Stochastic power management strategy for hybrid energy storage systems to enhance large scale wind energy integration

Prof. Linda BARELLI, Università degli Studi di Perugia

Rome, November 8th 2019
Outline

- Introductory aspects
- Methodology of data processing
- Power management strategy
  - SPSA algorithm description
  - Problem formulation
- Modeling and simulation of HESS coupled with a wind turbine
  - Preliminary sizing of the storage devices
  - Definitive sizing of the storage devices
- Results discussion
- Conclusions
Introductory aspects

- Conventional power generation is based on limited and unevenly geographically distributed energy sources.
- The strong variability of renewable energy sources (RES) often hinders their integration into power systems.
- Hybrid energy storage systems (HESS), based on complementary storage technologies, show the advantages of:
  - enabling high RES penetration towards modern and sustainable power generation
  - improving energy systems performances
  - enhancing power supply reliability
Aims of this research: design a battery/flywheel HESS coupled to a wind turbine (working in interconnected mode) and develop an innovative power management strategy (based on the simultaneous perturbation stochastic approximation principle - SPSA) to obtain a smooth power profile at the point of interface to the grid.

Underlying data:
- Dataset1: one year recordings for 10-minutes average power output of a wind turbine
- Dataset2: 5-seconds timestep instantaneous values for the turbine power

Research methods: optimal sizing of the HESS components through modeling and simulation in Matlab/Simulink; implementing a SPSA power management strategy based on simulation results in specific representative cases.
Methodology of data processing

Based on Dataset1, the following quantities are calculated:

- daily average power
- power ramp (power difference between two consecutive records)
- daily average power ramp
- bandwidth of the daily power profile (the difference between the maximum and the minimum power recorded over one day)

95% Confidence Interval is evaluated for the above mentioned variables in reference to both mean and standard deviation. Confidence interval length can reach a relative ratio of 62% in the case of distribution mean and around 65% for the standard deviation. Hence, stochastic approaches are strongly recommended.

95% confidence interval: interval in which the parameter has a 95% probability of being included
Methodology of data processing

<table>
<thead>
<tr>
<th>Representative Day</th>
<th>Selection criterion</th>
<th>Daily Average power [kW]</th>
<th>Energy generated [kWh]</th>
<th>Maximum &amp; Minimum power [kW]</th>
<th>Bandwidth [kW]</th>
<th>Bandwidth/Average power</th>
<th>Daily Average power ramp [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maximum bandwidth</td>
<td>1.059</td>
<td>25.434</td>
<td>2000 / 0</td>
<td>2000</td>
<td>1.88</td>
<td>122</td>
</tr>
<tr>
<td>2</td>
<td>Maximum mean power</td>
<td>1.781.8</td>
<td>42.763</td>
<td>2000 / 692.2</td>
<td>1307.8</td>
<td>0.73</td>
<td>122.19</td>
</tr>
<tr>
<td>3</td>
<td>Maximum bandwidth to mean power ratio</td>
<td>1.07</td>
<td>25.73</td>
<td>48.3 / 0</td>
<td>48.3</td>
<td>45.14</td>
<td>0.92</td>
</tr>
<tr>
<td>4</td>
<td>Minimum bandwidth to mean power ratio</td>
<td>909.07</td>
<td>21.818</td>
<td>2000 /0</td>
<td>2000</td>
<td>2.20*</td>
<td>165.40</td>
</tr>
<tr>
<td>5</td>
<td>Maximum daily mean ramp</td>
<td>1.093.4</td>
<td>26.241</td>
<td>1999.6 / 67</td>
<td>1932.6</td>
<td>1.77</td>
<td>252.88</td>
</tr>
</tbody>
</table>

*The day with the minimum value, excluding the days already selected according to other criteria, is chosen*
Power management strategy

SPSA algorithm description

**Initial assumptions**
- Set the initial estimate of the vector: \( \hat{\theta}_0 \)
- Define the loss function: \( y(\theta) \)
- Establish the convergence conditions: \( y(\theta_k) < y_{\text{limit}} \) and/or \( N_{\text{iter}}^{k} = N_{\text{max}} \)

**Iterative calculation**
- Update the algorithm coefficients: \( a_k = \frac{a}{(A+k+1)a} \) and \( c_k = \frac{a}{(A+k+1)a} \), \( k \) – iteration number
- Determine the perturbed vector: \( \hat{\theta}_k^\pm = \hat{\theta} \pm c_k \Delta_k \)
- Calculate the gradient of the loss function: \( g_k(\hat{\theta}_k) = \frac{y(\theta_k^+) - y(\theta_k^-)}{2c_k} \left[ \begin{array}{c} \Delta_{k1}^{-1} \\ \vdots \\ \Delta_{k1}^{-1} \end{array} \right] \)
- Update the initial estimate: \( \hat{\theta}_{k+1} = \hat{\theta}_k - a_k g_k(\hat{\theta}_k) \)
- Check the convergence condition

**Problem solution**
- Stop iterating when meeting convergence conditions
- Provide the final update of the initial estimate as the optimisation problem solution
Power management strategy

- **Problem formulation**
  - **Selected variables:** \( \theta = [q_{batt} \quad q_{fw} \quad q_{grid}] \) - shares vector
  
  \[
  P_{batt}^t = q_{batt} \cdot \Delta P \\
  P_{fw}^t = q_{fw} \cdot \Delta P \\
  P_{grid}^t = q_{grid} \cdot \Delta P
  \]

  where: \( \Delta P = P_{wind}^t - P_{grid}^{t-1} [W] \)

- **Problem objectives:**
  - **smooth grid profile:** 
    \[
    y_1^k(\theta) = \left( \frac{q_{grid} \cdot \Delta P}{P_{grid}^{t-1}} \right)^2
    \]
  - **smooth power profile delivered/absorbed by the battery:**
    \[
    y_2^k(\theta) = \left( \frac{q_{batt} \cdot \Delta P}{P_{batt}^{t-1}} \right)^2
    \]
  - **multi-objective aggregate:** 
    \[
    y^k(\theta) = w_1 \cdot y_1^k(\theta) + w_2 \cdot y_2^k(\theta),
    \]
    where \( w_1 = w_2 = 0.5 \)
Low speed mechanical flywheel with steel rotor; speed range of the driving electrical machine within the limits \((366 – 890) \text{ rad/s}\).

\[
E = \frac{1}{2} \cdot J \cdot (\omega_{\text{max}}^2 - \omega_{\text{min}}^2)
\]

Initial sizing: 450 kW power; 100 kWh energy

\(\text{LiFePO}_4\) battery pack with maximum charge current of 1C A, maximum discharge current of 3C A and a rated voltage of 420 V

Initial sizing: 500 kWh storage capacity

Modelling and simulation of HESS coupled with a wind turbine

- Storage devices: implemented technologies and preliminary sizing
Power management strategy

- Simulation model: Matlab/Simulink architecture
Modelling and simulation of HESS coupled with a wind turbine

- Definitive sizing of the storage devices is made according to simulations result, avoiding saturation and full discharge of either storage device on daily basis.

- Flywheel: 224 kg \cdot m^2
  - 21 kWh capacity
  - 495 kW power

- Battery:
  - 200 kWh capacity
Results discussion

- Power profile comparisons

Detail for maximum bandwidth day (Day 1)
Results discussion

- Cumulative distribution of power ramp analysis
- daily energy delivered to the grid/produced wind energy of 96% as average value over the simulated days

79% (70 – 83%)

26% (9 – 40%)

64% (55 – 69%)
Conclusions

- The need for energy storage coupling and robust real-time energy management implementation is evident.

- Customized energy management strategies can achieve optimal control of the energy flows amongst various components of the hybrid system.

- The power management strategy proposed enables substantial reductions of the power fluctuations at the point of interface to the grid.

- The proposed stochastic strategy proves to be robust, achieving the set objectives in all the considered simulation scenarios.

- Further research envisages applying this power management strategy to HESS configurations.
Thank you for your attention!