Third Generation Flywheels For High Power Electricity Storage

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ABSTRACT: First generation flywheels of bulk material such as steel can mass tens of tons, but have low energy storage density. Second generation flywheels of composite materials have higher energy storage density but limited mass due to structural and stability limitations. LaunchPoint is developing high energy third generation flywheels – "Power Rings" – using radial gap magnetic bearings to levitate thin-walled composite hoops rotated at high speed to store kinetic energy. Power levels exceeding 50 megawatts and electricity storage capacities exceeding 5 megawatt-hours appear technically feasible and economically attractive. Power Rings can be used to decrease the peak power requirements of electric transportation systems by supplying intermittent high power for vehicles such as maglev trains. They can also store braking energy, isolate the power grid from surges and spikes, reduce the incidence of transportation system power outages, and provide back-up power in case of blackouts.

1 INTRODUCTION

In 1973, Dr. Richard Post of Lawrence Livermore National Laboratory proposed the construction of 200-ton, 10-megawatt-hour composite flywheels (Post 1973) to provide electricity storage for the US power grid. Unfortunately, achieving dynamic stability and structural integrity in composite flywheels proved far more difficult and costly than expected. The largest commercial units constructed to date are 400 times smaller than those Dr. Post envisioned — in spite of a critical need and a huge potential market.

Now, discoveries made during the course of a magnetic levitation transportation project have finally opened the door to construction of utility-scale flywheel electricity storage systems. We call these devices “Power Rings”. Figure 1 shows what a 400 kilowatt-hour Power Ring might look like.

LaunchPoint began development of Power Ring technology in 2002, under contract to the US Navy, with a study of the potential for short duration, very high power units. This was followed by a contract in 2003 from the New York State Energy R&D Authority (NYSERDA) to design a long duration electricity storage unit for utility applications. These contracts enabled detailed analysis of the Power Ring concept, and led to additional development contracts from the Department of Energy and the National Science Foundation, which are in progress now (2006).

Figure 1. A 400 kWh Power Ring

2 ELECTRICITY STORAGE TECHNOLOGIES

Technologies such as pumped hydro, compressed air energy storage (CAES), batteries, fuel cells, superconducting magnetic energy storage (SMES), ultracapacitors (or supercapacitors), and flywheels can all be used to provide electricity storage. Flywheels, SMES, and ultracapacitors all cost too much for use in large installations. Fuel cells and flow batteries show promise but are also projected to be expensive. Lead-acid batteries are used in small systems, such as uninterruptible power supplies, and a few moderately large installations. Costs, concerns regarding toxic materials, sheer mass, and space requirements prevent their widespread use in large installations.

CAES systems can be scaled up to large capacities, but need a fuel supply and underground compressed air storage caverns or land area for compressed air storage pipelines. They are similar to turbine power plants, i.e. large and noisy, making them unsuitable for many areas. They also have a cold spin-up time of 15 minutes, making them impractical for some applications.

Pumped hydro was the premier storage system for decades, with over 22 gigawatts of capacity installed in the US and over 30 gigawatts in Japan (Bradshaw 2000). Capital costs for existing plants were low when they were constructed – \$250/kW for a Tennessee Valley Authority installation in the early 1980s and \$800/kW for the Rocky Mountain Pumped Storage facility constructed near Rome, Georgia in the early 1990s – but are now estimated to be \$1,100-\$2,000/kW, making them economically much less attractive. A 1600 MW system completed in Japan in 2001 cost \$3.2 billion. Prospects for additional pumped hydro facilities in many countries are limited. The best sites have already been used and the remaining sites are remote, requiring new transmission lines. Reservoir construction also presents major environmental impact issues.

Flywheels of various forms have been used in industry for hundreds of years or more, and both first generation (iron or steel) and second generation (composite) flywheels are now used for electricity storage. Power costs for commercial flywheels are higher than some other energy storage technologies, but data from the Electricity Storage Association, which factor in efficiency and expected longevity, show flywheels to be highly competitive for applications involving frequent charge-discharge cycles (ESA 2006). Unfortunately, for fundamental technical and economic reasons, they have been restricted to 6 kWh or less in most commercial applications. If they could be scaled to larger capacities at reasonable cost, they would clearly provide great benefit in many applications.

3 POWER RING TECHNOLOGY

3.1 *The Flywheel Dilemma*

Figure 2 illustrates the basic design of a second generation flywheel. The rim is attached by spokes or a hub to a central shaft, which is supported by bearings. A motor-generator operates as a motor to spin the flywheel to store energy, and as a generator to extract stored energy. The kinetic energy stored in the rotor (rim) is proportional to the mass of the rotor and the square of its velocity. The equation for stored kinetic energy is:

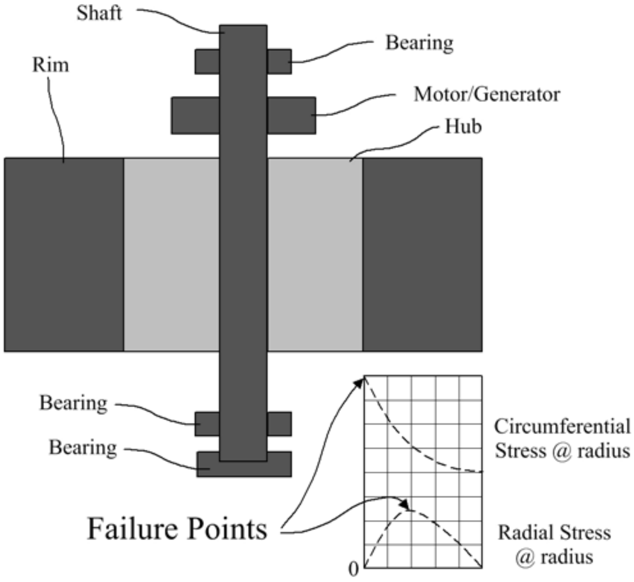

Figure 2. Flywheel structure

$$K.E. = \tfrac{1}{2} J \omega^2 = \tfrac{1}{2} kmr^2\omega^2 \quad (1)$$

where ω is the rate of rotation in radians per second, J is the moment of inertia about the axis of rotation in kilogram-meters squared, m is rotor mass, r is rotor radius (also known as the radius of gyration), and k is an inertial constant dependent on rotor shape. Stress produced in the rim is proportional to the square of linear velocity at the tip. When rotor speed is dictated by the rotor fabrication material, the maximum linear tip velocity is constant, regardless of rotor radius. The maximum rotation rate is then inversely proportional to rotor diameter.

The best materials for flywheels are not the densest, or even the strongest – they are those with the highest specific strength, i.e. the ratio of ultimate tensile strength to density. For a thin rim, the relationship of maximum rim stress to specific energy (energy stored per unit mass) is:

$$K.E./m = \sigma_h / 2\rho \quad (2)$$

where σ_h is the maximum hoop stress the ring can withstand in N/m^2 and ρ is the density of the ring material in kg/m^3. So, specific energy corresponds directly to specific strength, σ_h/ρ, and filament-wound rotors made of high strength, low density fibers will store more energy per unit weight than metal rotors.

Since energy is proportional to the square of speed, high performance is attained at high tip speed. Carbon fiber rims have attained tip speeds in excess of 1000 meters per second and are housed in evacuated chambers to minimize energy losses and heating due to friction.

As rotational velocity increases, the rotor experiences increasing radial force causing it to expand faster than the shaft. The spoke or hub assembly must compensate for this differential growth while maintaining a secure bond with the rim. High-speed carbon composite rims can expand by more than 1% in normal operation, E-glass even more. Hoop stress is highest at the inner boundary of the rim and causes a common failure mode in which the rim separates from the spokes.

Hoop stress decreases rapidly from the inner boundary of the rim to the outer boundary. The fibers used in the construction of the rim are extremely strong along their length, but are held together in the radial direction only by relatively weak epoxy binder. This results in another common failure mode in which the rim delaminates or fractures due to radial stress, which peaks at a point part way between the inner and outer edges. The longer the rim radius the higher the forces become.

Many methods have been proposed to alleviate these problems, but a fundamental limitation remains in all present designs – the rotating mass is far from the axle while the stabilization system (bearings and actuators) operates directly on the axle. If the arbor or spokes are flexible enough to expand as rpm increases, then the stabilization system must transmit control forces to the rim through a “floppy” structure – an impossible task – but if the structure is rigid it will delaminate under high radial stress. The only way to resolve this conflict, so far, has been to restrict composite flywheels to small diameters.

3.2 *A new class of magnetic bearing*

In a permanent magnet Halbach array (Halbach 1985), the field produced by each magnet reinforces the fields of all the other magnets on the “active” side of the array, and cancels them on the other side. The result is, in essence, a one-sided permanent magnet with an intense field. When two identical Halbach arrays are placed with their active sides facing each other, they produce powerful repulsive, attractive, or shear forces, depending on alignment. As compared to simple opposed pole faces, a 5-element Halbach array provides more than three times as much force per unit volume of magnet. This provides the basis for the “shear-force levitator”, shown in Figure 3.

Here two Halbach levitation arrays are arranged vertically with the “static” array attached to a stationary support. If the “moving” array is now offset, from the initial position shown, upward to the correct operating point, it will be subject to a large, stable upward force. This shear-force levitator is laterally unstable and must be actively stabilized. The stabilization actuator configuration and operation is illustrated in Figure 4.

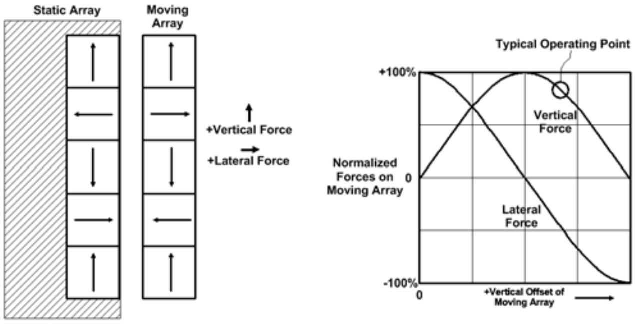

Figure 3. Shear-force levitator

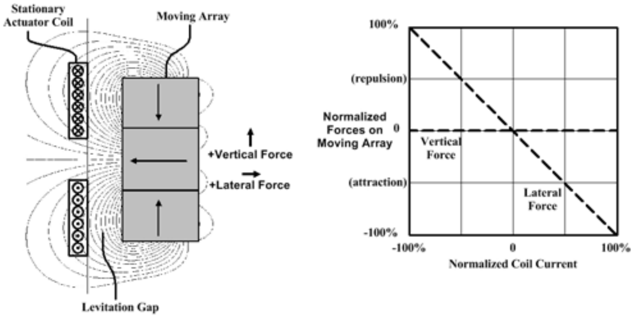

Figure 4. Stabilization actuator

Positive current through the coil in the direction shown causes a negative lateral force, i.e. attraction, on the magnet array. Negative current causes repulsion. Vertical forces produced by the upper and lower sides of the coil are equal and opposite so no net vertical force is applied to the magnet array. When driven by an active feedback control system operating in conjunction with a position sensor, the actuator force can be used to balance the lateral forces on the magnet array to achieve stable levitation.

3.3 *The Power Ring design*

Figure 5 shows the general configuration of a Power Ring, which exploits the shear force levitator to great advantage. Figure 6 is a top view of the Power Ring. In this design, a thin composite ring spins around the vertical axis in a toroidal vacuum chamber. The stationary arrays of two shear-force levitators, upper and lower, are embedded in the stator wall opposing the inside face of the ring. The moving arrays of the levitators are embedded in the inside face of the composite ring itself. Both the stationary and moving arrays are continuous around the ring and provide sufficient force to levitate a large mass. As ring height is increased for larger capacity, the levitator heights can also be increased. Actuator voice coils, upper and lower, are embedded in the stator wall where they interact with stabilization arrays on the inside face of the ring. These actuators keep the ring centered and prevent stator wall contact. A magnet array mounted at the vertical center of the inside face of the ring interacts with stator windings to form a motor/generator, which is used to spin up the ring to store energy and to extract that energy by generating electricity. A containment vessel prevents the ring or any components from escaping the chamber in case of ring failure. A solid model of a detailed utility-scale Power Ring is shown in Figure 7.

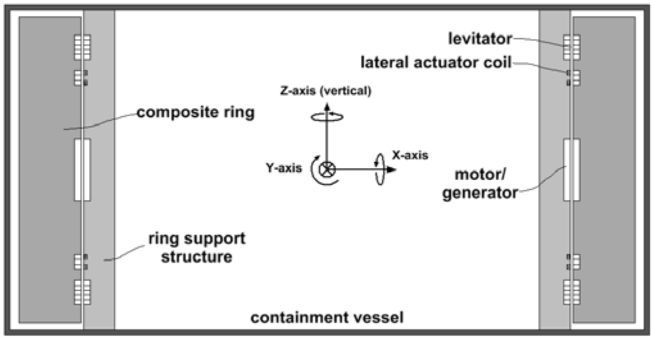

Figure 5. Power Ring cross section

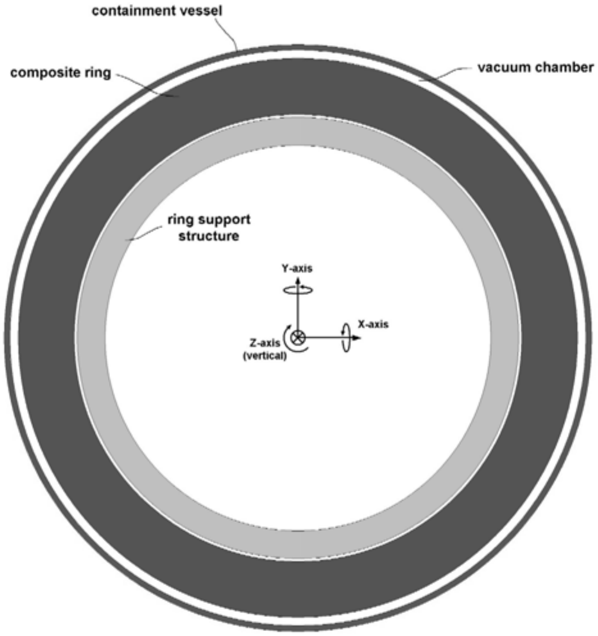

Figure 6. Power Ring top view

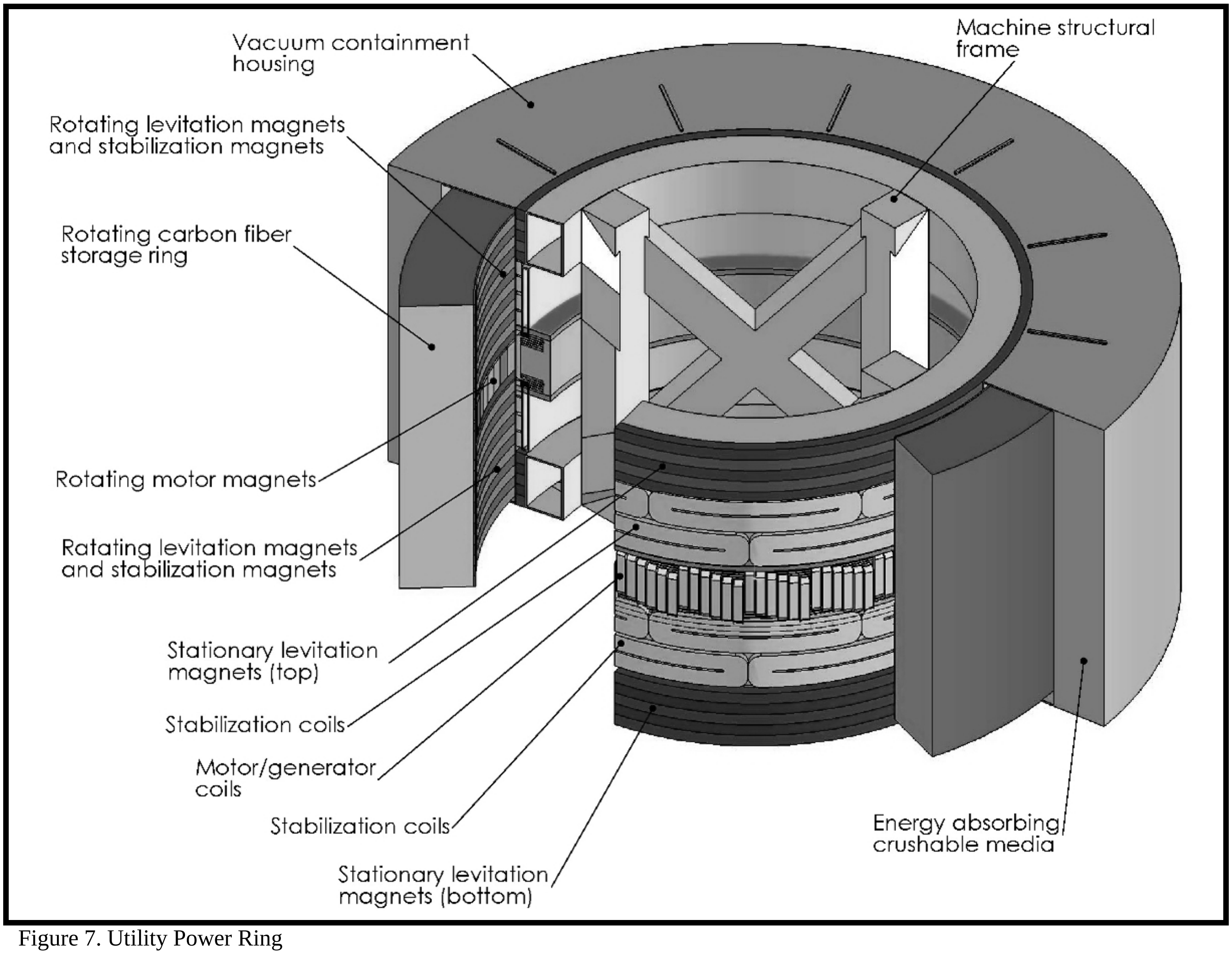

Figure 7. Utility Power Ring

To ensure stable rotation of the ring, six degrees of freedom must be considered: linear motion in the X, Y, and Z directions and rotation about the X, Y, and Z axes. The ring spins about the vertical or Z axis. Since vertical motion of the shear-force levitators is passively stable, the ring is stable in the Z direction and in rotation about the X and Y axes. Thus, four of the six degrees of freedom contribute little to the instability, leaving only two – linear motion in the X and Y directions – that must be strongly controlled. X and Y stabilization is performed by lateral actuators on the stator wall that interact with the stabilization arrays on the ring. The actuators are electronically controlled to maintain the desired gap and dampen vibration. Since ring vibrations are small (the ring is carefully balanced) linear control methods such as linear quadratic regulator design or H-infinity design can be applied. The modal frequencies depend on the rotational speed, so the controller may change with speed. Methods for designing the change include gain-scheduling or linear parameter varying (LPV) methods.

With sufficient dynamic control, the ring can be kept stable and floating at any rotational velocity from zero to the maximum that is structurally permissible. That maximum is determined almost entirely by the ultimate tensile strength of the fibers in the composite ring. The two prevalent failure modes of a thick-walled composite flywheel, hub-rim and radial delamination, are almost entirely suppressed. Furthermore, since control forces are applied directly to the rim, instead of a flexible intermediary, stabilization is far more robust.

3.4 *Design Methodology*

The goal of the design methodology was to find the combination of component parameters that meets all design specifications and minimizes system cost. To achieve this goal, a design optimization program was developed based upon equations derived from detailed analysis of Power Ring structure, operating forces, dynamics, and electrical characteristics. The major cost contributors are the composite rim and the magnets, so the optimization routine minimizes their mass by varying a number of free parameters while maintaining all givens and constraints. This optimization program has been used to produce several point designs. Table 1 lists the principal characteristics and dimensions of a short duration, high power unit. This unit would produce up to 100 megawatts at full discharge.

Table 2 lists the characteristics and dimensions of a lower power, longer duration Power Ring. A solid-model drawing of this unit is shown in Figure 7. Smaller or larger units, in terms of storage capacity or power, can be produced by the same optimization routine.

Table 1 High Power Short Duration Power Ring

Usable stored energy	90 MJ (25 kWh)
Output power (at full charge)	153 MW RMS
Output power (full discharge)	100 MW RMS
Storage unit dimensions	2.5m dia., 1.4m high
Inertial ring dimensions	2.22m OD, 1.11m high
Total spinning mass	1668 kg
Total unit mass	3600 kg
Max rotation rate	4576 RPM (76 Hz)
Tip speed	533 m/s

Table 2 Long Duration Utility Power Ring

Usable Stored Energy	200 kWh
Charge Rate	100 kW
Discharge Rate	100 kW
Design Life	100,000 discharge cycles
Storage unit dimensions	2.5 m dia., 1.2 m tall
Inertial ring dimensions	2.08 m dia., .98 m tall
Total spinning mass	2192 kg.
Total unit mass	4460 kg.
Max rotation rate	8400 RPM (140 Hz)
Tip speed	921 m/s

The maximum practical ring size is determined by the widest allowable levitation gap and the fiber modulus, since the levitation gap will grow as the ring spins up and begins to stretch. Carbon fiber, with a maximum elongation of about 2%, can be used for rings in excess of 6 meters in diameter with neodymium permanent magnets of conventional field strength. There is no fundamental limit to the axial length of these rings since the number of levitators can be increased as the axial length increases. The variable gap must also be factored into account in the design of the lateral actuators and the motor generator. In practice, ring dimensions are likely to be limited by transportation considerations — what is the largest ring that can be transported from the factory to the installation site? Rings with a storage capacity in the 5-10 MWh range appear to be feasible.

4 COST COMPARISON

Energy storage costs and the relative advantages of different storage technologies are application dependent. Figure 8 (Schoenung 2003) compares the annual costs, in \$/kW-yr, for a 1-hour distributed generation application. An added column shows Power Ring costs, using the same methodology. This assumes a 200kW, 1 hour ring with an estimated price in high-volume production of \$120k, AC/DC converter included, resulting in costs of \$.6k/kWh or \$.6k/kW, and a carrying charge of \$72/kW-yr. Operation and Maintenance (O&M) costs/kW-yr are assumed to be half as

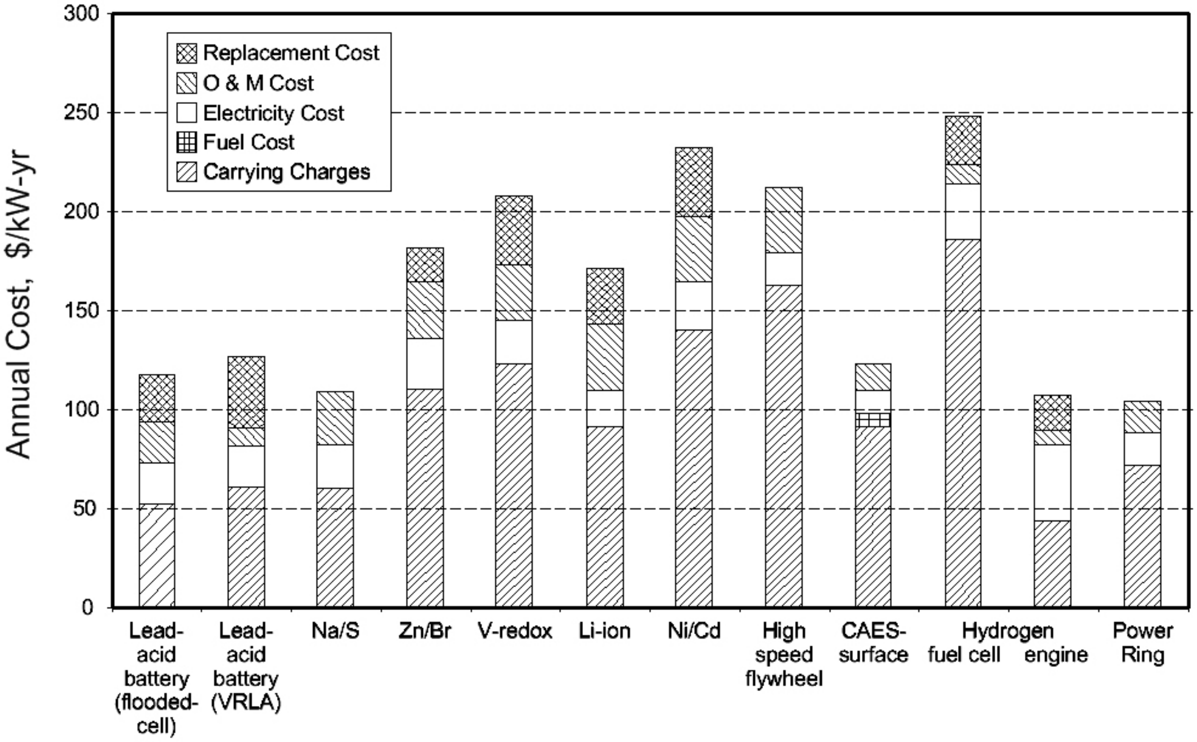

Figure 8. Components of annual cost for distributed generation technologies (1 hour discharge)

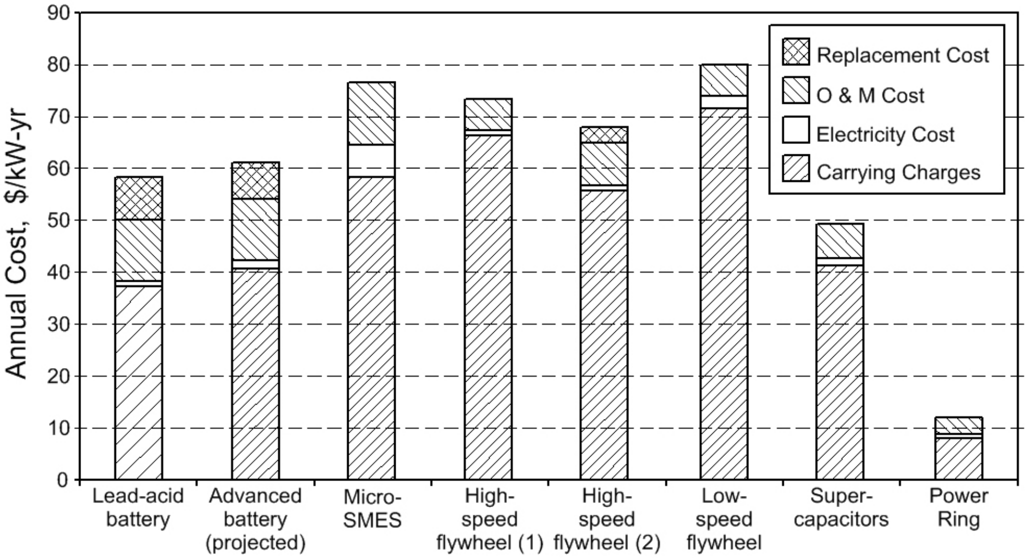

Figure 9. Components of annual cost for power quality technologies (20 second discharge)

much as for existing flywheels due to economies of scale. At this price, Power Rings will be comparable to the best current technologies, and significantly better than current flywheels.

Power Rings will be even more cost effective as storage duration decreases. Figure 9 (Schoenung 2003), shows comparative costs in a 20-second application. Again, a Power Ring column is added, this time for a 45 MW, 20 second ring with an estimated low volume production price, including converter, of ~$2.5 million ($10k/kWh or $55.5/kW), and a carrying charge of $6.67/kW-yr. This is far better than the alternatives and should improve even more over time.

5 APPLICATIONS

Electricity is the only major commodity created almost entirely on demand. Without local storage, the power grid must carry electricity from the power plant to the customer at the instant it is needed. The grid now operates at near capacity on peak demand days, degrading stability and causing more frequent outages. These disruptions are highly damaging to the national economy. The US economy experiences ~$80 billion in lost productivity per year as a result of poor power quality and reliability (LaCommare 2004). The blackout in the Eastern US and Canada on August 14, 2003 alone cost $4-6 billion. Blackouts during the summer of 1999 in Chicago and New York City and the severe energy crisis in California in 2001 also caused major economic losses. At the same time, the public has become increasingly aware of, and sensitive to, the environmental damage and intrusive nature of some elements of the power grid. Opposition to new transmission line installation prevents or slows system upgrades and makes them more expensive.

By making the grid more robust and resilient, Power Ring electricity storage could reduce these annual losses by tens of billions of dollars while providing ancillary benefits such as lower power costs and decreased air pollution. Power Rings could also make the grid less vulnerable to sabotage and, by improving efficiency, can increase energy independence. Applications include:

- Power Quality; providing "ride-through" for momentary outages, reducing harmonic distortions, and eliminating voltage sags and surges. Local storage can insulate the customer from short-term transmission fluctuations or interruptions, which comprise the vast majority of power problems.
- Frequency Regulation; maintaining the supply-demand balance to provide constant frequency on the grid.
- Renewables Support; increasing the value of solar, wind and wave-generated electricity by making supply coincident with periods of peak consumer demand.
- Spinning Reserve; increasing grid stability, bridging between energy sources, and preventing service interruptions due to failures of generating stations or transmission links.
- Energy Management; enabling load leveling, peak shaving and arbitrage, all of which help to improve generation efficiency and reduce energy costs.
- Facility Deferral; enabling a utility to postpone new generating or transmission capacity by supplementing existing facilities with another resource as demand approaches capacity.
- Transportation; providing electricity storage for diesel-electric hybrid locomotives for use in railroad switch yards to greatly reduce fuel consumption, air pollution, and noise.

6 CONCLUSIONS

The Power Ring third generation flywheel design has been extensively analyzed and promises to transcend the barriers that have constrained construction of compact, high power flywheel electricity storage systems. As a result of support from four government agencies in the US, the first hardware prototype began development in 2006. Further development could lead to production of commercial units for a wide variety of applications within three to five years.

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