Flywheels: An Overview of Applications and Technology

Don Bender, CTO Helix Power Corporation
HELIX POWER
Developing an Innovative Power Management Solution

Insight

• MW sags, surges, spikes, ramps
• Widespread and increasing
• No good storage solution exists

Solution

• High performance flywheel
• 1 MW, 90s, high cycle

Founded in 2013 to build best in class systems
Helix Power Tech Team

Matt Lazarewicz, President, Co-founder
• Beacon Power, CTO
  Built world’s largest flywheel energy storage facility
• GE Aircraft – Mechanical Design Manager for the F404 and F414 engines in the F-18 and F117 fighters

Don Bender, CTO, Co-founder
• AFS Trinity Power, CTO
  Numerous development programs: UPS, energy arbitrage, defense, mobile

40 years of flywheel design experience serving a broad range of customers and applications
Past Customers and Partners
What is an “advanced” flywheel?
Common Elements
Advanced Flywheels

A rotor spinning in vacuum electrically connected to the application through a variable speed drive

- High speed rotor
- Running in vacuum
- Built-in m/g
- Long life bearings
- High speed drive
Distinguishing Characteristics

- Power and energy are independent
- High cycle life (>500,000)
- No degradation
- SOC and availability well known
- Benign materials
- $\Delta$ energy cost $1k/kWh - $3k/kWh
- Individual modules up to 50 kWh

Cycle life differentiates flywheels from batteries
Cost Metrics for Flywheels

Cost = \( (A \times \text{Power}) + (B \times \text{Energy}) + C \)

- For batteries E:P is fixed by chemistry
  - $/kWh is a scalable metric

- Flywheels have multiple cost elements
  - Elements that scale with power = \( A \): $/kW
  - Elements that scale with energy = \( B \): $/kWh
  - Elements that are largely fixed = \( C \):$

At the system level $/kWh is not a scalable metric for flywheels
Flywheels, Batteries, Capacitors

Cost effectiveness characterized by power and discharge time

Flywheels are cost competitive when providing power for several seconds to 5 minutes at power > 100 kW

![Graph showing power and discharge time for different technologies like flywheels, batteries, and capacitors.](image-url)
Applications
Frequency regulation is currently the only market for grid connected flywheels. Additional markets are emerging.
Grid

Frequency regulation needs responsive high cycle-life storage

- Frequency error
  - Function of imbalance (MW) and time to correct
  - Correcting ACE faster => up to 40% less regulation need
- 15 minutes of storage provides continuous regulation
  - Equivalent of 6,300 charge/discharge cycles per year

Beacon is accumulating experience at the 20 MW facilities in Stephentown (NYISO) and Hazel Township (PJM)
Isolated Systems
High cycle storage is useful with high renewable penetration

Grid is difficult to manage without storage when renewables exceed 20%

Wind fluctuations are more frequent and severe than solar fluctuations

Flywheel demonstration systems are under development. Total global opportunity estimated to be 2,600 MW.
Isolated Systems
Lots of wind means severe tasking of generation assets

Flywheel energy storage rated at 5% of nominal output can result in significant O&M savings
Rail

Transit systems have predictable cyclic loads

Energy cost savings of 10% - 20%, reduced demand charge, T&D deferral. 9,000 stations world-wide

Flywheels are a more cost effective solution for transit energy recovery and PQ than batteries or ultracapacitors.
Mining
Electric draglines stress generators and the grid

6 MW during lift
-3 MW while lowering
Repeats every 100s

Diesel genset
Rated for peak draw
Average power is 50%

Significant PQ issues when grid connected

For draglines, flywheels are the only viable energy storage solution for reducing fuel consumption and O&M cost.
Material Handling

Energy recycling

RTG crane – 20 moves/hr
Powered by 300 kW genset
Flywheel benefits:
  - Lower emissions
  - Extended genset life
  - 15% - 30% lower energy cost

Emerging global market for energy storage to reduce energy costs in materials handling.
Roller Coasters
Energy storage for electric launch

Incredible Hulk
Universal, Orlando
1G launch up incline
0 to 40 mph in 2s
230 tire motors
8 MW during launch

Solution:
250 kW motor and
8 MW generator
attached to 10,000 lb
flywheel

Flywheel was a lower cost alternative
to a new substation
Vehicles

Demanding hybrid vehicle powertrain applications

Audi R-18 e-tron quattro

Hybrid Diesel
3.7 L V6 turbo
375 kW/510 hp

Flywheel:
74 kW/100 hp
500 kJ

Winner:
Le Mans 2012, 2013, 2014

Cars in top tier motorsport (F1, LMP1) are hybrids
Technology
The key issue: multiple expensive component technologies
Rotors
Steel and composites have been used in many configurations

\[ \frac{\$}{kWh} = K \frac{p\rho}{\sigma} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>$/kWh</th>
<th>mass/kWh</th>
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<tbody>
<tr>
<td>Carbon fiber</td>
<td>$1,200</td>
<td>1</td>
</tr>
<tr>
<td>260 ksi steel</td>
<td>$1,800</td>
<td>7x</td>
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<tr>
<td>160 ksi steel</td>
<td>$2,000</td>
<td>12x</td>
</tr>
<tr>
<td>90 ksi steel</td>
<td>$4,000</td>
<td>24x</td>
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Normalized to material strength after $10^6$ cycles

A heavier rotor needs higher capacity bearings and a heavier housing.

Carbon fiber reduces balance of system costs and is the lowest cost solution for storing relatively large amounts of energy.
Motor/Generator
Thermal management is the most important consideration

- On-rotor losses drive the design
  - The only heat transfer mechanism for on-rotor losses is radiation.
  - Even $<1\%$ loss can lead to excessive rotor temperature

- Induction motors are unusable

- Homopolar and Synchronous reluctance
  - Turn off completely for low coasting loss
  - On-rotor losses limit cycling ability

- PM machines have best cycling ability
  - Magnets on shaft, on rotor
  - Slotted, slotless, Halbach array

Permanent magnet motors/generators have significant advantages in cycling applications
Bearings

Ball bearings, magnetic suspension, active magnetic levitation

• Ball Bearings
  - Low loss, highly mature
  - Limited life at high speed

• Magnetic Suspension
  - Rotor weight partially supported by field coils or permanent magnets
  - Enables small ball bearings with large rotors

• Active Magnetic Bearings
  - 5-axis active control
  - Low rotor drag, monitor rotor health
  - Commercially available

Bearings are the life-limiting element of the system
Companies
Beyond UPS
Working on power management, energy arbitrage, and mobile

- Beacon Power
- Powerstor
- Powerthru
- Ricardo
- Temporal
- Vycon
- GKN (Williams) Hybrid Power

Seven companies offer product for non-UPS applications
GKN/WHP, Urenco, Ricardo roots
F1 and uranium centrifuge pedigree

Intense technology development
2014 F1 “Power Unit”
Focus on energy storage
Two F1 flywheel spinoff programs

Centrifuge cascade
1000s of rotors, 6m – 13m
Extremely high speed
20+ yr continuous operation

Flywheel development has benefited from F1 investment and centrifuge technology
Urenco Flywheel
Developed at Urenco by the centrifuge team

After 10 years of development Urenco consolidated and suspended all efforts outside of core enrichment mission
GKN Hybrid Power
A spinoff of the Williams F1 racing team with a Urenco engineer

- Founded in 2008 as WHP, sold to GKN in April 2014
- Series of well funded demonstration systems
- Branched out buses, rail, microgrids, ramping

A promising combination of F1 engineering competence and centrifuge background technology
GKN/WHP Technology

Ball bearings

MLC rotor – extreme approach to reducing on-rotor loss

45,000 RPM

Evolution: 74 kW for 7 s to 250 kW for 28 s

Unique configuration with features not found in other systems
Ricardo
Power transfer through magnetic gearing

• Excavators
  – No way to recover energy
  – Conventional powertrain (not hybrid)
  – Connect mechanically via CVT

Combines an F1 derivative rotor with novel transmission for retrofit energy recovery for non-hybrid powertrains
Evolved through several generations to produce the highest energy composite rotor flywheels ever deployed.
PowerStore

Performance Data:
- Net. energy content: 18 MWs
- Max Input/output power: 1650 kW
- Speed range: 1800 to 3600 rpm
- Total weight: 6000 kg
- Rotor weight: 2900 kg
- Idling losses: 12 kW
- Greasing frequency: 5 years
- Bearing service life: 8 years

Features:
- Helium filled
- Magnetic support
- Redundant bearings

Marketed by ABB for microgrid applications
Vycon
Steel rotor, PM motor, active magnetic bearings (160 kW, 24s)

DC systems for UPS and energy recovery markets
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