Center for Electromechanics
Energy Storage and Pulsed Power Research

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Presentation Overview

• CEM Introduction
• Pulse Power and Power Electronics
• Flywheel Energy Storage Systems
• Modeling, Simulation and Analysis Capabilities
University of Texas
Center for Electromechanics

CEM

- $12M-$18M industry and government sponsored R&D per year
- Leading edge, applied, multi-disciplinary engineering
- Emphasis on one-of-a-kind hardware demonstrations
- ~100 full time research staff
- Core expertise in energy conversion, flywheel energy storage, high performance electromechanical systems, and controlled actuation systems

Active Suspension Demonstration
2.5 GW Pulse Power Generator
12 Ton Precision Robot
CEM High-Bay Lab Facility
3 MW Turbine-Driven Generator
40,000 RPM Flywheel on Magnetic Bearings
CEM Power Management Systems for Military Applications

Super Conducting Homopolar Generator
13 kW, 0.9 kW-h
(1986)

Iron Core Compulsator
800 MW, 10.5 kW-h
(1987)

Composite Rotor Compulsator
664 MW, 2.5 kW-h
(1991)

Composite Rotor Compulsator
2.4 GW, 11 kW-h
(1995)

Composite Rotor Compulsator
3 GW, 6.4 kW-h
(1997)
EM Gun Power Supply and Energy Storage History

[Diagram showing stored energy density over time with various markers for different systems such as Small Caliber, SSFTP, SCEML, CCEML, ICC, Iron Core, and Cannon Caliber. The diagram also indicates present and future PA development with an arrow pointing forward.]
• 12,000 rpm
• 175 KA Peak Field
• 7 KV Peak Voltage
• Composite Arbors
• Actively Cooled (DI H₂O)
• 500 m/s tip speed
• 840 kg
• 46 MJ Stored Energy
• 1.87 m Length (shaft)
• 1.0 m Length (Rim)
• 160 C Outer Banding
• 1 Torr Operation
Pulsed Power Switch Development

Before

After

Diagram showing the development of a pulsed power switch.
Switch Development Continued with SiC and SGTOs

Individual Switch Characterization – ARL

Packaging

Integrating in Pulsed Power System
Power Electronics

- ALPS hybrid power system
  - 3 MW passive rectifier
  - 2 MW bi-directional converter
    - ARCP soft switching
- Multiple generations of EM gun switches and field controllers
  - Pulsed duty at GW power levels
  - Self excitation and energy recovery
- Novel packaging and thermal management designs
1999 state of the art technology metrics critical to the success of EMALS:

- **Motor Shear Stress**: 7-15 psi
- **PCS Power Density**: 5kW/kg
- **ESS Power** or **Energy Density**: 3-5 kW/kg or 2-5 KJ/kg

Navy’s required metrics, all 2-5 times 1999 state-of-the-art:

- **Motor Shear Stress**: > 30 psi shear stress
- **PCS Power Density**: > 10 kW/kg
- **ESS Power** and **Energy Density**: > 3 kW/kg and 5.0 kJ/kg

Demonstrated metrics:

- **Motor Shear Stress**: 33-37 psi
- **PCS Power Density**: 16 kW/kg
- **ESS Power** and **Energy density**: 3.1 kW/kg and 5.8 kJ/kg
Flywheel Topologies

Non-Integrated Topology
- Larger than other topologies, but may have most simple assembly
- Maximum use of conventional M/G systems and technology
- Flexible / adaptive design
- Power generation outside of vacuum
- Requires shaft seal and coupling

Partially-Integrated Topology
- Smaller and more efficient than non-integrated
- Good use of available M/G technology, but integration required
- Good design adaptability
- Favors use of PM generator
- Heat generation on rotor requires careful engineering

Fully-Integrated Topology
- Most compact system
- Special purpose flywheel system
- Favors use of PM generator
- Heat generation on rotor requires special engineering
- Rotating magnets at large radius
- Uses arbor or magnetic bearings to match rotor growth
Battery systems offer advantages where high energy density is the primary concern.

Flywheel systems offer advantages where shorter discharge times and very high cycle life are also of high importance.
Range of CEM Flywheel Systems Designs

**Transit Bus Flywheel**
150-250 kW (peak), 100 kW (cont.), 2 kW-h

**Combat Hybrid Power Systems (CHPS) Flywheel**
5-10 MW (peak), 350 kW (cont.), 7 kW-h

**Space Station Flywheel (FESS)**
\(~5.0\) kW (peak), 3.66 kW (cont.), 3.66 kW-h

**Advanced Locomotive Propulsion System Flywheel**
3 MW (peak), 2 MW (cont.), 130 kW-h
## FLYWHEEL COMPARISON

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NASA FESS</th>
<th>ALPS System</th>
<th>Bus System</th>
<th>CHPS System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
<td>Energy Storage</td>
<td>Load Leveling</td>
<td>Load Leveling</td>
<td>Leveling/Pulsed</td>
</tr>
<tr>
<td><strong>Energy Stored (kWhr)</strong></td>
<td>3.6</td>
<td>133</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td><strong>Peak Power (kW)</strong></td>
<td>5</td>
<td>2,000</td>
<td>150</td>
<td>5,000</td>
</tr>
<tr>
<td><strong>Typical Discharge Time</strong></td>
<td>30 minutes</td>
<td>~3 minutes</td>
<td>30 seconds</td>
<td>3 seconds</td>
</tr>
<tr>
<td><strong>Rotational Speed (RPM)</strong></td>
<td>53,000</td>
<td>15,000</td>
<td>40,000</td>
<td>20,000</td>
</tr>
<tr>
<td><strong>Machine Weight (lbs)</strong></td>
<td>250</td>
<td>19,000</td>
<td>450</td>
<td>1,100</td>
</tr>
<tr>
<td><strong>Motor/Generator</strong></td>
<td>Permanent Magnet</td>
<td>Induction</td>
<td>Permanent Magnet</td>
<td>Permanent Magnet</td>
</tr>
<tr>
<td><strong>Topology</strong></td>
<td>Partially Integrated</td>
<td>Non-Integrated</td>
<td>Partially Integrated</td>
<td>Fully Integrated</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>Cold Plate</td>
<td>Air/Oil and Water</td>
<td>Oil and Water</td>
<td>Oil</td>
</tr>
<tr>
<td><strong>Bearings</strong></td>
<td>Homopolar Magnetic</td>
<td>Homopolar Magnetic</td>
<td>Homopolar Magnetic</td>
<td>Homopolar Magnetic</td>
</tr>
<tr>
<td><strong>Backup Bearing Duty</strong></td>
<td>Limited</td>
<td>Limited</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td><strong>Gimbal</strong></td>
<td>NA (Torque Balanced)</td>
<td>Required</td>
<td>Required</td>
<td>Required</td>
</tr>
<tr>
<td><strong>Flywheel Design</strong></td>
<td>CEM Cylindrical</td>
<td>CEM Cylindrical</td>
<td>CEM Cylindrical</td>
<td>CEM Mass Loaded</td>
</tr>
<tr>
<td><strong>Rotor Tip Speed (m/s)</strong></td>
<td>920</td>
<td>1,015</td>
<td>935</td>
<td>600</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>RSL &amp; NDE</td>
<td>RSL &amp; Containment</td>
<td>RSL&amp;Containment</td>
<td>RSL</td>
</tr>
</tbody>
</table>
• Dual use flywheel energy storage system
  – “Inside-out” arbor-less technology
  – Continuous duty and pulse loads for offensive and defensive systems
  – Rotor assembly and material property matching key for life requirements

• Demonstrated
  – Assembly of multi-pole magnetic rotor subassembly
  – Assembly of full scale, liquid cooled stator
  – Static torque, voltage, and cooling testing
  – Full scale magnetic bearing under static load with simulated rotor growth
Combat Hybrid Propulsion System (CHPS – Navy)

Technical Objectives

• Adapt CHPS-A design and optimize for ship powertrain (60 Hz, shipboard 1800 RPM generator or high speed, 7,000 RPM generator).

• Emphasizes safety, focused on significant and credible failures.

• Bring the CHPS-N design to advanced state, supported by appropriate risk mitigation experiments.

15 Month Schedule

• Requirements definition: 2 months

• Configure CHPS-A for CHPS-N requirements: 5 months

• Safety/containment trade study: 1 month

• Design and risk mitigation experiments: 7 months

Features

• Smallest mass and volume topology – fits through 26” hatch

• Flexible mission support – pulse power, power quality and load leveling

• Capable of low power levels for ride-through during power outages – allows chemical stores to come on line

• Design can be scaled down or up

• Very long cycle life – can minimize cycling of chemical energy storage components

• Exploits recent advances in composite materials to enable high tip speeds – key enabler for very high power density generators.

• Exploits the CHPS-A permanent magnet (PM) cartridge technology to allow survival at high tip speeds – another key enabler for very high power density generators.

• Exploits the CHPS-A inside-out magnetic bearing technology to allow high rotor rotational speeds, even for large rotors – a third key enabler for very high power density generators.

• Potentially can exploit CEM composite arbor technology developed under NASA funding, Army pulse power funding, and Federal Railroad Administration funding.

• Represents significant advancement in state-of-the-art that can benefit other Navy applications.
Transit Bus Flywheel

Energy Storage: 2 kWhr stored, 1 kWhr delivered
Power: 150 kW peak, 110 kW cont.,
Between 30,000 and 40,000 RPM

Composite tip speed: 930 m/s at 40,000 rpm
Application: Power averaging for 15 ton Hybrid Electric Bus

Materials
- Aluminum
- Ceramic
- Permanent Magnet
- Windings
- Titanium
- Inconel
- Composite
- Stainless Steel
- Steel

Backup Bearings
Radial Bearing
Stator Winding
Permanent Magnet Rotor
Composite Flywheel
Combo Bearing
Flywheel Safety and Containment

DARPA $: CEM led Flywheel Safety and Containment Consortium
NASA $: Fatigue Testing and Standards Development

- CEM, Test Devices Inc (Spin/burst test facility), commercial flywheel manufacturers, Oak Ridge & Sandia National Labs
- Experimental and analytical based program
  - Extensive burst testing; numerous flywheel designs
  - Fatigue testing (>112,00 full charge discharge cycles on CEM wheel)
- Rotor Safe-Life Design
  - Material QA and manufacturing processes
    - CEM developed hydroburst testing to measure strain-to-failure
    - Mil-Hdbk-17 Statistical Analysis defines allowable stresses
    - Creep testing – characterize viscoelastic behavior
    - Focus on end of life design
    - CEM flywheel press fit ring technology limits burst events to outer ring only – no cascade failures
- CEM containment
  - Lightweight composite, rotatable structure contains burst energy
  - Dissipates rotational energy over extended time
Why Use Flywheels for ISS?

Operations advantages
- Higher round trip efficiency
- Known state-of-charge
- Offer more flexibility in charge/discharge profiles
- Doubled contingency power (energy)

Significant life cycle cost savings
- Reduced logistics (up-mass & down-mass)
- Reduced maintenance (EVA- IVA Hr/Yr)

<table>
<thead>
<tr>
<th>FW (+ Electronics)</th>
<th>Battery (+ Electronics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power</td>
<td>4.1 kW</td>
</tr>
<tr>
<td>Peak Power</td>
<td>6.6 kW</td>
</tr>
<tr>
<td>Energy Delivered</td>
<td>5.6 kW-hr</td>
</tr>
<tr>
<td>Contingency Power</td>
<td>2 orbits</td>
</tr>
<tr>
<td>Life Expectancy</td>
<td>&gt;15 years</td>
</tr>
</tbody>
</table>
ALPS Energy Storage Flywheel

- **Performance**
  - Max. Speed – 15,000 rpm
  - Stored/Delivered Energy – 480/360 MJ
- **Flywheel Characteristics**
  - Assembly weight – 8,800 kg
  - Diameter/Length – 1.5 m Ø x 2.8 m
- **Active magnetic bearings**
  - 3 g dynamic load capacity
- **Containment system**
  - Composite containment liner
- **High speed vacuum seal**
- **Flywheel Motor/Generator**
  - Squirrel cage induction machine
  - Continuous duty, 7,500 and 15,000 rpm
CEM HTSMB Flywheel System

Fully integrated, inside-out design – most energy dense.

HTSMB journal bearing configuration – facilitates scaling to larger flywheels by lengthening bearings.

25kW-hr; 25kW flywheel – good initial system; good compromise system for launch; community energy storage near-term application.
HTS Development for Flywheel Systems

- Experimental validation of the inside-out HTS journal bearings at large scale
- Integration and testing in complete flywheel system
- Future integration of HTS motor-generator

CEM, UH, and TECO Westinghouse radial flux superconducting motor using 17mm TFMs (Oct, 2006)
High Power Energy Storage Systems

Energy Flywheel
4 MW; 479 MJ

Pulse Power Flywheel
3 GW; 23 MJ

Pulse Capacitor Bank
0.5 GW; 10 MJ

Power numbers are nominal – Energy numbers are stored
Modeling and Simulation
Modeling and Simulation

• Electric power system simulation
  – Electric Ship Research and Development Consortium (ESRDC)
    • Naval power system architectures and advanced generation, conversion and distribution technologies
  – LMMFC tactical operations center modeling tools
  – Hybrid electric propulsion systems
  – Army/Navy EM gun power systems

• Electromechanical system simulations
  – Coupled models: Control system in Matlab/Simulink, directly transferred through autocode generation to final controller hardware; plant dynamics in SimMechanics or LMS DADS
  – Vehicle active suspension systems
  – HETDEX instrument package tracking system
Structural Analysis

- Structural analyst
  - Steve Manifold
- Finite Element Analysis
  - Static and Transient
  - 2D, Axisymmetric, 3D
  - Coupled thermal/mechanical/magnetic
- SolidWorks Simulation
- Patran
- ABAQUS™
- CEMWind
  - Composites design suite
Rotordynamics Analysis

- Rotordynamics analyst
  - Dr. Brian Murphy
- TXROTOR FEA
  - 2D axisymmetric code
  - Isotropic, anisotropic
  - Metallic & composite rotors
  - Coupled with CEMWIND and other structural FEA codes
CEMWIND

FE Mesh & Material Property Files

Fiber Geometry Input into Filament Winding Machine

Arbor Ply Thickness Build Profile
Thermal Analysis

• Thermal analyst
  – Dr. Hsing Liu
• Finite Element Analysis
  – 2D, Axisymmetric, 3D
  – Static and transient
• SolidWorks Simulation
• FloWorks™
  – Coupled CFD / Thermal
• PATRAN™
• MacroFlow™
• In house windage codes
Electromagnetic Analysis

- Extensive library of commercial codes
  - Maxwell (Ansoft) suite of 2D & 3D EM FEA analysis
  - Integrated Engineering Software – Faraday & Oersted
  - Vector Fields
  - Comsol – Matlab based physics module
  - Matlab/Simulink for lumped parameter models of systems and components

- In house capability of developing FEA/BEM codes for special applications that are not covered by commercial codes
  - Modeling type II bulk superconductors
  - Simulation of Dielectric breakdown phenomenon
HTSMB Modeling Considerations

- **Type of Models**
  - **Meissner model**
    - Zero magnetic permeability
    - London penetration skin depth
  - **Frozen image model**
    - Accounts for force and stiffness
    - Does not predict hysteresis and saturation
    - Can be implemented on many standard FEA codes
  - **Critical State model**
    - May assume current only at $J_c$ or with $J_c$ dependent on magnetic field
    - Not available on most FEA codes

- **CEM Approach**
  - **Frozen image model**
  - **Integrated Engineering Software**
    - Oersted 2D
    - Faraday 3D
    - Validate against published designs