Brief Overview of CURENT
Control Architecture for the Future Power Grid

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NSF Engineering Research Centers

• NSF program of focused research on an engineering problem. Among the most significant investments NSF will make in an area with support for up to 10 years.

• Program elements include:
  • Outreach (K-12 education)
  • Research experience for undergraduates
  • Entrepreneurship training
  • Industry program
  • Systems engineering approach
  • International collaboration
CURENT – NSF/DOE ERC

- One of only two ERCs funded jointly by NSF and DOE. Core budget: ~$4M/year for 5-10 years but highly leveraged to be able to fully support programs.
- CURENT only ERC devoted to wide area controls and one of only two in power systems.
- Partnership across four universities in the US and three international partner schools. Many opportunities for collaboration.
- Expect 50+ industry members to eventually join. Presently have 27 members.
- Center began Aug. 15th 2011
Best wind and solar sources are far from load centers.

Transmission networks must play a central role in integration.
Rapid Retirement of Coal Plants in North America

Change in generation mix challenge long term planning

Most of the retirements would be in NERC regions RFC, SERC and ERCOT.


Growth in electricity consumption

Transmission constraint events

- Transmission investment has lagged generation investment and led to several bottlenecks in the Eastern interconnect and Western interconnect.
- Limited transmission impacting reliability and cost, preventing full use of renewables.
- Inflexible capabilities leads to inefficient investment in grid infrastructure.
CURENT Vision

• A nation-wide transmission grid that is fully monitored and dynamically controlled for high efficiency, high reliability, low cost, better accommodation of renewable sources, full utilization of storage, and responsive load.

• A new generation of electric power and energy systems engineering leaders with a global perspective coming from diverse backgrounds.
Electromechanical Wave Phenomena
Wide Area Measurement

Unique Capabilities: UWA real-time grid monitoring system at UTK – Yilu Liu

FDR Sensor

FNET Monitors in the Field
What is CURENT?

Wide Area Control of Power Grid

Measurement & Monitoring

Communication

Actuation

HVDC

PMU

FDR

Storage

Solar Farm

PSS

Responsive Load

FACTS

Wind Farm

Generator

What is CURENT?
Today’s Operations
Some Wide Area and Some Fast but not Both

Ultra-wide Area
- Traditional uncoordinated controls
- Minimal sensing
- Limited communication

Wide Area
- HVDC
- Unit Commitment

Balancing Authority
- Economic Dispatch

Region
- AGC
- RAS Schemes

Substation
- SVC Fixed Comp.
- LTC

Device
- Fixed Comp.
- RAS Schemes
- PSS
- Device Protection

Distributed coordinated actuation with extensive measurements

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Distributed coordinated actuation with extensive measurements
Frequency Control
Wide area with distributed actuation

Ultra-wide Area
Wide Area
Balancing Authority
Region
Substation
Device

Wide area communication
Distributed coordinated actuation

Extensive Sensing

Integrated Secure Dispatch and Frequency Control
HVDC FACTS

Economic Dispatch
AGC
Demand Response
Renewables Support
UFLS

Wide area with distributed actuation
Distributed Frequency Control

Day
Hour
Minute
Second
Cycle
Resilience and scalability by

- Distributed – renewables, grid, storage, and demand as active control participants
- Measurements (learning and adaptive, data-driven)
- Modularized, hierarchical, global signals so distributed with context
- Sharing resources (reduced impact of uncertainty)
Objectives

• Develop a large scale simulation platform to demonstrate CURENT technology
• Establish regional system models for wide area system studies
• Demonstrate how CURENT technology can improve the existing systems

System Models

• Highly aggregated systems. Integration with Hardware testbed and RTDS
• Large system: EI 70,000 bus & WECC 15,000 bus
  • Detailed positive sequence models
  • Future scenario studies
• Regional – NPCC and WECC: Maintain unique characteristics with manageable data issues
• Show how wide-area monitoring and control can improve voltage security and oscillations in NPCC
• Dynamic modeling for 179+ bus system in WECC
Hardware System Testbed

Objectives
• Emulate grid with interconnected clusters of scaled-down generators and loads.
• Use modular, reconfigurable converters for generators, loads, flexible network, and scenario emulation.

System Models
• Developed several emulators: synchronous generator, wind generator (2 types), solar, flywheel, transmission line, ZIP load, and induction motor.
• Four clusters constructed. Use of real measurement (PMU and FNET) data as well as communication.
• Two area system demonstrated with voltage collapse scenario. PMU based.
• Remote control-room type environment using large display wall and Labview environment has been setup to allow a more coordinated operation.
## Research Roadmap

<table>
<thead>
<tr>
<th>Generation I (Y1-Y3)</th>
<th>Generation II (Y4-Y6)</th>
<th>Generation III (Y7-Y10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Regional grids (based on 48 machine Northeast system and 190 bus WECC system), with &gt;20% renewable (wind, solar)</td>
<td>• Reduced interconnected EI, WECC and ERCOT system, with &gt;50% renewable (wind, solar) and balance of other clean energy sources (hydro, gas, nuclear)</td>
<td>• Fully integrated North American system, with &gt;50% renewable (wind, solar) and balance of other clean energy sources (hydro, gas, nuclear)</td>
</tr>
<tr>
<td>• Grid architecture to include HVDC trunk lines, at least one multi-terminal DC grid for off-shore wind farm</td>
<td>• Grid architecture to include UHV DC trunk lines connecting with regional multi-terminal DC grids, and increased use of power flow controllers,</td>
<td>• Grid architecture to include UHV DC super-grid and interconnecting overlay AC grid</td>
</tr>
<tr>
<td>• System scenarios demonstrating a variety of seasonal and daily operating conditions</td>
<td>• System scenarios demonstrating complete seasonal and daily operating conditions and associated contingencies, including weather related events impacting wind and solar</td>
<td>• Future load composition (converter loads, EV loads, responsive loads), selective energy storage (including concentrated solar with thermal energy storage)</td>
</tr>
<tr>
<td>• Sufficient monitoring to provide measurements for full network observability as well as robustness against contingencies, bad topology or measurement data</td>
<td>• Full PMU monitoring at transmission level with some monitoring of loads</td>
<td>• Fully monitored at transmission level (PMUs, temperature and so on). Extensive monitoring of loads in distribution system</td>
</tr>
<tr>
<td>• Closed-loop non-local frequency and voltage control using PMU measurements</td>
<td>• Fully integrated PMU based closed-loop frequency, voltage and oscillation damping, control systems, and adaptive RAS schemes, including renewables, energy storage, and load as resources, demonstrating improved transfer limits and reduced required reserves</td>
<td>• Closed loop control using wide area monitoring across all time scales and demonstrating full use of transmission capacity</td>
</tr>
<tr>
<td>• Renewable energy sources and responsive loads to participate in frequency and voltage control</td>
<td></td>
<td>• Coordinated renewable energy source control over wide area for minimum reserves</td>
</tr>
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</table>
Example Wide Area Controls

- Sharing resources among different devices
  - Flat systems - distributed frequency control
- Communications
  - Distributed damping control
- Robustness
  - Sensor/communication failures
  - Actuator availability
Distributed Contextual Control: Frequency Regulation for High Penetration of Wind Generation

Maryam H. Variani, Kevin Tomsovic
Motivation

Primary Frequency Response

- Decline of the Eastern Interconnection frequency response of about 60-70 MW/0.1HZ/year.
- NERC new reliability standard: BAL003- balancing area frequency response obligation.

• **Energy Imbalance Market (EIM):**
  
  **Today:**
  Each BA must balance loads and resources within its borders

  **In an EIM:**
  The market dispatches resources across BAs to balance energy

Source: Briefing on Energy Imbalance Market, Mark Rothleder, California ISO
Introduction

- Frequency regulation at conventional units needs to be modified to cope with high penetration of wind and PV.
- Studies show that it may be both technically and economically feasible for wind plants to supply regulation under some circumstances.

Two-Level Control Structure

To allow high penetration (e.g., 50%) of renewable resources, conventional controls need to be replaced by a simpler structure.

The proposed structure consists of local control operating within a global context of situational awareness at different levels.

Contextual Control Selects one of a finite number of system-level control goals that best reflect needs based on overall system status at a given moment.

Local Control Individual components and loads operate in a manner to follow some desired trajectory based on local observations to manage deviations.

Flatness-based approach is well adopted to control systems in two levels of planning, trajectory generation, and tracking the desired trajectories.
The nonlinear system

\[ \dot{x} = f(x, u) \quad (x \in \mathbb{R}^m, u \in \mathbb{R}^n) \]

is said (differentially) flat if and only if there exists \( n \) independent scalar functions \( h = (h_1, ..., h_n) \) such that:

- \( y = h(x, u, \dot{u}, ..., u^{(\gamma)}) \)
- \( x \) and \( u \) are computable without integration:
  \[ x = \varphi(y, \dot{y}, ..., y^{(\alpha-1)}) \]
  \[ u = \psi(y, \dot{y}, ..., y^{(\alpha)}) \]

The vector \( y \) is called the flat output.
Trajectory Generation

To every curve $t \mapsto y(t)$ enough differentiable, there corresponds a trajectory

$$
\begin{align*}
t \mapsto & \left( x(t) \atop u(t) \right) \\
& = \left( \varphi \left( y(t), \dot{y}(t), \ldots, y^{(\alpha-1)}(t) \right) \atop \psi \left( y(t), \dot{y}(t), \ldots, y^{(\alpha)}(t) \right) \right)
\end{align*}
$$

that identically satisfies the system equations.
Trajectory Tracking

Stabilization of the tracking error:

Given the reference \( t \mapsto \left( y_{\text{ref}}(t), v_{\text{ref}}(t) \right) \) with \( v_{\text{ref}}(t) = y_{\text{ref}}^{(\alpha)}(t) \), assuming that \( y, \ldots, y^{(\alpha-1)} \) are measured or are suitably estimated. By setting:

\[
e = y - y_{\text{ref}}
\]

\[
e^{(\alpha)} = v - v_{\text{ref}} = - \sum_{i=0}^{\alpha-1} k_i e^{(\alpha-1)}
\]

The gains \( k_i, i = 0, \ldots, \alpha - 1 \), being chosen such that all the roots of the polynomial \( p^\alpha + k_{\alpha-1} p^{\alpha-1} + \cdots + k_1 p + k_0 \) have negative real part.
• Flatness-based control diagram

\[ v = -Ke \]

\[ \dot{u} = a(y, \dot{y}, ..., y^{(\alpha)}) \]

\[ x = f(x, u) \]
Background: ACE-Based AGC

- Conventional AGC is performed based on integration of Area Control Error (ACE) for each BA.
Background: ACE-Based AGC

- Conventional AGC is performed based on integration of Area Control Error (ACE) for each BA.

\[ ACE = \Delta P_{tie} + \beta \Delta f \]
Flatness Based AGC

• Flatness-based approach is applied to automatic generation control (AGC) of multi-area systems with wind generation units.

• In two level control structure, secondary control action represents local control and the reference trajectory, to be tracked by the local control, are determined in the contextual control.
Two Level Flatness-based AGC Structure

Economic Dispatch

Every 5 minutes

As fast as practical constrains allow

Phase
Frequency

Comprehensive Flatness-Based AGC
Multi-Machine Model

Synchronous machine classical model including network, prime mover and governor for generator $i$:

\[
\dot{\delta}_i = \omega_i - \omega_s
\]

\[
\omega_i = \frac{1}{2H} \left[ P_{mi} - D(\omega_i - \omega_s) - \frac{E_i V_i}{x'_{di}} \sin(\delta_i - \theta_i) \right]
\]

\[
\dot{P}_{gvi} = \frac{1}{\tau_{gi}} \left( \frac{P_i^{ref}}{\omega_i - \omega_s} - \frac{P_{gvi}}{R\omega_s} - P_{gvi} \right)
\]

\[
\dot{P}_{mi} = \frac{1}{\tau_{Ti}} (P_{gvi} - P_{mi})
\]
Flat System Model

Flatness-based formulation with $\delta_i$ as flat output for each generator:

$$\ddot{\delta}_i = \frac{1}{2H} \left[ P_{mi} - D(\omega_i - \omega_s) - \frac{E_i V_i}{x'_{di}} \sin(\delta_i - \theta_i) \right]$$

$$\dddot{\delta}_i = \frac{1}{2H} \left[ \frac{1}{\tau_T} P_{gvi} - \frac{1}{\tau_T} P_{mi} - D\dot{\delta}_i - \frac{E_i V_i}{x'_{di}} \dot{\delta}_i \sin(\delta_i - \theta_i) \right]$$

$$\delta^{(4)} = \frac{1}{2H} \left[ \frac{1}{\tau_T \tau_g} P_i^{ref} + \ldots \right]$$
Trajectory Tracking

• Finding appropriate speed changer position, through a feedback law, to maintain system stability, restore the frequency nominal value and track the scheduled net interchange.

• System perturbations: load changes, generation loss, wind generation variations.

• The feedback law:

\[
e_i = \delta_i - \delta_i^* \\
\delta_i^{(4)} = v_i \\
v_i = v_i^* - \sum_{j=0}^{3} k_{ij} e_i^{(j)}
\]

• The input is updated every 2 sec as it is performed in conventional AGC.

• Generator ramping rate constraint is considered.
Simulation: NPCC System

NPCC 140 Bus, 48 Generators System
Total Capacity ≈ 28 GW

User Defined Model (UDM) in TSAT:

ACE-based UDM

Flatness-based UDM

$P_{tie1}$

$P_{tie2}$

$\omega_r$

$V \angle \theta$

$P_g, Q_g$

$\omega_r$
Simulation: NPCC System

Scenario 1: Load Shedding 450 MW at t=100 sec in PJM

Active Power

Tie Line Flow
Simulation: NPCC System

Scenario 2: Wind Variation , total capacity

Wind Power

Tie Line Flow

Frequency

Wind Power

Tie Line Flow

Frequency
Two level control structure based on flat systems properties is studied for synchronous and DFIG machines for frequency regulation.

- **Flatness-based AGC for synchronous machines**
  - Two level control consisting of local and contextual controllers substitutes the ACE-based AGC.
  - Decoupling into $n$ linear controllable sub-systems in canonical form results in decentralized control.

- **Flatness-based DFIG**
  - Two level control consisting of trajectory generation and trajectory tracking replaces the field oriented based method to control active and reactive power.
  - Trajectories are generated through algebraic equations rather than PI controllers.
  - Linear control methods such as pole placement and LQR replace the PI controller to track the desired states.

- The two developed models build a generic AGC with two level controls at each machine working in coordination with higher level controls for planning.
- The model can easily be adopted to new market structures.
Distributed Damping Control: Communication Considerations

May Mahmoudi       Kevin Tomsovic
Wide Area Control of Power Grid

• The addition of wide-area feedback control to frequently used controls is an effective additional layer of defense against blackouts.

• Centralized Control: a single controller is able to measure all the system outputs, compute the optimal control solution, and apply that action to all actuators in the network, within one sampling period.

As power networks are large-scale systems, both computationally and geographically, a Centralized Wide Area Controller is practically difficult to implement.
Non-Centralized Controllers

- **Non-Centralized Controllers**
  - **Decentralized Controllers**: Do not allow for communication between local controllers
  - **Distributed Controllers**: Communication between different controllers is exploited to improve the performance

The Proposed Controller in our research is under this category
Proposed Distributed LQR Controller

- **Objective**: Stabilize the system through supplementary excitation control
- Graph of physical layer and communication layer coincide.
- **Full state information** exchange is assumed for neighboring generators.

\[ x_k = Ax_{k-1} + Bu + Kx \]

\[ u = Kx \]

\[ x_k \]

\[ x_{k+1} \]

Distributed LQR Controller for \( k \)th Generator
Distributed LQR Controller

• Consider a set of identical, decoupled linear time invariant dynamical systems:

\[ \dot{x}_i = Ax_i + Bu_i \]
\[ x_i(0) = x_{i0}. \]

• LQR Problem Cost Function:

\[ J(\tilde{u}, \tilde{x}_0) = \int_0^{\infty} \left( \sum_{i=1}^{N_L} (x_i(\tau)'Q_{ii}x_i(\tau) + u_i(\tau)'R_{ii}u_i(\tau)) + \sum_{i=1}^{N_L} \sum_{j \neq i}^{N_L} (x_i(\tau) - x_j(\tau))'Q_{ij}(x_i(\tau) - x_j(\tau)) \right) d\tau \]

• The LQR problem is in the form of:

\[ \min_{\tilde{u}} J(\tilde{u}, \tilde{x}_0) \quad \text{subj. to} \quad \dot{\tilde{x}} = \tilde{A}\tilde{x} + \tilde{B}\tilde{u} \quad \tilde{x}(0) = \tilde{x}_0 \]
## Power System Model

### Distributed LQR Control

<table>
<thead>
<tr>
<th>Mechanical Power Control Second-Order Model</th>
<th>Excitation Control Fourth-Order Model</th>
</tr>
</thead>
</table>
| \[
\frac{d}{dt} \omega(t) = \frac{\pi f_s}{H} (P_m - P_e - P_D + P_{DLQR})
\]
| \[
\frac{d}{dt} \omega(t) = \frac{\pi f_s}{H} (P_m - P_e - P_D)
\]
| \[
\frac{d}{dt} \delta(t) = \omega(t) - \omega_s(t)
\]
| \[
\frac{d}{dt} \delta(t) = \omega(t) - \omega_s(t)
\]
| \[
\frac{d}{dt} E_q'(t) = \frac{1}{T_{d0}} [E_{fd}(t) - E_q'(t) - (X_d - X_d')I_d(t)]
\]
| \[
\frac{d}{dt} E_{fd}(t) = \frac{1}{T_A} [-E_{fd} + K_A(V_{ref} - E_I + V_{DLQR}(t))]
\]

- Designed by Proposed Distributed LQR Controller
Angle Response for Uniform Test System

- **System**: 30x30 Mesh structure (Total of 900 generators)
- **Disturbance**: 0.5 pu power pulse for 0.5 sec on the generator in the center of the mesh
Remarks

• From control point of view distributed LQR control problem for PDEs achieves optimal solution, while for discrete models the solutions are sub-optimal and still is an open problem.

• For the given test system we can do the discretization in a way that matches the generators location which makes the controller application to the discrete system feasible. Application of this controller to an arbitrary system is a challenging problem that will be part of our future work.
Distributed Controls – Scalable

- **Objectives**
  - Scalable controls through distributed actuation, on-line measurements, modeling approximations and adapting to conditions.

- **Innovations**
  - Jointly design controller, communications and sensor needs by enforcing some regularity on connections.

**Example**
Two-area system communication structures and “sparsified” dynamics matrices

- **Case I**: Centralized
- **Case II**: Decentralized
- **Case III**: Star
- **Case IV**
- **Case V**
Two Area System with Communication Links

- Communication link in examples here assumes full state information but more structure can be imposed.
- Control design uses LQR but other methods possible
Centralized vs. Distributed vs. Decentralized

No Control

Centralized Control

Decentralized Control

Distributed Control
Comments

• Much of the value of wide area information can be gleaned from a few measurements.
• Best approach is to co-design communication and control system.
Wide-area Damping Controllers: Failures in Sensors and Actuators

M. Ehsan Raoufat
Kevin Tomsovic
Robust Controls – Fault Resilience

**Objectives**
- Reliable controls considering communication failures, sensor limits, and unavailability of actuator, (e.g., renewable resource variability).

**Innovations**
- Reconfiguration without need for redesign, i.e., fault hiding.
  - Virtual sensor
  - Virtual actuator

---

**Example – Virtual Actuator**

![Virtual Actuator Diagram](image)
Comments

- With our approach damping of WADC system recovered without the need to redesign the nominal WADC in case of faults in actuators.
- We consider the sensor faults as communication failures, cyber-attacks, significant delay in communication links or failures in the measurement devices.
- Design of the reconfiguration block is independent of the nominal controller and there is no need to redesign the nominal controller.
Final Summary Comments

- Wide area control is needed to provide flexibility and integrate renewables
- Wide area controls should be:
  - Distributed and modular but operating within a context (e.g., flat controls)
  - Robust to sensor, communication and actuator loss (e.g., virtual sensors and actuators).
  - Make efficient use of communications (e.g., distributed controllers)
Acknowledgements

This work was supported primarily by the ERC Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

Other US government and industrial sponsors of CURENT research are also gratefully acknowledged.
Discussion
Example Value of Improved Controls

Northwest Pacific Intertie

- Two 500kV AC lines and +/- 400kV DC line
  - Designed for transfer of 2000 MW AC and 1440 MW DC
  - Actual capacity was 1300 MW AC due to instability caused by AVRs
  - Power system stabilizers allowed increase to 1800 MW AC
  - Dynamic brake added at Chief Joe allowed up to 2500 MW AC
- Transmission upgrade – third AC line and DC upgrades
  - AC capacity today about 4800 MW (primarily voltage)
  - DC capacity today about 3000 MW

1990s work by DOE and BPA on WAMS and WACS a direct result of this type of need for improved controls.
Major Research Questions

Future Control Architecture

- Information flow
  - What information is needed where?
  - How much latency can be tolerated?
  - Trade-off – more information leads to better decisions but slower response

- Control architecture
  - Do all devices contribute to control?
  - For which phenomena do devices contribute (some fast and some slow)?
  - How much contribution is needed to ensure performance?
  - Trade-off – more devices contributing properly expands viable operating region but requires greater sophistication and cost

- Economics and optimization
  - What functionality should come from markets and what by regulation?
  - Contributions from certain devices are more cost effective
  - Trade-off – greater optimization leads to lower cost but requires more voluntary sharing of information and but some services may not lend themselves to an efficient market structure

Design needs to be a series of trade-offs between communication needs, device sophistication, resiliency, speed of response, economic performance and device reliability vs. system reliability.
Strategic Planning

- Brainstorm research directions based on SVT report, IAB, and self-review
- Continue system level projects
- Clarify control architecture and paradigms
- Continue to emphasize demonstration projects
  - Wide area oscillation damping control
  - Wide area voltage control
  - >50% renewable penetration
Project Planning Process

Schedule

- March
- April
- May
- June
- July
- August
Year 4 System Level Projects by Primary Thrust

- **Monitoring**
  - Measurement: Universal Grid Analyzer

- **Modeling**
  - Dynamic State Estimator and Parameter Estimation

- **Control**
  - Control Paradigms for Oscillations and Prevention of Cascading Outages
  - Grid Control Architectures

- **Actuation**
  - Advanced HVDC and Actuator Technologies
• **Hardware Testbed**: Grid Emulator Development and Real-time Scenario Demonstration

• **Large Scale Testbed 1**: Virtual Grid Simulator with an Energy Management and Control System

• **Large Scale Testbed 2**: A National Power Grid Model
Associated and Sponsored Projects

- Monitoring
  - Data Architecture and Analytics
  - Achieving High-Resolution Situational Awareness in Ultra-Wide-Area Cyber-Physical Systems
  - Oscillation Damping Control Design Using Measurement-Based Transfer Function Model

- Modeling
  - Design of Boundary Measurements to Isolate Zonal Solutions for Large Interconnected Systems
  - Entergy's Response to Smart Grid Investment Grant (SGIG) Program
  - SECO/Phasor Based State Estimation

- Control
  - A Cyber Physical Framework for Remedial Action Schemes in Large Power Networks
  - Scalable and Flat Controls for Reliable Power Grid Operation with High Renewable Penetration

- Actuation
  - Power Flow Control using CVSR
Year 5 Research Plans

- Increased system size – complete interconnected North American system
- Increased percentage of renewables to > 50% with higher levels of solar, storage and demand response
- Continue moving to faster system events, including cascading outages
- Improving resilience of monitoring and estimation
- Further development of LTB simulation environment
- Evaluation approach for HTB and LTB with complex scenarios
Industry Program

Utilities
RTOs/ISOs

Vendors

Consultants,
Research,
Consortia