A MECHANICAL BATTERY FOR POWER QUALITY
FLYWHEEL ENERGY STORAGE

Bryan B. Plater
Active Power
11525 Stonehollow Dr.
Austin, TX 78758
512-836-6464

Abstract

The concept of employing a rotating mass to store and deliver useful electrical power has been practiced for decades. However, until recently, no more than a small fraction of the potential energy from a flywheel could be extracted and delivered in an acceptable frequency range for the electrical load being supported.

By delivering DC power from a flywheel-generator and relying on power electronic inverter systems to regulate frequency, the amount of useful energy extractable from the momentum of the wheel has improved dramatically. This paper reviews the various technologies that have been developed to increase the amount viable energy that can be transferred from a flywheel mass to an electrical load and describes the innovative techniques used by one flywheel system to enable an extremely power-dense machine. Also discussed are the application of these devices to uninterruptible power supply (UPS) systems and the potential benefits of employing flywheel energy storage as part of the power quality solution in various system configurations.

Momentum, trusted energy

In general, the concept of storing energy in the form of a rotating mass is well understood and viewed as a reliable source for power delivery. The practice of including additional mass to a motor-generator set feeding a critical electrical load is one of the earliest forms used to achieve substantial gains in power quality. By adding a steel wheel to the system, one is able to increase the rotary inertia and gain longer ride-through and limit the interruptions a critical load might otherwise experience.

However, without adding incredible amounts of mass to a particular system, the traditional flywheel typically provides an effective increase in run time of less than one second. Only 5% of the additional stored energy from the wheel is used. As a direct coupled system, taking additional energy from the wheel effectively reduces the rotational speed to the attached generator and hence the electrical frequency of the generator output. Although these traditional systems provide improved protection against a substantial portion of power quality problems, they are unable to sustain power for a full re-closure event, extended power sags, or ride-through to the start of a typical standby engine-generator.

Extending ride-through, DC power

As was alluded above, the only means to increase the effective power delivery of a mechanically connected system is to add more mass. Substantial increases in mass can cause problems by complicating the required structural support, increasing the bearing wear and lowering of the efficiency of the system, and still may not enable the ride-through time desired.

Recognizing that the inherent frequency and voltage reduction that accompanies a decelerating generator is unacceptable for virtually all loads, several entities made the decision to provide DC power from the flywheel, enabling a significant improvement of the usable energy delivered by a mechanical system. Once the system is independent of frequency, not only can more energy be delivered from the wheel, but, potentially, more energy can be stored by the same wheel through increased rotational speed.

Low-speed flywheel

A simple, but expensive means of employing this concept is by inserting a rectifier after the generator, enabling the system to deliver approximately 75% of the flywheel's energy as usable DC power for a substantial increase in ride-through time. In such a configuration, the system is much like a battery so that the DC power then must be filtered and inverted back to AC power at 60 Hz (or other appropriate frequency). Adding a variable-speed drive 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.

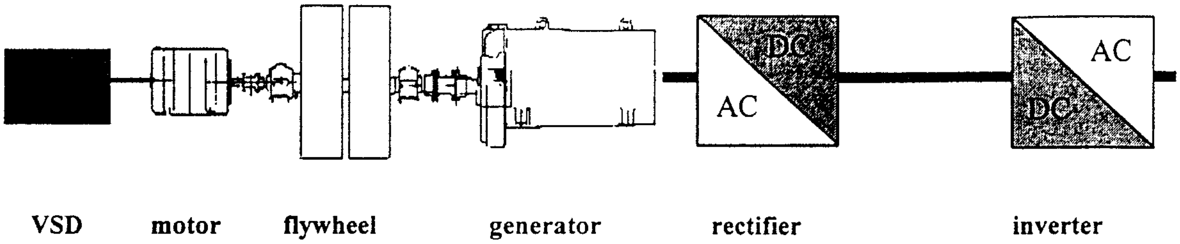

Figure 1: Traditional flywheel with variable-speed drive and rectification/inversion electronics

As is evident in **Figure 1,** the effective increase in ride-through offered by the modified flywheel configuration offers substantially more useful power delivery than the older version of the traditional flywheel. However, this added run time comes with higher cost and extra floor space due to requirement of several additional components to make the system function.

High-speed flywheel

In an effort to achieve higher energy and power densities and take advantage of modern composite material and power electronics technologies, many designers have attempted to develop compact flywheel batteries capable of extremely high "tip speeds" (linear velocity at outside radius of the flywheel). Until recently, the targeted applications for these composite flywheel systems have been electric or hybrid-electric vehicles and satellite momentum control. Invariably, these vehicular applications demand maximum stored energy and delivered power with extreme constraints on system weight and volume.

Since the stored energy in a flywheel is proportional to the square of its rotational speed, the obvious method for maximizing stored energy is to push the speed of the flywheel. Of course, all designs have a limiting speed, which is set by the stresses developed within the wheel due to inertial loads that are also proportional to the square of rotational speed. Composite wheels weigh less, and hence develop lower inertial loads at a given speed. In addition, high-tech composites are often stronger than conventional engineering metals. This combination of high strength and low weight enables extremely high tip speeds related to conventional wheels.

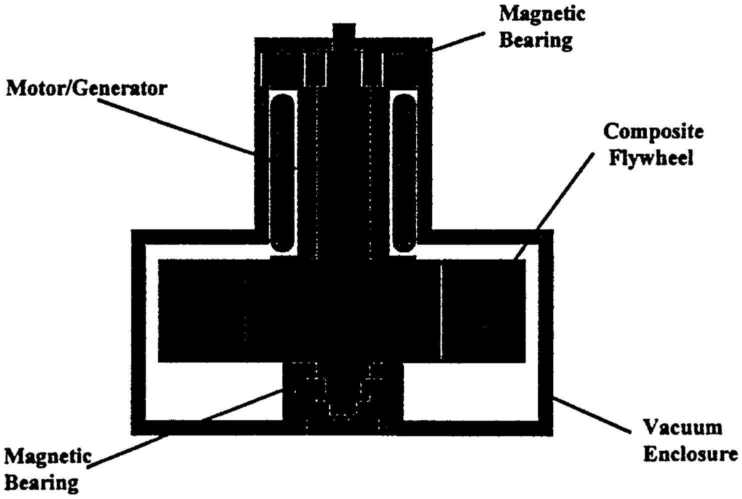

Figure 2: Diagram of high-speed flywheel

The ultrahigh rotational speeds that are required to store significant kinetic energy in these systems virtually rule out the use of conventional mechanical bearings. Instead, most systems run on magnetic bearings to "levitate" a rotor, eliminating the frictional losses inherent in rolling element and fluid film bearings. The system operates in a vacuum in order to eliminate windage losses and noise, but the presence of a vacuum introduces complications in removal of heat on the rotor and bearings. In addition, active magnetic bearings are inherently unstable, and require sophisticated computer control to maintain levitation.

The integrated generator of these systems is usually a rotating-field design, with the magnetic field supplied by rare-earth permanent magnets. Since the specific strength of these magnets is typically just fractions of that of the composite flywheel, they must spin at much lower tip speeds; in other words, they must be placed very near the hub of the flywheel. This compromises the power density of the generator. An alternative is to mount them closer to the outer radius of the wheel, but contain their inertial loads with the composite wheel itself. Obviously, this forces the designer to either de-rate the machine speed, or operate closer to the stress limit of the system, thus compromising safety. As in the case of the traditional flywheel that is coupled to an existing motor/generator set, these systems include significant electronics for rectification, filtering, and inversion electronics to allow delivery of a large percentage of stored energy.

Fully integrated flywheel

Employing some of the same principles used in the high-speed flywheel systems with a focus on the requirements for the power quality marketplace, a low-cost, high-performance and safe system has been developed. The fully integrated system is achieved with conventional material of a forged steel rotor that is the one active piece of the motor, generator and flywheel mass.

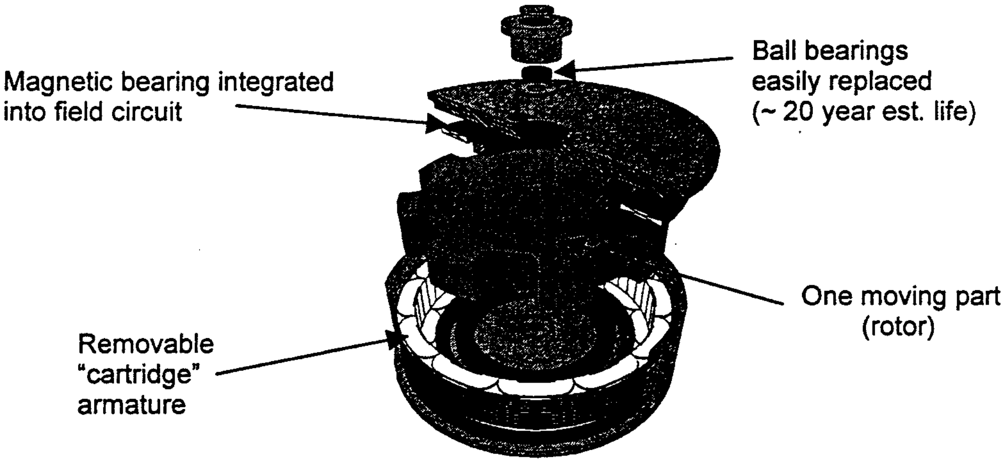

Figure 3: Exploded view of fully integrated flywheel

The integrated motor/generator/flywheel system that is shown above capable of storing and delivering up to 400 kW of DC power to the DC buss of a UPS or other DC to AC conversion system. The flywheel stores energy as angular momentum in a single piece forged steel rotor rotating in a rough vacuum. The motor, generator and storage functions are all performed by the same stator and rotor structure. Optical sensors control the motoring commutation. There are no permanent magnets used, nor are there coils or magnets on the rotor. No brushes are employed so that the bearings are the only point of potential wear. A magnetic bearing that is integral with the motor/generator field coil structure supports most of the rotor weight. This enables the mechanical bearings to be optimally loaded and greatly extends bearing life.

The field coil (arrow pointing to field circuit) provides current to magnetize the teeth of the steel rotor which pass the copper coils imbedded in the armature to generate power. As the RPM of the flywheel slows through delivery of energy, the field current is increased to raise the magnetic flux in the air gap, thus keeping output power constant through the entire RPM range of the flywheel. The wheel spins in a vacuum to minimize windage losses and noise.

Unlike the high-speed flywheel system, which must neck-down the diameter of the generator to preserve permanent magnets employed, the full length of a fully integrated flywheel can be used to generate power (the teeth of the rotor are magnetized and therefore can withstand higher tip-speeds). The result is an extremely power-dense electromechanical machine.

Applications of flywheel batteries

Flywheel energy storage systems now can deliver a substantial portion of their stored energy providing DC power to some sort of conversion system, typically a UPS. The most compelling application of flywheels are for short-duration power delivery of under a few minutes, for relatively low energy high power requirements. In the power quality market, a substantial portion of the power delivery problem is sags and outages for a few seconds or finding the appropriate vehicle for providing immediate power until a alternative to the normal utility power can be brought online.

Continuous Power

In many circumstances, the end user of critical power has a strong desire to eliminate the requirement for electrochemical batteries due to environmental restrictions, maintenance concerns and/or limited space. If the power quality configuration includes a standby engine/generator for long-term protection, a flywheel energy storage system may be well suited for providing power until the start and synchronization of the genset. Some flywheel systems may also deliver a means to provide the starting power for the engine to make a true alternative to traditional batteries in a continuous power solution.

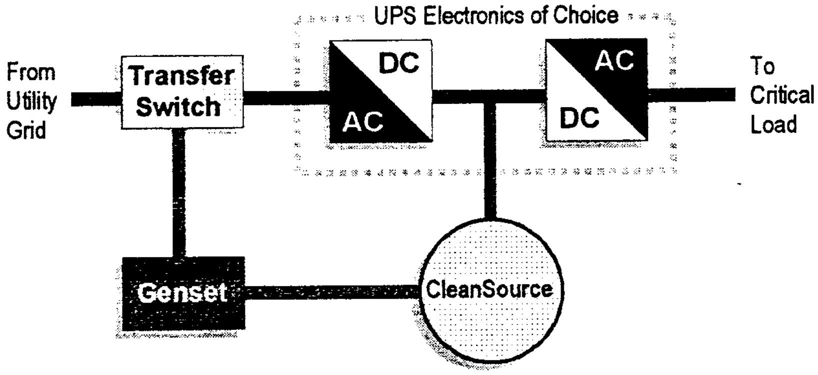

Figure 4: Continuous power solution

Power Quality Improvement

Due to the phenomenon of the vast majority of power quality events having a duration of only a few seconds, some power users have the opportunity to improve the quality of their power in all but long-term outage situations with minimal cost and space outlays. Batch or process manufacturing sites with a history of short-term power glitches or sags (which have remained unprotected due to the high costs or space requirements of traditional energy storage) are ideal applications for high-power flywheel systems.

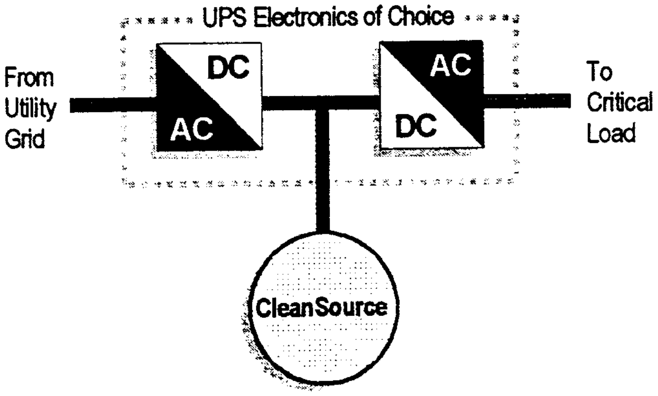

Figure 5: Glitch protection configuration

Battery Isolation and Redundancy

One of the primary determinants of electrochemical battery life is the number of times the cell is discharged, the battery life being inversely proportional to the number of discharge events. A flywheel battery is an effective means of protecting a chemical battery string with a small and durable package. The flywheel not only easily handles the vast majority of power quality events, but acts as a redundant DC power source in times of chemical battery maintenance or recharge.

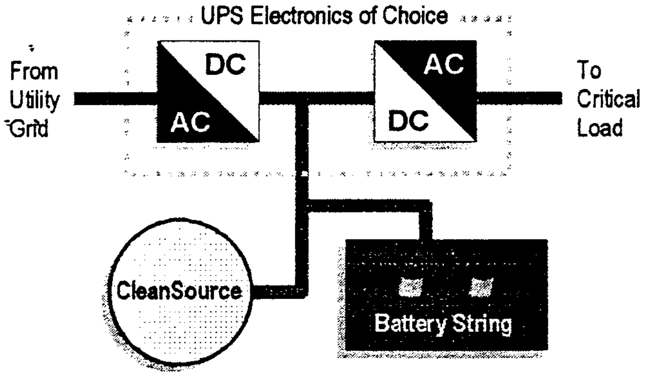

Figure 6: Battery Hardening and Isolation

Conclusion

By delivering DC power, flywheel systems are now able to provide a far greater percentage of their stored energy in useful form to an electrical load. These systems are particularly well suited for applications requiring short duration high power delivery. In power quality applications, the merits of a flywheel's small footprint, low maintenance and long life make these mechanical systems a viable alternative or supplement to traditional chemical energy storage.