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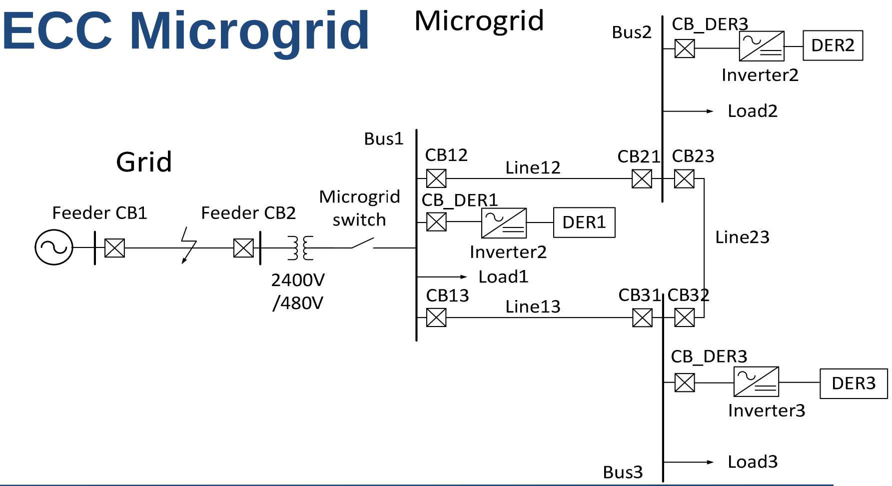
Smart Inverter (SI) Controls and Microgrid (MG) Interoperation

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.

DECC Microgrid



Life-cycle Funding Summary ($K)

Prior to FY 12[1]	FY12 authorized[2]	FY13 requested	Out-year(s)[3]
$1,404	$535	$605	$1,815

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

Technical 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

ORNL R&D directly addresses SG Targets.

- ✓ Complete
- ❑ Remaining
- • Out years

Smart Grid R&D Targets

FY12: 12% Load Factor Improvement

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

FY13: 98% Outage Time Reduction

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

FY14: Fast Voltage Regulation & 15% Load Factor Improvement

- MG transition
- Fast DER voltage regulation
- Utility coordination
- Responsive load
- Device protection

FY15 & 16: 5 and 10% SAIDI Reduction

- Embedded MGs
- Grid contingency
- With/Without Synchronous generation
- MG protection

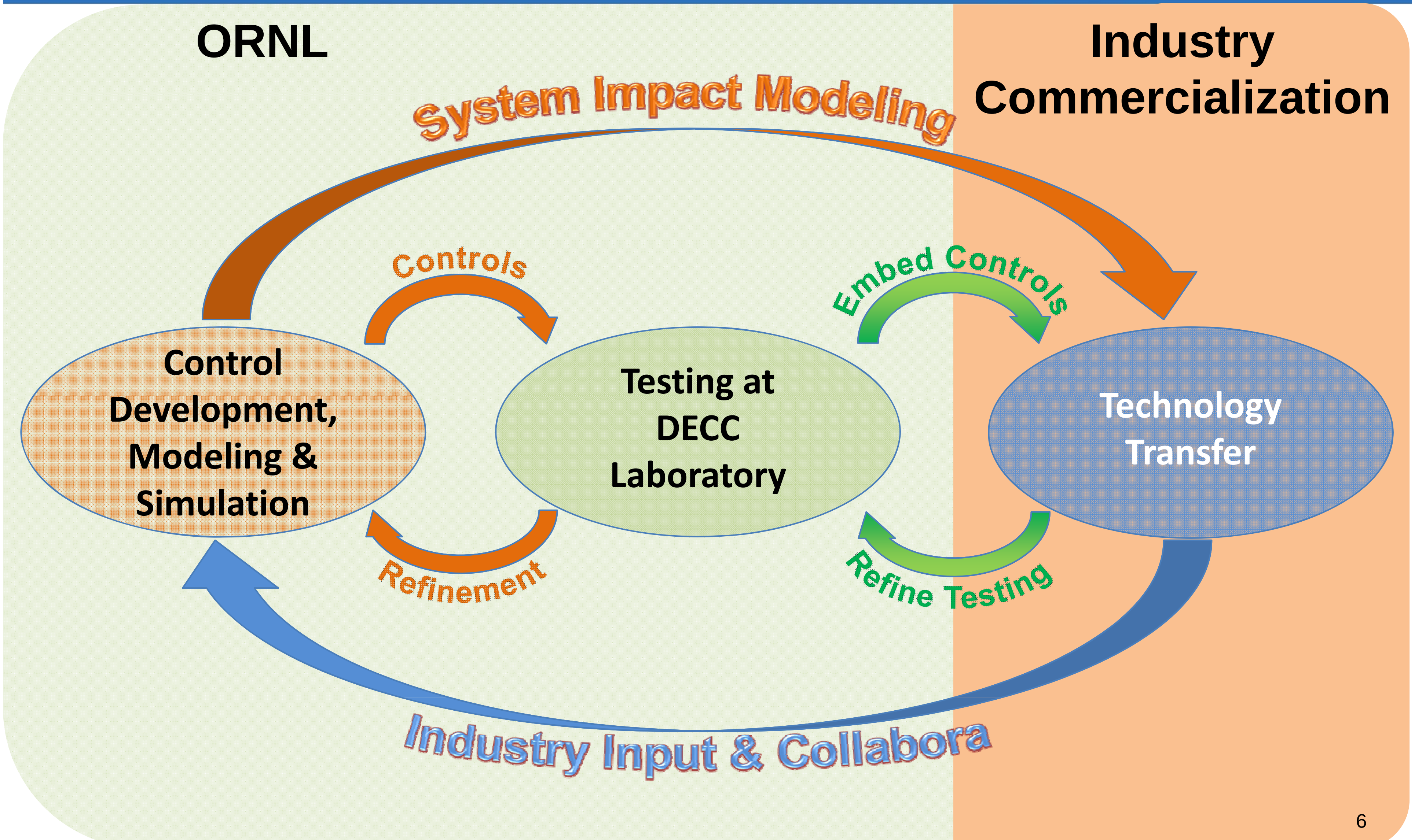
Significance and Impact
Supporting Smart Grid R&D Targets

- **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



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.

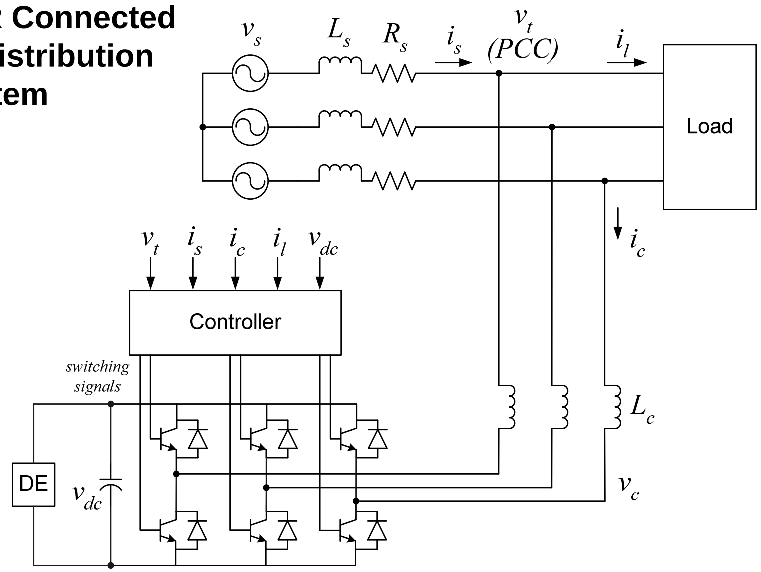
Technical Innovation vs. State of the Art

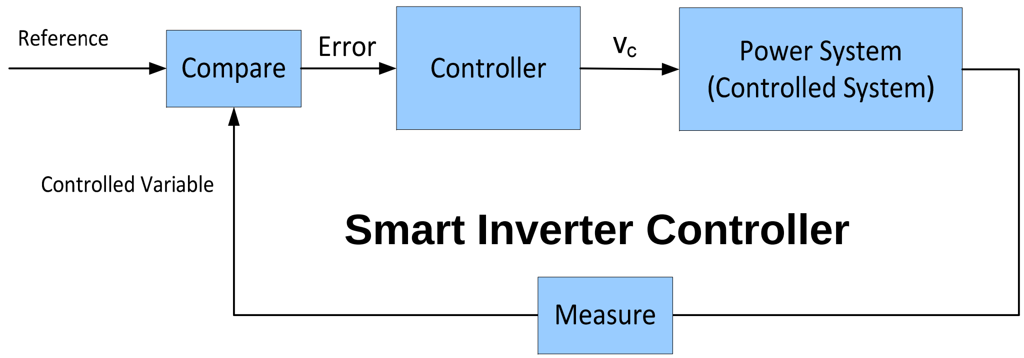
ORNL research is catalyzing the transformation of the electric distribution grid at the supply and consumer level.

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

Technical Accomplishments
Smart Inverter (SI) Controls

DER Connected to Distribution System





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).

Current FY12

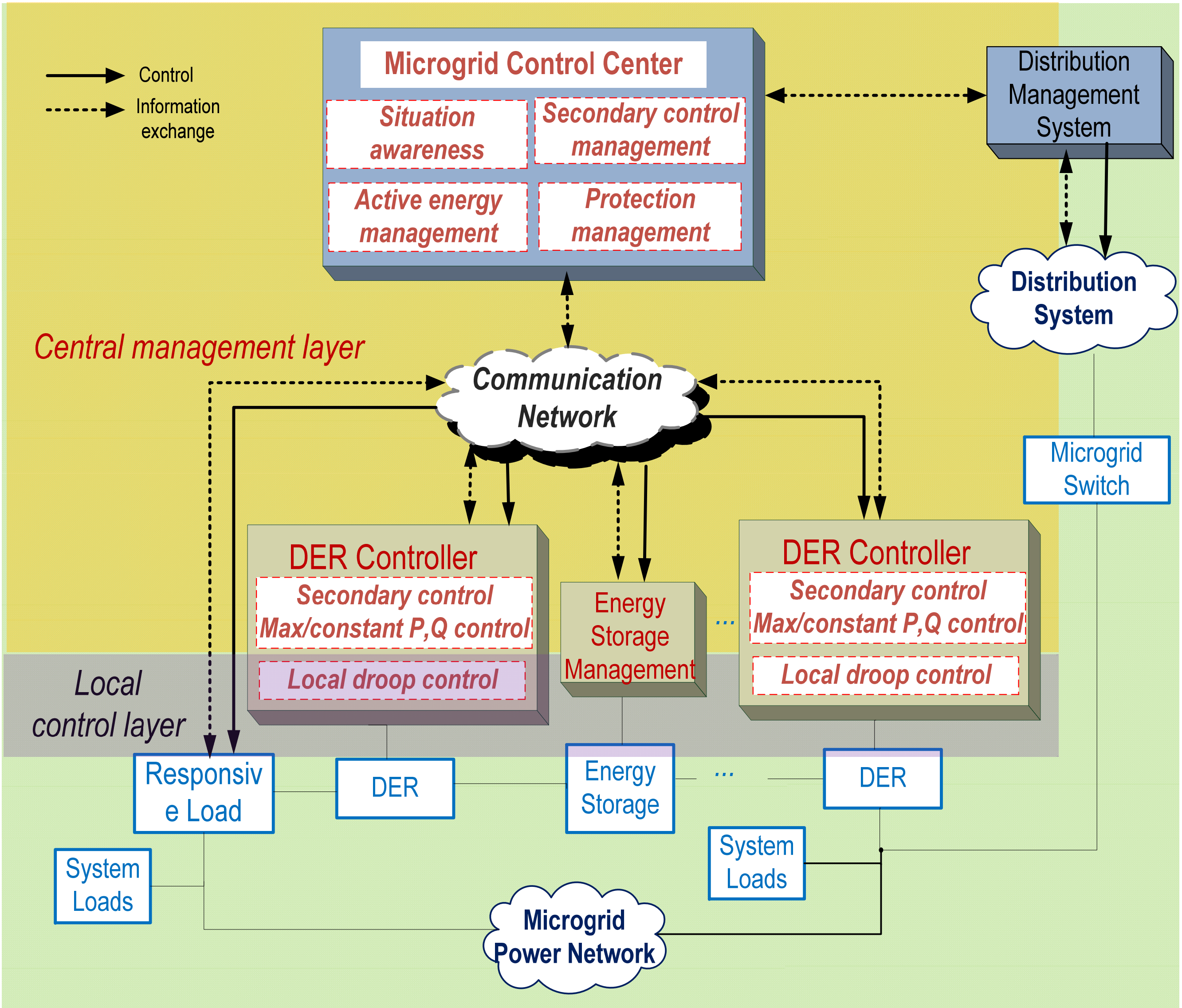
- ✓ Developed PV inverter model and control algorithms (Nov'11)
- ❑ Develop secondary frequency and voltage control for microgrid inverter operation (Sep'12).
- ❑ Work with vendor inverter on controls (Sep'12).

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 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

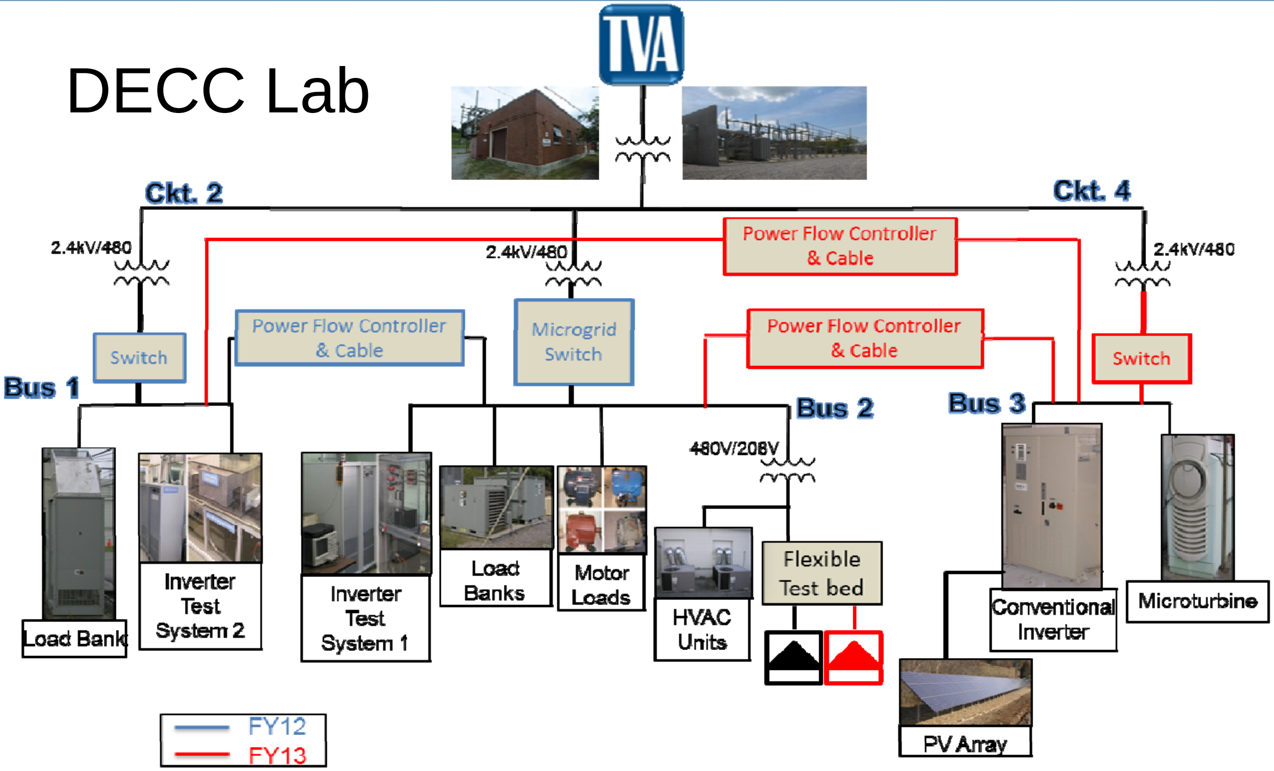
Prior FYs

- ✓ 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)

DECC Lab



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

✓	Prior year accomplishment
❑	FY12 focus
❑	Out Years

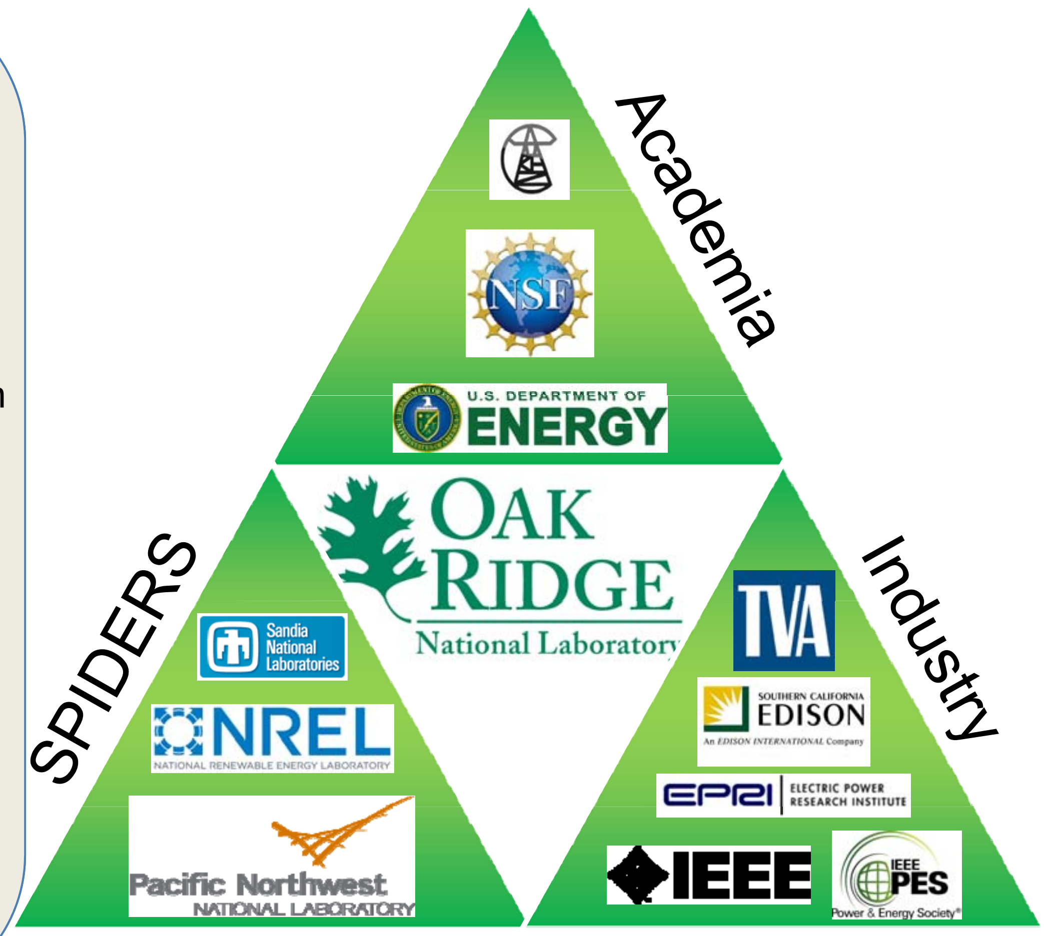
Project Team Capabilities

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

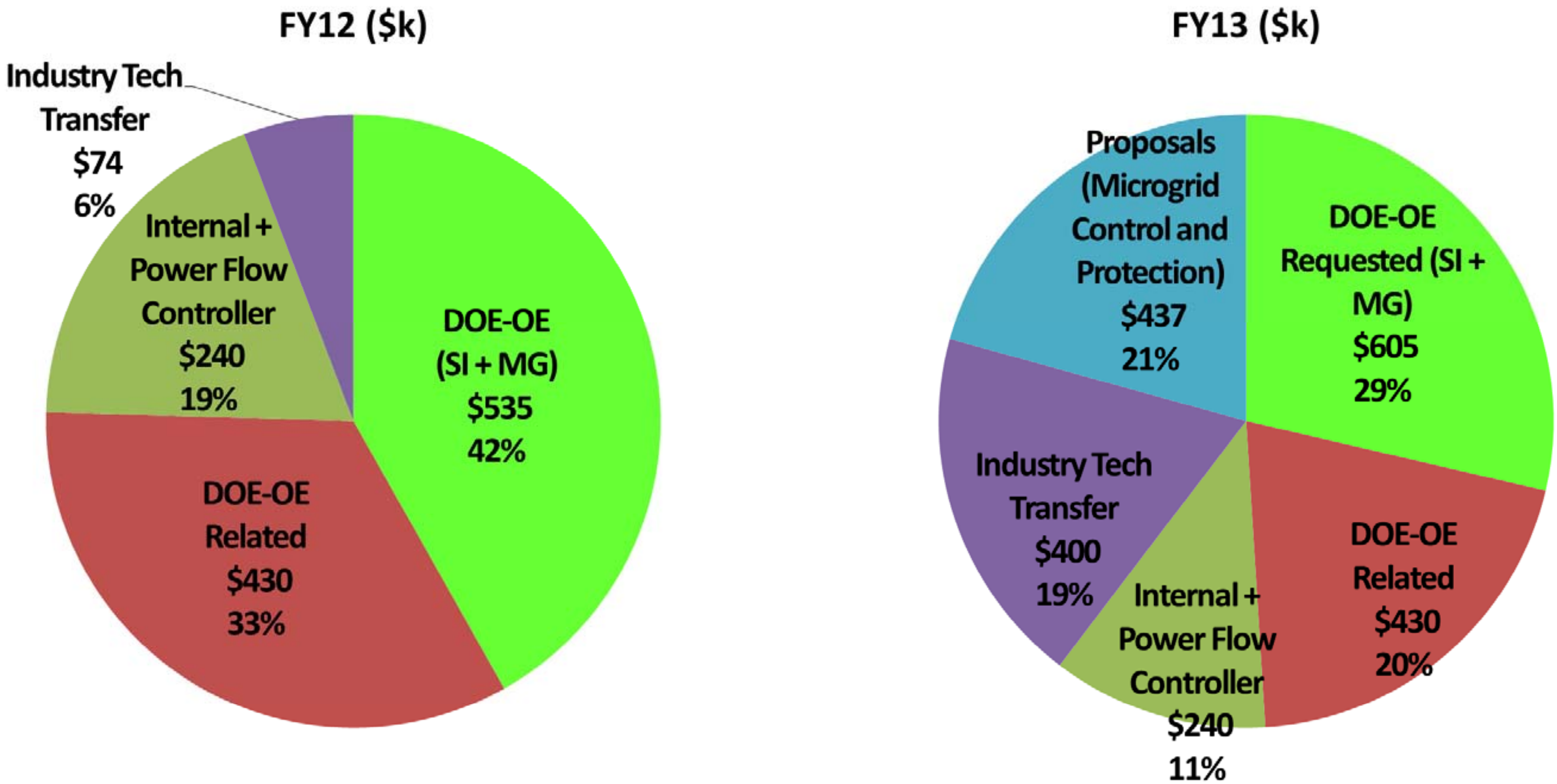
ORNL, UTK, and Industry Partners

- ✓ 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.
- ✓ SPIDERS 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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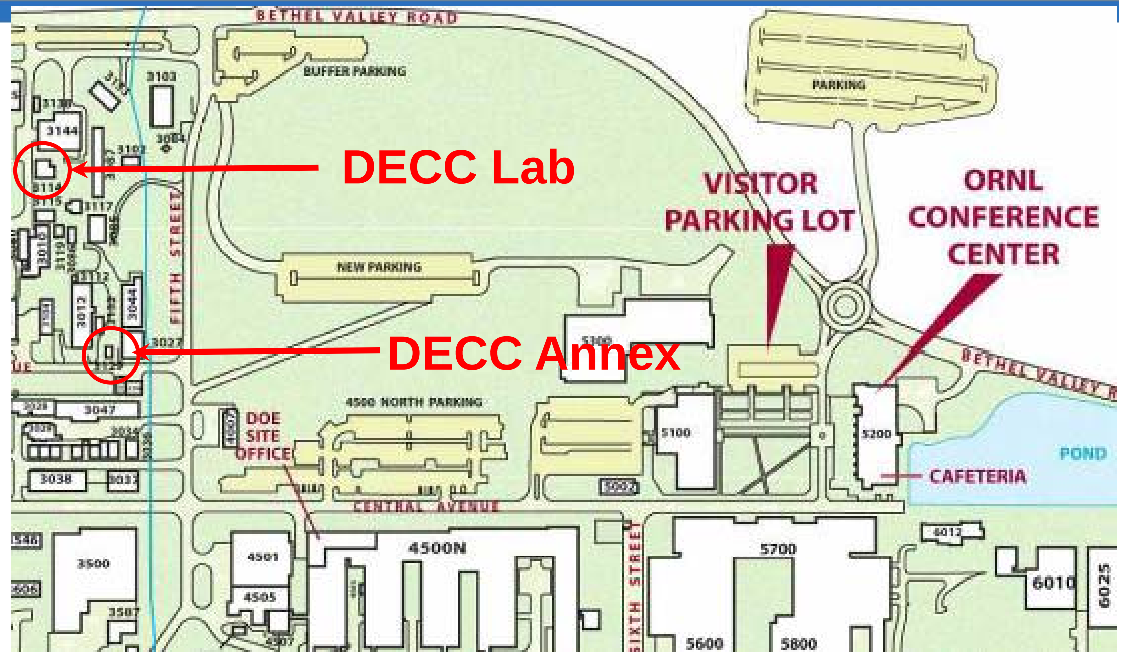
Electric Deliveries Technology (EDT) Program
http://www.ornl.gov/sci/electricdelivery/

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

BACK-UP SLIDES

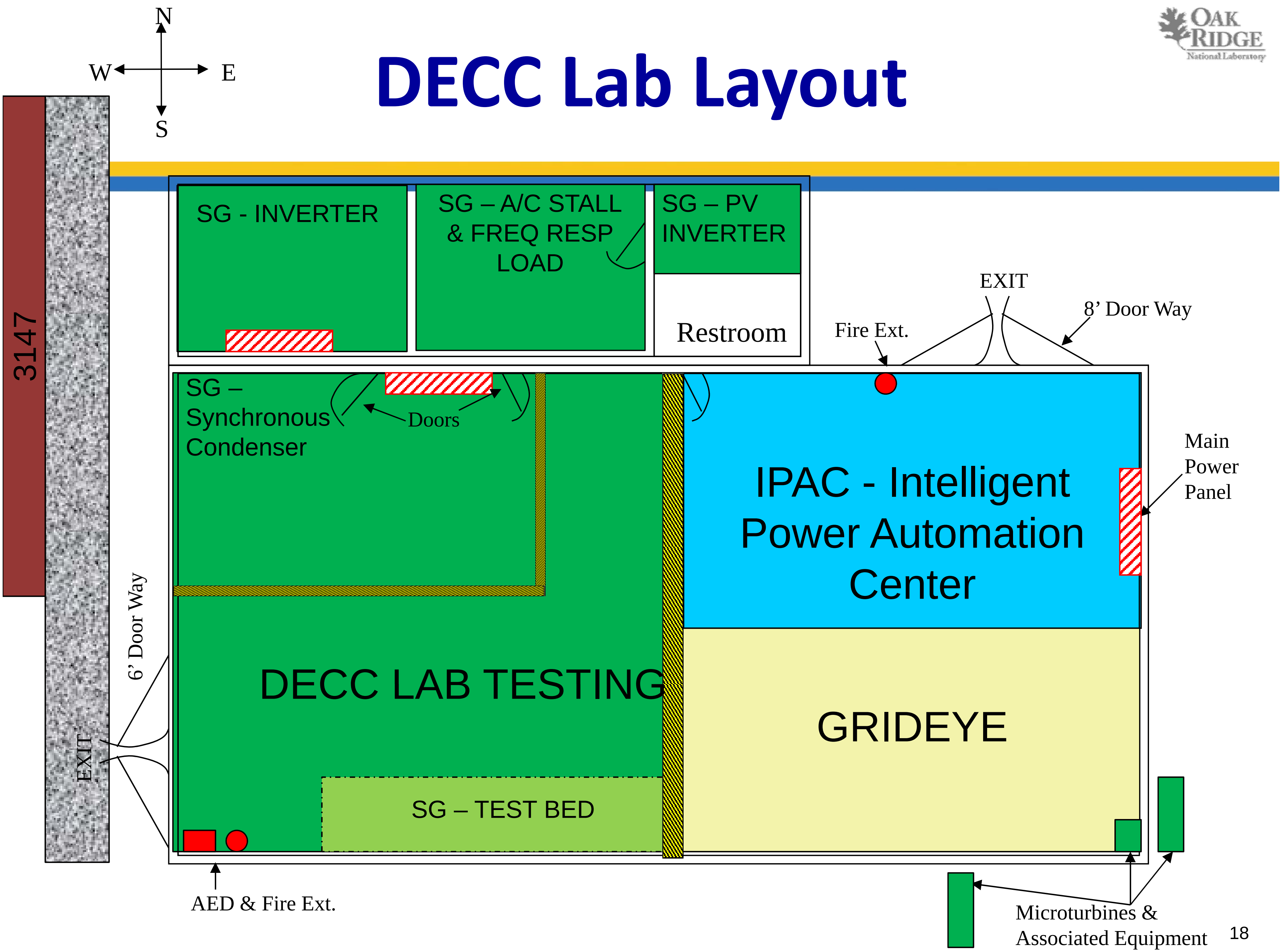
Distributed Energy Communications & Controls (DECC) Laboratory

DECC Laboratory is located on North ORNL Campus



Load Banks

DECC Lab Layout



DECC Lab Assets

Technical Approach – Microgrid Demonstration

Leverage DECC assets to demonstrate microgrid performance and B2G from vendor for energy storage.

Distribution System

Sources

Loads

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

Overhead DC Line to Conventional Inverter

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

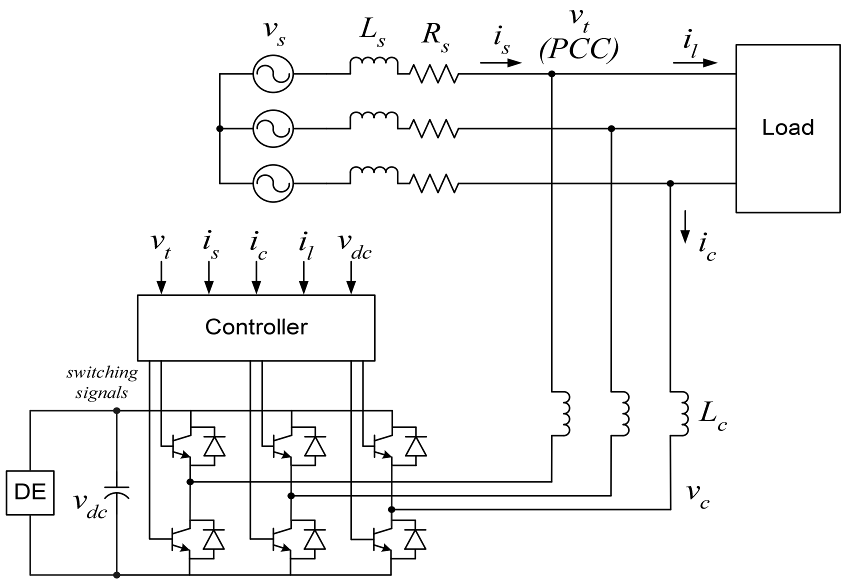
- DC Bus for Research Inverter

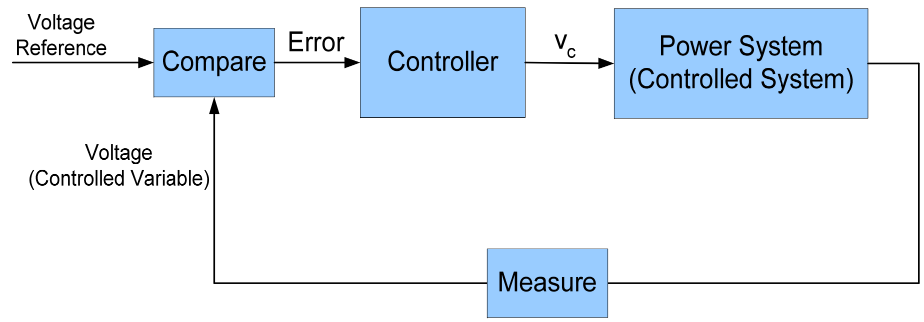
DC Bus in Room 2 for Research Inverter

Location of DC Transfer Switch inside Isolation Room

Smart Inverter (SI) Controls

Smart Inverter (SI) Adaptive Control





DE: **Distributed Energy Resource**

Control variable: **PCC voltage**

Reference: **Desired PCC voltage value**

Error: **Difference between reference and measured PCC voltage**

- **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

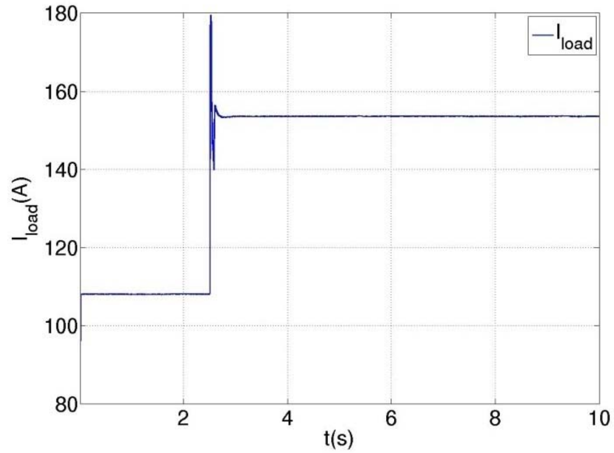
- **Adaptive control:**

  K_p and K_i are initially conservative but adjusted in real-time to achieve desired system response time

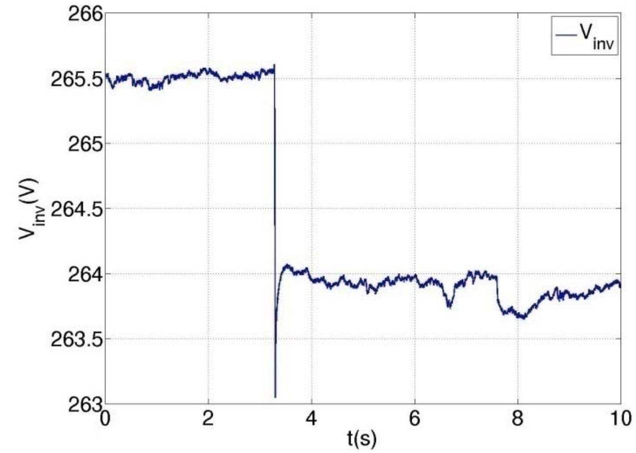
SI Controllable Variables

Active power related variables / Reactive power related variables	Active power	Active current	Power factor	Frequency
Reactive power	Yes	Yes	Yes	Yes
Reactive current	Yes	Yes	Yes	Yes
Power factor	Yes	Yes	NA	Yes
Local voltage	Yes	Yes	Yes	Yes

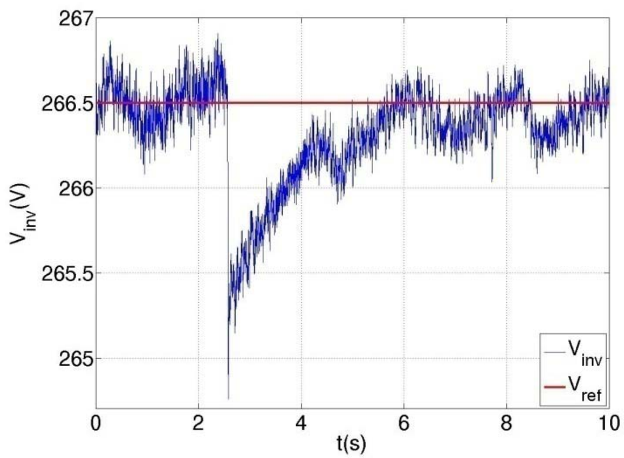
SI Voltage Regulation with Fixed vs. Adaptive SI Control



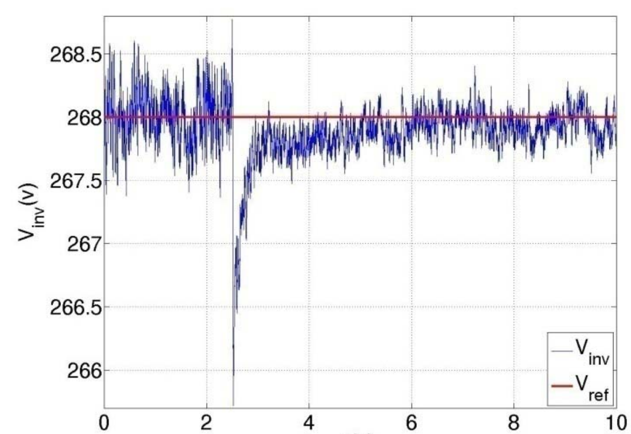
(a) Load current (rms) during load change



(b) PCC voltage (rms) without regulation

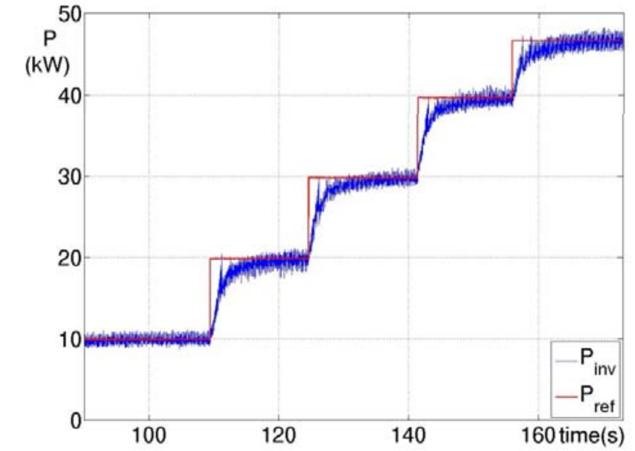


(c) PCC voltage (rms) with non-adaptive voltage regulation

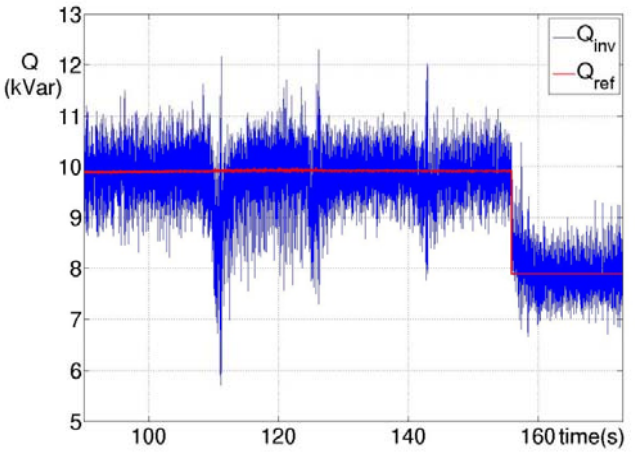


(d) PCC voltage (rms) with adaptive voltage regulation.

SI Active (P) & Non-Active (Q) Control
Increase P, Q Fixed

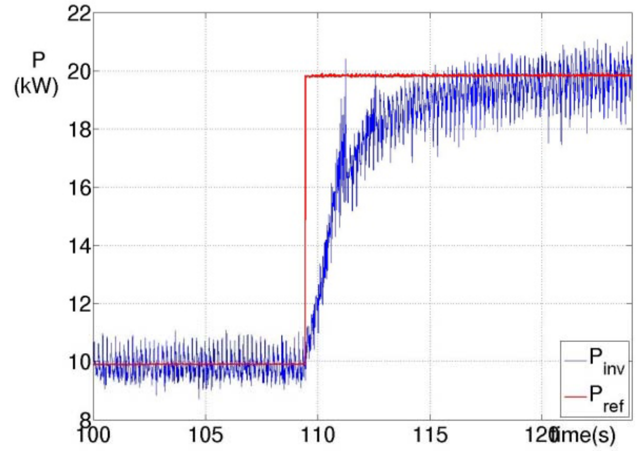


P_{ref} changed from 10 kW to 50 kW

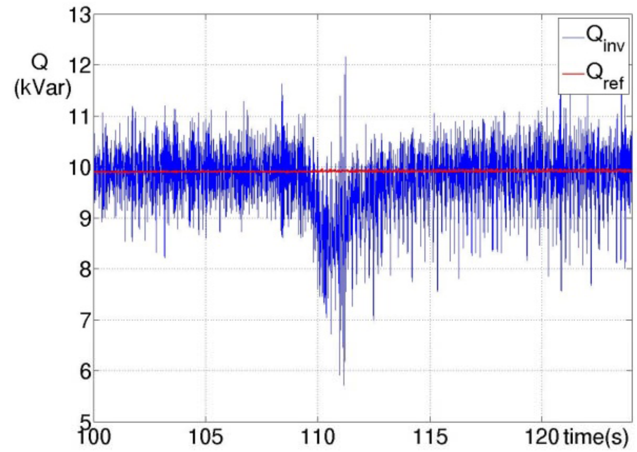


Q_{ref} set to10kVar

- Complete event on left.
- Zoomed in to 10 to 20 kW change on right.
- Active power reference (P_{ref}) from 10 to 50kW.
- Nonactive power reference (Q_{ref}) set to10 kVar.
- P does not reach 50 kW and Q drops because of the inverter current limit (60A).

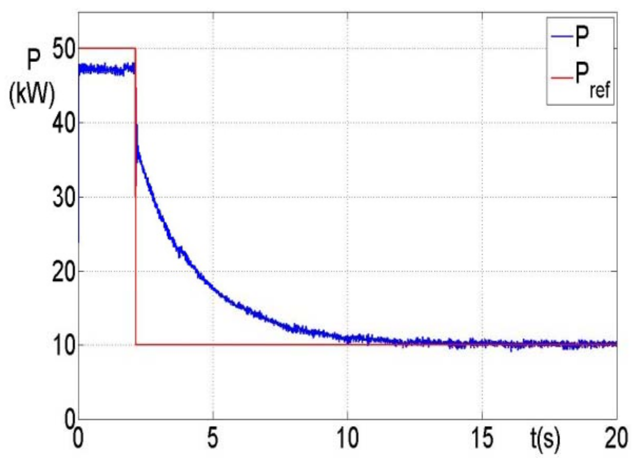


P_{ref} change from 10 to 20kW

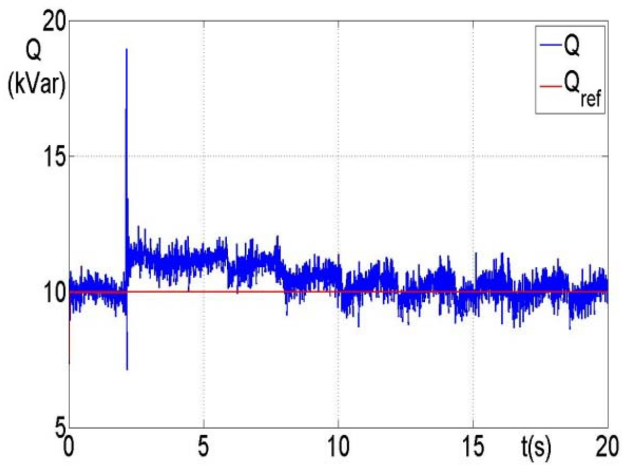


Q_{ref} set to10kVar.

SI Active (P) & Non-Active (Q) Control
Decrease P on Left, Decrease Q on Right

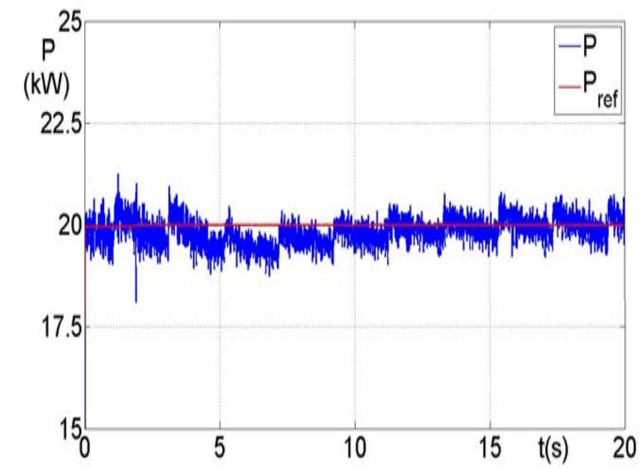


P_{ref} changed from 50 to 10kW

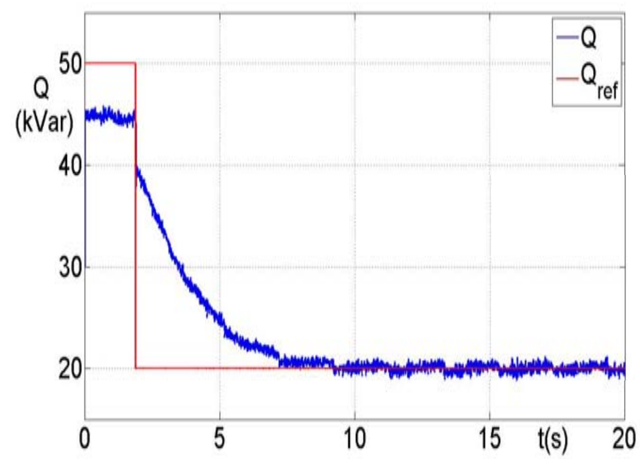


Q_{ref} set to 10kVar

- Active power (P_{ref}) change while keeping non-active power (Q_{ref}) constant on left.
- Nonactive power (Q_{ref}) change while keeping active power (P_{ref}) constant on right.
- Plots display the independent control of P & Q that has been achieved

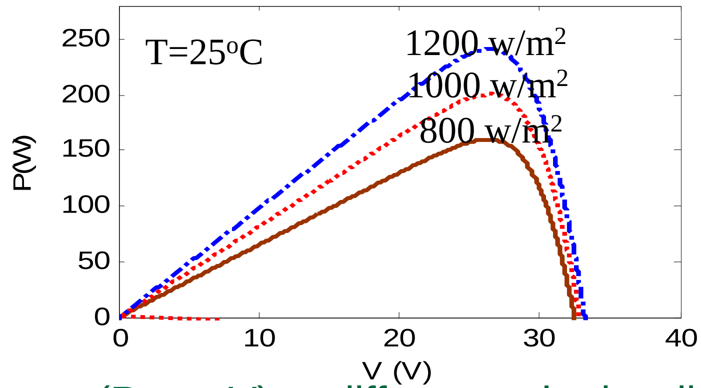


P_{ref} set to 20kW

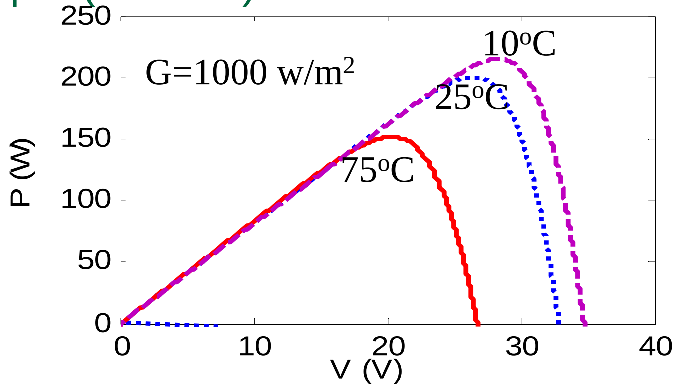


Q_{ref} changed from 50 to 20 kVar

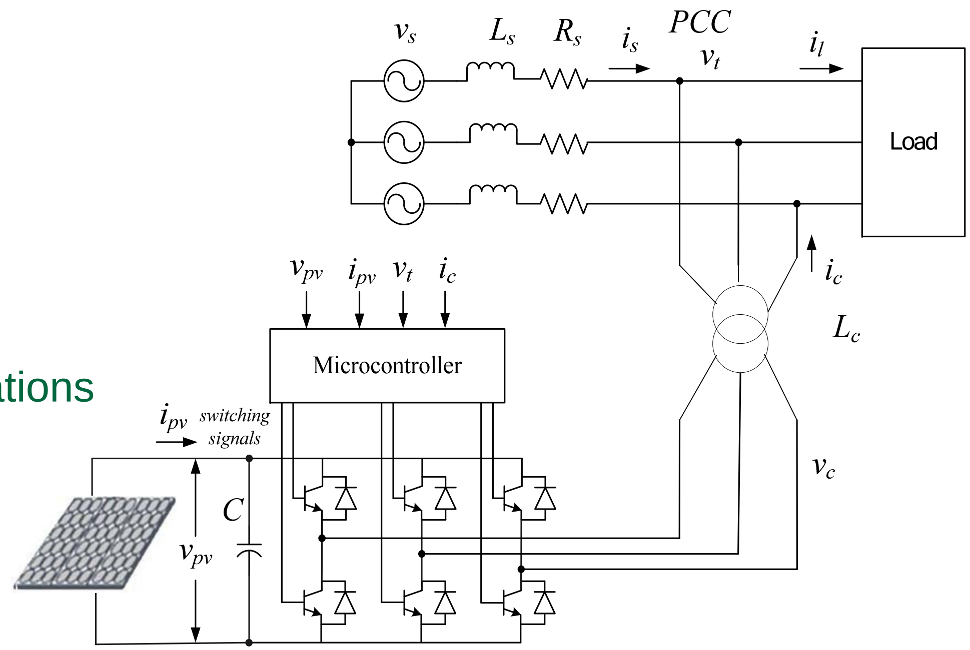
PV Inverter Active and Reactive Power Control



Output (P vs. V) at different solar irradiations



Output (P vs. V) at different temperatures

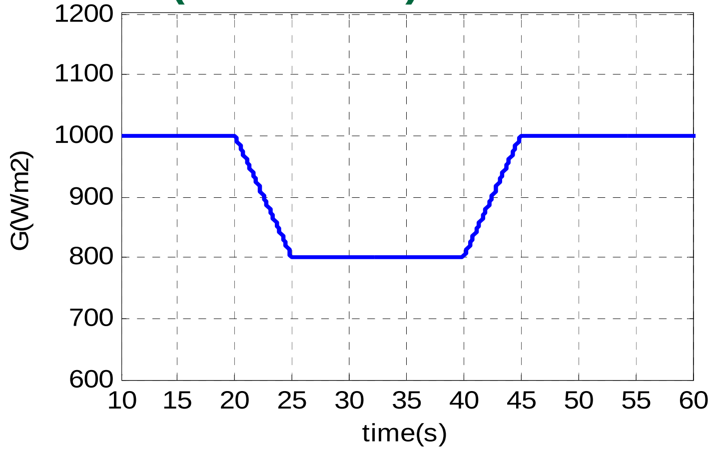


Grid-connected three-phase single-stage inverter PV system

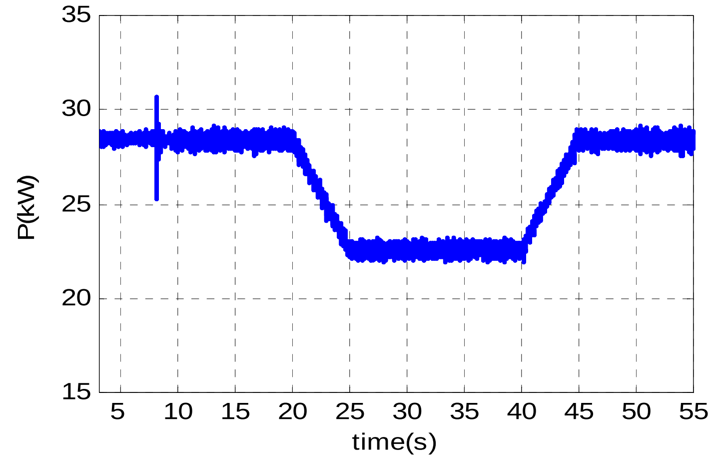
- **No DC-to-DC converter for lower cost and higher efficiency.**
- **P (MPPT or fixed P) and Q (PCC voltage or fixed Q) controlled by inverter.**
- **PV array DC voltage stability maintained by inverter control - resistant to disturbances caused by changing weather or system.**

PV Inverter Active and Reactive Power Control Simulation Results

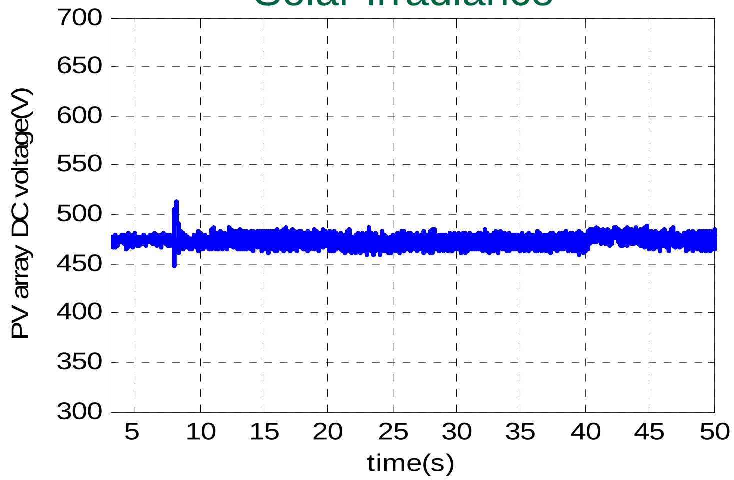
Case 1: Maximum power point tracking (MPPT) & PCC voltage control with varying solar irradiation (worst case)



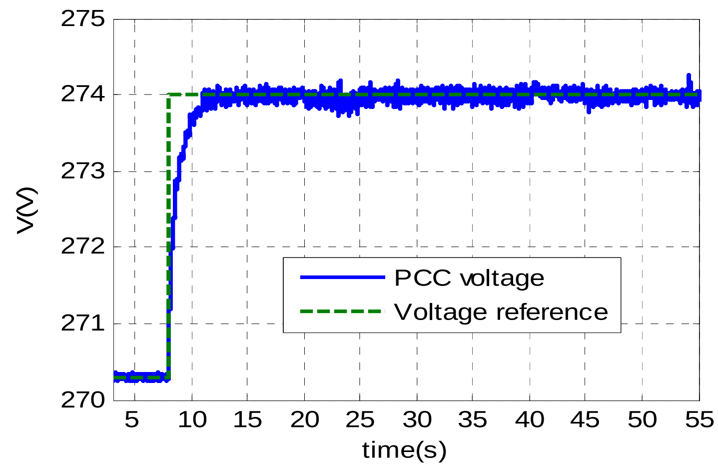
Solar Irradiance



PV array active power output



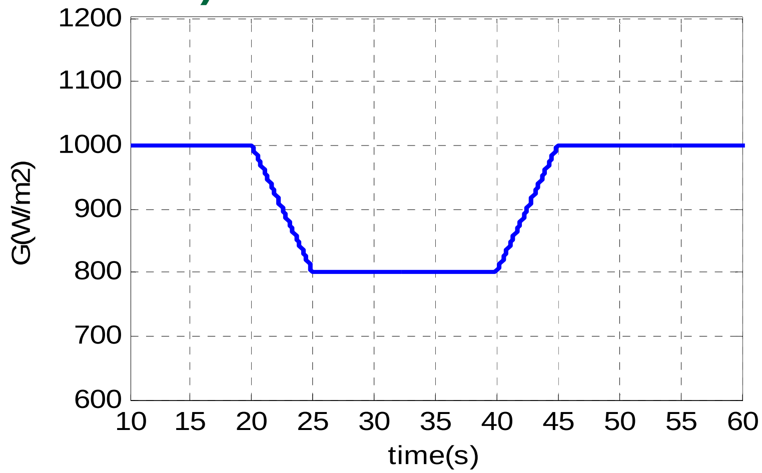
PV array output DC voltage



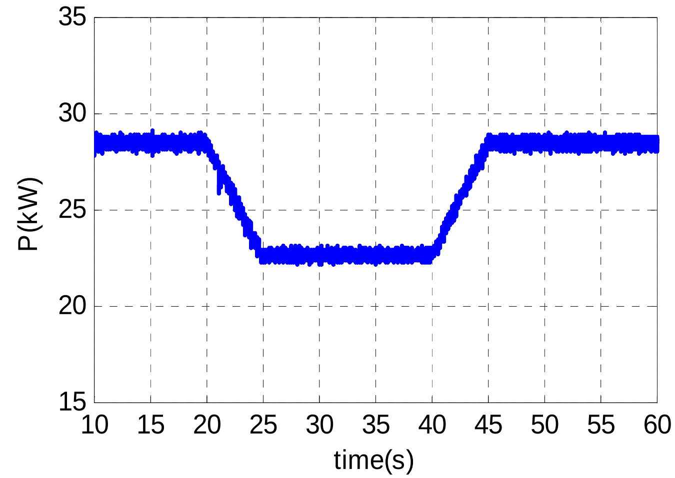
PCC voltage and reference (rms)

PV Inverter Active and Reactive Power Control Simulation Results

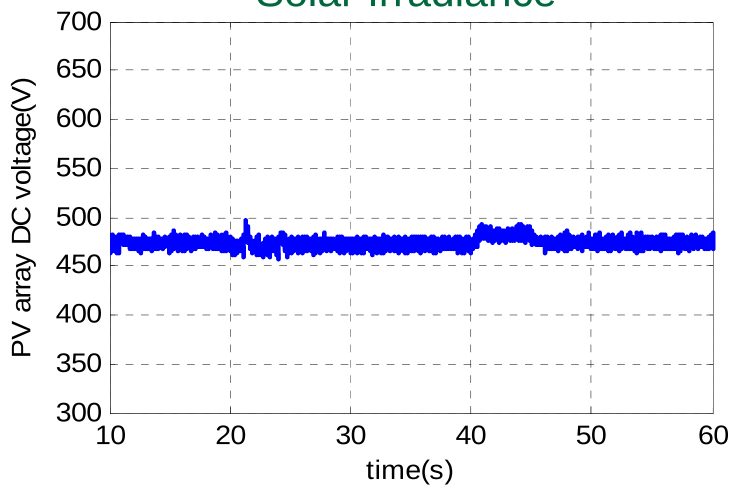
Case 2: MPPT & Fixed reactive power control with varying solar irradiation (worst case)



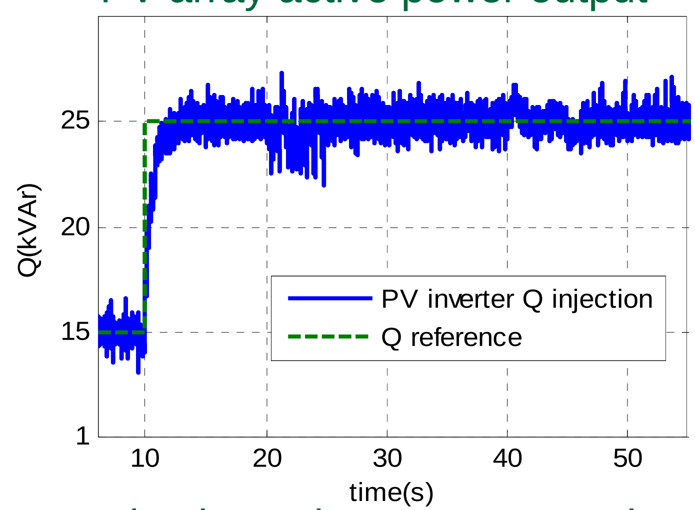
Solar Irradiance



PV array active power output



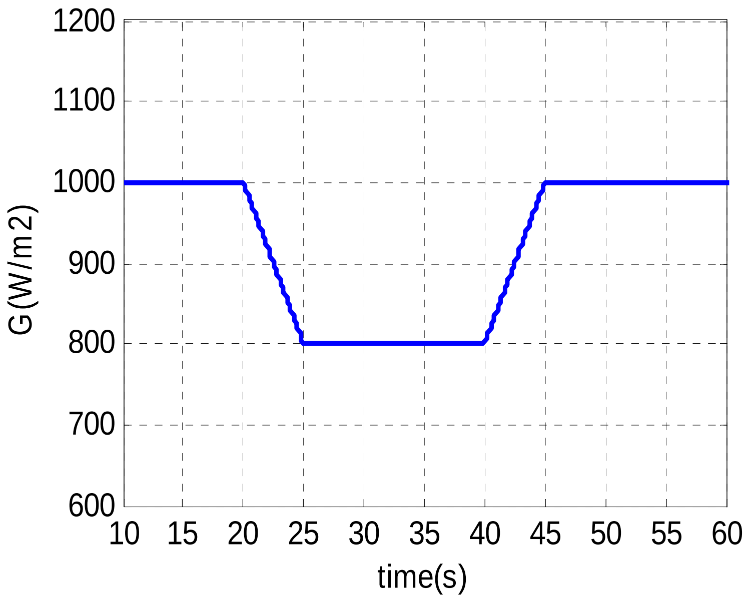
PV array output DC voltage



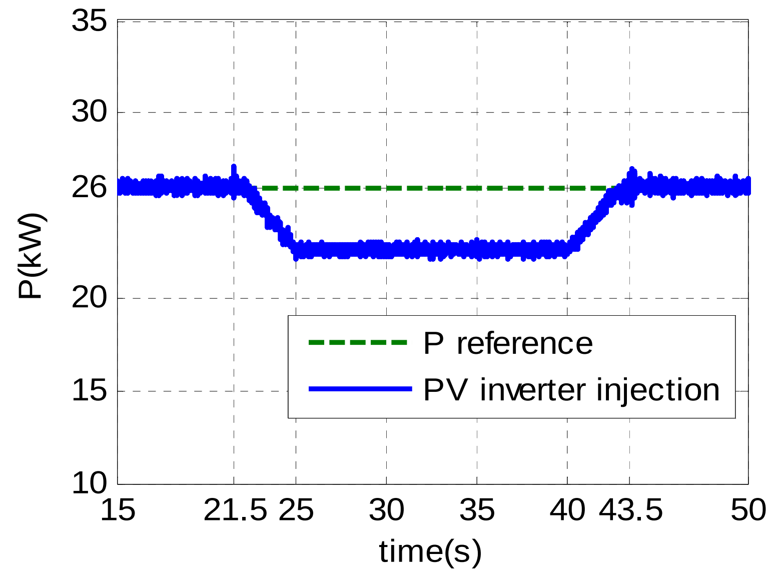
Fixed reactive power control

PV Inverter Active and Reactive Power Control Simulation Results

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

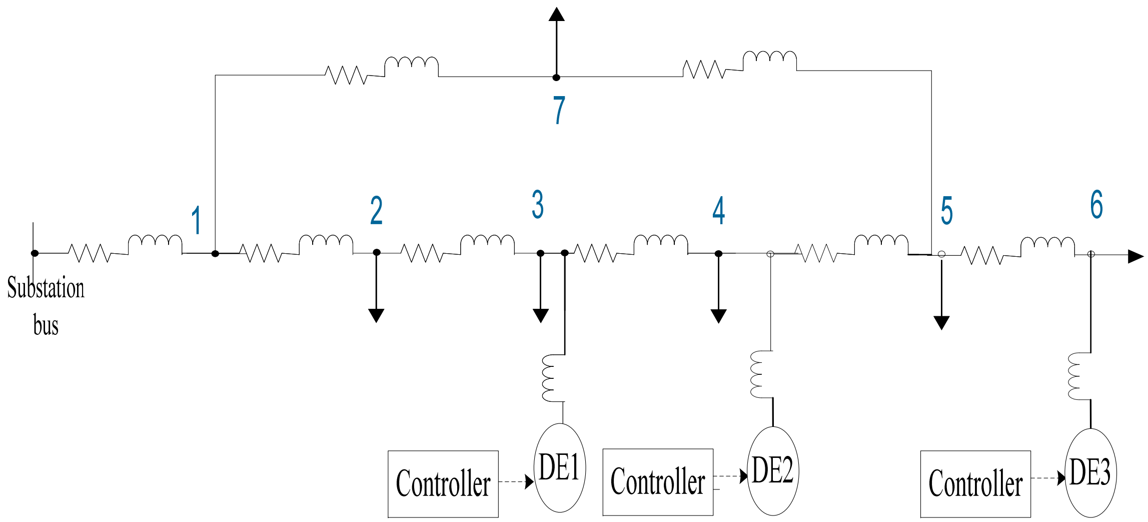


Solar Irradiance



Switching between fixed real power control and MPPT control

Adaptive Multiple Inverters Voltage Control

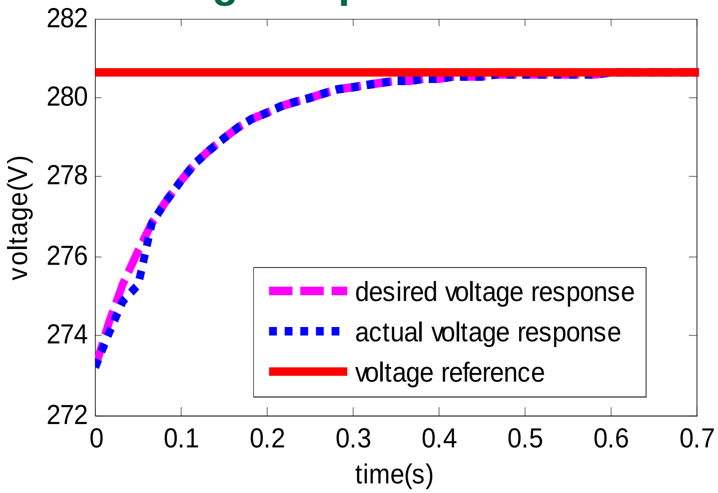


Applicable to radial with or without meshed distribution system with multiple DERs; simulated and proved with three in this case.

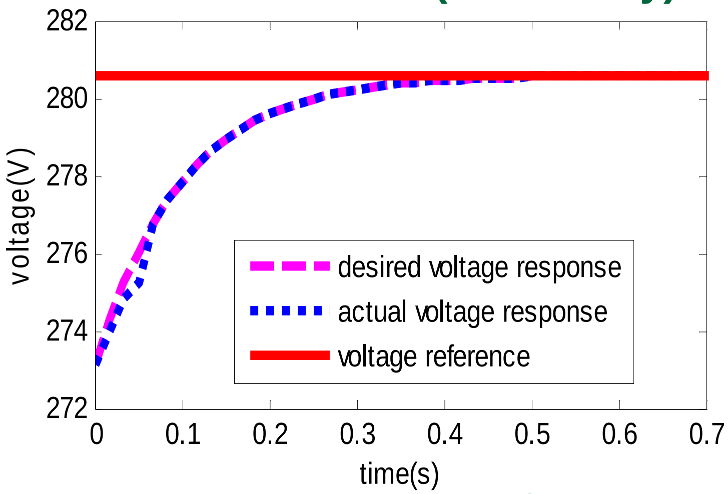
- **Multiple inverters for coordinated voltage control to prevent hunting.**
- **Self-adjusted control parameters to achieve fast response performance.**
- **Primarily local voltage control by inverters**
- **Only limited communication needed: initially, for large disturbance or for network change**
- **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

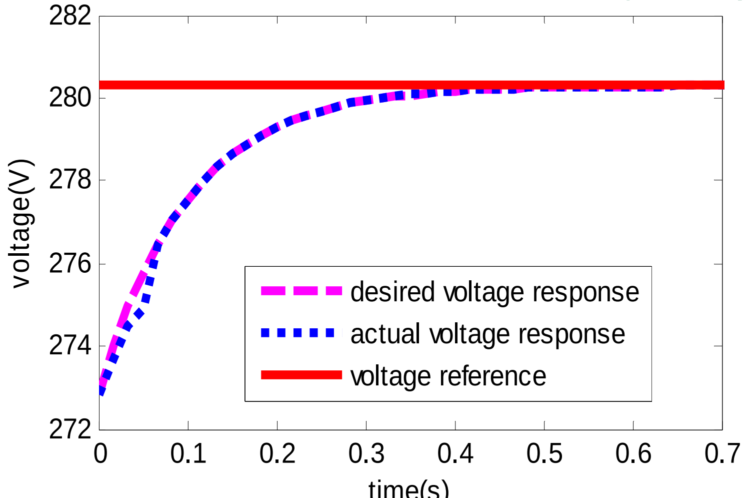
Case 1: Voltage responses of DER with ideal communication (No latency)



Voltage response of DER1



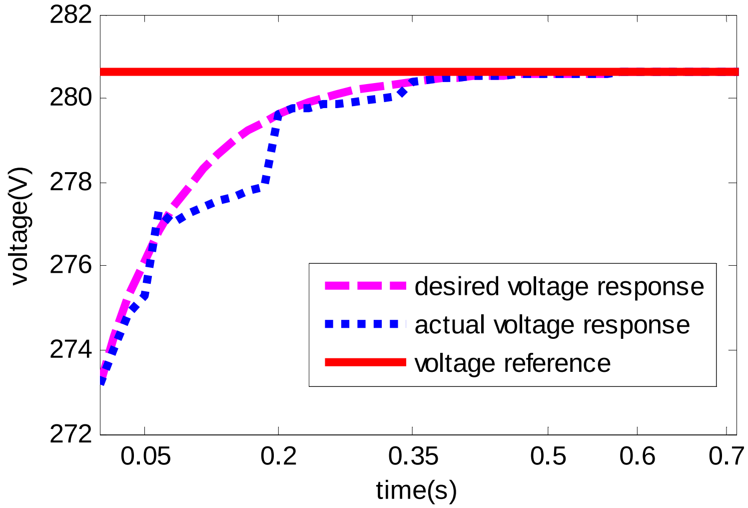
Voltage response of DER2



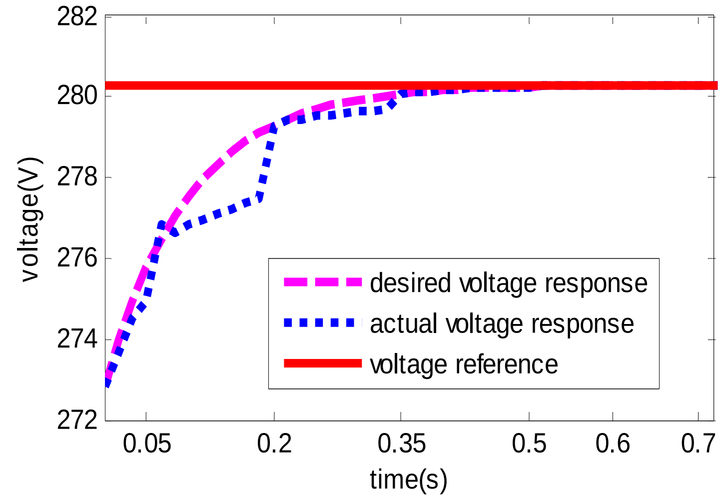
Voltage response of DER3

Adaptive Multiple Inverters Voltage Control Simulation Results

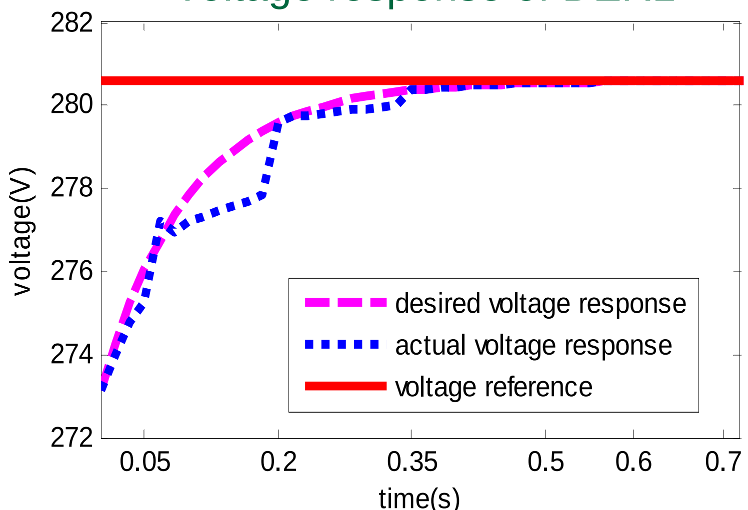
Case 2: Voltage responses of DER with communication latency (worst case)



Voltage response of DER1



Voltage response of DER3

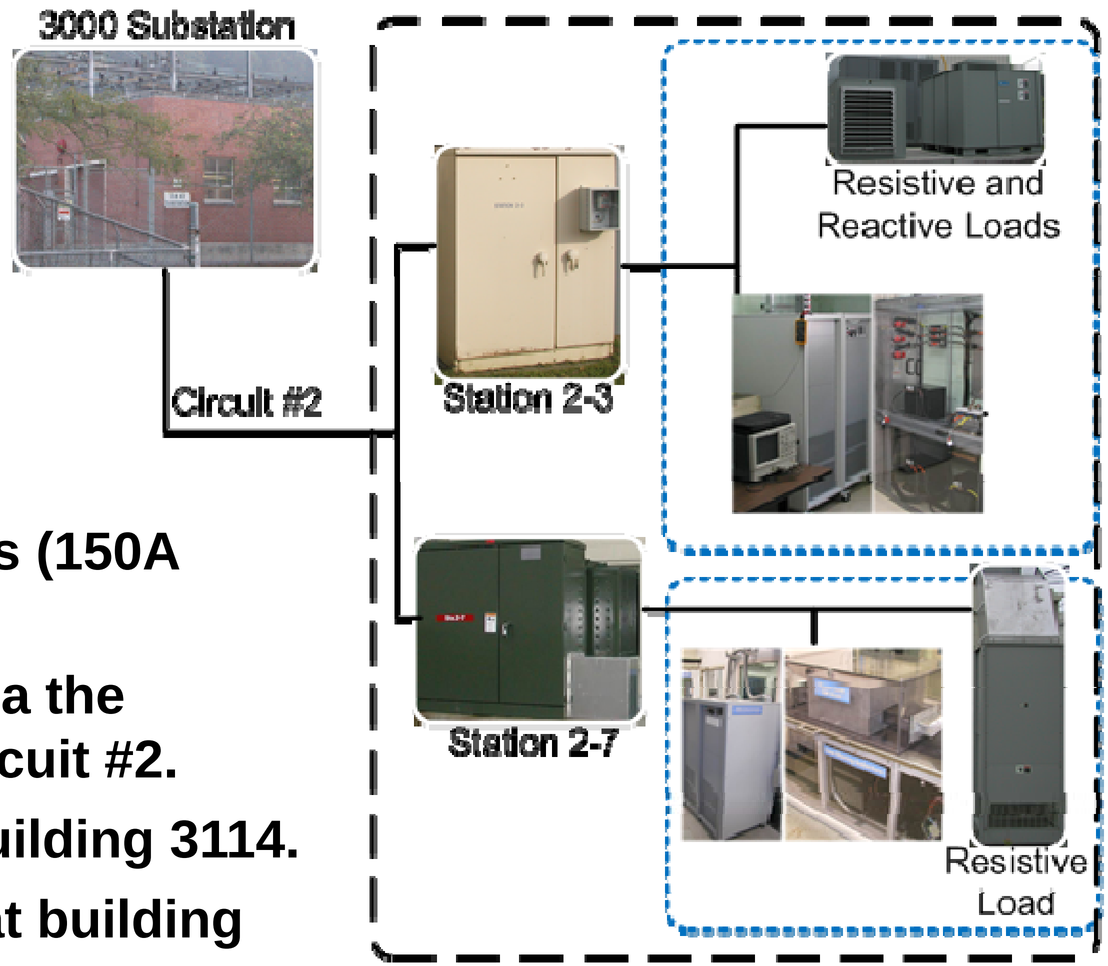


Voltage response of DER2

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

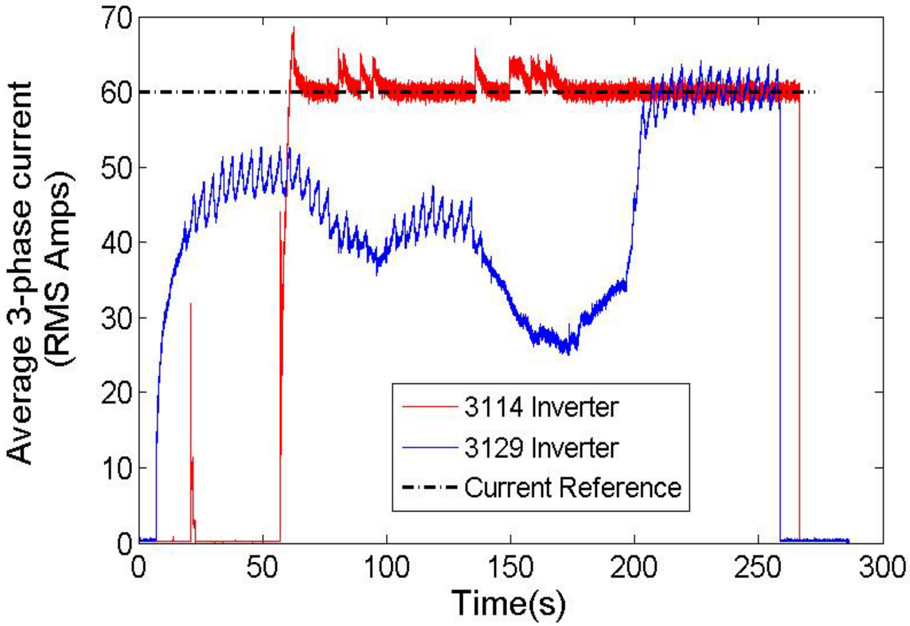
DECC Lab physical configuration for multiple DER testing.



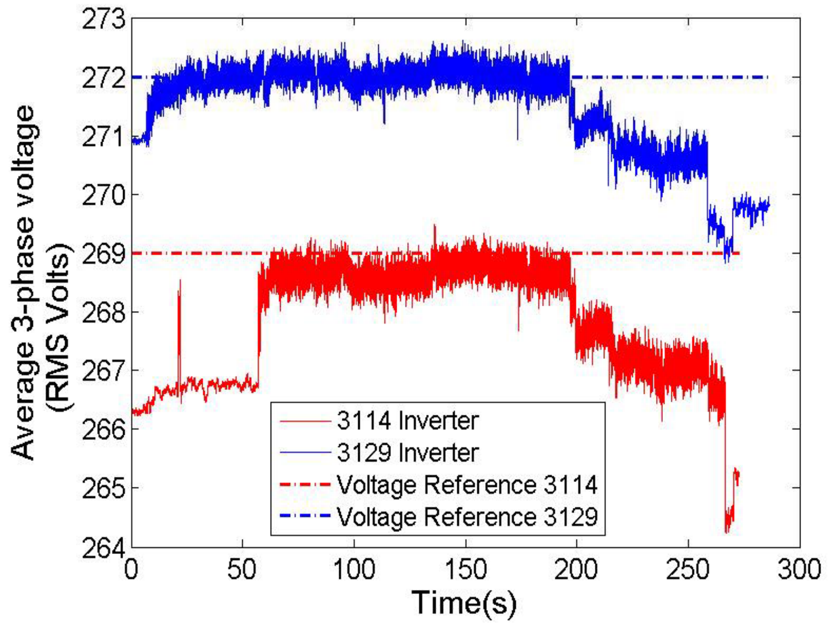
- **Two Inverter-based DERs (150A each) on same circuit.**
- **Electrically connected via the primary conductor of circuit #2.**
- **One DER is located at building 3114.**
- **Second DER is located at building 3129 which about 700ft away.**

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.**



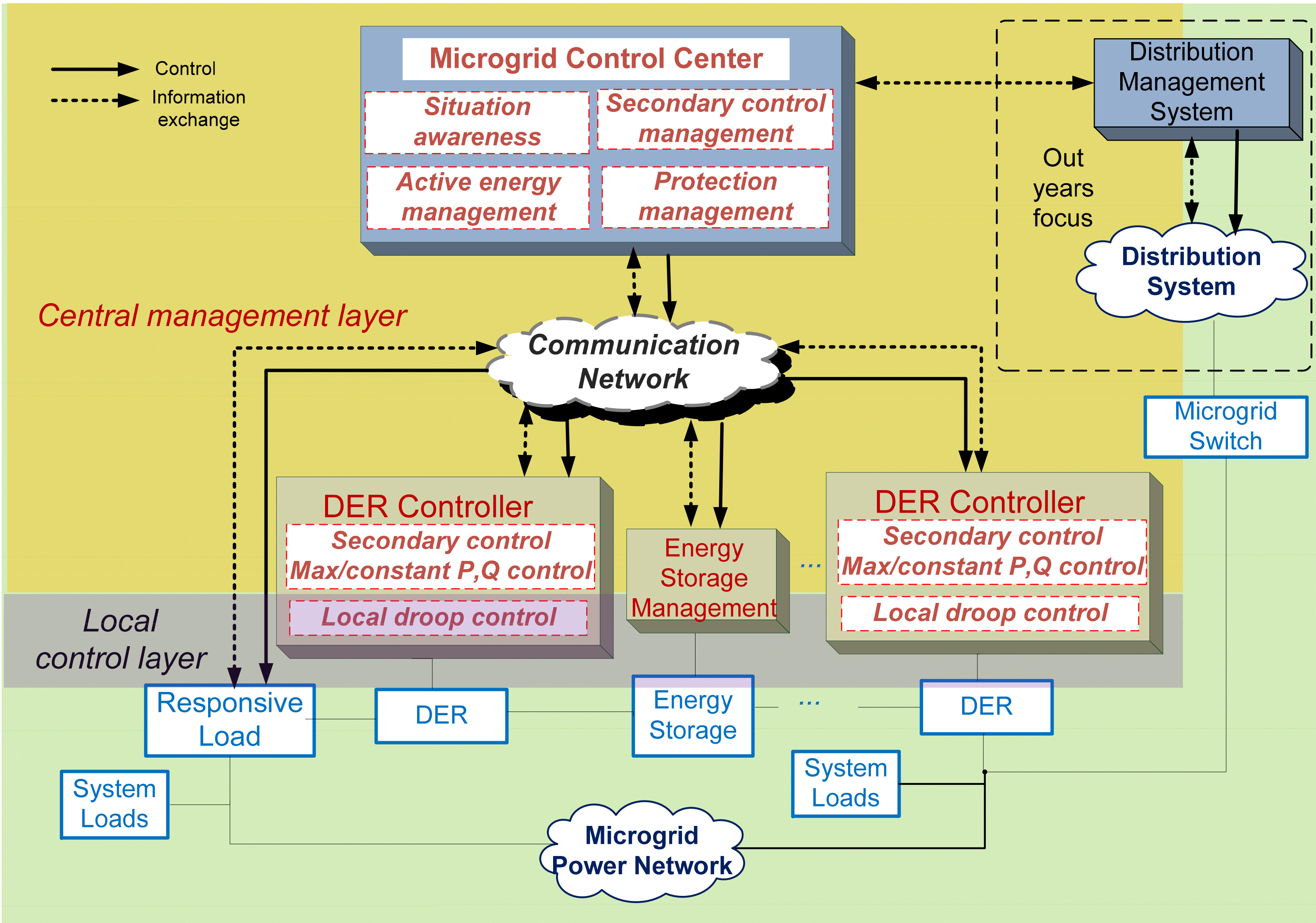
Current vs. Time



Voltage vs. Time

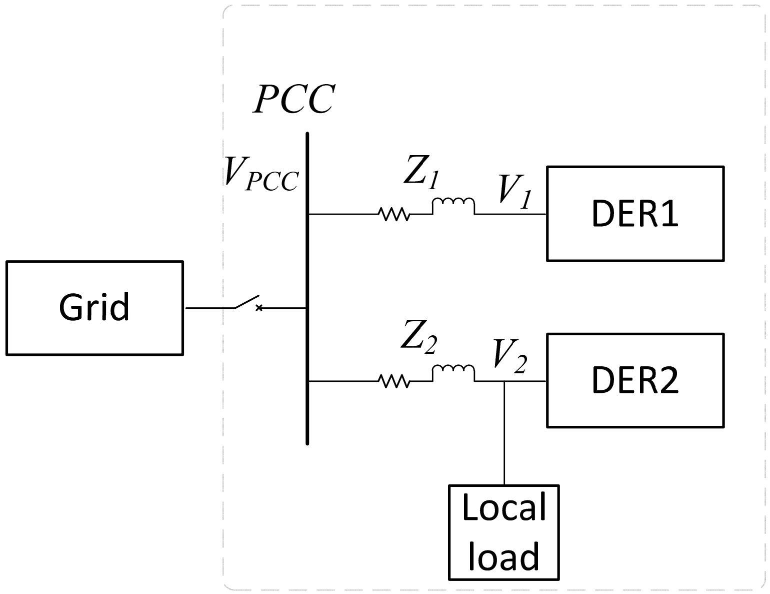
Microgrid (MG) Architecture & Interoperation

Multi-layer Microgrid Architechture



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



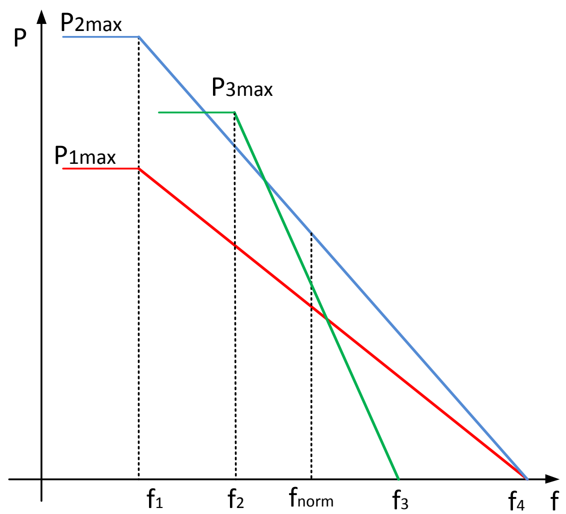
Effective Reactive Power at PCC

Total: $Q = Q_1 + Q_2$

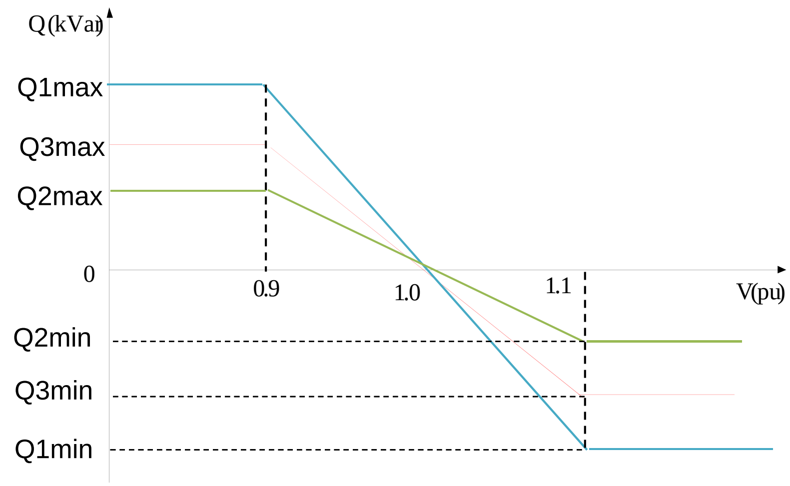
DER1: $Q_1 = Q_{DER1} - Q_{Z1}$

DER2: $Q_2 = Q_{DER2} - Q_{Z2} - Q_{Load}$

Microgrid Control Strategies Existing



DER P-f Droop factor

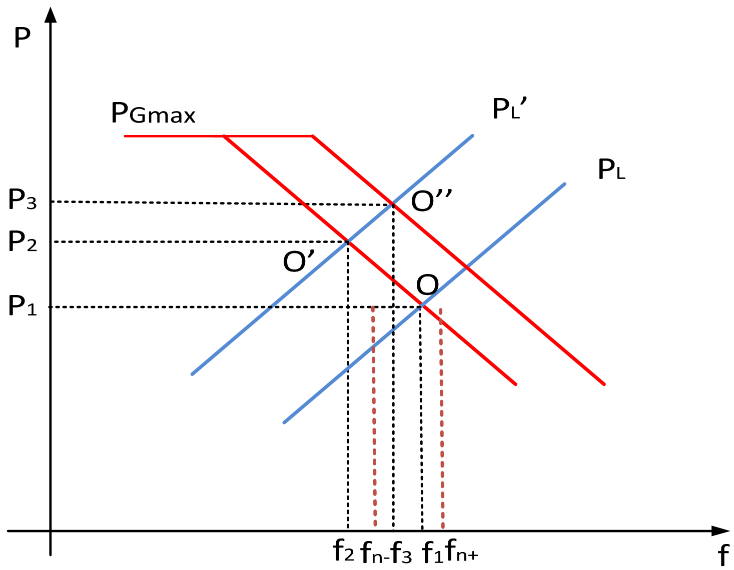


DER Q-V Droop factor

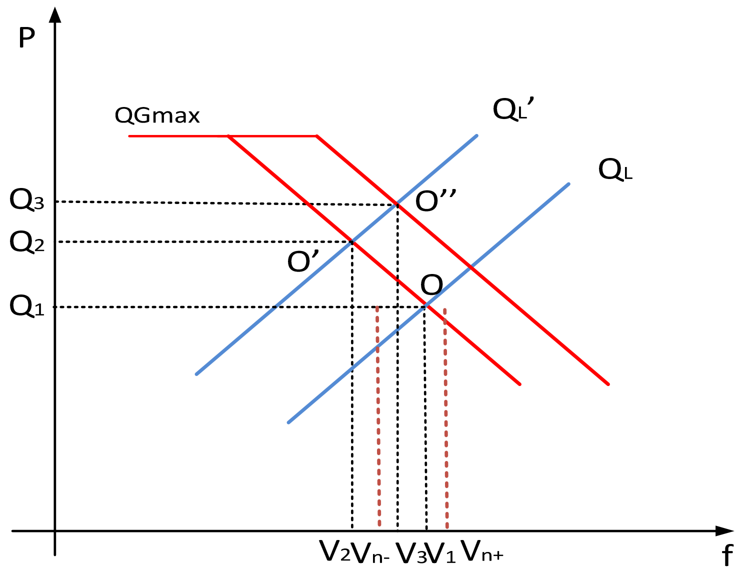
- Droop control with artificial droop curves
- Different slopes to have different responses
- Applicable to P-f and Q-V control
- Steady-state error
- No communication or central control required

42

Microgrid Control Strategies
ORNL Innovation



Frequency droop and secondary control



Voltage droop and secondary control

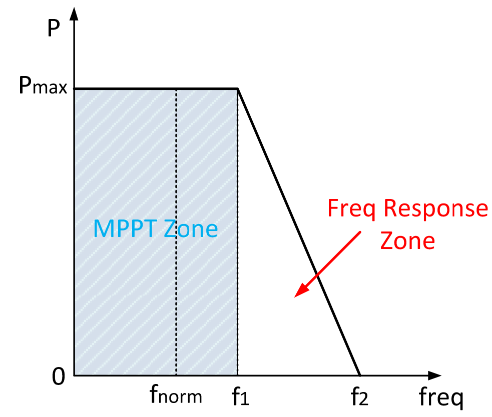
Enhanced Droop Control

- 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

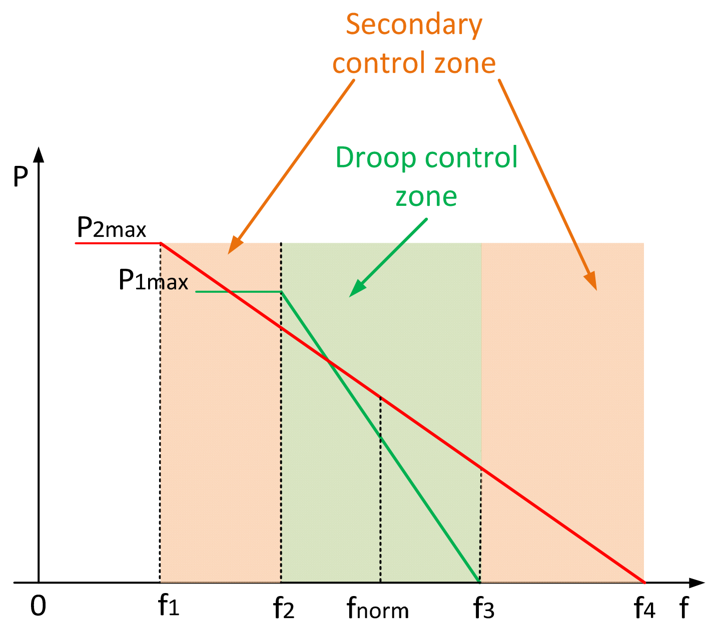
On-grid Mode

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

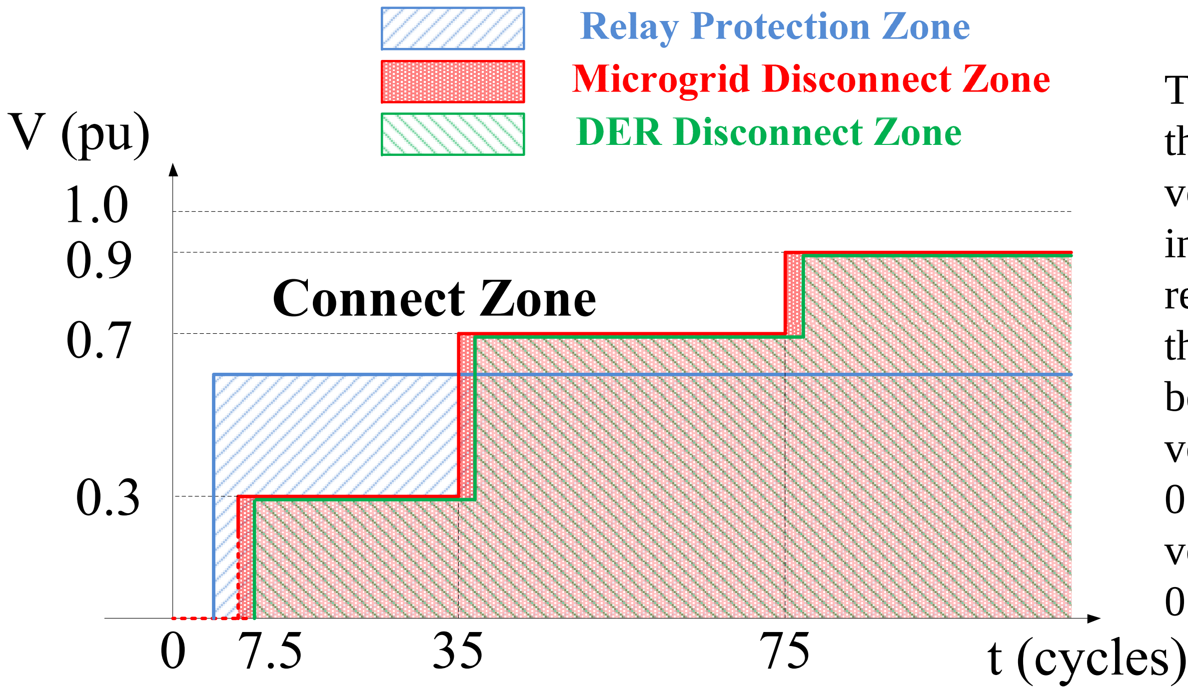


Islanding Mode

- Frequency control is top priority
- If multiple DE: one DE provides secondary while the others provide droop control
- Frequency within normal band (f_2 to f_3): DEs only use droop control
- Frequency outside of normal: secondary control is kicked



Microgrid Time Sequence and Low-Voltage Ride-Through



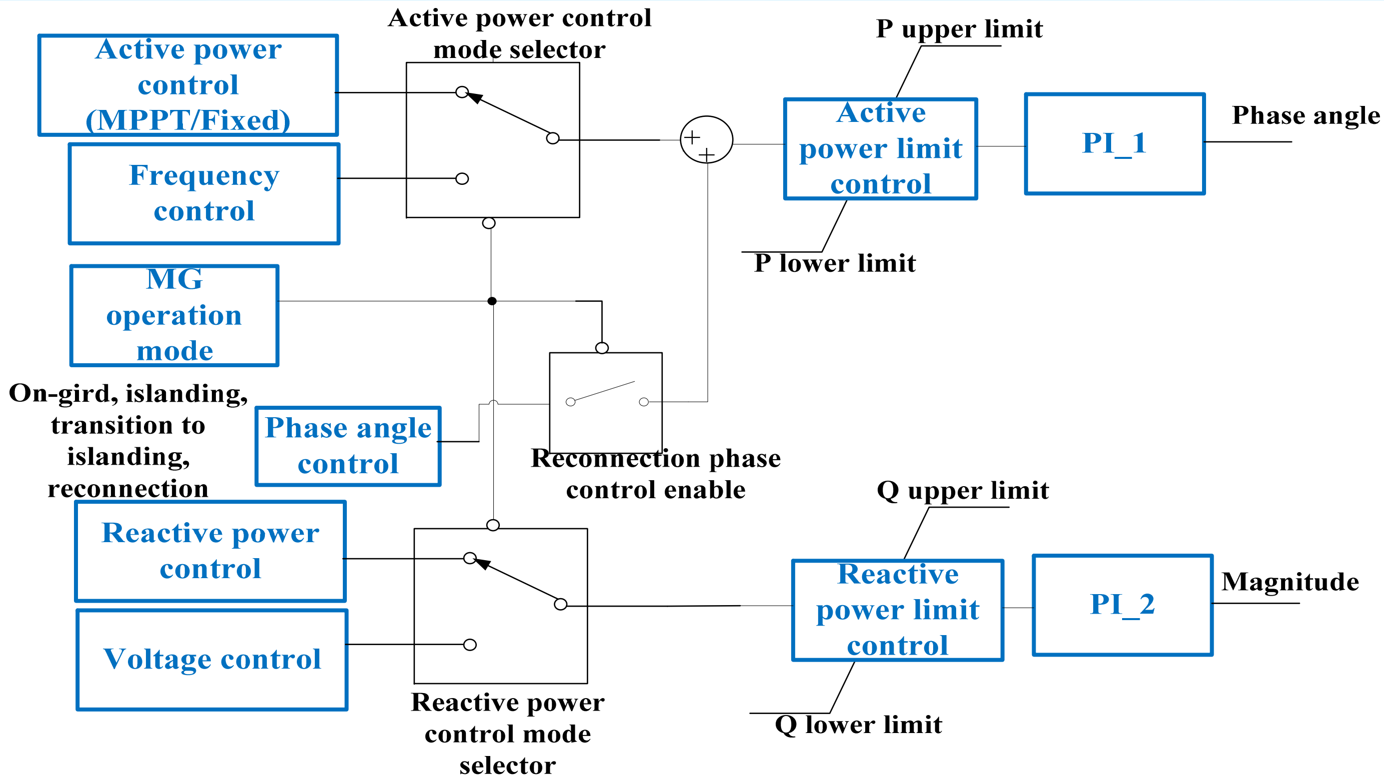
The German low-voltage ride-through standards for medium-voltage energy resources interconnection (BDEW) recommend 7.5 cycles ride through time if the voltage is below 0.3 pu, 35 cycles if the voltage is between 0.3 pu and 0.7 pu, and 75 cycles if the voltage is between 0.7 pu and 0.9 pu.

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

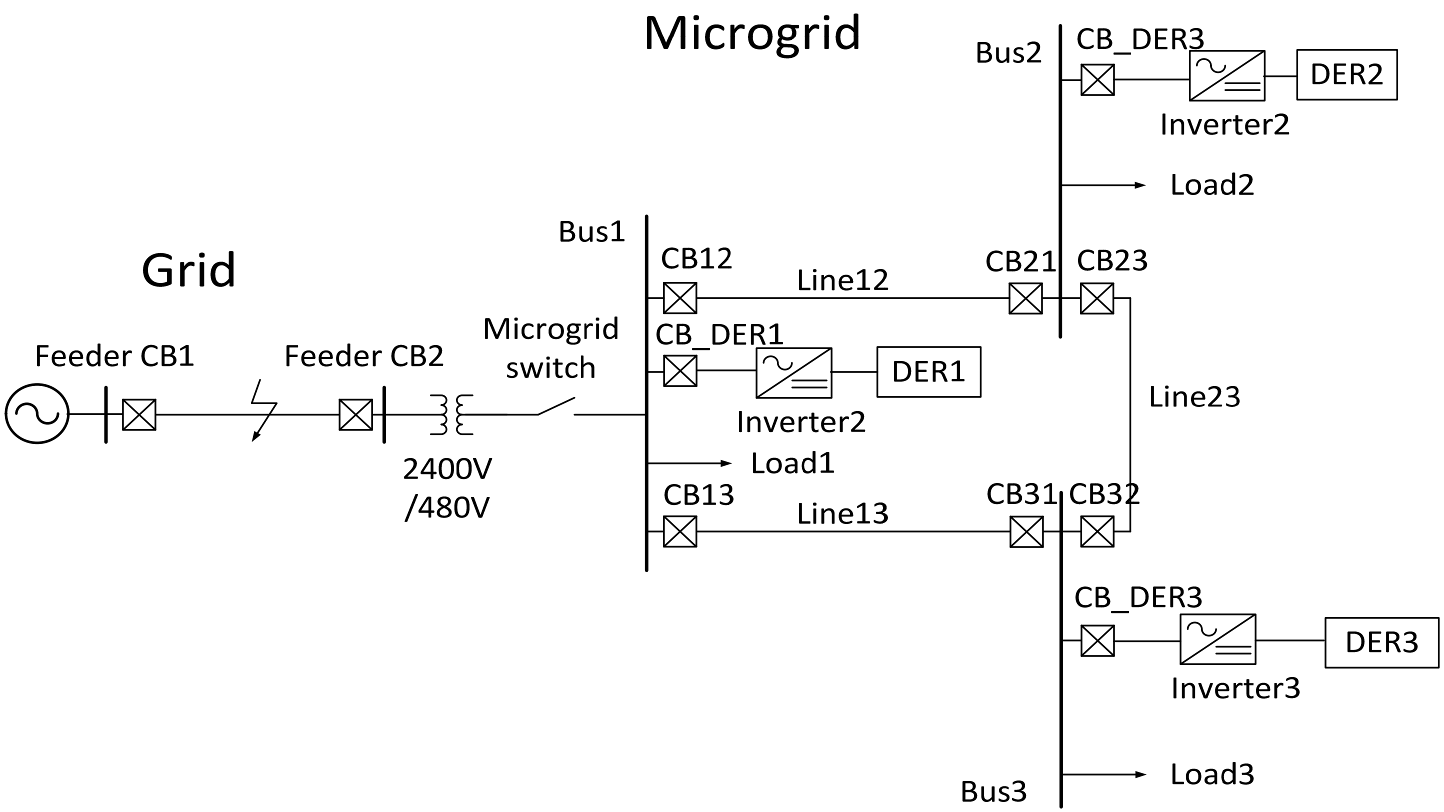
Low-Volt Ride-Through and Multi-Input PI Control



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



Publications

FY12 Publications

- Lakshmi Gopi Reddy, Leon M. Tolbert, Burak Ozpineci, Yan Xu, D. Tom Rizy, "Reliability of IGBT in a STATCOM for harmonic compensation and power factor correction", presented at *IEEE Applied Power Electronics Conference and Exposition*, Orlando FL, February 2012.
- Philip Irminger, D. Tom Rizy, Huijuan Li, Travis Smith, Keith Rice, Fangxing Li, Sarina Adhikari, "Air Conditioning Stall Phenomenon – Testing, Model Development, and Simulation", presented at the *IEEE PES T&D Meeting & Exposition*, Orlando FL, May 2012.
- Huijuan Li, Yan Xu, Sarina Adhikari, D. Tom Rizy, Fangxing Li, Philip Irminger, "Real and reactive power control of a three-phase single-stage PV system and PV voltage stability", to be presented at *IEEE Power Engineering Society (PES) Annual Meeting 2012*, San Diego CA, July 2012.
- Yan Xu, Huijuan Li, Leon M. Tolbert, "Inverter-based microgrid control and stable islanding transition", to be presented at *IEEE Energy Conversion Congress and Exposition*, Raleigh NC, September 2012.
- Rukun Mao, Huijuan Li, Husheng Li, Yan Xu, "Wireless communication for controlling microgrids: co-simulation and performance evaluation", submitted to 3rd IEEE International Conference on Smart Grid Communications, Tainan City, Taiwan, November 2012.
- Huijuan Li, Fangxing Li, Yan Xu and D. Tom Rizy, "Autonomous and Adaptive Voltage Control using Multiple Distributed Energy Resources". Under review, submitted to *IEEE Trans. Power Systems*

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.
- “Impacts of Varying Penetration of Distributed Resources with & without Volt/Var Control: Case Study of Varying Load Types”, 2011 IEEE PES General Meeting, Jul. 2011, pp.1-7, 24-29 July 2011.
- “Volt/Var Control Using Inverter-based Distributed Energy Resources”, 2011 IEEE PES General Meeting, Jul. 2011, pp.1-8, 24-29 July 2011.
- "Adaptive voltage control with distributed energy resources: Algorithm, theoretical analysis, simulation, and field test verification," 2011 IEEE PES General Meeting, pp.1, 24-29 July 2011.
- “Impact of Power Factor Correction and Harmonic Compensation by STATCOM on Converter Temperature and Reliability”, Paper No EC-0736, 2011 IEEE Energy Conversion Congress & Exposition, Phoenix, AZ, Sept. 2011.

FY10 Publications

- "An adaptive voltage control algorithm with multiple distributed energy resources," North American Power Symposium (NAPS), 2009 , pp.1-6, Oct. 2009.
- "Local Voltage Support From Distributed Energy Resources To Prevent Air Conditioner Motor Stalling," Innovative Smart Grid Technologies (ISGT), 2010 , pp.1-6, Jan. 2010.
- "Properly understanding the impacts of distributed resources on distribution systems," *2010 IEEE Power and Energy Society General Meeting*, pp.1-5, Jul. 2010.
- "Adaptive Voltage Control With Distributed Energy Resources: Algorithm, Theoretical Analysis, Simulation, and Field Test Verification," *IEEE Trans. Power Systems*, vol.25, no.3, pp.1638-1647, Aug. 2010.
- "Instantaneous active and nonactive power control of distributed energy resources with a current limiter," *2010 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 3855-3861, Sept. 2010.
- "Voltage and current unbalance compensation using a static var compensator," *IET Power Electronics*, vol.3, no.6, pp.977-988, Nov. 2010.

FY09 Publications

- "Using Distributed Energy Resources to Supply Reactive Power for Dynamic Voltage Regulation," *International Review of Electrical Engineering,* vol. 3, no. 5, pp. 795-802, October 2008.
- "Local Dynamic Reactive Power for Correction of System Voltage Problems, "ORNL/TM-2008/174*,* Oak Ridge National Laboratory, TN, November 2008.
- "A Framework to Quantitatively Evaluate the Economic Benefits from Reactive Power Compensation," *International Review of Electrical Engineering,* vol. 3, no. 6, pp. 989-998, December 2008.
- "Preventing delayed voltage recovery with voltage-regulating distributed energy resources," *IEEE PowerTech2009, Bucharest*, pp.1-6, June-July 2009.

FY08 Publications

- "The application of droop-control in distributed energy resources to extend the voltage collapse margin," *IEEE IAS Industrial and Commercial Power Systems Technical Conference 2008 (ICPS 2008),* May 4-8, 2008.
- "Voltage regulation with multiple distributed energy resources," *(invited) IEEE PES General Meeting 2008,* Pittsburgh, PA, July 20-24, 2008.
- "Interaction of multiple distributed energy resources in voltage regulation", *IEEE PES General Meeting 2008,* Pittsburgh, PA, July 20-24, 2008.
- "Active power and nonactive power control of distributed energy resources", *The 40th North American Power Symposium*, , Calgary Canada, September 28 – 30, 2008

FY07 Publications

- "Assessment of the Economic Benefits from Reactive Power Compensation," *Proceeding of the IEEE Power Systems Conference and Exposition 2006,* pp. 1767-1773, Atlanta, GA, October 2006.
- "Reactive Power from Distributed Energy," *The Electricity Journal,* vol. 19, no. 10, pp. 27-38, December 2006.
- "Dynamic Voltage Regulation Using Distributed Energy Resources," *Proceedings of CIRED 2007*, Vienna, Austria, May 20-24, 2007.
- "Nonactive-power-related ancillary services provided by distributed energy resources," *IEEE Power Engineering Society General Meeting*, June 24-28, 2007, Tampa, Florida.
- "Experiment and Simulation of Dynamic Voltage Regulation with Multiple Distributed Energy Resources," *IREP Symposium 2007 - Bulk Power System Dynamics and Control*, Charleston, SC, August 2007.