A Description of the Beacon Power High Energy and High Power Composite Flywheel Energy Storage Systems

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Energy storage is everywhere around us. We take it for granted and it is part of our modern life. We fill up our gas tanks in our cars, and home heating oil tanks. We see water tanks in the highest point in our towns. We change batteries in our watches, and carefully monitor usage of our laptops. Most of the time, our cars start when we expect them to. We even go sailing in lakes created by hydroelectric dams.

Hundreds of people come to meetings like EESAT 2002 and IEEE-PES to talk about Power Quality issues that need energy storage. Power interruptions and fluctuations affect all of us, and our businesses. As our lives and businesses become more dependent on sensitive equipment and processes, these power quality problems will become even more important. EPRI estimates that power quality problems cost industry billions of dollars per year. Correction of power quality problems requires stored energy.

By far the most dominant form of electrical energy storage has been the battery – and for very good reasons. Lead acid batteries are very low cost and store a lot of energy. Annual sales of $15 billion say that this form of energy storage is well suited for their applications. Distributed power generation, the explosive growth of Information Technology, and the increasing use of computers in industry has led to new demands of storage systems.

Lead acid battery lives, however, are significantly impacted by many deep discharges and high power draws. They like operating at low to medium power draws without significant deep cycling. Generators, microturbines, and many fuel cells have load following capabilities far slower than needed by most computerized applications. Batteries have played a role in addressing the transients, but where high power draws and more power cycling are required, lead acid batteries are operating outside their "sweet spot". High power needs have been addressed by using a large number of batteries to reduce the average battery draw or load. Many of these high power storage applications end up with stored energy far greater than needed. Because of the low cost of batteries, this approach has been cost effective.

Flywheels	Batteries
▪ Ideally suited for high power draw	▪ Operate best at low power draws
▪ Fast recharge, 10's of thousands charge/discharge cycles	▪ Slow recharge, 100's of charge/discharge cycles
▪ Low/mid energy (order of 1- 25kWh)	▪ Low/high energy (order of 1K-1MWh)
▪ Accurate remote monitoring/ predictable operation	▪ Monitoring less precise/ lower certainty of operation
▪ Low to no maintenance	▪ Requires maintenance
▪ Environmentally friendly - can bury in ground	▪ Lead-acid batteries require disposal procedures
▪ Little temperature sensitivity	▪ Narrow temperature operating range
▪ Emerging technology–cost potential	▪ Mature technology – very low cost
Better for short duration, high power, high cyclic applications	Better for long duration, low cyclic applications

Figure 1. Flywheels and batteries have complementary characteristics.

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Flywheels, whose strengths are rapid load following, very high cyclic life, and very high power draw capabilities, have been and are being considered as alternatives. Most commercially available flywheels, however, have low energy storage capability. Beacon's 6kWh (21.6 MJ) composite flywheel is the highest energy flywheel commercially available. Typically, ride-through flywheels are between 1 and 5 kWh, (3.6 and 18MJ) are usually made of steel, and are quite heavy. The initial cost of these wheels, higher than batteries, is somewhat offset because it is not necessary to incur the cost of excess energy. Flywheels also require less maintenance, and do not require periodic replacement, significantly lowering the life cycle cost. Figure 1 compares some of the major characteristics of flywheels and batteries.

Figure 2 shows the market segments served by flywheels today. Transient protection and ride-through support are supplied with high power, (100 kW to 1+ MW) relatively low energy flywheels from sources like Active Power, Piller, AFS Trinity, and Beacon Power. The Communication market, on the other hand, is a low power, long duration market served by Beacon Power. The communication flywheel energy requirements are higher than in the transient market. For example, telecommunication remote terminals require only 1 to 2 kW for 4 to 8 hours. (4-16kWh or 14.4 to 57.6 MJ), while the transient systems that range from 250kW to 1MW for 12 seconds, need only 1to 4kWh. (3.6 to 14.4 MJ)

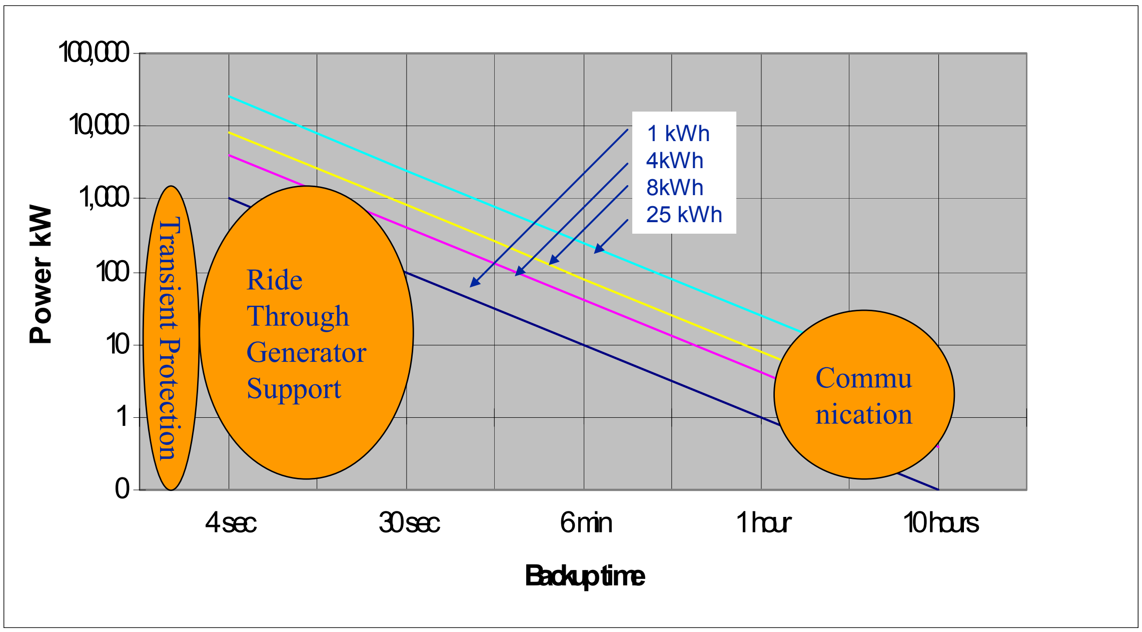

Figure 2. Power backup storage requirements served by flywheels

In addition to the higher energy requirement, the telecommunications industry has some other significant challenges as shown in Figure 3. The telecom customer's desire to bury the flywheels has lead Beacon Power to develop a no-maintenance and an earthquake tolerant design. It is impractical to dig up flywheels for repairs. As a result the Beacon flywheels have the following features:

- 20 year life.
- Storage capacity of up to six times as much energy as other commercial flywheels.
- Proprietary and proven maintenance free internal vacuum system and bearings.
- Tolerance for a wide range of hostile field environments – from deserts, to frozen locations, to under brackish water, and lightning prone environments.
- Earthquake tolerance. (Beacon wheels are qualified to a Telcordia Zone 4 earthquake Requirement -- Richter 7.6 for 20 seconds).

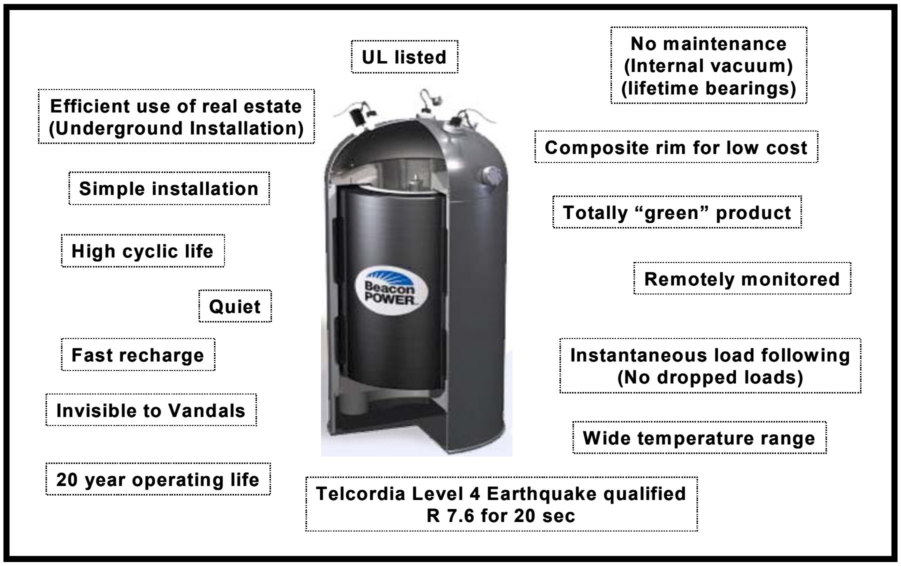

Figure 3. Beacon's 6kWh telecommunications flywheel

The emerging Power Quality requirements not only cover the existing segments shown in Figure 2, but also most of the uncovered space between the extremes. Today, the best practical solution is using batteries in the form of battery farms. Descriptions of such systems are plentiful in the literature. Other storage systems are not common. For example, there are no high power, high energy (25 kWh to 1 MWh or 90MJ to 3.6GJ) flywheels commercially available. If such flywheels existed, could they be an attractive alternative? Understanding the application of this stored energy may be helpful in determining the suitability of using flywheels. For example, how much excess energy exists in the installation? If the batteries were not highly loaded, a battery system would have excess energy so flywheels may present a solution with a much smaller footprint and much less weight. If the batteries were highly loaded with significant cycling, then flywheels could provide a much higher life and lower maintenance solution.

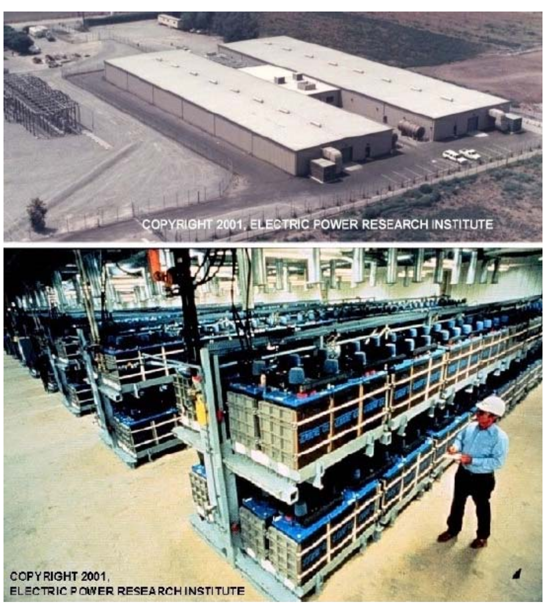

Figure 4. shows the 10MW, 40MWh (144GJ) Chino, California battery farm . An estimate, based on scaling Beacon's current 6kWh composite flywheel to 25kWh, suggests that a 40MWh farm would occupy less than one building versus the two. If the real need were 10MW for an hour, then the 40MWh capacity for a 25%load factor would not be needed for a flywheel. Less than 1/2 of one of the buildings would be needed, including electronics.

A similar farm, PREPA BESS in Puerto Rico closed after only five years because of low battery life, (expected life was 10 years) – suggesting either a high battery load factor or high cyclic operation. Flywheels in either case could have been better solutions if they were available

Figure 4. 10MW, 40 MWh Chino, California battery farm

Beacon believes future flywheels will require higher energy than most of today's commercial offerings. Sag protection, harmonic compensation, spinning reserve, peak shaving, frequency control, among others, require higher power for minutes or hours, not just seconds. Higher energy designs, scaled from today's, are suitable for flywheel farms where megawatt-hours would be stored, are under consideration. It would require only 40 25kWh (90MJ) wheels for a 1MWh (144GJ) application vs. 250-1000 of today's most common flywheels.

Figure 5 shows a flywheel rotor. Kinetic energy is stored in the composite rim by spinning the rotor. The amount of energy stored is dependent on driving the rim to a high surface speed. (Energy is roughly proportional to the mass of the rim and square of the surface speed). Careful composite rotor design can achieve significantly lower system cost and weight than a steel rotor design.

Figure 5. Beacon's composite rotor

The commitment to maintenance free, low cost, higher energy flywheels drives the design architecture. The key cost and weight driver is the rim design, where nearly all the energy is stored kinetically. Beacon has found that a composite rotor can be designed for a substantially lower cost and weight than a metal rotor.

The cost of stored energy in a wheel is related to material strength, density and cost per pound in the following way:

$$Energy/\$ \sim \frac{average.strength}{\left(density \times \frac{\$}{lb}\right)} \qquad (1)$$

Table 1 shows how the Energy Index from equation 1, for both steel and composite materials compare.

Material	Steel			Carbon/Glass Composites		
Average Strength (KSI)	50	100	150	100	125	160
Avearge Density (lb/in^3)	0.283	0.283	0.283	0.068	0.068	0.068
Raw Mat'l Cost ($/lb)	1	2	4	3.7	5.45	18.75
Energy Index (Wh/$)	5.55	5.55	4.16	12.48	10.59	3.94

Table 1 Energy Index for typical steel and composite flywheel rotor

It is evident that using low cost composites gives a significantly higher index and lower cost than using steel. Surprisingly, for a given energy level, it is not the lowest cost material that leads to lowest rotor cost. The reason this is true is because metal rotors are usually homogeneous – made from one grade of steel – and so they have uniform strength throughout the part. The maximum stress found on the rim must be less than the allowable strength of the metal. The rest of the rotor has excess strength capability. In contrast, composite rotors are usually tailored to have a small quantity of very high strength fibers (carbon fibers can be 3 or 4 times stronger than a steel forging) in locations where stress is high. Higher cost materials are sparingly used only where needed. Every place else, where stress is lower, lower cost materials are used.

For most materials, the cost of higher strength tends to go up faster than the strength itself, driving the index down. For example, there is a cost disadvantage to using higher strength steel. Lower strength steels are often used to keep cost down. On the other hand, high strength and low density carbon fiber has the most favorable Energy Index, despite the fact that that the cost per pound is several times that of steel.

The downside to using lower strength steel is the impact on rotor weight For a given material:

$$Weight \sim \frac{Energy}{strength} \tag{2}$$

The rotor weight for a given amount of energy is inversely dependent on the strength -- a steel rotor stressed to 50ksi will weigh 3 times that of a rotor stressed to 150ksi. There is an additional inherent weight advantage to using composites. Being able to tailor the composite to handle much higher peak local stresses, allows the rotor to spin faster – more kinetic energy from the same mass. The combined effect leads to Beacon's composite rotors weighing an order of magnitude less than steel ones with comparable stored energy. A composite rim for a 25kWh flywheel, suitable for utility applications, would weigh only 1200 lb as compared to 10,000 – 15,000 lbs for a steel one, and would have a $4,000 to $6,000 material cost advantage. The physical rim size is also smaller which cascades into a smaller vacuum housing for additional cost, footprint, and weight savings.

Low energy flywheels, below about 2kWh, have relatively small rims, so the absolute magnitude of the cost and weight differential is not very significant. As the wheels get larger, into the 25kWh range, the differential becomes substantial in favor of composite flywheels.

John D. Boyes from Sandia National Laboratories presented a paper entitled "Electric Energy Storage Systems" at New and Emerging Technologies 2002, February 21, 2002 in Tucson AZ. Figure 6 modifies one of his charts to show what the expected cost would be for a 1MWh flywheel farm consisting of 40 25kWk flywheels. The wheels would be scaled based on Beacon's current 6kWh flywheel. Each would only be roughly 5ft tall and 4 ft in diameter, thanks to scalable composite rim technology. In a flywheel farm, flywheels could compete head to head with batteries in cost with today's technology.

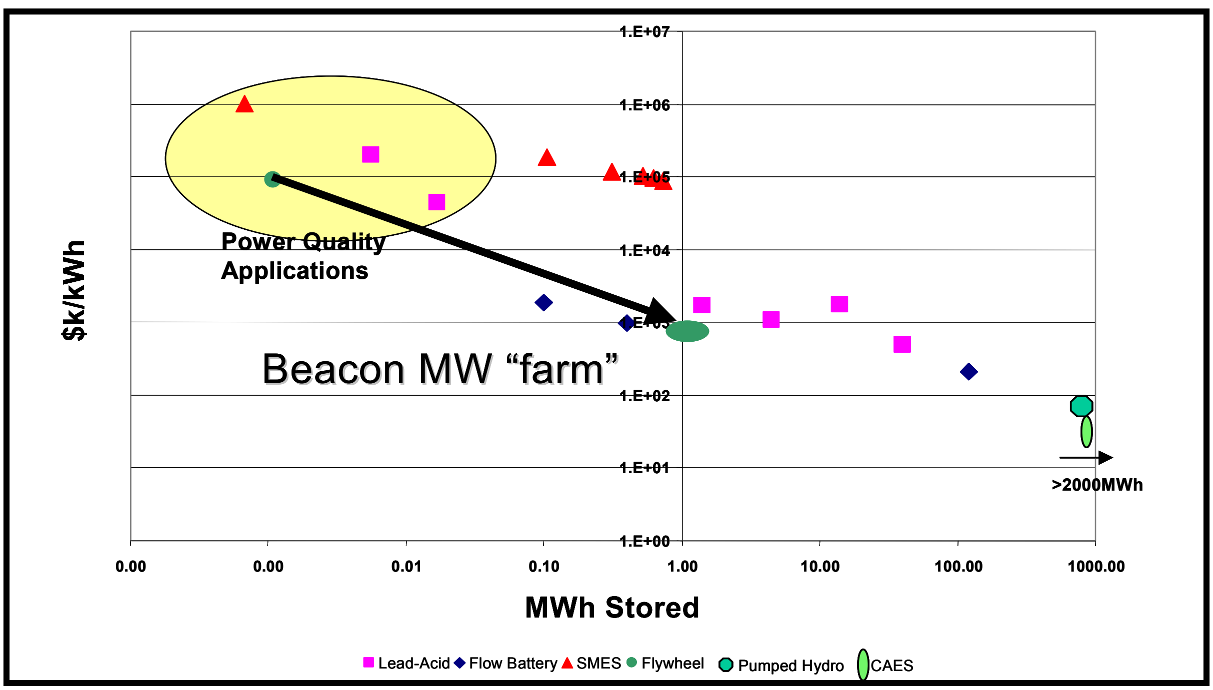

Figure 6. System Cost year 2000 modified to show cost potential of a 1 MWh flywheel farm.

Summary and Conclusions

- Industry appears to be looking for new solutions to high power and energy storage load management and power quality problems. Battery systems are effective for many applications, and are great for high energy long duration applications, but a need for rapid load following, high cyclic content and high power has a negative impact on battery lives. Flywheels have characteristics that match the emerging requirements, but to date do not have the high energy storage capacity. Many short duration applications, however, do not need the high energy stored by batteries, (an example would be fuel cell or microturbine load following).

There should be opportunities to look at batteries and flywheels not as competitors, but as complementary systems. Anywhere a battery system fails due to frequent discharge cycles is likely to benefit from a flywheel "buffer" to handle the cyclic content and allow the battery system to do what it does best; to discharge at a slow rate.

- Today's high power flywheels store relatively low energy (< 5kWh). At these small sizes, the rim cost is a major, but not the only, system cost contributor. There is little absolute difference between the cost and weight of a steel vs. a composite flywheel. Larger flywheels, (>25kWh), big enough to start addressing utility issues, have rims that dominate the mechanical system cost. In larger systems, composite rims will play a very significant role in reducing cost, weight, and footprint.

- The high energy wheels of tomorrow are a reasonable extension of today's commercial composite technology at Beacon Power.

- Flywheels are not just a 15 second solution!