Critical Assessment of R&D Needs for Future Electric Energy Systems---Why One Size no Longer Fits All?

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Outline

- The problem to be solved—the bigger picture
- Structural complexity underlying the problem and possible ways around it
- Hidden traps/counter-examples
- Representative architectures of future electric energy systems
- Relations to what and when should be distributed or coordinated
- The key role of Smart (intelligent) Balancing Authorities (iBAs)
The challenge of designing and operating low-cost green electric energy systems

- Today’s sources of energy rely on expensive and polluting fuels
- Making the future (electric) energy system “green”: Use more “sustainable” resources.
- This trend could lead to high electricity bills and/or hard to provide Quality of Service (QoS)
- Need to take a step back and re-think how today’s electric energy systems are operated, sensed and controlled. Production, consumption and delivery must be improved.
- What are obvious enhancements given technological progress (hardware and software)?
It works today, but...Problems to be solved

- Increased frequency and duration of service interruption (effects measured in billions)
- Major hidden inefficiencies in today’s system (estimated 25% economic inefficiency by FERC)
- Deploying high penetration renewable resources is not sustainable if the system is operated and planned as in the past (``For each 1MW of renewable power one would need .9MW of flexible storage in systems with high wind penetration” –clearly not sustainable)
- Problems with transportation electrifications and integration of responsive demand at value
- Long-term resource mix must serve long-term demand needs well
Huge opportunities and challenges

- Once in 50 years opportunity; progress/investments in hardware and small-scale pilot demonstrations.

- New physical architectures evolving; the old top-down operating and planning approach won’t work; one size no longer fits all.

- Cyber architectures trailing behind; one size doesn’t fit all but possible to have a unifying framework with common design principles.

- From grid-centric to secure cooperative user-centric.
Understanding the problem --
Coarse modeling of Socio-Ecological Systems

Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.
Some key questions..

- What is the problem we are solving? Governance dependent objectives (reliability, sustainability, efficiency)

- As different electric energy systems architecture evolve, different:
  - performance objectives
    - mathematical models and data needed Characterize users, resources and interactions in sufficient detail needed to meet performance objectives

- How can computing, control and communications tools help?
  - "smart grid" design implementation
“Smart Grid” ↔ electric power grid and IT for sustainable energy SES

<table>
<thead>
<tr>
<th>Energy SES</th>
<th>Man-made Grid</th>
<th>Man-made ICT</th>
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<tbody>
<tr>
<td>• Resource system (RS)</td>
<td>• Physical network connecting energy generation and consumers</td>
<td>• Sensors</td>
</tr>
<tr>
<td>• Generation (RUs)</td>
<td>• Needed to implement interactions so the objectives are met</td>
<td>• Communications</td>
</tr>
<tr>
<td>• Electric Energy Users (Us)</td>
<td></td>
<td>• Operations</td>
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<td></td>
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<td>• Decisions and control</td>
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<td>• Protection</td>
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IT-enabled smarter energy systems

- Given physical energy systems, how to design the grid infrastructure and the cyber overlay to make the most out of naturally available resources?

- Complex systems engineering problem (temporal, spatial, contextual)

- The main challenge: What information should be collected/processed/exchanged to minimally coordinate the multi-layered physical system for provable performance? MUST ACCOUNT FOR SYSTEM STRUCTURE!
An illustrative future system

Fig. 5. Small example of the future electric energy system.
Future Power Systems

Energy Sources

Electro-mechanical Devices (Generators)

Transmission Network

Load (Converts Electricity into different forms of work)

Photo-voltaic Device

Electro-mechanical Device

PHEVs

Demand Response

Energy Sources
Contextual complexity

ISO – Market Makers

Power Traders

Scheduling

Generator

Supply Aggregators

Customer

Demand Aggregators

Some Utilities Are all Three

Customer
Structural complexity of interconnected electric energy systems

- Determined by the complex interplay of component dynamics (resources and demand); electrical interconnections in the backbone grid and the local grids; and by the highly varying exogenous inputs (energy sources, demand patterns)

- Renewable resources are stochastic

- The actual demand is stochastic and partially responsive to system conditions

- Multi-physics, multi-temporal, multi-spatial, multi-contextual
## Modeling Dynamics of Electric Energy Systems

### Domains and variables.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Effort $e$</th>
<th>Flow $f$</th>
<th>Generalized Displacement $q$</th>
<th>Generalized Momentum $p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td>Voltage $V$ [V]</td>
<td>Current $I$ [A]</td>
<td>Charge $q$ [C]</td>
<td>Flux linkage $\phi$ [V-s]</td>
</tr>
<tr>
<td>Translation</td>
<td>Force $F$ [N]</td>
<td>Velocity $v$ [m/s]</td>
<td>Displacement $x$ [m]</td>
<td>Momentum $p$ [N-s]</td>
</tr>
<tr>
<td>Rotation</td>
<td>Torque $\tau$ [N-m]</td>
<td>Angular velocity $\omega$ [rad/s]</td>
<td>Angular displacement $\theta$ [rad]</td>
<td>Angular momentum $b$ [N-m-s]</td>
</tr>
<tr>
<td>Fluid</td>
<td>Pressure $P$ [N/m$^2$]</td>
<td>Volume flow $Q$ [m$^3$/s]</td>
<td>Volume $V$ [m$^3$]</td>
<td>Pressure momentum $\Gamma$ [N-s/m$^2$]</td>
</tr>
</tbody>
</table>

\[
x = \begin{bmatrix} I_L, V_C, \nu_{\text{mass}}, F_{\text{spring}}, f_S, T \end{bmatrix},
\]

- Electrical States
- Mechanical States
- Thermodynamic States

\[
\frac{dx}{dt} = f(x, u, p), \quad x(0) = x_0
\]

Structure of models used (this makes cyber design sustainable, otherwise too complex)—
Vast temporal and spatial scales-engineering view

Interaction Variable Simulation for Real Power Problem in 5 Bus System

Diagram of a power system with two areas (AREA 1 and AREA 2) connected by lines. The diagram includes generators (G1, G2, G3) and lines (L4, L5) to represent the network.
Vast temporal and spatial inter-dependencies
Questionable practice

- **Nonlinear dynamics related**
  - Use of models which do not capture instability
  - All controllers are constant gain and decentralized (local)
  - Relatively small number of controllers
  - Poor on-line observability

- **Time-space network complexity related**
  - Faster processes stable (theoretical assumption)
  - Conservative resource scheduling (industry)
    -- weak interconnection
    -- fastest response localized
  - Lack of coordinated economic scheduling
  - Linear network constraints when optimizing resource schedules
  - Preventive (the "worst case") approach to guaranteed performance in abnormal conditions
(Generally) coupled space-time complexity
The danger of system-wide instabilities—**the hidden trap to decentralized approaches**

Network for subsynchronous resonance simulation.
System-wide fast interactions

Fig. 16. Line current (real part of phasor) of a system experiencing subsynchronous resonance.

Fig. 17. Line current (real part of phasor) of a system with 23.0% compensation and FBLC.

Fig. 19. Line current (real part of phasor) of a system with 23.0% compensation and FBLC with fourth-order Butterworth acceleration filtering.

Fig. 20. Field voltage of a system with 23.0% compensation and FBLC with fourth-order Butterworth acceleration filtering.
Real-world examples of emerging problems

- 50.2Hz problem in Germany because of poorly controlled PV
- Must avoid emerging problems
- How to aggregate the new open access systems with new technologies (wind power plants, PVs, geothermal) so that there is no closed-loop control problem?
- Must understand time-spatial interactions in the interconnected system.
- Need for physics/model-based systematic scaling up
Physics/Model Based Structure—Basis for Systematic Spatial and Temporal Scaling

- **SBA**: Smart Balancing Authorities (Generalization of Control Area)
- **IR**: Inter-Region
- **R**: Region
- **T**: Tertiary
- **D**: Distribution
- **S**: Smart Component

- The actual number of layers depends on needs/technologies available/electrical characteristics of the grid

CONFLICTING OBJECTIVES—COMPLEXITY AND COST OF COMMUNICATIONS VS. COMPLEXITY AND COST OF SENSORS, CONTROL

``SMART BALANCING AUTHORITY” CREATED IN A BOTTOM-UP WAY (AGREGATION)--DyMonDS;
--COMPARE WITH CONVENTIONAL TOP-DOWN DECOMPOSITION
Interaction variables within a physical system

- Interaction variables --- variables associated with sub-systems which can only be affected by interactions with the other sub-systems and not by the internal sub-system level state dynamics.
- Dynamics of physical interaction variables zero when the system is disconnected from other sub-systems.
- A means of defining what needs coordination at the zoomed-out layer.
- The nature of interaction variables defines limits to decentralized implementation.
- Large-scale systems state of art needs revisiting.
IntV-based approach to coordinated dynamics

- Minimal coordination by using an aggregation-based notion of "dynamic interactions variable"
Potential Use of Real-Time Measurements for Data-Driven Control and Decision-Making (new)

- GPS synchronized measurements (synchrophasors; power measurements at the customer side).
- The key role of off-line and on-line computing. Too complex to manage relevant interactions using models and software currently used for planning and operations.
- Our proposed design: Dynamic Monitoring and Decision Systems (DYMONDS)
DyMonDS Approach

- Physics-based modeling and local nonlinear stabilizing control; new controllers (storage, demand control); new sensors (synchrophasors) to improve observability
- Interaction variables-based modeling approach to manage time-space complexity and ensure no system-wide instabilities
- Divide and conquer over space and time when optimizing - DyMonDS for internalizing temporal uncertainties and risks at the resource and user level; interactive information exchange to support distributed optimization - perform static nonlinear optimization to account for nonlinear network constraints - enables corrective actions
- Simulation-based proof of concept for low-cost green electric energy systems in the Azores Islands
Five qualitatively different physical power grids - different nature of interactions

|----------------------------------------|---------------------------------------------|-------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|


Bulk regulated power grids
The key role of on-line scheduling...could have prevented blackouts
On-line scheduling and automatic regulation

System Load Curve

Every 10 min Real Time Load of NYISO in Jan 23, 2010

- Forecasted Load
- Actual Load with Disturbance
Predictable load and the disturbance—graying boundaries (learning or automation??)
The role of cyber in bulk power grids

- On-line scheduling and automated regulation

- Potential use of big data for scheduling
  - The role of big data for accurate state estimation
  - The role of big data for on-line resource management

- Effects of paradigm shift on data needs

- Putting PMUs to use for enhanced Automatic Generation Control (E-AGC), enhanced Automatic Voltage Control (E-AVC) and enhanced automatic flow control (E-AFC) in systems with highly variable resources

- Possible ways forward
PMUs-enabled grid for efficient and reliable scheduling to balance predictable load

- PMUs and SCADA help more accurate state estimate of line flows, voltages and real/reactive power demand
- AC OPF utilizes accurate system inputs and computes settings for controllable grid, generation and demand equipment to help manage the system reliably and efficiently
- Adjustments done every 15 minutes
- Model-predictive generation and demand dispatch to manage ramp rates
Potential use of big data for scheduling

- Better time-stamped archives of large network data (inputs, states, outputs; equipment status)
- Enhanced system-level state estimation (not just static WLS)
- Begin to create data structures that reveal temporal and/or spatial correlations in complex grids; more efficient and reliable on-line resource management
- Off-line analysis (effects of large number of possible equipment failures and input variability)
State Estimation to support on-line scheduling implementation (Yang Wang)

Current Power System State Estimation Problems

- Nonlinearity
- Non-convexity
  - Convexification
  - Semi-definite Programming

- Historical Data are not really used
  - Non-parametric Static state Estimation
  - Parametric Dynamic state Estimation

- New devices (i.e. PMU) placement problem
  - Information Theory based algorithm for State Estimation

- Computational Burden
  - Graph-based distributed SDP SE
  - Parallel Computing Algorithm

Carnegie Mellon
Physical and Information Network Graphs Today

Network graph of the physical system

Load serving entities (LSEs)

Local Distribution Network (Radio Network)

PQ  Dies  el  PQ  Wind  PQ  PQ

Predicted $P_L, Q_L$

Information flow: MISO

Information graph of today’s SCADA

Local serving entities (LSEs)

State information exchange

Backbone Power Grid and its Local Networks (LSEs)

Backbone

Redundant measurement sent to Control center (hub)
Future Smart Grid (Physical system)
Critical: Transform SCADA

- From single top-down coordinating management to the multi-directional multi-layered interactive IT exchange.

- At CMU we call such transformed SCADA Dynamic Monitoring and Decision Systems (DYMONDS) and have formed a Center to work with industry and government on: (1) new models to define what is the type and rate of key IT exchange; (2) new decision tools for self-commitment and clearing such commitments. http://www.eesg.ece.cmu.edu.
New SCADA
DYMONDS-basis for next SCADA
Multilayer Information for State Estimation

Physical Layer Online Diagram

Load serving entities (LSEs)

Local Distribution Network (Radio Network)

Predicted $P_L, Q_L$

Information flow: MISO

Information Layer Diagram

Local serving entities (LSEs)

State information exchange

Backbone Power Grid and its Local Networks (LSEs)

Distributed SE Computation

Backbone

State information Exchange on the boundary nodes

Local State Estimation (LSE)

Distributed SE Computation
Ideal Placement of PMUs

14 bus example graphical representation
PMU Information Gain Index

IEEE 14-Bus System, PMU Only

Number of PMU

Normalized Information Gain

Upper Bound
Greedy
Observable
Imports can be increased by the following:

- More reliable dynamic rating of line limits
- Optimal generator voltages
- Optimal settings of grid equipment (CBs, OLTCs, PARs, DC lines, SVCs)
- Demand-side management (identifying load pockets with problems)
- Optimal selection of new equipment (type, size, location)

Natural reduction of losses, reduction of VAR consumption, reduction of equipment stress
LSS Nonlinear Network Optimization for Corrective Actions

Imports can be increased by scheduling:
- Optimal generator voltages
- Optimal settings of grid equipment (CBs, OLTCs, PARs, DC lines, SVCs)
- Demand-side management (identifying load pockets with problems)
- Natural reduction of losses, reduction of VAR consumption, reduction of equipment stress
- Studies have shown 20-25% economic efficiency by implementing corrective actions
On-line automated regulation

- Constrained Line
- Line-to-Ground Clearance
- Transfer Capacity in Real Time

PMU Control
Putting PMUs to Use for E-AVC, E-AFC and E-AGC

- Need for advanced sensing technology
  - **PMUs** to measure the coupling states (voltage phase angles) on real-time
- Need for communication channels
  - Upload info to the upper layer
  - Exchange info with neighboring layers for feedback control of the coupling

---

Highly limited Info Exchange

Lightly loaded Info Exchange
Putting PMUs to Use for AVC

Pilot Point: Bus 76663

Automatic Voltage Control for ONE Pilot Point Control Case
PMU-driven E-AGC for managing solar and wind deviation
PMU-driven E-AGC for managing solar and wind deviation

Areas 1 and 2: coupled by large reactance

Disturbances Injected from the Solar Power Resource

SBA-C locally stabilized (unstable, W-matrix condition for SBA-Cs unsatisfied)

SBA-Cs’ coupling minimized (stable, W-matrix for SBA-Rs satisfied)
E-AGC – strong interactions

(A) Disturbance (p.u.)

(B) Δf_{G1} (Hz)

(C) Δf_{G1} (Hz)

(D) Δf_{G1} (Hz)
Counter-example to decentralized AGC implementation - Red flag

- Consider a system comprising strongly interconnected large power plants
- AGC designed currently assuming fast dynamics stable (assn underlying droop)
- Insufficient AGC gain destabilize fast dynamics
- Lesson learned: Entirely decentralized AGC might require unacceptably high gains

(Reference: Qixing Liu, PhD ECE CMU, September 2013)
The key role of fast stabilizing power electronics switching
The role of high-gain adaptive control in preventing blackouts

- A 38-node, 29 machine dynamic model of the NPCC system
- A multi-machine oscillation occurred at .75Hz, involving groups of machines in NYC and the northeastern part of New York State, as well as parts of Canadian power system;
- The fault scenario selected for this test was a five-cycle three-phase short circuit of the Selkrik/Oswego transmission line carrying 1083MW. The oscillation grows until the Chateaguay generator loses synchronism, followed shortly by the failure of Oswego unit.
Rotor angles -- base case for Selkrik fault with conventional controller
Voltage response with conventional controllers-base case
Selkirk fault

This talk is partially based on the IEEE Proc. paper.
Bus voltages with new controllers

This talk is partially based on the IEEE Proc. paper, Nov 2005.
Rotor angle response with local nonlinear controllers--an early example of flat control design

This talk is partially based on the IEEE Proc. paper.
Nonlinear control for storage devices (FACTS, flywheels)

Fault:
- a short circuit at Bus 3
- created at $t = 0.1s$
- cleared at $t = 0.43s$

Critical clearing time:
$T_{CCT} = 0.25s$


Use of interaction variables in strongly coupled systems

Interaction variable choice 1:

Interaction variable choice 2:
Effects of Industry Changes on Data Needs

- Data-enabled distributed network of interconnected (groups of) components
- Many diverse decision makers; need for a cloud of clouds
- The key question #1: What data needs to be exchanged, at which rate and under which terms for pre-specified performance
- Probably not good enough to store data; data processing at different cloud layers and systematic data exchange protocols will be required.
- The key question #2: Model-based approach to designing information exchange for provable performance or less structured [1]?
- If done right, it could:
  - enable distributed secure state estimation; robust to topological failures
  - Support on-line resource management which is more efficient and reliable
  - Provide more insights about the system robustness to equipment failures; tradeoffs between the distributed and coordinated decision making; tradeoffs between preventive over-design and on-line flexible management of available resources
Hybrid power grids
Fully distributed power grids
Flores Island Power System

H – Hydro
D – Diesel
W – Wind
Modular Representation of the Flores Island Power System

H – Hydro
D – Diesel
W – Wind
Huge opportunity which will probably not be explored

- Daunting roadblocks:
- The fastest time scale – make it as localized as possible but use lots of data for model verification
- Can it be done to protect privacy of data that should not be exchanged? [2,3]
- Can it be done at provable performance?
  - secure reliable state estimation
  - off-line data processing for feed-forward applications (scheduling for the worst case; parallel processing of likely failures)
  - management of multi-area
  - limits to using big data
Must proceed carefully...

- The very real danger of new complexity.
- Technical problems at various time scales lend themselves to the fundamentally different specifications for on-line data.
- No longer possible to separate measurements, communications and control specifications.
- Major remaining open question: WHAT CAN BE DONE IN A DISTRIBUTED WAY AND WHAT MUST HAVE FAST COMMUNICATIONS.
Summary

- End-to-end CPS for future power grids; Next generation SCADA
- One possible unifying framework—Making Socio-Ecological systems (SES) sustainable
- Implications on CPS architectures
- Dynamic Monitoring and Decision Systems (DYMONDS)—A possible framework for man-made CPS in power grids that makes the socio-ecological energy system as sustainable as possible [http://www.eesg.ece.cmu.edu/](http://www.eesg.ece.cmu.edu/)
- Recent proof-of-concept on Azores Islands [2]
- Challenge of system-level demonstrations in power grids
- Possible paths forward for R&D
References


Minimally coordinated self-dispatch—DyMonDS

- Distributed management of temporal interactions of resources and users
- Different technologies perform look-ahead predictions and optimize their expected profits given system signal (price or system net demand); they create bids and these get cleared by the (layers of) coordinators
- Putting Auctions to Work in Future Energy Systems
- DyMonDS-based simulator of near-optimal supply-demand balancing in an energy system with wind, solar, conventional generation, elastic demand, and PHEVs.
Centralized MPC – Benchmark

- Predictive models of load and intermittent resources are necessary.
- Optimization objective: minimize the total generation cost.
- Horizon: 24 hours, with each step of 5 minutes.

Predictive model and MPC optimizer:

\[ \hat{L}(k), \hat{P}_{\text{wind}}^\text{max}(k), \hat{P}_{\text{solar}}^\text{max}(k) \]

Electric Energy System

\[ U^* = \{u_0^*, u_1^*, \cdots, u_{N-1}^*\} \]

\[ u_k^* : \text{Output vector of all generators at time step } k \]
Fig. 3. Required information exchange for DYMONDS-based dispatch.
DYMONDS Simulator
IEEE RTS with Wind Power

👀 20% / 50% penetration to the system [2]
<table>
<thead>
<tr>
<th>Conventional cost over 1 year *</th>
<th>Proposed cost over the year</th>
<th>Difference</th>
<th>Relative Saving</th>
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</thead>
<tbody>
<tr>
<td>$129.74 Million</td>
<td>$119.62 Million</td>
<td>$10.12 Million</td>
<td>7.8%</td>
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BOTH EFFICIENCY AND RELIABILITY MET
DYMONDS Simulator
Impact of price-responsive demand

- Elastic demand that responds to time-varying prices
DYMONDS Simulator
Impact of Electric vehicles

- Interchange supply/demand mode by time-varying prices
Optimal Control of Plug-in-Electric Vehicles: Fast vs. Smart

![Graph showing Fast Charging and Goal of Smart Charging](image-url)