Energy storage for stability enhancement in systems with high wind penetration

Claus Nygaard Rasmussen

Institute of Energy Technology
Aalborg University, Denmark
Energy storage areas of interest

• Application areas – the role of energy storage in the network
• Storage technology overview, applications and limitations
• Relation between energy storage capacity and the effect on wind power
• Cost/benefit of storage – How much benefit do we get from storage
• Storage operation schemes (modelling and laboratory testing)
• Battery operation and online lifetime estimation (modelling and laboratory testing)
Energy storage technologies

Energy storage

- Electromagnetic
  - Ultra capacitors
    - SMES
  - Flywheels
    - High speed
    - Low speed
- Mechanical
  - Pumped Hydro
    - Over ground
    - Underground
  - Compressed air
    - Adiabatic
    - Non-adiabatic
- Thermal
- Electro-chemical
  - Flow batteries
    - Vanadium-redox
    - Zn-Br
  - Batteries
    - Lead acid
    - Ni-Cd
    - Li-ion
    - NaS (high temp.)
    - Metal-air
    - Ultra batteries

Small capacity
~Minutes

Large capacity
>Weeks

Medium capacity
~Hours
# Energy storage application areas

1. Reducing conventional generation. Increasing the overall wind penetration level by capturing and storing excess wind power for use at times with low wind.

2. Ensuring stability by reducing wind power fluctuation rates to a level that can be handled by the fully controllable generation remaining in the grid.

3. Ancillary services – services that storage may provide to the grid in order to improve power quality in general, or reduce the consequences of serious grid events. Short timescale services.

<table>
<thead>
<tr>
<th>Application</th>
<th>Power [p.u.]</th>
<th>Time [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load following</td>
<td>1</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Tertiary reserve</td>
<td>1</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Power levelling</td>
<td>0.7</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Energy arbitrage</td>
<td>0.5</td>
<td>12</td>
</tr>
<tr>
<td>Forecast improvement</td>
<td>0.25</td>
<td>12 – 24</td>
</tr>
<tr>
<td>Stability enhancement</td>
<td>0.5</td>
<td>1 – 10</td>
</tr>
<tr>
<td>Peak shaving</td>
<td>0.7</td>
<td>1 – 10</td>
</tr>
<tr>
<td>Reserve power</td>
<td>0.5 - 1</td>
<td>5 – 10</td>
</tr>
<tr>
<td>Inertia enhancement</td>
<td>0.2</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Frequency regulation</td>
<td>0.2</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Soft stop</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>Black start</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Voltage stabilisation</td>
<td>-</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Low voltage ride through</td>
<td>0.1</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>
Grid stability – $\Delta p/\Delta t$ reduction

Controllable generation

$\Sigma P \sim 0$

Grid

Wind

Energy storage

Loads (Partly controllable)
Grid stability – $\Delta p/\Delta t$ reduction

Fluctuations – Western Denmark

- Load variations
- Wind - penetration 20%
- Wind - penetration 50%
- Wind - penetration 70%
The nature of wind power variations

Spectral power density of wind

- Van der Hoven plot
- Local effects: < ~1 hour
- 12 hours
- 24 hours
- 1 year
- Weeks / months
The nature of wind power variations

Power spectrum

$P(f) \propto f^{-1}$

Amplitude [p.u.]

Time scale [hours]

Wind power

Wind + storage
Storage operation scheme

Wind \[ P_w \] \rightarrow \text{Storage} \[ H_s(s) \] \rightarrow \text{Grid} \[ P_t \]

- Storage
- Voltage
- Current
- Frequency

Feed forward

\[ P_w \rightarrow H_s(s) \rightarrow P_t \]

Feed back

\[ P_w \rightarrow P_s \rightarrow H_s(s) \rightarrow P_t \]
Storage operation scheme

Discharge ($P_s > 0$):
\[
\frac{dE_s}{dt} = -\frac{P_s}{\varepsilon(P_s, E_s)}
\]

Charge ($P_s < 0$):
\[
\frac{dE_s}{dt} = -P_s \cdot \varepsilon(P_s, E_s)
\]

Power control:
\[
P_s = (P_{req} - P_w) + \frac{(E_s - E_{max} \cdot psoc)}{\tau}
\]
\[-P_{max} \leq P_s \leq P_{max}\]

Required power:
\[
P_{req} = \frac{1}{\Delta t} \int_{t_1}^{t} P_w dt
\]
(Or $P_{req}$ determined by system operator)

\(\tau\) – Time constant related to charge rate

\(psoc\) – Preferred state of charge

\(P_{max}\) – Storage power rating

\(E_{max}\) – Storage energy capacity

High availability:
\[
\tau_1 = \frac{4 \cdot E_s}{P_{avg}}
\]

Full dp/dt reduction:
\[
\tau_2 = \frac{E_s}{2 \cdot P_s}
\]
Modelling results

- Capturing excess energy - ES influence on wind penetration level
- Reduction of fluctuation rates (dp/dt)
- The influence of wind power aggregation
- Large scale variation reduction with storage
- High wind penetration system modelling
Capturing excess energy –

ES influence on wind penetration level

![Graph showing effective wind penetration vs. installed wind penetration]

- Effective wind penetration [% of consumption]
- Installed wind penetration [% of consumption]

Es [Hours of Pn]
Modelling results – fluctuation rates

Power variation rates

\[ \tau_{ch} = 20 \text{ min} \]

\[ P_s = \frac{1}{2} P_n \]

\[ \frac{E_s}{P_n} = 10 \text{ min} \]
Modelling results – fluctuation rates

\[ P_s = \frac{1}{2} P_n \]

\[ \frac{E_s}{P_n} = \frac{1}{2} \text{ hour} \]

\[ \tau_{ch} = 1 \text{ h} \]
Modelling results – fluctuation rates

Maximum power fluctuation rates with storage

Maximum variation ($\Delta P$) [p.u.]

Timescale
- 10 s
- 1 min
- 10 min
- 1 hour
- 4 hours

$P_s = \frac{1}{2} P_n$

Storage time ($E_s/P_n$)
The influence of wind power aggregation

\[ \sigma_{\text{total}} = \sigma_{\text{sum}} \]

D = 100 km, \( \tau = 1 \) h, \( v_{\text{avg}} = 8.5 \) m/s

\[ \sigma_{\text{total}} = \sigma \left( \sum_{i=1}^{N} P_i \right) \]

\[ \sigma_{\text{sum}} = \sum_{i=1}^{N} \sigma(P_i) \]

\[ \text{Corr} = \frac{\sigma_{\text{total}}}{\sigma_{\text{sum}}} \in \left[ \frac{1}{\sqrt{N}} ; 1 \right] \]

Distance factor \[ \frac{D}{\tau \cdot v_{\text{avg}}} \]
The influence of wind power aggregation

Single turbine vs. Western Denmark

Single turbine: $\sigma_s \sim 0.65$ p.u.
Western Denmark: $\sigma_{\text{tot}} \sim 0.37$ p.u.

$\text{Corr} = \frac{\sigma_{\text{total}}}{\sigma_{\text{sum}}} \approx 0.57$

Distance factor $\left[ \frac{D}{\tau \cdot v_{\text{avg}}} \right] \approx 3.2$

$D \sim 100 \text{ km}, \tau = 1 \text{ h}, v_{\text{avg}} \sim 8.5 \text{ m/s}$
Large scale variation reduction with storage

Maximum power gradients

\[ \frac{dp}{dt} \text{ - conventional generation} = 1 \text{ p.u. / 5h} \]

Storage capacity (Es) [Hours of Pn]

Installed wind penetration [% of consumption]
High wind penetration system modelling

Diagram:
- Wind
- Load (Constant impedance)
- Power plant (slow reaction)
- System voltage / frequency
- Storage (Fast reaction)
High wind penetration system modelling

\[ P_s = 0.5 \text{ p.u.} \quad E_s = \frac{1}{6} \text{ hour} \cdot P_s \quad \tau_1 = \frac{4 \cdot E_s}{P_{avg}} \approx \frac{2}{3} \text{ hour} \]
High wind penetration system modelling

\[ P_s = 0.4 \text{ p.u.} \hspace{1cm} E_s = \frac{1}{5} \text{ hour} \cdot P_s \hspace{1cm} \tau_1 = \frac{4 \cdot E_s}{P_{\text{avg}}} \approx \frac{2}{3} \text{ hour} \]
Conclusions

Storage application areas:

1) Energy management → better use of renewable sources (large capacity)
2) Stability enhancement → increased maximum wind penetration level (medium capacity)
3) Ancillary services (small to medium capacity)

Storage sizing for stability enhancement:

\[ E_s \sim \frac{1}{4} \cdot \tau \cdot P_{\text{avg}} \quad \tau = 1\text{h} - 10\text{h} \quad \Rightarrow \quad E_s = \frac{1}{4}\text{h} - 4\text{h} \text{ of nominal wind power} \]

\[ P_s \sim \frac{1}{2} \cdot P_n \]

Storage operation scheme:

1) Low-pass filter with cut of frequency \( f_0 = 1/\tau \)
2) Artificial inertia enhancement
3) Power on demand

Stability =>
- Aggregation
- Active loads
- Storage