Why We Need a 4th Generation Intelligent Grid and How to Get It

- NSF funding opportunities and priorities.
  - Who Gets Funds for What and Why: Strategic Goals
  - The US Grid Today – ISOs and Optimization Algorithms

4 Generations of the Idea of “Intelligent Grid”

- 1st: Before 2000: Modernization and new components
- 2nd: 2000: self-healing and stable global management
- 3rd: 2002: controlled by global dynamic stochastic optimization
- 4th: 2011: global optimization by market integrated but distributed intelligence – many opportunities, success stories

Two Really Big New Opportunities

- How 2 second optimization could save $2 trillion/year
- How ADP control of microgrids might be crucial to greater use of PHEVs (and breaking our need for oil)

ISGT: CVR (US) versus transmission capacity & new loads (EU)

Dr. Paul J. Werbos, Program Director for Energy, Power and Adaptive Systems, NSF. Personal, not official views, government public domain.
Electrical, Communications and Cyber Systems (ECCS)

Division Director: Dr. Robert Trew
Senior Engineering Advisor: Dr. Lawrence Goldberg

Communications, Circuits, and Sensing-Systems (CCSS)

Dr. Samir El-Ghazaly
- Microwave/mm-Wave/THz Devices & Circuits
- Novel & Next Generation Devices
- Vacuum Devices & Electronics
- Antennas
- Electromagnetic Propagation & Scattering
- Microwave Metamaterials-Based Devices
- Device /Circuit Simulation & Modeling

Dr. Anupama Kaul
- Flexible & Printed Electronics
- Light Emitting Devices & Displays
- Molecular /Organic Electronics & Photonics
- Energy-Efficient Green Electronics
- Next Generation Memories, Memristors, & other Novel Devices

Dr. Usha Varshney
- Bioelectronics & Biomagnetics Devices
- Science & Engineering Beyond Moore’s Law
- Quantum Devices
- Magnetics, Multiferroics, & Spintronics
- Sensor Devices & Technologies

Dr. John Zavada
- Optoelectronics & Photonics
- Nanophotonics
- Plasmonics & Optical Metamaterials-Based Devices
- Large-Scale Photonic Integration
- Ultrafast Photonics

Energy, Power, and Adaptive Systems (EPAS)

Dr. Radhakisan Baheti
- Control Theory & Hybrid Dynamical Systems
- Distributed & Mobile Networked Control
- Systems Theory in Molecular, Cellular, & Synthetic Biology/Medicine
- Estimation in Sensing & Imaging Systems
- Sensor Networks for Energy-Efficient Buildings
- Transportation Networks
- Human-Robot Interaction
- Stochastic Modeling & Applications

Dr. George Maracas
- Energy Collection, Photovoltaics, & Thermal Devices
- Novel Energy Conversion Devices
- Renewable Energy Devices & Systems
- Power Conversion, Generators, Motors & Network Interfacing
- Energy & Power Sensing Technologies
- Energy Storage Technologies
- High Voltage, High Power Switching & Conversion Devices

Dr. Paul Werbos
- Adaptive & Intelligent Systems *
- Transmission & Distributed Systems
- Intelligent Power Grid *
- Quantum Systems & Modeling *
- Neural Networks
- High Performance & Multiscale Modeling
- Cognitive Optimization & Prediction
- Intelligent Vehicles & Robots
Research Grant Proposals and Awards ECCS & ENG

ECCS Proposals & Awards

- ECCS Proposals
- ECCS Awards

ENG Funding Rate
- ENG Funding Rate

ECCS Funding Rate
- ECCS Funding Rate
Who Gets To The Winning 15%?

- **Clearly spell out your targets.** What do you really want to accomplish in 3 years that is new? (Always google a lot to be sure what is now and what you add.)

- **Why should we believe you can do it (as well or better than anyone else)?** New ideas, plan, analysis of obstacles, prior work, track record, research content.

- **Prove how important it is.** What is the size and the nature of the benefits to (1) understanding of general, basic principles; and (2) future of humanity at large? Can you prove it? How do your goals fit into a larger strategic plan or vision, as real as possible?
4th generation intelligent grid

New Adaptive Intelligent Algorithms For Anticipatory Optimization
-- At User Sites
-- At ISO/RTO
-- Elsewhere
-- Distributed but an Integrated System

New Pervasive Sensors

New Communications – Secure Fiber, Interoperable

New Actuators – Switching, Control

New Software Platforms

NSF/EPAS

DOE
“NSF is currently supporting research to develop a ‘4th generation intelligent grid’ that would use intelligent system-wide optimization to allow up to 80% of electricity to come from renewable sources and 80% of cars to be pluggable electric vehicles (PEV) without compromising reliability, and at minimum cost to the Nation (Werbos 2011).”

Werbos 2011: IEEE Computational Intelligence Magazine, August 2011

See paper for many examples of crucial benefits of computational intelligence and other new technology!
Two Grand Challenges

1. How can the US become totally independent from the need to use fossil oil at the soonest time, at minimum cost?
   
   Total independence is possible in 20-25 years at little cost or even savings, using combination of plug-in hybrid cars and three-way fuel flexibility, but transition may be hard. R&D can lower costs of new cars, new fuels, connection to grid. Also improve performance and reduce pollution of these.

2. How can the world become able to meet its electricity needs from >80% renewable sources at ≤10¢/kwh with maximum probability at soonest time?
   
   Total cost is mainly generation cost plus grid cost. E.g. guesstimate of 10¢/kwh best onshore wind for generation, 40¢/kwh total cost due to backups, storage, long lines, regulation services. 10¢/kwh for earth = $2 trillion/year
FUTURES OF THE PERSIAN - ARABIAN GULF REGION

Presented by

Dr. Ismail AlShatti

President
Gulf Institute for Futures and Strategic Studies
Escalating the importance of the region for western civilization

The use of oil as a weapon in confrontation between Western and Muslim societies is the main concern of the strategic decision makers in the west. This use will make the military power useless without fuel. It will remain pile of metal scrap.
WE CAN Zero Out Gasoline Dependency:
A Definite Option for 100% Renewable Zero-Net-CO2 cars & Total Security for Car Fuel

Highest mpg Hybrids Cut Gas per Mile By 50%

With GEM fuel-flexible cars, biofuels might supply ¼ of present liquid fuel demand trends

Plug-in Hybrids with 10kwh batteries get half their energy from electricity

GEM fuel-flexible plug-ins offer a 100% solution based on near-term technology! www.ieeeusa.org/policy/positions/PHEV0607.pdf
5 Grand Challenges for Adaptive and Intelligent Systems
– General-purpose massively parallel designs to learn…

\[ \Pr(A|B) = \frac{\Pr(B|A) \cdot \Pr(A)}{\Pr(B)} \]

\[ J(t) = \text{Max}\langle J(t+1) + U \rangle \]

\[ \frac{\partial^+ z_n}{\partial z_i} = \frac{\partial z_n}{\partial z_i} + \sum_{j=i+1}^{n-1} \frac{\partial^+ z_n}{\partial z_j} \frac{\partial z_j}{\partial z_i} \]
1st Generation: Highlights From Before 2000

- NSF power grid program from 1987.
  - “Large scale nonlinear systems.”
  - With EPRI, main source of R&D in US. $20 million/half-$trillion

- Deregulation versus regulation: misconceptions about markets
  - Markets do not always work: Nash equilibrium is not always Pareto optimal (a best outcome).
  - Yet price signals are essential to consistent rational choices especially in the face of complexity.
  - Solution: “Market Design” to make the Nash equilibrium become optimal, solve an optimization problem. ISO algorithms are designed markets.

- Breakthroughs with neural networks at grid component level
  - Kwang Lee and Mo-Yuen Chow in diagnostics/prediction
  - Wunsch, Venayagamoorthy, Harley: turbogenerator control to withstand disturbances three times larger than other controls
  - LeFebvre: recurrent networks in 20% of US coal-fired generation
Synchrophasor Sensors – NSF Award 0215731

Yilu Liu
Virginia Tech

http://en.wikipedia.org/wiki/FNET
Batteries Too: Two New Concepts to Use Those Membranes to Outperform Asia on Batteries for Plug-in Hybrids (Maybe Even Affordable True Electrics!)

<table>
<thead>
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<th>Like CAES</th>
<th>Specific Energy (Wh/kg)</th>
<th>Energy Density (Wh/l)</th>
<th>Discharge Rate (C)</th>
<th>Specific Power (W/kg)</th>
<th>Cycle Life</th>
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<td>2000</td>
<td>2000</td>
<td>5</td>
<td>400</td>
<td>500</td>
</tr>
</tbody>
</table>

New: [www.excellatron.com](http://www.excellatron.com): Argonne verifies >100 cycles recharge
Almost as good & easier to get: rechargeable ZnAir, Powell
Example 1 of Funded Work: Alireza Khaligh IIT
(Similar megawatt work by SMazumder for solar farms)

New integrated power electronics can cut cost of total power electronics for cars like Volt by $1/3 - 1/2$ while adding a flexible AC/DC fast recharge capability making fast recharge stations “free” instead of $100,000 - 200,000 each. Similar technology crucial to distribution level (Rahman issues) constraints.
Example 2: Thin AC Converters -- Harley and Divan, GA Tech

Truly intelligent grids require **actuation** and **intelligence**…

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A New Way to Provide Switching and Conditioning to the Grid:
-- Much Less Expensive Than “FACTS” (Flexible AC….)
-- Graceful Degradation in Case of Fault

Divan estimates:
-- Smart Grid With This and Other Key Items Can Reduce Real Marginal Cost of Wind to Ratepayers from $\approx 40\$\text{/}kwh$
To $\approx 10\$

-- New transmission line requirements for new solar/wind plans can be cut more than half using this
Neural Network in Commercial Power Grid Hardware

- First deployment of recurrent neural network from university in the field in a commercial electric power grid. (Improved prediction to allow unprecedented monitoring and control of harmonics.) Harley, Georgia Tech.
Why It Requires Artificial Neural Networks (ANNs)

- For optimal performance in the general nonlinear case (nonlinear control strategies, state estimators, predictors, etc...), we need to adaptively estimate nonlinear functions. Thus we must use universal nonlinear function approximators.

- Barron (Yale) proved basic ANNs (MLP) much better than Taylor series, RBF, etc., to approximate smooth functions of many inputs. Similar theorems for approximating dynamic systems, etc., especially with more advanced, more powerful, MLP-like ANNs.

- ANNs more “chip-friendly” by definition: Mosaix chips, CNN here today, for embedded apps, massive thruput
The Time-Lagged Recurrent Network (TLRN): Used by Prokhorov, and Lefebvre

\[ Y(t) = f(X(t), R(t-1)); \quad R(t) = g(X(t), R(t-1)) \]

\( f \) and \( g \) represent 2 outputs of one network

All-encompassing, NARMAX(1 \( \equiv n \))

Felkamp/Prokhorov Yale03: \( \gg \) EKF, \( \approx \) hairy
ADP Controller Cuts NOx emissions from Diesel Engines by 98%

J. Sarangapani MUST NSF grant

IJCNN07: JS shows mpg up 7% in ordinary car engines with ADP
Prokhorov shows mpg up 15% in Prius hybrid with Neural MPC
Stabilized voltage & reactance under intense disturbance where neuroadaptive & usual methods failed
Being implemented in full-scale experimental grid in South Africa
Best paper award IJCNN99
1st of many, being deployed...
Mathematical Foundations of Prediction Under Complexity

Erdos Lecture Series


• Why this is a crucial and timely piece of a larger problem
• Roadmap and definitions from vector prediction to grid and graph prediction and beyond
• Why it is not easy and not yet solved
• What must be built upon and improved
• Project CLION at FedEx Institute to implement optimization and prediction of very large systems
From Vector to Mammal

1. First ever system which learned master class chess
   Fogel, Proc IEEE 2004

2. Reptile
   Add Creativity System
   (Cognitive map of space of possible decisions)

3. Mouse

0. Vector Intelligence – HDP, DHP, GDHP, etc.

Add new spatial complexity logic
(ObjectNets +..., Suitable for CNNs)

Add ability to make Decisions, plays
(Modified Bellman eqs for Multiscale t.)
About 10 Independent Systems Operators (ISOs) Run the US Grid

ISOs Decide:
* Unit Commitment (Contracts to Generators a Day Ahead) & Advance Planning
* Economic Dispatch (Generators Used and Loads & Prices every 15 minutes)
* Some Regulation Functions (every 2 seconds): stability, $V$, $\omega$

See www.ferc.com, event calendar, June 2010
4th Generation Intelligent Power Grid – A Grand Challenge For Coming Decades

What Is It?
- General Concept and Why It is Important
- The US Grid Today – ISOs and Optimization Algorithms

4 Generations of the Idea of “Intelligent Grid”
- 1st: Before 2000: Modernization and new components
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- 4th: 2011: global optimization by market integrated but distributed intelligence

How Can We Get there?
- Algorithms, Megacore Chips, Neural Networks
- Essential New Technology for Components of the Grid like new types of switching, generation, storage, power electronics

Dr. Paul J. Werbos, Program Director for Energy, Power and Adaptive Systems, NSF. Personal, not official views, government public domain.
Dynamic Stochastic Optimal Power Flow (DSOPF): How to Integrate the “Nervous System” of Electricity

- DSOPF02 started from EPRI question: can we optimally manage & plan the whole grid as one system, with foresight, etc.?
- Closest past precedent: Momoh’s OPF integrates & optimizes many grid functions – but deterministic and without foresight. UPGRADE!
- ADP math required to add foresight and stochastics, critical to more complete integration.
- New work may deeply cut cost of hooking up solar (e.g. JTEC!) to electric power grids. Can we get do enough to get GE or ABB to follow through?
DSOPF Can Be a Simple Upgrade to Traditional OPF

- We can do DSOPF by just adding a new term to the utility function which OPF maximizes.
- Can do the same kind of thing with $\lambda$ instead of $J$. 

$U(\mathbf{X}(t)) \rightarrow \Sigma \rightarrow <J(\mathbf{X}(t+1))>$
For More Information on DSOPF or brain-style intelligence, see www.eas.asu.edu/~nsfadp

See the Handbook Chapter on DSOPF by James Momoh of Howard University…

www.cesac.howard.edu
From 3rd Generation to 4th: Some Key Elements

- One integrated optimization system – but optimal prices from ISO drive distributed agents, just as our higher brain drives our cerebellum.

- Germany’s OGEMA platform can handle this. They have shown (Mannheim) how price-driven intelligent agents in the home can shift loads over 24 hours to match renewable energy supply! With even more intelligent agents, we can do still better.

- Value function networks for dispatch and regulation levels must be trained to “respect each other” for cross-time optimization, also a key issue in brain-like intelligent systems (decision blocks).

- Function approximation, two-stage stochastic optimization, price-based optimization methods and parallel interior point methods are key parts of path to upgrade to ADP.

- New technologies for switching, storage, and generation -- examples.
Alternating Current Optimal Power Flow (AC OPF): ISO’s Next Step

- At economic dispatch time (every 5 or 15 minutes), send out voltage and frequency commands to every generator in the system.
- Ilic 2011 (reported at FERC): huge savings
- Momoh: already available from EPRI, underused (like CSRN and ObjectNets so far)
- AC OPF solves a one-stage nonlinear optimization problem, to maximize utility $U$ (perhaps using its gradient as input)
- To create foresight, just insert the $J$ from ADP into $U$, yielding Dynamic Stochastic OPF DSOPF, just now becoming feasible. Even a rough $J$ is better than no foresight at all.
But Big Gaps For Day Ahead and Planning (Crucial to Renewables)

- ISOs now use Mixed Integer (Linear) Programming, **MIP** – one stage optimization, no foresight, integer constraint
- Four important packages for MIP: **Gurobi**, CPLEX (IBM), COIN-OR, Shanno’s. Gurobi seems best to most today.
- The packages are based on two mathematical methods (**simplex and interior point**), plus balls of tricks.
- Circa 1995, the new interior point method surpassed the old simplex method, but **secret tricks allowed Gurobi**’s mainly simplex-based method to do better, for 1 to 14 processors.
- Since **interior point can make better use of many processors**, it is crucial to develop new tricks for it, maybe open source, to catch up and adapt to the new emerging computer world. Sandia conjectures that COIN-OR with the right tricks and many processors can outperform Gurobi on clock time.
- Since interior point handles nonlinearity, and is much closer to neural methods, this is a crucial step to ADP at these higher levels.
- Nonlinear one-stage optimization also is relevant to error minimization or training of neural networks. But can our EKF outperform the “standard best” BFGS widely used and standard in OR?
Two Big New Opportunities

- At ISO level: 2-second optimization to cut total cost of renewables in half (e.g. from 22¢ to 7¢/kwh gets to $3 trillion/year)
- ADP to solve problem of PHEV penetration at the distribution level
If we do DSOPF every two seconds, we can turn wind from liability to asset to grid.

Today wind fluctuations cause lots of fluctuation second-to-second, raising cost for “regulations services,” “AGC.” Add 5 cents to a 10 cents real cost and you get 15 cents per kwh.

Wind farms have lots of power electronics. Optimal control of that electronics every two seconds can change the costly fluctuation into a big asset, a provider of service. Cut 3 cents from the net cost, and you get 7 cents per kwh net.

Liang, Harley and Venayagamoorthy (COPN): use massively parallel chips implementing neural ADP to get to this massive speedup.
New Breakthrough Opportunity: Liang, Harley, Venayagamoorthy

- Can solve AC-OPF and add foresight every 2 seconds instead of every 15 minutes using:
  - DSOPF for the foresight
  - New Neural Networks to handle large problems
  - Massive scaleable chips for speed, using neural networks

- When we do optimization at the same time scale as we stabilize the grid, we can get net benefit from wind and solar (telling their power converters what to do), changing cost to benefit
Cellular Neural Networks for WAMS
Hardware Implementation

- **New parallel chips**, especially memristors, could allow huge breakthrough in general purpose computing, but only if general-purpose algorithms and apps to fit on them. Since massive parallel programming has been limited, brain-like learning may be essential to achieving this. But **how can we really link best learning & best chips?**

- Roska’s Cellular Neural Net (CNN) compiler did not give us a powerful enough direct pathway yet.

- Schmidhuber, He, CLION & LeCun have used GPUs, FPGAs directly for now – requiring time and patience chip-specific.

- On DARPA $ (Hylton), HP (Snider et al) have developed a new compiler which may give a seamless path for cognitive learning and related things.
Complementary Work Needed

- Replace simplex method optimization (as in most uses of Gurobi today) with **interior point**, which can more fully utilize truly massive parallellism. See work of John Paul Watson, Sandia. Advanced Lagrangian relaxation might also help.

- Move to and scale up nonlinear interior point – as in Momoh’s AC OPF. An action network based on nonlinear interior point, centralized or distributed, naturally takes signals from a nonlinear distributed Critic (cellular symmetric neural network).

- For the more conventional turbogenerators, exploit the existing neural network AGC and future ADP AGC to improve interface.
Breaking Barriers to More PHEV Use

- No problem at ISO level (Duke, …)
  - 1 PHEV/house less new load than AC was; high efficiency and overnight recharge means little stress

- Huge problems at distribution level: see seminal paper by Saifur Rahman

- Need radically new “meshed” networks, possibly based on integrated microgrids, not only for more PHEVs but for resilience, flexibility, DER. Needs optimization.

- Current EPAS funding: VaTech, WVU, Frank Lewis (Davoudi), Shuhui Li (Wunsch) at U. Alabama

- Li 2013: indication of big breakthrough using ADP in microgrids…
JTEC: A Possible Replacement for Stirling

- Lowest cost solar farms today: 10-12¢/kwh with dish solar (Sandia, SES) with heat to electricity of 30% via Stirling. JTEC at 800°C simulations say they can do 60%: 6¢?
- But options for 55% Stirling may exist!
- The inventor has had many successes from toys to rechargeable Li-Air batteries, featured in Atlantic and CNN News this year
- Successful hardware test at 300°C for NSF grant. Uses new basic method to convert temperature differences to electricity. No solid moving parts, cousin of ceramic membrane fuel cell. Design for 800°C is credible, needs further support.
- **NIAC Report**: New Design for 9¢/kwh if launch costs down to $500/kg-LEO

- **DARPA XS-1** Technology could get us to ≤$500/kg-LEO