FEEDER

&

ECE Research on

Distributed Technologies and Smart Grid

Zhihua Qu

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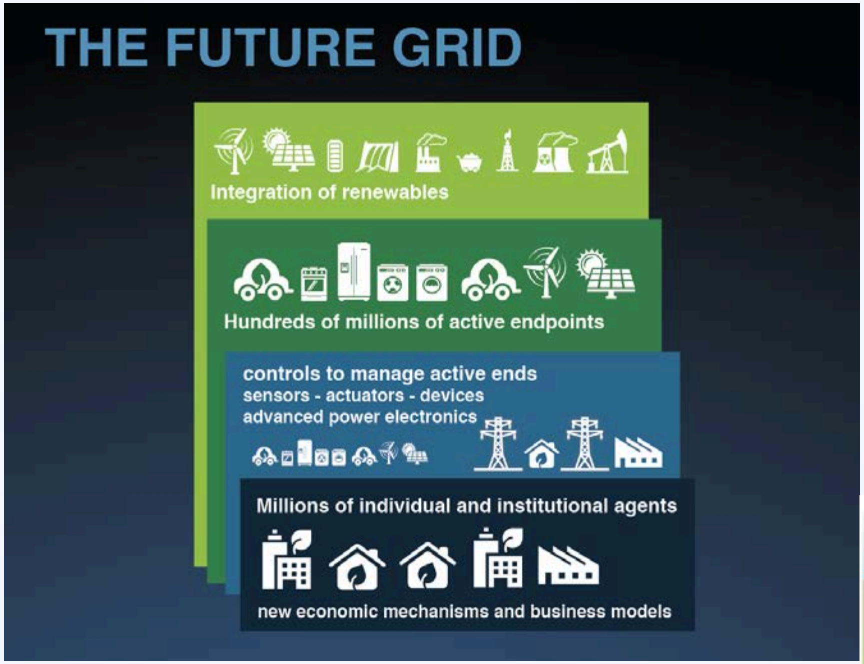
U.S. Department of Energy

Why Smart Grid?



DGs: Varying and unpredictable outputs

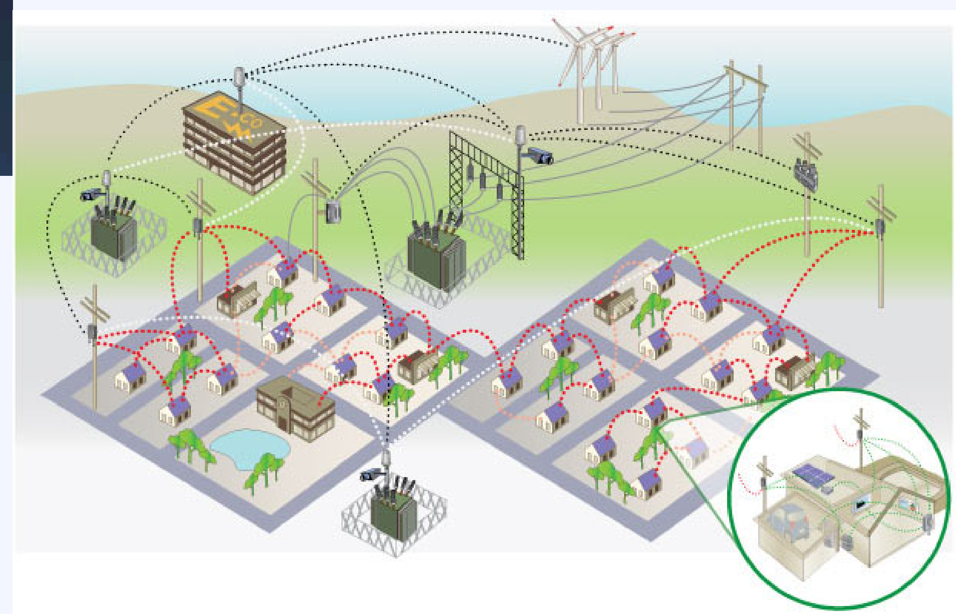
Devices: numerous, heterogeneous, and competitive

Information: dispersed and intermittent

DGs: close to consumption

Devices: controllable (loads), intelligent

Information: local but high resolution



``*IEEE Vision for Smart Grid Controls: 2030 and Beyond*,” IEEE Standards Association, 2013.

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FEEDER: The GEARED-Up Team

6,000 Students: Power & Energy

100,000 Utility Employees

7 Universities

University of Central Florida

University of Kentucky

Auburn University

University of Florida

Florida State University 1851

University of South Carolina

University of Arkansas

8 Utilities

Southern Company

Duke Energy

FPL

TVA

AEP Kentucky Power — A unit of American Electric Power

OUC The Reliable One

Lakeland Electric — Your Essential Link to a Quality Life

East Kentucky Power Cooperative

FEEDER Consortium

2 National Labs

Los Alamos National Laboratory EST. 1943

NREL National Renewable Energy Laboratory

Supporting Industries

OSIsoft

SAIC From Science to Solutions

Schneider Electric

SIEMENS

S&C Electric Company — Excellence Through Innovation

NPPT Northern Plains Power Technologies

Test Beds, Research, Collaborations

500,000 Industrial Employees

FEEDER Faculty

31 faculty members in 7 universities:

University of Central Florida: Zhihua Qu (distributed control and optimization for smart grid), Saeed Lotfifard (power system protection and monitoring), Alireza Seyedi (networked controls), Azadeh Vosoughi (communication), Marwan Simaan (optimization), Robert Reedy (electric utility and solar energy), David Click (PV energy systems), Jerry Ventre (photovoltaic systems engineering and workforce development)

University of Kentucky: Larry Holloway (energy systems and control), Y.T. Cheng (storage), Don Colliver (solar power systems), Aaron Cramer (power electronics), Paul Dolloff (protection and reliability), Zongming Fei (communication), Yuan Liao (automation and control), Vijay Singh (solar power systems), Joe Sottile (power systems)

Auburn University: Mark Nelms (power electronics) and Mark Halpin (power systems)

University of South Carolina: Roger Dougal (power sources, simulation methods, systems design, design tools), Herb Ginn (power electronics, digital controls, active power control and routing), Enrico Santi (power semiconductor devices, modeling, converters, controls), Charles Brice (power systems), Grigory Simin (wide bandgap semiconductor devices)

Florida State University: Richard Meeker Jr. (protection and control) and Omar Faruque (power systems simulation)

University of Arkansas: Juan Carlos Balda (power systems, power electronics, energy conversion), Roy McCann (power systems & controls, motors, energy storage), Alan Mantooth (power electronics, power semiconductors), Simon Ang (power electronics, electronic packaging)

University of Florida: Sean Meyn (control of networks, demand response)

Highly qualified faculty: 1 NAE Member, 7 IEEE Fellows, 2 AAAS Fellows, 1 APS Fellow, and 1 NSF CAREER awardee.

Past experiences: DoE SEGIS, SUNGRIN, PEIK; NSF; ONR; ARPA-E; utility & industry.

FEEDER Partners

National Renewable Energy Laboratory: Dr. Ben Kroposki, Director of Energy Systems Integration

Los Alamos National Laboratory: Mr. Scott Backhaus, LANL Scientist

Florida Power & Light: Mr. Buck Martinez, VP and Senior Director Project Development; Mr. Andrew Beebe, VP of Distributed Generation at FPL/NextEra

Duke Energy: Mr. Gary Freeman, General Manager-DSM/EE Operations; Mr. V. Nelson Peeler, VP of System Operations

Southern Company: Mr. Robert Schaffeld, VP Transmission at Southern Company Transmission

Orlando Utility Commission: Mr. Byron Knibbs, VP of Customer & Sustainable Services

Kentucky Power: Mr. Everett Phillips, Managing Director, Distribution Operations

TVA: Mr. Ernest Peterson, Jr., General Manager, Kentucky District

East Kentucky Power Cooperative: Mr. Rick Drury, Manager of Engineering

Siemens: Dr. Jerry Feller, Principal Expert Engineer and University Liaison Manager

SAIC: Dr. Jim Northrup, Assistant VP of Power and Energy

Leidos: Mr. Paul Grimes, VP and Chief Technology Officer of Engineering Solutions Group

Schneider Electric: Mr. Jim Pauley, SVP External Affairs and Government Relations

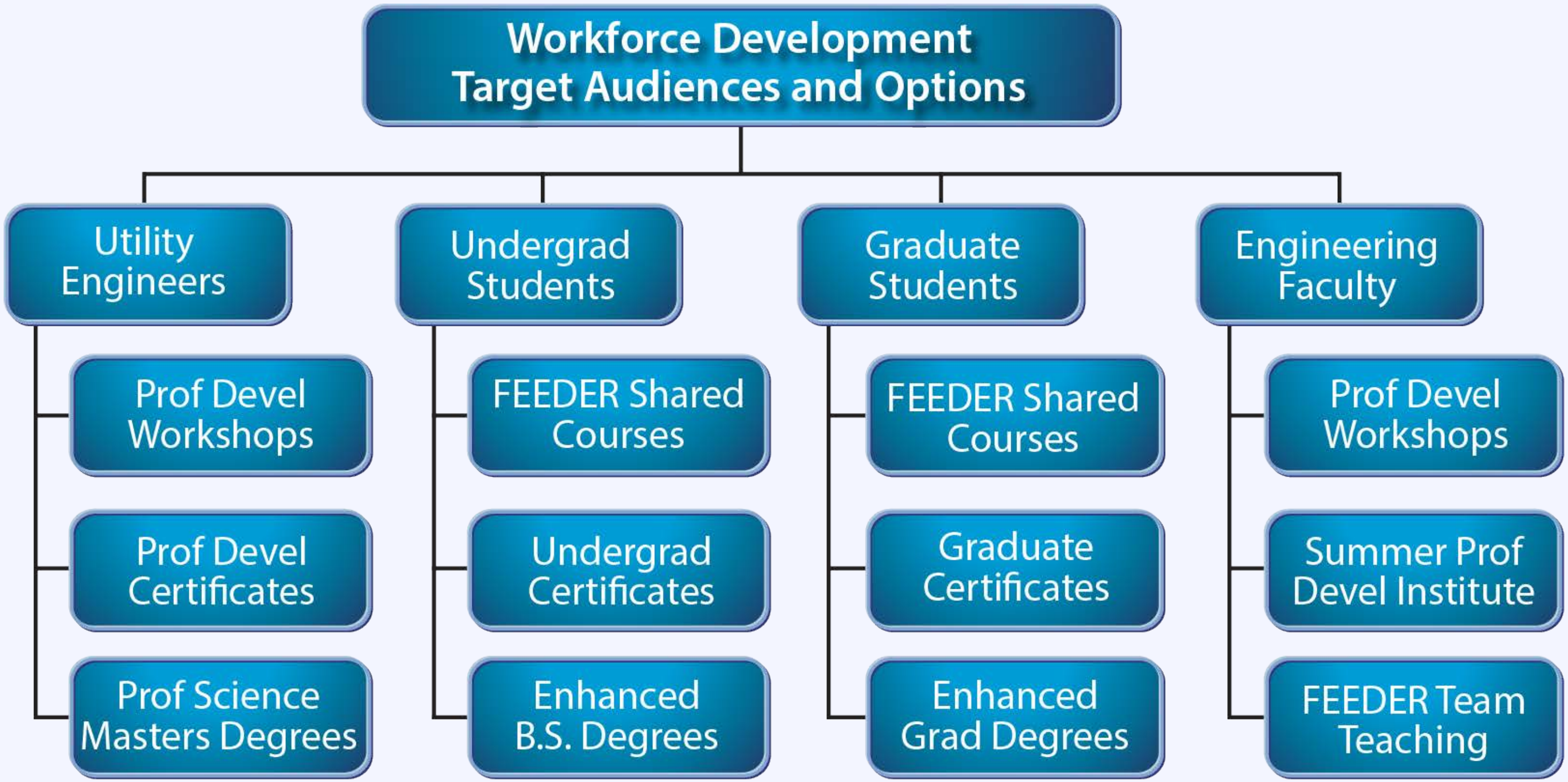
S&C: Mr. Troy Miller, Manager – Business Development, Power Quality Products

Northern Plains Power Technologies: Dr. Michael Ropp, President and Principal Engineer

OSI: Ms. Candace Keyes, Research Analyst/Emerging Markets/University Systems

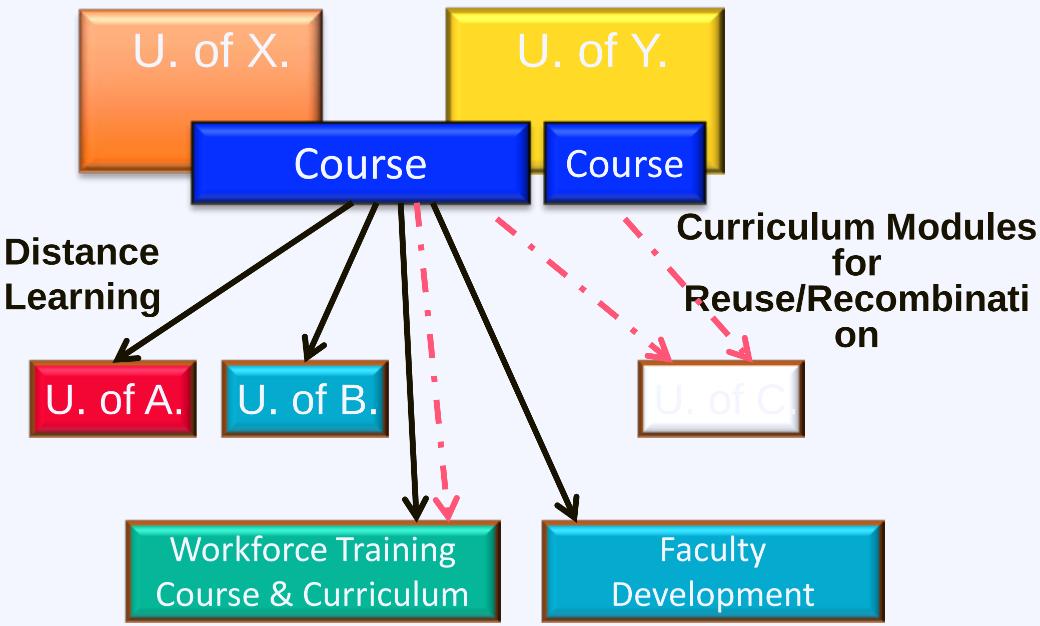
Mitsubishi Power Systems Americas: Ms. Lisa Batsch-Smith, Operations Support

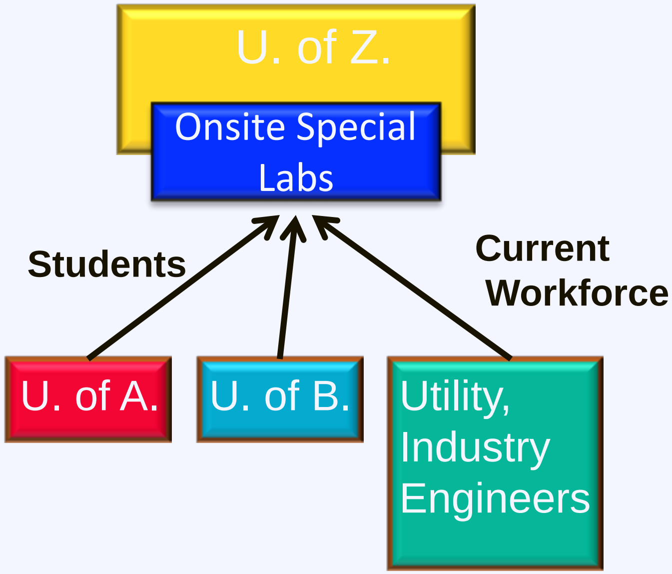
FEEDER Education and Training



GEAR-04

Innovative Paradigm on Education & Training





Education Modes:

- Cross-institution collaboration on curriculum and course development
- Cross-institutional offerings
- Cross-institutional (and beyond) sharing of curriculum and modules
- On-site courses for specialized lab experiences

Education Targets:

- Current Workforce
- Future Workforce (Graduate and Undergraduate)
- Faculty Development

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Features of FEEDER Paradigm

- Transforming Power Engineering Education
  - ***Share delivery*** of courses among multiple universities
  - Use modern information and communications technology for ***multiple delivery options***
  - Provide students with ***more program options and career pathways***
  - Implement course, credit, and tuition exchange agreements
  - Increase student throughput per course and per program
  - Better match faculty expertise with course teaching assignments
  - Enhanced industry collaboration

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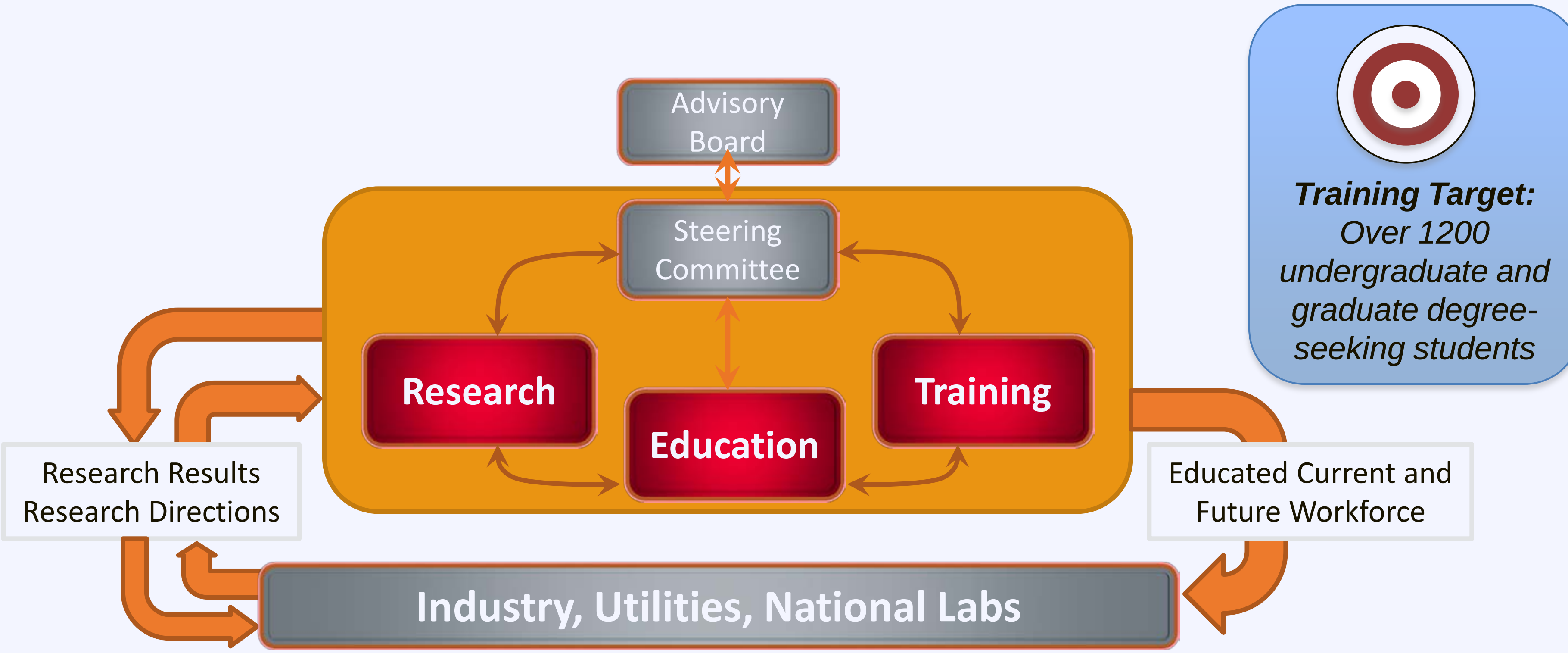
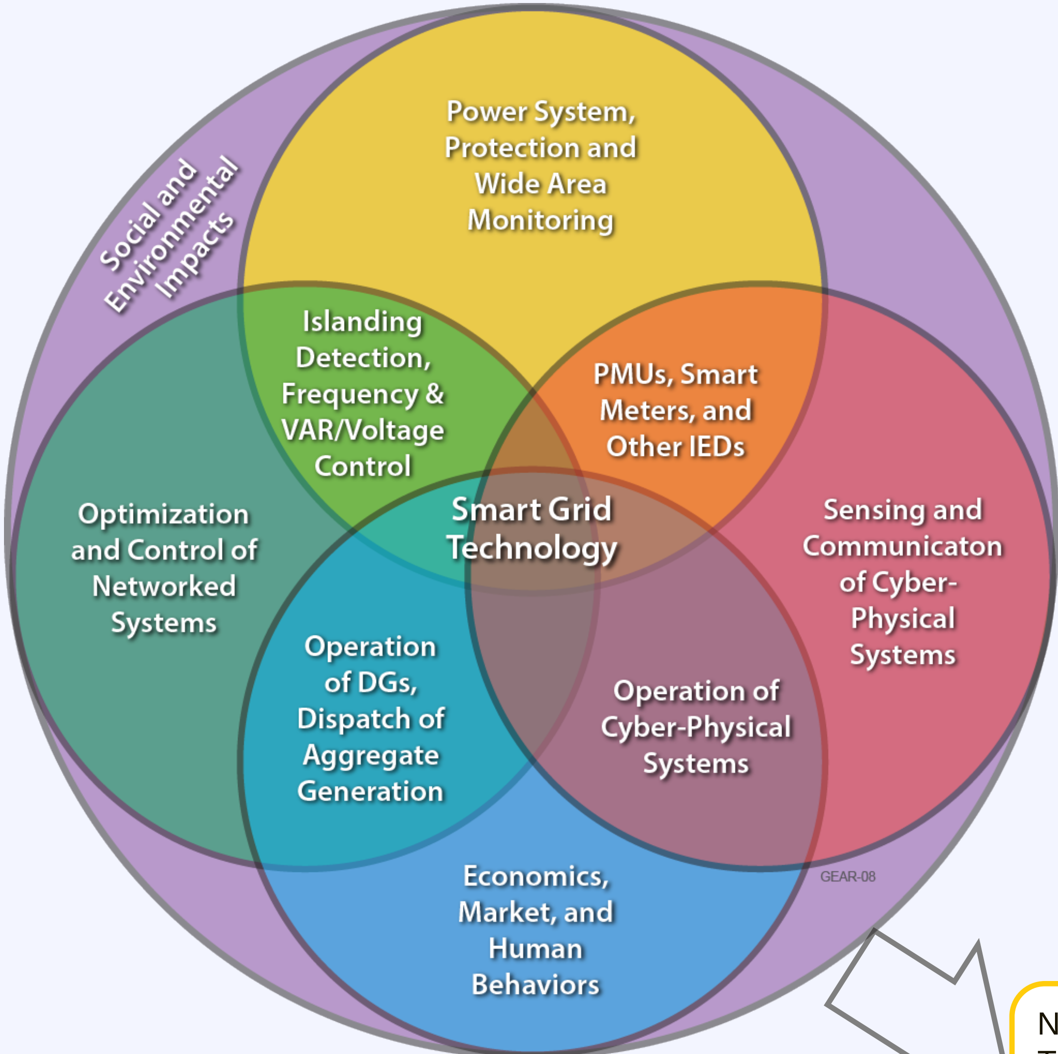
FEEDER: Stakeholders and their Interaction



- Create standard process for collaborations between university/utility/labs/industry
- Training and Collaborations
  - Interdisciplinary
  - Beyond organizational and geographical (including international) boundaries

FEEDER: Research Overview



Activities and Outcomes

- Establish the capacity and mechanism to pursue collaborative research, across multiple universities and with utilities, industry, and national labs
- Increase the capacity to integrate high penetrations of solar and other distributed generation and storage technologies
- Develop innovative, interdisciplinary approaches to quantify system implications of distributed technologies

New Subject Matter and Tech Transfer, Content for Course and Curriculum Integration

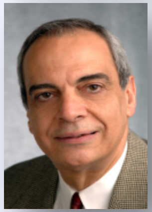
Relevant Research @ ECE

- Smart Grid Research Faculty

- Smart Grid Research Thrusts
  - Power systems protection and wide-area monitoring
  - Distributed sensing and communications for cyber-physical systems
  - Cooperative control of distributed generation
  - Multi-level and distributed optimization for smart grids
  - Secure cyber-physical systems against malicious attacks

Faculty and Their Expertise

Zhihua Qu
Cooperative control of networked systems
Distributed optimization
Power and energy systems



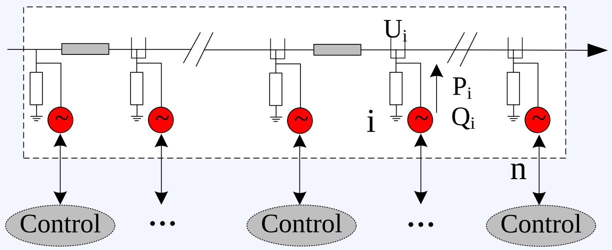
Marwan Simaan
Optimization of dynamic systems
Game theory

Azadeh Vosough
Communication
Wireless networks

Saeed Lotfifard
Power system protection and monitoring
Smart grid

Alireza Seyedi
Convergence of control and communication
Control and decision

Options for Communication/Control/Optimization

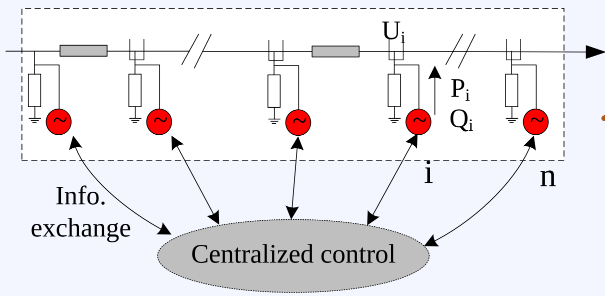


(a)

Decentralized Mode

Advantage: few information

Disadvantage: no cooperation

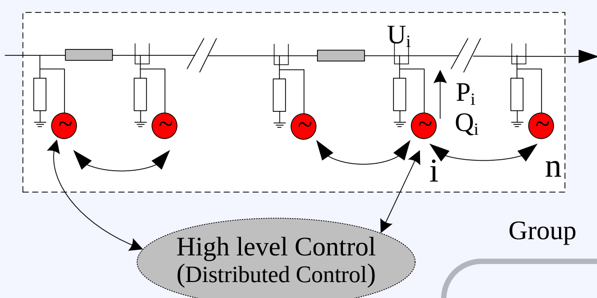


(b)

Centralized Mode

Advantage: cooperation, optimality

Disadvantage: global information



(c)

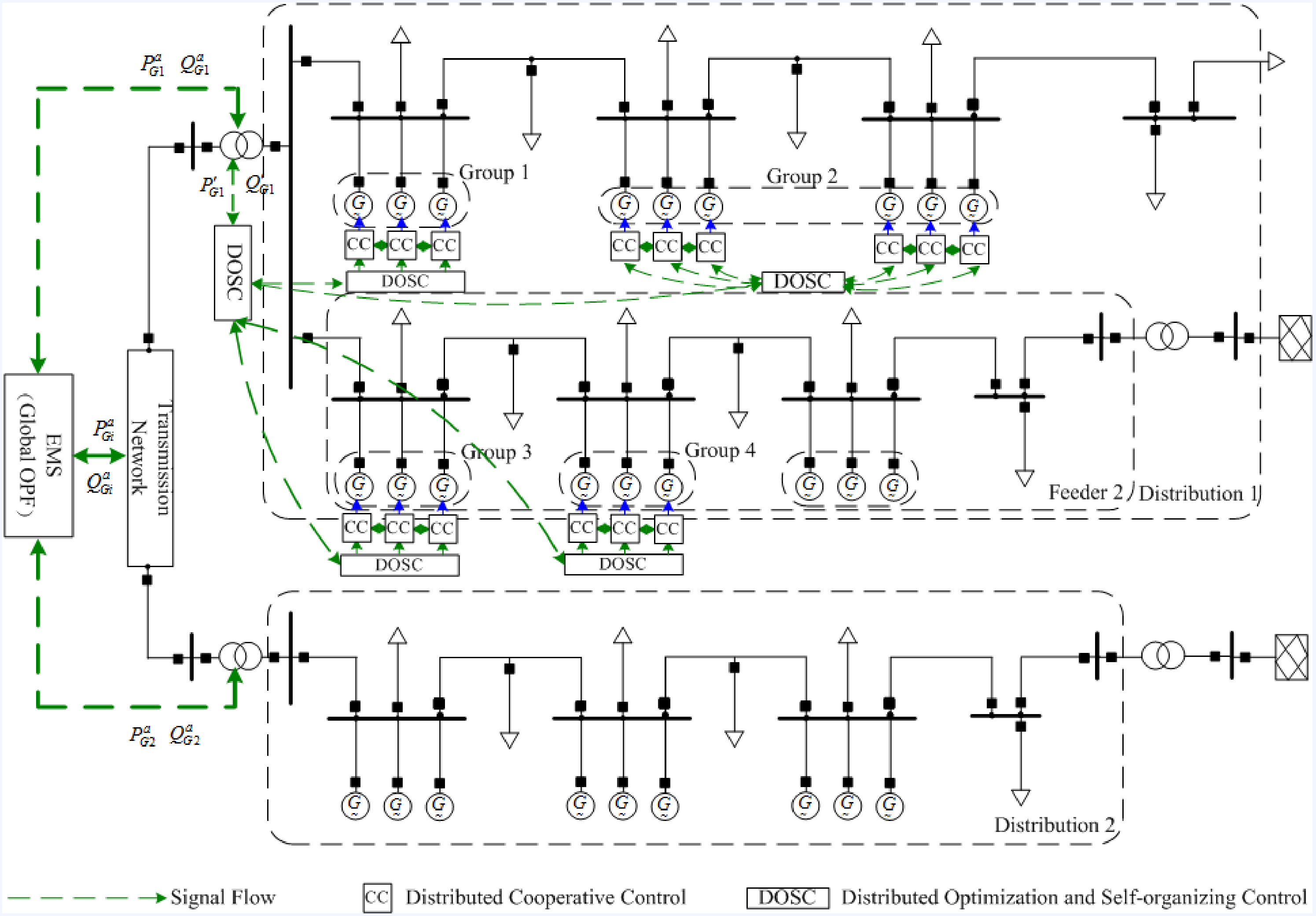
Distributed Mode

Best tradeoff

Other issues: intermittency, varying topologies, latency, uncertainties, attacks.

Objectives: stability, resiliency, robustness, optimality, security.

Distributed Optimization and Self-Organizing Control



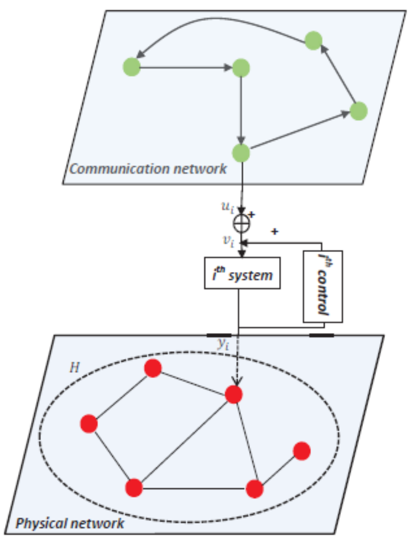
Networked Plug-n-Play Operation of Heterogeneous Systems

Considerations:
- heterogeneous dynamical systems
- physical network
- local communication networks
- variable topologies
- uncertainties

Outcomes:
- plug-n-play operation
- distributed controls
- topology optimization
- systematic designs
- game strategies

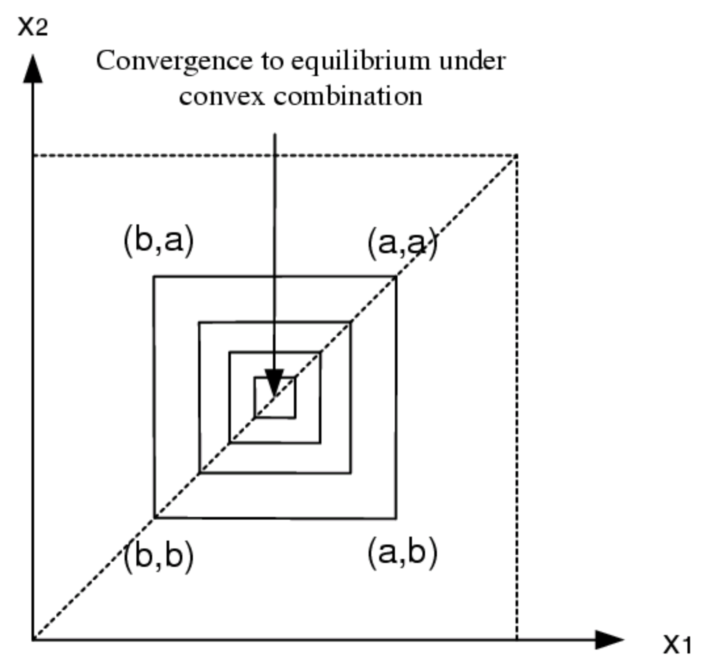
Heterogeneous systems: $z_i \in \Re^{n_i}$, $v_i, y_i \in \Re^m$, and $\partial H(z_i)/\partial z_i$ has rank m,

$$\dot{z}_i = F_i(z_i) + G_i(z_i)v_i, \quad y_i = H_i(z_i).$$



"An Impact Equivalence Principle of Separating Control Designs for Networked Heterogeneous Affine Systems," the 3rd *IFAC Workshop on Distributed Estimation and Control in Networked Systems* (NecSys'12), September 14-15, 2012, Santa Barbara, CA, USA.

Cooperative Stability: A Geometrical Explanation



Linear mapping:

$$x(k+1) = A(k)x(k),$$

where $A(k) \geq 0$ is row stochastic.

In 2-D, let $x(0) = [a\ b]^T$ and

$$A(k) = \begin{bmatrix} a_{11}(k) & 1 - a_{11}(k) \\ 1 - a_{22}(k) & a_{22}(k) \end{bmatrix}.$$

Then, the mapping is convex if $0 < a_{ii}(k) < 1$.

E.g.,

$x(1) = [a\ b]^T$ if $a_{ii}(1) = 1$.
$x(1) = [b\ a]^T$ if $a_{ii}(1) = 0$.
$x(1)$ lies in the first square if if $0 < a_{ii}(1) < 1$.

Convexity: simple but not necessary.

Nonlinear mappings: extending the contraction mapping theorem.

Distributed Control: Automatic dispatch & Voltage Stability

- Difficult to dispatch and control DGs due to intermittent and small outputs

- Operational requirements are expensive to achieve using the current framework

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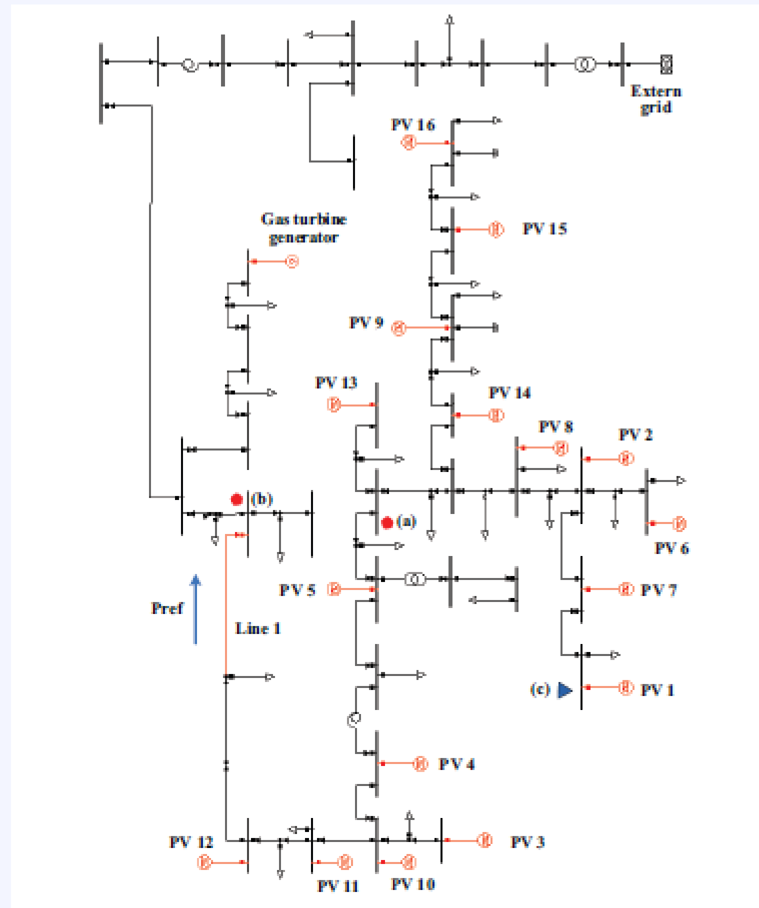
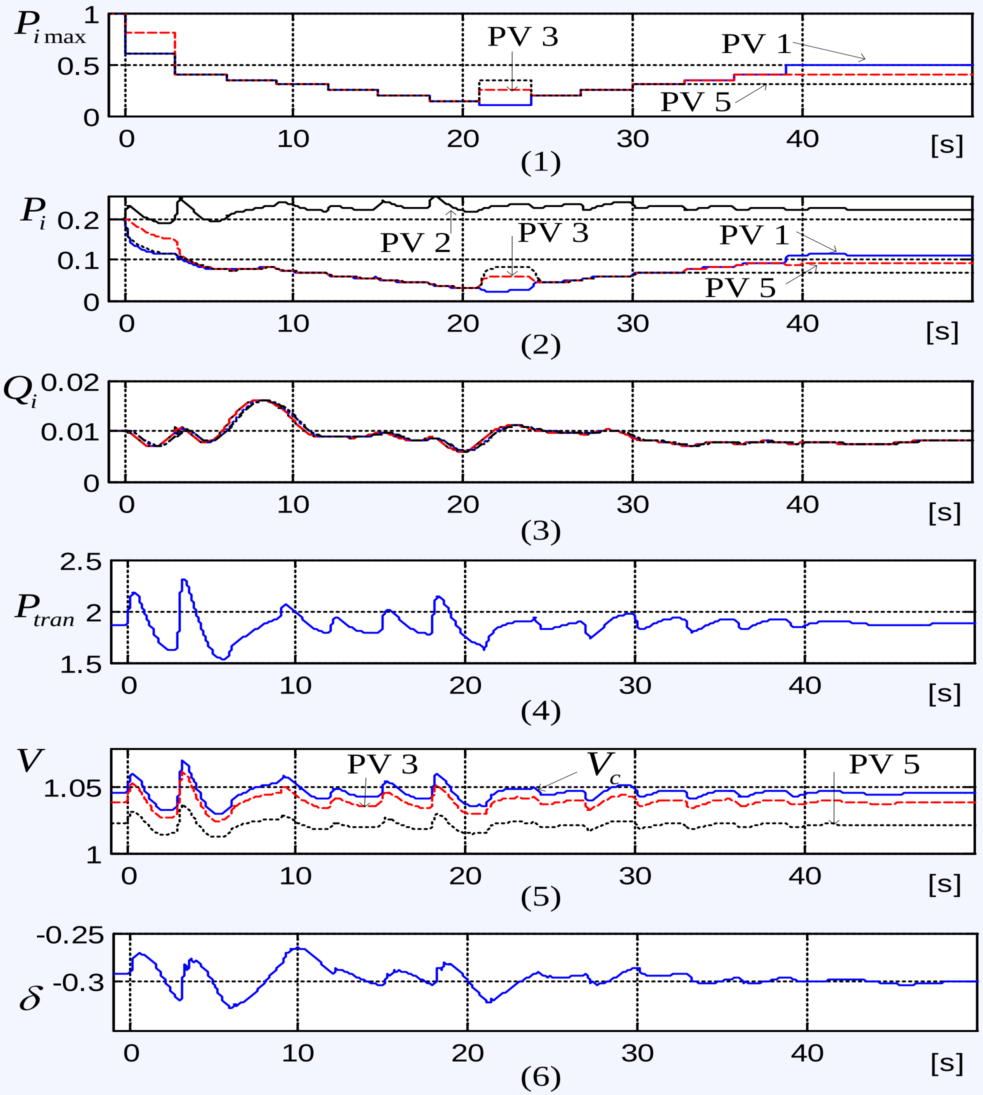
IEEE 34-bus network



Sample Results

Chang in the sunlight



“A Self Organizing Strategy for Power Flow Control of Photovoltaic Generators in a Distribution Network,” *IEEE Transactions on Power Systems*, vol.26, no.3, pp.1462-1473, August 2011.

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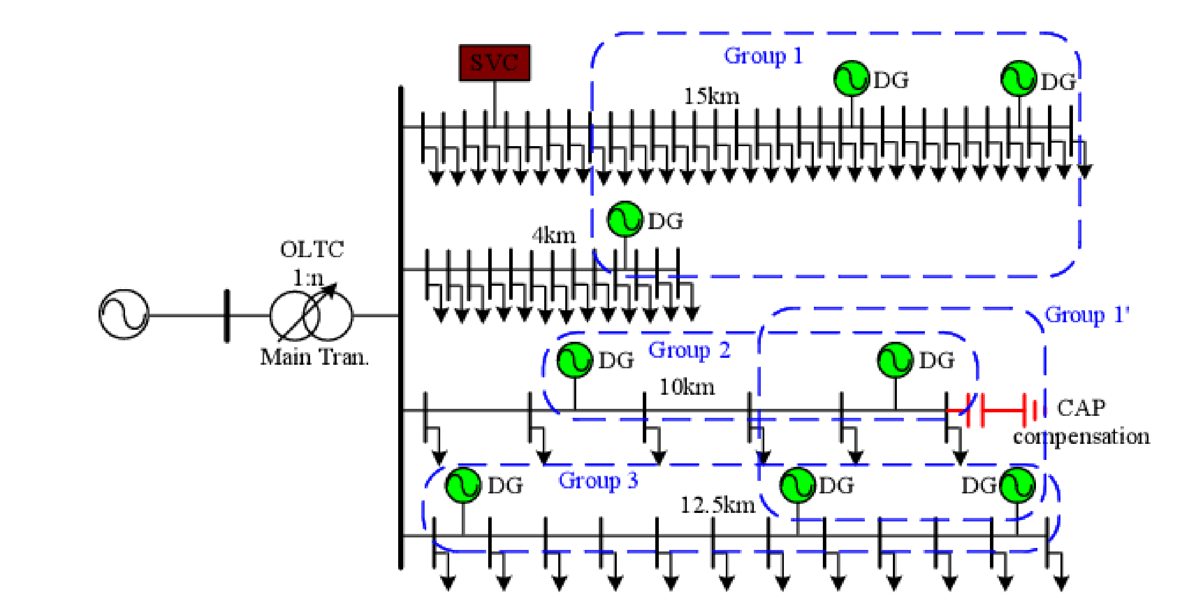
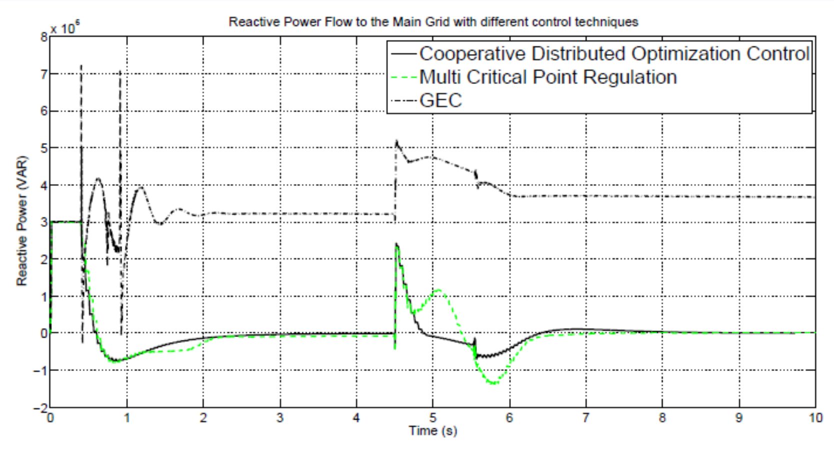
Self-Evolving Micro-Grids





“Clustering and Cooperative Control of Distributed Generators for Maintaining Microgrid Unified Voltage Profile and Complex Power Control,” 2012 *IEEE PES Transmission and Distribution Conference & Exposition*, Orlando, FL, USA, 7-10, May 2012.

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Secure Cooperative Systems Against Attacks

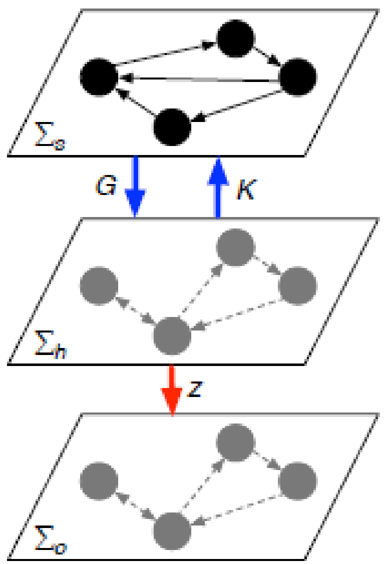


Fig. 1. Three-layer design of secure cooperative systems: networked system nodes (Σ_s of Laplacian L_s), hidden nodes for robustification (Σ_h of Laplacian L_h), and observation nodes (Σ_o)

"Robust Design of Cooperative Systems Against Attacks," Submitted to 2014 American Control Conference, Portland, Oregon, USA.

Cooperative system:

$$\dot{x} = -L_s x + L_a d,$$

which could be destablized under d.

Secure cooperative system:

$$\begin{aligned} \dot{x} &= -L_s x + \beta K z + L_s d, \\ \dot{z} &= -L_h z - \beta G x, \\ \dot{d} &= F_a d + B_a x, \end{aligned}$$

which is robustly stable.

Conclusions:

1) Unless more than half of all nodes are attacked, stability is ensured.
2) Attacks can be identified.

Summary of Activities

Collaborative efforts by ECE & FSEC are very productive:

- FEEDER Center (DoE, led by ECE)
- Electrical Vehicle Transportation Center (DoT, led by FSEC)

Fundamental research projects:

- NSF grants on smart grid and wireless sensor network
- Etc.

THANK YOU!

FEEDER:

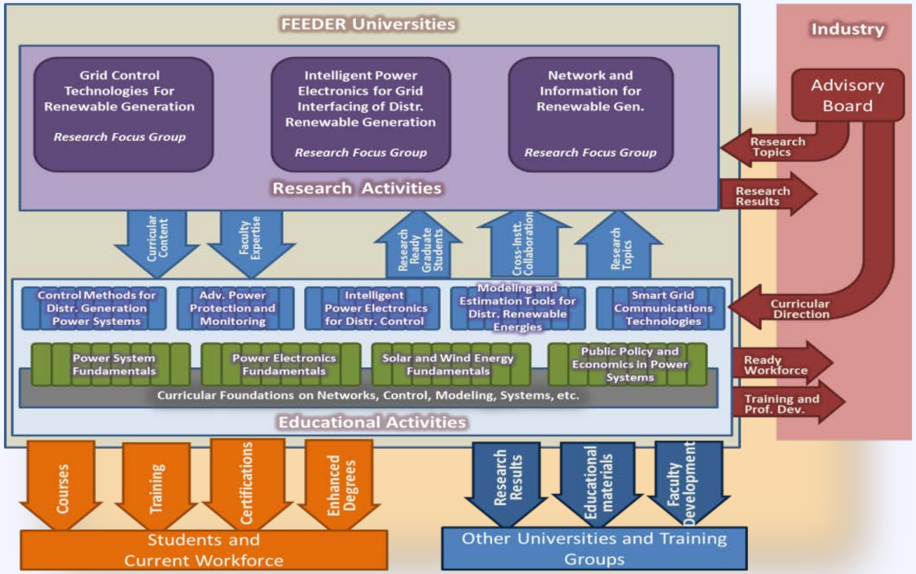
DoE Award #: DE-EE0006340

Foundations for Engineering Education for Distributed Energy Resources

PI: ZHIHUA QU

Project Summary

The FEEDER Consortium consists of seven Universities in the Southeast United States, eight utility companies, seven supporting industry partners and two national labs and a research center. This consortium will develop the engineering capability to accelerate the deployment of distributed renewable energy technologies onto the electric utility grid. This will be accomplished by upgrading the existing power systems engineering workforce, upgrading power systems engineering programs at our universities, and developing a pipeline of new power systems engineers and engineering faculty. Through the efforts of this Consortium, we will feed a new group of engineers into the workforce capable re-engineering the existing electrical grid infrastructure to include a highly sophisticated communications infrastructure.



Key Personnel/Organizations

PI Institution: University of Central Florida

Consortium Members: University of Kentucky, Auburn University, University of South Carolina, University of Florida, Florida State University, University of Arkansas

Budget and Timeline

Federal funds: $3.2M (5 Years) Cost-share: $1.67M Total: $4.87M

Key Milestones & Deliverables

Year 1:	Establish steering committee, advisory board, research protocol, curriculum enhancements, faculty development.
Year 2:	Conduct education and training, research collaboratives, technology transfer, and assessments.

Project Impact

The primary goal of the FEEDER Consortium is to significantly advance engineering capability to accelerate the deployment of distributed power systems technologies through well designed and complementary research, development, test, analysis, and evaluation supporting innovative and highly collaborative education of the current and future workforce.

Population Impact: 35,461,685 (US Census Data)