Dynamics and Control R&D for Energy Systems

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Overview

Mission: Operational Excellence for Energy Systems

• Goals and Objectives
  – Develop and deploy state-of-the-art dynamic modeling, simulation, and control tools
  – Leverage in R&D to maximize efficiency and profitability of energy system operations, while reducing negative environmental impact and improving safety

• Dynamic Simulators Development
  – High-fidelity real-time dynamic simulators
  – Full-scope operator training systems (OTSs)
  – 3D virtual immersive training systems (ITSs)

• Advanced Research
  – Dynamic Modeling
  – Advanced Process Control
  – Sensor Systems
  – Energy System Operations
Dynamic Simulator Development

Energy System Applications

• Integrated Gasification Combined Cycle (IGCC) with CO$_2$ Capture [OTS/ITS]
• Natural Gas Combined Cycle (NGCC) [OTS]
• Supercritical Once-Through (SCOT) Pulverized Coal [OTS]
• Subcritical Pulverized Coal (SubPC) [OTS]
• Oxy-Coal Carbon Capture (OCCC) [OTS]
• Shale Gas Processing (SGP) [OTS]

Key:
- Deployed (Completed Phases 1-5)
- Under Development (Completed Phases 1-2)
- Scoping (Completed Phase 1)
Dynamic Simulator Development

*IGCC with CO₂ Capture – OTS/ITS*

- **Motivation**
  - Flexible technology for clean power generation
- **Deployed OTS at NETL and WVU (2011)**
  - Software: DYNSIM v 4.5.3 / InTouch v9
- **Deployed ITS at NETL and WVU (2012)**
  - Software: EYESIM v1
- **Collaborated with Development Partners**

- **Collaborated with Industry**

- **Distributed Run-Time OTSs for Internal Use**
  - EPRI, BP, Doosan, Southern Company
- **New Developments in Progress**
  - SW Copyright License Agreement with Invensys
  - ITS upgrade to EYESIM v2.0
Dynamic Simulator Development

**Natural Gas Combined Cycle (NGCC) – OTS**

- **Motivation**
  - Shale gas plays leading to low gas prices
  - Stricter regulation for coal plants
  - Integration of growing amounts of renewable power

- **Completed Steady-State Design**
  - 2-on-1 design with 574 MW gross power
  - Two GTs (182MW each) x One ST (210MW)
  - Two 3-pressure HRSGs (1890, 385, and 62 psia)

- **Completed Prototype Dynamic Model**
  - Leveraged CC portion of IGCC dynamic simulator
  - Modified HRSG heat exchangers and drums
  - Modified steam turbine to match new conditions
  - Achieved stable full-load and tested ramping

- **New Developments in Progress**
  - Update process controls and HMIs
  - Collaborate with Invensys under CRADA to complete development, testing, and deployment
  - Collaborate on cycling studies with NRECA under CRADA (Associated Electric Coop, NGCC Power Plant, Dell, AR)

- **Potential Future Work**
  - Add hooks for post-combustion CO₂ capture (NG-CCS)
  - Integrate with variable renewable generators

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Dynamic Simulator Development

Supercritical Once-Through (SCOT) Pulverized Coal - OTS

• **Motivation**
  – Post-combustion CO₂ capture and cycling

• **Accomplishments/Results**
  – Generated functional design specification
    - Once-through water/steam circulation system
    - Enables quicker startup, variable pressure load-following, and on-off cycling
  – Developed DYNSIM dynamic model
  – Prototyped process controls and InTouch HMIs

• **New Developments in Progress**
  – Collaborate with Invensys (CRADA) to complete:
    - Development of HMIs, and operating procedures
    - Testing and deployment

• **Potential Future Work**
  – Add air quality control systems (AQCS)
    - Baghouse (PM), SCR (NOx), FGD (SO₂)
  – Implement process/heat hooks for CO₂ capture
  – Integrate with CO₂ capture dynamic models
  – Conduct transient studies, including startup, shutdown, cycling, load-following, and variable CO₂ capture rates

Dynamic Simulator Development

*Subcritical Pulverized Coal (SubPC) - OTS*

- **Motivation**
  - Post-combustion CO₂ capture and cycling
- **“Generic” but detailed design**
  - Sidewall-fired drum boiler
  - Westinghouse steam turbine (690 MW)
  - 2413 psig throttle pressure
  - 1005°F main and reheat steam temperature
  - Lube oil, steam seal, etc.
  - Full control system, permissives, alarms
  - Cold-metal start
- **DYNSIM Power for dynamic model and HMI**
- **Training literature developed by FCS**
- **Accomplishments/Results**
  - Reviewed features, capabilities, and documentation for generic SubPC dynamic simulator/OTS (Invensys)
- **Potential future work**
  - SubPC cycling project(s)
Dynamic Simulator Development

**Oxy-Combustion Clean Coal (OCCC) – OTS/ITS**

- **Motivation**
  - Nitrogen removed from process
  - Flue gas contains mainly CO₂ and H₂O
  - Compression and CO₂ purification unit (CPU)

- **FutureGen 2.0**
  - Meredosia Power Station, IL
  - 200 MWe, Unit 4, 160Bar/540C/540C
  - Babcock & Wilcox (B&W)
    - Purpose-built oxy-PC boiler
  - Air Liquide (AL)
    - Air separation unit (ASU) and CPU

- **Accomplishments/Results**
  - OTS/ITS(Ph1): Generated proposal for FG 2.0 Phase II – FEED

- **New Developments in Progress**
  - Participate in NETL collaboration with B&W and AL on FEED

- **Potential Future Work**
  - Develop and deploy OCCC OTS/ITS
  - Use FG 2.0 as template for NETL Large-Scale Clean Coal and Power System Demonstrations
Dynamic Simulator Development

Shale Gas Processing (SGP) – OTS/ITS

• Motivation
  – Regional Marcellus/Utica shale gas plays
  – Large, highly-integrated, multi-purpose facilities with high-value assets
  – Efficient operation and control of treatment and separation processes to generate pipeline-quality natural gas and natural gas liquids (NGLs)

• Potential Partners
  – ShaleNET
    o Industry Workforce Training; Drilling/fracking to SGP
    o 20 Approved Training Providers
      ✓ Westmoreland County Community College, PA
      ✓ Pierpont Community & Technical College, WV

• Accomplishments/Results
  – Completed scoping study for SGP OTS/ITS
  – Discussed collaboration opportunities with ShaleNET industry partners

• Potential Future Work
  – Collaborate with ShaleNET and industry partners on SGP OTS proposal to US. Dept. of Labor
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Dynamic Simulator Development
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Advanced Research
- Dynamic Modeling
- Advanced Process Control
- Sensor Systems
- Energy System Operations
Advanced Research Program

*Dynamics and Control*

- **Dynamic Modeling**
  - Plantwide/Process/Equipment
  - Physical and Chemical Submodels
  - Dynamic reduced models (D-RMs)

- **Process Control**
  - Plantwide Control System Design
  - Advanced Process Control

- **Sensor Systems**
  - State estimation, Disturbance rejection
  - Process monitoring, Fault diagnosis

- **Energy System Operations**
  - Startup, shutdown
  - Ramping, cycling, load following
  - Safety and environmental analysis

*NETL/ORD Computational Basic Sciences & Engineering*

*NETL Industry*

*DOE/NETL Programs (Gasification, IEP, CCSI, Major Demos)*

*Technology Transfer Accelerated Deployment*
Dynamic Modeling

Plantwide/Process/Equipment

- **Plantwide**
  - IGCC [APD, DYNSIM]
  - NGCC [DYNSIM]
  - SCOT [DYNSIM]

- **Process/Equipment**
  - Entrained-Flow Gasifier [ACM]
    - Approach: 1-D PDE [ACM]
    - Sub-models
      - Reaction Kinetics
      - Recirculation
      - Slag Flow/Penetration
    - Approach: Multizonal [DYNSIM]
  - Air Separation Unit (ASU)
    - Low/Elevated-Pressure Cryogenic ASUs [APD, DYNSIM]
  - Sulfur Capture
    - Claus unit and reactor [APD]
      - Sub-models
        - Reaction Kinetics

- **CO₂ Capture/Compression**
  - Post: Solid Sorbent Capture, Regeneration, and Transport [ACM]
  - Post: Liquid Solvents Capture/Regen [ACM, gPROMS]
  - Pre: Selexol [APD, DYNSIM]
  - Pre/Post: Multi-stage CO₂ Compression [DYNSIM, APD/ACM]
- Steam Turbines [ACM, DYNSIM]

- **Commercial Software**
  - Aspen Plus Dynamics [APD], Aspen Custom Modeler [ACM] (AspenTech)
  - DYNSIM (Invensys)
  - gPROMS (PSE)
  - MATLAB/Simulink (MathWorks)
Dynamic Modeling

Dynamic Reduced Models (D-RMs)

- **CCSI D-RM Builder**
  - **Data-driven Black-Box Methods**
    - Nonlinear Auto-Regressive Moving Average (NARMA) based on Neural Networks
    - Decoupled A-B Net (DABNet)
      - Sentoni, Biegler, Guiver, Zhao, *AIChEJ* (1998)
  - **Automatic D-RM Generation**
    - Run high-fidelity “ACM” models in Simulink
    - Create data-driven D-RMs as MATLAB models
  - **GUI Driven Workflow**
    - Configuration → Space-filling (LHS) → Training (Ramp Changes) → Post-processing → Export
  - **Test Cases**
    - VandeVusse Reactor (input-multiplicity)
    - CSTR (multiple SS, unsteady operation)
    - 4 Tank (multiple transmission zeroes)
    - 1D PDE Dynamic BFB CO₂ Capture Adsorber
  - **Product Release**
    - D-RM Builder R1 – Oct. 2013
    - D-RM Builder R2 – Oct. 2014
      - Enhanced D-RM Error Estimation
      - Training algorithm to prevent D-RM Overfitting
      - UQ-enabled D-RM with uncertainty (covariance) matrices and likelihood to assess goodness of fit

- **Order Reduction Methods**
  - **Spatial Reduction**
    - Proper Orthogonal Decomposition (POD)
  - **Temporal Reduction**
    - Eigenvalue Analysis and Quasi-steady State Approximation for Fast States
  - **Test Case**
    - 1D PDE Dynamic BFB CO₂ Capture Adsorber

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D-RM (DABNet) vs. ACM Output Data for BFB
Process Control

• **Plant-wide Control System Design for Advanced Energy Systems**
  – WVU, Prof. Bhattacharyya, Jones

• **Advanced Process Control for IGCC Power Plants with CO₂ Capture**
  – WVU, Prof. Bhattacharyya; NETL, Dr. Mahapatra

• **Advanced Process Control Framework for Carbon Capture System Operations**
  – MPC, State Estimation, and UQ
  – CCSI: NETL, Drs. Mahapatra, Zitney; WVU, Prof. Bhattacharyya; LLNL, Dr. Ng

• **Integrated Biomimetic Control Framework for Advanced Energy Plants**
  – Self-Organization, Distributed Intelligence, Adaptability, Intelligent Monitoring, Cognition, and Decision Capabilities
  – WVU, Profs. Bhattacharyya, Lima, Turton, Perhinschi; VRI, Dr. Diwekar

IGCC with CO₂ Capture response to ramp increase in coal feed flowrate (Bhattacharyya et al., 2011)

Schematic of Proposed Biomimetic Control Framework (Bhattacharyya et al., 2014)
Sensor Systems

• Development of Optimal Sensor Placement Algorithms for Energy Systems
  – Application: IGCC Power Plant with CO₂ Capture
  – Objective: Maximize Plant Efficiency
  – WVU, Prof. Bhattacharyya, Prof. Turton, Paul

• Multi-Objective Optimal Sensor Deployment Under Uncertainty for Advanced Power Systems
  – VRI, Dr. Diwekar; WVU, Prof. Bhattacharyya

• Smart Refractory Sensor Systems for Wireless Monitoring of Temperature, Health, and Degradation of Slagging Gasifiers
  – WVU, Profs. Sabolsky, Bhattacharyya, Graham, Kutathumani; ANH Refractories, Palmisiani
Energy System Operations

• **IGCC Power Plant Load Following**
  – Improved GT-Lead/Gasifier-Follow and Gasifier-Lead/GT-Follow modes
  – Improved ramp rates
  – WVU, Prof. Bhattacharyya
  – NETL, Mahapatra

• **NGCC Shutdown, Startup, and Cycling**
  – Operational strategies to reduce plant derates, emissions, profit loss, and equipment damage
  – CRADA with the National Rural Electric Cooperative Association (NRECA)
  – NETL, Liese, Zitney

**Transient Response of IGCC Plant Pressure in Face of Load Turndown (Bhattacharyya et al., 2012)**

**NGCC Shutdown of one GT from full-load conditions (Liese and Zitney, 2013)**
Thank you! Questions?

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