Smart Grid and Renewable Electric Generation

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Outline

Electric Grid - Background
Smart Grid
Renewable Generation
Grid Integration
Storage
Future Directions

*Focus on system operations, not on specific hardware technologies*
Current Electric Grid

Edison and Tesla
Top engineering achievement of the 20th century (NAE)
Mostly AC system
Large scale, dynamic network
Works reliably but has occasional major failures
**GENERATION**
Electricity is generated at various kinds of power plants by utilities and independent power producers.

**TRANSMISSION**
Electric transmission is the vital link between power production and power usage. Transmission lines carry electricity at high voltages over long distances from power plants to communities.

**DISTRIBUTION**
Electricity from transmission lines is reduced to lower voltages at substations, and distribution companies then bring the power to your home and workplace.

Source: DOE
See also: http://www.npr.org/templates/story/story.php?storyId=110997398
Three Synchronous Zones
DC Interconnects

Source: DOE
FRCC
Electric Grid Characteristics

High voltage transmission network is a *mesh* network

Distribution networks are largely *radial* networks

Dynamic system with multiple time scales

  - Milliseconds, seconds, minutes, hours, days, months, and years

Electric energy storage is very expensive and nearly impossible

  - Pumped hydro is traditional

Energy produced must equal energy consumed on a second-by-second basis – *power balance*

*A complex hierarchical control system has evolved over the years to ensure stability and performance of the large scale networked power system*
Power System Operations

*Power balance* – balance power generation and consumption on a second-by-second basis

Main Approach: *adjust supply to meet demand with reliability*

Natural uncertainty in consumption [load]

Use of reserve capacity to manage uncertainty and contingencies

Day-ahead – hourly schedules, one day ahead

Real-time – 5 minute schedules, 15 minutes ahead

Automatic generation control using system frequency

Fast relays and circuit breakers for protection

Deregulation of the electricity sector – *unique mix of engineering and economics*
Aging Grid Infrastructure

Transmission and distribution infrastructure is aging in the US

More than 70% of transmission lines and transformers are 25 years or older

More than 65% of circuit breakers are 25 years or older

25-35% of generation and transmission nearing end of useful life and 8% are already beyond useful life

Almost 50% of GT assets will be replaced by 2030

*Total investment ~ $975B*

Source: Black and Veatch, 2009
Smart Grid = Power Grid + Sensors + Communications + Computation + Control

Source: DOE
Smart Grid is a Vision

“a stronger, smarter, more efficient electricity infrastructure that will encourage growth in renewable energy sources, empower consumers to reduce their energy use, and lay the foundation for sustained, long-term economic expansion”

Steven Chu, U.S. Energy Secretary, 2009
Smart Grid Principal Characteristics

Smart grid is a “Transactive Agent”

1. It will enable active participation by consumers.
2. It will accommodate all generation and storage options.
3. It will enable new products, services, and markets.
4. It will provide power quality for the digital economy.
5. It will optimize asset utilization and operate efficiently.
6. It will anticipate and respond to system disturbances (self-heal).
7. The Smart Grid will operate resiliently against attack and natural disaster.

Source: DOE – Smart Grid Vision
Smart Grid Scope

Electric energy delivery infrastructure
End-use systems and related distributed-energy resources
Management/control of generation and delivery at various levels of system coordination
The information networks
The financial and regulatory environment that fuels investment and motivates decision makers to procure, implement, and maintain all aspects of the system
Smart Grid Assets

Demand response (DR)
  • communications and controls for end-use devices
  • coordination of multitude of resources

Distributed generation (DG)
  • micro-generators, wind turbines, and solar connected at the distribution level.

Distributed storage (DS)
  • batteries, flywheels, magnetic storage connected at the distribution level.

Distribution/feeder automation (DA/FA)
  • communications and control in substations and feeders with remotely actuated switches for reconfiguration

Electric and plug-in electric hybrid vehicles

Enablers: communications, computing, control/automation

Source: Pratt et al., PNNL-19112, Revision 1
Smart Grid – Assets and Functions

Value streams

Investments

DR = demand response, DG = distributed generation, DS = distributed storage, DA/FA = distribution automation/feeder automation, EVs & PHEVs = electric vehicles/plug-in hybrid electric vehicles

Source: Pratt et al., PNNL-19112, Revision 1
### Smart Grid Benefits by 2019

**$ Billions annually, 2009 dollars**

#### Customer Applications
- **Shift peak**: $16
- **Energy conservation**: $17
- **Avoided cost of capacity**: $26

**Total**: $59

- Shifting demand away from the peak lowers peak prices
- Demand-side management programs aim to reduce energy consumption by customers and the number of KWh that need to be generated
- Decrease in peak and energy consumption reduces need for new power plants in the future, resulting in an avoided cost of capacity

#### AMI
- **Meter data over network**: $7
- **Advanced meter functions**: $2

**Total**: $9

- Automated meters eliminate the need for manual meter reading and meter reading equipment
- Operational and billing benefits from remote disconnection/connection

#### Grid Applications
- **Volt-VAR**: $43
- **FDIR**: $10
- **M&D**: $8
- **WAM**: $2

**Total**: $63

- Volt-VAR increases energy efficiency through conservation voltage reduction (CVR)
- Fault detection, isolation and restoration (FDIR) reduces outage time through automated switching
- Monitoring and diagnostics (M&D) reduces inspection and maintenance costs; provides early warning of potential failures
- Wide area measurement (WAM) increases transmission throughput

*Source: McKinsey, 2010*
Climate Change

Carbon emissions must be stabilized

Reduce dependence on fossil fuels

Renewable sources of energy

DOE

Figure 4. U.S. energy-related carbon dioxide emissions, 2008 and 2035

2008
- Electric power: 5,814 million metric tons (2,350, 41%)
- Buildings and industrial: 1,530 million metric tons (26%)
- Transportation: 1,925 million metric tons (33%)

8.7% growth per year

2035
- Electric power: 6,320 million metric tons (2,634, 42%)
- Buildings and industrial: 1,571 million metric tons (25%)
- Transportation: 2,115 million metric tons (33%)

*Achieving all targets is very aggressive, but potentially feasible.

EIA Base Case 2007

DOE

NAS

EPRI
“The magnitude of these reductions suggests that, while a smart grid is not the primary mechanism for achieving aggressive national goals for energy and carbon savings, it is capable of providing a very substantial contribution to the goals for the electricity sector.”
Renewable Generation
Main RG Technologies

Wind

Solar
Concentrated solar power (CSP)
Photovoltaics (PV) - a-Si, poly-Si, c-Si, CIGS, ...)

Biomass
Wind Turbine Technology Evolution

Source: (U.S. DOE, 2008)
Wind Energy Potential

This map shows the annual average wind power estimates at a height of 50 meters. It is a combination of high resolution and low resolution data sets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.

Mismatch Between Production and Consumption

Missing Link: Transmission Capacity

Source: EPRI
Rapidly Increasing Wind Adoption

Source: GWEC Annual Report, 2010
### Table 1. Estimated Levelized Cost of New Generation Resources, 2016.

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Capacity Factor (%)</th>
<th>U.S. Average Levelized Costs (2009 $/megawatthour) for Plants Entering Service in 2016</th>
<th>Total System Levelized Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Levelized Capital Cost</td>
<td>Fixed O&amp;M</td>
</tr>
<tr>
<td>Conventional Coal</td>
<td>85</td>
<td>65.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Advanced Coal</td>
<td>85</td>
<td>74.6</td>
<td>7.9</td>
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<tr>
<td>Advanced Coal with CCS</td>
<td>85</td>
<td>92.7</td>
<td>9.2</td>
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<tr>
<td>Natural Gas-fired</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Conventional Combined Cycle</td>
<td>87</td>
<td>17.5</td>
<td>1.9</td>
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<tr>
<td>Advanced Combined Cycle</td>
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<td>17.9</td>
<td>1.9</td>
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<tr>
<td>Advanced CC with CCS</td>
<td>87</td>
<td>34.6</td>
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<tr>
<td>Conventional Combustion Turbine</td>
<td>30</td>
<td>45.8</td>
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<tr>
<td>Advanced Combustion Turbine</td>
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<tr>
<td>Advanced Nuclear</td>
<td>90</td>
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<tr>
<td>Wind</td>
<td>34</td>
<td>83.9</td>
<td>9.6</td>
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<tr>
<td>Wind – Offshore</td>
<td>34</td>
<td>209.3</td>
<td>28.1</td>
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<tr>
<td>Solar PV&lt;sup&gt;1&lt;/sup&gt;</td>
<td>25</td>
<td>194.6</td>
<td>12.1</td>
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<tr>
<td>Solar Thermal</td>
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<tr>
<td>Geothermal</td>
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<td>79.3</td>
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<tr>
<td>Biomass</td>
<td>83</td>
<td>55.3</td>
<td>13.7</td>
</tr>
<tr>
<td>Hydro</td>
<td>52</td>
<td>74.5</td>
<td>3.8</td>
</tr>
</tbody>
</table>

<sup>1</sup> Costs are expressed in terms of net AC power available to the grid for the installed capacity.

Variability of Wind and Solar

Power output varies in all time frames:

Annual
Seasonal
Daily
Hours
Minutes
Seconds

Intermittency, uncontrollability, and uncertainty - principal causes of difficulty at the operational level in integration of wind and solar into the grid.
Large ramps, up and down, pose particular difficulties.
Variability – Three Distinct Issues

Uncertainty – reliable predictions of power output are hard, particularly day ahead

Uncontrollability – power output cannot be controlled as desired

Intermittency – even if we could predict perfectly, the power output is inherently variable

*Variable Generation captures all three aspects into a single phrase*
Capacity Credit

Regulatory guidelines require periodic assessment and multi-year planning to ensure sufficient generation capacity to meet demand

- LOLP - 1 day in 10 years criterion (p=0.9997)
- Resource Adequacy (RA) requirements; capacity markets
- Particularly challenging in deregulated markets

Capacity credit

- Nameplate capacity fraction for meeting RA requirements
- Several probabilistic analysis techniques for CC calculation

What is the capacity credit of VG (wind)?

- PJM, MISO – 13%, NYISO – 10% (summer), SPP – 10%, E.ON – 8%, ...
  Could be even less at deep penetration

What are the impacts on power system planning?

How much traditional generation can be displaced by VG?

What happens at deep penetration of VG?
Forecasting

Better forecasts are extremely valuable
Prediction error decreases with horizon
Forecast of wind velocity or solar flux – numerical weather prediction models
Conversion of wind velocity or solar flux into electric power
Use of neural networks and statistical forecasting methods

Natural opportunity for nonlinear estimation methods enabled by sensors and communications

Event detection methodologies to predict the timing and magnitude of ramp events
Current Strategy

Subsidies and public policy – absorb all renewable power
  Deal with variability injected by the renewables
  Adds to natural load variability
  Increases the need for additional reserves

Consequence:
  Increased reserves
    Expensive
    Reduce carbon reduction benefits

*This will become almost impossible at 30-40% renewable penetration*
California Results

Large simulation studies to estimate the impact of 20% and 33% RPS

Load following reserves:
- 2,292 MW in 2006 - 3,207 MW in 2012 - 4,423 MW in 2020

Up Regulation reserves
- 277 MW in 2006 - 512 MW in 2012 - 1,135 MW in 2020

Questions:
- Is there a more rigorous method for estimating the additional reserves?
- Are there techniques to reduce the need for these additional reserves?
- Will/should renewable producers be required to provide their own reserves?
Suppose a VG plant owner has some probabilistic information on its production. Contracts are offered for fixed level of power output over 1 hour.

**Questions:**

- Given a market structure for profits and losses, what is the optimal offering strategy for the wind producer?
- Suppose the wind producer has access to recourse markets. What is the optimal multi-stage bidding strategy to maximize its profits?
- Suppose wind producer can get extra information using sensors and prediction algorithms. What is the value of this extra information?

**Answers:**

- Optimal bid = $\gamma$ quantile of the averaged wind power
- Formulae for $\gamma$
- Formulae for multi-stage optimal bids
- Formulae for the economic value of extra information

Bitar et al CDC’2010, ACC’2011, HICSS’2012
Quantile Policy

amounts to price based curtailment
provides a price signal to "firm" variable output

Fig. 1. Graphical illustration of the optimal bidding policy $C^*$ as a function of the expected imbalance prices $(\mu_q, \mu_\lambda)$. 
Benefits of Aggregation

Consider a collection of geographically dispersed VG producers.

Intuition: *Averaging can reduce variability*

**Question:**

Can a group of wind power producers increase their collective profits by aggregating and offering their power output as a single entity?

**Answer:** *For the single bus case:*

2. There exists a distribution of profits that keeps the coalition *stable.*
3. The coalitional game is not convex and the famous Shapley value does not satisfy the required stabilizing property.

Bayens et al. CDC’2011
Storage

Source: Electrical Storage Association

Big hole
Storage

Power system applications: arbitrage, peak load shifting, reserves, frequency regulation

Questions:

What is the optimal location and operations policy for storage?

Given a VG resource with some small amount of storage, what is the optimal policy for storage operation?

Answers: Tool: stochastic dynamic programming

For a simple storage model:

Optimal contract: convex optimization problem

Optimal profit: concave and monotonic in storage size

Optimal storage operation

Formula for marginal value of storage capacity

Bitar et al ACC'2011
Paradigm Change

Current: adjust the generation to meet random demand

**Future: adjust demand to meet random generation**

Flexible Demand: heating, air-conditioning, refrigeration, water heaters, EVs, ...

These are *energy consumers*, not power consumers

Questions:

How can we optimize aggregate and optimize flexibility of large numbers of individual flexible loads?

How can sensing and communications be used for distributed control of flexible loads?

What incentive and pricing mechanisms will be effective in getting consumers to participate in adjustable demand programs?

How can these distributed resources be integrated into power system operations with large RG penetration?
Distributed Renewable Generation

Scenario:

Large numbers of solar, wind, CHP, and micro-generators in the distribution system
Adjustable demand, electric vehicles
Storage
Sensing, communications, computing, control (SG)

Questions:

What is the optimal, scalable, control and communications architecture to control such a large scale distributed power system?

How can we do this while respecting the legacy centralized grid and minimize the need for additional reserves?

What level of renewable penetration can be achieved in such a distributed scenario?

Answer:

GRIP: Grid with Intelligent Periphery
Coordinated aggregation & control using smart grid sensing, communications, computation, and control

Bakken et al, SmartGridCom’2011
Smart Grid - PMU

Fact: Most control loops in power systems are local due to fast dynamics and lack of wide area measurements

Synchrophasors or PMU:

   GPS time stamped measurements of voltage and current magnitude and phase across the electric grid

NASPINet – a special network for transmitting PMU data

Questions:

   What wide area control loops become feasible as a result of PMUs?
   Ex: wide area oscillations

Can we design better algorithms for prevention of cascading failures using PMU measurements?

Can PMUs help improve the cybersecurity of the SCADA system?

Answer: Graph-theoretic characterization of small coordinated attacks and mitigation strategy using PMUs

Giani et al, SmartGridCom’2011
Our Publications


Future Directions

Renewable integration into smart grid

Cybersecurity issues in smart grid

Connect energy research at UF with electric grid issues

Interdisciplinary collaborations in energy systems leveraging systems/control expertise

Connect with Florida industry and government
Questions?

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