Flywheel energy storage: principles and possibilities

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Abstract
The main problems of contemporary energy-hungry society are steep fluctuations in consuming: short-time power peaks are mirrored in the overdimensioned infrastructure. Applications are operating at underload most of the time – a circumstance, not favourable for economic reasons. The idea of load levelling by the means of storage buffers is well known, but hard to implement, especially in kWh and MW ranges. One of the oldest storage technologies – the flywheel – has made a challenge to this hardship, having considerable perspectives in increasing the efficiency and reliability of power supply alongside the ultracapacitors.

Keywords
Energy storage, buffering, levelling, flywheel, electomechanical battery, electric traction.

Introduction
The levelling and buffering problems do not exist in public transmission and distribution networks only. In electric traction high power is needed during acceleration, in steady state remarkably less, about 10% of the maximum. In the past, the surplus of energy generated during braking was dissipated as heat on resistances, today it is converted back to electricity by changing the traction drive over into generator mode. The economised energy must be stored for being available for the next acceleration. Traditionally the energy is stored electrochemically inside batteries using various technologies (VRLA, Ni-Cd, Ni-MH, Li-Io etc); the main drawback being that peak power is limited due to internal resistance. During ageing, the batteries’ internal resistance increases, their lifetime does not exceed 10 years as a rule. Over the last decade, new alternative energy storage technologies have been emerging to substitute conventional electrochemical solutions. Most remarkable among them are superconducting magnetic energy storage (SMES), hydraulic or pneumatic storage applications. This paper is dedicated to the revival of the flywheel as a complex electomechanical battery with power electronics and control circuits.

1 History
The principle of storing kinetic energy was known in ancient cultures already, potter’s wheel can be brought as an example. After steam engine was invented, the flywheel began to smooth periodically changing torque and assist to overcome the dead point in piston’s movement sequence. In internal combustion engines the flywheel has a similar role in transferring pistons’ movements via the crankshaft to the transmission. The need for greater amount of storable energy by small angular velocities caused the diameters to grow. Consequently severe accidents happened when centrifugal forces exceeded the mechanical strength of forged steel.

In 1889 the US Navy ordered 50 torpedoes designed by John A. Howell. The Howell torpedo was driven by a 60 kg flywheel spun to 10,000 rpm prior to launch by a steam turbine mounted on the tube and was able to hit its target over 360 m distance. Two variable pitch propellers on parallel shafts were driven bevel gearing from the flywheel. The diminishing speed was compensated for by propeller pitch to maintain a 25 knot (12.8 m/s) velocity.

By 1931 Anatoliy Ufimtsev had constructed the first wind power station in equipped with flywheel buffer in Kursk, Russia, supplying electricity to his workshop as well as neighbouring households.

Before the introduction of battery-based uninterruptible power supplies, the steel flywheels coupled with motor/generator sets were the only option to achieve back-up for critical loads (Fig. 1).

![Fig. 1: The traditional flywheel set](image)

The increase in rotary inertia and hence stored kinetic energy allowed longer ride-through during utility power interruptions. The effective increase in run time for such systems rarely exceeded a few seconds at rated load, corresponding to delivery of less than 5% of the additional stored energy from the wheel. Delivery of more energy would result in reduced rotational speed, and hence reduced
electrical frequency, which was usually unacceptable. Although these systems provided adequate protection against a large segment of power sags and outages, they were unable to sustain power for a full re-closure event, or allow sufficient ride-through for the start of a typical standby generator.

One can extend the power delivery time of the basic system by making a few modifications to the design. The inherent frequency and voltage reduction that accompanies a decelerating generator is unacceptable for virtually all loads. By inserting a rectifier after the generator, the system is capable of delivering approximately 75% of the flywheel's energy as usable DC power for a substantial increase in ride-through time. The DC power then must be filtered and inverted back to AC. Adding a variable-speed drive (VSD) to the system allows efficient motoring of a large inertia from lower rotational speeds, enabling a smaller motor to be used for this standby power source. As is evident in Fig. 2, the effective increase in ride-through offered by the modified flywheel configuration offers substantially more protection than the older version of the traditional flywheel. However, this added run time comes with a higher price and also requires several additional components and more floor space.

In the early 1950's, a so-called "gyrobus" was introduced by the Swiss company Oerlikon, having a Ø1.5 m and 1500 kg flywheel accelerated up to 3,000 rpm by an electric motor on its axis. The power supply came from overhead points at the bus stops, located at 4...6 km range from each other. Between stops, the motor was used as a generator, driven by the spinning flywheel, to run a traction drive which drove the bus before the flywheel's speed decreased to 1,500 rpm. Generator's output was controlled by the driver switching the poles and adjusting excitation.

Regarding aerospace industry, prior to its usage as energy storage buffer the flywheel played an important role in satellite position control thanks to gyroscopic forces created by high angular velocities.

2 Components
Modern flywheel storage systems comprise of an electrical machine linked to a rotating mass. Electrical energy is converted into kinetic energy of rapidly rotating compact rotor in minimal friction environment. If short-time back-up supply is needed, i.e. in the case of mains voltage loss or fluctuations, the inertia preserves the rotor's rotation and the kinetic energy is converted back to electricity. Motor/generator parameters are selected taking into account the need for longer back-up times or maximal delivered power respectively. To minimise friction, magnetic bearings are used, air drag is eliminated by creating vacuum inside the housing. Output parameters are sustained and regulated by integrated static switches.

![Fig. 2: The improved flywheel storage system](image)

The main components of the system (Fig. 3):
1. flywheel,
2. electrical machine,
3. magnetic bearings,
4. vacuum enclosure.

Cooling system, decompression pump, safety devices, control and power electronic applications are not depicted.

![Fig. 3: Modern compact flywheel](image)

The described flywheel systems have been in serial production for years, mainly in the USA. As market leaders, Pentadyne, Active Power and Beacon Power can be mentioned, in Europe also RWE Piller.

The advantages of compact flywheel systems:
- high output power,
- compact,
- high efficiency,
- low maintenance costs,
- low aerodynamic noise.

Disadvantages:
- safety concerns,
- high material costs, including the magnetic bearings,
- not fully developed technologies.
2.1 The Flywheel

The kinetic energy of a rotating body can be calculated using the formula

\[ W_k = \frac{J\omega^2}{2} \quad (2.1) \]

where \( J \) – momentum of inertia and \( \omega \) – angular velocity.

Since the stored energy in a flywheel is proportional to the square of its rotational speed, the obvious method for maximising stored energy is to push the speed of the flywheel rather than increasing the momentum of inertia. The latter, in turn, is defined by the flywheel's mass and geometrical shape:

\[ J = kmr^2 \quad (2.2) \]

where \( m \) – mass, \( r \) – radius and \( k \) – shape factor.

The specific energy of steel flywheels is relatively poor between 8...13 Wh/kg limits, lighter titanium, aluminium and magnesium alloys store 50% more energy per mass unit before bursting. That is why alternative materials have been explored for flywheel manufacturing, epoxy resin and carbon fiber composites have been proven to be perspective. Surpassing steel around 5 times in specific energy they act more sustainably in failure situations, bursting into many small particles instead of a few big fragments. The use of magnetic bearings has put the rotational speeds well over 100,000 rpm limit, with tip speeds in excess of 1,000 m/s. The problems emerging at such parameters are mainly related to centrifugal forces affecting the permanent magnets on rotor's surface as well as removing dissipated heat from vacuum environment.

2.2 The Electrical Machine

The electrical machine, sometimes also referred as motor/generator, must operate at very high revolutions and maintain acceptable efficiency over the whole speed range. While the most easily controlled DC machine cannot be used due to rapid wear of brushes and heat dissipation on the contact surfaces, permanent magnet synchronous machines prevail, functioning equally effectively in both motor and generator modes.

As mentioned before, the permanent magnets on the rotor are subjected to strong centrifugal forces, presenting additional requirements for the construction. One solution is to change for external rotor design; the Dynastore project in Germany has paid attention to switched reluctance machines (SRMs), which lack both rotor windings and permanent magnets. The wider application of reluctance machines was made possible thanks to the developments in power electronics, enabling to improve the efficiency and power factor.

2.3 The Bearings

The magnetic bearings are intended to reduce the load of mechanical bearings or to replace them at all. Essentially they can be either passive based upon permanent magnets, active with controlled electromagnets or a combination of both, providing frictionless suspension. The air gap \( \delta \) between the bearing and rotor (Fig. 4) excludes any friction between moving details.

In the case of current rupture the magnetic field ceases momentarily, therefore mechanical back-up bearings must be accounted to carry the loads until the flywheel is fully stopped.

2.4 Power Converters and Controller

In case of buffering energy in AC networks, the three-phase mains voltage is rectified and inverted back over DC link to alternating current with parameters appropriate for drive's operation. When connected to a DC grid, as in traction applications, the system consists of one two-quadrant converter only. Both rectifier and inverter must be bi-directional to enable regenerative braking. In generator mode, the converter has to keep the output voltage constant while the speed decreases. As power semiconductors, mostly IGBTs with PWM control are applied.

The controller's task is data acquisition and adjustment of output parameters. The values to be set are e.g. rotational speed, current, voltage and phase angle as well as power demand on the load side. The use of magnetic bearings necessitates determination of rotor's position for field adjustments. Based upon these data, the processor calculates control signals for static switches.

The monitoring apparatus has to react to any thinkable disturbances and to halt the system when necessary. The disturbances may be windings' overheating, cooling system malfunction, exceeding the maximal rotational speed, bearing or flywheel damages.
The supply of electrical urban public transportation takes place from medium voltage network over rectifying substations with 600 V DC voltages. The traction grid must withstand peak currents, occurring during accelerations, returning braking energy is not always possible while accelerating vehicles are not present on the same line section. Peak loads and power losses can be remarkably diminished by energy buffering (Fig. 6).

The flywheel buffers are connected either to substation's busbars or to a connection point on the traction grid in a special weather-proof enclosure. As control parameters, actual voltage and current values acquired from measuring instruments inside the substation are used. Using these results together with flywheel's angular velocity the controller calculates available stored energy with demanded output power and drives the static switches accordingly.

The recharge begins after substation's load current has fallen under predefined lower limit. The number of revolutions and medium traction current give a basis for controller's charging current calculation, whereby substation's load must not exceed allowable upper value. The recharging current is usually taken smaller than discharging current, therefore the load on medium voltage network does not increase remarkably during steady operation. The charging power is calculated on the consideration that enough energy is stored before the next engagement.

The rosseta Technik GmbH company in Rosslau, Germany, has already designed and applied flywheels for trams’ braking energy buffering. The test results have shown reduction of 15 minutes peak loads by 20% and hourly energy savings by 27%.

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<tr>
<th></th>
<th>Flywheel</th>
<th>Ultracaps</th>
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<tbody>
<tr>
<td>Specific energy [Wh/kg]</td>
<td>5.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Specific power [W/kg]</td>
<td>320</td>
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<td>Recharge/discharge cycles</td>
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<tr>
<td>Weight [kg]</td>
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Table 1: comparison between 300 kW, 6 kWh energy storage options

Conclusion

In this report, the main characteristics and an application possibility of flywheel energy storage were described. Undoubtedly there are many other fields where flywheels may come into action, including buffering in wind and photovoltaic power stations. The design and construction of flywheel energy storage systems is an interdisciplinary matter, involving both electrical and mechanical sides assisted by fundamental sciences. The main competitor to the flywheel is ultracapacitor (see Table 1), both excelling in different aspects and applications. Which of them shall prevail, is up to the attention paid to R&D.

References