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Design of flywheel energy generation system

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ABSTRACT

The concept of flywheel and storing energy in a spinning object is very old, potter's wheel, ancient turbines made of wood which were immersed in a river to get the turbine spinning from the flowing water of the river, modern flywheels were initiated over 100 years ago, they were solely used to keep machinery running smoothly from cycle to cycle, power plants use flywheels in their steam turbines, steam engines use flywheels, hydro power plants use flywheel in the form of hydro turbines, internal combustion engines use them, they are used to supply a surge of energy for particle accelerators. The proposed device employs a system by which rotational energy i.e., kinetic energy of an object having large moment of inertia is stored & converted to electrical energy, this is intended for electricity generation application by discharge kinetic energy stored in the flywheel, the device works by charging the flywheel i.e., spinning the flywheel to a defined rpm, the flywheel will rotate so that the electrical energy is transformed into mechanical energy and stored in it & then discharging the flywheel i.e., using up the stored kinetic energy in the flywheel to generate electricity via a generator.

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1. INTRODUCTION

With respect to the ongoing global situation like, Russia – Ukraine conflict which has led to a rapid increase in the crude oil & natural gas prices, coal shortage in India leading to frequent power outages all over the country & global warming resulting to the hottest summer in 112 years India has faced, all these are the ill effects of fossil fuels, fossil fuels are finite in quantity & are bound to be exhausted. Global CO2 levels are at an alarmingly all-time high levels since the past 300 years, lithium mining for EV batteries is also responsible for large scale pollution & the recent boom in the EV market demands more electricity from the grid resulting in more coal being burnt leading to more pollution [1]-[6].

With most of the countries including India wanting to cut down on CO2 emissions & becoming net zero, renewable energy plays a major role in this transition, it's become clear that current energy production methods pose a major threat to the environment & us human beings. The energy demand will only increase with time so many countries are making new amendments & policies to ensure that our future will be sustainable. There are many types of renewable energy like solar, wind, hydro, geothermal & tidal out of which solar is the popular of all, among these types flywheel energy storage & generation is also receiving lot of attention lately [7]-[12].

As mentioned above flywheels are an ancient device or method used to store energy, kinetic energy particularly. The way a flywheel stores energy can be explained by moment of inertia which states that "it is a quantity expressing a body's tendency to resist angular acceleration, which is the sum of the products of the mass of each particle in the body with the square of its distance from the axis of rotation" & conservation of angular momentum which states that "angular momentum remains constant if the net external torque applied on a system is zero [13]-19]. So, when net external torque is zero on a body, then the net change in the angular momentum of the body is zero".

Flywheels are heavy discs or wheels which have most of their mass concentrated as far away as possible from their axis of rotation at the periphery or at the circumference, once they get up to speed they will resist any changes that opposes or tries slow them down, a fast spinning heavy flywheel is difficult to stop due to its inertia, due to the developments in material science, magnetic bearings & power electronics FESS has been established as a strong option for energy storage [20]-[28].

FESS is emerging as an ideal form or as an ideal solution for energy storage & generation, flywheel energy systems have high efficiency, long cycle life, wide range of operating temperature, are not affected by weather, has high power & energy density, fast response, less start up time, quick charging & discharging. These are some of the aspects which led to the creation of gyrobus in Switzerland in1960s & now flywheels are used in F1, electric cars to recuperate energy while braking & is used later to propel the vehicle this system is known as kinetic energy recuperation system (KERS). The main objective of the paper is to impart energy into a flywheel, to generate energy from stored energy in the flywheel and utilize the energy as a backup power source.

2. FLYWHEEL ENERGY STORAGE SYSTEM

Today's advanced flywheel energy storage system (FESS) as shown in Figure 1 range from kWs to several MWs for utility grid scale purposes, they consist of the following components:

- Flywheel: Usually made of composite materials like fiberglass or carbon fibre, these flywheels are hollow in the centre, they store kinetic energy by spinning at very high rpm in the range of 60,000 to 1,00,000 rpm.
- Motor/Generator: The motor/generator unit is used to impart & extract energy from the flywheel.
- Bearings: 2 types of bearings are used magnetic & mechanical, magnetic bearings are used to support the flywheel while operating they ensure that there is no friction present by magnetically levitating the flywheel. Mechanical bearings are used as a backup, if any of the magnetic bearings fail these bearings take the load & ensure there is no catastrophic failure.
- Vacuum Pump: It is used to pump out the air in the housing of the flywheel & to maintain a near vacuum atmosphere hence reducing air drag along the flywheel surface & eliminating the losses from it as a result increasing efficiency.
- Housing: All the above-mentioned components are housed in a strong container to ensure safety i.e. to contain any failure of components with in itself & no harm is caused to the surroundings, it also ensures the vacuum is maintained.

The energy is usually drawn from the grid or any other source, the motor/generator unit acts as motor and spinning the flywheel to high rpm anywhere between 60k to 100k rpm as the flywheel speeds up it stores energy i.e., it's being charged. When energy needs to be supplied the motor/generator unit now acts as a generator extracting energy from the flywheel i.e., it's being discharged this energy can be fed to the grid or to anything depending on its application.

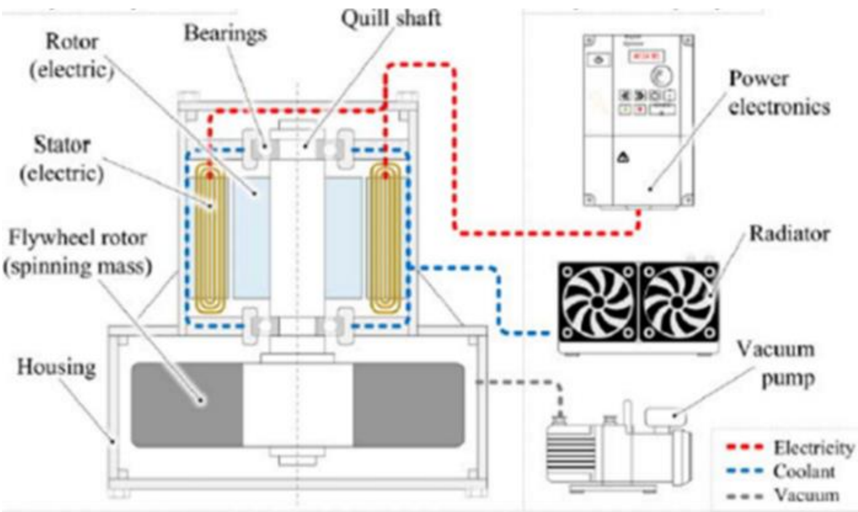


Figure 1. Fess & its auxiliary components

3. FLYWHEEL ENERGY/POWER GENERATION SYSTEM

This paper tries to present an approach to harvest power from the kinetic energy in a flywheel, through electrical machines, the hardware setup consists of the following components:

- Drive Motor
- Pulley & Belt arrangement
- A Shaft
- 2 Bearings
- Flywheel
- Jaw Coupling
- Generator
- Load
- Batteries & Power Electronics
- A frame to support all the above-mentioned components

A drive motor is used to get the flywheel spinning at the required rpm through the pulley & belt arrangement, the pulley & belt arrangement is used to increase the torque output of the drive motor to get the flywheel spinning from stand still. A larger pulley on the flywheel shaft & a smaller pulley on the drive motor shaft will multiply the torque by the pulley ratio, both the pulleys are connected by a V-belt. The flywheel is supported on 2 bearings, 1 at each end the 2 bearings take all the static & dynamin loads exerted by the spinning flywheel & the shaft.

At the other end of the shaft a jaw coupler is used to mechanically connect the flywheel shaft to the generator, through this connection the speed of the flywheel & generator will be same, the output of the generator will be connected to a feedback loop consisting of batteries & power electronics which will generate an AC output & at the same time power the drive motor, all the mentioned components are mounted on sturdy frame. If we were to connect a motor & generator directly without the flywheel in between them, the motor would stall because of the counter torque offered by the generator as the load on the generator increases.

To harvest the kinetic energy stored in the flywheel, mechanical energy in the form of kinetic energy needs to be converted in to electrical energy, firstly the flywheel needs to be charged i.e., it needs to be spun this done with the help of the drive motor the flywheel is spun to a determined rpm where it can store as much as kinetic energy possible & also overcome the counter torque offered by the generator when load is applied, once the flywheel is at the rated rpm it is fully charged meaning it contains maximum amount of kinetic energy possible.

Now the process of generating energy from the flywheel begins, so when the flywheel is spinning it will have large inertia & it will resist the forces trying to stop or slow it down in our case the counter torque from the generator. A heavy flywheel once spinning is very difficult to stop, it will also absorb any fluctuations & gives a smooth output, when the flywheel is spinning electrical energy is converted to mechanical energy & is stored in the flywheel as kinetic energy in the form of rotation (rpm).

The flywheel will spin the generator with all its energy at the same rpm as itself thus generating an electrical output, as the load on the generator will increase it will slow down the flywheel to overcome this some energy should be provided back to the flywheel from time to time, this output can be used to power homes, industries, hospitals, offices, restaurants, malls etc. 2 cases will be explained below on how to provide energy back to the flywheel:

- CASE 1: To provide power to the flywheel the drive motor needs to be powered, a fraction of the generated energy will be fed back to the drive motor via a speed sensing feedback loop, this ensures that the flywheel has enough energy in it to keep the generator spinning, the speed sensing feedback loop senses the rpm of the flywheel & decides whether to supply power to the drive motor or not if the rpm drops below a certain limit below which it can’t keep the generator spinning so the drive motor provides a push to the flywheel to keep the generator spinning at a constant rpm. The majority of the power will be used to power everything normally like from a wall socket getting power from the electricity grid.
- CASE 2: Instead of using speed sensing feedback loop to ensure the flywheel spins at the required rpm & constant power supply is coming from the generator pulse width modulation (PWM) can be used. PWM is a method where the supply is switched on & off several times a second, this method can also be used as an alternative to case 1, a speed sensing feedback loop is still used when it detects that the flywheel rpm is decreasing & will drop below the needed rpm it will cut off the power supply from the generator for a fraction of time, thus decreasing the counter torque from the generator acting on the flywheel & allowing it to regain the required rpm.

To do so batteries will be needed, when the PWM cuts supply from the generator the batteries will supply the needed power for that fraction of time interval, the size of the batteries can be determined by the amount of backup power needed, these batteries are also intended to supply power if the system is facing any issues & is not able to generate power. 2 sets of battery bank can be used, one charging from the power generated & the other used supply power for utility, the power supply can be switched between the 2 battery banks.

The methodology started out by designing the flywheel first, its diameter was decided as 1m, weight as 250kg and the material as cast iron as it is economical, other design parameters of the flywheel were made according to mechanical design handbook. The frame is made out of steel channels which were welded together to make the structure as seen in figure (frame photo), I chose cylindrical roller bearings as they can carry more load compared to ball bearings. The belts & pulleys sizes were also determined from the mechanical design handbook, for the drive motor I had used an AC induction motor earlier it was not able to generated the torque needed to get the flywheel spinning, the AC induction motor was driven by a VFD, it was overheating. The motor was changed to a BLDC motor of 3kW, the BLDC motor came with its own motor controller and throttle, the BLDC motor was powered by lead acid batteries, it was able to spin the flywheel but it again threr was a heating issue and fan was added to cool. Due to the issues faced by these motors, PMSG of 5kW was chosen to run the flywheel without any difficulty.

3.1. Flywheel

3.1.1. Composite flywheel

As they are anisotropic in nature, composite materials have higher longitudinal tensile strength but considerably lesser radial tensile strength, which restricts their energy capacity. Composite materials are recognised for their low density and high tensile strength. An optimization technique is frequently used to discover the ideal design while taking into account rim thickness, fit allowances, and various material combinations. A composite flywheel, as illustrated in Figure 2, incorporates multiple distinct materials, including carbon fibre, fibre glass, and epoxy. Despite having a high specific energy of 50–100 Wh/kg, composite materials frequently require a metallic shaft to interact with bearings and a motor or generator, which lowers their overall specific energy [29]-[30].

3.1.2. Steel flywheel

Steel flywheels were considered as low-speed and old technology associated with high-loss from mechanical bearing, by focus on improving the specific energy and energy density by finding the optimal geometric profile their energy content can be increased. Steel flywheels as seen in Figure 3 are regaining interests due to their advantages, like low cost, easy fabrication, and better recyclability [29].

Figure 2. Composite Flywheel [29]

Figure 3. Steel Flywheel [29]

The flywheel, a spinning mass that is typically axisymmetric and the primary component of the FESS, stores kinetic energy during rotation. The flywheel's energy storage capacity is given by (1):

$$E = \frac{1}{2} I \omega^2 \text{ [15]} \quad (1)$$

where E is the kinetic energy stored in the flywheel (kW or J)
I is the moment of inertia of flywheel (kgm^2)
ω is the angular velocity of flywheel (rad/s)

The moment of inertia is influenced by the rotor's mass and shape factor. Both lengthy, hollow or solid cylinders in the form of drums as well as short, disc-shaped cylinders are widely used to create flywheels. The moment of inertia for a solid cylinder or disc-type flywheel is given by (2):

$$I = \frac{1}{2} m r^2 \text{ [2]} \quad (2)$$

where m is the mass of rotor (kg)

r is the outer radius (m)

As with any storage technology, it is always desirable to provide a constant power level P irrespective of state of charge, and this implies that M/G torque $T_{M/G}$, follows an inverse relationship with speed:

$$T_{M/G} = P/\omega \text{ [15]} \quad (3)$$

where P is the power of flywheel (kW)
ω is the angular velocity of flywheel (rad/s)

In order to avoid high motor/generator torque $T_{M/G}$, a minimum value of speed ω_{min} is set between 1/2 to 1/3 of maximum ω_{max}, which is itself limited by structural integrity of the rotor, the useable energy of a flywheel is given by (4):

$$E_{usable} = ½ I (\omega^2_{max} – \omega^2_{min}) \text{ [15]} \quad (4)$$

Steel rotors are typically solid, and solid rotors formed of isotropic materials exhibit the best energy density. A heavy steel rotor is always tuned for high inertia, hence more energy is acquired linearly by adding additional weight. In high-inertia rotors, a large quantity of power is easily obtained because, for a spinning body, kinetic energy grows quadratically with speed, and for its mass, the energy content grows four times / fourfold with radius and rotational speed.

Composite materials as shown in Tables 1 to 3 are made of carbon could be used to create a thin rotating shell because unidirectionally wound carbon composite rotors have an incredibly high strength in one direction and the majority of centrifugal stress develops in the circumferential direction. It is a more efficient design to place the mass near to the flywheel/periphery. rotor's Since greater speeds at larger radii will provide more kinetic energy for their weight, flywheels that are designed for operating at high speeds typically have high energy densities [1].

Table 1. Rotor materials & their properties [17]

Rotor Material	σ_m (GPa)	ρ (kg/m^3)	E_{sp} (Wh/kg)
E glass	3.5	2540	190
S glass	4.8	2520	265
Kevlar	3.8	1450	370
Spectra 1000	3	970	430
T 700graphite	7	1780	545
Steel	2.7	8000	47

The maximum tensile strength of the rotor material determines the fastest speed at which a flywheel may run. An appropriate safety margin must be maintained in the flywheel/rotor design in order to keep the stress sustained by the rotor below or within the maximum tensile strength of the rotor material. The formula for a narrow rotating ring's maximum stress is given by (5):

$$\sigma_{max} = \rho\, r^2\, \omega^2 \text{ [2]} \quad (5)$$

where σ_{max} is the maximum tensile stress experienced by the flywheel (Pa)
ρ is the density of the material that the flywheel is made of (kgm^3)
r is the radius of the flywheel (m)
ω is the angular velocity of flywheel (rad/s)

Shape factor K is used to account for the effect of rotor/flywheel geometry, and max specific energy and energy density are provided by (6) and (7):

$$E/m = K (\sigma_{max} / \rho) \text{ in J / kg [2]} \quad (6)$$

$$E/V = K\, \sigma_{max} \text{ in J / m}^3 \text{ [2]} \quad (7)$$

Figure 4 along with Tables 2 to 4 illustrates some typical flywheel forms and their K values, which are critical for determining a flywheel's maximum speed and amount of energy that can be stored.

It is crucial to enhance the amount of energy stored in a flywheel by either increasing the rotational speed (rpm or ω) or the moment of inertia [1], which can be realised by increasing the mass or radius of the flywheel. This will result in two distinct types of flywheels: low speed (10,000 rpm) and high speed (from 10,000 rpm to 1,00,000 rpm).

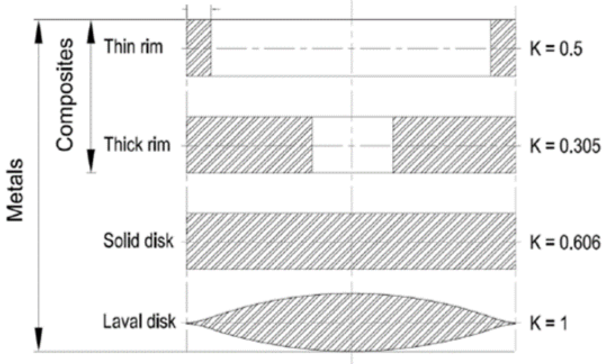
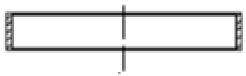
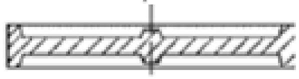
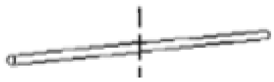


Figure 4. Different cross section/shapes of flywheel with K Value [1]

Table 2. Rotor shape & shape factor [5]

Flywheel Geometry	Cross Section	Shape Factor K
Disc		1
Constant Stress Disc		0.93
Conical disc		0.8
Flat Disc		0.6
Thin Firm		0.5
Shaped Bar		0.5
Rim with Web		0.4
Single Bar		0.33
Flat Bar		0.3

Heavy metals are frequently used to make low speed flywheels, which are then supported by magnetic or mechanical bearings. Magnetic bearings and lighter, stronger fibre composite materials are widely used in high-speed flywheels. The design of a flywheel system as a whole determines its price; the rotor's design may influence the designs of the other system parts. The rotor would be formed of laminated steel, which has the potential to be both inexpensive and tiny. This new class of intermediate speed flywheels takes advantage of the low cost of steel materials while being sufficiently high in energy density [2].

There are 2 stress which are of concern, they are the radial stress and hoop stress acting on a flywheel as shown in Figure 5, for an isotropic material the radial stress and hoop stress are given by (8) and (9)

$$\sigma_r = 3 + \vartheta/8 * \rho\, \omega^2 \left(r^2_0 + r^2_i - (r^2_0 * r^2_i / r^2) - r^2\right) \quad (8)$$

$$\sigma\theta = 3 + \vartheta/8 * \rho\, \omega^2 \left(r^2_0 + r^2_i + (r^2_0 * r^2_i / r^2) - (1 + 3\,\vartheta/3 + \vartheta)\, r^2\right) \quad (9)$$

where σ_r is the Radial Stress (MPa)
$\sigma\theta$ is the Hoop Stress (MPa)
ϑ is the Poisson Ratio
r_0 is the outer radius of flywheel/rotor (m)

r_i is the inner radius of the flywheel/rotor (m)
r is any radius in the flywheel/rotor (m)

The flywheel/rotor is more likely to create circumferential cracks by creating fibre reinforced composites with the fibres orientated circumferentially, which is considerably less likely to produce free-flying fragments in the event of a failure [5].

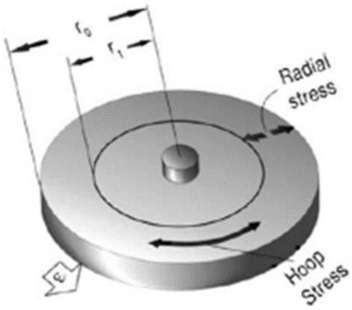
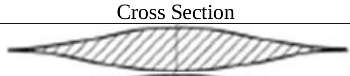
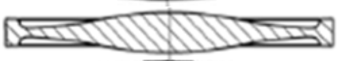
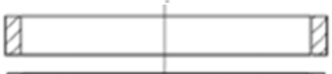
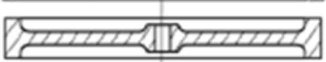


Figure 5. Radial and hoop stress acting on a flywheel [5]

Table 3. Different rotor materials & their properties [2]

Materials	Density (kg/m^3)	Tensile Strength (MPa)	Max Energy Density for 1 kg of weight (kWh/kg)
4340 Steel	7700	1520	0.05
E glass	2000	100	0.01
S2 glass	1920	1470	0.2
T1000 graphite	1520	1950	0.3
AS4C carbon	1510	1650	0.3

Table 4. Different rotor shapes & their K value [8]

Flywheel Geometry	Cross Section	Shape Factor K
Laval Disc		1
Laval Disc Real		0.7 to 0.9
Laval Disc with Rim		0.8 to 0.95
Conical Disc		0.7 to 0.85
Solid Disc		0.6
Thin Ring		0.5
Disc with Rim & Center hole		0.4 to 0.5
Thick Rim		0.3

3.2. Flywheel shape

Shape 1: Laval Disk with Rim

The infinitely thin fringe will be replaced by a rim at the outer radius of the laval disc, which results in a shape factor of K = 0.95. This form combines high density and high energy content because of the rim's higher moment of inertia. Due to the fact that it takes into account an endlessly thin fringe at the radius, a form factor of K = 1 for a laval disc is not practically feasible [8].

Shape 2: Thin Ring

Flywheels with a thin ring shape are made of orthotropic materials like fibre composites; in contrast to materials with a disc shape that are isotropic, the circumferential direction of the fibres in a carbon fibre flywheel exhibits the greatest strength, making it the best material to withstand circumferential stress. The radial stress that would typically limit the flywheel's performance is minimal because it is in the shape of a thin ring. As CNTs have a yield strength of 30GPa, they would be appropriate for FESS and have the potential for 2900Wh/kg of energy density if they could be produced in the order of cm as opposed to mm.

Laval Disk vs Thin Ring

The yield strength, density and energy density of different material for laval disc and thin ring shapes is mentioned in the Table 5. The Table 5 displays the mass specific energy densities, which are independent of the flywheel's absolute dimensions. The energy density of isotropic materials is maximum at disc shapes, as shown in the Table 5, due to the increase in shape factor K. Orthotropic materials also exhibit greater absolute energy densities because to the larger strain-to-density ratio.

Table 5. Different rotor materials &their properties for the 2 shapes

Materials	Density (kg/m3)	Yield Strength (MPa)	Energy Density for Thin Ring shape in Wh/kg (K = 0.9)	Energy Density for Laval Disc with rim shape in Wh/kg (K = 0.95)
CNT	1400	30,000	2693	-
T 1000	1500	3040	254	-
T 300	1500	1860	156	-
Resin	1151	69	7.6	16
TiAl6V4	4430	1100	32.3	65.5
Steel 60SiCr7	7430	1400	24.5	49.7
Al AW 7075	2700	400	19.3	39.1
Wolfram	19300	1920	12.9	26.3

As shown in Figure 6, metal flywheels have better stress distribution, therefore higher speed can be seen in a disc shape rather than a ring shape. CFRPs have higher yield strengths and are lighter than metal flywheels, so their rotating velocities will be higher than those of metal flywheels. As seen in Figure 7, CNTs arranged in a ring form have the largest energy content.

The CNTs exhibit the best energy content-to-volume ratio since the volume of ring and disc shapes is equivalent. Wolfram material exhibits the second-highest energy content but only in a disc shape. While both the steel disc shape and the T1000 composite ring exhibit an identical amount of energy, titanium and aluminium are the least advantageous materials from the standpoint of their energy density in terms of volume because these materials are too light weight to achieve adequate values [8].

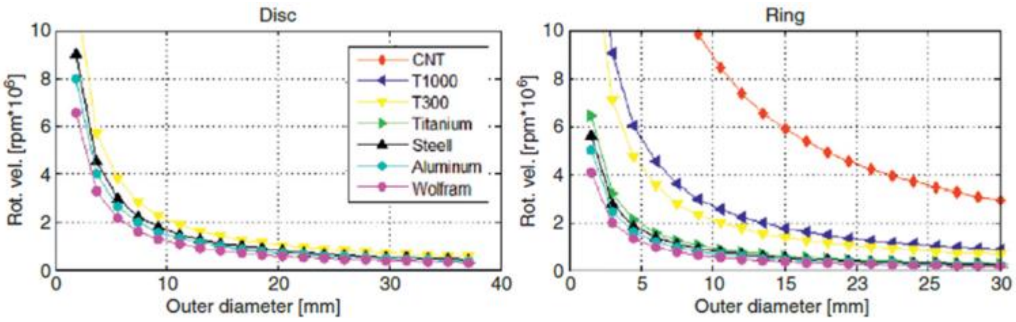


Figure 6. Flywheel Rpm vs outer diameter for disc & ring shapes [8]

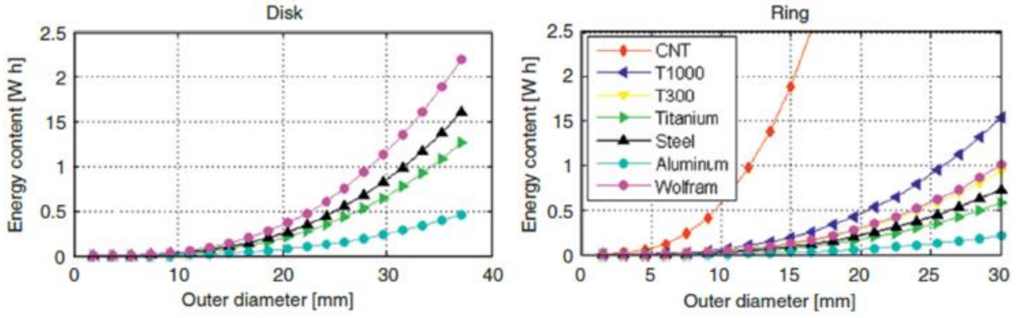


Figure 7. Flywheel energy content vs outer diameter for disc & ring shapes [8]

3.3. Bearings

The bearings are used to support the flywheel and to keep it spinning with very low friction, the bearings can be mechanical, magnetic, pneumatic (gas) or hydraulic (hydrodynamic or hydrostatic) depending on the weight, lifecycle, losses, static and dynamic loads. Pneumatic & hydraulic bearings cannot be used due the vacuum inside the encloser as mentioned in [15], so we are left with either mechanical or magnetic bearings.

Mechanical bearings used in FESS have low losses, these are lubricated by oils which are readily available and require maintenance, mechanical bearings as shown in Figure 8 have benefited from advancements in materials like ceramics and steel of high hardness, the main issue with these bearings are not the material but the lubricant, lubricant life mainly depends on temperature if the temperature is low and the lubricant doesn't deteriorate the bearing life would be unlimited as mentioned in [17]

Magnetic bearings have zero frictional losses, these bearings are of two types passive and active, i.e., passive meaning the magnetic bearings using permanent magnets and active meaning magnetic bearings as seen in Figure 9 use electromagnets which needs a constant power supply to energise the electromagnets, magnetic bearings don't have any frictional losses and doesn't need any lubrication. Passive magnetic bearings (PMBs) costs less, and have lower losses due to the absence of current as compared active magnetic bearings (AMBs), in an AMB the rotor position is controlled by the electromagnets (current carrying coils) through a feedback system which applies force on the rotor to keep it in the desired position. AMBs are costly compared to PMBs and uses a complex control system which consumes energy contributing to the total overall losses of the system as mentioned in [2] both these PMBs and AMBs are always used with auxiliary mechanical bearings in case of any failure of magnetic bearings.

Figure 8. SKF Ball Bearing [17]

Figure 9. Active magnetic bearings (AMB) [2]

Magnetic bearings are used for very high spinning speeds, there exists a spin speed limit above which the magnetic bearings will perform better as compared to mechanical bearings, below this spin speed limit mechanical bearings will have an advantage, the spin speed limit falls in between 20k rpm and 40k rpm, the power loss in mechanical bearings is approximately 5 to 200W and 10 to 100W in magnetic bearings for a 30kg rotor as mentioned in [17]. Below we will see a mechanical vs. magnetic bearings comparison in Table 6. Below we will see the advantages and disadvantages of mechanical and magnetic bearings in Table 7. For our application we'll be using cylindrical roller bearings as shown in Figure 10, in the below section we'll discuss about bearing selection, bearing lubrication and selection and about bearing life.

Table 6. Mechanical bearings vs magnetic bearings [2]

Mechanical Bearings	Magnetic Bearings
It's a very well-known technology	Industry standards are yet to mature
Comparatively higher losses	Very low losses
Low speed	High speed
Lubricants will evaporate in vacuum	Very well suited for vacuum operation
May require active cooling	Active control and cooling is needed

Table 7. Advantages & disadvantages of mechanical bearings & magnetic bearings [2].

Bearing Type	Advantages	Disadvantages
Mechanical	Simple	Needs Lubrication
	Low Cost	Needs Seals
Magnetic	Low Loss	Needs Auxiliary Bearings
	No Friction	High Cost

Figure 10. Cylindrical roller bearing

3.3.1. Selection of bearing

The choice of bearing for flywheel applications is influenced by factors such the static and dynamic load on the bearing, the operating speed, and the acceptable amount of maintenance. The chosen bearing must be able to withstand the weight of the flywheel and dynamic forces as well as have a satisfactory life with minimal maintenance and an acceptable degree of losses.

3.3.2. Lubrication of bearing

The operating temperature, speed restriction, and bearing losses all affect the type of lubrication used in rolling element bearings. Smooth functioning is made possible by oil lubrication, however there are drawbacks including frequent maintenance and additional equipment for oil pumping in pressurised systems. The pressurised oil feed system, which uses an advanced oil supply system, a high-pressure pump with a filter and an oil cooler, raises the cost of the system overall but is also an excellent alternative for controlling temperature.

Another choice is grease, which is superior than oil lubrication in terms of maintenance requirements and lifespan but has less cooling effect and a lower flywheel operating speed. The most typical lubrication method utilised in the majority of bearing systems is either oil or grease lubrication method, taking into consideration significant elements such as lubricant viscosity, cooling impact, quantity, and mode of supply.

3.3.3. Life of bearing

Manufacturers of bearings describe bearing life as the amount of time a bearing can safely withstand a load while rotating. High cyclic stresses on the bearings' rolling surfaces can result in cracks forming beneath or on the surface of the rolling elements, which will cause the material to fail. Noise or vibration originating from the bearing can be used to detect bearing fatigue signs, which signify the end of the bearings' useful life. The bearing can continue to function for a long enough period of time before being replaced in this failure category. Fatigue life calculation of the bearing becomes a crucial step in the bearing selection process for flywheel applications where maintenance should be kept to a minimum and bearing failure or breakdown could result in a catastrophe.

The bearing life rating is a straightforward and widely used calculation method for calculating bearing fatigue life. When 10% of the bearings fail to operate due to flaking, it is defined as the total number of operational hours that a number of bearings working separately under the same load conditions have completed. Basic life rating of bearings is calculated using the relation below as a function of bearing load:

$$L_{10} = (C/P)^{p} \text{ [3]} \tag{10}$$

where, L_{10} is the basic life rating of the bearing in millions of revolutions at 90% reliability
C is the basic dynamic load rating in newtons (N)
P is the equivalent dynamic load in newtons (N)
p is 3 for ball bearing and 10/3 for roller bearing

$$L_{10h} = 10^{6}/60_{n} * L_{10} \text{ [3]} \tag{11}$$

where, L_{10h} is the basic life rating of the bearing in operating hours at 90% reliability
n is the rotational speed in min^{-1}

3.4. Power transfer

An electric machine is used to convert electrical energy into kinetic energy or mechanical energy and back, hence the electric machine will act as a motor and also as a generator, for our application we will be using two separate electric machines one to drive the flywheel and another to extract energy from the flywheel. There are two ways to get energy into the flywheel: electrically or mechanically. At the moment, electric machines are more popular, which has the benefit of ensuring a long system life. The usual service/operational life of electrical machinery is over 25 years, and the usage of magnetic bearings can further increase the period of time without maintenance. Because fewer components are required, the complexity of the system is reduced when a flywheel's power transfer unit is directly connected to its shaft.

Permanent magnet synchronous machines (PMSM), which are a handful of these electric machines that are detailed below, are a popular option for flywheel applications due of their high performance, high efficiency, and small size. Flywheel applications also use other electric machines like the induction machine (IM) and switch reluctance machine (SRM). According to the information in the motor and generator's design specifications, the power density and current carrying capability are essential for the flywheel's power rating [29].

3.4.1. Mechanical power transfer

As mentioned in [1] continuously variable transmissions (CVTs) could be used to transfer mechanical energy from the drive motor to the flywheel, CVTs can vary the ratio according to the load condition like, while starting the flywheel from stand still it can make the driven pulley diameter larger than the driver pulley diameter therefore multiplying and providing adequate torque to get the flywheel up to the rated speed, once the flywheel is spinning at the rated speed the ratio can be varied to be of the same diameter for both the driver and driven pulley or the driver pulley can be made larger than the driven pulley so that even with fewer rotations of the driver pulley the driven pulley rotates more than the driver pulley also spinning the flywheel along with it, this ensures that less power is consumed by the driver motor to spin the flywheel, this case is known as overdrive.

3.4.2. Electrical power transfer

No DC machines or wound rotor synchronous machines are typically used to eliminate brushes. The following are some examples of electrical machines in use:

– PMSM:

High power density and efficiency characterise a PMSM. The size, quality, and number of poles of permanent magnets are design factors for PMSM, which are common choices for FESS. The highest charge/discharge efficiencies are achieved in PMSMs because the rotor is powered by highly magnetic materials (NeDyFeB or AlNiCo). The disadvantage is that the magnetization from the permanent magnets continues to exist even if the windings are not energized which causes iron losses in laminated steel. Using a coreless stator is one technique to stop iron losses in high-speed machines. The ultimate tensile strain for neodymium magnets, as indicated in [1], is only 0.06 percent, demonstrating how fragile these magnetic materials are.

For FESS applications, PMSM are most frequently employed due to their high efficiency, high power density, and minimal rotor losses. Because of the speed restrictions of induction motors (IMs), torque ripple, vibration, & noise of variable reluctance motors, they are commonly utilised in high-speed applications (VRMs). The issue with a PMSM is its expensive cost, low tensile strength of the permanent magnets utilised in it, and idling losses brought on by stator eddy current losses. The two primary types of PM motors used in FESS applications are PMSM and Brushless DC Motor (BLDCM), as stated in 2. The fact that PMSMs use permanent magnets, which are prone to demagnetization over time, makes them less durable, more expensive, and more expensive than SRMs and IMs, as indicated in [29] and [20].

– IM:

Due to the absence of permanent magnetization, induction motors and generators are less efficient and have a lower power density than permanent magnet motors and generators. This greatly eliminates the problem with idle losses. Although the IM rotor is straightforward and durable, it is where the majority of losses are produced. Due to their durability, great torque, and low price, induction machines are employed in high power applications. Although IMs have less efficiency than PMSMs and have speed restrictions, they are commonly employed in wind turbine applications because they allow for the power smoothing of wind production systems as indicated in [2].

– SRMs/VRMs:

SRMs/VRMs are extremely durable, do not require a permanent magnet, operate efficiently at wide speed range, have little losses from standby, and do not include any rare earth elements. The performance of permanent magnet motors has been attained by reluctance motors by employing high performance materials as indicated [1]. Recently, there has been a trend to limit the employment of rare earth materials such as neodymium in electrical devices.

The negative is that it has a poor power factor, low power density, and strong torque ripples. It is also thought to be less developed and unproven than PMSMs and IMs, as indicated in paragraphs [2 & 29]. It features a simpler control mechanism than IMs, fast acceleration capability, and no cogging torque. They are capable of working in hazardous conditions with temperatures as high as 400°C [19].

– Brush less direct current machine (BLDCM):

BLDCMs are mainly used as motor rather as generators, they contain permanent magnets in their rotor and stator coil windings around it. BLDCMs have high power density, high efficiency, wide speed range, compact design and low maintenance as stated in [19 & 20].

– Axial flux permanent magnet machines (AFPMMs):

Brushless machines known as AFPMMs have also been suggested for use with FESS. Figure 11 shows the vertical arrangement of an AFPMMs in contrast to the horizontal arrangement of radial flux machines. An AFPMMs has two stators and one central rotor, which increases round-trip efficiency by fully utilising the axial forces. If desired, the central rotor could also serve as a flywheel. An axial-flux flywheel power production system has been mentioned in [30].

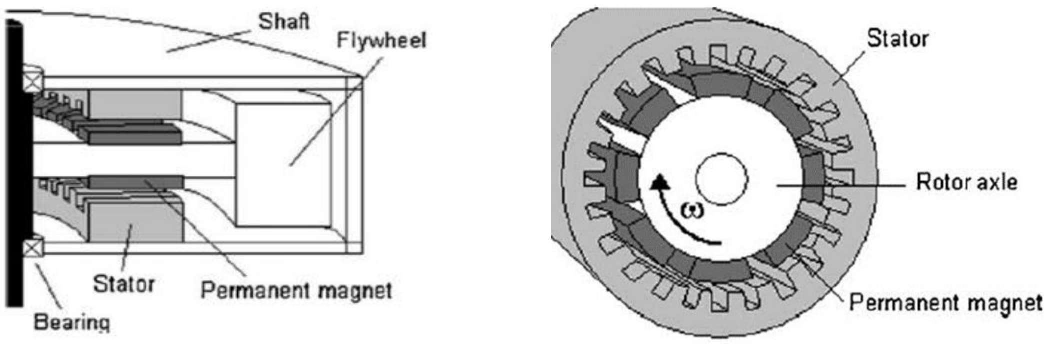


Figure 11. AFPM arrangement on left & RFPM arrangement on right [30]

Contrary to radial flux machines, axial flux machines can have two power generating surfaces, either it can be two rotors combined with one stator or it can be one rotor combined with two stators. There are many designs for an AFPM machine, such as internal rotor, internal stator, multidisc, and rotors with surface-mounted magnets. The increase in power is a benefit of having two power generating surfaces. In the Table 8 compares between the various aspects of the above-mentioned machines are listed. Advantages and disadvantages of the above discussed electric machines are as in Table 9.

Table 8. Induction vs switched reluctance vs permanent magnet synchronous [2]

Machines	IMs	SRMs / VRMs	PMSMs
Power	High	Medium & Low	Medium & Low
Specific Power	Medium (0.7kW/kg)	Medium (0.7kW/kg)	High (1.2kW/kg)
Rotor Losses	Copper and Iron	Iron	Very Low
Efficiency	High (93.4%)	High (93%)	Very High (95.5%)
Size	1.8 L/kW	2.6 L/kW	2.3 L/kW
Tensile Strength	Medium	Medium	Low
Torque Ripple	Medium (7.3%)	High (24%)	Medium (10%)
Demagnetisation	No	No	Yes

3.4.3. Cycle life time

In contrast to batteries, flywheels do not have a relationship between cycle life and depth of discharge. Batteries lose their ability to store energy when they are cycled, discharged quickly, or exposed to extreme temperatures. For instance, a battery pack can only operate at 3% depth-of-discharge in an application requiring 106 cycles, necessitating the purchase of a battery 33 times bigger. The specific energy then falls off with the same factor, and it could even be lower than in a flywheel system.

Table 9. Advantages & Disadvantages of IM Vs SRM Vs PMSM [2 & 5]

Machines	IMs	SRMs / VRMs	PMSMs
Advantages	Low Cost	High Efficiency	Low Loss
	Simple to Manufacture	Robustness over Temperature	Magnetic Field produced without Excitation Loss
	Mature Technology	Lower Loss at Starting	High Power Density
	Variable Power Factor	Easy Heat Dissipation	Less Complex Rotor
	No Spinning Losses	High Power Density	High Torque Density
	No Demagnetisation	Low Loss	High Reliability
	No Running Losses	Overcurrent Capability	Small Volume
			High Efficiency
			No Losses in Field Winding
			Flexible Shape
			Easy to Control
Disadvantages	Rotor Slip is High	Difficult to Regulate Speed	Low Robustness to Temperature
	Transformer Losses	Difficult to make	Demagnetisation
	Limited Speed	Low Power Factor	High Cost
	Large Volume	Torque Ripple	Fragile
	Low Power Quality	Noise	Low Tensile Strength
	High Losses	Vibration	
	Low Efficiency	Complex Structure	
	Rectifying Loss		
	Complex Rotor		

Regardless of charge rate or depth of discharge, flywheels have demonstrated outstanding ageing characteristics, with cycle lives exceeding 1,000,000 cycles. The carbon composite is a crucial part of any contemporary high-speed flywheel. The ultimate fatigue limit for composites, which is an unlimited number of cycles, depends on the binding matrix and is 0.6% for epoxy in the hoop direction, which is the primary stress direction. The 0.6% limit of epoxy, it is crucial to note, does not relate to the flywheel's charge/discharge cycles, but rather to the flywheel's state-of-charge, which means that as long as the flywheel's state-of-charge does not exceed a particular limit or threshold, a very long cycle life is assured [1].

3.5. Containment & safety

The housing of the FESS serves two functions: first, it creates a low gas drag environment, and second, it contains the rotor in the case of a failure. Losses from aerodynamic drag in a FESS rise with the cube of rotational speed if the system is operated at atmospheric pressure. To increase system performance and safety, the flywheel can be mounted in a vacuum housing to decrease aerodynamic losses. The vacuum housing is often composed of thick steel or another material with high strength, such as composites. The containment keeps the rotor in a vacuum to maintain the low pressure or partial vacuum inside the chamber, which reduces aerodynamic drag losses.

Operating the system in such a low-pressure environment necessitates a vacuum pump to maintain low pressure in the chamber and an effective cooling system to deal with the heat produced by the M/G and other components of the FESS, such as the bearings. The flywheel is operated by an electric machine, so no rotary seals are necessary and the leakage is very small, indicating that the vacuum pump does not need to operate continuously or the vacuum pump can be completely electric. The rotor material affects the vacuum pump's performance because composite rotors have extremely fast tip speeds and thus demand very low chamber pressures due to the composition of the polymer resin matrix components [2].

Another option is to employ a gas combination of air and helium (He), which lowers the system's cooling needs while simultaneously reducing aerodynamic drag loss. Composite rotors would/tend to shatter into several little pieces or fragments in the case of rotor failure, and the energy would be lost through friction as the fragmented parts continued to rotate inside the chamber. As a result, pressure would build up at the chamber's end plates. A considerably greater explosion of the dust kind must also be contained if air enters the chamber during failure, necessitating a stronger containment system.

Steel flywheels and rotors produced in one piece run the risk of shattering into several pieces, which would be impossible for the chamber to withstand. As a result, they require extremely robust containment mechanisms. Making steel flywheels out of a stack of thinner discs can solve this problem, and doing so makes them considerably safer since, in the case of a catastrophic collapse, only a small portion of the energy stored in the flywheel/rotor would be released. There is no published literature on what is necessary to include both composite and steel flywheels/rotors, and no standards have been formally approved. The majority of flywheel manufacturers advise bundling together flywheels for safety.

3.6. Failure mechanism

Failure Mechanisms as shown in Tables 10 and 11 are associated with the rotating parts like flywheel/rotor, motor/generation and bearings, the housing acts as the first protection against any failure, flywheel's structural failures can have many different causes which can lead to various hazards, some of the failure modes are general for all rotor material types and some only apply to fiber reinforced rotors, all flywheel designers strive to achieve the highest possible rotor speed in order to attain highest possible energy content and energy density. The maximum specific energy (E/m) is limited by the maximum allowable stress in the rotor material (σ_{max}), the material, density of the rotor material (ρ) and shape or form factor (K):

$$E/m = K \times \sigma max / \rho \quad (12)$$

In applications like UPS the flywheel mainly operates at full speed in steady condition compared to other applications like in frequency regulation the flywheel will speed up, slow down again speed up while operating. Depending on the application, the designer will need to determine the maximum allowable speed and stress while keeping safety factors in mind, in case, of the flywheels which do not have any protecting housings, the manufacturers have to define the safe lifetime and inspection intervals.

Ageing and material defects like voids, cracks or segregations can cause an early failure of flywheel, some defects if the flywheel can be detected by non-destructive testing, but other defects can't be detected or only detected to a limited extent, as structure gets thicker, the number of non-detectable defects will be larger. Therefore, the defects which cannot be detected have to be accounted for during the design phase. Fracture mechanic tools could be used to determine the growth of crack.
General failure root causes and their failure mode:

Table 10. Failure Modes of Flywheel Along with Its Cause [26]

Trigger & Cause	Failure Mode
Trigger: Because of circumferential pressures, the rotor breaks Cause: rotor speeding up or developing cracks	The rotor breaks in to fragments and fly off in radial and tangential direction
Trigger: Torsional tension or other forces cause the rotor shaft or hub to break. Cause: radial vibrations or a jammed bearing	The rotor as a whole takes off in a radial direction.
Trigger: Rotor cracks or softening could result from an overheated composite flywheel/rotor. Cause: Insufficient vacuum.	The rotor breaks in fragments and fly off in radial and tangential direction
Trigger: earthquakes, excitations, and penetrations are examples of external risks	Excess forces on the rotor leads to rotor breaking into fragments and air will rush in to the chamber

Table 11. Failure modes of flywheel & its consequences [26]

Failure Mode	Consequences
Entire rotor does not break	– Large radial and bending impulses on the housing and ground attachment in significant quantities – Rotor components that pierce the housing and shoot out like projectiles – The housing and ground attachment are subjected to significant torsional loads – Strong axial impulses that raise or pierce the housing top and exert stress on the ground connection – Lot of noise – Hot crash gas – There is a risk of fire or explosion if there is any organic substance, such as oil or grease.
Rotor fragments fly off	– Excessive bending impulses on the attachment and housing – Housing penetration – There is a considerable torsional load on the ground attachment and the housing. – Excessive noise – Hot crash gas

Consequences of flywheel rotor failures:

The rotor should still have an adequate safety factor, typically of S≈2, to reduce the chance of rotor failure even if the flywheels are in safe housings or in bunkers. Because breaking the last safety limit will be a catastrophic risk given that flywheels operate at extremely high circumferential speeds, sometimes even up to 800 m/s, three design possibilities exist.:

– A safe housing must be constructed so that no penetration or gas release/intake due to any known internal failure can take place.
– Install the system in a sturdy bunker to prevent penetration or bunker destruction in either the radial or axial direction, including the risk of "dust like explosion" if air and oxygen are present.

- The rotor should be constructed with a substantial safety margin to make any known rotor failure type extremely unlikely [26].

3.6.1. Flywheel characteristics

- High Power Density
- High Energy Density
- Long Cycle Life
- No Capacity Degradation
- Easy Estimation of State of Charge
- Fast Response
- No Maintenance
- Highly Scalable
- Universal Localization
- Eco Friendly
- Recyclable

3.6.2. Issues with FESS

Safety Management

The safety of flywheel energy storage is a natural concern; in the US, the defence advanced research projects agency (DARPA), the Houston Metro Transit Authority, and NASA have all financed safety-related projects. The following strategies are suggested in for dealing with the difficulty of safety [17]:

- In order to achieve safe operation, the maximum speed is frequently derated, which is a common practise. The planned margins should be tested to failure at speeds much above the rated speed. Destructive spin tests and dynamic stress analysis should be used to determine the maximum allowable operating speed. The spin tests will determine the rotational speed at failure, and the analysis will determine the margin of safety by analysing how the stresses in the rotor will change with its speed. Next, the maximum speed for safe operation will be determined by reducing the rotational speed of failure
- Fault Protection - The control techniques ought to be incorporated into the on-board computer and sensors used to monitor system health will assess the performance of all FESS characteristics, including the structure, electromagnetic bearings, the motor/generator, and electronics. Therefore, the system can be safely shut down if any abnormal circumstances develop.
- Containment - The FESS containment is specifically made to handle two sorts of flywheel failures: (i) a rotor failure with an unbroken rotor, in which the rotor is virtually unharmed during the failure, and (ii) a rotor failure with a fragmented rotor, in which the carbon composite layer shattering.

Loss Management

Energy efficiency is one of the key components of FESS; the overall efficiency greatly depends on the losses; to overcome the mechanical losses, the flywheel must be continuously revolving. The losses can be computed using the formula (13)

$$P_{loss} = P_{ax} + P_{wind} + P_{Cu} + P_{Fe} \tag{13}$$

where, P_{ax} is the axial rotating loss
P_{wind} is the windage loss
P_{Cu} is the copper loss
P_{Fe} is iron core loss

High-speed flywheels are typically mounted in vacuum enclosures or chambers, as previously mentioned, which helps eliminate air drag thus reducing mechanical loss. Adding these technologies can undoubtedly increase the overall efficiency of the system because windage losses account for a significant portion of the total losses. Therefore, reducing windage losses is the most efficient and simple way to minimize the total losses in the flywheel and to improve the efficiency of the system

However, doing so will make the system more complicated and expensive because equipment like a vacuum pump, vacuum chamber, and cooling system will be included. Using helium gas and air mixture is a good approach for reducing windage losses, as shown in [17], which shows that the drag on the flywheel/rotor is reduced to 43% in the case of 50% helium per air compared to that of 100% vol of air, and that the loss can be reduced to over 70%, in the case of 75% helium gas per air.

4. COMPARISON WITH OTHER TECHNOLOGIES

4.1. Flywheels Vs batteries

As indicated in [1], batteries are a flywheel's main rival in most applications, although flywheels have several benefits over batteries, which are listed below:

– Usable Life: Flywheels are advantageous due to their long cycle life and lack of ageing degeneration.
– Environmental Footprint: Flywheels have a very low environmental impact because, unlike batteries, they may be made of non-hazardous materials and are simple to recycle.
– Temperature Sensitivity: Compared to batteries, flywheels are less sensitive to the outside temperature, but there are still certain thermal restrictions that must be met, including those for the windings to prevent melting, the magnets to prevent demagnetization, and the composite material to prevent burning. If ambient temperatures vary, Li-ion batteries will undergo capacity and power fading.
– State of Charge Estimation: There are several methods for determining the battery's state of charge, each of which performs differently under various operating circumstances. These methods include open circuit voltage, terminal voltage, impedance spectrum estimation, Coulomb counting, etc. The status of charge for flywheels may be determined immediately from the rotor speed.

4.2. Flywheels Vs Supercapacitors

Electric double-layer capacitors (EDLCs), the industry standard and available from Maxwell Technologies for $6500 USD, are built expressly for use as a power buffer in automobiles. For big volumes, the price is quite likely to decline. Supercapacitors and flywheels are competing with each other in high-power applications. According to their peak power and specific energy, multiple energy storage methods are compared in Figure 12 and Table 12. The Table 12 compares three flywheel systems and an EDLC system that were specifically created for transportation applications:

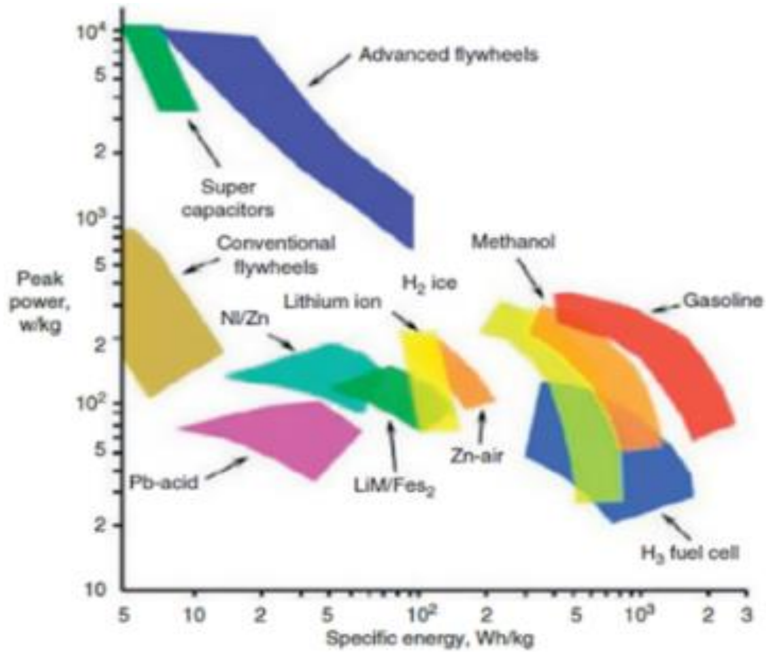


Figure 12. Flywheel Vs Other Storage Technologies [1]

Table 12. Comparison of flywheel vs supercapacitor from different manufacturers [1]

Specifications	Flywheel System	Flywheel System	Flywheel System	EDLC System
Manufacturers	GKN Hybrid Power	GKN Hybrid Power	Flybrid Formula 1	Maxwell Technologies
Used In	Porsche GT3R	Audi e - tron	2009 season	
Power (kW)	180	150	60	103
Energy (Wh)	375	97	111	150
No of Cycles	>10,00,000 cycles	>10,00,000 cycles	N/A	>10,00,000 cycles
Specific Energy (Wh/kg)	6.4	3.5	4.4	2.3
Specific Power (kW/kg)	3.15	5.5	2.4	1.7
System Weight (kg)	57	27	25	61

The above Tables 13 and 14 compares different energy storage systems characteristics which include Batteries, flywheel energy storage systems (FESSs), electrochemical double layer capacitors (EDLCs) and superconducting coils (SCCs). SSCs store energy magnetically by circulating current with no ohmic losses this requires a cryogenic system and are very costly, Batteries are well-proven technology, their useful lifetime depends on number of charge/discharge cycles, the depth of discharge and temperature also in batteries SOC monitoring is difficult. EDLCs have very high capacitances in the order of kF which allows high number of charge/discharge cycles with easy monitoring of SOC, many strings of EDLCs are required to achieve proper levels of working voltage. A comparison of specific energy content between FESS rotor materials and batteries and petrol is shown in Figure 13 [6].

Table 13. Comparison of batteries vs supercapacitors vs smes vs compressed air vs flywheels [6]

Devices	Cost	Cycle Life	Efficiency	Issues
Batteries	Low	Low	High	Expensive periodic replacement due to short cycle life and Thermal runaway
Super Capacitor	High	Medium	High	High Initial Cost, will take up too much space
Hybrid Super Capacitor	High	Medium	High	High Initial Cost, will take up too much space
Superconducting Magnetic Energy Storage	High	High	High	High Initial Cost, will take up too much space
Compressed Air	Medium	High	Low	Round trip efficiency of only 50%
Flywheels	Medium	High	Medium	No such issues but advancement in low loss bearings and high energy rotor and cost reduction

Table 14. Comparison of batteries Vs FESS Vs EDLC Vs SCC [21]

Devices	Battery	FESS	EDLC	SCC
Storage Mechanism	Chemical	Mechanical	Electrical	Magnetic
Peak Power (kW)	Medium (≈102)	High (≈103)	Medium (≈100)	High (≈103)
Efficiency (%)	80 to 85	90 to 95	>95	90
Pulse Duration	>1 hr	Seconds to Minutes	Minutes	Seconds
Magnitude for SOC	Voltage	RPM	Voltage	Current
SOC measure reliability	Medium	High	High	High
Powe Density (kW/m3)	Medium (10	High (≈102)	High (≈102)	High (≈102)
Energy Density (kWh/m3)	High (102)	Medium (10)	Medium (10)	Low (1)
Useful Life span (Years)	3 to 5	>20	10 to 20	20
Technology Maturity	Proven	Proven and Promising	Proven and Promising	Proven and Promising
Temperature Range	Limited	Less Limited	Less Limited	Controlled
Environmental Concerns	Disposal Issues	Slight	Slight	Slight

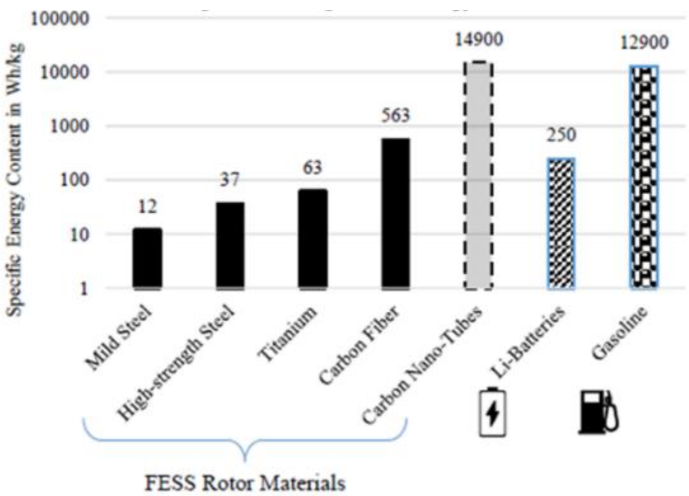


Figure 13. Specific energy content of fess rotor materials vs li ion and petrol [6]

4.3. Flywheels in the storage landscape

The interest in energy storage has grown exponentially over the years with penetration of weather-dependent renewables particularly solar and wind which could replace large coal-fired steam power plants, issues with renewables is their intermittent generation, the inertia of the grids which has to be reduced and weakening frequency stability. Large steam power plants provide substantial mechanical inertia, which is similar to flywheels, reacting if the frequency varies due supply and demand imbalances.

The technology mainly used to compensate for the lag between supply and demand, Li-ion batteries are mass produced and are guaranteed by manufacturers for a defined operating duty. Reports on levelized cost of storage (LCOS) shows that Li-ion will out-compete flywheels on cost, but a more recent study which considered the degradation and other effects that batteries will experience has shown that flywheels will be the most cost-effective technology for fast response as shown in Figure 14.

The major issues with Li-ion are the supply of raw materials and ethical issues concerning their source, the difficulty of recycling with current rates of Li-ion battery recycling being very low, cycle life and calendar life are limited to around 8 years this will be lower for applications with high number of charge/discharge cycles and they are affected by temperature, these issues with Li-ion batteries have fuelled the development of alternatives. There will be overlap of storage system characteristics in terms of duration and response, there is no storage system available that is able to cover all timescales needed from fast response and all the way to seasonal storage, most of the storage systems with durations greater than Li-ion have response times in the order of 10s of seconds due to mechanical or thermal inertia.

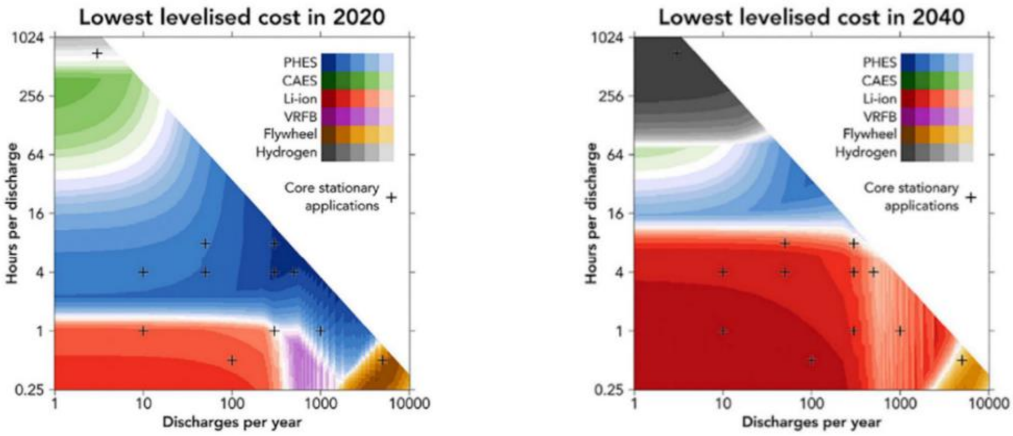


Figure 14. Comparison of lowest LCOS for different energy storage methods in 2020 and in 2040 [15]

Since long-duration technologies like pumped hydro, compressed air, heat-to-electric, or engines running on renewable fuels like biodiesel or biogas are able to provide power within 1 minute, the only thing required from the fast-duration technology is a low-minute duration power supply, the result is that at least two systems will be needed, one for a fast response and another for a long duration supply. Flywheels or other fast-response technologies can compete with Li-ion in this market because of their lower power costs than Li-ion. One drawback of flywheels is its standby losses, although in a well-designed flywheel, these losses can be minimised, 1 to 2 hours of power provided by Li-ion batteries overlaps with the power already being provided by other long-duration technologies; therefore, if long-duration, slow-response technologies are used, Li-ion batteries may be eliminated. For a given power, its standby losses may be no higher than the ancillary power required for thermal management of Li-ion to maximise the battery life.

Supercapacitors are a mature and well-established technology at this point, and they have the potential to compete with flywheels in fast response applications. Flywheels and supercapacitors are two examples of a hybrid system of fast response and long-duration technologies that are being tested with liquid air storage. Although they have low power costs, they do not yet have enough duration to close the gap in response time between short-duration and long-duration technologies. Supercapacitors must be connected in long strings in series to provide grid power, which compromises system reliability because, unlike flywheels, they will degrade with time and temperature. This demonstrates how flywheels perform admirably in high-cycle and short-duration applications.[15]

5. APPLICATIONS

5.1. Renewables

By enhancing system stability, FESS can aid in the broader integration of wind and solar energy into power networks. They are excellent for applications utilising RES for balancing grid frequency because of their quick reaction times. By storing the energy generated during sunny or windy times and supplying it back when needed, solar and wind power oscillations are balanced. In solar systems, flywheels may be linked with batteries to increase system output and prolong the life of the batteries. Flywheels can be used particularly for wind systems to correct oscillations and enhance system frequency.

According to the article [2], combining solar panels and wind turbines into a hybrid system would not result in any fuel savings. Diesel generators should only be activated when there is a need and left off the majority of the time, as they can burn up to 40% fuel even when not loaded. As a result, this occurred. Therefore, employing FESS lessens how frequently diesel generators start up and shut down, which lowers fuel use and GHG emissions

As long as standing losses are kept to a minimum, flywheels supporting solar PV can be highly advantageous since they can withstand the high cycles brought on by cloud passings and still deliver enough energy. To help renewable energy sources penetrate more deeply, a broad variety of FESS have been created. FESS has been made available for use in wind and solar applications by ABB's PowerStore, Urenco Power, Beacon Power, and VYCON Technology.

The first high penetration solar PV diesel power station in the world, constructed in 2010, was mentioned in the study [2] and is located in the town of Marble Bar, Western Australia. While used as a UPS system, a FESS maximizes the use of solar energy when it is sunny and activates the diesel generators when the sun is obscured. As a result, 4,05,000 liters of gasoline and 1100 metric tonnes of GHG emissions were saved annually. Due to the inclusion of flywheels, the PV system can now provide 60% of the town's typical daytime energy needs, producing 1 GWh of renewable energy annually.

5.2. Motorsports/automotive

The development and introduction of flywheels in automobiles has accelerated in the last decade. The major driving force behind this is the new emission standards regarding fuels and fuel consumption in cars which aim consistently reducing CO2 emissions, the target for 2020 is set to <80 g of CO2 per km as mentioned in [1]. Hybridization improves vehicle efficiency and environmental issues including noise and pollution. Since the rules were altered in 2009 to allow for the installation of such equipment, flywheels have been utilised in Formula 1 as a temporary energy storage unit, as seen in Figure 15. In Formula 1, this flywheel system is known as the kinetic energy recovery system (KERS). It should be noted that the power requirements for F1 applications are substantial, and a continuously variable transmission (CVT) plays a significant role in the mechanical power transfer system. Table 15 provides the specifications of KERS Flybrid Systems.

Figure 15. Flybrid Systems KERS for Formula 1 [1]

Table 15. KERS Flybrid Systems [1]

Properties of KERS from Flybrid Systems	Values
Energy available for use (Wh)	111
Power (kW)	60
Maximum Speed of Rotor (Rpm)	64,500
Weight of Rotor (kg)	5
Total system weight (kg)	25
Energy Density (Wh / L)	8.5
Specific energy of Rotor (Wh / kg)	22.2
Specific energy of System (Wh / kg)	4.4

Stand-by losses are not a significant issue in motorsport due to the frequent charge and discharge cycles that flywheels undergo. Typical drive patterns, on the other hand, have longer standby times, necessitating higher standby efficiency standards. According to Flybrid Systems, the 1.7-ton saloon car saved 18% on the new european driving cycle (NEDC) and the 2.6-ton SUV saved 35% on the federal test procedures (FTP) driving cycle in the United States. [1]. Figure 16 depicts the hybrid Jaguar XF from 2011 using a mechanical flywheel technology.

The flywheel was constructed from composite materials, and the Torotrak/Xtrac CVT gearbox, which is 65 kg and can store 120 Wh of energy at 60,000 rpm, was used to transmit power to the driving wheels. The system can deliver up to 60 kW of power, and it was discovered that this resulted in fuel savings of about 20 percent. For power handling, Volvo also uses mechanical flywheels. Their flywheel technology, which was placed in a Volvo S60, was comparable to the Jaguar system and enabled a boost of 60 kW and a fuel consumption decrease of about 20 percent.

Figure 16. Flywheel system used in jaguar XF in 2011 [1]

The R18 e-tron quattro from Audi was the first hybrid vehicle to win the Le Mans 24-hour race in 2012. Other races have also utilised this technology. Instead of using solid magnets, the flywheel was made of magnetically-loaded composite material, and it was operated in a partially depressurized environment to reduce peripheral drag losses while still allowing the bearings to function at atmospheric pressure. The system has a 140 Wh storage capacity and a 150-kW rated output. The Porsche 911 GT3 RS Hybrid was introduced in 2010 and includes GKN Hybrid Power's electric 120 kW flywheel power buffer. The maximum speed of flywheel is 40,000 rpm, it charges when braking and recharges in 6-8 seconds.

5.3. Buses

Approximately two million kilometres are covered by a Swedish bus before it is retired from service. The flywheel was a highly intriguing possibility if the bus operated in metropolitan areas because this meant there would be a great deal of starts and stops. On the London bus driving cycle, Flybrid Systems claims that a 17-tonne bus may save 45% in gasoline. Gyro-buses, created by the firm Oerlikon in the 1940s, were the first buses to employ flywheels. They depended on large, sluggish steel flywheels with a diameter of 1.6 m and a weight of 1500 kg. At 3000 rpm, the energy storage capacity was 6.6 kWh. In 1950, Switzerland's first two buses were unveiled to the general public and ran for ten years.

5.4. Military

There has been a recent tendency in the military to use electricity for weaponry, navigation, and communications, as well as in military applications including ships and ground vehicles. Electric energy must be stored in order to be used at varying rates and power levels; this allows them to react quickly and dependably to changes in energy demand. Future combat vehicles, which are expected to be powered by electricity, require hybrid electric power. Flywheels appear to be the perfect energy storage device for the aforementioned purposes. They are used in conjunction with supercapacitors to provide power for high-speed devices that need to be powered in less than ten seconds. It is quite likely that flywheels will be used to launch fighter fighters from aircraft carriers. Flywheels might take the place of the steam accumulators that currently power these systems, which would result in a reduction in system size.

Using a network of smaller microgrids connected to form a larger microgrid of 1.1 MW, this installation includes batteries, DGs, solar PV systems and a FESS rated at 60 kW power and energy storage of 120 kWh. The microgrid provides power to the US Marine Corps in California. Its goal is to provide military facilities with energy security through the use of renewable energy. The FESS is designed to reduce reliance on DGs by roughly 40% and enable peak shaving by powering loads which need high power like elevators, hence increasing the battery life. The FESS is anticipated to run for 50,000 cycles and a life span of 25 years [2].

US aircraft carrier Gerald R Ford has an electromagnetic aircraft launch system known as EMAILS shown in Figure 17, for this to work properly, flywheels are used to store energy from the ship's engine for quick release of power when needed to help launch the aircraft. This technology is able to release122MJ in just 2–3 sec and the energy needed is restored in 45 sec, the flywheels rotate at 64,000 rpm, having an energy density of 28 kJ/kg. [20]

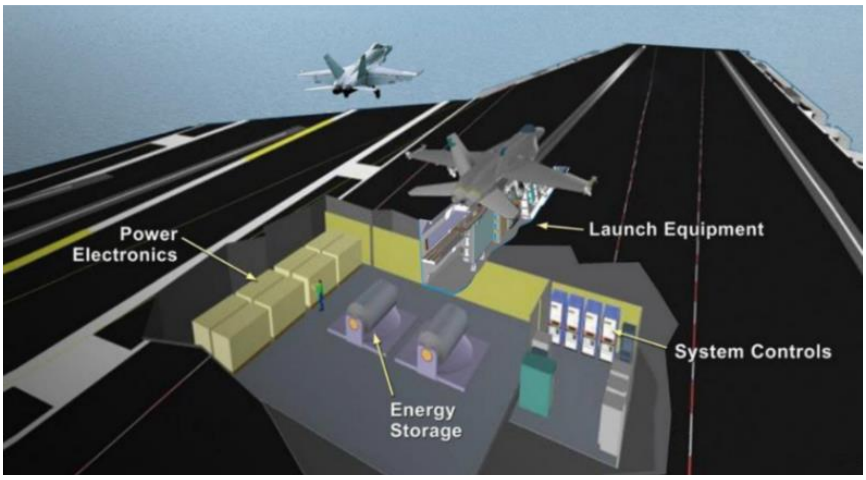


Figure 17. EMAILS of aircraft carrier USS Gerald R ford [20]

5.5. Frequency regulation

Frequency oscillations in the grid are brought on by the disparity between the loads and the supply, which occur when one surpasses the other and vice versa. Demand exceeding supply forces power plants to work harder to handle the added load, which reduces system frequency. On the other hand, whenever the generation exceeds the demand, the frequency increases. The frequency is regulated to stop it from changing constantly when demand shifts and generators turn on and off. To ensure the stability of output and consumption, the generators must retain a portion of their capacity in reserve. In addition to increasing fuel costs and emissions, scaling up and down the generators slows the producing power plants' ability to respond. 1 MW of flywheel energy storage is comparable to 1.4 MW of hydropower, 22 MW of steam turbines, or 23 MW of mixed cycle combustion plants [2].

A cyclic application that demands thousands of charge-discharge cycles per year is frequency control. Any storage system utilised for this purpose will almost never be inactive or in standby mode and will continually charge and discharge at radically disparate rates, ranging from extremely slowly to swiftly and profoundly. Flywheels and batteries are two fast-acting solutions that grid operators are seeking for nowadays. Due to flywheels' quick reaction and frequent charge-discharge capabilities, they are expected to outperform batteries in this application. Flywheels are comparable to the instantaneous energy produced by gas-fired power plants due to their capacity to swing from full production to complete absorption in only a few seconds. FESS may reduce carbon emissions by 50% and provide twice as much frequency control per megawatt of power produced.

It was a 200kW device developed by Urenco Power Technology that was placed in Shimane, Japan, in 2003, and it was the first flywheel system used to regulate frequency using renewable energy. The flywheel was deployed to lessen system fluctuations caused by wind output. Beacon Power is the top provider of FESS for power regulation, and they operate two facilities in the northeastern United States that offer frequency control to the grid. Their two plants have a combined capacity of 20 MW and 5 MWh, and their round-trip efficiency is 81%. If flywheels are utilised for frequency control instead of coal or natural gas, CO2, SO, and NOx emissions can be significantly decreased by between 72 and 98%. [1]

5.6. Spacecraft

Flywheels can be employed in spacecraft when the sun serves as the main energy source. As a result, energy must be conserved for use when the satellite is dark to keep it in orbit. International Space Station (ISS) FES was originally considered in the 1970s and first suggested in 1961. The first plans for the ISS relied on batteries for storage; presently, FESS are being investigated to supplement or replace batteries; the combined functioning of batteries and flywheels will increase efficiency and decrease the bulk and expense of the spaceship. The flywheel system for NASA as seen in Figure 18 was a composite rotor and had magnetic bearings, as per NASA's calculations, switching from space station batteries to flywheels would save 200 million US dollars since it can store more than 15 MJ and provide 4.1 kW of maximum output with a net efficiency of 93.7 percent.

A flywheel system would be more weight-efficient than using batteries in spacecraft since it offers a 35 percent mass reduction, a 55 percent volume reduction, and a 6.7 percent area reduction for the solar array [2]. Only FESS is capable of performing dual tasks that assist satellites with both renewable energy storage and attitude control. A flywheel and a two-pole, three-phase PM synchronous motor/generator were connected, this system's motor has a rating of 7kVA at 80V and 50A with a frequency of 1000 Hz. [5]

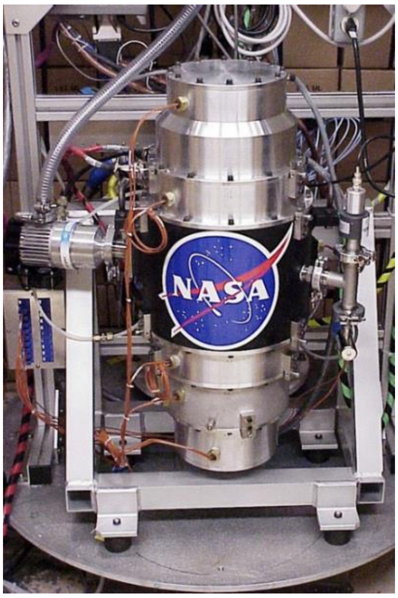


Figure 18. FESS by NASA [5]

5.7. Locomotives/trains

Recent innovations include the REGEN system, which has been successfully tested at the Los Angeles metro subway and saved them 10 to 18% of the daily traction energy needed and 99,000 USD every year. The Texas University's 2 MW flywheel system has 4 flywheel units, an energy capacity of 8.33 kWh, and a power rating of 2 MW. The steel flywheel spins between 10,000 and 20,000 revolutions per minute and is completely levitated by magnetic bearings. [29].

Recent innovations include the REGEN system, which has been successfully tested at the Los Angeles metro subway and saved them 10 to 18% of the daily traction energy needed and 99,000 USD every year. The Texas University's 2 MW flywheel system has 4 flywheel units, an energy capacity of 8.33 kWh, and a power rating of 2 MW. The steel flywheel spins between 10,000 and 20,000 revolutions per minute and is completely levitated by magnetic bearings. [20].

5.8. UPS

Uninterruptible power supply (UPS) is a term used to describe a temporary (seconds to minutes) energy storage system with control electronics. UPS is one of the existing and most successful applications for high power flywheels to supply power for occasions of power outages, which typically last no longer than 15 seconds. Power interruptions and voltage and frequency variations result from the fact that more than 80% of power outages last less than a second and 97% last under three seconds [2]. The UPS serves as a backup storage device in this application, bridging the time between the grid loss of power and the activation of backup sources during a power outage.

The most sophisticated and widely used kind of energy storage in UPS systems are batteries. When just flywheels are used as backup storage, the flywheel provides enough power to keep the system running until another power source comes up or the electricity is restored. In a UPS system, FESS can be utilised in place of batteries or in addition to batteries. The key advantages of flywheel-based UPSs are high power quality, extended life cycles, and less maintenance. Active Power Inc. created flywheels with a 2.8 kWh and 675 kW capacity, they weigh 4976 kg and rotate at 7700 RPM. Calnetix/Vycons's VDC is another example of FESS designed for UPS applications, the VDC has a max power and max energy rating of 450 kW and 1.7 kWh respectively, they operate between 14,000 RPM and 36,750 RPM [29]. General Electric provides industrial solution from 50 to 1000 kVA using flywheel-based UPS systems, shown below in Figure 19.

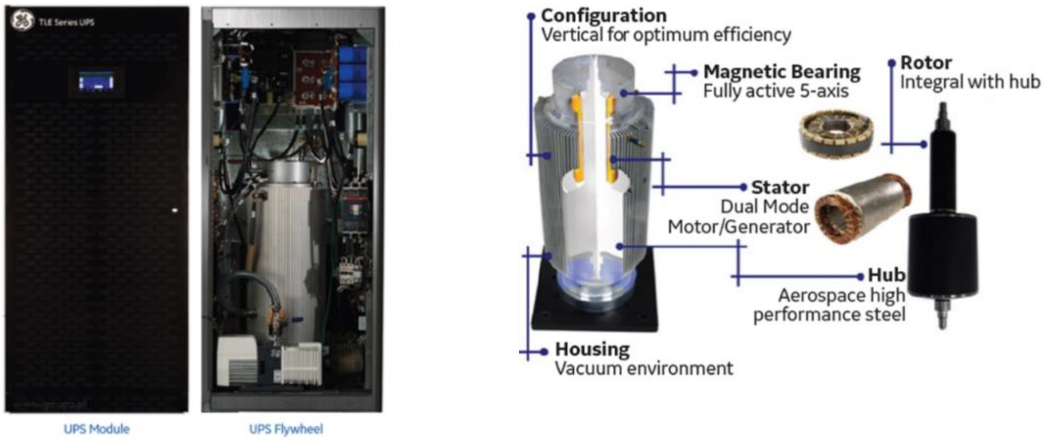


Figure 19. Components used in a flywheel-based UPS system [29]

6. EXPERIMENTAL SETUP

The hardware experimental setup consists of the following components see Figures 20 to 30:

- Drive Motor
- Pulley & Belt arrangement
- Shaft
- 2 Bearings

Figure 20. Drive motor with motor mount & drive pulley

Figure 21. Drive motor with cooling |unit

Figure 22. Driver & driven pulley, belt arrangement, flywheel mounted on shaft, 2 cylindrical roller bearings & jaw coupling

– Flywheel
– Jaw coupling
– Generator

Figure 23. Machined flywheel

Figure 24. Both half of jaw coupling

Figure 25. Jaw coupling with rubber bush in between

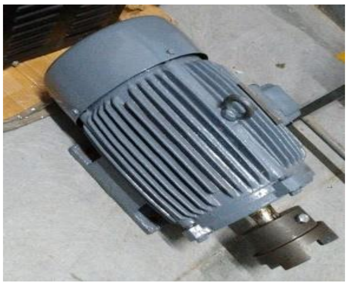


Figure 26. Generator with coupling

Figure 27. Flywheel Connected to Generator via Jaw Coupling supported by Bearing

– Batteries & power electronics
– A frame to support all the above-mentioned components
– Load on Generator

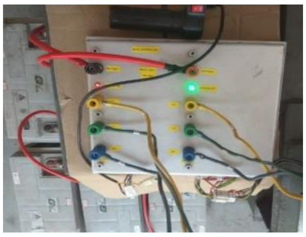


Figure 28. Batteries connected to motor controller

Figure 29. Flywheel – shaft - bearing mounted on frame with drive motor & generator mount

Figure 30. Generator connected to load

6.1. Specifications
– Flywheel Weight = 250kg
– Flywheel Outer Diameter = 1000mm
– Flywheel Internal / Bore Diameter = 76mm
– Shaft Diameter = 76mm
– Shaft Length = 1000mm
– Drive Motor Configuration = BLDC

- Drive Motor Power Rating = 3kW
- Drive Motor RPM = 3000rpm
- Drive Motor Input Voltage = 48V
- Generator Configuration = PMSG
- Generator Power Rating = 5kW
- Generator Output Voltage = 230ACV
- Generator RPM = 1200rpm
- Battery Voltage = 12V
- Battery Capacity = 100Ah
- Battery Nos = 4

7. CALCULATIONS

7.1. Flywheel Calculations

Kinetic Energy (KE) Stored in Flywheel:

$$KE = \frac{1}{2} \times I \times \omega^2 \quad (14)$$

$$I = \frac{1}{2} \times m \times r^2 \quad (15)$$

$$\text{Therefore, } KE = \frac{1}{2} \times \frac{1}{2} \times k \times m \times r^2 \times \omega^2 \quad (16)$$

$= \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times 250 \times 0.5^2 \times 125.6637^2$
= 1,23,370.0429J
1J = 0.000000277777kWh
= 1,23,370.0429 x 0.000000277777
= 0.034269kWh
= 0.034269kWh / 250 kg
= 0.000137077kWh / kg

Centrifugal Force experienced by the flywheel:

$$F_C = 2 \times \rho \times b \times h \times r^2 \times \omega^2 / g \quad (17)$$

F_C = 107kN

Tangential Force experienced by the flywheel:

$$F\theta = \rho \times b \times h \times r^2 \times \omega^2 / g \quad (18)$$

$F\theta$ = 54kN

Tensile Stress in the Rim due to Centrifugal Force

$$\sigma = 0.01095 \times (\rho / g) \times r^2 \times n^2 \quad (19)$$

σ = 11.477kPa

Centrifugal Force at flywheel Rim:

$$F_C' = 0.01095 \times (\rho \times r^2 \times n^2 \times h / g) \quad (20)$$

F_C' = 0.523kN

Bending Stress:

$$\sigma b = 0.2146 \times (\rho \times r^3 \times n^2 / g \times h \times i^2) \quad (21)$$

σb = 1.326MPa

Combined Tensile Stress:

$$\sigma R = 0.75 \times \sigma + 0.25 \times \sigma b \quad (22)$$

σR = 8.609kPa

7.2. Shaft calculations

Weight of Flywheel = 250kg
To convert kg to N multiply kg x 9.81, therefore 250 x 9.81 = 2452.5N
Reaction at both ends of the shaft, $R_A + R_B$ = 2452.5N
R_A = 1144.5N, R_B = 1308N, therefore $R_A + R_B$ = 2452.5N
SF left B = 1308N, SF left C = 1144.5N
Bending Moment at C = 228.9Nm
Bending Stress, σbending = 610.4N/m^2
Distance from left side of shaft where Max Deflection will occur, x = 0.1915m
Max Deflection of the shaft, Y_{max} = 0.00779mm
Torque acting on Shaft, T = P x 60 / 2 x π x N = 19.098Nm
Twisting Force acting on Shaft, τ_F = 221.575kN/m^2
Equivalent Torque acting on Shaft, T_{eq} = 229.69Nm
To find the Diameter of Shaft,

$$T_{eq} = \pi / 16 \times D^3 \times \tau \quad (22)$$

$$D = \sqrt[3]{19.1 \times 16 / \pi \times 221.575 \times 10^3} \quad (23)$$

therefore, Shaft Diameter = 76mm

7.3. Torque calculations

Graph 7.1 shows the torque required to spin the flywheel see Figure 31, Torque is calculated by the below mentioned formula:

$$\tau = I \times \alpha \quad (24)$$

where τ is the Torque spin the Flywheel (Nm)
I is the Moment of Inertia of Flywheel (kgm^3)
α is the Angular Acceleration (rads/s)

$$I = ½ \times m \times r^2 \quad (25)$$

where m is the Mass of Flywheel (Meter)
r is the Radius of the Flywheel (Kg)
therefore, ½ x 250 x 0.5^2 = 31.25 kgm^3

$$\alpha = Wf – Wi / t \quad (26)$$

where, Wf is the Final Speed of Flywheel (rads/s)
Wi is the Initial Speed of Flywheel (rads/s)
t is the time duration taken to accelerate the Flywheel from rest to rated speed
Therefore, 1500rpm is the final speed – 157 rads/s, initial speed – 0 rpm
157/5 = 31.4 rads/s
157/10 = 15.7 rads/s
157/15 = **10.46 rads/s**
157/20 = **7.85 rads/s**
157/25 = **6.28 rads/s**
157/30 = **5.23 rads/s**
157/35 = **4.48 rads/s**
157/40 = **3.92 rads/s**
157/45 = **3.48 rads/s**
157/50 = **3.14 rads/s**
157/55 = **2.85 rads/s**
157/60 = **2.61 rads/**

τ = I x α
31.25 x 31.4 = **981.25Nm** for **t = 5sec**

31.25 x 15.7 = **490.62Nm** for **t = 10sec**
31.25 x 10.46 = **326.87Nm** for **t = 15sec**
31.25 x 7.85 = **245.31Nm** for **t = 20sec**
31.25 x 6.28 = **196.25Nm** for **t = 25sec**
31.25 x 5.23 = **163.43Nm** for **t = 30sec**
31.25 x 4.48 = **140.15Nm** for **t = 35sec**
31.25 x 3.92 = **122.65Nm** for **t = 40sec**
31.25 x 3.48 = **109Nm** for **t = 45sec**
31.25 x 3.14 = **98.12Nm** for **t = 50sec**
31.25 x 2.85 = **89.18Nm** for **t = 55sec**
31.25 x 2.61 = **81.75Nm** for **t = 60sec**

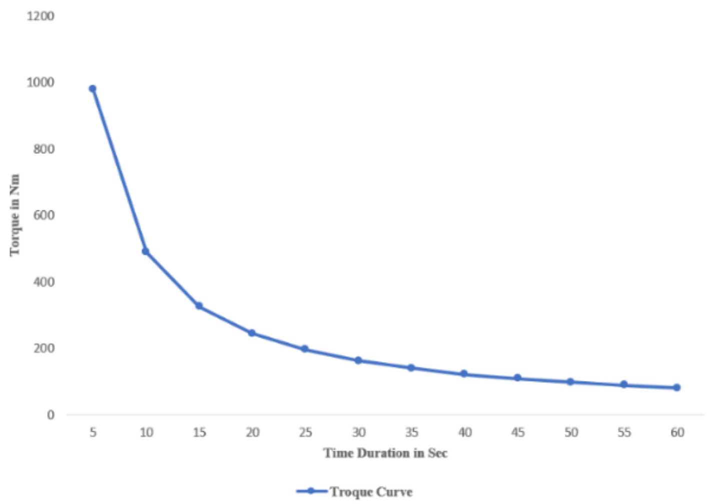


Figure 31. Torque required to spin the flywheel for the given time duration

8. RESULTS

The results from the test run are as mentioned in the Table 16

Table 16. Results of test run

DRIVE MOTOR			GENERATOR			Flywheel RPM	Applied Load in kW
Input Voltage V_{DC}	Input Amps A	Input Power W_{DC}	Output Voltage V_{AC}	Output Amps A	Output Power $_{AC}$		
49.6	36	1785.6	240	1	240	1170	0
47.4	56	2654.4	225	8	1800	1100	1
45	86	3870	200	10	2000	1035	2
44	103	4532	190	13	2470	934	3
42	109	4578	175	14.3	2502.5	860	4

8.1. Drive motor vs generator

From the Table 16 and Figure 32 it is observed that the power consumption of drive motor is approximately 2 times the output generated or it can be stated as the generator only produces approximately half of the power that is consumed by the drive motor as shown in Figure 32.

8.2. Drive motor vs flywheel Rpm

From the Table 16 and Figure 33 it is observed that as the power consumption of drive motor increases the flywheel rpm decreases because of the load applied on the generator as shown in Figure 33

8.3. Drive motor vs applied load

From the Table 16 and Figure 34 it is observed that the power consumption of drive motor increases as the load applied on the generator increases as shown in Figure 34.

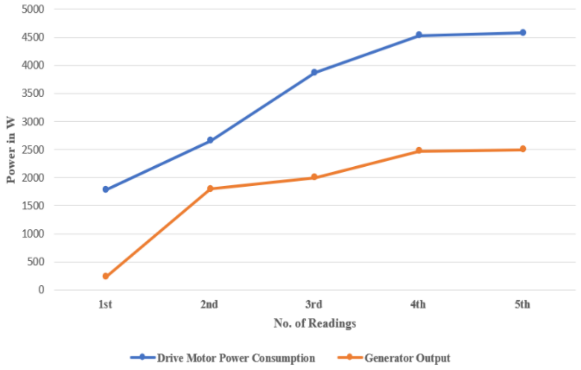


Figure 32. Drive motor power consumption vs generator output

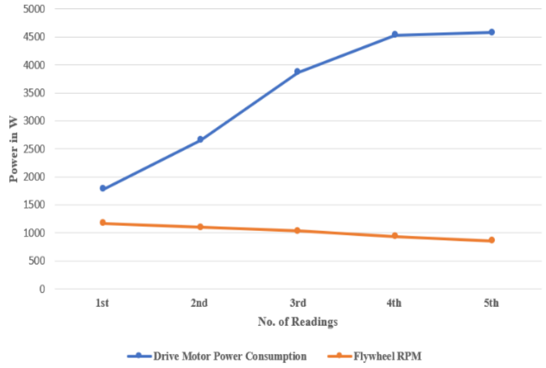


Figure 33. Drive motor power consumption vs flywheel Rpm

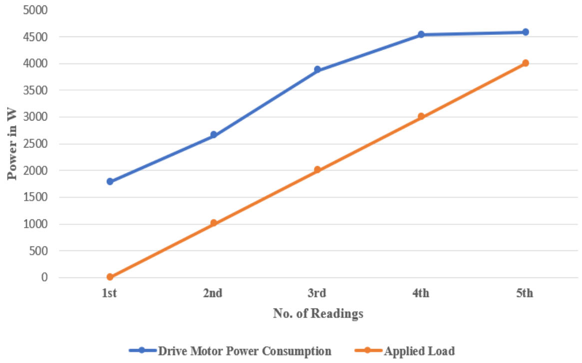


Figure 34. Drive motor power consumption vs applied load on generator

8.4. Generator vs flywheel Rpm

From the Table 16 and Figure 35 it is observed that as the power output from the generator increases the flywheel rpm decreases, this is due to the resistance / counter torque offered by the generator as power is being drawn from it, so the counter torque slows down the flywheel as shown in Figure 35.

8.5. Generator vs applied load

From the Table 16 and Figure 36 it is observed that the generator output increases with the applied load on the generator as shown in Figure 36.

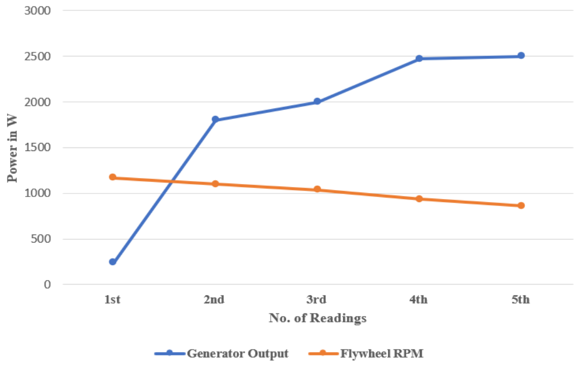


Figure 35. Generator power output vs flywheel rpm

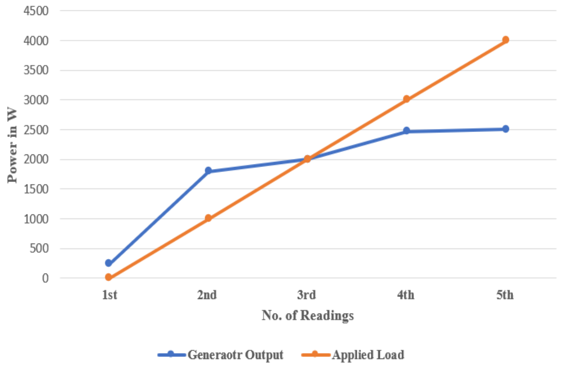


Figure 36. Generator power output vs applied load on generator

8.6. Flywheel Rpm Vs Applied Load

From the Table 16 and Figure 37 it is observed that the flywheel rpm decreases with the increase in applied load on generator as shown in Figure 37. Consolidated graph Figure 38 it is Graph comparing every aspect with each other.

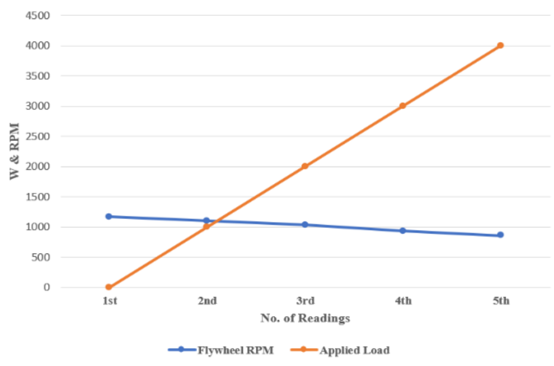


Figure 37. Flywheel rpm vs applied load on generator

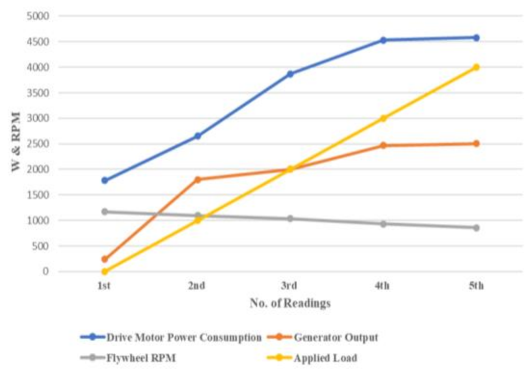


Figure 38. Graph comparing every aspect with each other

9. CONCLUSION

This research paper attempts to highlight the flywheel energy generation system in terms of its history, design calculations, elements, traits, applications in various fields, maintenance and future prospects. Based on the findings of this research, we can say that the flywheel technology will be a reliable candidate for increasing renewable energy generation and integrating it into the existing grid, for backup power and it also holds promise for future commercialization, in comparison to other energy systems, it has advantages like Modular and Easily recyclable in nature, Quick response, Larger peak power, long life-cycle, High energy density, High efficiency and Eco-friendly. The advantages of flywheel technology have been thoroughly compared to those of other energy technologies. The components such as the rotor, shaft, drive motor, generator, bearings, belt arrangement, and pulley arrangement have also been covered, along with the properties of the materials used, the flywheel shape factor, and the flywheel shape. Frequency regulation, locomotives, military, racing, spacecraft, and UPS are just a few of the applications that have been discussed, along with their safety and operational concerns. The test results of the experimental setup show that the flywheel rpm will decrease with increase in load on the generator, the generator output increases with load on the generator, the output power from the generator increases and the flywheel rpm decreases, the power consumption of drive motor increases as the load on the generator increases, the power consumption of drive motor increases the flywheel rpm decreases.

From the above results it's clear that there are losses majorly from the belt – pulley arrangement and bearings, the flywheel is not able to overcome the resistance / counter torque offered by the generator while power is drawn from it due to its rpm and energy stored in it being low hence the drive motor is consuming more power to produce an output from the generator via the flywheel. These issues can be solved if the losses are reduced by using magnetic bearings instead of mechanical bearings, a CVT instead of a fixed ratio pulley, optimizing the existing flywheel shape to a laval disk with rim shape, ensuring the electrical machinery is of high efficiency, reducing the power consumption and mitigating the load on the generator according the needs.

It was known that the counter torque in the generator would slow down the flywheel when load is applied on it, it was not expected that the counter torque in the generator would slow down the flywheel so much that the flywheel could not overcome the counter torque of the generator when loaded.

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