Flywheels for Renewable Energy and Power Quality Applications

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Donald A. Bender

Trinity Flywheel Power

Trinity Company Overview

Founded: 1993 to commercialize technology developed at Lawrence Livermore National Lab

High power, compact systems for mobile and stationary applications

Corporate office: San Francisco, CA
Engineering Center: Livermore, CA

First customer delivery: 1998

Classes of Flywheel

Direct mechanical

- Inertia of rotating machinery
  - 30 meters per second was considered fast

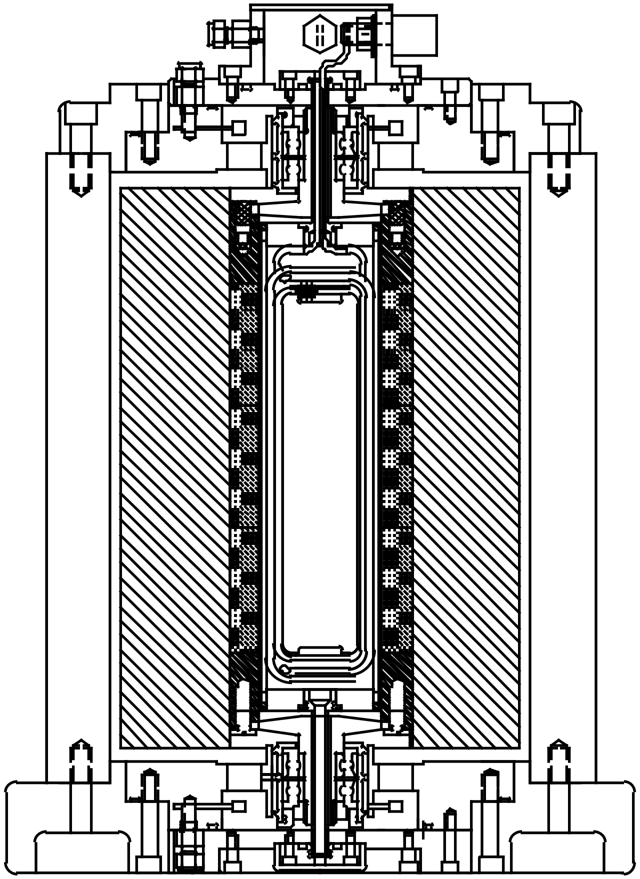
Electromechanical battery

- Connection to application is electrical
  - Power electronics enable this class of machine
- Steel and composite rotors are usable
  - Composite is better (cheaper, safer)
  - High speed (>500 m/s) yields high specific energy

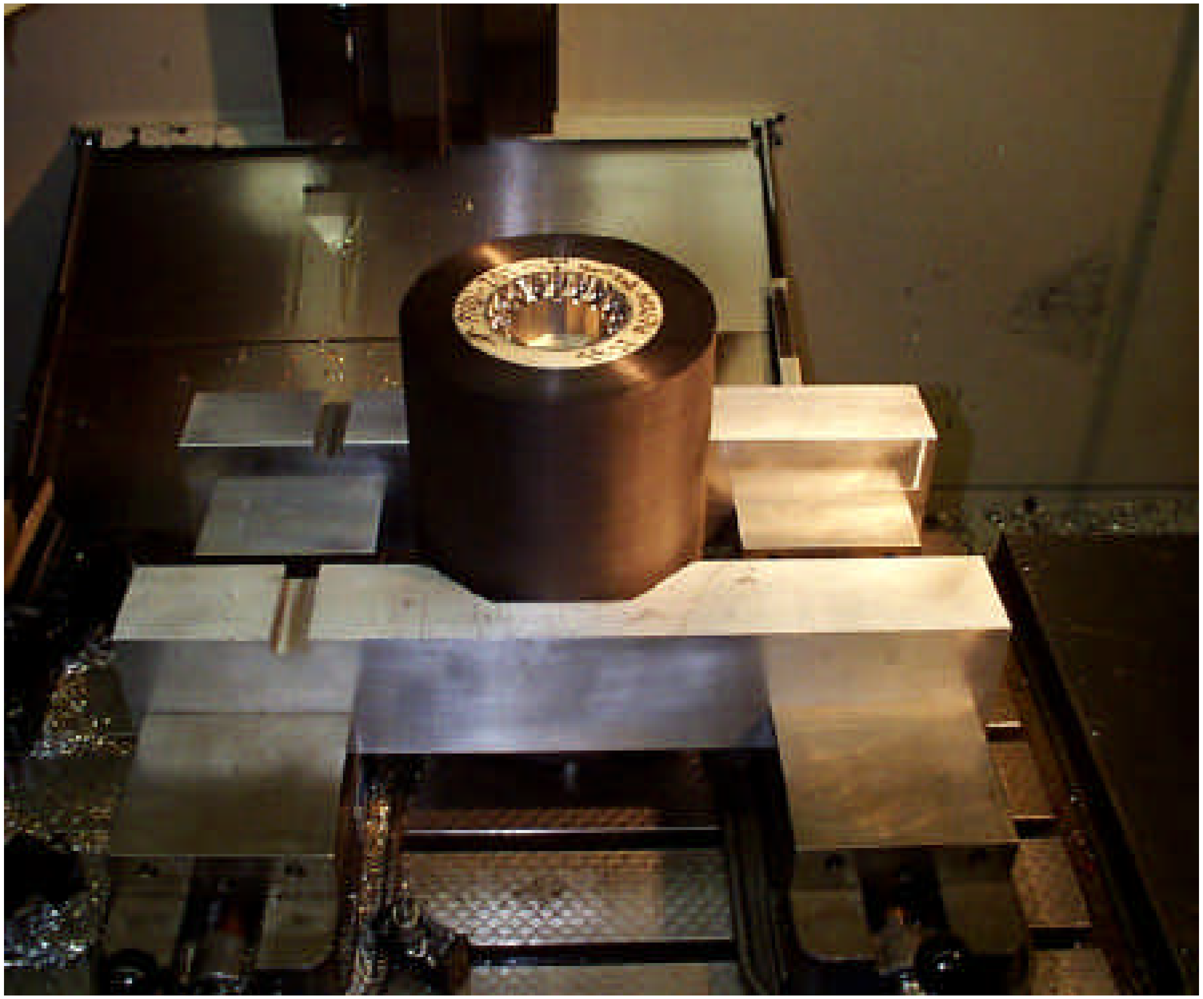
Flywheel Motor Generator

FMG

- Composite rotor
- Permanent magnet motor/generator
- High speed ball bearings
- Containment
- Vacuum enclosure



Trinity Composite Rotor



Stationary Flywheel Power System

The Promise of Flywheels

Performance

- High power density (5 kW/kg demonstrated* 10 kW/kg design)
- High cycle life: material tests support design $>10^6$ cycles
- Controllability: SOC precisely known, output formatting

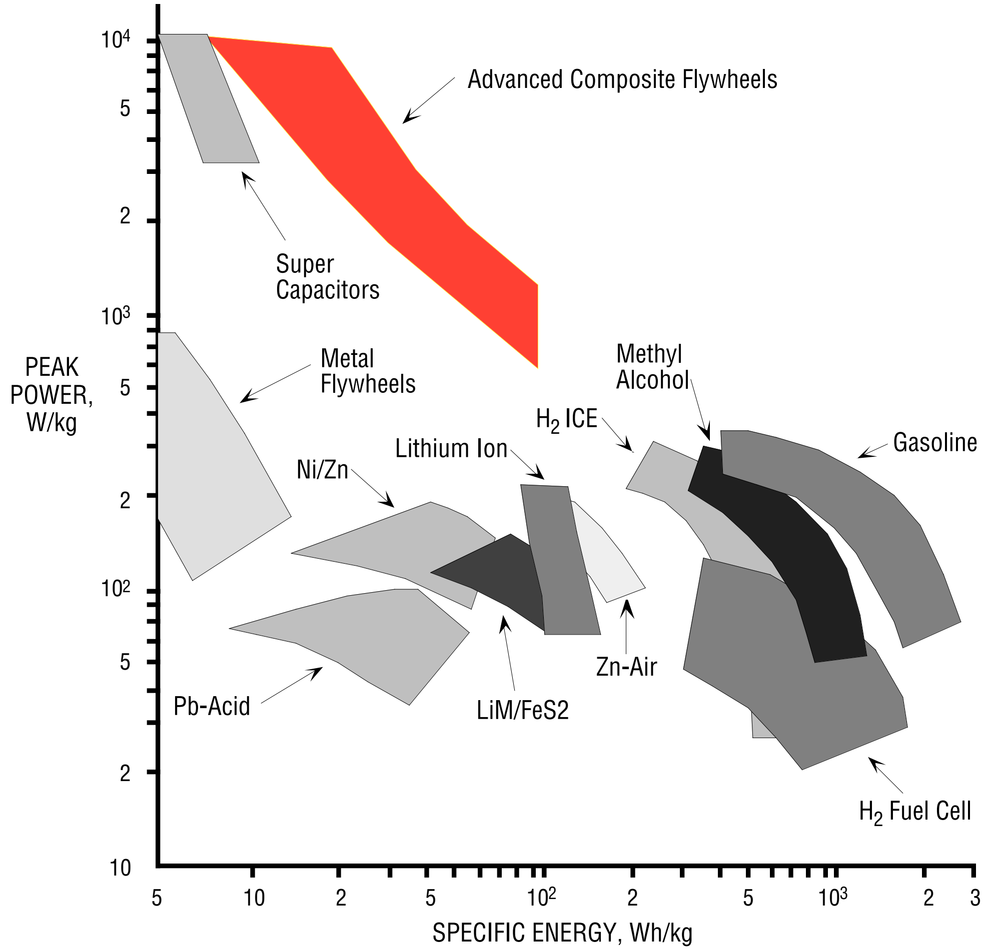
Caveat

- A flywheel is an engineered system - specific power and specific energy trade off
  - Power components do not store energy
  - Energy storage components do not produce power

****based on power processing components only***

Storage Technology Compared

Compiled by LLNL (1994)



TRINITY
FLYWHEEL POWER

Why not Yet?

Last decade: much attention on vehicle applications

- **AFS**
- **Rosen Motors**
- **Unique Mobility**
- **Satcon/Chrysler Patriot program**
- **LLNL/GM/Trinity demo project**
- ***DARPA/AVP projects through regional consortia***

Why they have come up short

- **Subcritical**
  - **Emphasis on a component or technology**
  - **By comparison: underfunded**
- **Requirements for vehicular applications are too severe for success in a single step**

Obstacles and Opportunities

Technology needs

- Bearings, bearings, bearings, integration
- Everything else rides favorable trends

System integration

- Major component of cost, weight, and size
  - Grossly underestimated in most programs to date

Non-existent market for vehicular flywheels

- Market for vehicular flywheel system: E/HEV manufacturers
  - Insufficient market to justify equity investment

Natural path to stationary applications

- Short duration systems capitalize on clear strengths
- Long duration systems follow composite cost, integration expertise

Engineering for Systemic Safety

Approach to safety considers whole system

- **Rotor failure is only one aspect**
- **Containment and Assuring rotor integrity over life are alternatives and are not required simultaneously**
- **Rotor burst testing is essential to assure engineering margin**
- **All testing uses production rotors and equipment**
- **All testing is at full scale**

Key Objective: Engineered basis that is fully understood and supported by the end user

Criteria for operation without containment

1. **Design margin**
   - *Apply relevant accepted criteria*
     - Margin: 2.00 -> op. 70.7% of burst
     - Margin: 2.40 -> op. 64.5% of burst
   - *Design margin qualification test*
     - Set of burst tests
       - Statistically valid sample size
   - *Cycle test*
     - Coupon and rotor tests

2. **Physical and operational rotor safety**
   - *Assure snubbing of loose rotor event*
     - Bushing/bearing restraint of spindle
     - Demonstrate rotor drop at full speed
   - *Withstand externally applied loads*
     - Demonstrate full speed operation in upset condition
   - *Protection against overspeed*
     - Controller specific safety plan
     - Demonstrate protection:
       - Set software to allow overspeed
       - Elevated bus voltage

3. **System fault tolerance**
   - *Assure system safety under fault conditions*
   - Demonstrate with physical faults:
     - Loss of vacuum
     - Loss of coolant (for liquid cooled systems)
     - Loss of DSP/microprocessor control voltage
     - Loss of mag bearing control voltage
     - Stator dead short
     - Loss of sensed signals (e.g. phase angle, bearing temperature, etc.)

4. **Homology**
   - Test system and deployed system equivalent

5. **Proof testing (every system)**
   - *Rotor margin*
     - Operate flywheel at 120% of design speed
   - *System fault*
     - Demonstrate automatic shutdown for subset of faults

6. **Documentation and acceptance**

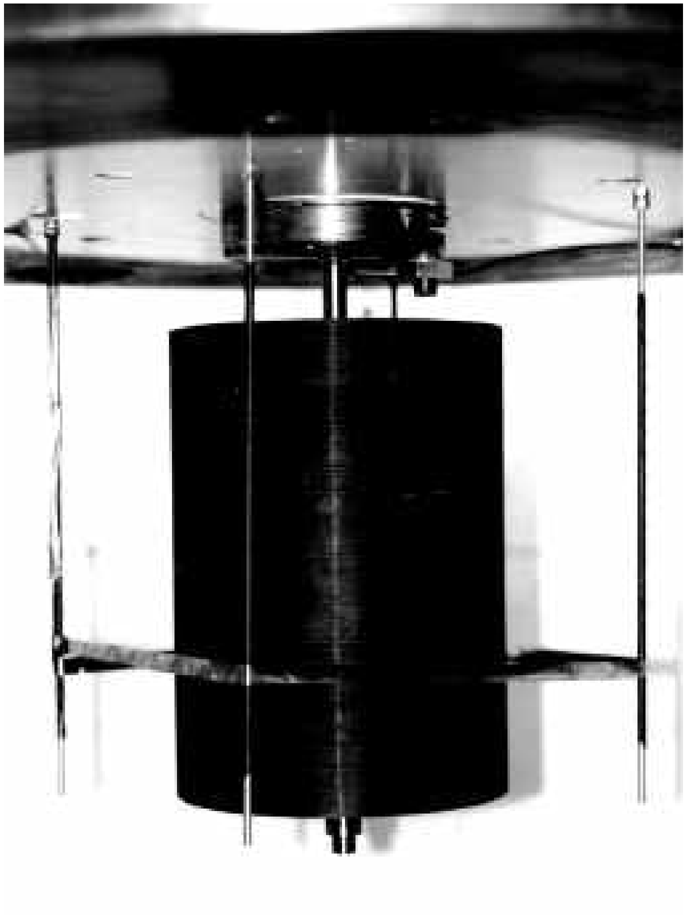
Typical Rotor Burst Testing

Burst testing is essential

- Otherwise margin is inferred

Dedicated spin test facility

- Quill shaft suspension/turbine drive
- Preferred manufacturer and operator:
  Test Devices, Incorporated



Key diagnostics

- Speed
- Displacement (quill and rotor)
- In-pit high speed video
  13,500 frames per second

One Example of Successful Cooperation

Flywheel Safety and Containment Group

- **Participants**
  - Management: Southern Coalition
  - Developers: Beacon Power (Satcon)
Trinity Flywheel Power
U. S. Flywheel Systems
University of Texas CEM
  - Testing: Test Devices

- **Activities and Results**
  - Each developer submits test articles and shares results within group
  - Cooperation has been stable since inception, for 4 years
  - Scope now includes life testing