EERA JP ENERGY STORAGE
Mechanical Storage Sub-program

KINETIC ENERGY STORAGE BASED ON FLYWHEELS: BASIC CONCEPTS, STATE OF THE ART AND ANALYSIS OF APPLICATIONS

TECHNICAL REPORT

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I. BASIC CONCEPTS

1 Introduction

Storing energy is a way of modifying the basic equation of the electrical energy production which states that the energy produced must equal the consumed one. If an energy storage device is present in the network the equation is modified; the produced energy is now the sum of the consumed and the stored energy with its corresponding sign: “plus” when storing and “minus” when pumping back. This means that storing is a way of “decoupling” the offer and the demand at a certain moment.

These ESD are Super Capacitors, Flywheels (also called Kinetic Energy Storage Systems-KESS) and Superconducting Magnetic Energy Storage (SMES).
In the first case, the energy is stored in the electrical field of a capacitor, in the second as kinetic energy in a rotating flywheel and finally, in the third one, in the magnetic field of a lossless inductor (superconducting). All forms of storage are dual and can be expressed as half the product of a parameter given by the geometry of the device, times the square of a state variable (see table 1)

Table 1. Energy equations for three fast ESD.

ESD	Geometrical parameter	State Variable	Energy
Supercapacitors	Capacitance (C)	Voltage (V)	$\frac{1}{2}CV^2$
KESS	Moment of inertia (J)	Angular speed (ω)	$\frac{1}{2}J\omega^2$
SMES	Self-inductance (L)	Current (I)	$\frac{1}{2}LI^2$

Any ESD can be defined by two basic parameters, the power and the energy. Usually both are independent resembling, somehow, the flow rate and the volume of a water tank: One can image for instance, a big deposit (high energy) with a small drain (low power) or any other combination of these two variables. It is also very common to speak in terms of energy and power densities, normalizing with the mass or the volume of the device.

2. Flywheel Mechanics

A kinetic Energy storage system is simply a flywheel driven by an electrical machine, able to work as a motor or a generator. When the machine (acting as a motor) exerts a positive torque T to a flywheel with moment of inertia J, it increases its speed at a rate T/J, until it reaches maximum velocity, storing a given kinetic energy. At this stage the energy can be maintained constant by just supplying the idle losses with the motor. For releasing the energy, the electrical machine (acting as a generator) applies a negative torque –T to the flywheel, braking at a rate – (T/J) and pumping the energy back to the source to where it is connected.

In a similar way to the SMES and in order to achieve an efficient charging/discharging processes, flywheel losses should be kept to a minimum. Basically, there are two sources of losses: aerodynamic friction between the wheel and the gas surrounding it and mechanical friction in the bearings that support and guide the wheel. The roundtrip efficiency of flywheel modules is in the 80-85% range, being dependent on bearing and winding losses and cycle time. During the power exchange the efficiency is relatively high, depending on the type of electric machine used. However, the time on standby (no power exchange) affects very much this value depending on the aerodynamic friction. The way of reducing them is by decreasing the pressure and using advance bearing systems with low losses. Ideally the flywheel should work in vacuum, but sometimes a residual pressure is left to help evacuating any heat which is generated inside. Concerning the bearings, most of the flywheels use either magnetic or even superconducting bearings and in many cases magnetic levitation is required.

Regarding the mechanical design of a flywheel for a KESS, in principle, things are simpler than for the magnet of a SMES, since the energy is concentrated in the flywheel volume and not spread all over an infinite volume like for the SMES magnet.

For a rotating disk, there are some useful and simple mechanical expressions that allow making interesting considerations on its size and speed. On the one hand, the kinetic energy stored in a spinning disk will be proportional to its mass times the square of the tip speed, while centrifugal stresses will be proportional to the material density times the tip speed, hence the specific energy (per unit mass "e_m" or volume "e_v") can be expressed as:

$$e_m = \frac{\xi\sigma}{\rho} \quad (1)$$

$$e_v = \xi\sigma \quad (2)$$

Where σ is the maximum stress level in the disk, ρ its density and ξ a form factor that only depends on the disk shape [2]. For a cylinder its value is 0.6, for a ring 0.3 (even if it is a thick-wall cylinder) and 0.87 for an optimized geometry with the highest possible value for ξ. Obviously, mechanical stresses in the flywheel during operation must be below the yield strength of the material.

Equations (1) and (2) allow making considerations on how an optimum flywheel should be designed. First, it is important to distinguish whether volume or mass restrictions are more important. In general, for stationary applications volume is more a concern than the mass, while for moving applications mass optimization is mandatory. In any case, to

achieve high energy densities, a high value of ξ is required. Ring-shape flywheels should be avoided. Optimum-shape ones provide a high value for ξ but are difficult to fabricate. Cylindrical flywheels are usually the preferable option.
Regarding the material, there are also two choices: for high mass energy density, high strength and light materials should be used, while for high volume energy density, only the high strength of the material is a concern. Table 2 shows the mechanical properties of some selected materials and their ideal energy storage capability for a disc-shape flywheel.
It can be inferred from table 2 that the best choice for making an "energetic" and light flywheel is using carbon fiber, while using high strength steel will allow to make "energetic " and small machines but much heavier. Nevertheless carbon fiber is usually wound for making ring-shape flywheels leading to a very anisotropic behaviour, with poor properties in the radial direction. For a fair comparison between materials, this fact should be taken into account [48]. Steel rotors have specific energy up to around 5 Wh/kg, while high speed composite rotors have achieved specific energy up to 100 Wh/kg.

Table 2 Mechanical properties of some selected materials.

Material	σ(MPa)	ρ(Kg/m^3)	e_m(kJ/kg)	e_v(kJ/m^3)
Steel (AISI 4340)	1800	7800	140	1.092.000
Alloy (AlMnMg)	600	2700	135	364.500
Titanium (TiAl62r5)	1200	4500	162	729.000
Fiberglass (60%)	1600	2000	485	970.000
Carbon fiber (60%)	2400	1500	970	1.455.000

A very interesting point to consider is the required speed to achieve a given energy. Apparently, once the flywheel material is chosen, Eq. 1 states that a certain amount of mass is required regardless the rotational speed: it doesn't matter how slow or fast the wheel turns. The reason is that the material is supposed to work at a certain level of stress and this automatically imposes the speed as a function of the density: Light materials will rotate fast while heavy ones will be slow [3].
A crucial aspect when designing a flywheel is its dynamical behavior. The flywheel shaft, the bearings and the housing, constitute an elastic structure prone to oscillate in two typical modes: conical and cylindrical (Fig. 1). The problem is that gyroscopic effects must be taken into account leading to the fact that the natural frequencies for those two modes depend on the rotating speed [5].
A typical way of representing the solution is using the so called Campbell diagram in which the natural frequency is plotted against the rotating speed. Intersection with the line frequency equal to speed, will give the natural frequencies which should be avoided for both cases.

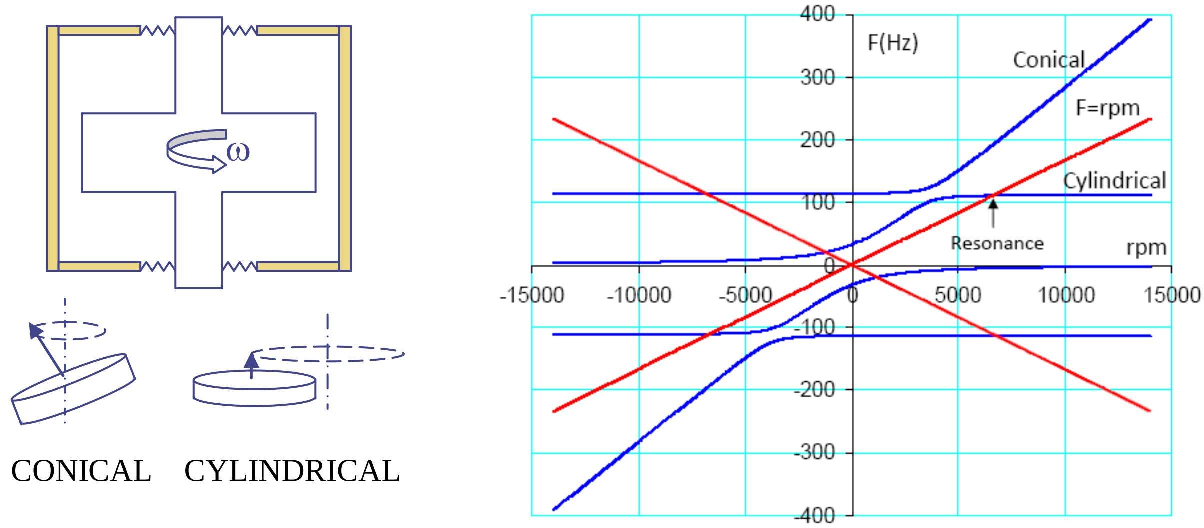


Fig. 1 a) KESS Mechanical Structure and Oscillating Modes b) Campbell Diagram

The interesting fact is that bellow a certain flywheel aspect ratio (Height/Radius) both lines will never intersect for the conical mode.

3 Flywheel Electromagnetics

Two electromagnetic systems are the basis for operating flywheels: Electrical machines and in some cases electromagnetic bearings.

There are many types of machines with very good performances in terms of efficiency, robustness or reliability, among others. Nevertheless, not all the electrical machines are good candidates for driving a flywheel. Those of them with wound rotors should be avoided. This includes dc machines, conventional synchronous machines and induction motors (although some successful applications for flywheels have been done with asynchronous machines or with modified synchronous ones [4]). The reason is that when spinning at such speeds, brushes or slip rings should be avoided and even for the case of squirrel-cage induction machines where none of those elements are present, the heat generation in the rotor windings is inadmissible, since heat is difficult to extract.

Presently, there are three families of electrical machines that fulfil the previous conditions for driving flywheels: Homopolar, Reluctance and Permanent Magnet machines [5].

In fact, practically all of them can be considered as special cases of a synchronous machine with three corresponding windings in the equivalent d-q model: two d-q windings in one side and one D excitation winding in the other (which can be present or replaced by a permanent magnet). Rotor dumping rings are not present.

The main characteristic of this machine is that the magnetising D-winding in charge of creating the magnetic field is now fixed in the stator and encircles the rotor rather than being placed in the rotor like in conventional synchronous machines [6]. The rotor is a massive piece of high-strength magnetic steel, the poles are conveniently machined in its periphery and the stator windings are distributed to achieve a sinusoidal magneto-motive force distribution, thus avoiding rotor heating due to harmonic content in the field. Some commercial developments have been done using this type of machine [7]. Figure 2 shows a scheme of a homopolar motor, including the magnetic flux direction in the rotor poles. This type of machine is very robust and suitable to run at very high speeds since rotor losses can be very small, even at high frequencies.

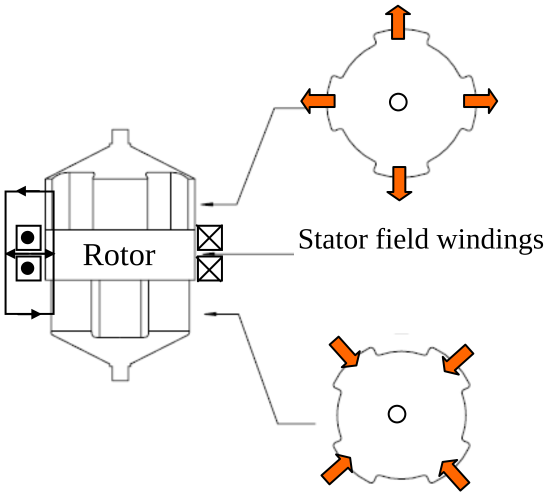


Fig. 2. The homopolar machine

The second group is Reluctance machines which again can be divided into two groups, Synchronous and Switched Reluctance machines. The first one is like a conventional synchronous machine with no magnetising D-winding, only d and q windings in the stator. The way of producing torque in this case is ensuring that the corresponding inductances of the stator windings (L_d and L_q) are very different. This can be achieved by two ways. One is with poles in the rotor that vary the airgap lengths in the d and q axes and hence the values of each inductance. The other is introducing different magnetic permeability in each axis (Fig. 3).

In a two-pole machine this is easier to attain; the rotor uses a magnetic anisotropic material made from alternating magnetic and non-magnetic laminations [8]. This type of machines is also suitable for high speeds due to the low losses in the rotor if the magneto-motive force distribution is sinusoidal. On the other hand, since big differences in the values of L_d and L_q are not easy to achieve, power density of the machine is usually low.

Switched Reluctance Machines (SRM) are conceptually very different, especially from the stator side. The rotor is laminated and has no windings. It is shaped in a certain number of poles N_r. Stator is also laminated and has concentrated windings around a number of stator poles N_s which are connected in pairs separated 180 electrical degrees. The coils are made from Litz wire to minimize eddy current losses. Every group of pole pairs connected in series constitutes one of each m stator phases [9]. Each phase is switched on and off sequentially and normally individually so that, usually, there is only one phase active. Every time a stator pole is energized, the closet rotor pole will try to align with it to minimize the reluctance of the magnetic circuit. There are different combinations of stator and rotor poles numbers. In general, the rotor angular stroke, θ_d, every time a new phase is switched on is given as:

$$\theta_d = \frac{2\pi}{mN_r} \quad (3)$$

Ideally, θ_d should be maximum in order to work with the lowest possible commutation frequency, which implies the minimum values for m and N_r.
From the magnetic point of view, SRM can work fully saturated or in the linear mode. Working in saturation means that the relative magnetic energy to magnetise the circuit is smaller, thus reducing the dimensions of the power supply for a given machine power. On the contrary, not all rotor topologies are allowed if the machine is saturated.
By far, the most common SRM topology is the 6/4 (6 Stator poles and 4 Rotor poles). Figure 3b shows the geometry of a 6/4 poles machine with the field lines when the upper and lower poles are energized while Fig. 3c shows a top view picture of the same machine for a flywheel application [10].
The SRM is very robust and simple to fabricate, since the concentrated stator winding is much simpler than the distributed one for synchronous machines. Negative aspects are the acoustic noise due to the presence of high electromagnetic radial forces and higher losses in the iron induced by the commutation of the phases. Several topologies have been proposed to reduce the iron path and hence these losses [11].

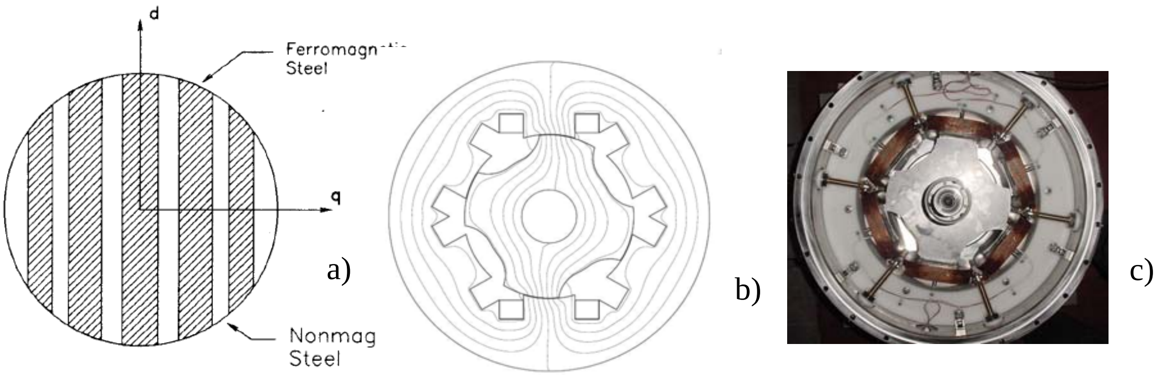


Fig. 3. a) Anisotropic rotor in a synchronous machine b) Magnetic field lines in a SRM c) Top view of a real SRM for flywheel applications

Finally, the last type of machine than has also been used for flywheel applications is the Synchronous Permanent Magnet (SPM) Machine, basically a conventional synchronous machine where the magnetising D winding has been substituted with an array of permanent magnets.
The main two issues in this type of machine are the magnetic material for the magnets and the topology in which they are arranged.

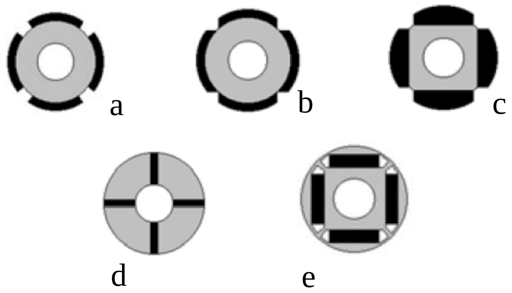


Fig. 4. Magnet topologies in SPM

Regarding the material, Neodymium Iron Boron (NdFeB) and Samarium Cobalt (SmCo) are the only competing candidates since their remanence and coercitivity are much higher than for any other alternative. Although NdFeB has better values than SmCo its temperature stability is not so good and since rotor heating can be a problem in flywheels, SmCo is usually the preferable option.

Concerning the topology there are, generally speaking, two options: external or internal magnet arrangement. Figure 4 shows different alternatives for placing the magnets (in black) in the rotor: Alternatives a), b) and c) are different options for the so called surface mounted magnets, d) is the spoke topology, while e) represents the buried magnet solution.

Normally, surface mounted topology achieves a higher power density with a smaller harmonic content than any other alternative, but for flywheel applications a special concern must be considered: The high centrifugal stresses induced in the magnets and their poor mechanical properties [12]. The way to overcome this problem is pre-compressing the magnets by some procedure like shrink fitting or by means of a carbon fiber bandage around them. The distribution of the permanent magnets can be oriented to produce a dipole field aligned across the bore of the rotor as in the so called "Halbach array".

The SPM is also a good candidate for driving a flywheel. It is a high performance machine with a very good efficiency. The main drawbacks are the cost and the potential demagnetization of the magnets due to armature reaction or to temperature increase. A particular problem for this type of machine is the "cogging torque", which is due to the attraction of the magnets against the stator slots, producing an undesired ripple. For high speed machines like those used for KESS, it is not a major concern. There is also another drawback for the PM machines which is the iron losses when the machine is not exchanging power with the load, since there is always an *emf* present.

The other aspect where electromagnetism plays a key role in KESS is in the guidance of the flywheel. Either in high mass energy density machines or in high volume energy density ones, conventional bearings are limited. In the first case, because their weight is small, but the speed is very high (> 50,000 rpm). In the second one, speed is admissible (<10,000 rpm) but not the weight. Even if high speed precision bearings can be used, the loads they are subjected are huge and their life is significantly reduced making maintenance very expensive.

In the case of low speed flywheels there is a simple solution: alleviating the weight of the flywheel using magnetic suspension. Usually, a set of permanent magnets is placed in the upper cap of the housing. Since the wheel is generally made from a magnetic material, an attraction force will pull upwards compensating its weight and reducing static loads on the bearings.

A step forward is replacing the conventional bearings with active magnetic bearings [13]. They are based on the use of coils exerting forces on the axis to be guided, as Fig. 5 shows. Since this type of levitation is intrinsically unstable a feedback is required: a sensor measures the axis position and a power amplifier feeds the coils to keep the axis rotating in its position.

Finally, some prototypes of flywheels use HTc superconducting bearings are possible. They are usually based on the interaction between bulk superconductors and permanent magnets. A superconductor in front of a permanent magnet behaves like a magnetic mirror: it is equivalent to place another magnet in front of the real one, thus exerting a force. This force appears when the superconductor is cooled below critical temperature and is intrinsically stable: The superconductor will react to any change in its relative position to the magnet trying to maintain the initial magnetic flux [14].

Most of the developments using this technology take profit of the stable levitation force between the magnets (usually placed in the flywheel) and the superconductor (placed in the housing). Nevertheless it is very usual that conventional bearings are still used to enhance radial stability as well as a touch-down system in the event of a failure [15-16].

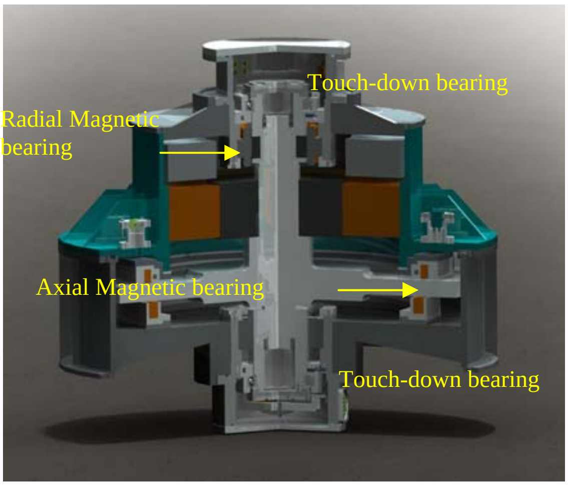


Fig. 5 Flywheel based on SRM and magnetic bearings (courtesy of Tekniker)

4 Power Converters

The power electronic converter used as interface between a flywheel and the load or the electric grid is usually a pulse width modulated (PWM) bi-directional converter that uses insulated-gate bipolar transistor (IGBT) technology, as Fig. 6 shows, and depends on two different topics: the connection point to exchange the power with the load and the type of electric machine used for driving the flywheel.

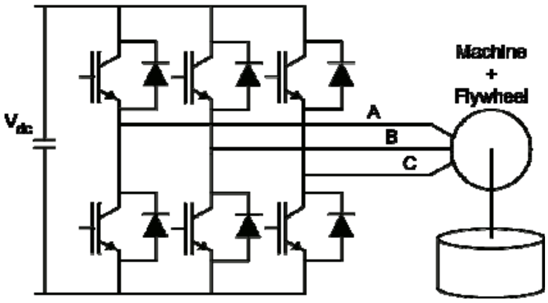


Fig. 6. PWM Power converter connecting a flywheel

Connection point

Most of the renewable applications where a flywheel is suitable to be installed are composed by a back to back converter with a common dc-link. The dc voltage is maintained constant by one of those converters. The connection to it ensures a faster response, a lower cost for the whole system and a better energy management due to the integration with the generation device. Many times the owner of the generation power system does not permit the access to the already installed power converter because it implies several design and operation modifications and responsibilities in the system behavior. That is not only the case of connecting flywheels but any other type of energy storage device. Fig 7 presents the two connection possibilities, a) for AC connection and b) for DC connection. The recommendation is to connect the smallest power converters to increase the reliability of the system.

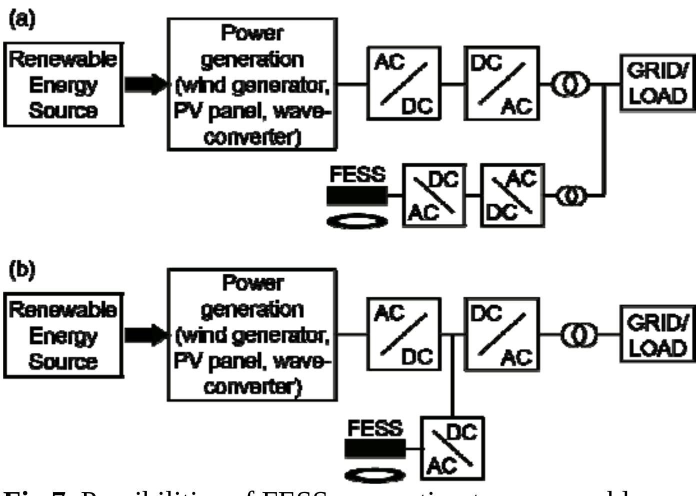


Fig.7. Possibilities of FESS connection to a renewable generation plant

For instance, in wind energy and wave energy converters, the FESS can be connected to the dc-link easily. However, in the case of solar PV-plants, if the FESS is connected directly to the inverter at the PV-panels side, the dc voltage depends on the optimum operation point and it will change continuously, so the flywheel-machine might have variable voltage and an extra dc/dc converter could be required, as presented in Fig. 8.

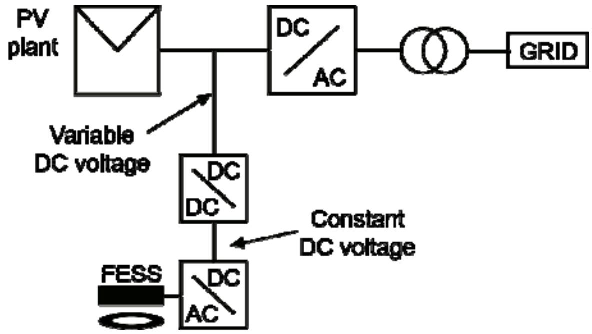


Fig. 8. PV-solar plants with FESS

Considering the previous limitations related to the modifications in the control, it would be better option to connect after the PV inverters, using a grid-side converter (GSC).
One important factor to take into consideration is the voltage level at the connection point. When the connection voltage level is the same as the flywheel-machine voltage (supported by commercial IGBTs) a conventional dc/ac converter should be used. IGBTs technology permits to achieve a dc-link of 4 kV using 6.6 kV IGBTs with currents of 1 kA and a switching frequency of around 500Hz. Only in the case of necessity of improvement of current quality or even higher voltages, a multilevel converter results a better option. However, machines for flywheels with voltages higher than 1 kV are not common.
In case of dc connection, a dc/dc converter should be used. When power level and the voltage ratio are low a boost-buck topology results appropriate; for other options it is better to select a topology with intermediate ac link using a medium frequency transformer.
In case of ac connection, the voltage adaptation is usually carried out with a power transformer. This solution might appear more expensive -since an extra converter is required- but the FESS adds value to the system through its grid-side converter (GSC), which permits controlling the reactive power supplied to the grid. Currently, many of the inverters used in renewable energies do not provide the possibility to adjust power factor or protection against voltage sags.

Modularity and Integration of FESS

Large power machines have not been developed for flywheel application but usually the applications, like frequency regulation, require an important amount of power and energy. Usually there will be a matrix of FESS [5] to accomplish the power regulation problem with higher level of power and energy, as presented in Fig. 9. Using just one GSC, all the units of this matrix can be connected to the same converter using single power transformer and electric grid protections for the whole system. Modularity is an important issue because it reduces the total cost of the elements (especially the flywheels), increasing the reliability of the system. Moreover, it results convenient to package the FESS together with the power electronics in a similar way of a dc battery to increase the integration and robustness of the FESS.

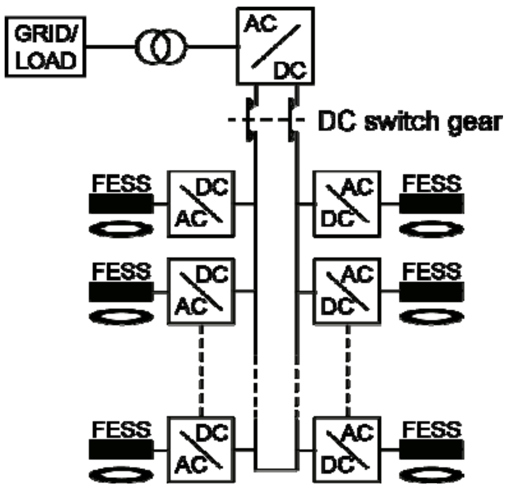


Fig. 9. Matrix connection of FESS

Typologies of machines and converters

The most important electric machines used for flywheels are: the synchronous homopolar machine (SHM), the permanent magnet synchronous machine (PMSM), the synchronous reluctance machine (SYNRM) and the switched reluctance machine (SRM). From the point of view of power electronics particular differences can be considered, especially related to rotational speed, number of poles and switching frequency, all connected to each other. The energy depends on the square of rotational speed. So high speed is mainly considered (range from 5000rpm to 50000rpm) and therefore a low number of poles are always preferred. The rotational frequency of the machine will be in the range of 2 to 20 kHz. Moreover, the power converter has to commutate at least to this frequency, considering the switching pattern selected. The efficiency, which is mainly dependent on the mechanical losses, is also affected by the power converters in terms of switching and conduction losses. The main challenge is to

reduce the power converter losses in order simplify the cooling system and to reduce the total cost.
On the other hand the switching frequency affects the quality of the power supplying the machine. Harmonic distortion in the machine currents and torque oscillations depend on the switching pattern and the switching frequency selected. Those variables in this type of load do not result as a critical issue since the torque is just applied to accelerate or decelerate an inertia. However, they had to be taken under control because mechanical behavior (flywheel and bearings) depend on the torque dynamics.
As a result, an agreement between power quality and the switching frequency has to be achieved.

Power converter control

Operation of a flywheel system depends on the connection to the rest of the system, as mentioned above. When the FESS is connected to the dc-link, the usual regulation scheme is based on the regulation of the dc voltage using a dead-band control scheme. The flywheel charges when the voltage exceeds the top of the dead-band and discharges when the voltages drops to the lower limit. The width of the dead-band is adjusted depending on the application and the response time of the frequency at the electric grid.
The control scheme for reducing the grid frequency variation [17] by using FESS is presented in Fig. 10. The electric grid frequency (F) is measured with an appropriate method [18]. A PD controller determines a primary output active power reference ($P_{0,ref}$); When the frequency decreases, the FESS supplies power to the grid. When the frequency increases, the FESS absorbs power. This power value is modified by a term named ΔP_w that depends on how far is the flywheel speed from the speed related with the half of the maximum stored energy, denoted by $\omega_{0.5E,FESS}$. The value of $P_{0,ref}$ is modified to a lower value when the rotor speed is under $\omega_{0.5E,FESS}$ or to a higher value when the speed is over $\omega_{0.5E,FESS}$. That way, the flywheel increases the charging power level when is more discharged and the discharging power level when is more charged. The new reference is P'_{ref} would have some limitations due to boundary speeds, ω_{max} and ω_{min}, as included in Fig. 10.

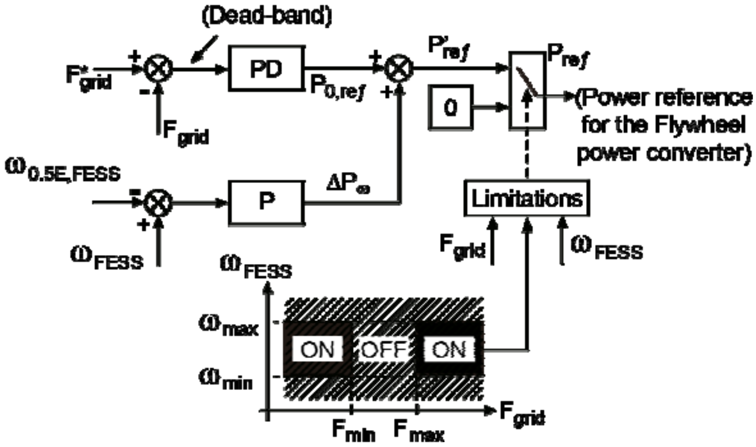


Fig. 10. Regulation scheme for frequency stabilization with Flywheels

II. STATE OF THE ART IN FLYWHEEL

The following manufacturers and developer have been identified in Europe and in the rest of the world and some characteristics of their products will be described in the chapter.

1. **Active Power**
2. **Beacon Power**
3. **BluePrint Energy**
4. **AFS Trinity Power Corporation**
5. **Kinetic Traction Systems Inc.**
6. **Piller**
7. **Tribology Systems Inc.**
8. **Vycon Energy Systems**
9. **Powercorp**
10. **Powerthru**
11. **Centre for Concepts in Mechatronics (CCM)**
12. **Flybrid Systems LLP.**
13. **Hykinesys**
14. **Magnet-motor GmbH**
15. **Ricardo UK Ldt.**
16. **Williams Hybrid Power Limited**
17. **Optimal Energy systems Inc.**
18. **Volvo**
19. **Tekniker**
20. **Uppsala University**
21. **Ciemat**
22. **Caterpillar**

1. Active Power.

Website: http://www.activepower.com/
Address:

Germany | Active Power (Germany) GmbH

- An der Leege 22
- 37520 Osterode am Harz
- Osterode | Germany
- Tel: 49.0. 5522.507700

UK | Active Power Solutions Ltd.

- Unit 7, Lauriston Business Park
- Pitchill
- Evesham | Worcestershire | WR118SN | United Kingdom
- Tel: 44.1386.870.006

Power: 250 kW
Energy: 1 kWh (2 minutes)
8 machines can be provided in parallel.

Applications: UPS, starting of Diesel generators
Commercial products: Clean Source2, CleanSource DC, GenSTART

Technology description: Forged steel rotor, ball bearings, magnetic levitation and reluctance machine.

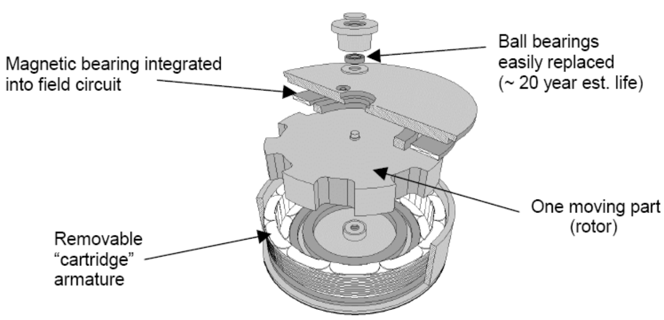


Figure 6: CleanSource exploded view

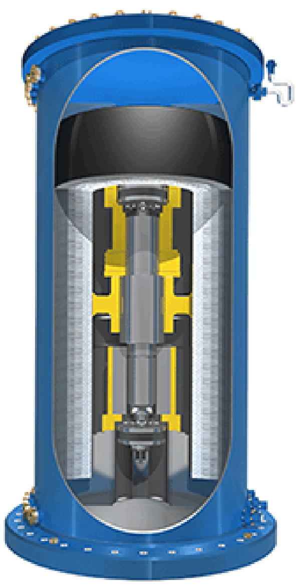
2. Beacon Power

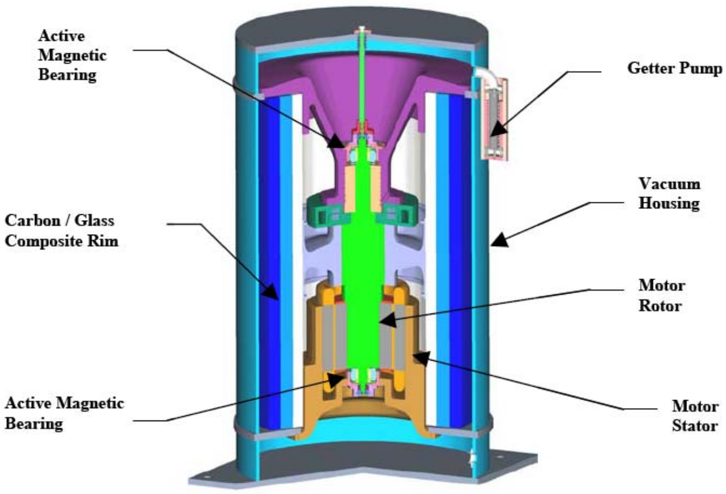
Website: http://www.beaconpower.com
Address: 65 Middlesex Road, Tyngsboro, MA 01879. USA
Phone (978) 694-9121 |

Power: 250 kW
Energy: 1.7 kWh and 6kWh.

Applications: Frequency regulation in electric grids, transportation, UPS.
Commercial products: Smart Energy Series. BHE-6 (2 kW); BHP-250 (250kW).

Technology description: Composite flywheel, magnetic bearings BHE, 20-year life time, temperature range -20 to 70ºC. Grid connection is three-phase 480V.





3. Blueprint Energy –

Website: http://www.blueprintenergy.com/index.html
Address: Flywheel Energy Systems Inc. 25C Northside Road, Ottawa, Ontario, Canada, K2H 8S1.
Phone +1 (613) 596-0856
info@flywheelenergysystems.com

Power: 120 kW (70 kW continuous)
Energy: 0.77 kWh

Applications: spacecrafts (satellites), motorsports, hybrid vehicles (trucks and busses), light trains, lifting devices, marine transportation.
Commercial products:

Characteristic	Units	Existing unit	Commercial unit	% change
DC link voltage	V	600 - 750	550 - 850	N/A
Power	kW	120	120	0%
Energy	kWh	0.77	0.75	-3%
Mass	kg	150	230	53%
Volume	liters	103	70	-32%
Specific power	W/kg	800	520	-35%
Power density	W/liter	1,165	1,715	47%
Specific energy	Wh/kg	5.1	3.3	-35%
Energy density	Wh/liter	7.5	10.7	43%
Outside diameter	mm	610	400	-34%
Length	mm	460	540	17%
Average one-way efficiency	N/A	93%	97%	4%
Average round trip efficiency	N/A	86%	94%	8%

Technology description: DC connection between 500 and 750V. Composite flywheel, magnetic bearings BHE, 20-year life time, temperature range -20 to 70ºC. Grid connection is three-phase 480V.

Flywheel: glass and carbon reinforced epoxy rim. Aluminum alloy hub
Speed: 14.000 – 28.000 rpm
Machine: Permanent magnet synchronous AC, liquid cooled
Bearings: Hybrid ceramic ball bearings
Power electronics: Bidirectional DSP controlled converter
Power and energy densities: 800 W/kg 960 W/litre. 5 Wh/ kg, 6 Wh/litre
Round-trip efficiency: 86%
Cost: Actual $75.000, objective: $20.000

4. AFS Trinity

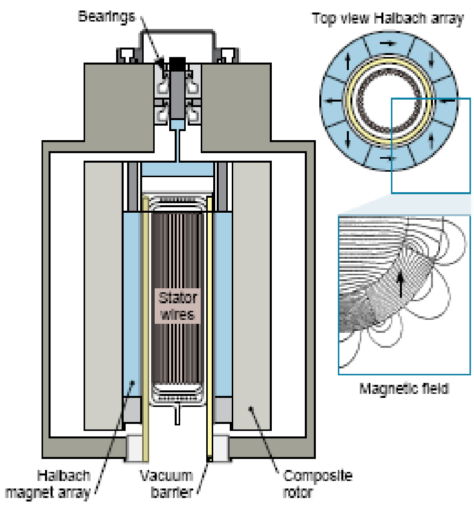
AFS TRINITY
POWER CORPORATION

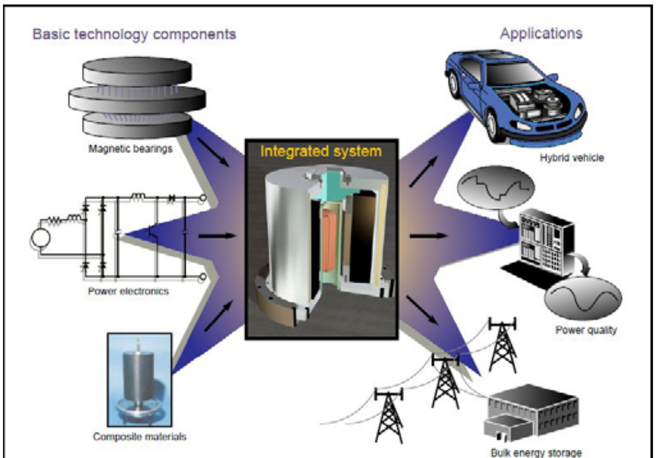
Website:
Address: Trinity AFS flywheel Lawrence Livermore National Lab

Power: 100kW, 200 kW
Energy: 0.42 kWh, 2kWh

Applications: hybrid vehicles

Technology description: carbon fiber composite flywheel, 40.000 rpm. DC connection 350 to 800V. Machine is a permanent magnet base don Halbach matrix.





Concept of the flywheel battery system and its applications

5. Kinetic Traction Systems Inc.

Website: http://www.kinetictraction.com/
Address: 20751 Marilla Street Chatsworth, CA 91311. USA.
From URENCO and PENTADYNE

Power: 200kW
Energy: -

Applications: Railway.

A trackside energy recycling traction power systems that absorb braking energy, convert it to kinetic energy, store it in advanced high-speed flywheel units and regenerate clean, instant power to accelerating trains.

- Lowers electric power usage through highly efficient energy recycling
- Improves train capacity and performance with instantly available power
- Reduces resistor heating and lowers HVAC requirements
- Reduces stress on train traction power equipment and braking systems
- Provides effective, safe and reliable energy storage and delivery
- Minimizes carbon emissions of train systems

In-station power traction systems that efficiently store energy to stabilize voltage levels in areas prone to low voltage sag. KTSi traction power systems can satisfy incremental peak power demands at a significant cost savings over traditional substations.

- Reduces capital expenditure through more efficient operation and faster deployment than substations
- Provides low voltage sag correction
- Eliminates slowdowns, supports increased ridership and enhances system performance
- Lowers stress on train traction power equipment
- Can provide backup power in the event of outages
- Generates zero emissions and hazardous materials
- Creates a reliable power quality solution with minimal maintenance

Technology description:
Composite rotor, magnetic bearings. PM brushless DC machine with two poles. Speed range: 25.000 – 37.800 rpm (430 – 630 Hz). Voltage supply: 570 – 900V.
Diary can provide 1000 charge-discharge cycles during 20 years.

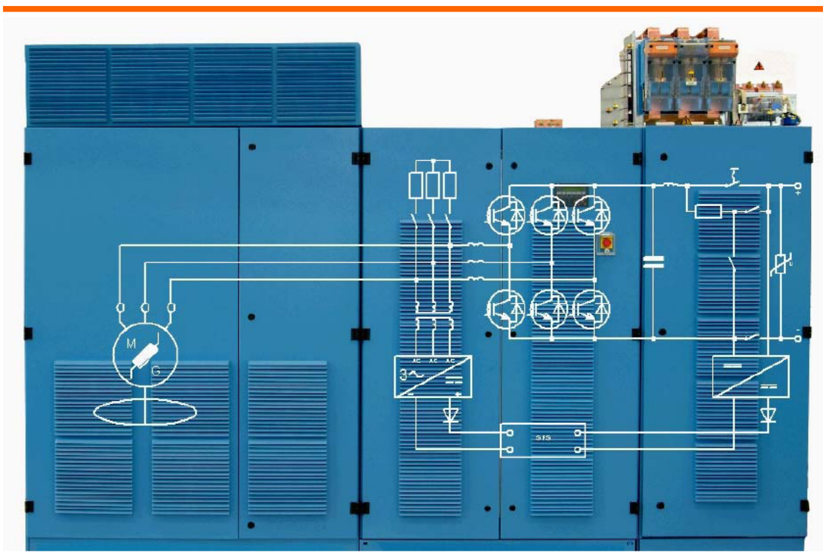
6. Piller

Website: http://www.piller.com/home
Address: Osterode, near Hanover in Germany. Founded in 1909 by Anton Piller
Power: 1MW,
Energy: 18MJ (5kWh)

Applications: rotary UPS and railways
Commercial products: Powerbridge

The Powerbridge is a battery-free alternative for DC energy supply in a Piller UPS system. A vertically mounted flywheel and generator, the Powerbridge is designed to operate within a speed range of 3,600 to 1,500 rpm. The unit can deliver 8 seconds of ride-through at 2.4 MW load and proportionately longer ride-through at lesser loads. The highly reliable, easily maintainable Powerbridge is an environmentally clean source of back up power.

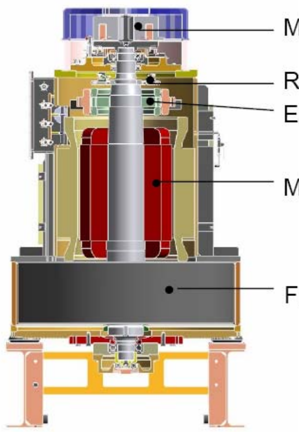
- 6 MWs, 16.5 MWs and 21 MWs energy storage available
- Bridging time of minutes possible during total power failures
- No air-conditioning required
- Defined, predictable charging states
- Parallel units are possible

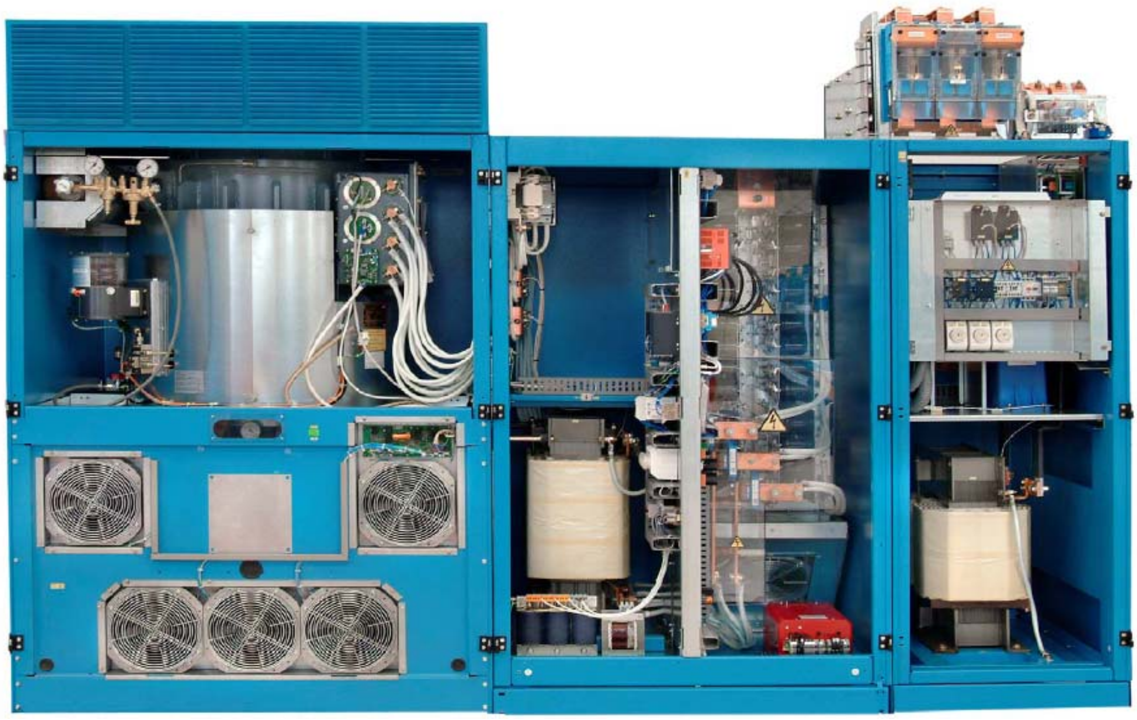


PILLER POWERBRIDGE
Kinetic energy storage device

PILLER Power Systems

- Alternative to new substation
  - ⇒ **Reduction of investment cost necessary to improve DC power supply**
- Lowering energy cost
  - ⇒ **Potential savings of more than 500 MWh/a per storage device**
- Energy content 5 kWh (= 17.8 MWs)
- Power 1000 kW
- Nominal Voltage 600 V - 750 V (1500 V)
- Field proven: More than 500 systems running worldwide





7. Tribology Systems Inc.

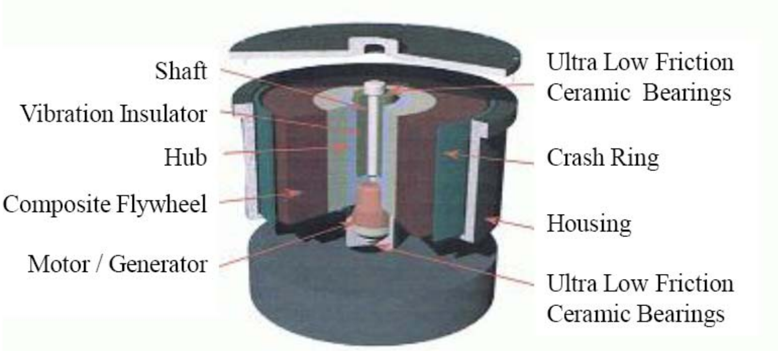
TRIBOLOGY SYSTEMS, INC.

Website: http://www.tribologysystems.com/
Address: 239 Madison Ave., Ste. K, Warminster, PA 18974 USA

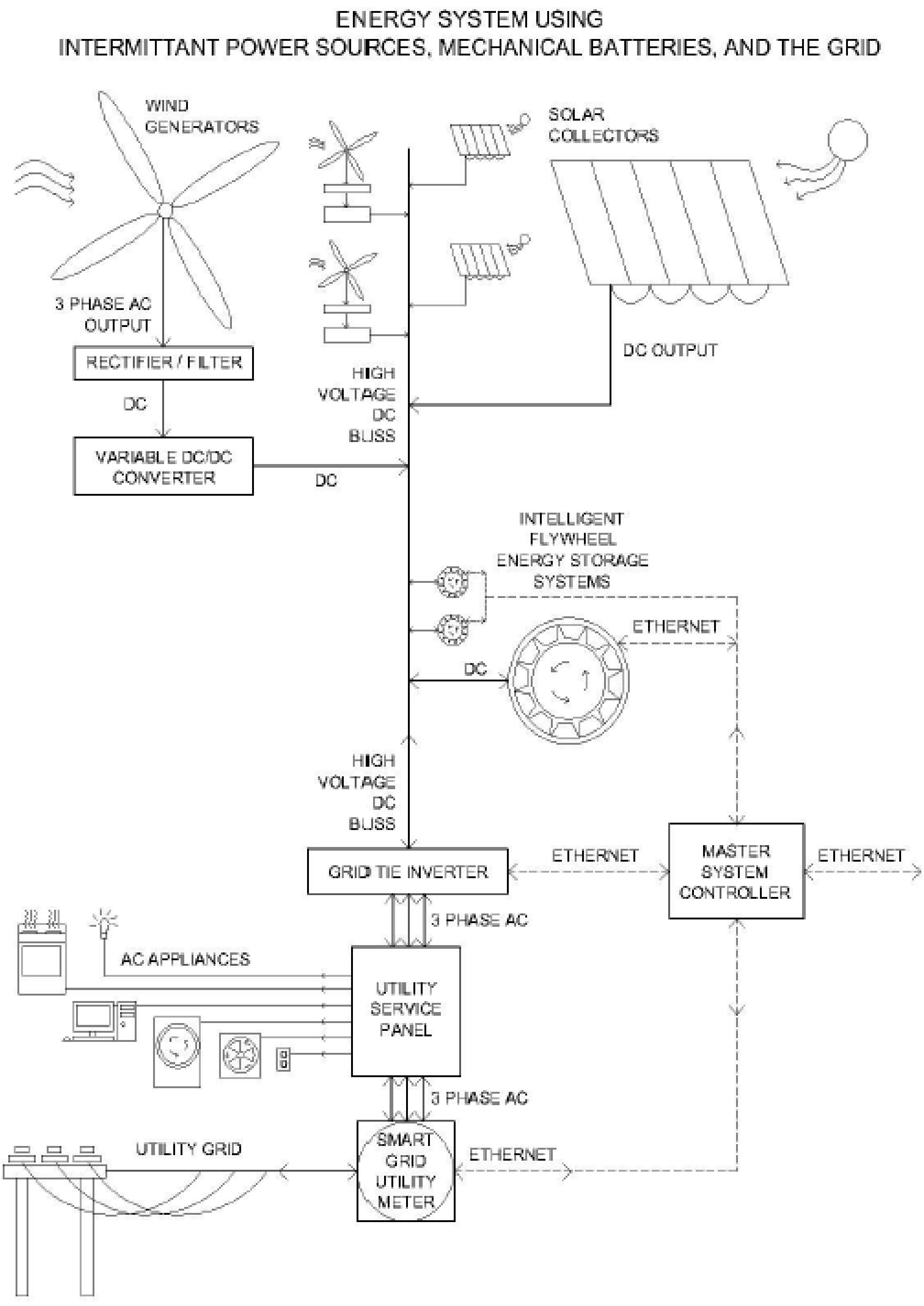
Power: 40 kW peak (25 kW continuous)
Energy: 1 kWh

Applications: Grid regulation, smartgrids, hybrid vehicles.
Technology description:

- Flywheel: Continuous-wound biannular carbon/glass fiber composite
- Speed: 30.000 rpm
- Bearings: Hybrid ceramic ball bearings
- Power electronics: 400 V DC connected, Bidirectional IGBT converter
- Power and energy densities: 317 W/kg, 678 W/litre. 7.9 Wh/ kg, 16.9 Wh/litre
- Round-trip efficiency: 74-90%
- Objective Cost: $14.000



Scheme for the smartgrids applications:



8. Vycon Energy Systems

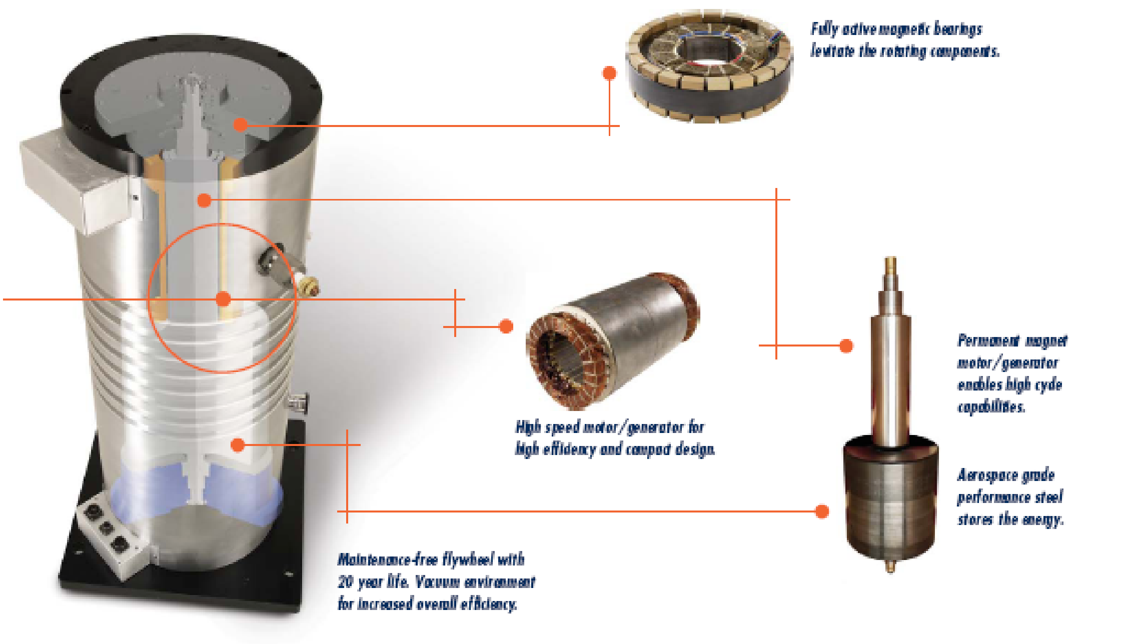
Website: http://www.vyconenergy.com/pages/flywheeltech.htm
Address: 16323 Shoemaker Avenue, Suite 600, Cerritos, CA 90703. USA.

Power: -
Energy: 12 sec.

Applications: Data Centers, healthcare facilities, mobile power, industrial plants, casinos and others, as a DC source for UPS systems. The same flywheel can be repackaged for shipyard cranes, traction power in rail as well as for wind power and smart grid energy storage

Technology description:

Composite rotor spinning between 12.000 and 36.750 rpm. Permanent magnet machine. Magnetic bearings.



9. Powercorp,

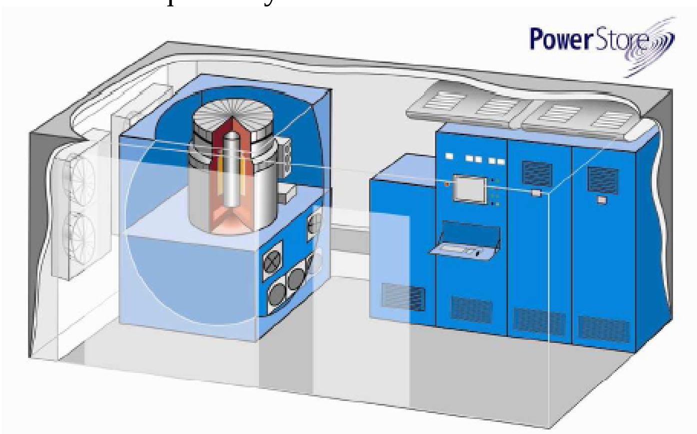
Website:
http://www.pcorp.com.au/index.php?option=com_content&task=view&id=83&Itemid=132

Address: Powercorp Operations P/L ABN - 45 070 662 369
Powercorp Research & Development P/L ABN - 47 099 592 819
Powercorp Alaska LLC , Export Drive, Darwin Business Park,
Berrimah, N.T. 0828 | p:+61(0)889470933, email: mail@pcorp.com.au

Power: -
Energy: 18MJ

Applications: Electric Grid.
Commercial products: powerstore-prodspec-08112007.pdf

Technology description: low speed machine (3,600 rpm). Piller technology. Company adquired by ABB.



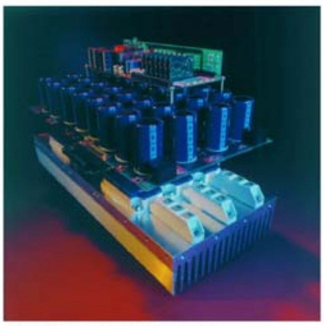
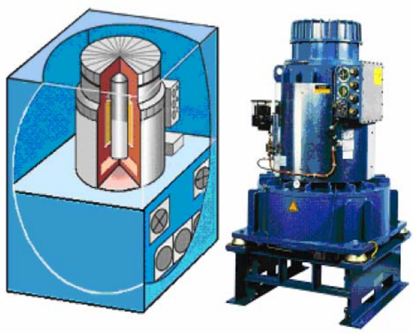


Figure 6 - IGBT Inverter Module used for PowerStore



10. Powerthru

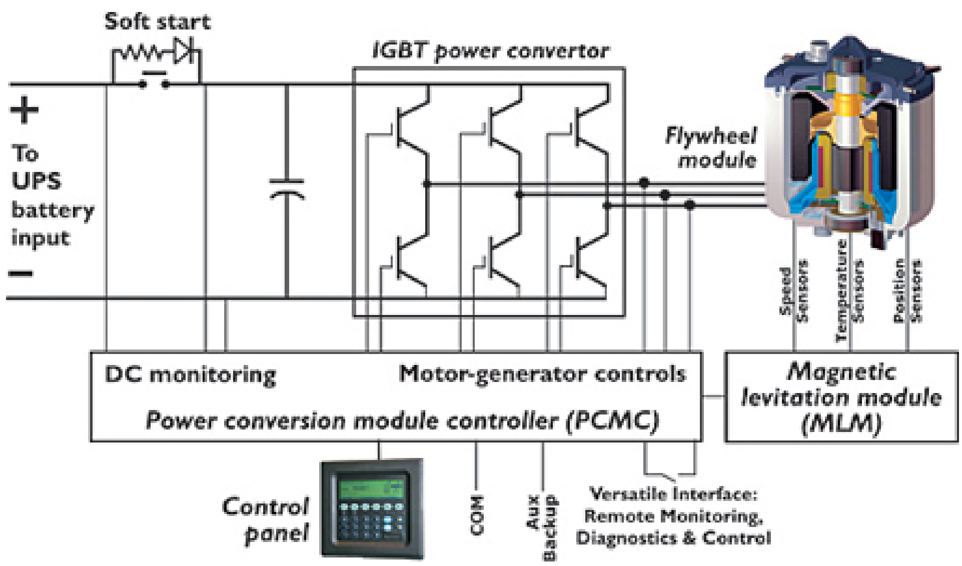
Website: http://www.power-thru.com/index.html
Address: 11825 Mayfield. Livonia, MI 48150, USA. Phone: 877-920-5004.

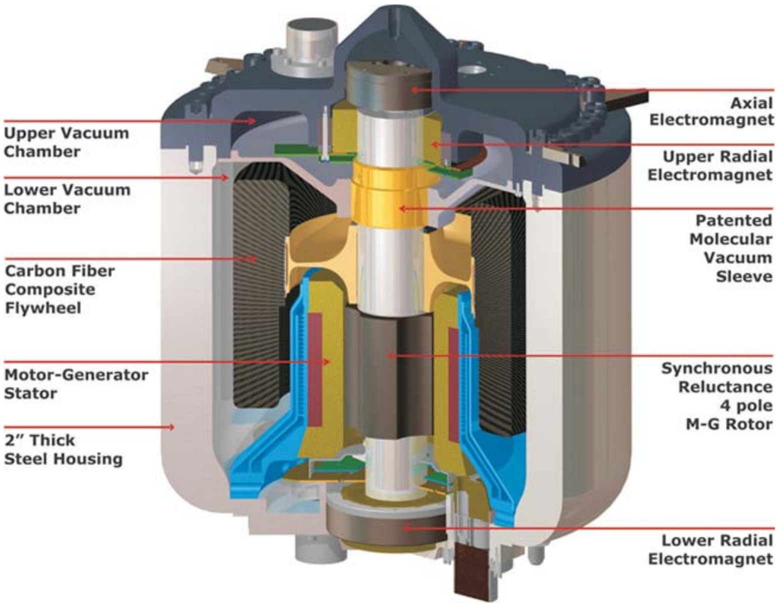
Power: 190 kW
Energy: 0.667 kWh

Applications: Electric vehicles.

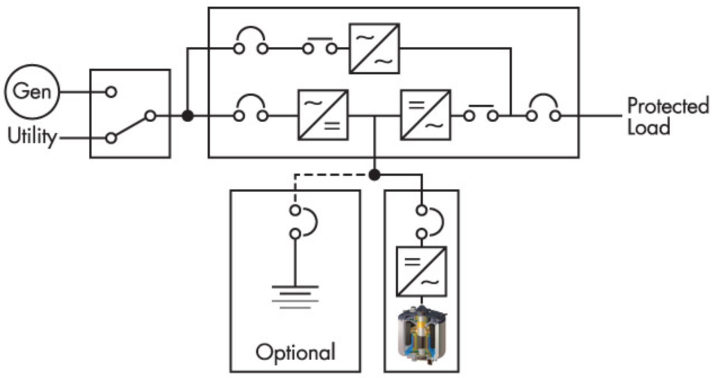
Technology description:

Flywheel: carbon fiber composite mounted on a fiber glass rim and titanium hub
Speed: 25.000 - 52.500 rpm
Bearings: Five axis active magnetic bearings
Electrical machine: Synchronous reluctance motor, 4 poles
Power electronics: 1200 V, Bidirectional IGBT converter
Power and energy densities: 693 W/kg, 2065 W/litre. 2.43 Wh/ kg, 7.25 Wh/litre




Upper Vacuum Chamber
Lower Vacuum Chamber
Carbon Fiber Composite Flywheel
Motor-Generator Stator
2" Thick Steel Housing
Axial Electromagnet
Upper Radial Electromagnet
Patented Molecular Vacuum Sleeve
Synchronous Reluctance 4 pole M-G Rotor
Lower Radial Electromagnet


ATS
UPS
Utility feed
Protected load
Back-up genset
Flywheel
Optional batteries


Gen
Utility
Protected Load
Optional

11. Centre for Concepts in Mechatronics (CCM)

Website: http://www.ccm.nl/en/projects/projects/22-energy-storage-system
Address: PO Box 12 NL-56700 Nuenen (Holland).

Power: 300 kW peak (200 kW continuous)
Energy: 4 kWh

Applications: Electric vehicles.
Commercial products: EMAFER (Electro Mechanical Accumulator for Energy Re-use. 250kW/3kWh
Technology description:

Flywheel: thick rim of carbon fiber composite integrated with machine rotor
Speed: 22.000 rpm
Bearings: ceramic ball bearings
Electrical machine: Synchronous permanent magnet machine.
Power electronics: Current source inverter based on thyristors, with an integrated chopper with IGBT
Power and energy densities: 800 W/kg, 1578 W/litre, 10.6 Wh/ kg, 21 Wh/litre

CCM's flywheel technology is used in two ultra modern vehicles: Autotram (Intermediate Transport Vehicle) from Fraunhofer Gesellschaft, and Avanto (Light Rail Vehicle) from Siemens. Notably are the long service lifetime (upto 30 years) and the high energy efficiency (90% round trip).


Synopsis

General

The **EMAFER** flywheel system is based on a high speed composite (carbon fibre) flywheel integrated with a synchronous permanent magnet motor/generator and controlled by a powerful bi-directional power converter with high frequency power switches. The complete flywheel system can, e.g. for rail vehicle application, be packaged into a roof cabinet as illustrated below and is comprised of the following modules, see also next Figure.

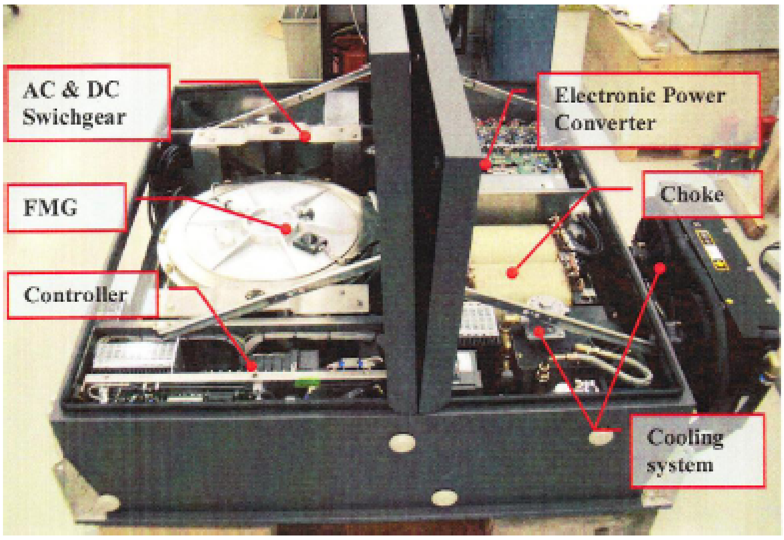
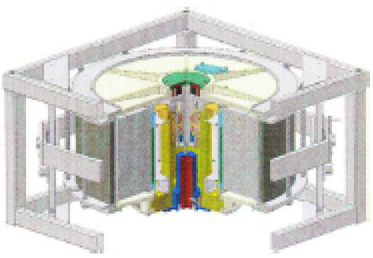


Figure: Flywheel box

Flywheel-Motor/Generator-Unit (FMG)

The FMG is very compact by its modular construction. The energy is stored as mechanical energy (rotational) and is exchanged electrically via the three phases of the synchronous permanent magnet machine (motor/generator).
The containment is coupled to the vehicle via a cardanic suspension. This cardanic suspension isolates vibrations and gyroscopic forces to and from the vehicle.



EMAFER RxV-II:
4 kWh / 300 kW, 22000 rpm 0780 x 450 mm, 375

Assessment of Flywheel High Power Energy Storage Technology for Hybrid Vehicles" ORNL/TM-2010/280. December 2011. Oak Ridge National Laboratory. James G. R. Hansen , David U. O'Kain.

12. Flybrid Systems LLP.

Website: http://www.flybridsystems.com/F1System.html

Address: Flybrid Automotive Limited
Silverstone Technology Park, Silverstone.
Northamptonshire NN12 8GX United Kingdom
Telephone: 01327 855190
Email: mail@flybrid.co.uk

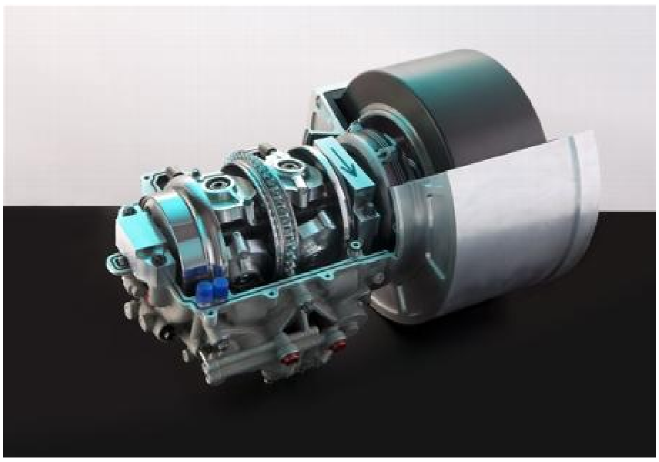
Power: 110 kW peak (60 kW continuous)
Energy: 400 kJ of usable storage

Applications: Electric vehicles.

Technology description:

Flywheel: made of steel and carbon fibre inside an evacuated chamber
Speed: 60.000 rpm
Bearings: ceramic ball bearings
Electrical machine: -
Power electronics: -

- The flywheel casing featured containment to avoid the escape of any debris in the unlikely event of a flywheel failure
- The flywheel was connected to the transmission of the car on the output side of the gearbox via several fixed ratios, a clutch and a Continuously Variable Transmission
- A total system weight of 25 kg
- A total packaging volume of 18 litres



13. HyKinesys

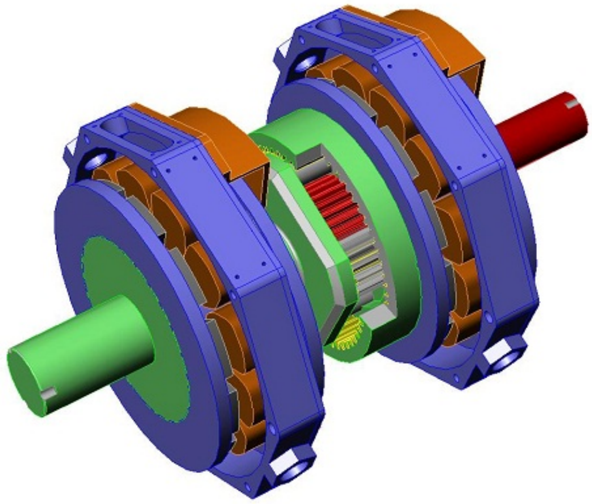
Website: http://www.hykinesys.com/technology1.html
Address: 25C Northside Road. Otawa, Ontario. K2H 8S1 Canada

Power: 70 kW
Energy: 400 kJ of usable storage

Applications: Electric vehicles.

Technology description:

Flywheel: Aluminum alloy hub. Glass and carbon reinforced rim
Speed: 14.000 – 28.000 rpm
Bearings: hybrid ceramic ball bearings
Electrical machine: PM synchronous AC, liquid cooled.
Power electronics: -DSP controlled bi-directional frequency converter.
Power and energy densities: 800 W/kg, 960 W/litre, 5 Wh/ kg, 6 Wh/litre
Roundtrip efficiency: 86%
Cost: Present: $75.000 Future: <$20.000



14. Magnet-Motor GmbH.

Website: http://www.magnet-motor.de/index.php?id=3&L=1
Address: Petersbrunner Straße 2, D-82319 Starnberg. GERMANY

Power: 400 kW
Energy: 5 kWh

Applications: Electric traction.

Technology description:

Flywheel: Hollow cylindrical rotor, filament wound carbon and glass fiber
Speed: 12.000 rpm
Bearings: steel and ceramic ball bearings, magnetic levitation
Electrical machine: PM radial gap synchronous machine
Power electronics: -IGBT inverter
Power and energy densities: 750 W/kg, 1580 W/litre, 5 Wh/ kg, 10.5 Wh/litre
Roundtrip efficiency: 87%

2 kWh / 150 kW MDS flywheel, mounted in gimbals.
Operated in trolleybuses in Basel, Switzerland

15. Ricardo UK Ltd.

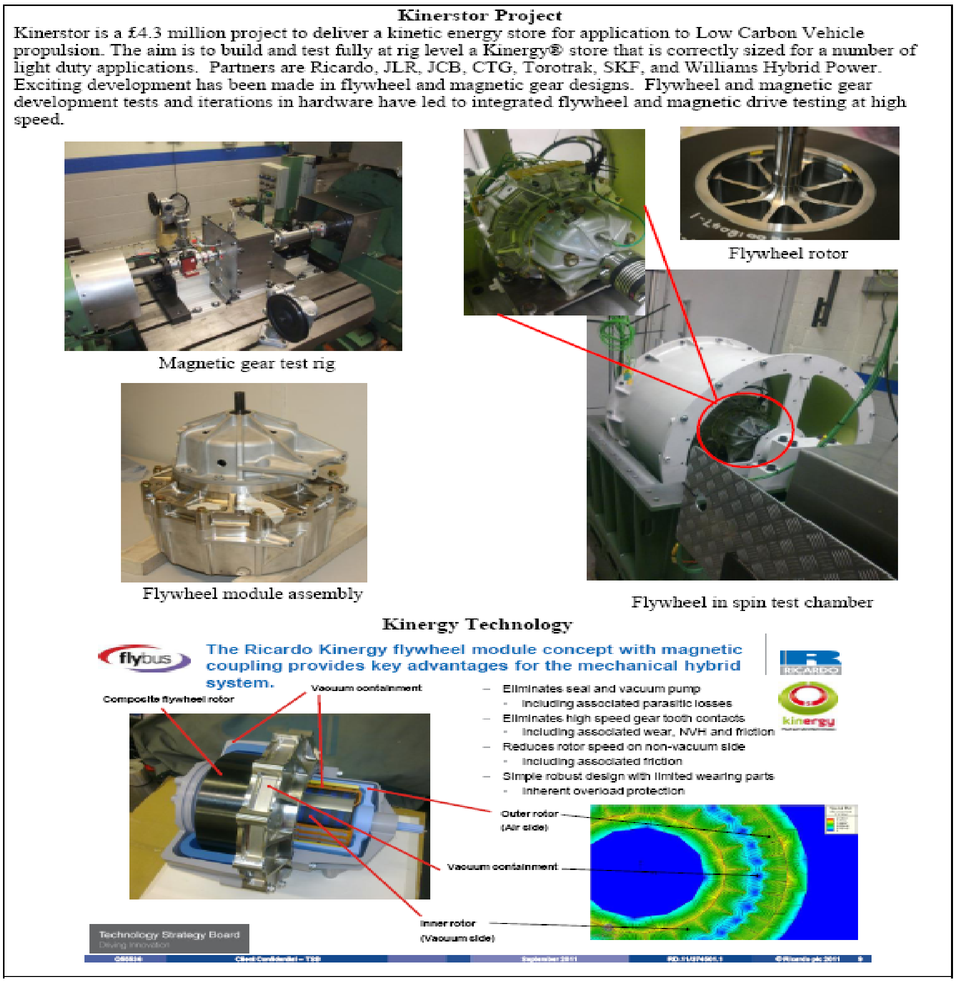
Website: http://www.ricardo.com/en-GB/
Address: Shoreham Technical Centre, West Sussex, BN43 5FG, United Kingdom

Power: 60 kW peak (40 kW continuous)
Energy: 0.22 kWh

Applications: Electric traction.

Technology description:

Flywheel: Filament wound carbon fiber
Speed: 60.000 rpm
Bearings: ball bearings
Electrical machine: kinergy drive (http://www.kinergy.com/kinergy_drive_system)



16. Williams Hybrid Power Limited.

Website:) http://www.williamshybridpower.com/
Address: Williams F1, Grove, Wantage, OX12 oDQ, United Kingdom

Power: 120 kW peak (110 kW continuous)
Energy: 0.36 kWh (1.3MJ)

Applications: Electric vehicles.

Technology description:

Flywheel: wholly composite rotor. Carbon fiber. Rotor magnetized after construction
Speed: 18.000 – 36.000 rpm
Bearings: hybrid ceramic ball bearings
Electrical machine: Brushless DC with liquid-cooled stator
Power electronics: -IGBT water cooled inverter. 600V.
Power and energy densities: 2180 W/kg, 3160 W/litre, 6.55 Wh/ kg, 9.47 Wh/litre
Roundtrip efficiency: 95%
Cost $10.000

Porche 911 hybrid uses this system
http://www.poweronline.com/doc.mvc/No-Batteries-Required-Acumentrics-Introduces-0001

17. Optimal Energy Systems Inc.

He encontrado un documento de 2006 donde explica una aplicación a eólica.

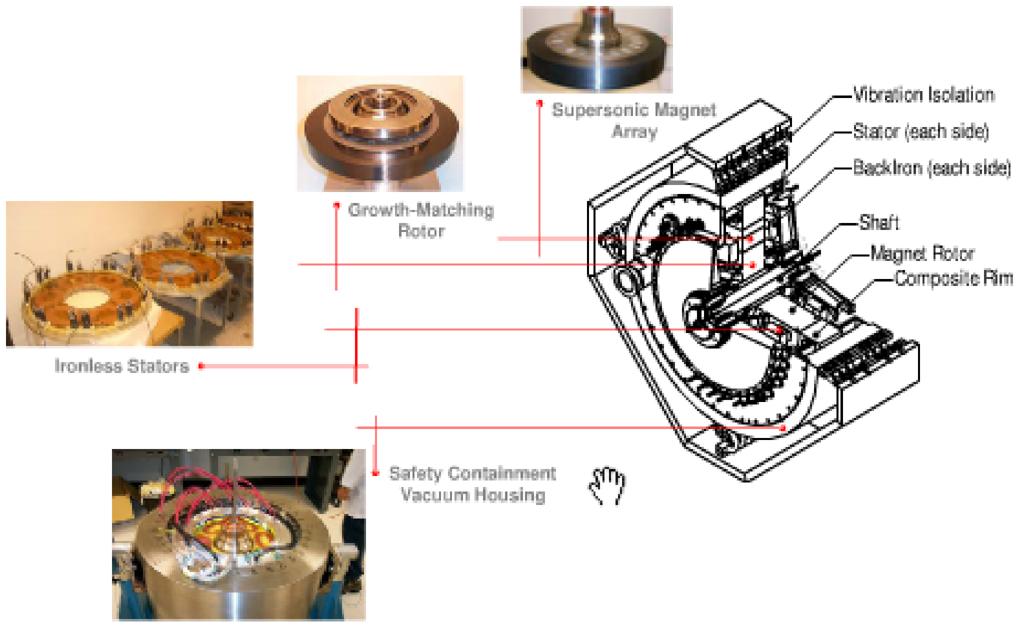
Website: http://www.docstoc.com/docs/21287808/FLYWHEEL-POWER-MODULE-WIND-POWER-ENERGY-STORAGE-Revised-January

Address: 2560 West 237th Street, Torrance, CA 90505 USA.

Power: 105 kW peak (37 kW continuous)
Energy: 47 MJ

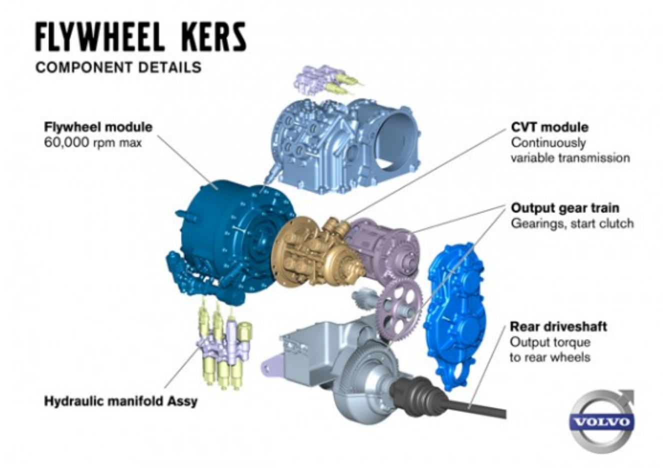
Application: Wind power

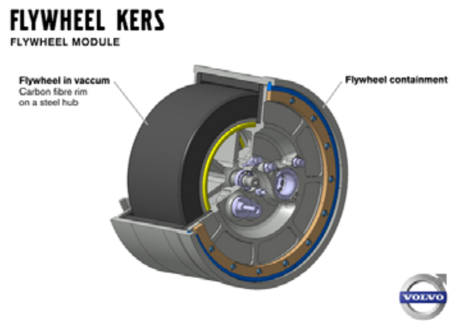
1.3 Anatomy of an Optimal® Flywheel Power Module

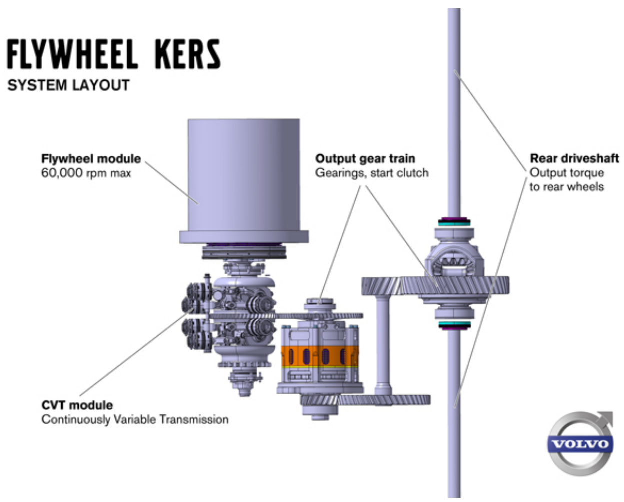


18. Volvo.

Only a few information about the flywheel speed has been collected from this company, the speed 60.000 rpm and the application in electric vehicles.







19. Tekniker

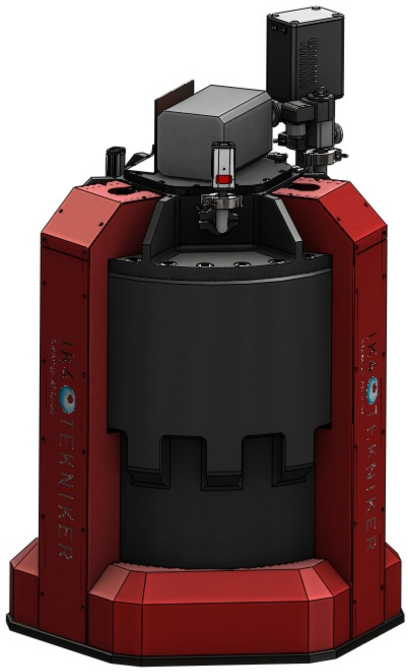
Website: www.tekniker.es
Address: Calle Iñaki Goenaga, 5· 20600 Eibar · Gipuzkoa (Spain)

Power: 100kW
Energy: 2.5MJ (0.69 kWh)

Applications: UPS.

Technology description:

Flywheel: Composite material.
Speed: 50,000 rpm
Bearings: Magnetic bearings
Vacuum: 10^{-5} bar



20. Uppsala University

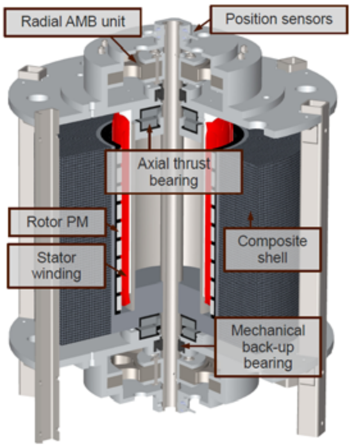
Website: http://www.el.angstrom.uu.se/
Address: Ångströmlaboratoriet Lägerhyddsvägen , 1 751 21 Uppsala, Sweden.

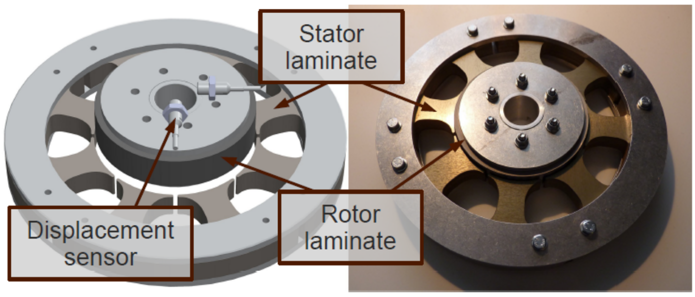
Power: 15 kW
Energy: 0.45 kWh
Applications: Concept test, Electric traction.

Technology description:

Flywheel: Filament wound glass and carbon fiber
Speed: 30.000 rpm
Bearings: Active radial magnetic bearings, passive axial magnetic bearings
Electrical machine: Permanent Magnet Synchronous

The KESS is in development stages. The KESS operates in parallel with a low power-high energy rated battery in the power train of a city bus. The flywheel acts as a power buffer to smooth the power transients and increase the lifetime of the battery pack.





21. CIEMAT

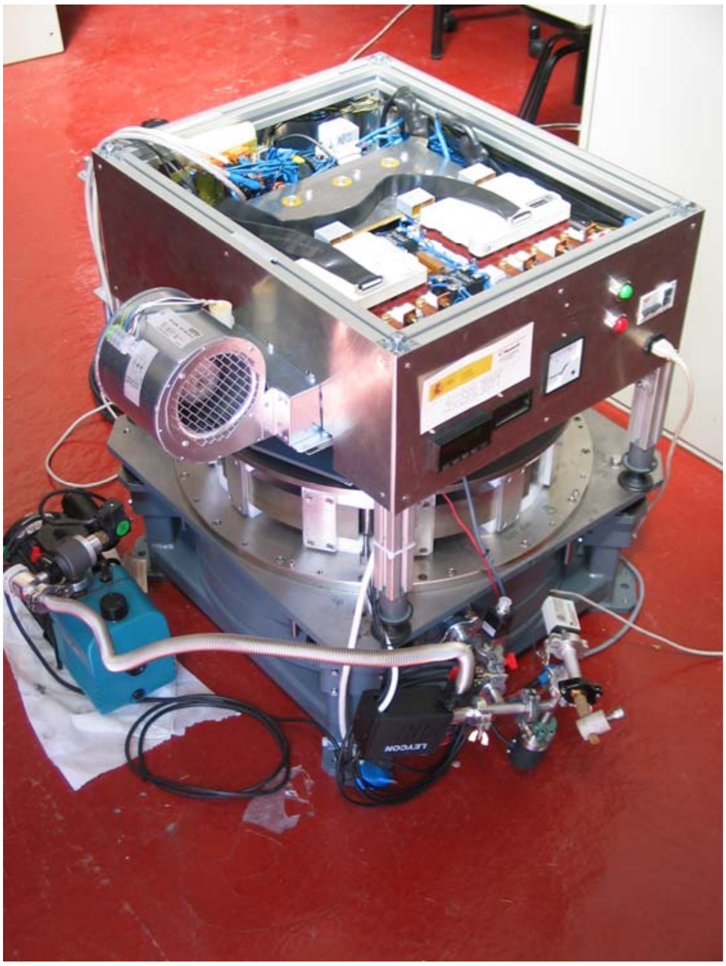
Website: http://www.ciemat.es
Address: Av. Complutense, 40. 28040 Madrid, SPAIN

Power: 30 kW
Energy: 10 MJ

Application: Renewable energy, transportation.

Technology description:

Flywheel: high strength steel	
Speed:	12.000 rpm
Bearings:	ceramic ball bearings, magnetic levitation
Electrical machine:	Switched reluctance machine
Power electronics:	-IGBT inverter. 600V.



22. CATERPILLAR

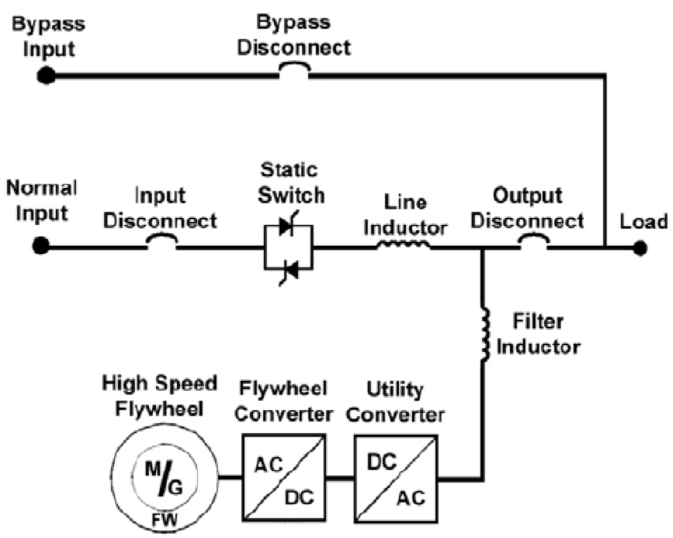
Website http://www.cat.com/power-generation/ups

Power: 300, 600, 900, 1200 kVA
Energy: 14 sec autonomy at rated power (4.2 – 16.8 MJ)

Application: UPS

Technology description:

Efficiency:	98%
Voltage:	480V, 3-phase system.



Caterpillar kinetic UPS

III. APLICATIONS

Some specific applications have been identified as suitable for flywheels utilization in different areas:

1. **Transportation**, to reduce CO2 emissions and to increase the efficiency.
   1.1. Electric and hybrid large automobiles (electric buses)
   1.2. Railway: Light trains and underground transportation
   1.3. Ferries
2. **Renewable energy generation**, to ensure the grid stability, frequency regulation and voltage support.
   2.1. Wind energy
   2.2. Solar photovoltaic energy
   2.3. Wave energy generation
   2.4. Smartgrids
3. **Industry applications**, to ensure power supply or increase the efficiency
   3.1. Uninterrupted power supply to critical loads (UPS)
   3.2. Cranes and elevators
4. **Electric grid applications and Energy Management.**
   4.1. Starting of backup generators
   4.2. Generation
   4.3. Power transportation and distribution

Several phenomena related with grid stability in transportation and distribution can be faced by kinetic energy storage. Economical consequences are related with this issue. where the

A deep study of the potential applications reveal some interesting uses described in the following chapters.

.

1. APPLICATIONS IN TRANSPORTATION

The use o fan energy storage system in transportation can be faced by locating the system on board or aside of the vehicle. The discussion about one option or the other depends on a number of factors: space availability, weight, security issues, efficiency and mechanical interferences.

The functionality provided by an energy storage system in a transportation system can be summarized in three points:

4. *Increasing of the efficiency*
5. *Stabilization of the power lines (in the case of railways)*
6. *Reduction of CO_2 emissions*.

However, a more detailed list of advantages have been compiled:

- Lowers electric power usage through highly efficient energy recycling
- Improves train capacity and performance with instantly available power
- Reduces resistor heating and lowers HVAC requirements
- Reduces stress on train traction power equipment and braking systems
- Provides effective, safe and reliable energy storage and delivery
- Minimizes carbon emissions of railway systems
- Increase peak power capacity for the demands at a significant cost savings over substation dimensioning
- Reduces capital expenditure through more efficient operation and faster deployment than substations
- Increases the energy and power density of systems
- Reduces the substations power and the number of them.
- Provides low voltage sag and power peaks correction
- Balance the power consumption in the electric grid
- Eliminates slowdowns, supports increased ridership and enhances system performance
- Lowers stress on train traction power equipment
- Can provide backup power in the event of outages
- Generates zero emissions and hazardous materials
- Creates a reliable power quality solution with minimal maintenance
- It has an important rule in the hybridation concept when combining with diesel, increasing the efficiency and reliability of this systems

Different applications have been identified in different areas of transportation.

1.1.Electric and hybrid busses.

There are some research projects, as pointed out in the state of the art chapter, where the application of flywheels has been tested, by itself or together with batteries. For this application, the most important characteristics to be accomplished by the system are: high power and energy densities, low weight, low dependence of vibrations and mechanical solicitations, and security for the vehicle. Although there are some products for small vehicles we find more interesting the application in electric busses together with batteries, being able to increase the life time of them.

1.2. Railways.

The American company Beacon Power, among others, has identified railways as one of the most promising applications for flywheels, focussing on the voltage support of the overhead power lines.

As the number of passengers carried by rail increases, trains become heavier, the spacing between trains decreases and rail systems become more prone to voltage drops that impair performance and reliability. While substations can be upgraded to add power conditioning equipment, space constraints and the related difficulty of increasing local power distribution can make it very costly to upgrade some substations. Another solution would be to install flywheels to boost voltage. Our flywheel systems can be located in places where the voltage sag is severe. For retrofit of existing rail systems or construction of new light rail transit systems, installing flywheels at strategic trackside locations can support voltage and reduce both the number and cost of substations required. Reduction in the number of substations needed and associated savings in equipment, land and maintenance may provide an attractive economic basis for installation of our flywheel systems. Another related secondary application for rail systems is regenerative braking. Most new trains are designed to use regenerative braking to generate electricity as they decelerate. Instead of wasting this energy by sending it to a resistive load bank, our flywheels can be used to capture that energy. Savings would derive from lower energy costs, reduction in peak power demand charges, and reduced maintenance on brake systems [20].

The increase of transport energy consumption is higher than in other energy uses (in Spain, for instance, railway has increased 6 % annually since 2002). Although improvement of the railway service quality implies a greater energy cost, it is the transportation mode that consumes less energy and that is one of the main arguments for public authorities to invest in railways (In Spain: 10.000 km of high speed lines are planned to be in operation in 2020). Since other transportation modes are improving energy efficiency railways should not neglect their competitive advantage and have to investigate and innovate to keep it.

Energy savings, quality, reliability, power peaks reduction, acceleration capacity when starting and voltage drops reduction at the catenary are some of the concepts considered in railway transportation research. These problems concern mainly DC railway lines DC (subways, short-distance trains and light trains). Energy Storage Systems is one of the main solutions to improve those topics and the one to be described in this paper. Recent studies from ADIF (the Spanish Railway Infrastructure Manager) have concluded that in railway DC-lines the waste of energy due to regenerative braking is almost 20% of the consumed energy since the power can not be returned into the grid (due to diode rectifiers) and it could be re-utilized by means of energy storage devices. Moreover the number of diary supply interruptions could be reduced from 15 to 1 with the same technology.
The following decision is: What type of energy storage device is more appropriate for railways? There is not an easy answer and depends on the particular problem to be afford. Most of the publications and research works during the last years are focussed on on-board solutions for trains and present the solution of ultracapacitors or batteries. The on-board solution is more efficient since the energy storage device acts directly over the electric machine but a system off-board, connected to the DC catenary, has some other advantages such as no extra space occupied in the vehicle, no modifications in the train distribution and that the system can be connected to the catenary sector where problems are and not in every train. From the different off-board solutions Kinetic Energy Storage Systems (KESS) have been selected for this type of application. because of three main reasons: First, the high power and energy levels as well as energy/power ratio to achieve the requirements; second, the total cost is not so linearly increasing with the power and energy level compared to some other technologies like batteries or ultracapacitors; and finally the advantage of installing the system in a static location near the substation reduces the mechanical problems that flywheels or other technologies would introduce when mounting on board.

1. Flywheels are a good option to connect to a supply catenary in higher power levels
2. Power and energy densities and charge-discharge frequency requirements are very appropriate
3. Not modification of vehicles
4. The traffic can be increased. Just vary the exchange frequency
5. The technology is cost-effective when large scale application
6. It has an interesting extension when combining with some other systems like batteries, for this or other applications
7. Flywheels can provide continuously charge and discharge cycles, permitting to manage the energy without technological limitations.

The system developed and presented in this paper is designed to be commercially competitive and presents several benefits: The technology is completely proper (machine, flywheel, power electronics and control); the materials used are conventional and the team has previous experience in fabrication of this type of electromagnetic devices, vacuum, power electronics and control platforms construction and testing, achieving an optimal cost and ensuring the success. The system is composed by a metallic flywheel of 6 tons driven by a reversible switched reluctance machine used to increase and to decrease the speed and therefore the energy stored. Nominal speed is 6500 rpm and the total inertia of the flywheel is 895 $kg{\cdot}m^2$. Figure 1 presents how the machine and the flywheel look like. Conventional ceramic bearings have been used but since the weight and speed level are too high for any commercial bearings, a magnetic levitation has been disposed by means of permanent magnets pulling up the metallic flywheel.

Flywheel testing facility for railway applications in Madrid (Spain)

The power electronics equipment is composed by the converter stage to drive the machine and the isolated DC/DC converter to connect to the railway DC catenary. Dedicated control hardware has been designed based on microprocessors and will be responsible of controlling the power electronics and communicating with the substation control.

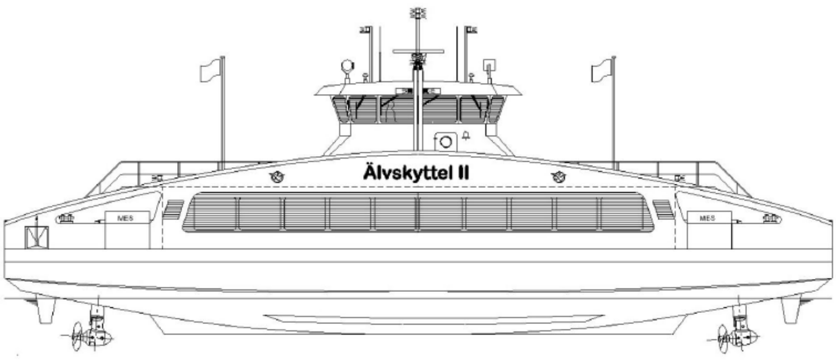
Railway lines with a lot of traffic, the energy from breaking is usually consumed by another train that probably is accelerating is that moment. So, in those cases, energy storage is not a reliable option, but in railway lines with no much traffic, it results in an improvement in the efficiency.

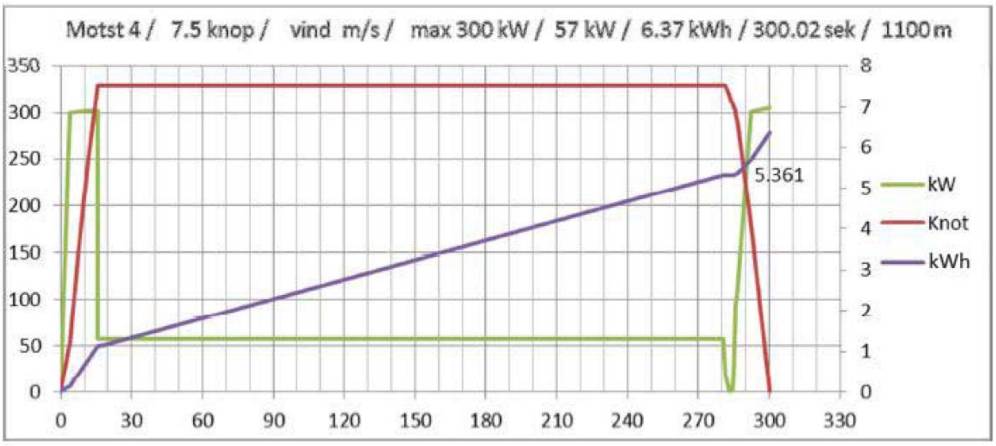
The recommendations about the power and energy ratio, in short distance trains, the breaking power are between 500 kW and 2000 kW, depending on the demanding conditions of the breaking and the type of machine. On the other hand, the time is around 10 sec. So as, high power and low energy systems would be required.

Manufacturers recommend providing several units in series or parallel instead of building big machines for the required conditions. That results in a higher reliability and lower cost.

1.3. Ferries

There is an increasing interest in the electrification of boats and ferries especially in lakes and rivers due to strict environmental restrictions. KESS in some marine applications have similarities with the electric and hybrid busses case as they run on well known drive cycles. The weight and size are not as restricted as in busses, so an intermediate technology between stationary and onboard flywheels is possible.
The power requirement of the ferry line Älvskytteln in Gothenburg (Sweden) is presented in the figure. The peak power is about six times higher than the average power. This type of ferry makes over 50 round trips a day. If batteries are used in the driveline, the batteries would be charged with the energy for 50 trips by night. If flywheels or ultracapacitors were used, charging between trips would reduce the energy storage requirements to the energy of only one trip. That is one fifth of the energy rate of the battery solution. More information is found in [23]





Power (green) and energy (purple) required to complete a trip in the ferry line Älvskytteln in Gothenburg (Sweden)

2. APPLICATION IN RENEWABLES

2.1. Wind power generation

In the context of wind power energy, being able to integrate an energy storage system in a wind power plant might solve many problems related to operations and interconnection. These obstacles can be summarized in three main problems: power quality (frequency and voltage variations, the flicker effect, harmonics and power flux variations), voltage stability and electric angle stability.

	Ramp Rate (dP/dt)	Instantaneous	Average (Max variation)
Netherlands	< 12 MW per minute		
Denmark	< 10% P_{nom} per min.		< 5% P_{nom} per min.
Hawaii	< 2 MW per minute	1 MW change per 2 sec scan	< 0.3 MW per min.
Germany	< 10% P_{nom} per min.		
Scottish Grid Code	• No limit for P_{nom} < 15 MW • 6.7% P_{nom} per min. for P_{nom} between15-150 MW • 10 MW per min. for P_{nom} > 150 MW		

Table 1: Wind Farm Power Output PPA Index Requirements

Flywheel-based energy storage could act as both a buffer and balancing resource between variable wind generation, slower-ramping conventional fossil generation, and various fast- and slow-acting demand response resources. Flywheel energy storage offers an excellent set of features to accomplish this new energy balancing application. These include a ramp rate up to 100 times faster than conventional fossil-fired generation plants; high-cyclic capability without any degradation of energy storage capacity over time; low maintenance; zero fuel consumption and no direct CO2 emissions; no use of toxic materials; and a 20-year life.

Unfortunately, wind power plants do not have limitless capacity to reduce this power fluctuation. There are several options to solve this matter:

1) Increase spinning reserve in the grid
2) Dump the wind energy produced in wind power plants
3) Use energy storage systems in wind power plants

First it is accomplished a research in several wind power plants [22] and then we standardized the power to a 100MW value. Later on and after analyzing the probability of problematic events to happen, it has been estimated the power needed to solve those obstacles. Around 20 events will need 20MW of stored power.

There are several conclusions of this study: the power of the storage system PESS in the context of a wind power plant is around 15% of the nominal power of the wind power plant. Another main conclusion is based on the energy. The energy needed is concluded to be 25 seconds times the power of the energy storage system.

If we were about to apply an energy storage system to a wind power plant of 25MW we would use a system based on flywheels with a 190MJ energy and a 3.8MW peak power in the charge-discharge process.

It is especially interesting the case of hydrid Wind-Diesel generation plants when the electric grid is very weak. A wind turbine placed in parallel with a diesel generator works to reduce the fuel used by that generator by allowing it to be shut down when wind power exceeds load. However, when load approximately matches available wind power, the generator must be kept at idle for the occasional event when wind power drops for a few seconds or minutes below connected load. This mode of operation is not very efficient, since much of the diesel generator's time is spent either at idle or inefficient low power settings. The introduction of energy storage can act to further reduce diesel fuel consumption by using the stored energy to provide both load following and supplying the occasional shortfall, while leaving the generator turned off [20]. Flywheel energy storage should be ideal for this application thanks to its low maintenance, long design life, high cycling capability without any degradation in storage value, its ability to respond almost instantaneously (thus improving load following), and its ability to provide real and/or reactive power.

Application cases:

- Autonomous hybrid systems: Synchronous flywheel in a wind-diesel system, Punta Jandia, Fuerteventura, Spain.
- Smoothing wind power fluctuations from a single wind turbine: urenco 100kW in Fuji, Japan.
- Wind-diesel including flywheel at Denham in Australia, with three Enercon E-30 wind turbines have total rated power of 690kW.
- El Hierro island (Spain) where Enercon company has installed stand alone wind generators with hybrid energy storage units composed by batteries and a flywheel.

2.2. Solar Photovoltaic generation

Solar energy applications are not maybe the most direct ones, but the possibilities that can occur in plants to include solar energy storage have been analyzed.
One of the open discussions to use the energy storage in this application is the ability to make the storage in AC or DC. The main problem of put it in the continuous phase is the impossibility of using the terminals of the solar panels because the control of solar inverters designed to make the system work in the maximum power point may be modified. It would be necessary to provide a DC/DC converter that will handle this action and then connecting the storage device in the subsequent continuous phase.

The following applications within a solar park have been identified:

a) Photovoltaic park disconnections by the electric company.

If the frequency of these disconnections were high enough to involve a financial problem to the plant, the system could be designed and controlled to keep collecting and storing the energy from the panels and then introducing it on the grid moments later with grid access. If the storage system was attached to the continuous phase of the inverters, the storage would be transparent to grid access or not. If it was connected to the AC, the system should be designed to be able to work as uninterruptible power supply (UPS) creating a separated grid in the plant aiming to collect the generated energy by the panels and maintaining the operation of the inverters.
For proper implementation of this option, a "witness signal" of the state of the company contactor would be required to start the operation as UPS and also a contactor itself to perform the reconnecting task. This option depends on the frequency of such disconnections.

b) Power curve displacement. Mass storage device support.

For an application in which it is intended to change the power generation curve, a storage system with low self-discharge (as batteries) is needed. This allows generation curve smoothing in a time scale of an hour quarter hours. The kinetic energy storage device would extend the life of batteries so that the loading and unloading curves thereof were optimal. This option could be implemented in both AC and DC, using in any case an additional converter for the connection of the batteries, being able to control their charge-discharge independently of the other systems. A DC/DC would be implemented connected to a stack of batteries (any type of), whose charge and discharge would be programmatically managed together with the charge and discharge of the flywheel.

c) Improvement of the maximum power point (MPP) search.

Connecting the storage system to the continuous phase of the inverters involves introducing a current source which can be controlled. It has been determined that the operation of this input current is stable from standpoint of MPP algorithm. The possibility of using the storage to improve the MPP search process was studied, but it is not expected to involve a major difference because the inertias of the panel are much more important.

d) Generated power peaks

Under certain generation conditions, and since normally no inverters are dimensioned for the peak power of the panels, peaks may occur in the power generated by the panels that make the inverter work in saturation being un able to give full power to the grid. In these situations, the kinetic storage device could absorb the power excess that the inverter can not deliver to the grid and return it to the grid at the time that the production is smaller. This option would allow to construct power electronics inverters for a mean generation power instead of peak power thereof, saving money both in inverters and in the rest of the installation. At this point, it would be also interesting for times when there is an expansion of the solar plant with new panels and it is not wanted to modify nor the electrical part of the plant neither the number of inverters. For this application, the connection must be made in continuous phase. Obviously, this option makes sense at the moment to occur the connection of the storage device in DC, not AC. To make it possible, a DC/DC converter is needed for the DC connection of the panels. Nowadays there are already companies developing these equipments.

e) Clouds effect mitigation

Cloud effect on PV panels can produce important fluctuations in the output power. A passing cloud, for example, can easily decrease PV power output by 80 percent or more within seconds. Conversely, as the cloud passes, power output can increase just as rapidly. Most PV resources are interconnected at distribution voltages, and such power fluctuations can cause unacceptable voltage disturbance. Depending on local conditions, utilities may refuse to allow a PV resource to interconnect unless something is done to mitigate these fast ramps in power output [20]. It is not only due to the reduction of the solar radiation but also because the system is obliged to search continuously for a different operation point, not standing in a high efficiency operation point during this period, which can takes some seconds. Energy storage could provide a smooth response of the system

The energy storage system could exchange the power in the DC point or in the AC connection point, supplying a smoother generation curve into the grid.

A pyranometer would be required for this application in order to measure the solar radiation level.

f) Correction to the power forecast deviation

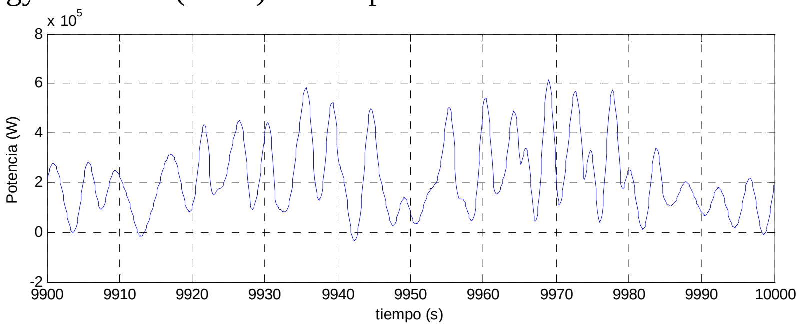
In most of the PV generation plant, a foresight model is used to determine the capacity of the power plant to supply electric energy into the grid. Providing an accurate model to forecast the expected power is an important issue to achieve the reliability of the power plant when the case of renewable.

By means of energy storage devices, deviations over the forecasted model can be corrected, providing to the company the previously contracted energy pattern.

2.3. Wave energy generation

Wave Energy is oscillatory in its nature, and although having multiple wave energy converter elements may dampen the oscillation of the generated energy, oscillation is unavoidable. This oscillation can harm the grid stability and reliability, and it also requires a oversized transportation system. The typical oscillation frequency of waves is around 10 seconds and the expected number of cycles is very high. Kinetic energy storage is well suited for the application as its storage capacity is usually from some seconds to a few minutes and is has very good behaviour for high number of cycles.

Next figure shows the evolution of the power obtained from a particular type of wave energy converter (WEC) named point absorber.



Evolution of the power obtained from a wave energy converter with 12 sec period waves.

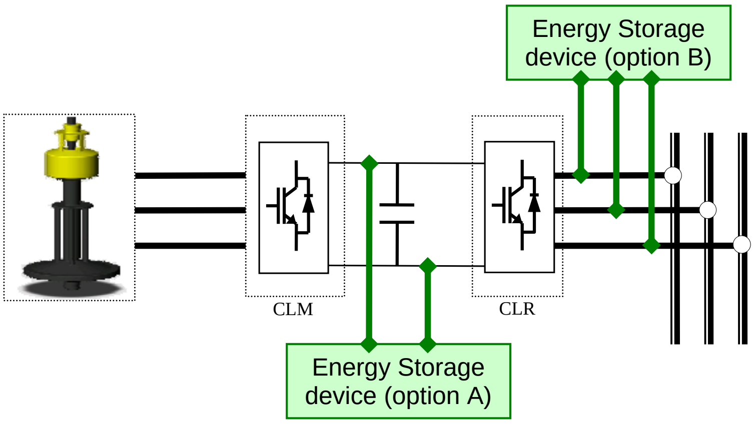
A certain average power level is determined during a period of time (remaining that no regular power will be obtained and therefore the convenient output power reference has to change continuously), considering that the amount of energy over this reference (crest) should be stored and delivered some time later, during the valley.

After the analysis of the amount of energy required based on the power different technologies can be considered for the specific application. The selection will be taken considering a lot of specifications such as: power level, energy level, response speed, power and energy densities limitations (mass and volume densities), charge-discharge frequency, number of operation cycles, exchanging – non exchanging times ratio, maintenance limitations, environmental issues, cost limitations, etc.

For the wave energy application several statements can be established in general terms:

- The amount of energy is low compared to power, so a high power and low energy system will be required.
- The number of operation cycles is very high as well as the frequency since the energy storage system would be operating continuously.
- The response time has to be very high.
- Volume is more critical than mass, so a high power density is more convenient than energy density.
- Maintenance has to be reduced due to the low accessibility of this application.

From the most available energy storage devices present in the market, some batteries could be used but would be more appropriate to use systems as ultracapacitors or flywheels since the power density is higher, the electrical response is higher, maintenance is low and the frequency and number of cycles is extremely high in both cases. However, some advantages can be found in each one, so the final choice will depend on the particular scenario considered and that would be a topic for a different paper. Several options can be also considered about where can be the energy storage device connected in the WEC. The study depends on the amount of WEC connected, the power configuration (every WEC has a double converter and the connection in AC side or all WECs are connected to a common DC-Link to deliver the power to the grid through a common grid-side power electronic converter. Two options have been included in Fig. Option A represents an energy storage device connected to the DC-link. A simpler and cheaper power electronics converter has to be used for this solution but the access to the system control has to be permitted and some control modifications have to be implemented. Option B, on the other hand does not interfere in the conventional system control but as a disadvantage complicates the power electronics since a double converter is required.



Implementation options for the energy storage device at the WEC.

2.4. Smartgrids

Smartgrids is another application where flywheels can provide an interesting contribution. In a smartgrid the target is to achieve an efficient operation of the distributed generation by managing the power flow and energy consumptions by means of the use of energy storage, among others. Although a higher energy device should be installed, such as batteries or hydropower, flywheels results as an appropriate device to maintain the frequency regulation in the case of high penetration of renewable generation, and especially in the case of weak electric grids or even if a stand-alone operation is required in the grid.

Most of the possibilities of actuation of a flywheel in a smartgrid are compiled in the chapter 4, related to grid regulation and energy management.

3. INDUSTRIAL APPLICATIONS.

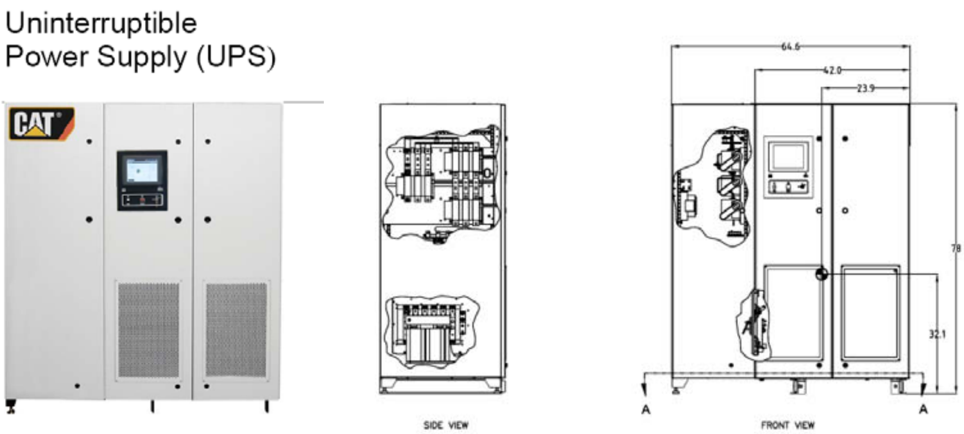
3.1. Uninterrupted power Supply (UPS)

The application of flywheels as UPS for critical loads supply is one of the most successful activities where has been used. It is an advance over conventional technologies based on batteries since for similar VA ratings the weight is reduced by 10 and the volume by 3. The basic difference between a flywheel-based uninterruptible power supply and a battery based UPS is that energy storage occurs with the inertia of a high speed rotating fiber composite wheel instead of using lead-acid batteries.
Other advantage is the efficiency achieved in the round trip. With flywheels can be got around 90% efficiency while using batteries, the efficiency is rarely over 80%.

One important issue in flywheels used as UPS is the fact that the charge level just depend on the speed of the rotary mass, easy to measure and very reliable. On the other hand the charge level of a battery is not really a certain variable to be measured and it can not be obtained directly the charge level from the voltage measurement.

Flywheel technology has also the advantage of being virtually maintenance-free compared to maintenance-intensive and less-reliable battery-based UPS.

One of the challenging points to achieve a competitive flywheel technology as UPS is to be able to reduce the self-maintaining losses, which means to be able to maintain the flywheel as much time as possible at the higher speed, waiting for the moment to be used, losing the minimum amount of energy. An example from Caterpillar is shown in the figure.



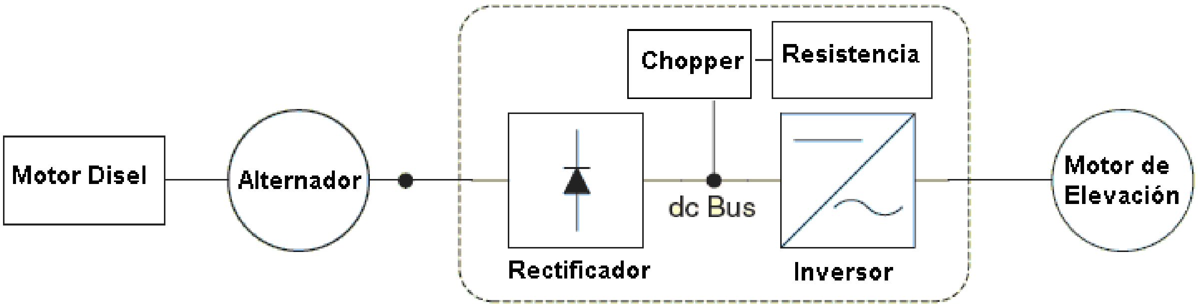
Uninterruptible power supply (UPS) based on a flywheel. Caterpillar.

3.2. Cranes and lifts

Some companies like Vycon Energy have identified the application of big cranes as one of the suitable for flywheels, in order to increase the efficiency of a system which is continuously wasting energy in every roundtrip.

Containers stacker crane

The simplified electrical diagram of the power system of a containers stacker crane without flywheel storage is shown in the Figure..

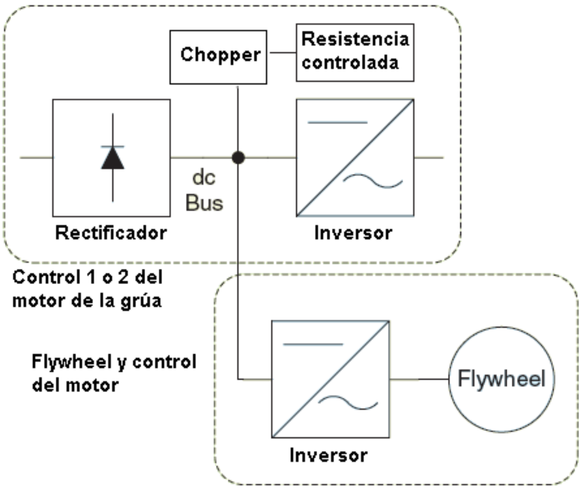


Crane lifting motor control

The diesel motor is 455 kW and three-phase alternator is data: 500 kVA, 460V. The nominal voltage of the continuous phase is 650V.
When the crane lifts a container the required energy by the lifting motor is provided by a diesel motor. The rectifier converts the AC voltage into DC voltage which will be stored in the continuous phase. Moreover the inverter converts the DC voltage into AC voltage aiming to feed the AC motor with the desired frequency. The required power flows to the motor through the rectifier, the continuous phase and the inverter. However, the amount of stored energy in the continuous phase is very small in comparison with the required power, that is, the

rectifier has to constantly feed the motor with the needed power plus the drive system losses.
During the generator mode operation of the electrical machine, i.e. when the crane puts down a container, the energy is dissipated in the resistor banks through a chopper which increases fuel consumption, emissions and reduces system efficiency. The rectifier can only supply power to the continuous phase from the AC grid but not the other way around. When changing the flow of power, the supplied power by the continuous machine charges the DC capacitor following the formula and its voltage increases. The components of the frequency converter can only stand voltages up to a certain level.
When it comes to 730V, the regenerated energy is dumped into a resistor bank by an electronic DC-DC chopper converter. This chopper is an electric switch which connects the voltage of the continuous phase to a resistor bank in which the energy turns into heat.

VYCON system introduces a storage module which is flywheel composed. Its circuit diagram representing the connection to the rest of the system is shown in the next Figure. The flywheel comprises a three-phase permanent magnet machine coupled to a steel flywheel. The rotor levitates above the magnetic bearings and rotates in a reduced pressure atmosphere with the aim of minimizing losses.



Storage system conection based on the flywheel with the rest of the system

A three-phase inverter connects the continuous phase with the flywheel's machine. This system has been designed to transfer maximum power of 150 kW. The energy that can be stored is 4.57MJ (1.27kWh) at a maximum speed of 36000 rpm. The mass of the flywheel is 320 kg producing a specific energy of 14.2 kJ/kg. The tests of the flywheel system show that this system reduces emissions by 45% and fuel consumption by 20.9%. Furthermore, peak power demand reduction increases the lifetime of the machine.

4. ELECTRIC GRIDS AND ENERGY MANAGEMENT.

4.1. Starting of big generators

In the context of a weak grid, mainly when generation does not compensate the power demand, frequency starts to drop. Consequently generators cannot deal with the power demand. In order to decrease this high level of load, when frequency reaches the lowest limit permitted, a power relay disconnects certain grid points. Once this decrease is done, frequency starts to oscillate until the regulators of the generators interact.
In order to solve this problem we propose the use of an energy storage system. This system will help to compensate the frequency drop with a virtual inertia (in this case we use energy instead of mass).
If we run the energy storage system after the support of the relay we will delay the frequency response of the generator. Since this option only delays the frequency response of the entire system we propose to run the system before connecting the relay. If so, we are able to reduce the delay of the system.
Taking into account the fact that we need to act in a matter of seconds the energy storage system will have to be characterized with high power, low energy and fast response ability. Flywheels solve all this requirements.

4.2. Generation

System Regulation

Storage can serve to meet short–term random fluctuations in demand and so avoid the need for frequency regulation by the main plant. It can also provide ride through for momentary power outages, reduce harmonic distortions and eliminate voltage sags and surges.
When there is a sudden loss of a power plant, transmission line or distribution line, a rapid drop in grid frequency can occur. While most generators must be able to compensate for a rapid drop in frequency on a fractional basis according to their capacity rating, some parts of the grid lack sufficient frequency response resources, either because there is not enough fast-response generating capacity, and/or because of transmission constraints. A flywheel based energy storage system has the inherent ability to provide frequency response support without compromising the efficacy of the primary frequency regulation application [20].

Peak Shaving

Energy Storage accommodates the minute-hour peaks in the daily demand curve.
A large number of applications exist that collectively can be categorized under "peak power support." For example, oil drilling rigs typically maintain a number of diesel power systems to meet the peak power needs of an oil drilling platform. Collectively, much of this diesel power capacity stands idle or operates at a low capacity factor (often with high emissions) based on the irregular power demands of drilling. A flywheel system could augment the capacity of the diesel generators,

thereby making it possible for fewer diesels to meet peak power demand requirements [20].

Reactive power support
One of the added values of an energy storage device connected to the grid through power electronics is that it offers the possibility to control the reactive power supplied to the grid, apart of the active power demanded by that. So, FACTs and energy storage can be combined in just one system.

Step Load Response
In case of loss of generation plant, step load respond supplying nominal power to dampen the step load impact on the system frequency and voltage.

Fault Ride Through
A flywheel can ride through faults maintaining the grid stability in case of loss a generator or large system disturbance. Reactive power can be supplied by the grid-side converter if control is appropriate to compensate voltage sags or voltage phase shift.

Power smoothing,
Avoiding rapid voltage fluctuations and flicker (continuous cycling)

4.3. Power transportation and distribution

Transmission System Stability
This is the ability to keep all components on a transmission line in synchronization with each other and thus prevent system collapse.

Transmission Voltage Regulation
This refers to the ability to maintain the voltages at generation and load ends of a transmission line within 5% of each other. This encompasses the active and reactive components of power and phase angle.

Power bridging
When switching from one power source to another, to ensure the continuity of the power supply.

Angular Instability Control
Angular instability is essentially a low-frequency (usually less than 1 Hz) undamped power fluctuation traveling from one end of a power grid to the other end. This traveling wave cannot be easily damped and can take up significant capacity on transmission lines. If the low-frequency oscillation could be damped, the transmission line capacity could be restored making it easier to relieve congested lines or reduce possible grid instability. This type of instability has been linked to wide-scale regional blackouts costing billions of Euros in lost productivity, goods and services. A flywheel energy storage system, combined with phasor measurements and an integrated communications and control network, has the potential to overcome this vulnerability and prevent such blackouts [20].

IV. ECONOMICAL STUDY

One of the handicaps of flywheel technology is the high cost of the technology compared with others like batteries. However, it has been seen that the success of these devices is demonstrated and they result very convenient when special applications, environments, constrains are on the table.

Since one of the most important goals in the development of a flywheel is to achieve a competitive cost, a great effort is necessary to

There is a big question to be answered, what is the cost per kW and cost per kWh that should be bet?. It is not really an easy question since it depends on the specific conditions of the application that is considered.

Prototype cost

Identification of the relative weight in the total cost of the device.

Identification of the fixed and variable costs.
There are some engineering cost that consider the design of the device. Here there might be included the mechanical design, electromagnetic design, electronic design, and control programming.
When considering fabrication, some special tools have to be developed for special procedures.
Those costs are only required once, and therefore considered as fixed cost once.
Eventually, some improvement can be applied to the initial design and that would be traduced in a variable engineering cost but for this first exercise that will not taken into account.

How the cost is reduced when the series fabrication is carried out?
What market cost can be achieved for the total device?

Model by Taylor et Al. from Sandia Lab predicts the total cost of a flywheel system with 5-second storage time between $200 to $500/kW. For 1hour storage time $1000 - $3000/kW. The price of a composite material is around 10 to 15 times the steel one, considering that the main cost is the rotor, it can be considered that the cost is x10.

V. CHALLENGES AND NEEDS OF RESEARCH

Where are the most urgent needs for energy storage in 10-20 years?

Most urgent needs for the energy storage applications where flywheel technology is suitable to be used are:

- Fast and robust energy storage with very low maintenance requirements.
- Energy storage devices where the available volume is very reduce and therefore a very high power and energy density are required.
- Energy storage with the possibility to locate in any place or with no especial specifications.
- Uninterrupted Power Supply with the security of the level of energy available, more direct in flywheels than in batteries, since it is dependent of the speed, easy to measure.
- Very fast response energy storage systems to solve the stability problems in the electric grids, especially the weak ones.
- Very high efficient energy storage devices to improve the total energy efficiency of industrial facilities.
- Integration in transportation to reduce the CO_2 emissions and to improve the efficiency.

Where are the decisive challenges for meeting the needs in 10-20 years?

Challenges to increase the use of energy storage in the areas of transportation, energy generation and industrial environments are to work hard in R&D to increase the reliability and efficiency of the existing systems, reducing the investment costs at the same time.
Demonstration plants are one of the key issues that will probe to the industry the convenience or not of flywheel technology for certain applications. So as, research centres together with companies have to work together in the integration of flywheels in facilities where fast energy storage is required to test its reliability. That would achieve further cost reduction.

Technical development perspectives

The technology gaps in detail have been separated in relation with the different parts of a flywheel device:

- Flywheel disc, especially fibre flywheels. It is desired to get higher energy density flywheels at a lower cost by improving the fabrication procedure. Metallic flywheels can also be used in some applications, where the power and energy densities and the performance required are different. The mechanical dependence has been considered as a drawback compared to batteries or ultracapacitors (as examples of fast energy storage) but it is becoming more and more released of maintenance in the case of flywheels and in fact they are more robust in terms of number of charge-discharge cycles.
- Electrical machines, which drive the flywheels. The machine is related to the system power as well as the flywheel is responsible of the energy. The machine is also related to how fast the flywheel is able to exchange the energy with the load or the grid. In any case there is a need for developing very high speed electrical machines that are robust and efficient at those velocities.
- Bearings. Since the system is usually rotating to a very high speed (in many cases > 50,000 rpm) at the same time than supporting a high axial force, conventional bearings are not always suitable to be used. Magnetic bearing is a quiet extended technology for high speed systems but a lot of research is still required to ensure the robustness in flywheels and also to guarantee a good dynamic behaviour, avoiding dangerous resonances. Since magnetic bearing consume energy, its efficiency is also a key issue to improve the overall performance of the kinetic energy storage.
- Power electronics. The speed range of the flywheel is quiet large and the machine has to be able to supply or to absorb a certain amount of power. A power electronic converter is in charge of managing the power behaviour of the system, both towards the machine and the electric grid. Moreover, it is possible to get additional advantages of the use of a power converter since it can be used as STATCOM or any other type of grid support, with a minimum increase of the complexity and cost. As the case of the Electrical Machine, there is a challenge in developing efficient power converters for very high speed drives.
- Digital control and communications. Digital control provides a powerful platform to achieve a high performance in fast energy storage systems together with power electronics, being able to implement complex control strategies and permitting a high performance drive. High operational speeds require ultrafast control strategies that need to be developed.
- Security case or frame. The safety conditions of the flywheel have to be deeply studied and the design of the external case is one of the important issues to work in.

Need for research

Scientific and technological challenges to be covered comprise:

- Flywheel disc. Study of better materials for fibre flywheels (high density) might be carried out in order to reduce the total cost. Also optimization of geometries are required to reduce stresses to the minimum possible level, specially in those directions in which composite materials are very sensitive due to their strong anisotropy.
- Electrical machines. High performance/High speed machines are required to be used in these devices and although permanent magnet machines seemed to be the best option, the high cost of the magnets has redirected the research to search new machine concepts with less magnets.
- Bearings. Faster control systems are being developed to improve the bearings response and more efficient actuators are used to increase the performance of the complete system. There are also interesting and promising approaches like the use of superconducting magnets that can highly improve the efficiency of the bearings.
- Power electronics. Increase the added value of the power electronics in an energy storage system, ensuring the robustness and reliability, specially working at such speeds which imply working at very high commutation frequencies.
- Digital control and communications. Communication improvements permit to control the system with guaranties of robustness, being able to analyze a lot of variables, maintaining a complete analysis of the application from anywhere, being easily integrated with some other subsystems. Fast control strategies and technologies are mandatory for driving such high- speed systems
- Security case or frame. A better knowledge and a wider experience in prototypes would reduce the cost in security.
- Increasing the energy density of storage materials
- Reduction of the losses in the magnetic material of the electrical machine as well as the switching losses at the power electronics.
- To identify the possibility of hybridizing with some other energy storage technologies which provide higher energy, such as batteries or hydro pumping storage.

APPENDIX

Flywheels characteristics

The kinetic energy of a rotating mass is:

$$E = \frac{1}{2} J w^2$$

The moment of inertia is a function of the mass and shape of the flywheel:

$$J = \int_x x^2 dm$$

For the particular case of a circular rim of radius r:

$$J = mr^2$$

Therefore, $E = \frac{1}{2} mr^2 w^2$

The tensile strength of the material defines the upper limit of angular velocity. In the case of the rim,

$$\sigma = \rho r^2 w^2$$

The specific energy is

$$E_m = \frac{1}{2} r^2 w^2$$

	Density [$kg.m^{-3}$]	Strength [$MN.m^{-2}$]	Theoretical maximum specific energy [$Wh.kg^{-1}$]
Steel (AISI 4340)	**7800**	**1800**	**32**
Alloy (AlMnMg)	**2700**	**600**	**31**
Titanium (TiAl6Zr5)	**4500**	**1200**	**37**
GFRP Glass fibre reinforced polymer (60 vol% E-glass)	**2000**	**1600**	**111**
CFRP Carbon fibre reinforced polymer (60 vol% HT Carbon)	**1500**	**2400**	**222**

Table 1. Specific strength of rotor materials
(Material properties taken from Aspes Engineering AG website)

Steel rotors have specific energy up to around 5 Wh/kg
Composite rotors have specific energy up to around 100 Wh/kg
Specific power is up to around 1600 W/kg.
However, the energy density must be reduced by a factor of 10 when consider to complete system weight (containment, vacuum system and electric interface)

Lifetime
is typically of 20 years with full charge-discharge cycle every 100 minutes. Adequate thermal design of the system is required to maintain the temperature levels in the range.

Self discharge.
Two situations could be considered:
a) open circuit, when the electric part is disconnected (only mechanical losses are considered)
b) standby, when the electric part is connected and losses are equivalent to the rotor losses plus the power interface losses

Considering units of nominal capacity C per hour, the self-discharge rates are found in the range of 0.18 to 2 times stored capacity per hour. That confirms that flywheels are not suitable choice for long-term energy storage.

Installation
Some manufacturers recommend installation in a cabinet, others underground installation.

Efficiency.
The key point about efficiency is the amount of energy required to keep the energy storage equipment charged. In the case of a flywheel, for instance, this is called standby loss. It takes more energy to keep a flywheel spinning (0.2% to 2% of the power load, depending on the technology of the flywheel, if it is metallic or composite) than to keep a battery charged (0.2% of the power load).

Flywheels advantages:
- Fast recharge
- Results more economic for applications of 500kW or above
- Wide operating temperatures (0 to 100º C) compared with batteries
- Lifetime of more than 15 years
- Smaller footprint than batteries for more than 50 kW

Disadvantages:
- Maintenance cost
- Complexity of installation
- More potential single points of failure since the complexity of the system
- Standby losses (losses to maintain the flywheel rotating)

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