Reliability-Based Storage Sizing for Mitigation of Variability of Renewable Generation

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Outline

• Introduction
• Operational challenges with variable generation
• Use of storage for variability mitigation
  – Standalone system
  – Island-capable system
  – Grid-connected system
• Other research toward energy assurance with variable generation
• Concluding reflections
ERiSe Lab (ENERGY RELIABILITY & SECURITY)

– Director: Joydeep Mitra
– Graduate students (current): 5 Ph.D., 1 M.S.

Research Mission:

*Energy assurance*. We develop innovative systemic approaches to facilitating secure and reliable energy delivery solutions.

Research Sponsors:

DOE, ARPA-E, NSF, National labs, Utilities
Operational challenges with variable generation

- Increased need for frequency regulation
- Reduction of regulation capability
- Increased need for ramp rate
- Increased uncertainty (uncertainty of wind + uncertainty of load)
- Increase in overall ramp range
- Decrease of base load and impact on base-load generators
Frequency regulation issues

• Stable and secure operation of the grid relies considerably on the rotational inertia and governor characteristics of conventional turbine generators.
• Variable sources contribute very little to inertia.
• The short-term variation in variable generation often increases the regulation burden borne by conventional generators like gas turbines.
Increased ramping needs

Ramp Range (Increases in this two-week period from 19.3 GW/day to 26.2 GW/day)

Variation in wind output increases net load ramp rate (Increases in this period from 4,052 MW/hour to 4,560 MW/hour)

Uncertainty in wind output increases uncertainty in net load to be met with conventional generators

NREL, The Role of Energy Storage with Renewable Electricity Generation
Mitigation of variability

• Options for variability mitigation
  – Storage (exploitation of temporal diversity)
  – Transmission (exploitation of geospatial diversity)
  – Control of curtailable loads (flex loads)

• Technology and cost
  – Storage is expensive
  – Exploitation of geospatial diversity requires significant (and costly) transmission upgrades
  – Need “smart grid technologies” to monitor and control
Sizing storage for reliability

Problem:

• Can we determine the amount of storage required to meet a specified level of reliability?
  – Power capacity
  – Energy capacity

• Can we determine how much storage we need to mitigate variability?
Three scenarios

• We shall systematically develop the solution by going through three scenarios:
  – Isolated system
  – Island-capable system
  – Grid-connected system
Scenario 1: Isolated system

- Consider a system with availability $A_0$ for which it is desired to increase the availability to $A_1$.
- The problem is to determine the amount of storage required to achieve the increased reliability.

**Availability** is defined as the probability that a component or system is performing its designated functions at a given point in time under the conditions in which it was designed to operate.

Storage sizing approach

• Define the unavailability reduction ratio

\[ \alpha = \frac{1 - A_1}{1 - A_0} \]

• Denote:

- \( S_F \) event that the existing resources have failed
- \( L \) event that the critical load experiences failure of power supply
- \( t_A \) length of time for which the additional storage can support the load in the event of failure of the existing resources
- \( R \) random variable representing the down time (outage duration) of the existing system
- \( f_R(r) \) probability density function of \( R \)

Example:

If \( A_0 = 0.999 \) and \( A_1 = 0.9999 \), then \( \alpha = 0.1 \)
Storage sizing (continued)

$L$ occurs when down time with existing resources exceeds $t_A$

The probability of $L$ is given by

$$P\{L\} = P\left[\{R > t_A\} \cap S_F\right]$$

$$= P\{R > t_A\}P\{S_F\}$$

$$= \left(\int_{t_A}^{\infty} f_R(r)dr\right)P\{S_F\}$$

$$= 1 - A_1$$

$$= 1 - A_0$$

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Storage sizing (continued)

• But $P\{L\} = 1 - A_1$ and $P\{S_F\} = 1 - A_0$
• Hence

$$\int_{t_A}^{\infty} f_R(r)dr = \alpha$$  \hspace{1cm} (1)

• The solution to this equation yields the energy capacity of the additional storage required
• The power capacity is given by the size of the load—$P_L$
Exponentially distributed down time

\[ f_R(r) = \frac{1}{r} \exp\left(-\frac{r}{r}\right), \quad r \geq 0 \]

then \( t_A = -\bar{r} \ln \alpha \)

Example:
If \( \alpha = 0.1 \) and \( \bar{r} = 4 \) h,
then \( t_A = 9.21 \) h
Weibull distributed down time

\[ f_R(r) = \frac{\beta r^{\beta-1}}{r'} \exp \left[ \left( \frac{r}{r'} \right)^\beta \right] , \quad r \geq 0 \]

where

\[ r' = \frac{r}{\Gamma(1 + 1 / \beta)} \]

then

\[ t_A = r'(-\ln \alpha)^{1/\beta} \]
Lognormal distributed down time

\[
f_R(r) = \frac{1}{\sqrt{2\pi \beta r}} \exp\left\{-\frac{1}{2 \beta^2} \left(\frac{\beta^2}{2} + \ln\frac{r}{\beta}\right)^2\right\}, \quad r \geq 0
\]

then

\[
t_A = r \exp\left(\beta z - \frac{\beta^2}{2}\right)
\]

where

\[
\Phi(z) = 1 - \alpha = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{t^2}{2}\right) dt
\]
Scenario 2: Island-capable system
System characteristics

- On-site resources include PV and standby generators
- Target reliability can be defined based on system need; example: determine the storage required at different parts of system to increase availability by an additional ‘9’

Solution strategy

• Use sequential Monte Carlo Simulation to determine distribution of down time

• Use

\[
\int_{0}^{t_A} r f_R (r) dr = (1 - \alpha) \bar{r}
\]

(2)

to determine \( t_A \) at every node. This can be shown to be approximately equivalent to (1) [see Mitra & Vallem, 2012]

• Assign storage based on loads and \( t_A \) values
System modeling

• Consider islanded operation
• (Grid ties can be modeled as generators with same availability as supply reliability)
• All components considered two-state
• Transportation model assumed for network flows
• Use hourly load curve and insolation curve
• PV panels generate whenever available, following insolation curve
• On-site backup generators follow prescribed dispatch and operation logic
Generator dispatch logic

1. Draw state of each component
2. Find least-curtailment dispatch
3. Check if \(C_T > 0\)?
   - If No, Shut down fuel-powered generators by priority
   - If Yes, Start fuel-powered generators by priority
4. Advance to next hour
5. Send dispatch signal to turn OFF next most expensive generator
6. Send dispatch signal to turn ON next least expensive generator
Generator operation logic
## Reliability improvement

<table>
<thead>
<tr>
<th>Bus</th>
<th>LOLP without augmentation</th>
<th>$t_A$ (hours)</th>
<th>Storage augmentation (MW)</th>
<th>LOLP with augmentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.000706</td>
<td>28.34</td>
<td>0.1885</td>
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<td>8</td>
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<td>System</td>
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<td>11.71</td>
<td>14.428</td>
<td>0.075569</td>
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</table>
Scenario 3: Grid-connected system with wind farm

**Problem**

We want to use storage to “firm up” the wind generation.

– How do we quantify the notion of “firming up”? 
– How do we apply the method developed?

**Questions**

• How do we specify the target availability?
• How do we determine power capacity ($P_L$)?
  – No longer equal to the size of the load!
Firming up wind generation

• By “firming up” a variable resource, we expect to neutralize its intermittency and variability, thereby causing it to behave like a dispatchable resource.

• The target reliability of the system should therefore be the reliability that the system would attain if the wind farm were replaced by a dispatchable generator with the same nameplate capacity (as the wind farm).
Questions

**Capacity value** of a resource is the amount of load it can reliably support. Different ways of understanding it:

1. What is the size of a dispatchable resource that would replace the wind farm and provide the same level of system reliability?
2. How much additional load can the system with the wind farm support at the same level of reliability it had without the wind farm (and additional load)? (ELCC)
Example

- IEEE Reliability Test System (RTS)
- Augmented with wind farm
  - 200 MW nameplate capacity
  - $100 \times$ Vesta V90 turbines, each 2 MW, MTTF 3600 h, MTTR 150 h
  - Correlation coefficient of $-0.1059$ between hourly wind variation and RTS load
Solution strategy

• Determine the capacity value of the wind farm
  – From this the power capacity (storage) is found to be 157.5 MW

• For each candidate location, determine reliability by adding a 200 MW conventional generator at that location
  – This helps define the target availability $A_1$

• For each candidate location, determine system indices by adding the wind farm at that location (in place of the conventional unit)
  – The resulting availability $A_0$ allows calculation of the unavailability reduction ratio $\alpha$
  – The sequential simulation data also allows determination of $t_A$
# Results

<table>
<thead>
<tr>
<th>Bus</th>
<th>Target LOLP (System)</th>
<th>Power Capacity (MW)</th>
<th>$\alpha$</th>
<th>$t_A$ (h)</th>
<th>LOLP with Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
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</table>

Comments

• Target buses were identified in this by examining where the wind farm provided the most benefit

• Results were validated by applying Monte Carlo simulation again, with the storage added (and a reasonably detailed model for storage operation)

• Additional considerations may be applied to storage sizing, e.g., float charge levels
Other recent work on energy assurance with variable generation

• Quantization of reduction in regulation capability

Frequency regulation with reduced inertia

- with gas turbine (0.045), 20% inertia reduction
- with gas turbine (0.062), 20% inertia reduction
- no gas turbine, 20% inertia reduction
- no gas turbine, 0% inertia reduction

Frequency deviation (Hz)

Time (s)
Other work, continued...

• Development of operational constraint resulting from diminution of frequency regulation and inclusion in reliability analysis


• Concept of virtual storage (based on NERC plans to relax frequency standards) to support increased penetration of variable resources

Concluding reflections

• Renewable resources present complex challenges to energy assurance.
• Competitive markets and “smart grid” technologies are additional elements that push system operation closer to stability and reliability margins.
• Creative ideas are emerging but they will need support from regulating bodies.
• In the meantime, there is tremendous thrust in deployment of storage technologies and transmission upgrades (including flow control technologies).
• Thanks to my students who contributed to this research—Mallikarjuna Vallem, Mohammed Benidris, Nga Nguyen, Samer Sulaeman and Yuting Tian.
Thank You!