRef]
12. Abdelkareem, M.A.; Lootah, M.A.; Sayed, E.T.; Wilberforce, T.; Alawadhi, H.; Yousef, B.A.; Olabi, A. Fuel cells for carbon capture applications. *Sci. Total. Environ.* **2021**, *769*, 144243. [CrossRef] [PubMed]
13. Wilberforce, T.; Olabi, A.; Sayed, E.T.; Elsaid, K.; Abdelkareem, M.A. Progress in carbon capture technologies. *Sci. Total. Environ.* **2021**, *761*, 143203. [CrossRef] [PubMed]
14. Olabi, A.; Abdelkareem, M. Energy storage systems towards 2050. *Energy* **2021**, *219*, 119634. [CrossRef]
15. Olabi, A.; Abdelkareem, M.A.; Wilberforce, T.; Sayed, E.T. Application of graphene in energy storage device—A review. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110026. [CrossRef]
16. Sayed, E.T.; Abdelkareem, M.A.; Alawadhi, H.; Salameh, T.; Olabi, A.; Alami, A.H. Facile and low-cost synthesis route for graphene deposition over cobalt dendrites for direct methanol fuel cell applications. *J. Taiwan Inst. Chem. Eng.* **2020**, *115*, 321–330. [CrossRef]
17. Abdelkareem, M.A.; Wilberforce, T.; Elsaid, K.; Sayed, E.T.; Abdelghani, E.A.; Olabi, A. Transition metal carbides and nitrides as oxygen reduction reaction catalyst or catalyst support in proton exchange membrane fuel cells (PEMFCs). *Int. J. Hydrogen Energy* **2020**. [CrossRef]
18. Liu, S.; Li, W.; Zheng, G.; Yang, H.; Li, L. Optimization of Cattle Manure and Food Waste Co-Digestion for Biohydrogen Production in a Mesophilic Semi-Continuous Process. *Energies* **2020**, *13*, 3848. [CrossRef]
19. Abdelkareem, M.A.; Tanveer, W.H.; Sayed, E.T.; Assad, M.E.H.; Allagui, A.; Cha, S. On the technical challenges affecting the performance of direct internal reforming biogas solid oxide fuel cells. *Renew. Sustain. Energy Rev.* **2019**, *101*, 361–375. [CrossRef]
20. Wilberforce, T.; Sayed, E.T.; Abdelkareem, M.A.; Elsaid, K.; Olabi, A.G. Value added products from wastewater using bioelectrochemical systems: Current trends and perspectives. *J. Water Process Eng.* **2020**, *39*, 101737. [CrossRef]
21. Sayed, E.; Alawadhi, H.; Elsaid, K.; Olabi, A.; Almakrani, M.A.; Bin Tamim, S.; Alafranji, G.; Abdelkareem, M. A Carbon-Cloth Anode Electroplated with Iron Nanostructure for Microbial Fuel Cell Operated with Real Wastewater. *Sustainability* **2020**, *12*, 6538. [CrossRef]
22. Salameh, T.; Abdelkareem, M.A.; Olabi, A.; Sayed, E.T.; Al-Chaderchi, M.; Rezk, H. Integrated standalone hybrid solar PV, fuel cell and diesel generator power system for battery or supercapacitor storage systems in Khorfakkan, United Arab Emirates. *Int. J. Hydrogen Energy* **2021**, *46*, 6014–6027. [CrossRef]
23. Rezk, H.; Sayed, E.T.; Al-Dhaifallah, M.; Obaid, M.; El-Sayed, A.H.M.; Abdelkareem, M.A.; Olabi, A. Fuel cell as an effective energy storage in reverse osmosis desalination plant powered by photovoltaic system. *Energy* **2019**, *175*, 423–433. [CrossRef]
24. Olabi, A.G.; Onumaegbu, C.; Wilberforce, T.; Ramadan, M.; Abdelkareem, M.A.; Al-Alami, A.H. Critical Review of Energy Storage Systems. *Energy* **2020**, 118987. [CrossRef]
25. Khzouz, M.; Gkanas, E.I.; Shao, J.; Sher, F.; Beherskyi, D.; El-Kharouf, A.; Al Qubeissi, M. Life Cycle Costing Analysis: Tools and Applications for Determining Hydrogen Production Cost for Fuel Cell Vehicle Technology. *Energies* **2020**, *13*, 3783. [CrossRef]
26. Wilberforce, T.; El-Hassan, Z.; Khatib, F.; Al Makky, A.; Baroutaji, A.; Carton, J.G.; Olabi, A.G. Developments of electric cars and fuel cell hydrogen electric cars. *Int. J. Hydrogen Energy* **2017**, *42*, 25695–25734. [CrossRef]
27. Baroutaji, A.; Wilberforce, T.; Ramadan, M.; Olabi, A.G. Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. *Renew. Sustain. Energy Rev.* **2019**, *106*, 31–40. [CrossRef]
28. Wilberforce, T.; Alaswad, A.; Palumbo, A.; Dassisti, M.; Olabi, A. Advances in stationary and portable fuel cell applications. *Int. J. Hydrogen Energy* **2016**, *41*, 16509–16522. [CrossRef]

29. Mahmoud, M.; Ramadan, M.; Olabi, A.-G.; Pullen, K.; Naher, S. A review of mechanical energy storage systems combined with wind and solar applications. *Energy Convers. Manag.* **2020**, *210*, 112670. [CrossRef]
30. Bolund, B.; Bernhoff, H.; Leijon, M. Flywheel energy and power storage systems. *Renew. Sustain. Energy Rev.* **2007**, *11*, 235–258. [CrossRef]
31. Wicki, S.; Hansen, E.G. Clean energy storage technology in the making: An innovation systems perspective on flywheel energy storage. *J. Clean. Prod.* **2017**, *162*, 1118–1134. [CrossRef] [PubMed]
32. Strzelecki, R.M. *Power Electronics in Smart Electrical Energy Networks*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2008.
33. Barelli, L.; Bidini, G.; Bonucci, F.; Castellini, L.; Fratini, A.; Gallorini, F.; Zuccari, A. Flywheel hybridization to improve battery life in energy storage systems coupled to RES plants. *Energy* **2019**, *173*, 937–950. [CrossRef]
34. Kondoh, J.; Funamoto, T.; Nakanishi, T.; Arai, R. Energy characteristics of a fixed-speed flywheel energy storage system with direct grid-connection. *Energy* **2018**, *165*, 701–708. [CrossRef]
35. Rupp, A.; Baier, H.; Mertiny, P.; Secanell, M. Analysis of a flywheel energy storage system for light rail transit. *Energy* **2016**, *107*, 625–638. [CrossRef]
36. Zhao, P.; Wang, M.; Wang, J.; Dai, Y. A preliminary dynamic behaviors analysis of a hybrid energy storage system based on adiabatic compressed air energy storage and flywheel energy storage system for wind power application. *Energy* **2015**, *84*, 825–839. [CrossRef]
37. Suzuki, Y.; Koyanagi, A.; Kobayashi, M.; Shimada, R. Novel applications of the flywheel energy storage system. *Energy* **2005**, *30*, 2128–2143. [CrossRef]
38. Boukettaya, G.; Krichen, L.; Ouali, A. A comparative study of three different sensorless vector control strategies for a Flywheel Energy Storage System. *Energy* **2010**, *35*, 132–139. [CrossRef]
39. Okou, R.; Sebitosi, A.; Pillay, P. Flywheel rotor manufacture for rural energy storage in sub-Saharan Africa. *Energy* **2011**, *36*, 6138–6145. [CrossRef]
40. Olabi, A. *Renewable Energy and Energy Storage Systems*; Elsevier: Amsterdam, The Netherlands, 2017.
41. Boukettaya, G.; Krichen, L. A dynamic power management strategy of a grid connected hybrid generation system using wind, photovoltaic and Flywheel Energy Storage System in residential applications. *Energy* **2014**, *71*, 148–159. [CrossRef]
42. Huang, C.-N.; Chen, Y.-S. Design of magnetic flywheel control for performance improvement of fuel cells used in vehicles. *Energy* **2017**, *118*, 840–852. [CrossRef]
43. Ferreira, H.L.; Garde, R.; Fulli, G.; Kling, W.; Lopes, J.P. Characterisation of electrical energy storage technologies. *Energy* **2013**, *53*, 288–298. [CrossRef]
44. 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; IEEE: Piscataway, NJ, USA, 2011; pp. 1–6.
45. McMahon, R.; Infante, L. Energy Storage in the United States. In *Renewable Energy Integration*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 281–292.
46. Bitterly, J.G. Flywheel technology: Past, present, and 21st century projections. *IEEE Aerosp. Electron. Syst. Mag.* **1998**, *13*, 13–16. [CrossRef]
47. Pullen, K.R. The Status and Future of Flywheel Energy Storage. *Joule* **2019**, *3*, 1394–1399. [CrossRef]
48. Mousavi, G.S.M.; Faraji, F.; Majazi, A.; Al-Haddad, K. A comprehensive review of Flywheel Energy Storage System technology. *Renew. Sustain. Energy Rev.* **2017**, *67*, 477–490. [CrossRef]
49. Wang, Y.; Wang, C.; Xue, H. A novel capacity configuration method of flywheel energy storage system in electric vehicles fast charging station. *Electric Power Syst. Res.* **2021**, *195*, 107185. [CrossRef]
50. Goris, F.; Severson, E.L. A Review of Flywheel Energy Storage Systems for Grid Application. In Proceedings of the IECON 2018—44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, USA, 21–23 October 2018; pp. 1633–1639.
51. Amiryar, M.E.; Pullen, K.R. A Review of Flywheel Energy Storage System Technologies and Their Applications. *Appl. Sci.* **2017**, *7*, 286. [CrossRef]
52. Kousksou, T.; Bruel, P.; Jamil, A.; El Rhafiki, T.; Zeraouli, Y. Energy storage: Applications and challenges. *Sol. Energy Mater. Sol. Cells* **2014**, *120*, 59–80. [CrossRef]
53. Zakeri, B.; Syri, S. Electrical energy storage systems: A comparative life cycle cost analysis. *Renew. Sustain. Energy Rev.* **2015**, *42*, 569–596. [CrossRef]
54. Dhand, A.; Pullen, K. Review of flywheel based internal combustion engine hybrid vehicles. *Int. J. Automot. Technol.* **2013**, *14*, 797–804. [CrossRef]
55. Doucette, R.T.; McCulloch, M.D. A comparison of high-speed flywheels, batteries, and ultracapacitors on the bases of cost and fuel economy as the energy storage system in a fuel cell based hybrid electric vehicle. *J. Power Sources* **2011**, *196*, 1163–1170. [CrossRef]
56. Gabrys, C.W. High Performance Composite Flywheel. U.S. Patent US6583528B2, 24 June 2003.
57. Liu, H.; Jiang, J. Flywheel energy storage—An upswing technology for energy sustainability. *Energy Build.* **2007**, *39*, 599–604. [CrossRef]

58. Sotelo, G.; De Andrade, R.; Ferreira, A. Magnetic Bearing Sets for a Flywheel System. *IEEE Trans. Appl. Supercond.* **2007**, *17*, 2150–2153. [CrossRef]
59. Werfel, F.; Floegel-Delor, U.; Rothfeld, R.; Riedel, T.; Goebel, B.; Wippich, D.; Schirrmeister, P. Superconductor bearings, flywheels and transportation. *Supercond. Sci. Technol.* **2011**, *25*, 014007. [CrossRef]
60. Ren, M.; Shen, Y.; Li, Z.; Nonami, K. Modeling and control of a flywheel energy storage system using active magnetic bearing for vehicle. In Proceedings of the IEEE 2009 International Conference on Information Engineering and Computer Science, Wuhan, China, 19–20 December 2009; pp. 1–5.
61. Karrari, S.; Noe, M.; Geisbuesch, J. High-speed Flywheel Energy Storage System (FESS) for Voltage and Frequency Support in Low Voltage Distribution Networks. In Proceedings of the 2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS), Kyiv, Ukraine, 10–14 September 2018; pp. 176–182.
62. Daoud, M.I.; Abdel-Khalik, A.S.; Massoud, A.; Ahmed, S.; Abbasy, N.H. On the development of flywheel storage systems for power system applications: A survey. In Proceedings of the 2012 XXth International Conference on Electrical Machines, Marseille, France, 2–5 September 2012; pp. 2119–2125.
63. Bianchini, C.; Torreggiani, A.; David, D.; Bellini, A. Design of motor/generator for Flywheel Batteries. *IEEE Trans. Ind. Electron.* **2020**, 1. [CrossRef]
64. May, G.J.; Davidson, A.; Monahov, B. Lead batteries for utility energy storage: A review. *J. Energy Storage* **2018**, *15*, 145–157. [CrossRef]
65. Gerada, D.; Mebarki, A.; Brown, N.L.; Gerada, C.; Cavagnino, A.; Boglietti, A. High-Speed Electrical Machines: Technologies, Trends, and Developments. *IEEE Trans. Ind. Electron.* **2014**, *61*, 2946–2959. [CrossRef]
66. Chao, W.; Xingjian, D.; Yong, W.; Xi, L.; Guobin, Z. Research progress of energy storage composite flywheel. *Energy Storage Sci. Technol.* **2017**, *6*, 1076.
67. Cansiz, A.; Yildizer, I.; Oral, E.A.; Kaya, Y. An Effective Noncontact Torque Mechanism and Design Considerations for an Evershed-Type Superconducting Magnetic Bearing System. *IEEE Trans. Appl. Supercond.* **2013**, *24*, 22–29. [CrossRef]
68. Kale, V.; Secanell, M. A comparative study between optimal metal and composite rotors for flywheel energy storage systems. *Energy Rep.* **2018**, *4*, 576–585. [CrossRef]
69. Lee, H.; Shin, B.Y.; Han, S.; Jung, S.; Park, B.; Jang, G. Compensation for the Power Fluctuation of the Large Scale Wind Farm Using Hybrid Energy Storage Applications. *IEEE Trans. Appl. Supercond.* **2011**, *22*, 5701904. [CrossRef]
70. Suvire, G.O.; Molina, M.G.; Mercado, P.E. Improving the Integration of Wind Power Generation Into AC Microgrids Using Flywheel Energy Storage. *IEEE Trans. Smart Grid* **2012**, *3*, 1945–1954. [CrossRef]
71. Abrahamsson, J.; Hedlund, M.; Kamf, T.; Bernhoff, H. High-Speed Kinetic Energy Buffer: Optimization of Composite Shell and Magnetic Bearings. *IEEE Trans. Ind. Electron.* **2013**, *61*, 3012–3021. [CrossRef]
72. Bernard, N.; Ahmed, H.B.; Multon, B. Semi-analytical inductance calculation on an axial-field synchronous machine for a flywheel storage system using surfacic permeances. In Proceedings of the IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No. 01EX485), Cambridge, MA, USA, 17–20 June 2001; pp. 382–390.
73. Abdel-Khalik, A.S.; Elserougi, A.A.; Massoud, A.M.; Ahmed, S. Fault Current Contribution of Medium Voltage Inverter and Doubly-Fed Induction-Machine-Based Flywheel Energy Storage System. *IEEE Trans. Sustain. Energy* **2012**, *4*, 58–67. [CrossRef]
74. Wang, L.; Yu, J.-Y.; Chen, Y.-T. Dynamic stability improvement of an integrated offshore wind and marine-current farm using a flywheel energy-storage system. *IET Renew. Power Gener.* **2011**, *5*, 387–396. [CrossRef]
75. Sun, X.-D.; Koh, K.-H.; Yu, B.-G.; Matsui, M. Fuzzy-logic-based $ V/f $ control of an induction motor for a DC grid power-leveling system using flywheel energy storage equipment. *IEEE Trans. Ind. Electron.* **2009**, *56*, 3161–3168.
76. Wu, J.; Wen, J.; Sun, H. A new energy storage system based on flywheel. In Proceedings of the 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, Canada, 26–30 July 2009; pp. 1–6.
77. Ran, L.; Xiang, D.; Kirtley, J.L. Analysis of Electromechanical Interactions in a Flywheel System with a Doubly Fed Induction Machine. *2010 IEEE Ind. Appl. Soc. Annu. Meet.* **2010**, *47*, 1–8. [CrossRef]
78. Liu, G.; Zhang, C. Sliding mode control of reaction flywheel-based brushless DC motor with buck converter. *Chin. J. Aeronaut.* **2013**, *26*, 967–975. [CrossRef]
79. Gurumurthy, S.R.; Agarwal, V.; Sharma, A. Optimal energy harvesting from a high-speed brushless DC generator-based flywheel energy storage system. *IET Electr. Power Appl.* **2013**, *7*, 693–700. [CrossRef]
80. Strasik, M.; Johnson, P.; Day, A.; Mittleider, J.; Higgins, M.; Edwards, J.; Schindler, J.; McCrary, K.; McIver, C.; Carlson, D.; et al. Design, Fabrication, and Test of a 5-kWh/100-kW Flywheel Energy Storage Utilizing a High-Temperature Superconducting Bearing. *IEEE Trans. Appl. Supercond.* **2007**, *17*, 2133–2137. [CrossRef]
81. Subkhan, M.; Komori, M. New Concept for Flywheel Energy Storage System Using SMB and PMB. *IEEE Trans. Appl. Supercond.* **2011**, *21*, 1485–1488. [CrossRef]
82. Chang, X.; Li, Y.; Zhang, W.; Wang, N.; Xue, W. Active Disturbance Rejection Control for a Flywheel Energy Storage System. *IEEE Trans. Ind. Electron.* **2015**, *62*, 991–1001. [CrossRef]
83. Bist, V.; Singh, B. PFC Cuk Converter-Fed BLDC Motor Drive. *IEEE Trans. Power Electron.* **2015**, *30*, 871–887. [CrossRef]
84. Vijayakumar, K.; Karthikeyan, R.; Paramasivam, S.; Arumugam, R.; Srinivas, K.N. Switched Reluctance Motor Modeling, Design, Simulation, and Analysis: A Comprehensive Review. *IEEE Trans. Magn.* **2008**, *44*, 4605–4617. [CrossRef]
85. Lee, D.-H.; Ahn, S.-Y.; Ahn, J. *Switched reluctance motor (SRM)*; IntechOpen: London, UK, 2017.

86. Severson, E.; Nilssen, R.; Undeland, T.; Mohan, N. Magnetic Equivalent Circuit Modeling of the AC Homopolar Machine for Flywheel Energy Storage. *IEEE Trans. Energy Convers.* **2015**, *30*, 1670–1678. [CrossRef]
87. Li, W.; Chau, K.T.; Ching, T.W.; Wang, Y.; Chen, M. Design of a High-speed Superconducting Bearingless Machine for Flywheel Energy Storage Systems. *IEEE Trans. Appl. Supercond.* **2014**, *25*, 1. [CrossRef]
88. Severson, E.; Nilssen, R.; Undeland, T.; Mohan, N. Outer-Rotor Ac Homopolar Motors for Flywheel Energy Storage. 2014. Available online: https://experts.umn.edu/en/publications/outer-rotor-ac-homopolar-motors-for-flywheel-energy-storage-2 (accessed on 1 January 2021).
89. Jiancheng, F.; Xi, W.; Tong, W.; Enqiong, T.; Yahong, F. Homopolar 2-Pole Radial Permanent-Magnet Biased Magnetic Bearing With Low Rotating Loss. *IEEE Trans. Magn.* **2012**, *48*, 2293–2303. [CrossRef]
90. Severson, E.; Nilssen, R.; Undeland, T.; Mohan, N. Suspension force model for bearingless AC homopolar machines designed for flywheel energy storage. In Proceedings of the 2013 7th IEEE GCC Conference and Exhibition (GCC), Doha, Qatar, 17–20 November 2013; pp. 274–279.
91. Davey, K.; Filatov, A.; Thompson, R. Design and analysis of passive homopolar null flux bearings. *IEEE Trans. Magn.* **2005**, *41*, 1169–1175. [CrossRef]
92. Wang, Q.; Liu, C.; Zou, J.; Fu, X.; Zhang, J. Numerical Analysis and Design Optimization of a Homopolar Inductor Machine Used for Flywheel Energy Storage. *IEEE Trans. Plasma Sci.* **2013**, *41*, 1290–1294. [CrossRef]
93. Brauer, H.J.; De Doncker, R.W. Thermal Modeling of a High-Speed Switched Reluctance Machine with Axial Air-gap Flow for Vacuum Cleaners. *EPE J.* **2012**, *22*, 22–29. [CrossRef]
94. Severson, E.L. Bearingless AC Homopolar Machine Design and Control for Distributed Flywheel Energy Storage. Available online: https://conservancy.umn.edu/bitstream/handle/11299/182757/Severson_umn_0130E_16116.pdf?sequence=1%2015 (accessed on 17 January 2021).
95. Bianchi, N.; Bolognani, S.; Carraro, E.; Castiello, M.; Fornasiero, E. Electric Vehicle Traction Based on Synchronous Reluctance Motors. *IEEE Trans. Ind. Appl.* **2016**, *52*, 4762–4769. [CrossRef]
96. Donaghy-Spargo, C.M. Synchronous reluctance motor technology: Opportunities, challenges and future direction. *Eng. Technol. Ref.* **2016**, 1–15. [CrossRef]
97. Ngo, D.-K.; Hsieh, M.-F. Performance Analysis of Synchronous Reluctance Motor with Limited Amount of Permanent Magnet. *Energies* **2019**, *12*, 3504. [CrossRef]
98. Lipo, T.A. Synchronous Reluctance Machines-A Viable Alternative for AC Drives? *Electr. Mach. Power Syst.* **1991**, *19*, 659–671. [CrossRef]
99. Jack, A.G.; Mecrow, B.C.; Haylock, J.A. A comparative study of permanent magnet and switched reluctance motors for high-performance fault-tolerant applications. *IEEE Trans. Ind. Appl.* **1996**, *32*, 889–895. [CrossRef]
100. Szabo, L.; Ruba, M. On fault tolerance increase of switched reluctance machines. In Proceedings of the IEEE EUROCON 2009, St. Petersburg, Russia, 18–23 May 2009; pp. 734–739.
101. Davis, R. A comparison of switched reluctance rotor structures. *IEEE Trans. Ind. Electron.* **1988**, *35*, 524–529. [CrossRef]
102. Matsuo, T.; Lipo, T.A. Rotor position detection scheme for synchronous reluctance motor based on current measurements. In Proceedings of the 1994 IEEE Industry Applications Society Annual Meeting, Denver, CO, USA, 2–6 October 1994; Volume 1, pp. 627–634.
103. Luo, X.; El-Antably, A.; Lipo, T. Multiple coupled circuit modeling of synchronous reluctance machines. In Proceedings of the 1994 IEEE Industry Applications Society Annual Meeting; Institute of Electrical and Electronics Engineers (IEEE), Denver, CO, USA, 2–6 October 1994; Volume 2, pp. 281–289.
104. Wang, X.-L.; Zhong, Q.-C.; Deng, Z.-Q.; Yue, S.-Z. Current-Controlled Multiphase Slice Permanent Magnetic Bearingless Motors With Open-Circuited Phases: Fault-Tolerant Controllability and Its Verification. *IEEE Trans. Ind. Electron.* **2011**, *59*, 2059–2072. [CrossRef]
105. Warberger, B.; Kaelin, R.; Nussbaumer, T.; Kolar, J.W. 50-N·m/2500-W Bearingless Motor for High-Purity Pharmaceutical Mixing. *IEEE Trans. Ind. Electron.* **2012**, *59*, 2236–2247. [CrossRef]
106. Chen, L.; Hofmann, W. Speed Regulation Technique of One Bearingless 8/6 Switched Reluctance Motor With Simpler Single Winding Structure. *IEEE Trans. Ind. Electron.* **2012**, *59*, 2592–2600. [CrossRef]
107. Pust, L. Oscillations of rotor supported on magnetic bearings with impacts in retainer bearings. *J. Theor. Appl. Mech.* **2007**, *45*, 99–117.
108. Schneeberger, T.; Nussbaumer, T.; Kolar, J.W. Magnetically Levitated Homopolar Hollow-Shaft Motor. *IEEE/ASME Trans. Mechatronics* **2010**, *15*, 97–107. [CrossRef]
109. Kailasan, A.; Dimond, T.; Allaire, P.; Sheffler, D. Design and analysis of a unique energy storage flywheel system—An integrated flywheel, motor/generator, and magnetic bearing configuration. *J. Eng. Gas Turbines Power* **2015**, *137*. [CrossRef]
110. Grabner, H.; Amrhein, W.; Silber, S.; Gruber, W. Nonlinear Feedback Control of a Bearingless Brushless DC Motor. *IEEE/ASME Trans. Mechatron.* **2010**, *15*, 40–47. [CrossRef]
111. Mukoyama, S.; Nakao, K.; Sakamoto, H.; Matsuoka, T.; Nagashima, K.; Ogata, M.; Yamashita, T.; Miyazaki, Y.; Miyazaki, K.; Maeda, T.; et al. Development of Superconducting Magnetic Bearing for 300 kW Flywheel Energy Storage System. *IEEE Trans. Appl. Supercond.* **2017**, *27*, 1–4. [CrossRef]

112. Johnson, B.R.; Columbro, F.; Araujo, D.; Limon, M.; Smiley, B.; Jones, G.; Reichborn-Kjennerud, B.; Miller, A.; Gupta, S. A large-diameter hollow-shaft cryogenic motor based on a superconducting magnetic bearing for millimeter-wave polarimetry. *Rev. Sci. Instruments* **2017**, *88*, 105102. [CrossRef]
113. Nagashima, K.; Seino, H.; Sakai, N.; Murakami, M. Superconducting magnetic bearing for a flywheel energy storage system using superconducting coils and bulk superconductors. *Phys. C Supercond.* **2009**, *469*, 1244–1249. [CrossRef]
114. Stephens, L.S.; Dae-Gon, K. Force and torque characteristics for a slotless Lorentz self-bearing servomotor. *IEEE Trans. Magn.* **2002**, *38*, 1764–1773. [CrossRef]
115. Bartholet, M.T.; Nussbaumer, T.; Kolar, J.W. Comparison of Voltage-Source Inverter Topologies for Two-Phase Bearingless Slice Motors. *IEEE Trans. Ind. Electron.* **2011**, *58*, 1921–1925. [CrossRef]
116. Rodriguez, E.F.; Santisteban, J.A. An Improved Control System for a Split Winding Bearingless Induction Motor. *IEEE Trans. Ind. Electron.* **2010**, *58*, 3401–3408. [CrossRef]
117. Yang, Z.; Ding, Q.; Sun, X.; Ji, J.; Zhao, Q. Design and analysis of a novel wound rotor for a bearingless induction motor. *Int. J. Electron.* **2019**, *106*, 1829–1844. [CrossRef]
118. Nussbaumer, T.; Karutz, P.; Zurcher, F.; Kolar, J.W. Magnetically Levitated Slice Motors—An Overview. *IEEE Trans. Ind. Appl.* **2011**, *47*, 754–766. [CrossRef]
119. Recheis, M.N.; Schweighofer, B.; Fulmek, P.; Wegleiter, H. Selection of Magnetic Materials for Bearingless High-Speed Mobile Flywheel Energy Storage Systems. *IEEE Trans. Magn.* **2014**, *50*, 1–4. [CrossRef]
120. Ooshima, M.; Kitazawa, S.; Chiba, A.; Fukao, T.; Dorrell, D.G. Design and Analyses of a Coreless-Stator-Type Bearingless Motor/Generator for Clean Energy Generation and Storage Systems. *IEEE Trans. Magn.* **2006**, *42*, 3461–3463. [CrossRef]
121. Asami, K.; Chiba, A.; Rahman, M.A.; Hoshino, T.; Nakajima, A. Stiffness analysis of a magnetically suspended bearingless motor with permanent magnet passive positioning. *IEEE Trans. Magn.* **2005**, *41*, 3820–3822. [CrossRef]
122. Reichert, T.; Nussbaumer, T.; Kolar, J.W. Bearingless 300-W PMSM for Bioreactor Mixing. *IEEE Trans. Ind. Electron.* **2012**, *59*, 1376–1388. [CrossRef]
123. Asama, J.; Hamasaki, Y.; Oiwa, T.; Chiba, A. Proposal and Analysis of a Novel Single-Drive Bearingless Motor. *IEEE Trans. Ind. Electron.* **2013**, *60*, 129–138. [CrossRef]
124. Silva, F.A. Power Electronics Handbook, Third Edition (Rashid, M.H.; 2011) [Book News]. *IEEE Ind. Electron. Mag.* **2011**, *5*, 54–55. [CrossRef]
125. Dragicevic, T.; Sučić, S.; Vasquez, J.C.; Guerrero, J.M. Flywheel-Based Distributed Bus Signalling Strategy for the Public Fast Charging Station. *IEEE Trans. Smart Grid* **2014**, *5*, 2825–2835. [CrossRef]
126. Hearn, C.S.; Flynn, M.M.; Lewis, M.C.; Thompson, R.C.; Murphy, B.T.; Longoria, R.G. Low Cost Flywheel Energy Storage for a Fuel Cell Powered Transit Bus. In Proceedings of the 2007 IEEE Vehicle Power and Propulsion Conference, Arlington, TX, USA, 9–12 September 2007; pp. 829–836.
127. Gyugyi, L.; Pelly, B.R. *Static Power Frequency Changers: Theory, Performance, and Application*; John Wiley & Sons: Hoboken, NJ, USA, 1976.
128. Amodeo, S.J.; Chiacchiarini, H.G.; Oliva, A.R. High-performance control of a DC–DC Z-source converter used for an excitation field driver. *IEEE Trans. Power Electron.* **2011**, *27*, 2947–2957. [CrossRef]
129. Wang, Z.; Palazzolo, A.; Park, J. Hybrid Train Power with Diesel Locomotive and Slug Car–Based Flywheels for NOx and Fuel Reduction. *J. Energy Eng.* **2012**, *138*, 215–236. [CrossRef]
130. Meinert, M.; Prenleloup, P.; Schmid, S.; Palacin, R. Energy storage technologies and hybrid architectures for specific diesel-driven rail duty cycles: Design and system integration aspects. *Appl. Energy* **2015**, *157*, 619–629. [CrossRef]
131. Unique Cars and Parts. How It Works: Cranshafts and Flywheel. 2020. Available online: https://www.uniquecarsandparts.com.au/how_it_works_crankcase (accessed on 4 May 2020).
132. Volvo Cars. Volvo Cars Tests of Flywheel Technology Confirm Fuel Savings of Up to 25 Percent. 2013. Available online: https://www.media.volvocars.com/global/en-gb/media/pressreleases/48800 (accessed on 4 April 2020).
133. Doyle, M.; Samuel, D.; Conway, T.; Klimowski, R. Electromagnetic aircraft launch system-EMALS. *IEEE Trans. Magn.* **1995**, *31*, 528–533. [CrossRef]
134. Bender, D. *Flywheels*; Sandia Report; Sandia National Laboratories: Albuquerque, ME, USA, 2015.
135. Total Immersion: Theme Park for the 21st Century, Orlando, Florida: USA Networks. Available online: https://www.youtube.com/watch?v=VNDlM-1gvMY (accessed on 3 April 2021).
136. Elbouchikhi, E.; Amirat, Y.; Feld, G.; Benbouzid, M.; Zhou, Z. A Lab-scale Flywheel Energy Storage System: Control Strategy and Domestic Applications. *Energies* **2020**, *13*, 653. [CrossRef]
137. Elbouchikhi, E.; Feld, G.; Amirat, Y.; Benbouzid, M. A flywheel-based distributed control strategy for grid congestion at domestic level. In Proceedings of the 2020 International Conference on Electrical and Information Technologies (ICEIT), Rabat-Sale, Morocco, 4–7 March 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1–6.
138. Nasa Glenn Research Center. NASA Flywheel Programme. 2018. Available online: https:www.grcnasa.gov/WWW/portal/pdf/flywheel.pdf (accessed on 7 April 2021).
139. Brown, K. Europe's Largest Hybrid Flywheel Battery Project to Help Grid Respond to Energy Demand. 2017. Available online: https://www.sheffield.ac.uk/news/nr/flywheel-europe-energy-1.704921 (accessed on 4 May 2020).

140. Conteh, M.A.; Nsofor, E.C. Composite flywheel material design for high-speed energy storage. *J. Appl. Res. Technol.* **2016**, *14*, 184–190. [CrossRef]
141. Sebastián, R.; Alzola, R.P. Flywheel energy storage systems: Review and simulation for an isolated wind power system. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6803–6813. [CrossRef]
142. Grant, C.; Garcia, J.; Hicks, A. Environmental payback periods of multi-crystalline silicon photovoltaics in the United States—How prioritizing based on environmental impact compares to solar intensity. *Sustain. Energy Technol. Assessments* **2020**, *39*, 100723. [CrossRef]
143. Han, Y.; Ren, Z.; Tong, Y. General Design Method of Flywheel Rotor for Energy Storage System. *Energy Procedia* **2012**, *16*, 359–364. [CrossRef]
144. Rastegarzadeh, S.; Mahzoon, M.; Mohammadi, H. A novel modular designing for multi-ring flywheel rotor to optimize energy consumption in light metro trains. *Energy* **2020**, *206*, 118092. [CrossRef]
145. Wen, S.; Jiang, S. Optimum design of hybrid composite multi-ring flywheel rotor based on displacement method. *Compos. Sci. Technol.* **2012**, *72*, 982–988. [CrossRef]
146. Carbone, R. *Energy Storage in the Emerging Era of Smart Grids*; IntechOpen: London, UK, 2011.
147. Danfelt, E.L.; Hewes, S.A.; Chou, T.-W. Optimization of composite flywheel design. *Int. J. Mech. Sci.* **1977**, *19*, 69–78. [CrossRef]
148. Lokke, B. *Industrial Ecology: A Collection of Articles from Science and Technology Review*; Diane Publishing: Collingdale, PA, USA, 1996.
149. Baer, M.R. Aerodynamic heating of high-speed flywheels in low-density environments. *NASA STI Recon Tech. Rep. N* **1978**, *80*, 16548.
150. Van Deusen, B.D. Analytical techniques for designing riding quality into automotive vehicles. *SAE Trans.* **1968**, 155–166.
151. Blake, R. *Shock and Vibration Handbook*, 2nd ed.; Harris, C.M., Crede, C.E., Eds.; McGraw-Hill: New York, NY, USA, 1976.
152. Himelblau, H.; Piersol, A.; Wise, J.; Max, R. Guidelines for Dynamic Data Acquisition and Analysis. In Military Handbook MIL-HDBK-XXX. In *Military Handbook MIL-HDBK-XXX*; U.S. Department of Defense: Washington, DC, USA, 1989.
153. Northrop Grumman. *System Specification for ATTB System, Advanced Technology Transit Bus*; Final Report; Northrop Grumman: Falls Church, VA, USA, 1995.
154. Vance, J.M. *Rotordynamics of Turbomachinery*; John Wiley & Sons: Hoboken, NJ, USA, 1988.
155. Chen, H.; Ku, C. Virtual Balancing of Rotor Supported by Magnetic Bearings. In Proceedings of the 13th Biennial ASME Conference on Mechanical Vibration and Noise, Miami, FL, USA, 22–25 September 1991; pp. 22–25.
156. Beale, S.; Shafai, B.; LaRocca, P.; Cusson, E. Adaptive forced balancing for magnetic bearing control systems. In Proceedings of the 31st IEEE Conference on Decision and Control, Tucson, AZ, USA, 16–8 December 1992; IEEE: Picataway, NJ, USA, 1992; pp. 3535–3539.
157. McDonald, A.T. Simplified gyrodynamics of road vehicles with high-energy flywheels. In Proceedings of the 1980 Flywheel Technology Symposium; US Department of Energy: Washington, DC, USA, 1980; pp. 240–258.
158. Den Hartog, J. Chapter 7: Self-excited vibrations. In *Mechanical Vibrations*, 4th ed.; McGraw-Hill: New York, NY, USA, 1956.
159. Murphy, B.T.; Bresie, D.A.; Beno, J.H. Bearing Loads in a Vehicular Flywheel Battery. 1997. Available online: http://www.xlrotor.com/Paper_PDFs/flyweel%20bearing%20loads.pdf (accessed on 21 February 2021).
160. Marion, J.B. *Classical Dynamics of Particles and Systems*; Academic Press: Cambridge, MA, USA, 2013.