CURENT
CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

Flywheel energy storage systems

ECE-620 Ultra-wide-area resilient electrical energy transmission networks

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THE UNIVERSITY OF TENNESSEE KNOXVILLE Northeastern Rensselaer TUSKEGEE

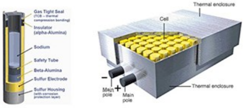
Outline

- 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)



Sodium-Sulfur (NaS) Batteries

1. Introduction

Technology	Advantage	Disadvantage	P.A.	E.A.
Pumped hydro-power	High E and low cost	Special location		⊕
Flywheels	High P	Low E	⊕	
Electrochemical capacitors	Long lifespan	Low E	⊕	
Lead-acid battery	Low cost	Reduce lifespan	⊕	⊙
NAS Battery	High P and E	High cost and temp	⊕	⊕
Li-Ion Battery	High P and E	Cost and control system	⊕	⊖
Compressed air	High E and low cost	Special location		⊕

⊕ Feasible and reasonable

⊖ Feasible for this application

⊙ Feasible but economically unattractive

P Power

E Energy

Source: Energy Storage Association

P.A. Power application

E.A. Energy application

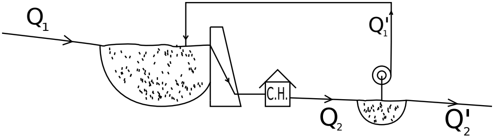
1. Introduction

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

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 (λ_k) and an hour i with a low marginal cost (λ_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 ($>$80%), long lifespan ($\approx$20 years) and low operational and maintenance costs

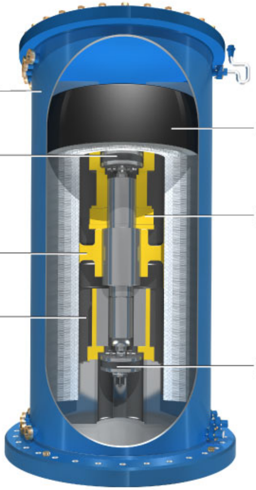
1. Introduction

Example: Stephentown Flywheel Plant, 20 MW, NY

- With 200 flywheels, began operation in January 2011
- Provides frequency regulation (≈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*



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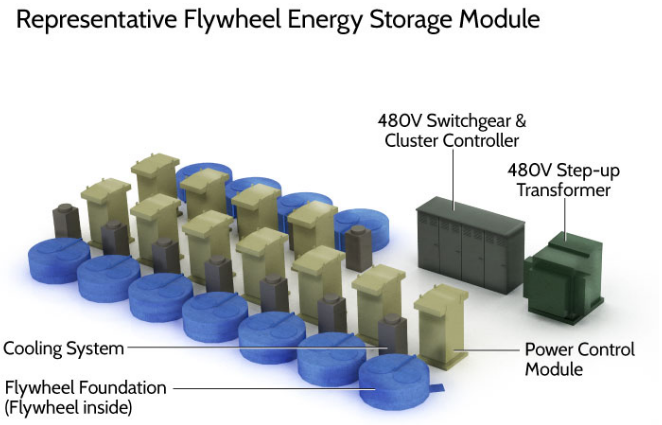

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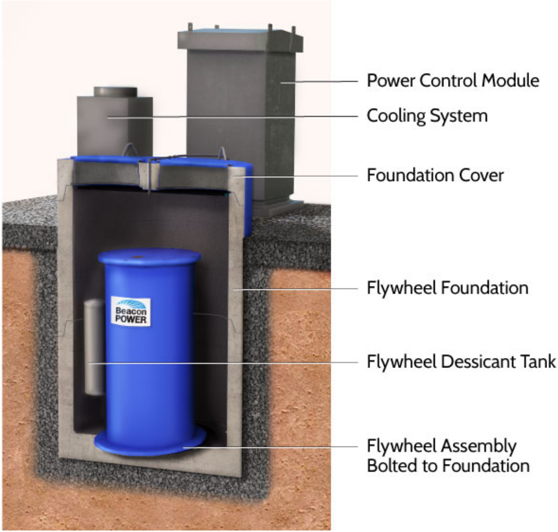


1. Introduction

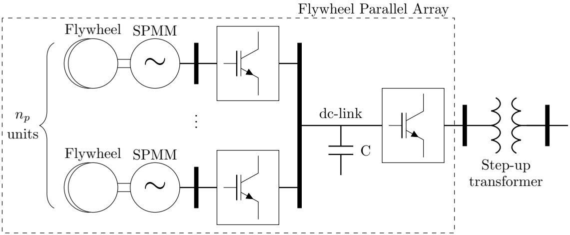
Beacon Power 450 XP: Specifications

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

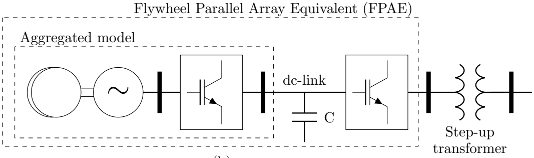
2. Flywheel modeling

2. Flywheel modeling

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



(a)



(b)

2. Flywheel modeling

Mathematical representation of the FPAE:

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

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

$$2H \frac{d\omega_r}{dt} = T_m - \underbrace{\Phi_f i_q}_{T_e}$$

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

$$P_g = v_c i_g$$

Open-loop fundamental FPAE model:

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

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

$$P_g = v_c i_g$$

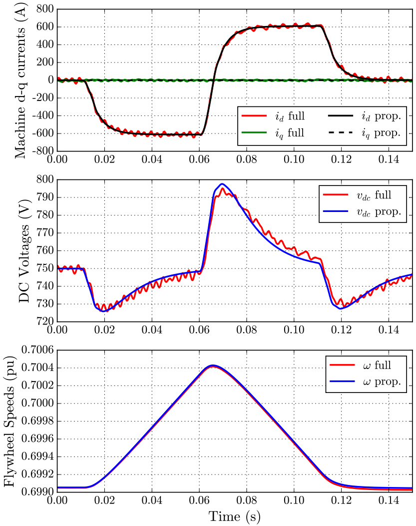
where

$$v_d = -\omega_r L_q i_q$$

$$v_q = \omega_r \Phi_f$$

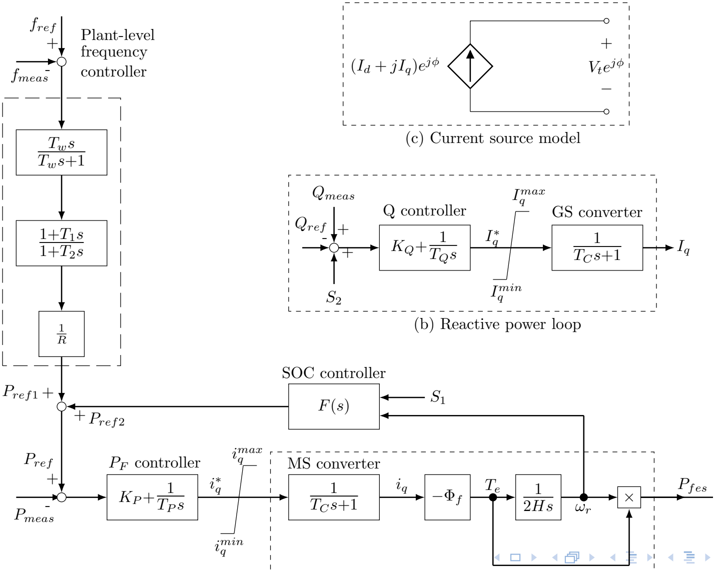
2. Flywheel modeling

Validation using PLECS:



2. Flywheel modeling

Model and controllers:

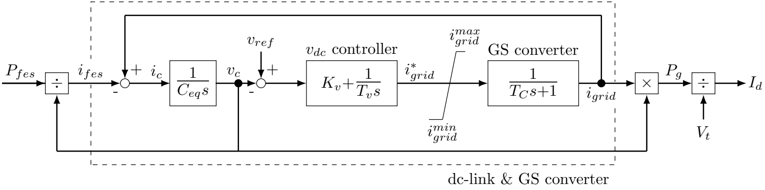


(c) Current source model

(b) Reactive power loop

2. Flywheel modeling

Model and controllers:



(a) Active power loop

3. Application of flywheels to improve power system dynamics

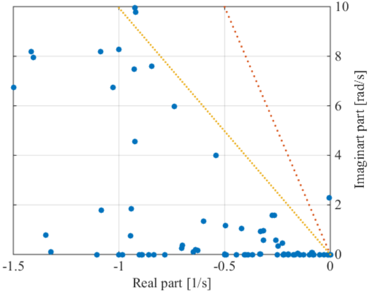
3. Application of flywheels

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%.

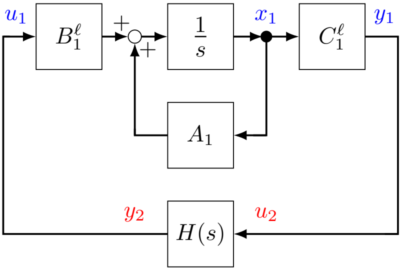
BES plants have marginal effects on the inter-area mode damping due to limitations imposed by dead-bands.

3. Application of flywheels

Flywheel's location analysis

$$\left.\begin{aligned}\dot{x}_1 &= A_1 x_1 + B_1 u_1 \\ y_1 &= C_1 x_1\end{aligned}\right\} \text{Open-loop system}$$

$$\left.\begin{aligned}\dot{x}_2 &= A_2 x_2 + B_2 u_2 \\ y_2 &= C_2 x_2\end{aligned}\right\} \text{Controller}$$



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 ℓ:

y_1: Bus frequency

u_1: Flywheel active power

3. Application of flywheels

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

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

In the closed-loop system:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} A_1 & B_1^\ell C_2 \\ B_2 C_1^\ell & A_2 \end{bmatrix}}_{A_{cl}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \Rightarrow A_{cl} \begin{bmatrix} v_{cl,1} \\ v_{cl,2} \end{bmatrix} = \lambda \begin{bmatrix} v_{cl,1} \\ v_{cl,2} \end{bmatrix}$$

$$\begin{bmatrix} w_{cl,1}^T & w_{cl,2}^T \end{bmatrix} A_{cl} = \lambda \begin{bmatrix} w_{cl,1}^T & w_{cl,2}^T \end{bmatrix}$$

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

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:

$$\lambda' = w_{cl}^T A_{cl}' v_{cl} \quad (1)$$

$$= w^T \begin{bmatrix} I & B_1^\ell C_2 M(\lambda) \end{bmatrix} \begin{bmatrix} 0 & B_1^\ell C_2' \\ B_2' C_1^\ell & A_2' \end{bmatrix} \begin{bmatrix} I \\ M(\lambda) B_2 C_1^\ell \end{bmatrix} v \quad (2)$$

$$= w^T B_1^\ell \Big(C_2' M(\lambda) B_2 + C_2 M(\lambda) A_2' M(\lambda) B_2 + C_2 M(\lambda) B_2' \Big) C_1^\ell v \quad (3)$$

$$= \underbrace{w^T B_1^\ell}_{MC^\ell} H(\lambda)' \underbrace{C_1^\ell v}_{MO^\ell} \quad (4)$$

MC: Mode controllability
MO: Mode observability

3. Application of flywheels

Flywheel's location analysis: Controllability index

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

Observations:

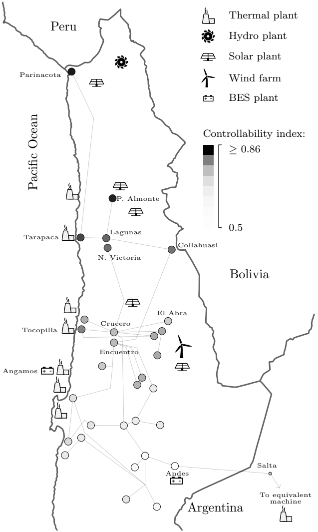
- $H(\lambda)$ does not depend on the location
- $MO^\ell \approx MO^m$ for any buses ℓ and m
- λ' can be fairly considered to be proportional to MC^ℓ.

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

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

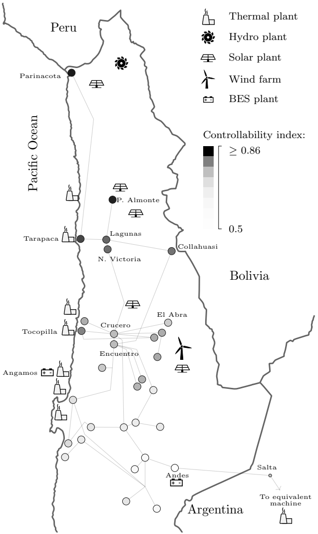
The bus ℓ with the highest controllability index would the most attractive place to install a flywheel.

3. Application of flywheels



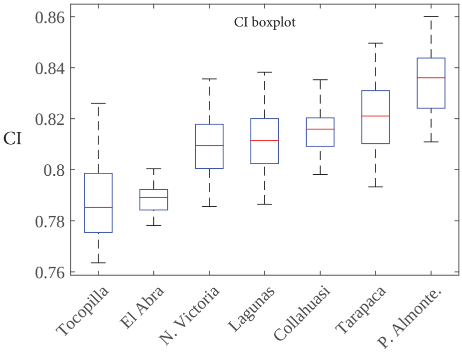
All 220 kV buses are considered as prospective locations of a flywheel plant.

3. Application of flywheels

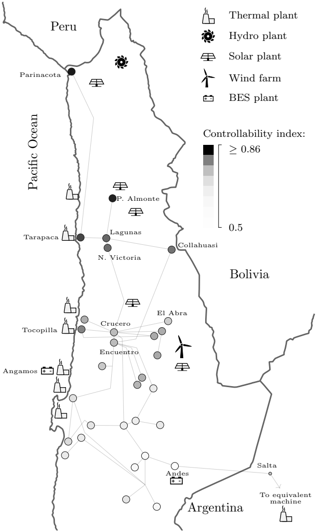


All 220 kV buses are considered as prospective locations of a flywheel plant.

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



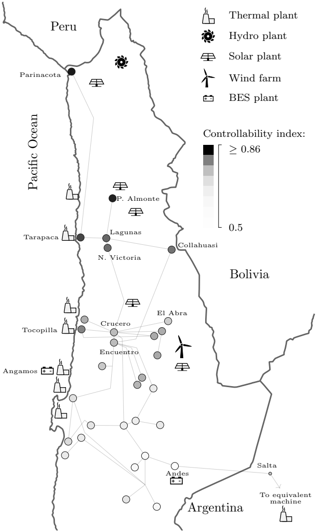
3. Application of flywheels



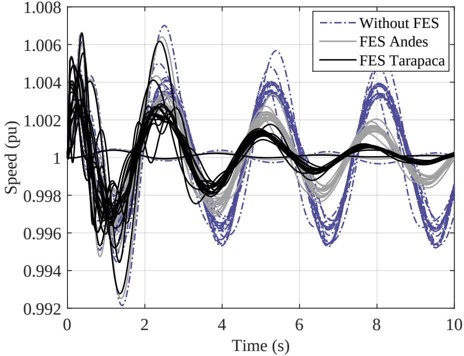
When a flywheel plant is connected to the buses, actual inter-area eigenvalue shows high agreement with respect to CI:

Location	Eigenvalue	f [Hz]	σ [%]
No FES	$-0.012 + i2.297$	0.37	0.53
Parinacota	$-0.243 + i2.448$	0.39	9.9
P. Almonte	$-0.303 + i2.324$	0.37	12.0
Tarapaca	$-0.303 + i2.289$	0.36	13.1
Collahuasi	$-0.293 + i2.293$	0.36	12.7
Lagunas	$-0.295 + i2.282$	0.36	12.8
N. Victoria	$-0.294 + i2.284$	0.36	12.8
El Abra	$-0.283 + i2.319$	0.37	12.1
Tocopilla	$-0.294 + i2.228$	0.35	13.1
Andes	$-0.139 + i2.294$	0.37	6.0

3. Application of flywheels



Generators speed when flywheel plant is installed in two locations:



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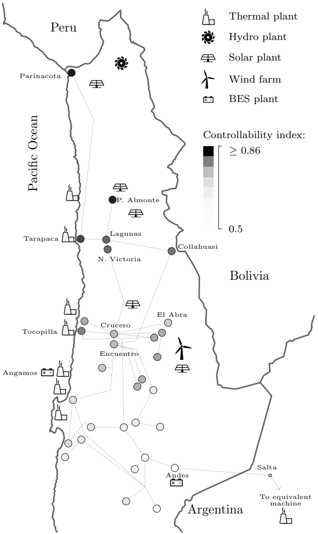
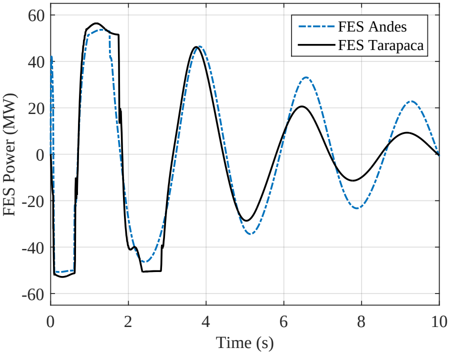


Flywheel power for the aforementioned locations:



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 depends on operational conditions.

Homework

In page 23,

a. Derive equation (1)

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

References

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Thanks for your attention

Questions?