Flywheel energy storage systems
ECE-620 Ultra-wide-area resilient electrical energy transmission networks

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Outline

- General description of energy storage systems
- Flywheel modeling
- Application of flywheels to improve power system dynamics
1. Introduction

Example of storage systems:

- Pumped hydro-power
- Flywheels
- Solid state batteries (Li-Ion, Ni-Cd, NAS)
- Flow batteries (Redox, Vanadium Redox, Zinc-Bromine)
- Compressed air energy
- Thermal (Pumped heat electrical storage, hydrogen energy storage)
# 1. Introduction

<table>
<thead>
<tr>
<th>Technology</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>P.A.</th>
<th>E.A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped hydro-power</td>
<td>High E and low cost</td>
<td>Special location</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Flywheels</td>
<td>High P</td>
<td>Low E</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Electrochemical capacitors</td>
<td>Long lifespan</td>
<td>Low E</td>
<td>⊗</td>
<td></td>
</tr>
<tr>
<td>Lead-acid battery</td>
<td>Low cost</td>
<td>Reduce lifespan</td>
<td>⊖</td>
<td>⊙</td>
</tr>
<tr>
<td>NAS Battery</td>
<td>High P and E</td>
<td>High cost and temp</td>
<td>⊗</td>
<td>⊗</td>
</tr>
<tr>
<td>Li-Ion Battery</td>
<td>High P and E</td>
<td>Cost and control system</td>
<td>⊗</td>
<td>⊖</td>
</tr>
<tr>
<td>Compressed air</td>
<td>High E and low cost</td>
<td>Special location</td>
<td>⊗</td>
<td></td>
</tr>
</tbody>
</table>

⊕  Feasible and reasonable  
⊗  Feasible for this application  
⊙  Feasible but economically unattractive
P  Power  
E  Energy  

Source: Energy Storage Association
## 1. Introduction

<table>
<thead>
<tr>
<th>Technology</th>
<th>Energy density (Wh/Kg)</th>
<th>Power density (W/Kg)</th>
<th>Life cycles</th>
<th>Time response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped hydro-power</td>
<td>0.3-1.5</td>
<td>—</td>
<td>&gt;25 yrs</td>
<td>min</td>
</tr>
<tr>
<td>Flywheels</td>
<td>5-70</td>
<td>1,000-5,000</td>
<td>&gt;20,000</td>
<td>ms</td>
</tr>
<tr>
<td>Electrochemical capacitors</td>
<td>5-25</td>
<td>&gt;1,000</td>
<td>&gt;20,000</td>
<td>&lt; ms</td>
</tr>
<tr>
<td>Lead-acid battery</td>
<td>20-45</td>
<td>25-100</td>
<td>200-2,000</td>
<td>s</td>
</tr>
<tr>
<td>NAS Battery</td>
<td>120-240</td>
<td>120-220</td>
<td>3,000-9,000</td>
<td>s</td>
</tr>
<tr>
<td>Li-Ion Battery</td>
<td>100-200</td>
<td>360</td>
<td>500-4,000</td>
<td>s</td>
</tr>
<tr>
<td>Compressed air</td>
<td>10-30</td>
<td>—</td>
<td>&gt;25 yrs</td>
<td>min</td>
</tr>
</tbody>
</table>

Source: R. Cardenas, *An overview of systems for the storage of electrical energy, Workshop on Storage Systems, University of Chile, 2014*
1. Introduction

Pumped-hydro power (for E.A.)

- Water is sent to the upper pond when the marginal cost is low
- The hydro potential is reserved for the hour when the marginal cost is high
- The pump-generation cycle has an efficiency around 70

In general...

If there exists an hour $k$ with a high marginal cost ($\lambda_k$) and an hour $i$ with a low marginal cost ($\lambda_i$) such that $\lambda_k > \frac{\lambda_i}{\eta}$ the use of the pumped hydro storage system is economically attractive.
1. Introduction

Example: Okinawa Yanbaru Pumped-Hydro Power Plant

- First high head seawater pumped-hydro power plant
- Maximum output 30MW
- Maximum discharge of 26 $m^3/s$
- Upper pond is artificial, 150 m over the sea level, and 25 m deep
- Lower reservoir is the Philippine Sea
1. Introduction

Flywheels (for P.A.)

- Store rotational kinetic energy in a rotating cylinder or disc
- The amount of stored energy depends on the flywheels mass and speed
- Increasing the rotational speed allows storing more energy, but stronger materials are needed to avoid desintegration
- To keep the energy for hours, mechanical friction needs to be reduced (flywheels with mechanical-bearing may even lose 50% of energy in a couple of hours)
- High efficiency (>80%), long lifespan (∼20 years) and low operational and maintenance costs
1. Introduction

Example: Stephentown Flywheel Plant, 20 MW, NY

- With 200 flywheels, began operation in January 2011
- Provides frequency regulation (\(\approx 30\%\) of the NYISO ACE correction)
- Flywheels perform between 3,000 to 5,000 full discharge cycles a year
1. Introduction

Components and arrangement Source: Beacon Power LLC
1. Introduction

Components and arrangement Source: Beacon Power LLC

Representative Flywheel Energy Storage Module

- 480V Switchgear & Cluster Controller
- 480V Step-up Transformer
- Power Control Module
- Cooling System
- Flywheel Foundation (Flywheel inside)
1. Introduction

Components and arrangement *Source: Beacon Power LLC*
### Beacon Power 450 XP: Specifications

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>45 XP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid output/supply voltage</td>
<td>3 phase, 600 V rms</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>50/60 Hz</td>
</tr>
<tr>
<td>Nominal output rating</td>
<td>Up to 360 kVA</td>
</tr>
<tr>
<td>Overload output capability</td>
<td>150% of nominal real and reactive power for 10 seconds</td>
</tr>
<tr>
<td>Usable energy at full charge</td>
<td>36 kWh</td>
</tr>
<tr>
<td>Response time</td>
<td>15 ms or less from receipt of signal to start of changing output</td>
</tr>
<tr>
<td>Ramp time</td>
<td>Full output in 100 ms from receipt of signal</td>
</tr>
<tr>
<td>Round trip efficiency</td>
<td>85%</td>
</tr>
</tbody>
</table>
2. Flywheel modeling
2. Flywheel modeling

**Assumptions:** Surface permanent magnetic machine (SPMM), field oriented control, and a simplified representation for converters are considered.
2. Flywheel modeling

Mathematical representation of the FPAE:

\[
\frac{1}{\omega_b} L_d \frac{di_d}{dt} = v_d - r_s i_d + \omega_r L_q i_q
\]

\[
\frac{1}{\omega_b} L_q \frac{di_q}{dt} = v_q - r_s i_q - \omega_r (L_d i_d + \Phi_f)
\]

\[
2H \frac{d\omega_r}{dt} = T_m - \Phi_f i_q
\]

\[
C_{eq} \frac{dv_c}{dt} = \frac{\omega_r T_e}{v_c} - i_g
\]

\[
P_g = v_c i_g
\]

Open-loop fundamental FPAE model:

\[
2H \frac{d\omega_r}{dt} = -\Phi_f i_q
\]

\[
C_{eq} \frac{dv_c}{dt} = \frac{\omega_r \Phi_f i_q}{v_c} - i_g
\]

\[
P_g = v_c i_g
\]

where

\[
v_d = -\omega_r L_q i_q
\]

\[
v_q = \omega_r \Phi_f
\]
2. Flywheel modeling

Validation using PLECS:
2. Flywheel modeling

Model and controllers:

- **Plant-level frequency controller**
  
  \[
  f_{\text{ref}} + \frac{T_w s}{T_w s + 1}
  \]

- **SOC controller**
  
  \[
  \frac{1}{R}
  \]

- **P_{ref} controller**
  
  \[
  K_P + \frac{1}{T_P s}
  \]

- **Q controller**
  
  \[
  K_Q + \frac{1}{T_Q s}
  \]

- **GS converter**
  
  \[
  \frac{1}{T_C s + 1}
  \]

- **Current source model**
  
  \[
  (I_d + jI_q)e^{j\phi}
  \]

- **Active power loop**

- **Reactive power loop**

- **Diagram notations:**
  
  \[
  S_1, S_2, P_{\text{ref}}, P_{\text{meas}}, f_{\text{ref}}, f_{\text{meas}}, T_w, T_1, T_2, R, f_{\text{ref}}, f_{\text{meas}}, \omega, q, \Phi, I_d, I_q, I_{\text{max}}, I_{\text{min}}, V_t, I_{\text{q}}, K_P, K_Q, T_P, T_Q, T_C, \]
2. Flywheel modeling

Model and controllers:

(a) Active power loop
3. Application of flywheels to improve power system dynamics
3. Application of flywheels

Northern Chile Interconnected System (NCIS)

- **Installed capacity**
  - 4,150 MW

- **Total demand**
  - 2,400 MW

- **Mining companies**
  - 90% of total demand

- **H-constant inertia**
  - 3.86 s based on installed power

- **Renewable energy**
  - Solar (high potential)

- **Storage systems**
  - BESS, 12MW and 20 MW

- **Operational issues**
  - Frequency excursions (isolated)
  - Oscillations (interconnected)
3. Application of flywheels

Base case (high demand scenario)

Inter-area oscillation:

\[ \lambda = -0.012 + j2.297 \]
\[ f_{osc} = 0.37 \text{ [Hz]} \]
\[ \sigma = 0.53\% \]

All other modes have damping ratios above 10%.

BES plants have marginal effects on the inter-area mode damping due to limitations imposed by dead-bands.
3. Application of flywheels

Flywheel’s location analysis

\[
\dot{x}_1 = A_1 x_1 + B_1 u_1 \\
y_1 = C_1 x_1 \\
\dot{x}_2 = A_2 x_2 + B_2 u_2 \\
y_2 = C_2 x_2
\]

\{ \begin{align*}
\text{Open-loop system} \\
\text{Controller}
\end{align*} \}

Closing the loop:

\[ u_1 = y_2 \]
\[ y_1 = u_2 \]

\[ H(s) = C_2 M(s) B_2 \]
\[ M(s) = (sI - A_2)^{-1} \]

For a flywheel in bus \( \ell \):

\( y_1 \): Bus frequency
\( u_1 \): Flywheel active power
3. Application of flywheels

Flywheel's location analysis (eigenvalue and eigenvectors) If $\lambda$ is the inter-area eigenvalue of interest, then right and left eigenvectors of the open loop system are given by:

$$A_1 v = \lambda v \quad A_1^T w = \lambda w$$

In the closed-loop system:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_1 & B_2^T C_2 \\ B_2 C_1^T & A_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \Rightarrow A_{cl} \begin{bmatrix} v_{cl,1} \\ v_{cl,2} \end{bmatrix} = \lambda \begin{bmatrix} v_{cl,1} \\ v_{cl,2} \end{bmatrix}$$

By forcing $v_{cl,1} = v$ and $w_{cl,1} = w$ (open-loop eigenvectors), then $v_{cl,2} = M(\lambda)B_2 C_1^T v$ and $w_{cl,2}^T = w^T B_1^T C_2 M(\lambda)$.
### 3. Application of flywheels

**Flywheel's location analysis (eigenvalue and eigenvectors)** We can show that, in closed-loop, the sensitivity of the eigenvalue with respect to a parameter of the controller becomes:

\[
\lambda' = w_{cl}^T A_{cl}' v_{cl}
\]

\[
= w^T \begin{bmatrix}
I & B_1^\ell C_2^\ell M(\lambda) & B_1^\ell C_2'^\ell & I
\end{bmatrix} \begin{bmatrix}
0 & B_1^\ell C_2'^\ell & M(\lambda) B_2 C_1^\ell
B_1^\ell C_1'^\ell & A_2'^\ell & M(\lambda) B_2 C_1^\ell
\end{bmatrix} v
\]

\[
= w^T B_1^\ell \left( C_2'^\ell M(\lambda) B_2 + C_2 M(\lambda) A_2'^\ell M(\lambda) B_2 + C_2 M(\lambda) B_2' \right) C_1^\ell v
\]

\[
= w^T B_1^\ell H(\lambda)' C_1^\ell v
\]

**MC**: Mode controllability

**MO**: Mode observability

\[MC^\ell \quad MO^\ell\]
3. Application of flywheels

Flywheel’s location analysis: Controllability index

\[ \lambda' = \underbrace{w^T B_1^\ell H(\lambda)'}_{MC^\ell} \underbrace{C_1^\ell v}_{MO^\ell} \]

Observations:
- \( H(\lambda) \) does not depend on the location
- \( MO^\ell \approx MO^m \) for any buses \( \ell \) and \( m \)
- \( \lambda' \) can be fairly considered to be proportional to \( MC^\ell \).

Thus, for location purposes, we define the controllability index as:

\[
CI^\ell = \frac{|MC^\ell|}{\max_k |MC^k|} = \frac{|w^T B_1^\ell|}{\max_k |MC^k|}
\]

The bus \( \ell \) with the highest controllability index would be the most attractive place to install a flywheel.
3. Application of flywheels

All 220 kV buses are considered as prospective locations of a flywheel plant.
3. Application of flywheels

All 220 kV buses are considered as prospective locations of a flywheel plant.

108 scenarios are considered based on load profiles and generation dispatch:

![Controllability index boxplot](CI_boxplot.png)
3. Application of flywheels

When a flywheel plant is connected to the buses, actual inter-area eigenvalue shows high agreement with respect to $CI$:

<table>
<thead>
<tr>
<th>Location</th>
<th>Eigenvalue</th>
<th>$f$ [Hz]</th>
<th>$\sigma$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No FES</td>
<td>$-0.012 + i2.297$</td>
<td>0.37</td>
<td>0.53</td>
</tr>
<tr>
<td>Parinacota</td>
<td>$-0.243 + i2.448$</td>
<td>0.39</td>
<td>9.9</td>
</tr>
<tr>
<td>P. Almonte</td>
<td>$-0.303 + i2.324$</td>
<td>0.37</td>
<td>12.0</td>
</tr>
<tr>
<td>Tarapaca</td>
<td>$-0.303 + i2.289$</td>
<td>0.36</td>
<td>13.1</td>
</tr>
<tr>
<td>Collahuasi</td>
<td>$-0.293 + i2.293$</td>
<td>0.36</td>
<td>12.7</td>
</tr>
<tr>
<td>Lagunas</td>
<td>$-0.295 + i2.282$</td>
<td>0.36</td>
<td>12.8</td>
</tr>
<tr>
<td>N. Victoria</td>
<td>$-0.294 + i2.284$</td>
<td>0.36</td>
<td>12.8</td>
</tr>
<tr>
<td>El Abra</td>
<td>$-0.283 + i2.319$</td>
<td>0.37</td>
<td>12.1</td>
</tr>
<tr>
<td>Tocopilla</td>
<td>$-0.294 + i2.228$</td>
<td>0.35</td>
<td>13.1</td>
</tr>
<tr>
<td>Andes</td>
<td>$-0.139 + i2.294$</td>
<td>0.37</td>
<td>6.0</td>
</tr>
</tbody>
</table>
3. Application of flywheels

Generators speed when flywheel plant is installed in two locations:

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Without FES</th>
<th>FES Andes</th>
<th>FES Tarapaca</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.992</td>
<td>1.002</td>
<td>1.008</td>
</tr>
<tr>
<td>2</td>
<td>0.994</td>
<td>1.004</td>
<td>1.006</td>
</tr>
<tr>
<td>4</td>
<td>0.996</td>
<td>1.006</td>
<td>1.008</td>
</tr>
<tr>
<td>6</td>
<td>0.998</td>
<td>1.008</td>
<td>1.008</td>
</tr>
<tr>
<td>8</td>
<td>1.002</td>
<td>1.002</td>
<td>1.002</td>
</tr>
<tr>
<td>10</td>
<td>1.004</td>
<td>1.004</td>
<td>1.004</td>
</tr>
</tbody>
</table>
3. Application of flywheels

Flywheel power for the aforementioned locations:

![Graph showing FES power over time for Andes and Tarapaca locations.](image-url)

Controllability index:
- ≥ 0.86
- 0.5
Conclusions

- Comprehensive electro-mechanical model for a flywheel plant has been derived.
- When applied to the NCIS, at the optimal location, the damping ratio of the inter-area mode is increased from 0.55% to 12.7%.
- The proposed controllability index does not strongly depend on operational conditions.
In page 23,

a. Derive equation (1)

b. Show that equations (3) and (4) are equals.
References


Acknowledgement

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Questions?