Toward a Unified Approach to Sustainable and Resilient Electric Energy Systems--Modeling, Control and Testbeds

Marija Ilic  milic@ece.cmu.edu; ilic@mit.edu
Carnegie Mellon University/M.I.T.-LL
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On leave at MIT-LL; the presentation based on CMU work.
Cyber-physical electric energy systems (CPEES) *

Hindsight view

- Innovation in power systems hard and slow
- Outdated assumptions in the new environment
- No simulators to emulate time evolution of complex event driven states
- Fundamental need for more user-friendly innovation/technology transfer
- General simulators (architecture, data driven) vs. power systems simulations (physics-based, specific phenomena separately)
- Missing modeling for provable control design
- Difficult to define performance objectives at different industry layers; coordination of interactions between the layers for system-wide reliability and efficiency; tradeoff between complexity and performance
- Challenge of managing multiple performance objectives
Acknowledgements

- EESG Ilic group [http://www.eesg.ece.cmu.edu/](http://www.eesg.ece.cmu.edu/)
- Dynamic Monitoring and Decision Systems (DyMonDS) framework for enabling smart SCADA; direct link with sustainability (enabler of clean, reliable and efficient integration of new resources); main role of interactive physics–based modeling for IT/cyber
- Cooperative effort with National Institute of Standards (NIST) for building Smart Grid in a Room Simulator (SGRS)
- ***Recent new unifying modeling in support of DyMonDS***
- Early version of DyMonDS simulator (precedural; centralized)
- Data on Azores Islands power grids by EdA; many early concepts shown in the monograph under CMU-MIT-Portugal programs
Outline

- Technological and social drivers in the electric energy systems; basic landscape
- Socio-ecological systems (SES) view
- Systems view of multi-layered electric energy systems
- New SCADA for aligning diverse objectives (cyber)
- Unified multi-layered modeling
- Multi-layered control
- Smart Grid in a Room Simulator (SGRS) testbed
Technological and social drivers in the electric energy systems

- Multiple objectives (reliability/resiliency, efficiency and environmental)
- Portfolio of non-utility-owned resources
- Renewable resources and demand response
- Technology drivers: Cost-effective IT; GPS synchronized wide-area measurement systems (WAMS)
- Emergence of electricity markets
- Technologies for plug-and-play deployment
An illustrative future electric grid

Fig. 5. Small example of the future electric energy system.
Conventional Power System

Energy Sources

Electro-mechanical Devices (Generators)

Transmission Line

Load (Converts Electricity into different forms of work)

The next four slides drawn by Andrew Hsu.
More Complex Power 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
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)
Hybrid Open Access Electric Energy System
Fully distributed small-scale systems
Re-think modeling

- Mathematical formulations of market objectives un-aligned with technical objectives of physical controllers
- Can one have a modular multi-layered modeling which supports interactive information exchange in terms of variables common to physical and market processes?
- Key to managing a stratum of operationally implementable market derivatives (energy, ancillary services)
  - internalizing externalities
  - synthetic reserves
  - incentives across temporal/spatial spectrum
Main claims

- Not a radical concept, natural evolution from today’s engineering & market practices
  - view physical system as a dynamical system with lots of structure
  - treat all components as dynamical components (resources, consumers, wires)
  - pose the problem as a control design problem—decision makers define performance objectives, physical models define feasible trajectories

- Protocols for managing market and physical dynamics (DyMonDS)
Basic Backbone SCADA-Today
Simple protocols that may work?
Dynamic Monitoring and Decision Systems (DyMonDS)—new SCADA
Toward unified modeling...

- Establish sufficiently accurate (but not too complex) modeling framework which captures inter-dependencies of energy Socio-Ecological Systems (SES), physical grid, IT and governance system
- The key objective: Match attributes of energy SES, physical grid, ICT and governance system by designing around a given energy SES
- Interaction variables: A means of going from very coarse to granular and back
- IT design to manage interaction variables (temporal, spatial and contextual)
- Interaction variables-based unifying framework for relating engineering design, financial and environmental objectives
Vast temporal and spatial scales-engineering view

Interaction Variable Simulation for Real Power Problem in 5 Bus System
Vast temporal and spatial inter-dependencies (deeper-level)
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 actions taken at the sub-system level.

- Dynamics of physical interaction variables zero when the system is disconnected from other sub-systems.

- Existence – consequence of general power conservation laws.
Coarse modeling of Socio-Ecological Systems (using SES interaction variables) [16]
“Smart Grid” ↔ electric power grid and IT for sustainable energy SES [14]

**Energy SES**
- Resource system (RS)
- Generation (RUs)
- Electric Energy Users (Us)

**Man-made Grid**
- Physical network connecting energy generation and consumers
  - Needed to implement interactions

**Man-made ICT**
- Sensors
- Communications
- Operations
- Decisions and control
- Protection
  - Needed to align interactions
IT Design for New Architectures

- Measuring, communicating and controlling (physical) grid interaction variables to shape the deeper-level interaction variables of SES systems to induce sustainable performance.

- The creation of “smart grids” is the application of information technology to the power system while coupling this with an understanding of the business and regulatory environment.

- Critical to the creation of “smart grids” is:
  - development of models of the power system
  - development of control software
  - incorporation of security, communications, and safety systems
Is there a more general simple paradigm?
General structure of electric energy systems

- general idea---rethink physical dynamics in terms of interaction variables

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

• Note: SBAs renamed to iBAs (suggestion by a PSERC member)

General structure in operating interconnected electric energy systems

• All about balancing power at the right temporal and spatial granularity
• But, the models used are not explicitly posed this way
• New modeling to capture this fact
• Use to support interactive Dynamic Monitoring and Decision Systems- DyMonDS
• Much room for generalizing today’s hierarchical control
• Much room for making use of nonlinear control
Interactive MPC-driven market dynamics

• **General result**—there exists interaction dynamics as sent and reflected power travels between the components (scattering, positive system formulations needed) *[CMU provisional patent, Ilic]*

• Yet, to shape this dynamics no internal details about the technology-specific processes are necessary!!! (MAJOR)

• Zoomed out interactive model/architecture in terms of $z(t)$ only. Transparent market in terms of common physically meaningful variables.

• The only derivatives traded—incremental energy over time $T$ (market clock) $E(t)$, instantaneous power $p(t)$ and rate of change of power $dp(t)/dt$. 
Example 1: Prototype TE

- Market for EVs

- Simulation of charging strategies for electric vehicles
- Different methods for smart charging:
  - Fast charging
  - MPC based charging – price taker; time of use; ALM
  - MDP based charging – ALM
- Cost comparison

![Diagram of market layers and charging power/energy prices](image-url)
Centralized MPC – Benchmark

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

Predictive Model and MPC Optimizer

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

Electric Energy System

\[
u_k^* : \text{Output vector of all generators at time step } k
\]

- 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.
Required information exchange for distributed power dispatch—DyMonDS (Xie)
Typical supply-demand – diverse technologies
(result of distributed MPC)

General observation:
Prices -- adjoint variables for DAM/RTM energy constraints
Missing prices—adjoint variables for LTM, power, rate of power change
DYMONDS Simulator
IEEE RTS with Wind Power

- 20% / 50% penetration to the system [2]
**Conventional cost over 1 year**

<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>
</tr>
</tbody>
</table>

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

**Fast Charging**

- Residential Load
- PHEV Load at 10% Fleet Penetration

**Goal of Smart Charging**

- Residential Load
- PHEV Load at 10% Fleet Penetration

![Graphs showing fast and smart charging patterns.](image-url)
Unaligned TE and system dynamics

- Based on prices, market computes active power set points $P^*$ from each component
- Since currently the market does not specify reactive power set points $Q^*$, data for $Q^*$ is randomly created
- Place a voltage source inverter and a flywheel variable speed drive controller on the hydro and diesel generator buses
- Control the sum of the power out of the hydro and diesel generators to match the active and reactive power set points
Market command destabilizes wind generator

General problem
-----Not all adjoint variables exchanged! (missing prices)
Flexible technologies for risk management — missing price for reliability/resiliency

Stochastic DP (Donadee)?
General CMU-NIST simulator

Implementation on the SGRS

- Multi-layered, interactive DYMONDS architecture
- Object-oriented agent modeling
- Event-driven, distributed simulation
- Each module runs as a separate computing process
- Communication by TCP/IP
General SGRS Module Structure

![Diagram of General SGRS Module Structure](image)

**Table: General SGRS Module Structure**

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameters</th>
<th>Initial States</th>
<th>Exogenous Input</th>
<th>Equipment Status Flag</th>
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<td><strong>Learned Structure Data</strong></td>
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<td>L-Database I</td>
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<tr>
<td>L-Database II</td>
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<tr>
<td>L-Database III</td>
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<tr>
<td><strong>Communicated Structure Data</strong></td>
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<tr>
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<tr>
<td>C-Database II</td>
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<tr>
<td>C-Database III</td>
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</tbody>
</table>

**Flowchart:**
- Module I (Subclass)
- Module II (Subclass)
- Large Disturbance/ Emergency happen
  Or Equipment fails to work
- Real Time Data

**Additional Notes:**
- Pointer connections indicate data flow between modules.
- The flowchart illustrates the interaction between the learned and communicated structure data, highlighting how real-time data influences the system's decision-making processes.
Information Exchange Between Modules in SGRS

LEGEND

- Load Module
- General-Generator Module (Abstract Class)
- Market-Generator Module (Subclass)
- SDYNS-Generator Module (Subclass)
- Market Purpose Communication
- 24 Hour Information
- 1 Hour Information
- 10 Min Information
- Dynamics Purpose Communication
- AGC Information
- Stabilization Information (Small Signal)
- Transient Stabilization Information
- Regulation Information
- Equipment Status Communication
Dynamics of interaction variables between the areas—Sao Miguel System

Key notion of interaction variable dynamics and their control

- Interactions variables of area-1 and area-2
• Controlled IntV v.s. uncontrolled IntV
A multi-layered frequency stabilization and regulation

• Control objective
  - Stabilization of the interconnected system
  - Eigenvalues of the closed-loop system negative real parts

• Multi-layered control approach
  - Component-level: distributed control with limited coordination
  - Subsystem-level: distributed control with limited coordination
  - Interconnected system-level: coordinated control
Continuous real power load fluctuations around predictable load -- continuously varying non-zero mean disturbances
Time response of the interaction variables
Time response of continuous frequency deviations
Control efforts provided by the generators
Example 3--Market for power electronics automation? (Cvetkovic)

Interaction variable choice 1:

Interaction variable choice 2:
“Primary frequency reserve” (BAAL3)—how much?
Non-linear control for transient stabilization

Fault:
- a short circuit at Bus 3
- created at \( t=0.1\,s \)
- cleared at \( t=0.43\,s \)
Critical clearing time:
\[ T\downarrow\text{CCT}=0.25\,s \]
Islanded microgrid dynamics? (Rupamathi Jaddivada)

Feasibility issues when islanded!
Gen-set droops invalid for assessing instabilities in systems with gen-sets and PVs
Potentially unstable very fast electro-magnetic phenomena not typical of bulk electric systems
Similar problem to off-shore islanded wind farms
Thank you!

Contact info:
Marija Ilic (milic@ece.cmu.edu)
References

[1] Private correspondence with Dale Osborn, MISO.


Reference


