2012 Smart Grid R&D Program Peer Review Meeting

Smart Inverter Controls & Microgrid Interoperation

at the Distributed Energy Communications & Controls (DECC) Lab

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Smart Inverter (SI) Controls and Microgrid (MG) Interoperation

Objectives

- Develop and test SI controls for multiple renewable/nonrenewable DER.
- Develop MG controls and communication requirements for high penetration DER.
- Implement MG at DECC Lab.
- Transfer technology to industry.

Life-cycle Funding Summary ($K)

<table>
<thead>
<tr>
<th>Prior to FY 12¹</th>
<th>FY12 authorized²</th>
<th>FY13 requested</th>
<th>Out-year(s)³</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1,404</td>
<td>$535</td>
<td>$605</td>
<td>$1,815</td>
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</tbody>
</table>

¹Funding shown is what was received FY09 to FY11 for the DECC Lab.
²FY12 initial funding delayed until mid February, remaining funding delayed until end of March.
³Funding out to the end of FY16 assuming level funding based on FY13.

DECC Microgrid

Microgrid

Technological Scope

- Develop advanced smart inverter control consisting of local droop (P-f, Q-V) control integrated with secondary closed loop power control enhanced with communications.
- Develop advanced self-healing MG architecture consisting of two layers:
  - Fundamental local and adaptive DER device control and protection
  - MG Control to communicate with DERs and distribution system operations and provide active energy management.
Significance and Impact
Annual Performance Targets

• **2012 Target – Demo Integration of Renewable DER for 12% Load Factor Improvement**
  - SI controls for multiple inverter-based DER (later energy storage) to increase penetration to improve load factors.
  - Work with major inverter manufacturer to embed SI controls in inverter hardware.

• **2013 Target – Smart Microgrid (MG) for >98% reduction in outage time**
  - MG concepts developed and tested at DECC provide seamless transition from grid to islanding and back and for greater use of DER and energy storage.
  - Proposed work with vendors to demonstrate MG at ORNL and later at military base(s).

• **2014 Target – Integration of High Penetration PV for 15% Load Factor Improvement**
  - PV model and control development for maximum power tracking with smart inverter control.
  - Supports integration of high penetration PV for load factor improvement.

• **2015 Target – Integrated Distribution Management Systems (DMS) for reduce SAIDI by 5%**
  - Enable DER fast voltage ride-through of high/low system voltage and frequency events.
  - MG advanced architecture to establish functions for interfacing with DMS for reducing SAIDI.

• **2016 Target – Protection integrated with DMS to reduce SAIDI by 10%**
  - MG protection schemes (another project) integrated with SI and MG controls and DMS for greater reduction of SAIDI.
Significance and Impact
Trend for Addressing Targets

**ORNRL R&D directly addresses SG Targets.**

**Smart Grid R&D Targets**

- **FY12:** 12% Load Factor Improvement
- **FY13:** 98% Outage Time Reduction
- **FY14:** Fast Voltage Regulation & 15% Load Factor Improvement
- **FY15 & 16:** 5 and 10% SAIDI Reduction

- **Complete:**
  - MG interoperation
  - On-grid/islanding modes
  - MG Energy Management
  - Integration of renewables and energy storage
  - Grideye incorporation

- **Remaining:**
  - Fast DER voltage regulation
  - Utility coordination
  - Responsive load
  - Device protection

- **Out years:**
  - MG transition
  - Grid contingency
  - With/Without Synchronous generation
  - MG protection

- **MG architecture**
- **Energy storage deployment**

- **Flexible test bed**
- **Tech transfer**

- **Multiple smart inverters**
- **Flexible test bed**
- **Tech transfer**
- **MG architecture**
- **Energy storage deployment**

- **remaining**
  - Out years
Significance and Impact
Supporting Smart Grid R&D Targets

• Load Factor Improvement (20% by 2020)
  ➢ **Goal:** Achieve high penetration of DER (both renewable and nonrenewable)
  ➢ **Approach:** Develop fast and flexible controls for multiple and PV inverter-based DER; transfer technology with vendor involvement.
  ➢ **Benefit:** More local power generation and regulation of voltage resulting in reduced central generation, losses and higher load factor.

• Reduction of Load Outage Time (>98% reduction by 2020)
  ➢ **Goal:** Develop self-healing microgrid controls building on adaptive smart inverter controls
  ➢ **Approach:** Fast transition from grid-to-island mode and back with minimal communications; test at DECC Lab and demo at military facilities.
  ➢ **Benefit:** Reduced down time for loads due to continuity of generation.

• System Reliability Improvement (20% SAIDI reduction by 2020)
  ➢ **Goal:** Integrate microgrid protection (leverage another project) with microgrid controls
  ➢ **Approach:** Implement and test adaptive protection with DECC Lab microgrid under varying operational scenarios.
  ➢ **Benefit:** Faster and reliable detection and isolation of microgrid faults (both grid and island operation), reduced down time for system generation and loads.
Technical Approach

ORNL

Control Development, Modeling & Simulation

Refinement

Testing at DECC Laboratory

Refine Testing

Embed Controls

Industry Commercialization

Technology Transfer

System Impact Modeling

Industry Input & Collaboration
Technical Innovation

• Smart Inverter Control Innovations
  ➢ Local closed loop adaptive self-tuning control of multiple inverters
  ➢ Development of secondary voltage and frequency inverter control for MGs

• Microgrid (MG) Control Innovations
  ➢ Self-healing, highly stable/reliable multiple-layer MG architecture
    ➢ Fast and adaptive local DER control
    ➢ System-wide control of frequency and voltage enhanced with communications
    ➢ System-wide management of high penetration DER along with DR and energy storage
    ➢ MG control center provides interface to DMS
  ➢ Seamless DER hybrid control transition modes:
    ☐ Maximum or some constant power output (P, Q)
    ☐ Frequency (P-f) and voltage (Q-V) droop control
    ☐ Secondary closed loop frequency and voltage control

• Innovative DECC Laboratory for Technology Transfer
  ➢ On-grid testing of smart inverters controls of nonrenewable and renewable on an actual distribution system.
  ➢ Flexible MG test bed: conductor between test systems with innovative ORNL developed power flow controller for varying electrical distance for wide range of testing.
Technical Innovation vs. State of the Art

*ORNL research is catalyzing the transformation of the electric distribution grid at the supply and consumer level.*

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>ORNL FOCUS</th>
<th>EXISTING TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>DER Composition</td>
<td>High penetration inverter-based for both on-grid and islanding.</td>
<td>Low penetration inverter-based for on-grid; Rotating generation for MG frequency.</td>
</tr>
<tr>
<td>Smart Inverter Control</td>
<td>Adaptive “on the fly” control: self-tuning parameters for flexibility and adaptability.</td>
<td>Non-adaptive control parameters preset and fixed (based on studies).</td>
</tr>
<tr>
<td>Microgrid (MG) Architecture</td>
<td>Multi-layer: (1) communication-capable local DER layer and (2) central management layer.</td>
<td>Single local DER layer.</td>
</tr>
<tr>
<td>MG Control</td>
<td>Hybrid control: local droop control (P-f, Q-V) with secondary frequency and voltage control based on central MG-wide management.</td>
<td>Local open loop droop control (P-f, Q-V) with steady-state frequency and voltage control error</td>
</tr>
<tr>
<td>MG communications</td>
<td>Cost vs. performance evaluation of MG control for different communications.</td>
<td>Literature review has not revealed similar work.</td>
</tr>
<tr>
<td>MG energy management system</td>
<td>Economic DER dispatch (P, Q) with responsive load and energy storage management.</td>
<td>Literature review has not revealed similar work.</td>
</tr>
<tr>
<td>MG protection</td>
<td>Current magnitudes and direction change with on-grid vs. islanding modes: ORNL developed adaptive methods (leveraging another project).</td>
<td>Overcurrent methods designed for unidirectional flow in distribution systems. Directional protection currently used in transmission systems.</td>
</tr>
</tbody>
</table>
Technical Accomplishments
Smart Inverter (SI) Controls

DER Connected to Distribution System

Smart Inverter Controller

Current FY12
- Developed PV inverter model and control algorithms (Nov’11)
- Develop secondary frequency and voltage control for microgrid inverter operation (Sep’12).
- Work with vendor inverter on controls (Sep’12).

Out Years
- SI mode switching (i.e., P2030)
- SI controls for microgrid applications for frequency and voltage transition and smooth transition from grid to microgrid

Prior FYs
- Developed adaptive controls for single inverter (FY06 to FY11).
- Extended adaptive control methodology to support multiple inverters connected to distribution system/circuit (FY11).

Prior year accomplishment
- FY12 focus
- Out Years
Technical Accomplishments
Microgrid (MG)

Prior FY
✓ Support SPIDERS military MG dynamic modeling and design (FY11).

Current FY12
✓ Develop model of self-healing MG architecture with advanced controls (May’12).
☐ Identify the communication requirements for MG control (Sep’12).

Out Years
☐ Design and implement MG protection.
☐ Determine MG transition requirements.
☐ Develop and implement MG energy management system.

Prior year accomplishment
☐ FY12 focus
☐ Out Years
Technical Accomplishments
Testing & Tech Transfer

Prior FYs
✓ Established DECC for inverter controls testing (FY06)
✓ Completed second inverter test system at DECC (FY11).
✓ Multiple (Two) inverters tested together on-grid at DECC under voltage control (FY11).
✓ Designed and began constructing plug-and-play, flexible and reconfigurable low-voltage and low-power test bed (FY11).

Current FY12
✓ Completed new test bed and installed third inverter (Mar’12)
✓ Partnered with major inverter manufacturer (Feb’12)
☐ Test inverter controls in new test bed (Jun’12)

Out Years
✓ Prior year accomplishment
☐ FY12 focus
☐ Out Years

- Install MG communications
- Install cables to form radial-loop MG
- Test MG in islanding mode
- Install MG transition hardware
- Test MG mode transitions
Project Team Capabilities

ORNL Team has key domain experts from industry, academia, and other National Labs needed to advance the R&D of the future electric grid.

TEAM CAPABILITIES

ORNL, UTK, and Industry Partners

- Smart inverter (SI) controls (>7 yrs) expertise advancing in self-healing microgrids (MGs).
- Power systems, protection, power electronics and control expertise.
- Chair task force on volt/var control with high penetration renewables.
- Member of IEEE PES WG in smart distribution and DER integration
- Support SI standards development (SCC21, 1547, NIST, and EPRI).
- DECC Lab provides “in-the field” SI and MG testing with actual distribution system.
- SPIDES leveraging ORNL inverter controls expertise for military MGs.
- ORNL partnership with UTK’s DOE/NSF sponsored CURENT center.
- Industry team (TVA, EPRI, SCE, TVPPA, LCUB, …) provides technical input and guidance
- Inverter companies provide technical support and materials.
Funding Leverage

ORNL plays a unique role in both providing innovative SI and MG development (controls, communications & protection) and a testing platform on an actual distribution system.

These figures above do not reflect the leverage value of a PV inverter, an automobile battery assembly, and MG equipment to be provided by industry.
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Energy & Transportation Science Division (ETSD)
http://www.ornl.gov/sci/ees/etsd/
Electric Deliveries Technology (EDT) Program
http://www.ornl.gov/sci/electricdelivery/
BACK-UP SLIDES
Distributed Energy Communications & Controls (DECC) Laboratory
DECC Laboratory is located on North ORNL Campus
DECC Lab Layout

SG - INVERTER
SG - A/C STALL & FREQ RESP LOAD
SG - PV INVERTER
Restroom

SG - Synchronous Condenser

DECC LAB TESTING

IPAC - Intelligent Power Automation Center

GRIDEYE

8' Door Way

EXIT

3147

6' Door Way

AED & Fire Ext.

Fire Ext.

Main Power Panel

Microturbines & Associated Equipment

December 2008
DECC Lab Assets

Microgrids and Distributed Energy Resources (DER)

Oak Ridge National Laboratory (ORNL) is developing and testing advanced controls and systems at the Distributed Energy Communications and Controls Laboratory (DECC)

Distribution System for DECC Lab
Substation between TVA Transmission System and ORNL's Campus Distribution System
ORNL owns and operates its own electric distribution system which allows for a versatile testing environment with various DER systems installed and has the capability for testing a microgrid through the existing infrastructure.

DER Test Equipment at the DECC Lab

Static and Dynamic Loads at the DECC Lab

Transformers for Interface between DECC Lab and ORNL Distribution System

- 1500kVA/1247/480V transformer for larger inverter-based test system on chl. 2.
- 750kVA/1247/480V transformer for inverter test system, load banks, and motors on chl. 2.
- 200kVA/1247/480V transformer for rotating based test system and 100kW microturbine on chl. 4.
- 30kW/1247/240V transformer for PV inverter and 100kW microturbine on chl. 4.
- Rotating-based test system for providing reactive power on chl. 4.
- Inverter-based test system with programmable dc power supply on chl. 2.
- Inverter-based test system with programmable dc power supply on chl. 2.
- Static and Dynamic Loads: Various sizes (C75hp, 2hp) of induction motors in addition to distribution system loads.
Technical Approach – Microgrid Demonstration

Leverage DECC assets to demonstrate microgrid performance and B2G from vendor for energy storage.
DECC Lab’s Test Systems

Rotating-Based DR (SC) Test System

Inverter-based DR Test System

Air Conditioning Stall Test System

Remote Large Inverter-based DR Test System
DECC Lab Flexible Test Bed
Completed Electrical Infrastructure

- Lower Voltage and Power
- Plug and Play AC and DC
- Reconfigurable test rack
- Accelerated smart inverter testing
- Bridges design, development and simulation with higher voltage and power testing
DECC Lab PV Test System

- PV Arrays & Conventional Inverter
- DC Bus for Research Inverter

Overhead DC Line to Conventional Inverter

50kW PV Array across Bethel Valley Road supply 400-600Vdc, 135Adc

DC Bus in Room 2 for Research Inverter

Location of DC Transfer Switch inside Isolation Room
Smart Inverter (SI) Controls
Smart Inverter (SI) Adaptive Control

- **Fixed control:**
  - PI control with fixed $K_p$ and $K_i$
  - $K_p$ and $K_i$ determined typically by trial & error

  Incorrect gains result in under-performance, oscillation, or instability

- **Adaptive control:**
  - $K_p$ and $K_i$ are initially conservative but adjusted in real-time to achieve desired system response time

**DE:** Distributed Energy Resource  
**Control variable:** PCC voltage  
**Reference:** Desired PCC voltage value  
**Error:** Difference between reference and measured PCC voltage
### SI Controllable Variables

<table>
<thead>
<tr>
<th>Reactive power related variables</th>
<th>Active power</th>
<th>Active current</th>
<th>Power factor</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive power</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Reactive current</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Power factor</td>
<td>Yes</td>
<td>Yes</td>
<td>NA</td>
<td>Yes</td>
</tr>
<tr>
<td>Local voltage</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
SI Voltage Regulation with Fixed vs. Adaptive SI Control

(a) Load current (rms) during load change

(b) PCC voltage (rms) without regulation

(c) PCC voltage (rms) with non-adaptive voltage regulation

(d) PCC voltage (rms) with adaptive voltage regulation.
SI Active (P) & Non-Active (Q) Control
Increase P, Q Fixed

- Complete event on left.
- Zoomed in to 10 to 20 kW change on right.
- Active power reference ($P_{\text{ref}}$) from 10 to 50 kW.
- Nonactive power reference ($Q_{\text{ref}}$) set to 10 kVar.
- $P$ does not reach 50 kW and $Q$ drops because of the inverter current limit (60A).

$P_{\text{ref}}$ changed from 10 kW to 50 kW

$Q_{\text{ref}}$ set to 10 kVar.

$P_{\text{ref}}$ change from 10 to 20 kW

$Q_{\text{ref}}$ set to 10 kVar.
SI Active (P) & Non-Active (Q) Control
Decrease P on Left, Decrease Q on Right

- Active power ($P_{\text{ref}}$) change while keeping non-active power ($Q_{\text{ref}}$) constant on left.
- Nonactive power ($Q_{\text{ref}}$) change while keeping active power ($P_{\text{ref}}$) constant on right.
- Plots display the independent control of P & Q that has been achieved.
PV Inverter Active and Reactive Power Control

Output (P vs. V) at different solar irradiances

Output (P vs. V) at different temperatures

- No DC-to-DC converter for lower cost and higher efficiency.
- P (MPPT or fixed P) and Q (PCC voltage or fixed Q) controlled by inverter.
- PV array DC voltage stability maintained by inverter control - resistant to disturbances caused by changing weather or system.
PV Inverter Active and Reactive Power Control Simulation Results

Case 1: Maximum power point tracking (MPPT) & PCC voltage control with varying solar irradiation (worst case)
PV Inverter Active and Reactive Power Control Simulation Results

Case 2: MPPT & Fixed reactive power control with varying solar irradiation (worst case)

- Solar Irradiance
- PV array active power output
- PV array output DC voltage
- Fixed reactive power control

Graphs showing the simulation results for power control with varying solar irradiation.
PV Inverter Active and Reactive Power Control Simulation Results

Case 3: Automatic smooth transition between fixed active power control to MPPT and then back

Solar Irradiance

Switching between fixed real power control and MPPT control
Adaptive Multiple Inverters Voltage Control

Applicable to radial with or without meshed distribution system with multiple DERs; simulated and proved with three in this case.

- Multiple inverters for coordinated voltage control to prevent hunting.
- Self-adjusted control parameters to achieve fast response performance.
- Primarily local voltage control by inverters
- Only limited communication needed: initially, for large disturbance or for network change
- Adaptability to radial distribution feeder or looped distribution systems
- Plug and play feature without need for network parameters
Adaptive Multiple Inverters Voltage Control
Simulation Results

Case 1: Voltage responses of DER with ideal communication (No latency)

Voltage response of DER1
Voltage response of DER2
Voltage response of DER3

- Desired voltage response
- Actual voltage response
- Voltage reference
Adaptive Multiple Inverters Voltage Control Simulation Results

Case 2: Voltage responses of DER with communication latency (worst case)

Voltage response of DER1

Voltage response of DER2

Voltage response of DER3

A 9-cycle latency is assumed, which is typical to wide-area-monitoring based on paper by Anjan Bose (WSU) and should be much higher than the latency in a distribution system.
Multiple Inverter Testing at DECC Lab

DECC Lab physical configuration for multiple DER testing.

- Two Inverter-based DERs (150A each) on same circuit.
- Electrically connected via the primary conductor of circuit #2.
- One DER is located at building 3114.
- Second DER is located at building 3129 which about 700ft away.
Multiple Inverter Controls Development Testing Results

- Two inverters operated simultaneously on the same 480V circuit in ORNL distribution system.
- Inverters performing voltage regulation with different reference settings.
- Inverter current limited to 60Arms.

![Current vs. Time](image1)

![Voltage vs. Time](image2)
Microgrid (MG) Architecture & Interoperation
Multi-layer Microgrid Architecture

Central management layer

Communication Network

DER Controller
- Secondary control
- Max/constant P,Q control
- Local droop control

DER Controller
- Secondary control
- Max/constant P,Q control
- Local droop control

Responsive Load
DER
Energy Storage
DER
System Loads

Local control layer

Microgrid Control Center
- Situation awareness
- Secondary control management
- Active energy management
- Protection management

Distribution Management System

Out years focus

Distribution System

Microgrid Switch
Microgrid Control
Reactive Power and Voltage Regulation (Q-V)

- Voltage is a local variable
- Droop control is applicable
- Challenges:
  - DER Q output sharing errors due to the impedances and local loads
  - Q circulation because of improper voltage references
- Voltage Regulation Approaches
  - Ideally system model & monitoring
  - Preset local PCC voltage reference and use droop control without communication
  - Setting local PCC voltage reference via central dispatch or schedule

Effective Reactive Power at PCC
Total: \( Q = Q_1 + Q_2 \)
DER1: \( Q_1 = Q_{DER1} - Q_{Z1} \)
DER2: \( Q_2 = Q_{DER2} - Q_{Z2} - Q_{Load} \)
Microgrid Control Strategies
Existing

DER P-f Droop factor

- Droop control with artificial droop curves
- Different slopes to have different responses
- Applicable to P-f and Q-V control
- Steady-state error
- No communication or central control required
Microgrid Control Strategies
ORNLI Innovation

Enhanced Droop Control

- Secondary control in addition to droop control for frequency and voltage control to minimize steady-state error
- Optimal power dispatch
- Only low-speed and infrequent communication needed
Microgrid Control for Renewables
Ongrid vs. Islanding Modes

On-grid Mode

- MPPT is the default
- Or dispatch P based schedule
- Adjust P if high or low frequency if not all operating at MPPT

Islanding Mode

- Frequency control is top priority
- If multiple DE: one DE provides secondary while the others provide droop control
- Frequency within normal band (f2 to f3): DEs only use droop control
- Frequency outside of normal: secondary control is kicked
The German low-voltage ride-through standards for medium-voltage energy resources interconnection (BDEW) recommend 7.5 cycles ride through time if the voltage is below 0.3 pu, 35 cycles if the voltage is between 0.3 pu and 0.7 pu, and 75 cycles if the voltage is between 0.7 pu and 0.9 pu.

Coordination with Protection and DER LVR and Tripping

- Microgrid switch is coordinated to be slower than grid relay protection.
- Microgrid switch is coordinated to be faster than Individual device tripping.
- Microgrid switch needs to be high speed to meet the individual inverter low-voltage ride-through setting.
Microgrid
Low-Volt Ride-Through and Multi-Input PI Control

Smart Inverter Control for Microgrid

- Decoupled PQ control
- Multiple control modes
- Hierarchical control coordination to determine mode selection
- Multi-mode PI controller ensures smooth transition between modes
Microgrid Simulation
Diagram of ORNL Microgrid

Grid

Feeder CB1

Feeder CB2

Microgrid switch

2400V /480V

Bus1

Bus2

CB12

Line12

CB_DER1

Inverter2

Load1

CB13

Line13

CB_DER3

Inverter3

Load3

Bus3

CB21

Line23

CB23

CB21

Load2

CB_DER2

DER2

CB_DER3

DER3

Microgrid
Publications
FY12 Publications


FY11 Publications

- “Microgrids and Distributed Energy Resources (DER)”, Poster, 8th International Conference on Power & Electronics (ECCE Asia), Jeju, South Korea, May 30-Jun 3, 2011.


FY10 Publications


FY09 Publications


FY08 Publications


• “Active power and nonactive power control of distributed energy resources”, *The 40th North American Power Symposium*, , Calgary Canada, September 28 – 30, 2008
FY07 Publications


• “Nonactive-power-related ancillary services provided by distributed energy resources,” *IEEE Power Engineering Society General Meeting*, June 24-28, 2007, Tampa, Florida.