Undergraduate Curriculum

- ECE3070: Electromechanical Energy Conversion
- ECE4320: Power System Analysis
- ECE4321: Power System Engineering
- ECE4330: Power Electronics
- ECE4325: Electric Power Quality
Graduate Courses in Power Systems

- **ECE6320**: Control and Operation of Power Systems
- **ECE6321**: Power System Stability
- **ECE6322**: Power System Planning
- **ECE6323**: Power System Relaying
- **ECE8843**: Topics in Electric Power Computational Intelligence in Power Systems
# Graduate Courses in Power Electronics

<table>
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<tr>
<th>Course Code</th>
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<tr>
<td>ECE6330</td>
<td>Power Electronic Devices &amp; Subsystems</td>
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<tr>
<td>ECE6331</td>
<td>Power Electronic Circuits</td>
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<tr>
<td>ECE6335</td>
<td>Electric Machinery Analysis and Design</td>
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<tr>
<td>ECE6336</td>
<td>Dynamics &amp; Control of Electric Machine Drives</td>
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ECE6320  Power Systems Control and Operation  Fall 2010

The Power System Control Problem
Control Functions
Operational Constraints/System Operating States
Vertically Integrated Operation
Independent System Operation – Standard Market Design

Review of Energy Management Systems
Real Time Modeling Subsystem
Energy/Economy Functions and Control
Security Monitoring and Control Subsystem
Smart Grid Technologies

Analysis Techniques:
The Power Flow Problem
Solution Techniques
Large Scale Systems
Sparsity Techniques
Security Assessment/Contingency Analysis
Power System Equivalents

Real Time Modeling
The SCADA System, IEDs and PMUs
Communications, Computers
Network Configuration
State Estimation
Data and Topology Error Detection

Energy/Economy Functions and Control, Part I
Description of Control Loops
Automatic Generation Control
Frequency/interchange Control
Economic/Pollution Dispatch/Optimal Power Flow
Open Markets
Ancillary Services under Deregulation

Energy/Economy Functions and Control, Part II
Operations Planning
Electric Load Forecast
Reactive Power Control
Supply Management Options and Impact
Scheduling and Control of Energy Storage
Unit Commitment

System Security Monitoring and Control
Real Time Modeling
Security Monitoring and Security Controls
Voltage Security – Dynamic vs Static VARs
Simultaneous Transfer Capability Analysis
Risk Assessment/Impact of Deregulation

ECE6323  Power System Protection  Spring 2010

Introduction
The Power System
Protection Philosophy
Zones of Protection
Protective Equipment

Review of Background Material
Power System Modeling
Symmetrical Components
Three Phase/Asymmetric Faults
Fault Transients
Transformer In-Rush Currents
Motor Starting Transients
Effects of Grounding
High Impedance Faults
Grounding Potential Rise - Safety

Relaying Instrumentation
Instrument Transformers VTs, and CTs
Characteristic of VTs, and CTs

Protection Fundamentals
Overcurrent Protection
Overvoltage / Undervoltage Protection
Underfrequency / Overfrequency Protection
Zone Distance Protection
Differential Protection
Pilot Relaying
Computer Relaying

Protective Relaying Applications
Generator Protection
Motor Protection
Transformer Protection
Bus Protection
Line Protection - Network, Radial
Reactor and Shunt Capacitor Protection

Stability, Reclosing, and Load Shedding
Out-of-Step Relaying
Synchronizers (Dynamic, Static)
Load Conservation

Fundamentals of Automation
Objectives
Communication Standards, Interoperability
Applications, Integration of Substation Functions
Continuing Education
Power Systems Certificate Program

Core Courses
- Power System Relaying: Theory and Application
- Modern Energy Management Systems
- Integrated Grounding System Design and Testing
- Grounding, Harmonics, & Electromagnetic Influence Design Practices
- Power Distribution System Grounding and Transients
- Power Electronic Devices, Circuits, and Systems

Elective Courses/Conferences
- Fault and Disturbance Analysis Conference
- Georgia Tech Protective Relaying Conference

- All Courses are Coordinated by the Department of Professional Education
- All Courses are Offered Annually
- Academic Administrator: A. P. Meliopoulos
### Present State of the Art: C&O and P&C

**Model Based Control and Operation**

#### Control & Operation

- **Real Time Model**
  - State Estimation

- **Applications**
  - Load Forecasting
  - Optimization (ED, OPF)
  - VAR Control
  - Available Transfer capability
  - Security Assessment
  - Congestion management
  - Dynamic Line Rating
  - Transient Stability
  - EM Transients, etc.

- **Markets:**
  - Day Ahead, Power Balance,
  - Spot Pricing, Transmission
  - Pricing (FTR, FGR), Ancillary Services

#### Protection & Control

- **Component Protection**
  - generators, transformers, lines, motors, capacitors, reactors

- **System Protection**
  - Special Protection
  - Schemes, Load Shedding,
  - Out of Step Protection, etc.

- **Communications**
  - Substation Automation,
  - Enterprise, InterControl Center

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The Infrastructure for Both Functions is Based on Similar Technologies: Thus the Opportunity to Merge, Cut Costs, Improve Reliability Integration of New Technologies
Power Systems Operation

Main Objectives

REGULATION
- Frequency
- Voltage
- Net Interchange
- Pollutants

SECURITY

ECONOMICS
- Net Interchange
- Pollutants
- Power Transactions
- IPPs
- Energy Balance Market
- Ancillary Services

Tools

DATA AQUISITION SYSTEM
SUPERVISORY CONTROL
STATE ESTIMATION
ANALYSIS
OPTIMIZATION
CONTROL

Restructuring

POWER MARKET (SMD)
TRANSMISSION TARRIFS (FTR,FGR)
CONGESTION MANAGEMENT
ERO (Electric Reliability Organization)
Component (Zone) Protection

- Generators
- Transformers
- Buses
- Transmission Lines
- Motors
- Capacitor Banks
- Reactors, etc.

20 kV

230 kV

G+GSU Backup

Xfmr

Bus

Line

FDR Zone

Radial
System Protection

Out of Step (Transient Stability)

Illustration of Two Power System Swings:
(a) Stable – Out of Step Relay Should not Operate
(b) Unstable – Out of Step Relay Should Operate

Special Protection Schemes

Special Protection Schemes are Protective Relaying Functions Concerned with the Protection Against Special System Conditions that May Lead to Catastrophic Results. These System Conditions are Determined with Extensive Studies of Specific System Behavior. Using this Information a SPS is designed that monitors the System and When the Special System Conditions Occur (Recognition Triggers) the System Operates (Automatically or with Operator Review and Action)

Load Shedding – Frequency / Voltage

A System Disturbance May Create Generation-Load Imbalance Leading to Sustained Frequency Decline. This Condition, if not Corrected, May Lead to Equipment Damage. The Condition Can be Temporarily Corrected by Load Shedding Until Additional Generation can be Dispatched.

Similarly, a Disturbance May Create Sustained Voltage Problems. These problems Can be Also Corrected by Load Shedding
Control & Operation
Modern Energy Management System Functional Diagram

ENERGY/ECONOMY FUNCTIONS SUBSYSTEM
- Load Forecast
- Unit Commitment
- Load Forecast
- Economic Interchange Evaluation
- Economic Dispatch
- Automatic Generation Control

DATA AQUISITION AND PROCESSING SUBSYSTEM
- Parameter Estimation
- SCADA Measurements
- GPS Synchronized Measurements
- Network Topology
- Displays
- External Equivalents

SECURITY MONITORING AND CONTROL SUBSYSTEM
- Optimal Power Flow
- Security Dispatch
- Environmental Dispatch
- Security Monitoring
- Contingency Analysis
- Preventive Controls
- VAR Dispatch
- Security Monitoring
- Emergency Controls
- Contingency Analysis
- Preventive Controls
- VAR Dispatch

Load Forecast
- Power Bids
- Ancillary Services
- Power Balance Market
- Congestion Management
- Transmission Valuation

Network Topology
- Normal State
- Insecure State
- Preventive Controls
- Restorative Controls
- Extremis State
- Emergency Controls
- Emergency State
OVERVIEW OF ENERGY MANAGEMENT SYSTEMS
Data Acquisition and Processing Subsystem

New Technology
GPS Synchronized Measurements (Phasors)
Network Configurator Example

AutoBank
500kV/230kV

Breaker
Oriented
Model

SG1

Bus
Oriented
Model

SG2
State Estimator

- **MEASUREMENTS:**
- **STATE:**
- **FORMULATION:**
- **SOLUTION:**

Traditional State Estimation
Centralized Procedure

**Observability**
Bad Data Detection/ID/Rejection Parameter Estimation
Technological Developments
The OLD and the NEW

Circuit Breaker

CT

CCVT

Relays

P

Q

I

V

CT

CCVT

IED-Relay

Comm Link

Circuit Breaker

CT

CCVT

IED-Relay

Comm Link
SCADA Evolution

SCADA circa 1923
Independent of Protection

SCADA circa 2003
Communication Standards
Project Background: Substation Architectures: SmartGrid

Physical System

Protection, Control, Communications

Industry Direction: Single Data Acquisition System for Protection, Control, and Operations
Important New Technology

GPS-Synchronization

History of GPS-Synchronized Measurements
History of GPS-Synchronized Measurements

- The Antikythera Mechanism
  87 BC

- GPS Satellite System
  Initiated 1989, Completed 1994
Important Milestones

1970: First Computer Relay (PRODAR, Westinghouse, Gilcrest, Rockefeller, Udren)

1984: First Commercial $\mu$Processor Based Relay (SEL)

1989: GPS Signal Becomes Commercially Available

1990-91: Phasor Measurement System (Arun Phadke)

1992: Phasor Measurement Unit (PMU) (Jay Murphy, Macodyne)
Arun Phadke’s Phasor Measurement System

Block Diagram Published by Arun Phadke

Vintage 1990-91
Several Units Were Sold to AEP, NYPA, others

CHARACTERISTICS
- Analog Filter with Cutoff Frequency of 360Hz
- Sample & Hold A/D Technology with Analog Multiplexing
- 12 bit S&H A/D 720 s/s

Time Accuracy Was Never Measured or Reported. Multiplexing and Design Suggest Very High Timing Error
Estimated Time Precision: 100 us, 2 degrees at 60 Hz
Macrodyne 1620 PMU

Released to Market January 1992

Jay Murphy (Macrodyne) Was First to Introduce Term PMU: Phasor Measurement Unit

CHARACTERISTICS

- Individually GPS Sync’d Channels
- Common Mode Rejection Filter with Optical Isolation
- 16 bit A/D ΣΔ Modulation

Time Accuracy 1 μs
0.02 Degrees at 60 Hz
Distributed Dynamic State Estimation Implementation

PMU Technology Enables Distributed SE

Data/Measurements from all PMUs, Relays, IEDs, Meters, FDRs, etc are collected via a Local Area Network in a data concentrator.

The data is used in a dynamic state estimator which provides the validated and high fidelity dynamic model of the system.

Bad data detection and rejection is achieved because of high level of redundant measurements at this level.
Numerical Results – B-G Plant
Transient Stability Monitoring

The dynamic state estimator is utilized to predict the transient stability or instability of a generator. The dynamic state of the system provides the **center of oscillations** of the generator swing. From this information the potential energy of the generator is computed as a generalization of the basic energy function method.

The total energy of the generator can also be trivially computed once the potential energy has been computed. The total energy is compared to the potential energy of the generator – if the total energy is higher than the peak (barrier) value of the potential energy this indicates that the generator will lose its synchronism (transient instability).

It is important to note that this approach is predictive, i.e. it identifies a transient instability before it occurs.

The figures provide visualizations of generator oscillations and the trajectory of the total energy superimposed on the system potential energy.
Energy Management Systems

Hierarchy of Scheduling Functions

Level 1: Load Forecasting
  Unit Commitment
  Emissions Control
  Economy Purchases

Level 2: Economic Dispatch
  Environmental Dispatch
  Economic Interchange Evaluation
  Optimal Power Flow
  Transfer Capability
  Day-Ahead Scheduling
  Spot Market Scheduling

Level 3: Automatic Generation Control
  - Frequency Control
  - Interchange Control
  - Transactions Control
  - Inadvertent Power Flow Control
Net Interchange Control

Area Control Error (ACE)

\[ ACE = \Delta P_{\text{int}} + B \Delta f \]

\[ \Delta P_{gi} = a_i ACE \]
Economic Scheduling Functions Hierarchical Structure

A. Resource Scheduling (weeks)
   - Mid Term Load Forecast
   - Units out for maintenance
   - Fuel Management
   - Weekly hydro energy usage

B. Unit Commitment (hours/Days)
   - Short Term Load Forecast
   - List of committed units
   - Hourly hydro energy usage
   - Interchange schedule

C. Economic Dispatch (minutes)
   - Economic Base Points
   - Participation Factors

D. Automatic Generation Control (seconds)
   - $p_{des_i}, i = 1,2,...,n$
Economic Dispatch

- MEASUREMENTS
- COST
- FORMULATION
- SOLUTION
Optimal Power Flow

- MEASUREMENTS
- STATE
- CONTROLS
- FORMULATION
- SOLUTION

Interconnection

G1

T1

L1

2

L2

L3

T1

T2

G2

1

3

4

5

6

MW Flow Measurement
MVAR Flow Measurement
kV Measurement
Transformer Tap Measurement
SYSTEM SECURITY
(Congestion Management)
Power System Operating States

NORMAL and SECURE System Optimization

D,O

PREVENTIVE Controls

RESTORATIVE Controls

RESTORATIVE System Security

D,O

NORMAL but VULNERABLE/INSECURE Optimization/Security

D,O

Emergency Controls

Emergency Controls

EXTREMIS System Security

D,O

EMERGENCY System Security

D,O

Transition Due to Disturbances

Transition Due to Control Action

Corrective Controls
Energy Management Systems
Hierarchical Structure

System Power Production and Control (SPPC)

Operations Coordination Office (OCO)

Regional Dispatch Center (RDC)

Substation

Power Plant

UCM

V_{exc}

P_{sched}

f_{sched}

ACE

V_{sched}
New Challenges: Wind/PV Farm Characteristics

Types 1 and 2 are Not Used for Large Projects

Types 3 and 4 Limit Fault Currents to About 120% of Nominal Current

Proposed Requirements – NERC PRC-024, >20 MVA or >75 MVA
Renewables and Uncertainty

Solar is Available During High Price/Cost Hours

Small Storage can provide huge add-on value to solar projects

Better capacity factor than other renewables (70 to 80%)

Wind Availability is Highly Volatile and Patterns May be Opposite to Grid Needs (i.e. CA)

Large Storage Schemes are needed to coordinate economic usage of wind energy and to provide add-on value

Very small capacity factor (10 to 25%)

Large Wind Swings
Energy Management Systems: Evolution

Control and Operation of Power Systems is Driven by

(a) Legislative action
(b) Economics
(c) Technical constraints

The envelop is always moving because of technological advancements

ERO Focus: Operational Reliability
History of Utility Regulatory Legislation

Federal Power Commission
• PUHCA – 1935 (Public Utility Holding Company Act)

Federal Energy Regulatory Commission (1977)
• PURPA – 1978 (Public Utility Regulatory Policies Act)
• Clean Air Act – 1990
• Energy Policy Act – 1992
• Orders 888 & 889 – 1996 (→ OASIS)
• CECA – 1998 (Comprehensive Electricity Competition Act)
• Order 2000
• SMD – Standard Market Design
• US Energy Policy Act, 2005 (provides authority to enforce reliability)
Visualization & Animation
University of Illinois/Georgia Tech (PSERC Project)

Large Scale Systems
Performance - Model Hierarchy
Bus Voltage - Min = 0.000 pu, Max = 0.006 pu
Bus Voltage Phase - Min = -0.110 Deg, Max = 0.095 Deg
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>OASIS</td>
<td>Open Access Same-Time Information System</td>
</tr>
<tr>
<td>UCA</td>
<td>Utility Communication Architecture</td>
</tr>
<tr>
<td>ICCP</td>
<td>Inter-Control Center Communications Protocol</td>
</tr>
<tr>
<td>CCAPI</td>
<td>Control Center Application Program Interface</td>
</tr>
<tr>
<td>CIM</td>
<td>Common Information Model</td>
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<td>IEC61850</td>
<td>Evolution of the UCA</td>
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<td>C37.118</td>
<td>Synchrophasor Data</td>
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Active Future Distribution Systems (with distributed energy resources – solar, wind, PHEVs, fuel cells,...).

Smart Grid technologies: Distributed Monitoring, Control, Protection and Operations system. Target Speeds 10 times per second

Functions: (a) Optimal operation of the distribution system under normal operating conditions, (b) Emergency management in cases of faults and assist the power grid when needed, (c) Assist Voltage recovery, (d) Assist cold load pickup, (e) Balance Feeder, (f) etc., etc.
Evolution, Naxos Island, Greece
June 25, 2011