Information-Embedded Power/Energy Systems: Recent Research Results

Chika Nwankpa
Drexel University, Philadelphia, PA
To Find Out More About Us:

Visit our website:

http://power.ece.drexel.edu/
PowerGrid Project - Power System on a Chip (PSoC) (DOE Sponsored)

Features of PSOC:

Analog emulation; Reconfigurable chips;
Real-time computation of solution
Features: 
(i) interconnecting remote laboratories
(ii) investigating processes related to large-scale power system breakdowns
Goal: Smart distribution systems – integrating enabling technology from the substation to the customer

Drexel Activities:

- Enabling Smart Grid Functions: control strategies to improve power system reliability (GE)
- Extensibility: optimal placement algorithms for advanced grid devices to support future smart grids
PECO Award P

• Goal: Create a smart regional grid that is interoperable and expandable.

• Drexel Activities: Create a smart grid to demonstrate:
  - lower electricity costs
  - lower peak demand (with loads)
  - lower line losses (generation)
  - reduced congestion

Smart Building Diagram:
- Distributed Generation (Ex. Gas Turbine)
- HVAC (Cool/Heat)
- Lighting (On/Off)
- Solar Input (W)
- Cost of Electricity: $0.10 / kWh
- Electric Power Network
- Temperature: 72°
Smart Grid Projects

- First Tier Sub-Awardee of DOE Smart Grid Investment Grant (SGIG) to PECO Energy Co.:
  “Smart Future Greater Philadelphia: Promoting Innovation, Opportunity and Sustainability Through Smart Grid Technology”
  - With Sub-Contract to Viridity Energy

- First Tier Sub-Awardee of DOE Smart Grid Investment Grant (SGIG) to PPL Electric Utilities:
  with 2nd Tier Sub-contract to GE Energy
  “Keystone Smart Distribution”
  - PI: K. Miu Miller
Work in Alternative Energy

Renewables (Solar)  Energy Storage  Power Electronics

1.8 kW Installation – Grid Connected  400 W Battery  DC/AC Inversion

25 kW DC Rectifier
Other
Ongoing & Recent Projects
Questions???

Acknowledgements are due to the National Science Foundation, the Department of Energy, the Office of Naval Research and Viridity Energy for their financial support of this project.

The Drexel University Facilities Department are also acknowledged for building access support for this project.
Observations

- An optimization problem was developed to find the optimal dispatch of the controllable electrical loads for a family of buildings.
- General problem formulation extended to include utility network constraints.
- Linearized static demand dispatch for an example 3-building problem was presented and the impact of network constraints was highlighted.
Demand Dispatch Application

Without Network Constraints

<table>
<thead>
<tr>
<th>Building #</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{HVAC}$ (kW)</td>
<td>90.41</td>
<td>83.05</td>
<td>102.73</td>
</tr>
<tr>
<td>$\Theta$ (degF)</td>
<td>55.0</td>
<td>60.0</td>
<td>49.90</td>
</tr>
<tr>
<td>$\Delta P_{HVAC}$ (kW)</td>
<td>-16.11</td>
<td>-32.50</td>
<td>-42.81</td>
</tr>
<tr>
<td>$\Delta \Theta$ (degF)</td>
<td>15.0</td>
<td>18.0</td>
<td>8.18</td>
</tr>
</tbody>
</table>

With Network Constraints

<table>
<thead>
<tr>
<th>Building #</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{HVAC}$ (kW)</td>
<td>90.58</td>
<td>114.07</td>
<td>73.39</td>
</tr>
<tr>
<td>$\Theta$ (degF)</td>
<td>54.91</td>
<td>42.00</td>
<td>52.22</td>
</tr>
<tr>
<td>$\Delta P_{HVAC}$ (kW)</td>
<td>-15.89</td>
<td>0.18</td>
<td>-73.33</td>
</tr>
<tr>
<td>$\Delta \Theta$ (degF)</td>
<td>14.83</td>
<td>-0.10</td>
<td>13.05</td>
</tr>
<tr>
<td>$</td>
<td>V</td>
<td>$ (pu)</td>
<td>0.997</td>
</tr>
</tbody>
</table>

- Building #2 dispatch restricted due to larger impedance between substation and bus
- Building #2 power changes overall much less for each interval when network constraints are included
Demand Dispatch Application

- Optimal $P_{HVAC}$ and corresponding temperature are determined for each building.
- Solution with/without network constraints compared
- Assume const. power factor load
Problem Formulation

Model Linearization

- To set up the linear programming problem, the load model is linearized around an operating point \( (\Theta_o) \)

\[
P_{HVAC}(\Theta) = \left( \frac{P_o \beta_s}{\Theta_s} \right) \Delta \Theta + P_o
\]

- Max. error \( \approx 5\% \), with the typical error being less than 3\%
Problem Formulation

Controllable (HVAC) Load Model

- A full dynamic HVAC load model developed in previous work
- For demand response, a facility’s load may be dispatched for an hour or longer
- HVAC load dynamics may be ignored and a static load model is sufficient

\[ P_s(\Theta) = P_o \left( \frac{\Theta}{\Theta_o} \right)^{\beta_s} \]

- \( P_o \): Initial HVAC load level (kW)
- \( \beta_s \): Static load model exponential index
- \( \Theta_o \): Initial chilled water temperature value
Problem Formulation

- Network Constraints
  - Linearized decoupled power flow
  - Voltage dependency of load directly impacts dispatch of customer demand
  - Ignoring sensitivity of load to network behavior can lead to undesirable bus voltages
  - Load characteristics important consideration in determining optimal dispatch
Problem Formulation

- Building “Power Flow Constraint”
  \[ B_L = \sum_{i=1}^{m} P_{HVAC,i} - \sum_{i=1}^{m} P_{L,i} - \sum_{i=1}^{m} P_{Loss,i} \left( P_{HVAC,i} \right) = P_D \]

- Dispatched load is the customer baseline load minus Customer actual load (sum of uncontrollable, controllable, and losses)

- Baseline is the estimated metered load when no demand response actions are taken
Problem Formulation

- Network Constraints

1) \[ \frac{-\Delta P_{HVAC,i}}{|V_i|} + \bar{B} \Delta \delta_i = 0 \]

2) \[ \frac{-\Delta Q_{HVAC,i}}{|V_i|} + \bar{B} \Delta V_i = 0 \]

Decoupled Power Flow

3) \[ |V_{\text{min},i}| \leq V_i \leq |V_{\text{max},i}| \]

Bus Voltage Constraint
Problem Formulation

- Building Constraints:

1) \( B_L - \sum_{i=1}^{m} P_{HVAC,i} - \sum_{i=1}^{m} P_{L,i} - \sum_{i=1}^{m} P_{Loss,i} \left( P_{HVAC,i} \right) = P_D \) “Power flow constraint”

2) \( \Theta_{\text{min},i} \leq \Theta_i \leq \Theta_{\text{max},i} \) Building Thermal constraint

3) \( 0 \leq P_{HVAC,i} \left( \Theta_i \right) \leq P_{\text{rated},i} \) HVAC Chiller Rating constraint

4) \( \Delta t_i \leq \Delta t_{\text{required},i} \) Load Recovery constraint
Problem Formulation

- When considering the case where a customer’s loads will be dispatched, several differences are noted.
  - The total load will consist of both a controllable (HVAC) and an uncontrollable part.
  - Cost will be a linear function with respect to load.

\[
\min C\left( P_{HVAC,it} \right) = \alpha \left( \sum_{i=1}^{m} \sum_{t=1}^{T} P_{L,it} + \sum_{i=1}^{m} \sum_{t=1}^{T} P_{HVAC,it} + \sum_{i=1}^{m} \sum_{t=1}^{T} P_{Loss,it} \left( P_{HVAC,it} \right) \right)
\]

- Uncontrollable
- Controllable (HVAC)
- Losses
Problem Formulation

- Classical economic dispatch problem for generators has been well defined and provides a natural parallel when developing a method for dispatching controllable loads

\[
\min \quad C_i = \sum_{i=1}^{m} C_i(P_{Gi})
\]

\[
C_i(P_{Gi}) = aP_{Gi}^2 + bP_{Gi} + c
\]

where:
\( C_i(P_{Gi}) \): Fuel cost function
\( P_{Gi} \): Real power generation of generator \( i \)
\( a, b, c \): cost function parameters
Candidate Buildings

- Bossone Research Building
- Law Building and Library
- Perlstein Business Learning Center
- General Services and Parking Facility
Background and Motivation

- Largest percentage of consumer load due to lighting and HVAC system
- Certain measures of control with regard to HVAC system load usage are employed.
  - “Pre-cooling” of buildings at night
  - Load curtailment programs with the utility or system operator.
- A more formalized approach to dispatching loads may provide better results
Introduction

- Considerable changes to the existing power system with push for “Smart Grid”

- New opportunities for demand response and customer load control

- **GOAL**: Develop a method of determining the economic dispatch of the controllable building electric loads (demand) for demand response purposes with utility network constraints considered
Economic Dispatch of Controllable Loads
Observations

- As the system reaches maximum loading condition the observability Jacobian is close to becoming singular
  - Smallest singular value approaching zero
  - The condition number increases significantly
    - Indicating duality between loss of observability and unstable point (max loading condition)

- For the purpose of system control this duality can be exploited
  - The observability criterion can be used as a metric to identify system performance
    - Allow one to foresee actions to avoid unwanted changes in the system
Bilateral Loading Studies (cont.)

- The observability Jacobian is analyzed along the \( V\alpha \) profile of the system.

- For each point along the upper \( V\alpha \) curve:
  - A singular value decomposition of the observability Jacobian is performed and the resulting condition number is extracted.

Figure 12: \( V\alpha \) curve for load buses 4 and 5 (top) and condition number vs \( \alpha \) (bottom)
Load at buses 4 and 5 in Fig. 4 are varied through the scalar quantity $\alpha$ (increased monotonically) according to the following equation:

\[
\begin{bmatrix}
    P_{PM} \\
    P_{pump}
\end{bmatrix} = \begin{bmatrix}
    P_{PM}^0 \\
    P_{pump}^0
\end{bmatrix} + \alpha \begin{bmatrix}
    \Delta P_{PM} \\
    \Delta P_{pump}
\end{bmatrix} \rightarrow \begin{bmatrix}
    \omega_{PM} \\
    \omega_{pump}
\end{bmatrix} = \begin{bmatrix}
    \omega_{PM}^0 \\
    \omega_{pump}^0
\end{bmatrix} + \alpha \begin{bmatrix}
    \Delta \omega_{PM} \\
    \Delta \omega_{pump}
\end{bmatrix}
\]

where

\[
\begin{bmatrix}
    \omega_{PM}^0 \\
    \omega_{pump}^0
\end{bmatrix} = \begin{bmatrix}
    1 \\
    0.3615
\end{bmatrix}
\]

\[
\begin{bmatrix}
    \Delta \omega_{PM} \\
    \Delta \omega_{pump}
\end{bmatrix} = \begin{bmatrix}
    0.0025 \\
    0.003
\end{bmatrix}
\]

And system parameters:

<table>
<thead>
<tr>
<th>$\tau_1$</th>
<th>$\tau_2$</th>
<th>$\tau_{PM}$</th>
<th>$\tau_{pump}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98</td>
<td>0.95</td>
<td>1.1</td>
<td>1.03</td>
</tr>
<tr>
<td>$R_1$</td>
<td>$R_2$</td>
<td>$R_3$</td>
<td>$R_4$</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

$\nu_1$, $\nu_2$

1.35, 1.2171

Figure 11: Simplified example of a shipboard power system
Setting the differentiation indices \( r = s = l \), the observability Jacobian has the following general form:

\[
J_o = \begin{bmatrix}
\frac{dF}{dx} & \frac{dF}{dx} & 0 & 0 & \ldots \\
\frac{dF^{(1)}}{dx} & \frac{dF}{dx} & \frac{dF}{dx} & \vdots & \vdots \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\frac{dh}{dx} & 0 & 0 & 0 & \ldots \\
\frac{dh^{(1)}}{dx} & \frac{dh}{dx} & 0 & 0 & \ldots \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
x & \dot{x} & \ddot{x} & \ldots & x^{(r)}
\end{bmatrix}
\]

where

\[
\frac{dF}{dx} = \begin{bmatrix}
\frac{D_{pm} + \tau_{pm}}{M_{pm}} & 0 & 2v_4 - v_5 & 0 \\
0 & \frac{D_{pump} + \tau_{pump}}{M_{pump}} & 0 & 2v_5 - v_3 \\
-\tau_{pm} & 0 & \frac{v_4 - 2v_5}{R_3} & 0 \\
0 & -\tau_{pump} & 0 & \frac{v_3 - 2v_5}{R_4}
\end{bmatrix}
\]

\[
\frac{dh}{dx} = \begin{bmatrix}
\tau_{pm} & 0 & 0 & 0 \\
0 & \tau_{pump} & 0 & 0 \\
0 & 0 & \tau_{pm} & 0 \\
0 & 0 & 0 & \tau_{pump}
\end{bmatrix}
\]
With generator power at bus # 2 kept constant and load at bus # 4 and # 5 varied simultaneously the system model of Fig. 3 is described by:

\[
\dot{\omega}_{PM} = -\frac{D_{PM}}{M_{PM}} (\omega_{PM}) + \frac{1}{M_{PM}} \left[ -\tau_{PM} \omega_{PM} + \left( v_3 - R_3 i_{L_3} \right) i_{L_3} \right]
\]

\[
\dot{\omega}_{pump} = -\frac{D_{pump}}{M_{pump}} (\omega_{pump}) + \frac{1}{M_{pump}} \left[ -\tau_{pump} \omega_{pump} + \left( v_3 - R_4 i_{L_4} \right) i_{L_4} \right]
\]

\[
0 = -\tau_{PM} \omega_{PM} + v_4 \left( \frac{v_3 - v_4}{R_3} \right)
\]

\[
0 = -\tau_{pump} \omega_{pump} + v_5 \left( \frac{v_3 - v_5}{R_4} \right)
\]

\[p_1 : h_1(x, N) = \tau_{PM} \omega_{PM}\]

\[p_2 : h_2(x, N) = \tau_{pump} \omega_{pump}\]

Figure 10: Simplified example of a shipboard power system
Observability Metric

- The condition number of the observability Jacobian is the metric used and it is defined as:

\[
\eta = \frac{\lambda_{\text{max}}(J_o)}{\lambda_{\text{min}}(J_o)}
\]  

(12)

where \( \eta \) are the singular values obtained from a singular value decomposition of the observability Jacobian.

- The condition number is monitored along a given system load profile.
  - Smallest \( \eta \) value indicates stronger observability (\( J_o \) is further from being singular).
  - As \( \eta \) increases the matrix is becoming ill-conditioned (system is less observable).
• The observability formulation derived from the generalized form of (6) is given in terms of the Jacobian:

\[ J_o = \begin{bmatrix} G_x & G_{\dot{x}} & G_w \\ H_x & H_{\dot{x}} & H_w \end{bmatrix} \quad (9) \]

\[ w = [\ddot{x}, \dddot{x}, \ldots, x^{(\sigma)}] \quad \sigma = \max(r, s + 1) \quad (10) \]

• The system is observable if the following two conditions hold:

1: \( \text{rank}(J_o) = n + \text{rank} \begin{bmatrix} G_{\dot{x}} & G_w \\ H_{\dot{x}} & H_w \end{bmatrix} \quad (11) \)

2: \( \text{rank}(J_o) \) is constant rank on \( S \)
A more generalized form of $F(.)$ is given by

$$F(\dot{x}, x, N) - u = 0 \equiv G(\dot{x}, x, u, N) = 0$$  \hspace{1cm} (6)

If we let indices $s$ and $r$ be the differentiation indices for the system ($F$) and observation ($p$) equations respectively, then

$$\bar{F} = \begin{bmatrix} F(\dot{x}, x, N) \\ F_x(\dot{x}, x, N)\dot{x} + F_{\dot{x}}(\dot{x}, x, N)\ddot{x} \\ \vdots \\ (F(\dot{x}, x, N))^{(s)} \end{bmatrix} = \begin{bmatrix} u \\ u^{(1)} \\ \vdots \\ u^{(s)} \end{bmatrix}$$  \hspace{1cm} (7)

$$H = \begin{bmatrix} h(x, N) \\ h_x(\dot{x}, x, N)\dot{x} \\ \vdots \\ h(x, N)^{(r)} \end{bmatrix} = \begin{bmatrix} p \\ \dot{p} \\ \vdots \\ p^{(r)} \end{bmatrix}$$  \hspace{1cm} (8)
Observability Formulation

- The general model used to investigate power system dynamics is that of the Differential Algebraic Equations (DAE) type in (1)

\[
\begin{align*}
\dot{x} &= f(x, u, N) \\
0 &= g(x, u, N) \\
p &= h(x, N)
\end{align*}
\]  \hspace{1cm} (1)

\[
F(\dot{x}, x, N) = u \\
p = h(x, N)
\]  \hspace{1cm} (5)

- \( f \) - set of non-linear differential equations - model dependent
- \( g \) - non-linear algebraic equations
- \( x \) - is the set of dynamic state variables and the set of static variables
- \( u \) - independent control parameters
- \( N \) - network parameters
- \( h \) - set of nonlinear algebraic equations related to measurements
- \( p \) - measurement vector
Specific Problem Statement

- What is being sensed, observed, controlled? Effects?

- Observability issues in shipboard power systems
  - System model
  - Declaring observability
  - How to quantify observability?
    - Static case where observability measure is monitored as the system approaches the maximum loading point
Figure 9: System state transitions due to a perturbation
Motivations

- **Shipboard Power Systems**
  - All electric ship vision
    - Electric drive
    - Integrated Power Systems
    - Zonal Distribution Systems
  - Crew force optimization trend
    - Cost reductions enabled by autonomous operation with reduced crew

- **Enabling Technology – System Automation**
  - Traditional control strategies are based on linearized power system models which are not sufficient due to large system perturbations
    - Pulse-power loads
    - Nonlinear interactions between system components

- A *measure of observability* of such systems will allow one to quantify their operational performance
  - Incorporation of nonlinear dynamics of converters and electromechanical behavior of generators and loads
Introduction

- *Inherent cross-regulation behavior* is expected due to the propagation of power electronic switching converters in the composition of power systems architectures
  - Converter controllers are built to be local
  - No consideration of coupling dependencies with other parts of the system

Figure 8: Shipboard power system figure showcasing converters interrelationship
Figure 7: Portrayal of a shipboard power systems
Multi-Converter Systems
Observations

- This work presented modeling/simulation framework to analyze deterministic and stochastic behavior of a dc-dc converter system with network models, under varying system parameters.
- First, the effects of modeling measurement delays in the averaged sense were studied.
- Then the deterministic model was transformed into a stochastic model to account for uncertainty.
- The effects of both converter specific and network specific parameters may be used to either quantify and/or control observability.
• As the scaling factors for noise intensity are increased, the variance of the steady state numerical solution of the trajectories increases.

• Framework has been developed where the effects of both converter specific (control gains) and network specific (noise intensities) parameters may be used to either quantify and/or control observability.
Results – Exponential White Noise Network Model

Figure 6. Numerical solution for output voltage over 100 trajectories
Simulation of Perturbed System Model

- Performed using SDE Toolbox
  - Developed by Umberto Picchini (http://sdetoolbox.sourceforge.net)

- System can be modeled using an Itô SDE or the corresponding Stratonovich SDE
  - Itô
    - Natural starting point for numerical schemes
    - Euler-Maruyama or Milstein integration method
  - Stratonovich
    - Easier to solve analytically
    - Only Milstein integration method
Exponential White Noise Network Model

- In this approach, the product “LC” is used to rescale the intensity of the noises.

- Network dynamics of the buck-boost converter with the exponential network model after substituting (8) into (6):

\[
\begin{align*}
\frac{dm_{e_i}}{dt} &= s(i_L - m_{e_i}) + \sqrt{2LC} \varepsilon (i_L - m_{e_i}) w_{i_L} \\
\frac{dm_{e_v}}{dt} &= s(v_C - m_{e_v}) + \sqrt{2LC} \varepsilon (v_C - m_{e_v}) w_{v_c}
\end{align*}
\]

(4)

where \( m_{e_v} \) and \( m_{e_i} \) are the perturbed versions of \( m_v \) and \( m_i \) respectively.
Perturbed System Model

- A noise parameter introduced to the existing exponential and logistic growth network models to account for randomness of network traffic
- Deterministic models transformed into stochastic models
  - Exponential White Noise Network Model*
  - Logistic Growth White Noise Network Model

* - included in present talk
Results (cont.)

- The logistic growth model responds faster than the exponential model.
- However, for non-zero initial conditions, the exponential model tracks the actual voltage and current values closely.
- For non-zero initial conditions a sudden drop in the system states was be observed when using the logistic growth model.
Results

Figure 5. Actual output voltage and output voltage as measured by network models
\(k_1=0.6, k_2=-0.2, E=8.5\text{V}, V_C^0=24.5\text{V}, r=60\text{ms}, L=5\text{mH}, C=220\mu\text{F} \text{ and } R=8\Omega\)
Figure 4. Buck-boost converter with logistic growth network model

\[
\begin{align*}
\frac{di_L}{dt} &= \frac{1}{L} \left[ -v_C + V_{\text{ref}} v_C - k_1 i_L v_C - k_2 v_C^2 + V_{\text{ref}} E - k_1 i_L E - k_2 v_C E \right] \\
\frac{dv_C}{dt} &= \frac{1}{C} \left[ i_L - V_{\text{ref}} i_L + k_1 i_L^2 + k_2 i_L v_C - \frac{v_C}{R} \right] \\
\frac{dmi_I}{dt} &= \frac{mi_I}{a} \left( 1 - \frac{mi_I}{i_L} \right) \\
\frac{dvm_C}{dt} &= \frac{m v_C}{a} \left( 1 - \frac{m v_C}{v_C} \right)
\end{align*}
\]

(1) → Buck-Boost Converter Model

Delay incorporated using \(a\) (function of \(r\))

\[ a = -\frac{r}{\ln \left( \frac{m v_C(0)}{V_C^0 - m v_C(0)} \right)} \]
Converter with Network Model

Figure 3. Buck-boost converter with exponential network model

\[ \frac{di_L}{dt} = \frac{1}{L} \left[ -v_C + V_{\text{ref}} v_C - k_1 i_L v_C - k_2 v_C^2 + V_{\text{ref}} E - k_1 i_L E - k_2 v_C E \right] \]

\[ \frac{dv_C}{dt} = \frac{1}{C} \left[ i_L - V_{\text{ref}} i_L + k_1 i_L^2 + k_2 i_L v_C - \frac{v_C}{R} \right] \]

\[ \frac{dmi_L}{dt} = \frac{1}{r} (i_L - mi_L) \]

\[ \frac{dmv_C}{dt} = \frac{1}{r} (v_C - mv_C) \]

(1) \rightarrow \text{Buck-Boost Converter Model}

(2) \rightarrow \text{Exponential Network Model}

Delay incorporated using the network time constant \( r \)
Buck-Boost Converter Model

Conventional Averaged Model

\[
\begin{align*}
\frac{di_L}{dt} &= \frac{1}{L} \left[ -v_c + V_{ref} v_c - k_1 i_L v_C - k_2 v_C^2 + V_{ref} E - k_1 i_L E - k_2 v_C E \right] \\
\frac{dv_C}{dt} &= \frac{1}{C} \left[ i_L - V_{ref} i_L + k_1 i_L^2 + k_2 i_L v_C - \frac{v_C}{R} \right]
\end{align*}
\]

Duty ratio

\[d(t) = V_{ref} - k_1 i_L - k_2 v_C\]

Equilibrium when,

\[
\frac{di_L}{dt} = 0, \quad \frac{dv_C}{dt} = 0
\]

Figure 2. Buck-boost converter
Model Derivation

• Buck-boost converter
  – Conventional averaged model

• Information embedded network
  – Modeling the delay in the averaged sense
  – Underlying stochastic nature ignored
  – Exponential model
  – Logistic growth model
Introduction (cont.)

Figure 1. Networked multi-converter system
Introduction

- Background Information
  - Power electronic converters are an important feature of renewable energy systems, dc distribution systems, shipboard power systems etc.
  - Operation of these systems reliant on their embedded communication infrastructures
  - Communication delays in delivering measurements across a computer controlled network can render parts of the system unobservable due to dropped measurements.
Network Delayed Converters
Facilities

- IPSL: Interconnected Power Systems Laboratory
- RDAC: Reconfigurable Distribution Automation and Control Laboratory
- Orthlip: Systems and Control Laboratory
- Multi-Media Supported Laboratory
- Power Electronics Laboratory
- Machine Laboratory
- High Voltage Laboratory
- Relay Laboratory

- Graduate Student Research Areas: 3-052, Bossone 402
Facilities

High Voltage

Transmission Systems

Distribution Systems

<table>
<thead>
<tr>
<th>Educational Activities</th>
<th>Students/Yr</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Outreach*</td>
<td>80+</td>
<td>80+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mandatory Power Courses (annual)</th>
<th>UG Students/Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>P352 Motor Control Principles</td>
<td>58 59</td>
</tr>
<tr>
<td>P354 Energy Management</td>
<td>29 32</td>
</tr>
<tr>
<td>P411, 412, 413 Power Systems</td>
<td>38 36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elective Power Courses*</th>
<th>UG Student/Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>P421, 422, 423 Power Distribution Systems</td>
<td>8</td>
</tr>
<tr>
<td>P451, 452, 453 Power Electronics I, II, III</td>
<td>---- 14</td>
</tr>
</tbody>
</table>

*co-taught with graduate students (15) (8)
CEPE Students

# of Current Graduate Students Supported: 10
CEPE: Who are we and what we do

Areas of interest include:
- Power Systems
- Power Electronics
- Intelligent Systems

On-going projects:
- NSF: Transmission and Distribution Power Systems
- ONR: Shipboard Power Systems
- DOE: PowerGrid - a “Power System on a Chip” (PSoC)
- ONR: Remote Non-destructive Testing of Power Systems
Talk Overview

• Center for Electric Power Engineering at Drexel:
  – Who are we and what we do
  – Facilities

• Topics to be covered
  – Network Delayed Converters
  – Multi-Converter Systems
  – Economic Dispatch of Controllable Loads