

FLYWHEEL ENERGY STORAGE SYSTEM AND IT'S INCORPORATION IN BATTERY ELECTRIC VEHICLES

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Abstract: Flywheel has been in use since long time for storing energy and other applications. The basic steps in flywheel energy storage system (FESS) are to convert the available energy into electrical energy by means of flywheel and make the electrical energy available for use whenever required. The battery electric vehicles (BEV) are running on the roads since many years. They generally use batteries as their main energy source but it some flaws such as cycle life time which limits their performance and affects its efficiency. To incorporate flywheel in battery electric vehicles it has to be combined with the driveline of the vehicle using suitable transmission. There are various transmission systems which help to combine flywheel system with vehicle drive line. A description of the flywheel structure and its main components is provided, and different types of materials, bearing systems along with different transmissions with layout for use in flywheel storage systems are discussed.

Key words: Flywheel, motor generator, battery electric vehicle, transmission

1. INTRODUCTION:-

Flywheel has been in use since long time for storing energy and other applications. Some early examples of flywheel are potter's wheel and spinning wheel. The basic steps in flywheel energy storage system (FESS) are to convert the available energy into electrical energy by means of flywheel and make the electrical energy available for use whenever required. Flywheels usually have two functions that are to supply energy continuously when there is interruption in primary energy source and to provide energy at higher rates which is beyond the reach of primary energy source. FESS also ability to disperse large power within small period of time (in sec). FESS is superior to other energy storage system as it has very less stand by losses compared to other ESS.

The battery electric vehicles (BEV) are running on the roads since many years. They generally use batteries as their main energy source but it some flaws such as cycle life time which limits their performance and affects its

efficiency. Flywheel also has many advantages over the batteries used in hybrid vehicles and electric vehicles such as high cycle life, quick recharge etc. So, FESS can be used in hybrid and electric vehicles as secondary energy storage. As it recovers and stores energy in mechanical kinetic energy which saves energy lost during energy conversion from one form to another. To incorporate flywheel in battery electric vehicles it has to be combined with the driveline of the vehicle using suitable transmission. There are various transmission systems which help to combine flywheel system with vehicle drive line.

A description of the flywheel structure and its main components is provided, and different types of materials, bearing systems along with different transmissions with layout for use in flywheel storage systems are discussed.

Flywheels store energy in a rotating mass of steel of composite material. Mechanical inertia is the basis of this storage method .By the use of motor/generator energy can be recycled (ie. Absorbed and then discharged). Increasing surface speed of the flywheel energy storage capacity (kWh) of the flywheel can be increased.

2. THEORY OF FLYWHEELS:

Kinetic Energy (E) gained by the flywheel can be given as:

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

Where I is the moment of inertia and ω is the angular velocity of a rotating disc.

$$I = \int r^2 dm$$

For a cylinder the moment of inertia is

$$I = \frac{1}{2} r^4 \pi a \rho$$

Hence the energy of the flywheel is increased if angular velocity(ω) is increased or if the moment of inertia (I) increases. Moment of inertia (I) can be increased by locating as much mass on the outside of the disc as

possible. But as the speed increases and more mass is located outside of the disc, mechanical limitations are more important.

The usable kinetic energy stored in a flywheel is the speed interval over which it is allowed to operate:

$$E = \frac{1}{2} I \Delta \omega^2 = \frac{\omega_{max}^2 - \omega_{min}^2}{2} \int r^2 dm$$

Where I is the moment of inertia of the wheel, ω is the rotational velocity and dm is the mass rotating at a distance r from the centre of the wheel.

The stored energy is released relatively soon after charging in a flywheel buffer used in a hybrid bus or a formula 1 flywheel. The ratio of available output energy to the input energy is calculated to focus on the optimization of the round trip efficiency sometimes called as AC-AC efficiency. $\eta = \frac{E_{output}}{E_{input}}$.

Other applications, like uninterruptible power supplies for data centers or satellite altitude control, are focusing on the standby efficiency, computed as:

$$\eta_{standby} = 1 - \frac{P_{standby\ loss}}{P_{discharge}}$$

There exist power flywheel such as the ABB short-circuit generator which was but in 1993 and is still used, which can deliver a stunning 4000MVA and short-circuit currents of 100 kA arms for short durations of time. On the other side, there exist's a light weight energy flywheel which has a rotor specific energy of 195 Wh/Kg, which is comparable to that of Li-ion batteries. Flywheel systems are best suited for peak output powers of 100kW to 2MW and for durations of 12 secs to 60 secs. The energy is present in flywheel to provide higher power for shorter duration, the peak output designed for 125kW for 16 secs stores enough energy to provide 2MW for 1 sec.

2.2 Material, Containment and Safety of Flywheel

Flywheels are manufactured using materials like steel (including electrosteel), aluminium and/or titanium, carbon composites, epoxy or pre-preg matrix, E-glass and/or S-glass, carbon composites and lastly, magnets such as AlNiCo, NeDyFeB or others.

The limit of rotational energy to be stored in a material is expressed in terms of e. Where e is energy stored per unit mass $e = \frac{E}{m} = \frac{\sigma}{2\rho}$.

σ is the tangential stress and ρ is the material density.

The table comparing various materials and there rotor energy density is given below –

Table-1

Material	Ultimate tensile stress(MPa)	Density (kg m ^{^3})	Rotor energy density (Wh/kg)
Aluminium 7075	572	2810	28
17-7 PH Stainless steel	1650	7800	29
Titanium Ti-15V-3Cr-3Al-3SnST	1380	4760	40
Advantex E-glass (glass fiber)	1400	2146	90
Toray T1000G composite	3040	1800	234
Toray T1000G fiber	6370	1800	491
Vapor grown carbon nanofibers	2920	2000	202
Single wall carbon nanotube (low end)	50,000	1300	5341
Single wall carbon nanotube (high end)	500,000	1300	53,418
Multi-walled carbon nanotubes (low end)	10,000	1750	793
Multi-walled carbon Nnanotubes (high end)	60,000	1750	4761

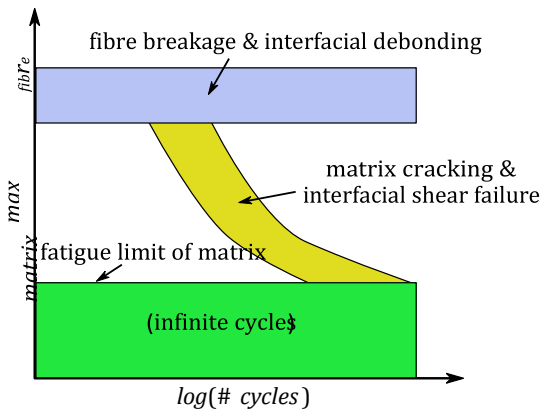
Heavy duty containment chambers cannot be used in mobile applications so it is must be strict to have safe catastrophic failure modes. Hence perfectly designed flywheel models undergo rigorous training to ensure that there behaviour is safe during failure.

2.3 CYCLE LIFE TIME

Flywheels have excellent life cycle. There cycle lifetimes are around 1000000 cycles, regardless of the charge rate and depth of charge. The material fatigue ids directly proportional to the cycle loading. Any modern flywheel is the carbon composite and for the composites the ultimate fatigue limit is proportional to the binding matrix, which for epoxy is 0.6 % in the direction of the main stress.. It should be noted that the charge or

discharge limit (for eg. which is 0.6% for epoxy) is not related to the charge or discharge profile but to the flywheel state of charge. This implies that a very long life cycle is guaranteed as long as the flywheel does not exceed a certain threshold.

Figure-1



2.3 COMPONENTS OF FLYWHEEL ENERGY STORAGE SYSTEM

- Flywheel
- Motor/Generator
- Power Electronics
- Magnetic Bearings
- External Inductor

2.3.1 MOTOR/GENERATOR

Permanent magnet machines (PM) have the most advantages, including higher efficiency and smaller size when compared with other types of motors and generators of the same power rating. PM also exhibit lower rotor losses and lower winding inductances which make it more suitable for a vacuum operating environment and the rapid energy transfer of flywheel applications. The motor or generator is designed to operate at high speed for minimum system size.

2.3.2 POWER ELECTRONICS

Flywheel energy storage system is the 3 phase IGBT-based PWM inverter/rectifier. The IGBT is a solid state device with ability to handle voltages up to 6.7 kV, current up to 1.2 kA and the most important high switching frequencies.

2.3.3 MAGNETIC BEARINGS

Magnetic bearings consist of permanent magnets, which support the weight of the flywheel by repelling forces, and electromagnets are used to stabilize the flywheel. The best performing bearing is the high-temperature super-conducting (HTS) magnetic bearing, which can support the flywheel automatically without need of

electricity or positioning control system. HTS magnets require cryogenic cooling by liquid nitrogen.

2.3.4 MECHANICAL BEARINGS

Mechanical bearings have high per volume stiffness. It is a known, previously used technology. There are many unaccounted forces in mechanical bearings which should be taken into account. There are higher standby losses in the bearings at high speeds. Lubricants present in the bearings get evaporated during vacuum operation and may require active cooling systems.

2.3.5 EXTERNAL INDUCTOR

The high speed PM machines offer low inductances with low number of stator turns and large operating magnetic air gaps. The low inductances result in high TOTAL HARMONIC DISTORTION (THD) which increases the machine power losses and temperature. Using an external inductor in series with the machine in charging mode is necessary to reduce the THD and bring it within accepted range.

The battery electric vehicle has been operating on the road since a long time. But with the improvement of internal combustion engines, battery electric vehicles started losing their popularity and there was a time when they were vanished. The introduction of production hybrid electric vehicles (HEV) by Toyota in 1997 and subsequently by Honda in 1999 triggered a number of HEVs to be mass produced by other manufacturers in the 2000s. Since the last few years a small number of mass produced BEVs such as the Nissan Leaf, the Mitsubishi iMiEV and the Tesla Roadster have been introduced in the markets worldwide and many more are in the pipeline. However their high cost and limited range, relative to ICEVs, are still issues that impede their popularity (Boulanger *et al.*, 2011). The major disadvantage of the battery electric vehicles is the battery itself, which hampers the range and cost of the battery electric vehicle. This problem can be resolved by hybridizing battery electric vehicles. Battery electric vehicles have either high specific energy or high specific power but not both, so to achieve it battery is combined with another high power source. This shields the battery from peak currents and improves its capacity and life. The concept of hybridization is discussed in (Chau and Wong, 2001). High speed flywheels have properties like long life cycle, quick recharge, low cost, high specific power, etc. which make it attractive to be used in battery electric vehicles.

The benefits of incorporating flywheel energy storage in battery electric vehicles are -

- By taking care of the peak loads the energy efficiency of the battery is increased which would also improve the range of the BEV and reduce the battery losses.

- Battery life is increased
- Thermal issues of the battery are resolved.
- Brake regeneration efficiency is increased by avoiding energy conversion.
- The size of the main electric machine can be reduced if the flywheel is connected via a mechanical transmission

3. Transmission for flywheel -

The flywheel is connected to the driveline of the vehicle in such a way that the flywheel can change its speed independently. The flywheel gains speed when the vehicle is slowing down and loses speed when the vehicle is accelerating, hence the transmission should be a continuously variable. The main difference between the continuously variable transmission (CVT) used in conventional vehicles and flywheel energy storage system is that they have to be bi-directional and highly efficient in both directions. In most of the cases, flywheel energy content is varied by varying the speed of the flywheel, but some authors have suggested of varying the inertia of the flywheel to for varying the flywheel energy content (Moosavi-Rad and Ullman, 1990; Van de Ven, 2009; Su and Liu, 2010).

Various types of transmission used are -

3.1 Hydrostatic transmission

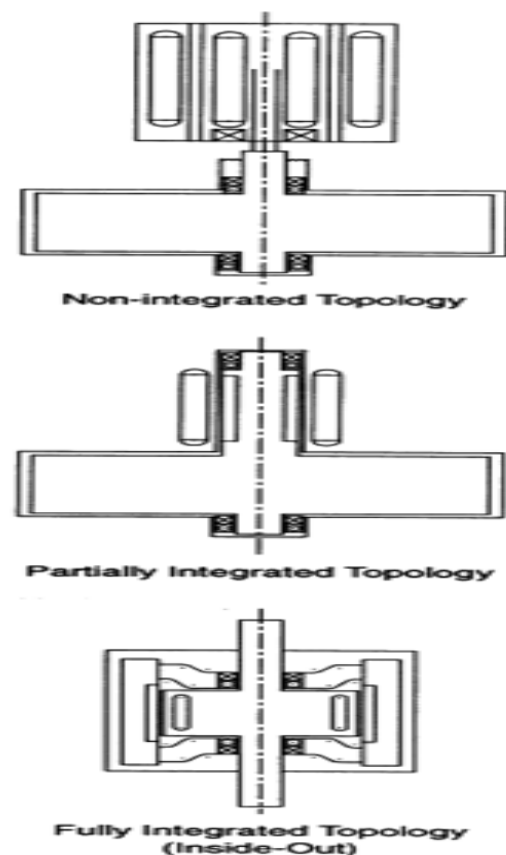
The hydrostatic transmission has a variable displacement pump which is connected to a hydraulic motor through hydraulic lines along with other necessary components. The variable displacement pump present in the hydrostatic transmission converts the mechanical power into hydraulic power which is reconverted at the motor. In the reverse direction, the pump acts as a motor and the motor behaves as a pump. The hydrostatic transmission is usually an infinitely variable transmission (IVT). The transmission is bi-directional as the stroke of the pump can be reversed, hence it can rotate in both the directions. During the 1970s these transmissions were popular due to their wide availability (Burrows *et al.*, 1980). Hydrostatic transmission being noisy and bulky makes it unsuitable for use in passenger cars.

3.2 Electrical Transmission

Electrical transmission is a type of transmission that is widely used for FESS since a long time and usually have magnetic bearings. It consists of two motorgenerators (MG) which are electrically linked together with necessary power electronics needed. During power generation one of the motorgenerator converts the mechanical power into electrical power and thus acts as a generator while the other acts as a motor to do the

reconversion. They add flexibility to the system, however they tend to be expensive because of their large size as whole power has to be transmitted via them. Secondly these usually include a number of power inverters and further have a disadvantage of energy conversion. Flywheel motogenerator assembly also called as electromechanical battery or flywheel battery is a popular choice of battery electric vehicles. There are three topologies defined for flywheel battery based on the positioning of the stator and rotor. The three different topologies are shown in the figure 2 below (Hayes *et al.*, 1999).

Figure-2



Types of electrical transmission are-

1. Fully integrated: In this case the flywheel and the motorgenerator are one unit. An inside out configuration is used in which the flywheel is the rotor with the stator inside it. The design is highly compact with the stator and rotor sealed inside vacuum chamber. This creates a new issue of heat dissipation. As both the units are sealed inside the chamber the heat generated is dissipated only through radiation and no other means. Hence machine cooling is a major problem. Another advantage of such structure is that it can be hermetically sealed and need only the electrical connections.

2. Partially integrated: In this case the rotor is inside the vacuum chamber and the stator being outside the chamber. The machine cooling is improved as the stator is outside the chamber however the problem of rotor cooling remains. It as a good design adaptability.
3. Non-integrated: The flywheel and he batteries are separate units mounted on the same shafts. This makes it bigger but simpler than other topologies. Flywheel and motor generator being different units the problem of cooling is avoided.

Various flywheels have been constructed by various organisations such as Technical University Eindhoven (Thoolen, 1993), the University of Texas-Austin (Hayes *et al.*, 1999) and Lawrence Livermore Laboratory (Post, 1996).

3.3 Traction Transmissions

- Belt drives: The power is transmitted over a belt, chain or band clamped between two pulleys. By varying the axial clamping forces for the two halves of the pulleys the speed ratio is varied thereby changing the rolling radii on the pulleys. The clamping forces are controlled by the hydraulics. One of the common designs is the Van Doorne steel v-belt in which a steel band is held with the help of steel segments, which was one of the first commercially successful CVTs. In this case the driven pulley is pushed by the driver pulley so it is a compression belt.
- Rolling contact traction drives: The two well known designs of the rolling contact traction drives are the toroidal traction drive and the roller cone traction drive. The two rolling elements that are transmitting power are separated by a lubricant film. In the toroidal drive to vary the ratio the inclination of the roller disc in the toroidal cavity is changed. A force is applied to the roller hydraulically and the required system torque is set, which allows the roller to follow the ratio automatically. Thus the drive is said to be torque controlled.

3.4 Planetary gear set-

The planetary gear set (PGS) is commonly used in automatic transmission in conventional cars as a speed coupling device. It gives an advantage of having multiple ratios in a compact space. In the conventional automatic transmission case usually out of the three arms of the PGS two arms act as input and output and the remaining arm acts as a brakes. However if it is to be used as a CVT it requires two degree of freedom implying that all of the arms should be individually free to rotate. As a speed coupling device it has property that the speed of the two arms can be individually controlled and the speed of the third arm is dependent on the speed of the other two

arms. In the Szumanowski and Brusaglino concepts (Szumanowski and Brusaglino, 1992) and the BMW (Braess and Regar, 1991) the single PGS is used as a CVT.

3.5 Power Split CVT

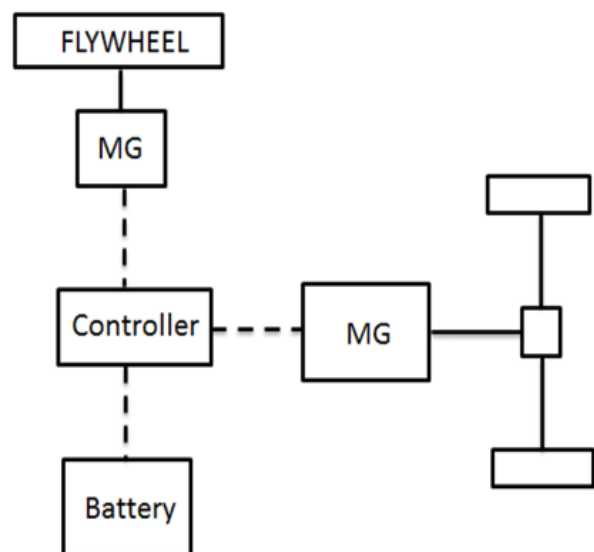
To avoid the low efficiency of the variator only transmission power split CVT is used. For the sake of clarity the previously mentioned transmissions will be referred as variator. The idea of a PSCVT is that a part of the power is transmitted through the highly efficient direct mechanical linkage and therefore the rest is transmitted through variator. The ratio range being smaller than that of the variator itself is a common disadvantage which can be altered by various means. Electromechanical, hydromechanical and various traction drive PSCVTs are the common PSCVTs used in FW hybrid vehicles (FHWV). The concept of PSCVT for flywheel in vehicular application has been explored by (Dhand and Pullen, 2014).

4. SYSTEM LAYOUTS

(The dashed line in the layout represents an electric link and therefore the solid line a mechanical link).

The FW in a BEV can be incorporated in many ways using the transmissions described above. When using a pure electrical transmission, the layout may be a standard one, shown as layout 1, usually with a number of power converters counting on the sort of electrical machine used The battery and the FWB are connected electrically to the main electric machine.

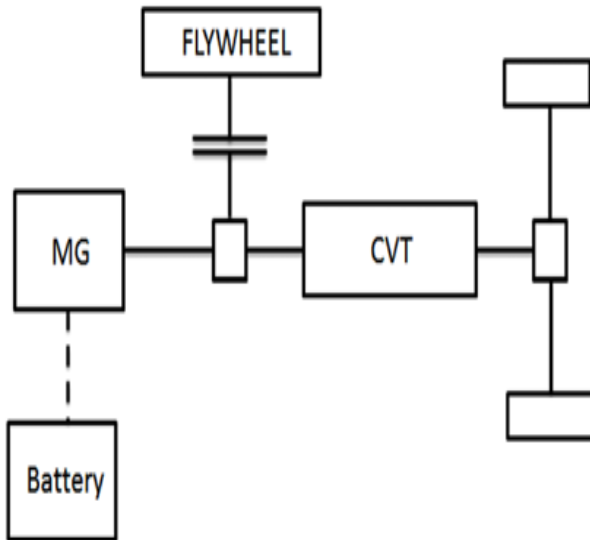
Figure-3 Layout 1.



For the mechanical/hydrostatic transmissions, the following two layouts as shown in layout 2 and layout 3 can be defined. In effect the layout 2 is simply an electrical machine with a bigger inertia. The layout 2 gives the possibility that the vehicle could be solely

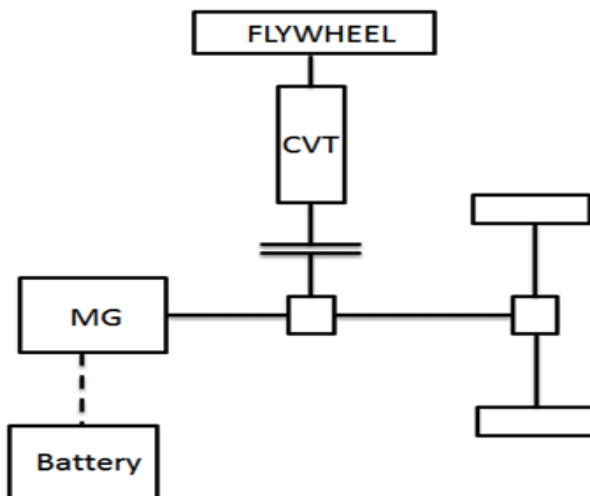
controlled by controlling the CVT, when using certain sorts of electric machines and no separate machine control is needed (Burrows and Barlow, 1981). The disadvantage is that the power has got to undergo the CVT all the time, which might not be desirable at lower efficiency points. Another is that the FW and MG speeds are always coupled together due to which the FW can't be independently controlled.

Figure-4 Layout 2.



In the layout 3, the CVT is only linked to the FW and the MG is either directly linked on the drive shaft or via some fixed gearing. The advantage of this layout is that the FW can be independently controlled and it can be integrated easily on an existing system, however the machine needs to be controlled separately.

Figure-5 Layout 3.



5. APPLICATION OF FLYWHEEL ENERGY STORAGE SYSTEM

- Buses
- Cars
- Container Cranes/Straddle Carriers
- Construction Machines
- Garbage Trucks
- Charging Stations
- Cable Ferries
- Train Stations
- Flywheel in distribution network

6. ADVANTAGES OF FESS

- High specific power
- long cycle life
- high energy efficiency
- quick recharge
- low cost
- environmental friendliness.
- They do not suffer from temperature dependence and their state of charge is most easily determined.

7. DISADVANTAGES OF FESS

- Complexity of durable and low loss bearings.
- Mechanical stress and fatigue limits.
- Material limits at around 700M/sec tip speed.
- Potentially hazardous failure modes.
- Short discharge time.

8. Conclusion-

This paper has presented the review of the flywheel structure and its main components, and different types of materials, bearing systems, power electronics along with different transmissions with layout for use in flywheel storage systems. Unique characteristics of the flywheel like very high life cycle, high specific energy, etc. make them suitable for use in many sectors including the automobile sector in battery electric vehicles. The disadvantage of the battery electric vehicle is its battery itself so hybrid electric vehicles are designed using flywheel in which flywheel acts as a power source and battery as energy source. Various powertrain concepts for the same have been discussed in the paper. With the advancements in flywheel technology, it will be of no surprise to see flywheel incorporated vehicles in upcoming future.

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