Kinetic Energy Storage: an Ideal Application for Magnetic Bearings

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***Abstract*—Kinetic energy storage systems have a long history, but in the last half a century many studies and projects aimed to make this form of energy storage competitive with other systems were developed. One of the main problems related to flywheel energy storage is linked to the energy dissipations due to aerodynamic and bearing drag: Magnetic bearings, also due to their ability of working in vacuum, are thus intrinsically required for these applications.**

I. INTRODUCTION

Storing energy in the form of kinetic energy is an old idea and its applications in the last hundred twenty years were many. However, it not easy to define what we mean with *kinetic energy storage*: any rotating object stores energy in kinetic form and thus any machine containing rotating elements could be considered as an accumulator of kinetic energy. Going further along this way, any moving object is a kinetic energy accumulator, being immaterial whether its motion is translational or rotational.

It is only slightly better if we define a kinetic energy storage system as a device which contains an element that stores energy by rotating (a flywheel), without requiring the motion of the machine as a whole. Apart from the fact that devices that comply with this definition are very old, and some of them dating back from 6,000 years ago have been found.

Flywheels have been used for millennia to regularize the angular velocity of rotating elements, in particular in connection with the use of cranks, and their use became widespread with the introduction of reciprocating thermal engines, both steam or internal combustion engines[1].

However, the use of flywheels to regularize the rotational motion involves storage of energy for a very short period of time, usually linked with the device's rotational speed. To be more precise, the time the flywheel goes through a complete charge-discharge cycle depends on the time passing between two subsequent 'pushes' the rotating shaft receives from what supplies the force setting it in motion. The latter could be the foot of the potter in the most ancient applications of the potter wheel, or the piston in a reciprocating engine. This time could span from a few seconds in the potter wheel to a small fraction of a second (for instance, in a four strokes cycle single cylinder piston engine running at 3000 rpm it is of 40 ms).

It must also be noted that in many applications a specific flywheel (or rotating mass) was not even required to regularize the motion of a reciprocating engine: the huge translating mass of a steam locomotive was enough to store the kinetic energy required to regularize the motion of its rotating parts (the wheels).

It is thus possible to devise a criterion to distinguish between what is simply motion regularization and true energy storage in the form of kinetic energy: in the latter case the energy must be stored for a much longer time, and in particular it might be advanced the suggestion that this time must not be linked with the period of rotation of the flywheel itself and at any rate must be larger than the latter by some orders of magnitude.

One of the first applications in history which satisfies this requirement is the Howell torpedo (Fig. 1), built in 1888: a flywheel rotating initially at 21,000 rpm gave it a range of 1,500 m at 55 km/h [1]

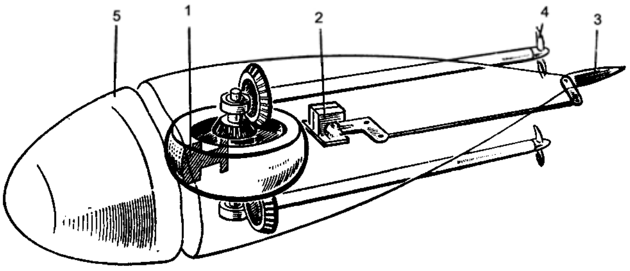

Figure 1. Flywheel torpedo built by Howell in 1888. 1) Flywheel, 2) steering mechanism, 3) rudder, 4) variable pitch propellers, 5) warhead.

The kinetic energy was stored for a time more than 35,000 times greater than the rotational period of the flywheel.

All the old applications of kinetic energy storage (for instance, the energy accumulator for a wind power plant designed by Ufimtsev in 1931 [1] and the Gyrobus built by Oerlikon in the 1960s [2]) shared this characteristics.

II. EFFICIENCY AND DRAG

Kinetic energy storage systems, like any other energy storage systems, are effective only if they are able to give back during the discharge a substantial amount of the energy they stored during the charge.

In the case of kinetic energy storage systems the losses that make it impossible to recover all the stored energy are mainly of two types: the drag torque on the flywheel (aerodynamic drag torque) and the drag torque of the bearings. Other losses, like the losses in the transmission, must be added.

To obtain the efficiency of the charge-discharge cycle the efficiency of the device that converts the energy must be accounted for. In the case of what is usually called a kinetic

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[1] Even some of the earliest electric motors worked on the same scheme: a coil operated a sort of 'piston' which set in rotation a shaft through a connecting rod and a crank. They needed a flywheel as well.

battery the energy is exchanged in the form of electric energy, so the efficiency of the electric motor (in the charge phase) and generator (in the discharge) must be accounted for.

Clearly, both the above mentioned losses act for all the time the energy is stored in the system and not only for the time in which the accumulator is charged or discharged, like the efficiency of the mechanical transmission or of the motor and the generator. This is much worse than what is typical of most other energy storage devices.

To reduce flywheel losses (aerodynamic losses) the only way is to have the flywheel to operate in a very low pressure container, although it may also help to use a low viscosity fluid. For this reason, all modern flywheel energy storage systems, in particular if the storage time is not short, operate in high vacuum, with all the difficulties this may involve.

Bearing losses might be even more serious and they affect much the efficiency of any flywheel energy storage system. Actually, the bearings were the main weak points of all old flywheel systems like that in Fig. 1, and, even if at that time rolling element bearings were much less common than today, they were a must in flywheel systems. Rolling element bearings have also a limited duration, which involves the need of bearing replacement as a part of the maintenance cycle.

It is possible to say that all flywheel storage system suffer from a self-discharge problem. A simple (and quite approximate) way to evaluate the seriousness of this problem is to evaluate the energy the flywheel accumulator loses during the standby phase. Assume that a flywheel accumulator is fully charged when the flywheel spins at a speed $\Omega_{\max}$ and fully discharged when it spins at speed $\Omega_{\min}$. Ratio $\alpha = \Omega_{\min}/\Omega_{\max}$ is the depth of discharge parameter.

Assume that the flywheel and bearing drag moment is $M(\Omega)$, and that the flywheel stores the energy for a time t, the speed loss is:

$$\Delta\Omega = \frac{1}{J\overline{(1/M)}}\, t \tag{1}$$

where

$$\overline{\left(\frac{1}{M}\right)} = \frac{1}{\Delta\Omega}\int_{\Omega_{\max}-\Delta\Omega}^{\Omega_{\max}} \frac{1}{M}\, d\Omega \tag{2}$$

is the average value of the reciprocal of the drag torque during slowing down and J is the moment of inertia of the flywheel plus the other elements which rotate together with it.

By introducing the energy density of the flywheel D, defined as the energy stored referred to the mass of the rotating elements of the system, the energy used to charge the kinetic accumulator (from its fully discharged to the fully charged state) and referred to the energy that can be extracted, is

$$e_{in} = \frac{1}{2} J\left(\Omega_{\max}^2 - \Omega_{\min}^2\right) = mD\left(1-\alpha^2\right) \tag{3}$$

The energy that can be extracted after time t is

$$e_{out} = \frac{1}{2} J\left[\left(\Omega_{\max} - \Delta\Omega\right)^2 - \Omega_{\min}^2\right] \tag{4}$$

With simple computations it is possible to compute the efficiency with which the flywheel can store the energy for time t

$$\eta = \frac{e_{out}}{e_{in}} = \frac{\left(1 - t\dfrac{1}{\overline{(1/M)}\sqrt{2DmJ}}\right)^2 - \alpha^2}{1-\alpha^2} \tag{5}$$

The efficiency reduces to 0, i.e. the flywheel accumulator self-discharges completely, at time t_{sd}

$$t_{sd} = \overline{(1/M)}\sqrt{2DmJ}\,(1-\alpha) = \overline{(1/M)}\, m\rho\sqrt{2D}\,(1-\alpha) \tag{6}$$

where ρ is the radius of inertia of the flywheel

By introducing the nondimensional time $t^* = t/t_{sd}$, the expression for the efficiency reduces to

$$\eta = \left(1-t^*\right)\left(1 - t^*\frac{1-\alpha}{1+\alpha}\right) \tag{7}$$

The efficiency is plotted as a function of the nondimensional time for some values of the depth of discharge in Fig. 2.

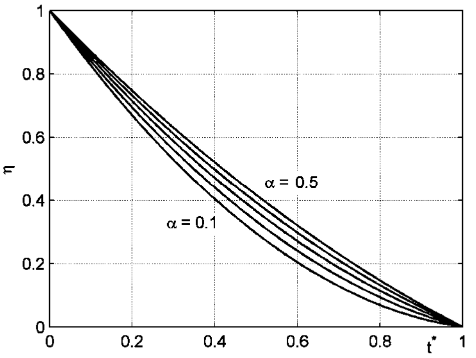

Figure 2. Efficiency of a flywheel system as a function of the nondimensional time t^* for various values of the depth of discharge α.

Eq. (6) may be misleading: if the drag moment M is a function of the speed, as it is usually the case, $\overline{(1/M)}$ depends on the speed range and hence on time t. The self-discharge time cannot be computed in closed form and, while Eq. (6) still holds, it cannot be used directly for computing t_{sd}.

Another point which must be stated is that the value of the efficiency so computed is just a storage efficiency: the overall charge-discharge efficiency is lower, since it should include also the efficiency during the charge and the discharge phases. If the system is left at idle between subsequent charge-discharge cycles, the energy losses at idle must be also accounted for and also the possibility that the flywheel speed goes below the minimum speed $\Omega_{\min}$, which implies that some energy must be spent to restore the minimum conditions.

The drag moment $M(\Omega)$ is the sum of several contributions. For the aerodynamic drag, an expression can be

$$M_a = \rho_g \Omega^2 r_o^5 C_M \tag{8}$$

where ρ_g is the density of the gas in the container and r_o is the outer radius of the flywheel [3]. The moment coefficient C_M is a function of at least 3 nondimensional parameters, the Reynolds number, the Mach number and the Knudsen number. Since these three numbers depend on the speed, the dependence of the aerodynamic drag moment on the speed is actually not quadratic, and the integral to obtain $\overline{(1/M)}$ must be performed numerically.

The Knudsen number is particularly important in high vacuum applications [4]. An expression for the drag torque in high vacuum (free molecular flow, Knudsen number > 10), valid only for a thin disc, is

$$M_a = \rho_g \Omega r_o^4 \sqrt{\frac{m_m}{2KT}} \tag{9}$$

where K is the Boltzman constant, T is the absolute temperature and m_m is the mass of the molecules, i.e. the molecular mass of the gas divided by the Avogadro number. The drag torque is in this case linear with the speed.

For the bearing drag several empirical formulae exist. For ball and roller bearings a formula that can be used is [3, 5]

$$M_b = C_1 mg + C_2 \Omega^{2/3} \tag{10}$$

where C_1 and C_2 are coefficient depending on the type and size of the bearings, on the direction of the load, the lubrication, and other factors.

For magnetic bearings an empirical formula is [6]

$$M_b = mg\left(C_1 + C_2 \Omega\right) \tag{11}$$

where C_1 and C_2 are empirical coefficients. This relationship dates back to the early developments of magnetic bearings, but it still can be used, provided that the two empirical coefficients are given updated values. It just approximates the dependence of drag with speed with a linear law.

Another type of drag linked with the bearing system, which is almost always overlooked, is the rotordynamic drag. Simply put, when a rotor spins in the supercritical mode, some bearing damping (nonrotating damping) is required to fight rotordynamic instability. Since the rotor spins in a more or less self-centered condition and cannot be perfectly balanced, the centers of the bearings have an orbital motion, which cause some energy dissipation which is seen as a further drag form. Rotordynamic drag has a strong increase when the rotor operates close to a critical speed, which may be of use when the rotor is free spinning, since it causes it to slow down below the critical speed, preventing it from operating for a long time in high vibration conditions. However, it increases with speed in the whole supercritical range.

In the case of a Jeffcott rotor with eccentricity ε and nonrotating damping coefficient c_n, the rotordynamic drag torque in the high superctitical range is asymptotically [7]

$$M_{rot} = \varepsilon^2 c_n \Omega \tag{12}$$

This drag may be high, particularly at high speed, if supercritical operation is chosen to relax the balancing requirements of the rotor, or in case strict balancing tolerances cannot be reached, as is the case with many composite material flywheels.

III. CRITICAL DESIGN POINTS

The difficulties to overcome in the design of flywheel storage systems had always been linked with:

- The high mass of the rotor, or better its low energy density
- The high flywheel (or aerodynamic) drag
- The high bearing drag

A further critical point was the need of a variable ratio transmission, in case the output of the storage system was mechanical, or of a mechanical-electric energy conversion when the output was electric.

Kinetic energy storage systems had a revival in the 1970s, after the energy crisis of 1973. With the increase of the price of oil and the forecasts of an impending drying out of the oil reserves, the research in the field of energy storage multiplied. It seemed that the perspectives of kinetic energy systems were bright and many research projects were started.

In particular, the three mentioned difficulties were thought to be easily manageable owing to some technological advancements:

- The use of composite materials and/or new geometries could increase, even substantially, the energy density of the flywheel
- Operation in high vacuum could reduce substantially the flywheel drag
- Magnetic bearings could allow to decrease substantially bearing drag.

The difficulties related with the energy input/output could be also improved, in particular with research in the field of variable ratio transmissions for mechanical solutions, and the striking progress in the field of power electronics could allow managing the power input/output in a completely sealed unit in case of electric solutions.

Some attempts were made to design variable inertia flywheels, with the aim of operating at a fixed speed and exchanging energy by varying the moment of inertia of the rotor instead of varying its speed. It is, however, possible to demonstrate that the mechanism producing the variation of the moment of inertia has a complexity and manages a power that are of the same magnitude than the device (transmission) that causes the speed to vary in conventional applications. As a consequence, variable inertia flywheels remained on the paper.

Some of these provisions reinforce each other, for instance using power electronics for a completely electrical transmission allows to completely seal the housing, without having a shaft connecting the flywheel to the outside world. This makes it much easier to have high vacuum, thus reducing aerodynamic drag.

However, most of them act in opposite ways, for instance to exploit high performance materials to improve the energy density implies running at higher speeds (at equal size of the device), which makes things much worse for the aerodynamic drag and the bearing problems. Increasing vacuum makes lubrication of standard bearings more difficult, and so on.

Above all these technical considerations there are economical considerations: kinetic energy storage systems are competing with energy accumulators of different types, mainly electrochemical batteries, and to be competitive they must not only show a better, or at least a comparable performance, but above all a lower cost. An exception may be those few applications like military or space applications where cost is not so important – or at least was not so important, since nowadays even those applications are much more cost-sensitive than in the past.

All these points were at the core of the revolution in the flywheel field which occurred starting from the beginning of the 1970s. At that time the idea that a large improvement of flywheel energy storage system was possible became quite widespread and it was a common opinion that flywheels would take over in many different applications, from hybrid vehicles (at that time seriously considered after a gap of 70 years from the first realizations of the 1900s), to stationary devices (mostly for renewable energy sources), from uninterruptible power supplies (UPS) for computers to aerospace applications, and so on.

The amount of research done at that time was impressive and most of the theoretical basis in the field date back to the 1970s. Molt of the references of the present paper date from those times, and most of what has been done later is at best implementation of what was then studied.

IV. SUPERFLYWHEELS OF THE 1970S

The confidence that high performance flywheels would change completely the prospects in the energy storage field was so widespread that a new term was introduced to designate these advanced flywheel system: **superflywheels**.

Superflywheels where characterized by

- a composite material structure, possibly with an unconventional shape,
- high vacuum operation,
- magnetic bearings
- and possibly some advanced mechanical or electric transmission

The idea that much better flywheels could be built using a composite structure was substantiated by a relationship yielding the maximum energy density a flywheel can attain:

$$\frac{e}{m} = K\frac{\sigma}{\rho_m} \tag{13}$$

where σ and ρ_m are respectively the stress present when storing the energy e and the material density, and K is a coefficient depending only on the flywheel shape, which can vary between 0.3 to 1.

To keep the costs compatible with the applications, many low-cost, high performance materials were suggested. Flywheels made of wood or even paper were seriously considered at that time, in particular for low cost applications.

However, in spite of all this work, the wide application of flywheel energy storage systems did not materialize, and this can be ascribed to a wide spectrum of reasons.

As a first point, many of these designs were unrealistic, or even basically flawed. Some configurations thus could never be tested or, if tested, didn't reach the performance their designers predicted. This was due to their geometry or design, to the material or both.

In other cases some overoptimistic assumption were made at the beginning of the design phase: the system could work, but never reached the predicted performance and their overall advantages over conventional systems vanished.

In particular, some confusion was made between the energy density of the flywheel and that of the accumulator and between the ultimate stress or the material and the stress that can be reached in operation, including the consideration of fatigue. To account for this a modification of Eq. (13) was proposed [3]:

$$\left(\frac{e}{m}\right)_{overall} = \alpha_1\alpha_2\alpha_3 K\frac{\sigma}{\rho_m} \tag{14}$$

where α_i are 3 coefficients smaller than unity which account for the realistically safe value of the stress, the depth of discharge and the ratio between the mass of the flywheel and that of the whole accumulator. The reduction due to these factors is easily by an order of magnitude or (much) more.

The disappointing outcome of many flywheel system was however linked in the majority of cases with the impossibility of reaching the cost objectives stated in the early design phase, in particular when the goal was that of building very low cost storage systems.

The introduction of new types of batteries, with much higher performance than the lead-acid batteries which were so common in the middle of the twentieth century, in term of energy density but even more of power density, was another good reason that hampered the diffusion of flywheels. Even in cases where this kind of energy storage system seem to have many advantages on other approaches like the KERS (Kinetic Energy Recovery System [8]) used on racing cars, the solution based on flywheels is less widespread than solutions based on batteries.

V. MAGNETIC SUSPENSIONS FOR FLYWHEELS

The problem of decreasing drag (aerodynamic and, above all, bearing) is an essential one for flywheel energy storage systems, in particular for cases where the energy must be stored for a time that is not very short. For this reason most advanced flywheels studied since the 1970s were designed to operate in high vacuum and incorporated magnetic bearings. Although magnetic bearings were not originated from studies aimed to store energy in flywheels, most of their earlier applications were connected with them [9, 10].

In general, flywheel systems are considered an ideal application for magnetic suspensions since they have relaxed specifications for what the suspension stiffness is concerned; this is particularly important since many advanced flywheel designs are characterized by intrinsic difficulties in achieving accurate balancing, compelling to resort to the self-centering occurring in the supercritical range. As already stated, in general this leads to higher rotordynamic losses.

Moreover, in stationary applications the only load applied to the flywheel is its own weight, which allows low stiffness operation without large and varying displacement of the rotor in the container. However, if the motor/generator is suspended together with the flywheel or the transmission system exerts forces on the latter, there are limitations to the bearing compliance which may become quite strict, in particular in case of applications characterized by high power density.

In case of applications on board of vehicles, inertia forces and gyroscopic moments due to the vehicle maneuvering are present and this may well pose strict limitations to the suspension compliance too.

All kind of magnetic bearings have been suggested for flywheel systems and most of them have been used at least on some prototype or demonstrator:

- Full 5-axes active suspensions
- Passive suspensions with at least one active axis
- Superconducting passive suspension

- Full passive suspensions stabilized by rotation (Levitron-style)
- Electrodynamic passive suspensions
- Magnetic/mechanical hybrid suspensions.

Generally speaking, each of them has its own advantages and there is a rationale under all choices. As a general rule, passive suspensions are often regarded as optimal for their low cost but usually are characterized by a low stiffness and low damping. The only possibility of having a fully passive suspension which is stable in the whole speed range is by resorting to superconducting levitation [11], which however needs low temperature operation and has particularly low stiffness and damping. High temperature superconductors seemed to be the solution to many problem, but they anyway require the use of liquid nitrogen (boiling point 77 K) or even lower temperatures to get higher performances.

Even if several designs of superconducting magnetic bearings have been developed and a number of prototypes of flywheel systems based on them have been built, this seems to be a technology limited to some niche applications.

The other fully passive technologies mentioned above require anyway external stabilization at low speed and have also other limitations, like for instance the relatively high bearing drag displayed by electrodynamic bearings. They too may be considered for niche applications.

Finally, hybrid mechanical-magnetic bearings in which the magnetic system acts as a load reliever for the mechanical bearings have several advantages, among which there is low cost and simple design, but they share with the traditional mechanical solutions the need of lubrication and a bearing drag which is higher than that of magnetic bearings (although less than purely mechanical solutions due to the lower mechanical bearings load). Solutions in which the flywheel axis is vertical and the passive magnetic bearing supports the axial load while the mechanical bearings give stability and deal with dynamic loads and unbalance have been used several times.

Active magnetic bearings, or a suspension system with at least some active axis, can be considered as the most suitable solution for what performance is concerned, but in some cases they can lead to costs which are higher than what can be accepted for low cost applications. The number of papers published on this subject is large, and many ideas have been forwarded and tested on demonstrators and full scale prototypes to lower the bearing drag, improve self balancing, increase the stiffness, make it easier to cross the critical speeds, etc.

Active magnetic bearings can be tailored on the application, allowing to solve the technical problems which still face the designer of flywheel systems. Whether the solution is also feasible from the economical viewpoint depends on the particular application.

VI. EXAMPLE 1

Consider a flywheel system based on 'pre-1970' technology: a 1600 mm diameter 1500 kg steel flywheel connected to a motor-generator whose rotor has a mass of 250 kg, storing 3.3×10^7 J = 9.15 kWh at a top speed of 3000 rpm. The minimum speed is 1500 rpm. This system is similar to the one that was installed on the Gyrobus city bus and is representative of 1950-1960 technology. It is thus possible to compute that the moment and radius of inertia are respectively of 668.7 kg m^2 and 668 mm.

The energy density of the flywheel alone is 6.11 Wh/kg but, if the whole accumulator is accounted for, a value of 3 or 4 Wh/kg is a realistic one.

Assuming that the flywheel operates in a hydrogen atmosphere at a pressure of 10 Torr, a practice then quite common to reduce the gas density while allowing a certain cooling to the motor/generator, the Reynolds, Mach and Knudsen numbers are respectively 2.44×10^4, 1.17×10^{-5} and 0.193. The flow around the flywheel is thus laminar, subsonic and not free-molecular.

The aerodynamic drag at top speed is about 0.88 Nm, and reduces to 0.31 Nm at the minimum speed. The self-discharge time due to aerodynamic drag is quite long, namely 55 hours.

In this case the bearing drag is much higher: assuming a pack of two preloaded angular contact ball bearings plus a deep grove bearing, a first approximation evaluation yields a constant bearing drag of 2 Nm. The total discharge time reduces then to about 11 hours. The storage efficiency as a function of the storage time is reported in Fig. 3.

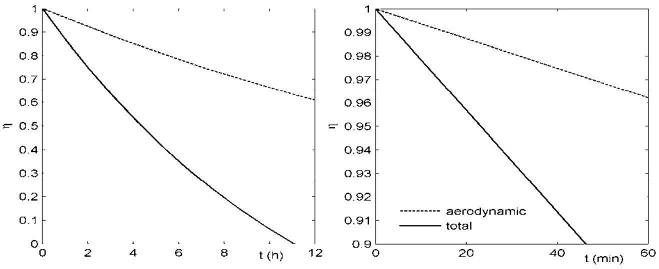

Figure 3. Efficiency of the flywheel system of Example 1 as a function of time; the zone of the plot related to short discharge times is repoorted on the figure on the right. The curves showing the effects of aerodynamic and total drag are reported.

It must be remembered that the actual efficiency is much lower, since also the drag during charging and discharging must be accounted for and other losses, like transmission losses and electric losses at idle must be included in the computation. The example shows however that a flywheel system of this kind can be used only for storing energy for quite a short time, of the order of a few tens of minutes as a maximum. It is also clear that with this technology the bearing drag is dominant, even in the case the flywheel operates in a partial vacuum.

VII. EXAMPLE 2

Consider now a 'modern' flywheel system, able to store the same quantity of energy, but using a CRP unidirectional composite. The cylindrical flywheel has an outer and inner diameter of 609 and 487 mm, a length of 1182 mm, a mass of 198 kg and a moment of inertia of 15.05 kg m^2. At a maximum speed of 20,000 rpm it stores 3.3×10^7 J = 9.15 kWh, with an energy density of 46.3 Wh/kg.

The energy density of the whole accumulator is much lower, and a value of 20 Wh/kg is a realistic one.

Assuming that the flywheel operates in air at very low pressure, namely 10^{-3} Torr, the Reynolds, Mach and Knudsen numbers are respectively 16.9, 1.86 and 0.165. The flow around the flywheel is thus laminar and supersonic. The Knudsen number is already in a region in which some free molecular flow effect start to be felt, but this can be neglected as a first approximation.

The aerodynamic drag at top speed, computed taking into account the flywheel length in an approximate way, is about 0.18 Nm, and reduces to 0.06 Nm at the minimum speed. The self-discharge time due to aerodynamic drag is quite long, namely about 40 hours.

It is quite difficult to state the bearing drag without specifying the details of their design, however using eq. (11) with reasonable values of the coefficient a bearing drag of 0.17 Nm at top speed, slightly smaller than the aerodynamic drag, can be evaluated. At low speed the bearing drag is larger than that due to air drag. The total discharge time is thus of about 18 hours. The storage efficiency as a function of the storage time is reported in Fig. 4.

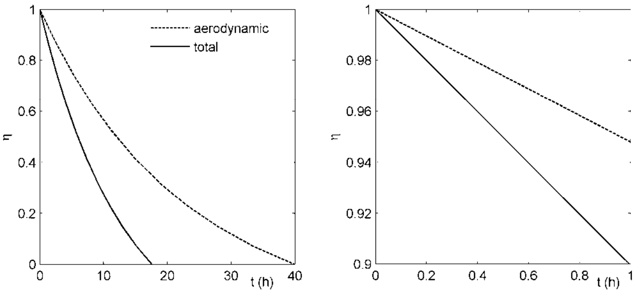

Figure 4. As Fig. 3, but related to Example 2.

VIII. CONCLUSIONS

Almost half a century has passed since when the research in the field of advanced flywheel energy storage systems has started. A large number of studies were performed and many prototypes were built with mixed success, but the wide diffusion of these systems on the market never materialized.

Some of the possible reasons may well be due to psycological factors: kinetic energy storage systems are something going against one of the most established trends of modern technology: the shift from rotating machinery technology to static machinery. An example of the same trend is the substitution of rotating converters (frequency converters and ac/dc converters) with converters based on power electronics. Also, rotating converters had a good flywheel effect, being able to use the energy stored as kinetic energy to smooth load variations.

Owing to the very high speeds (not only angular velocity but above all peripheral velocity), rotating elements compels to use high vacuum and complex magnetic suspension systems. This is perceived as a useless complication, causing also an unnecessary cost increase at least if the performance achieved is not much higher than that achievable with competing systems. When flywheels had to compete with lead acid and NiCd batteries this was considered well justified, while now the high energy and power density of advanced batteries make them less competitive.

Another point that may be labeled more as subjective than objective is safety. High speed rotating machines are perceived as quite dangerous, and the fact that failure modes of advanced, composite material, flywheels may well be more benign than those of solid steel flywheels (or at least they are advertised as such) doesn't change substantially the problem. It must be remembered that when a flywheel fails, there are not only the fragments to contain, but also the angular momentum to dissipate, which is difficult, being immaterial the type of flywheel. And that carbon dust, resulting from the flywheel of an advanced flywheel, ignites very easily once the container fails. Some severe accidents caused by the explosion of an energy storage flywheel [see, for instance, 12] make things worse. It is true that also advanced batteries have their own risks, and fuel tanks perhaps even more, but we are used to the latter and to the safety precautions allowing to use safely fuel. A crash between vehicles carrying a fast spinning flywheel or an advanced battery on board involves dangers we are not used to and thus we fear more. Many things in modern technology are "dangerous", and we have learned to deal with them safely, and there is no doubt that also flywheels may be made safe, but this requires much R&D work.

Magnetic bearing suffer themselves of this problem, as shown by the requirement of installing backup bearings. When the technology will be fully mature it is likely that the safety issue will be dealt with in another way, apart from the fact that it is unlikely that a touchdown bearing can guarantee a safe slowdown of a high speed flywheel in which a large quantity of energy is stored.

Several other technological issues have prevented flywheel energy storage systems from becoming common, one of which being the issues linked with the transmission: by their own nature flywheel energy storage supply a mechanical power output with a speed strictly linked with its state of charge (variable inertia flywheels have little definite advantage in this area). Variable ratio mechanical transmissions able to transfer a large power with a wide speed ratio range and good efficiency didn't materialize and electrical transmission, which on the contrary had striking advancements owing to brushless motors and power electronics, are in direct competition with all electric systems based on advanced electrochemical batteries.

It is thus likely that flywheel energy storage will be restricted to some niche applications, and that their success will be strictly dependent on a suitable set of magnetic bearings, the only technology able to allow storing energy in the mechanical form efficiently for periods of times comparable with those of other energy accumulators.

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