Office of Electric Transmission & Distribution
U.S. Department of Energy

NREL

Operation and Control of a Microgrid for feeding sensitive loads

Subcontract Number: AAD-0-30605-14

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Electric Distribution Transformation Program

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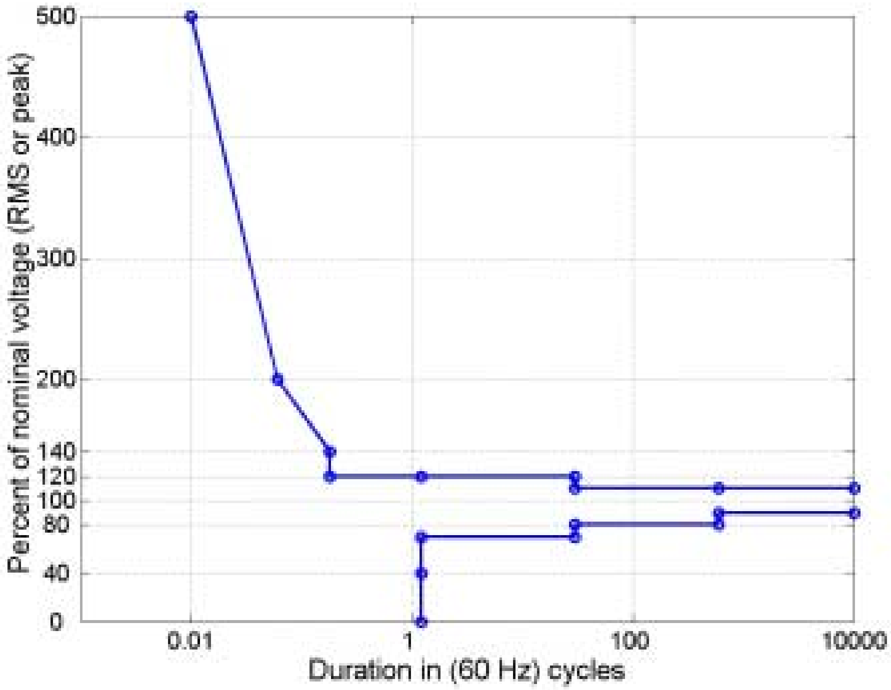
October 28-30, 2003, Coronado (San Diego), California

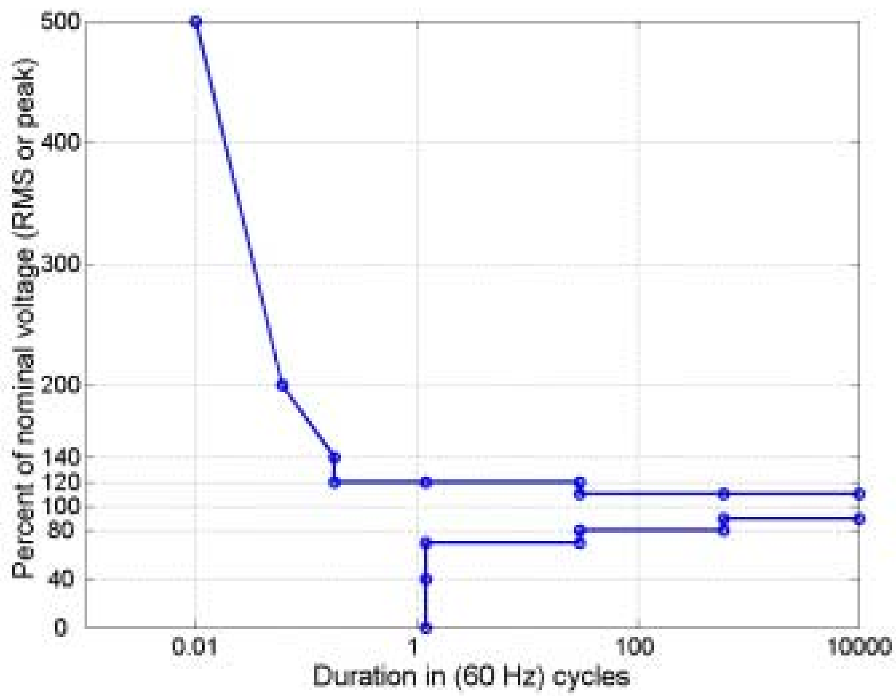
Problems and Needs of Sensitive Loads

- Loads sensitive to power quality disturbances
- Expensive process disruption
- Stringent demands on voltage deviations
- Custom Power devices – DVR, UPS, etc. are expensive
- An integrated energy solution that works in conjunction with the electric grid is needed



Relevance of DR for Sensitive Loads

- Provide pull for technology development
- Applications are more sensitive to power quality than capital cost
- Inverter embedded DR can ensure high power quality
- Inverter and generation control need advances



State of art control & operational strategy

- Operate as a balanced three phase current source in grid connected mode
- Operate as a balanced voltage source in off-grid mode
- Discontinuity between two operating modes
- Parallel connected units operated in a master-slave fashion with critical communication link
- Limited capability for premium power needs

Microgrids for Sensitive Loads

- Cluster of distributed resources
- Placed close to load locations
- Support grid to the extent capable
- Separate from grid upon deep disturbances
- Integrated heat harvest
- Minimize losses

Project Objectives

- Enable inverter embedded DR sources to meet demands of sensitive loads
- Enable parallel clusters of DR sources to operate in a stable manner without critical communication

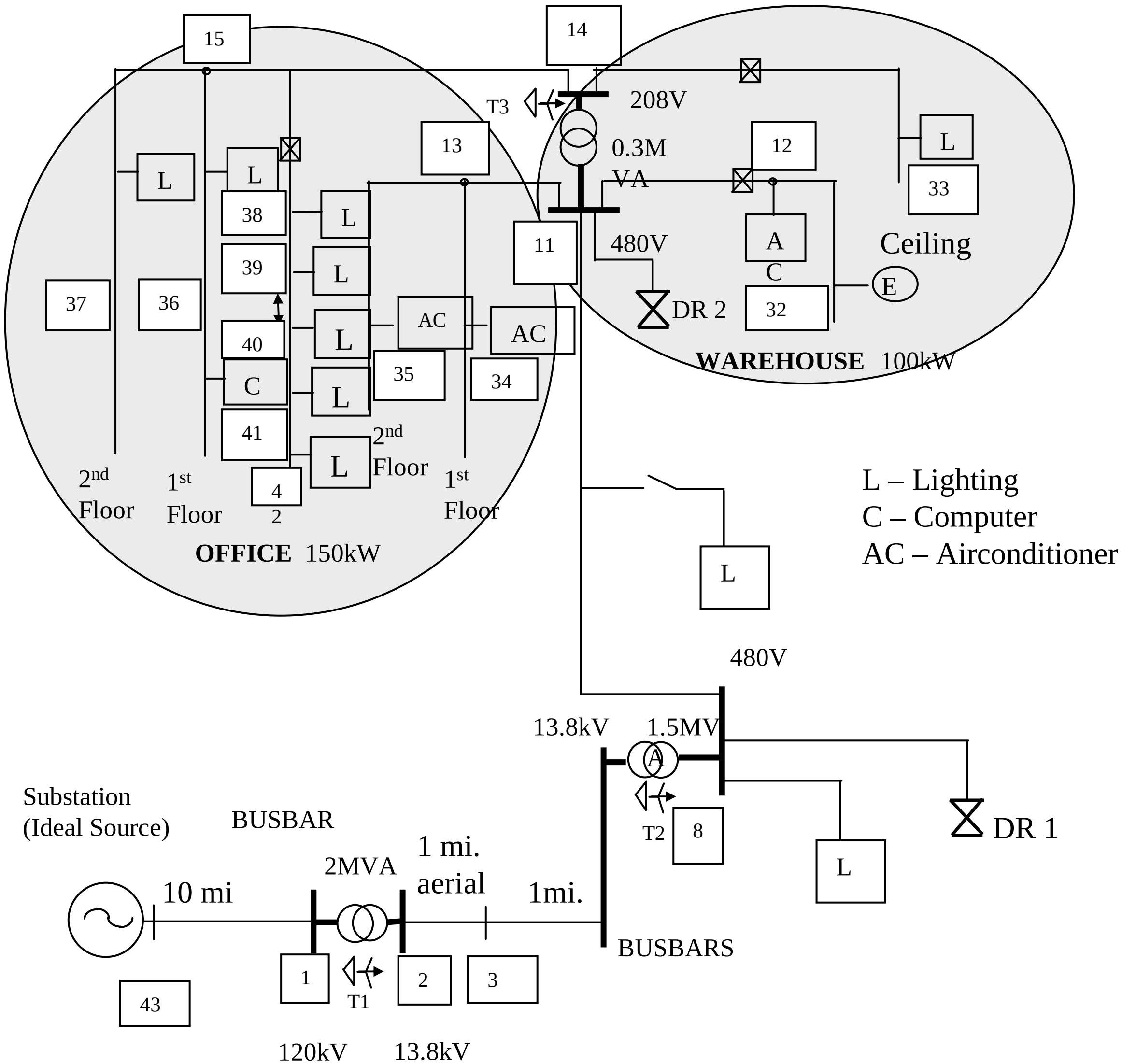
Technical objectives

- Control strategy
  1. Real Power-Frequency Droop Characteristics
  2. Reactive Power-Voltage Droop Characteristics
  3. Address short term power quality issues in control
- Operational strategy
  1. Ride through nominal amount of voltage sags and frequency deviations in a benign manner
  2. Intentionally island and feed local critical loads upon large deviation
  3. Reconnect upon system recovery seamlessly

Technical approach

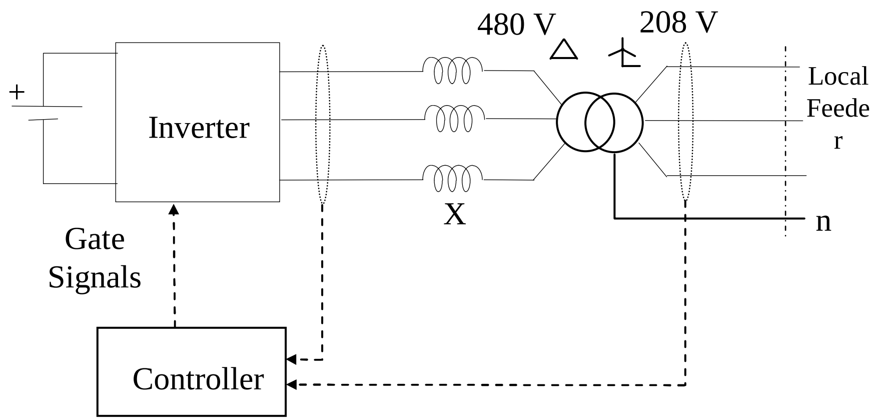
- Detailed analytical Modeling
  - Matlab, Mathcad, Mathematica
- Detailed computer simulation
  - EMTP, Matlab-Simulink
- Hardware verification
  - Laboratory scale microgrid
  - Multiple inverter platform

Analytical Modeling - microgrid

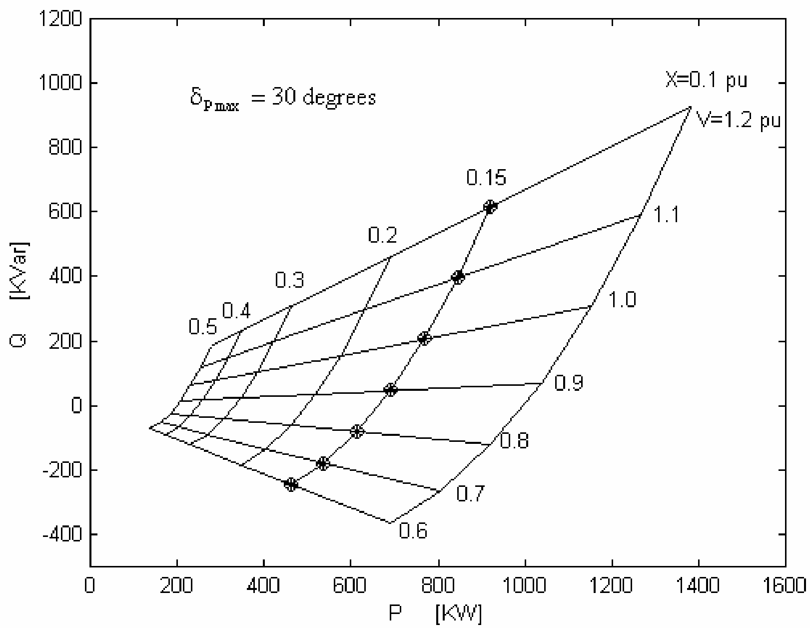


Modeling of facility

Analytical Modeling - microgrid

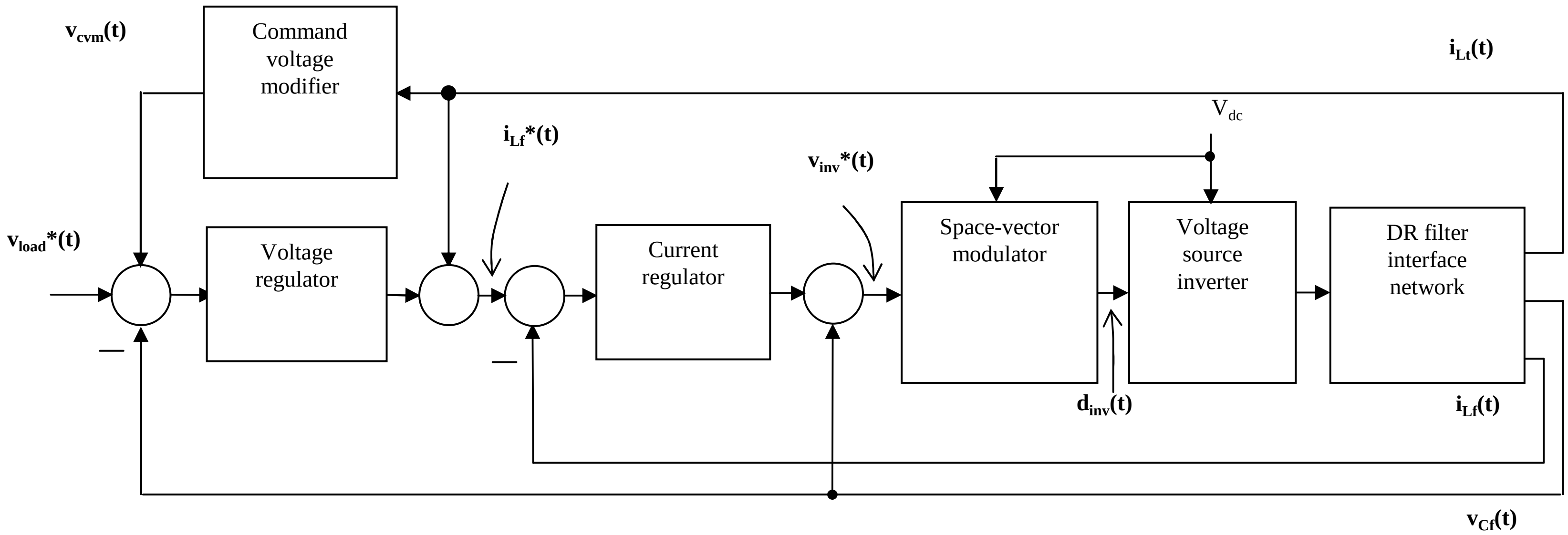


Inverter model



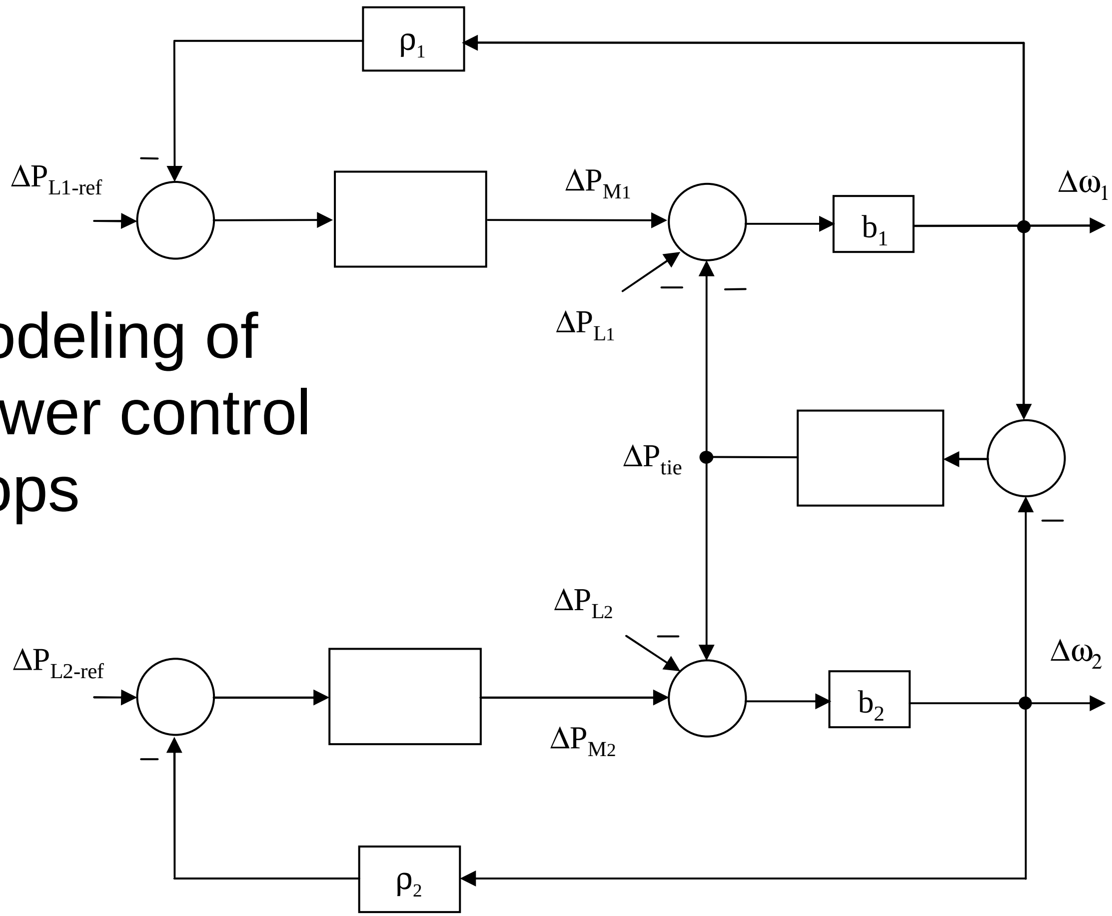
PQ spread for various coupling parameters

Analytical Modeling - inverter

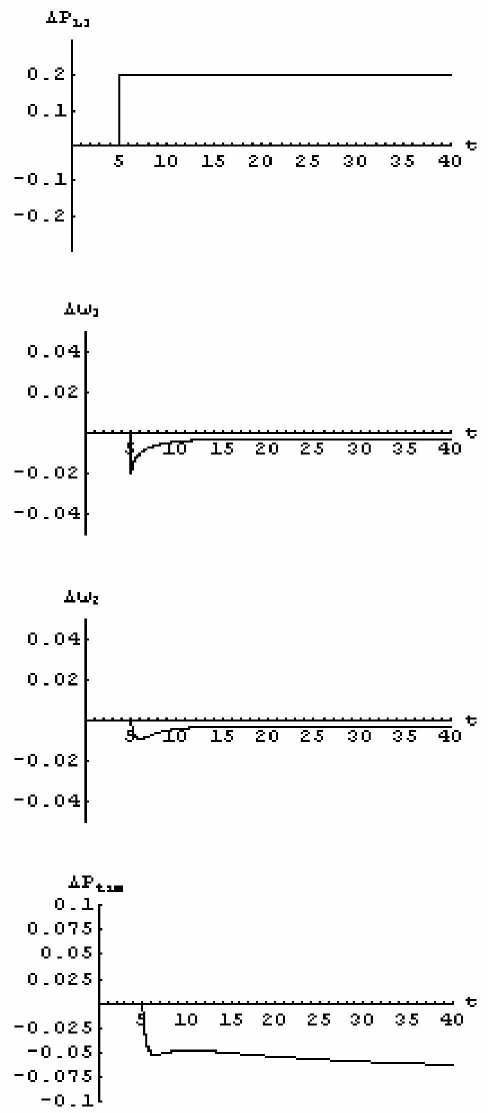


Modeling of internal control loops

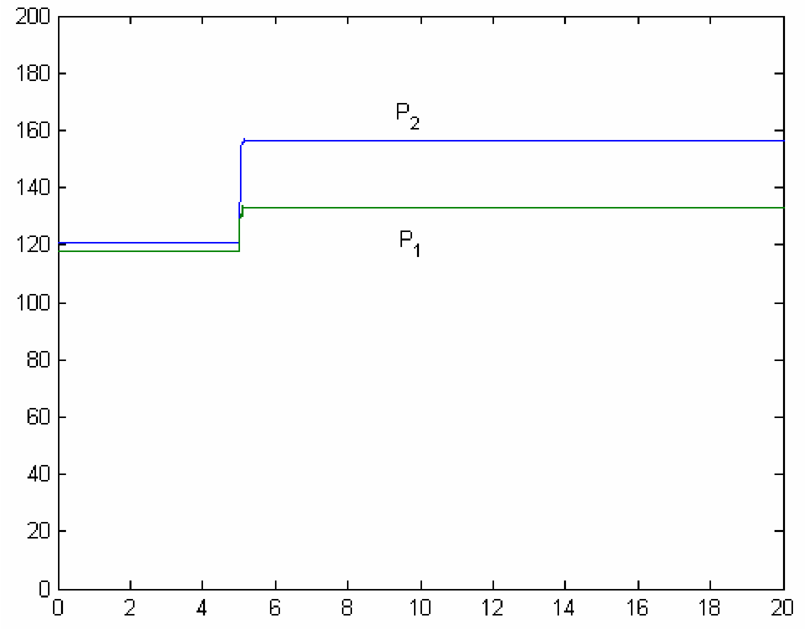
Analytical Modeling - interconnection



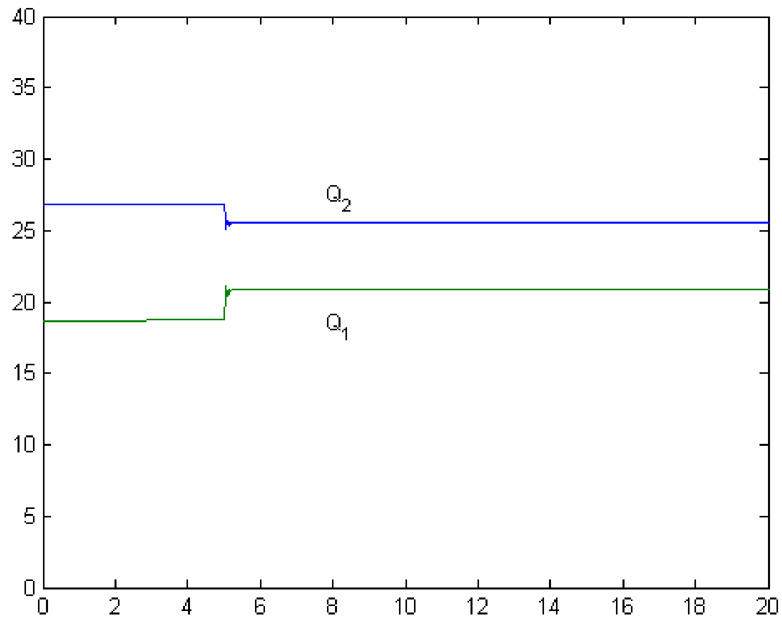
Modeling of power control loops



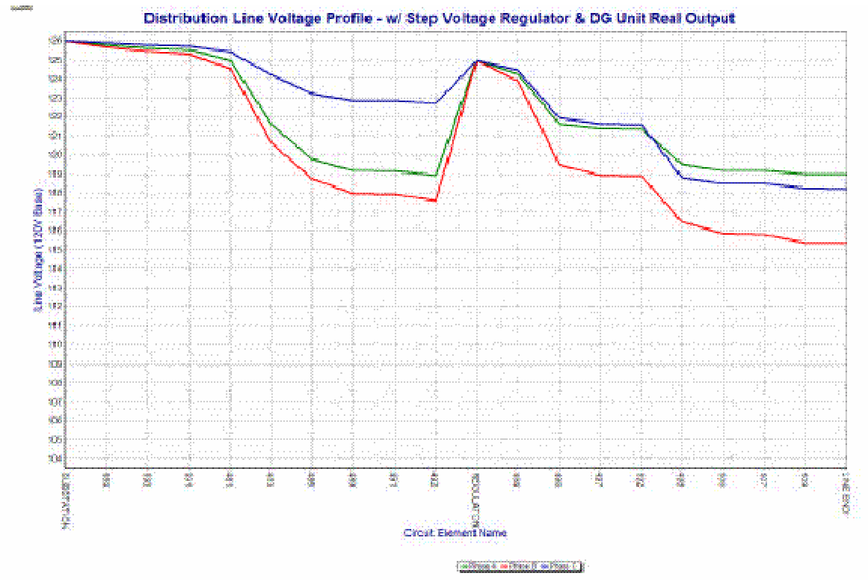
Computer simulations



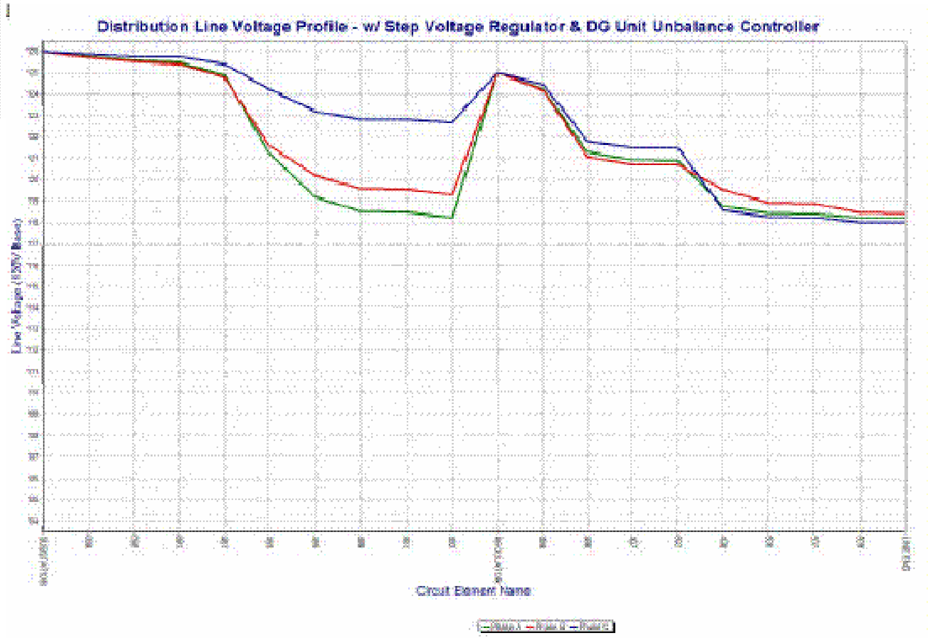
Step response during grid disconnection transient



Computer simulations

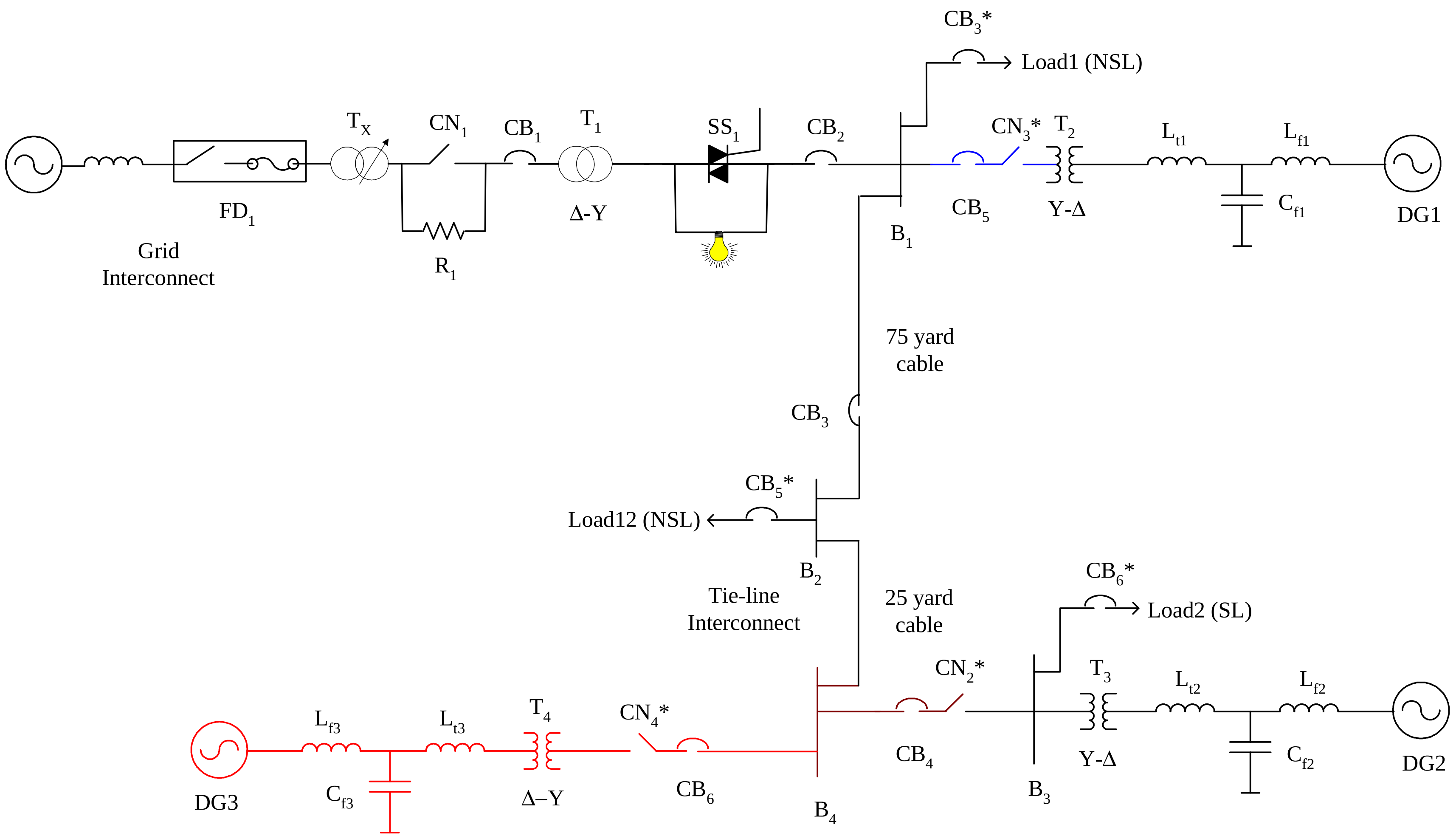


Voltage profile along an unbalanced distribution feeder
with conventional dg control



Voltage profile along an unbalanced distribution feeder
with unbalanced dg control

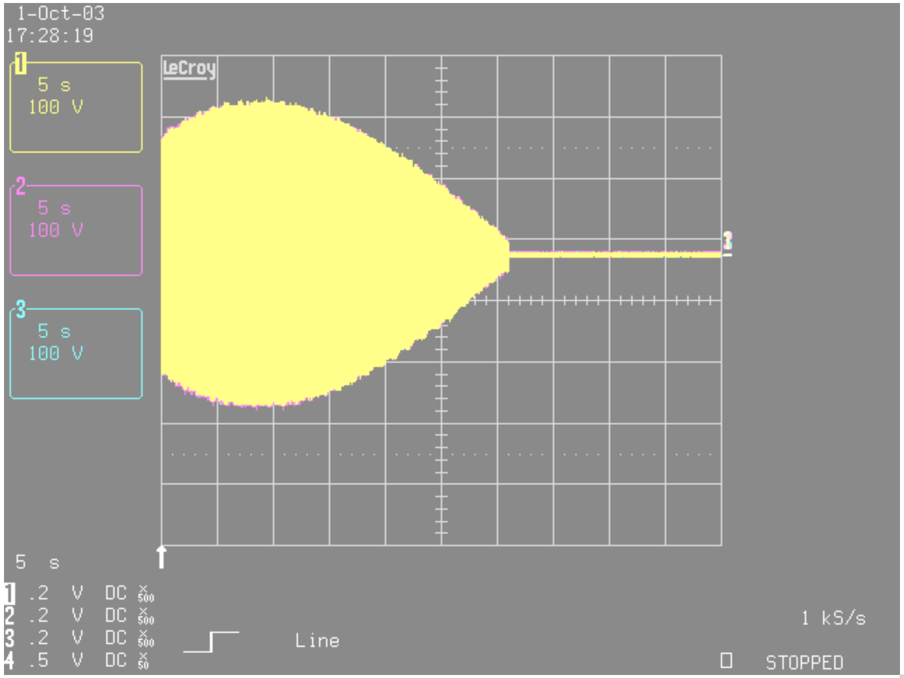
Laboratory scale microgrid



Laboratory scale microgrid hardware details

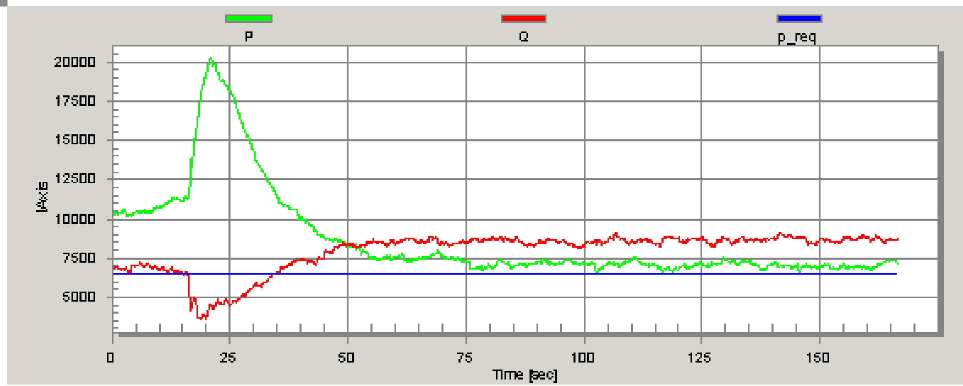
Laboratory scale microgrid hardware details

Laboratory scale microgrid hardware results

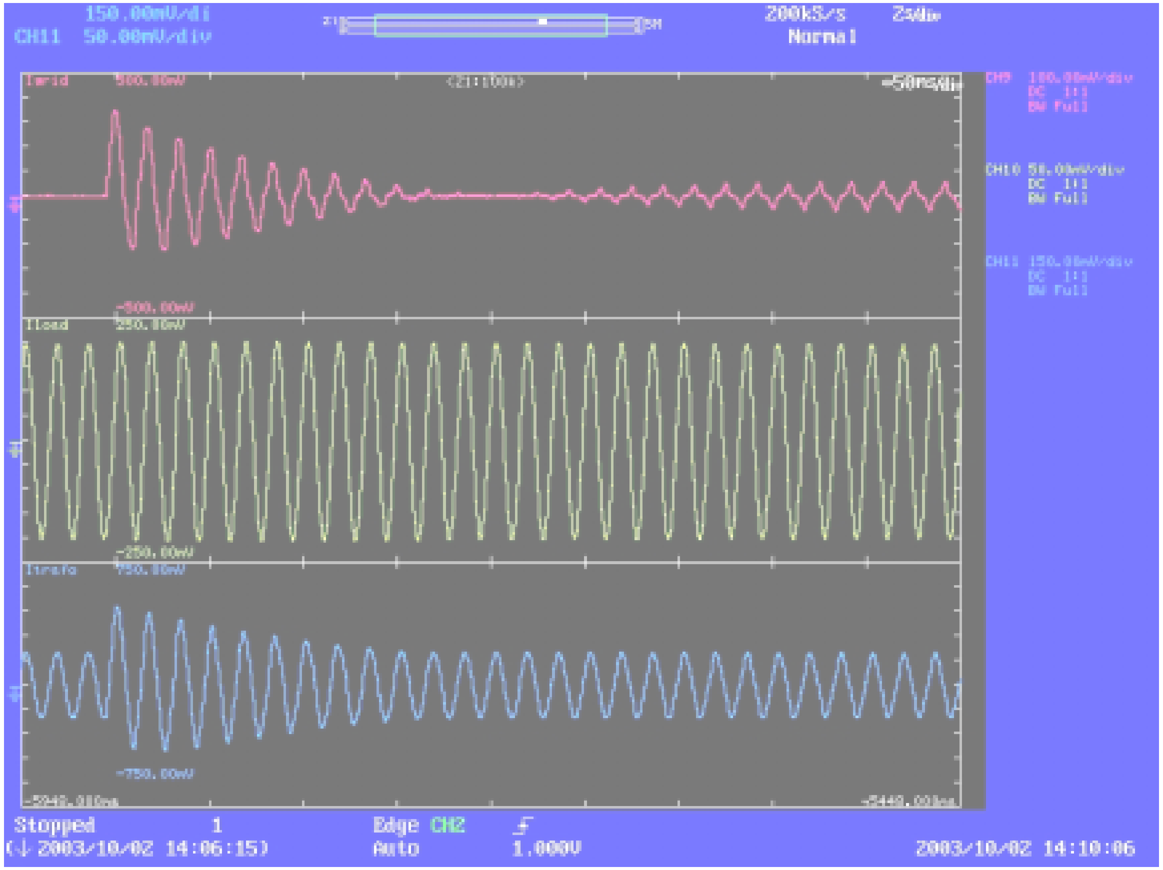


Synchronization to grid 'beat voltage'

P and Q transients



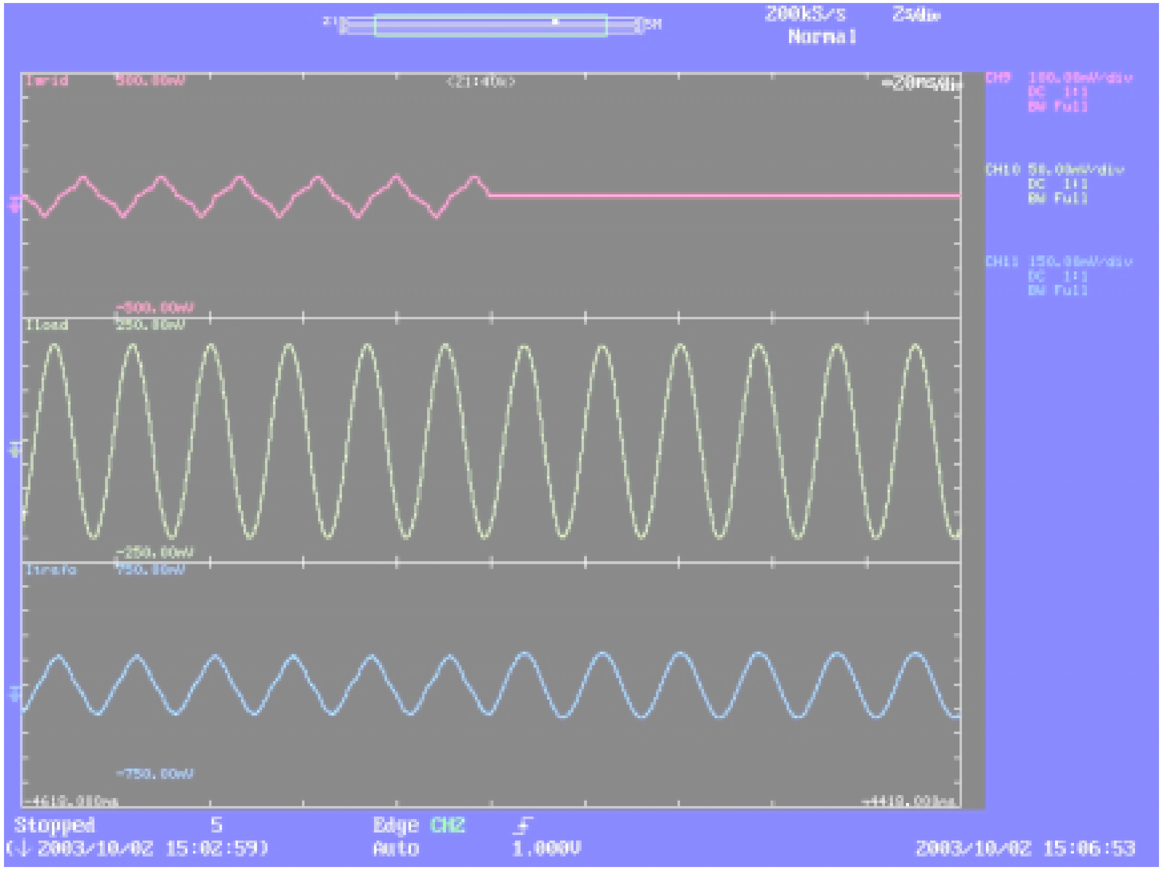
Laboratory scale microgrid hardware results



Synchronization to grid

Voltage and current waveforms

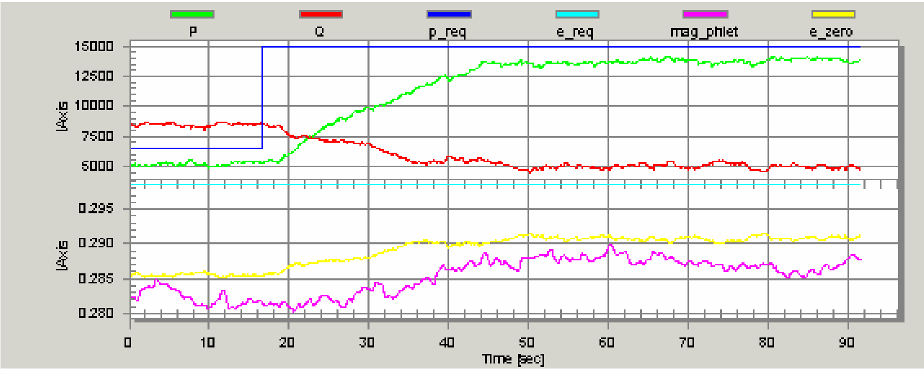
Laboratory scale microgrid hardware results



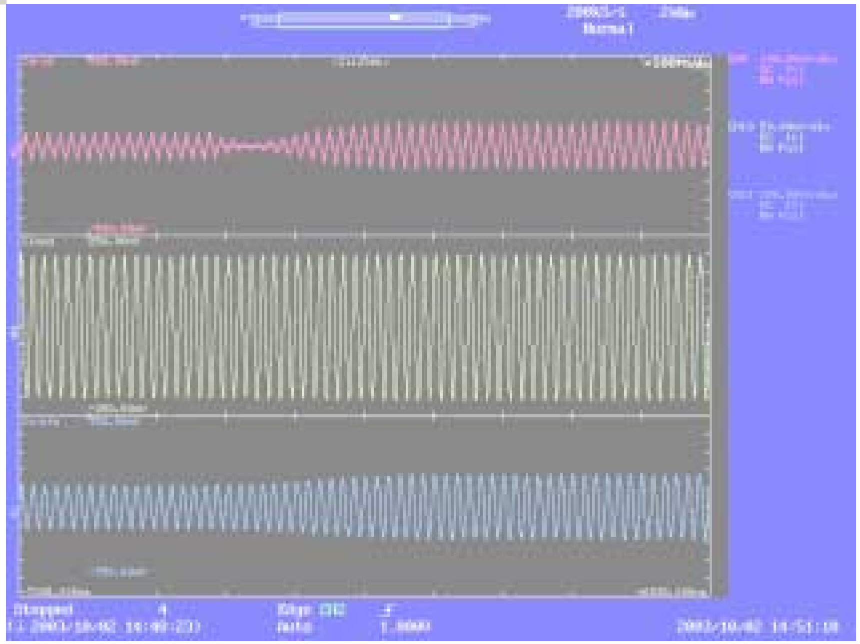
Disconnection from grid

Voltage and current waveforms

Laboratory scale microgrid hardware results



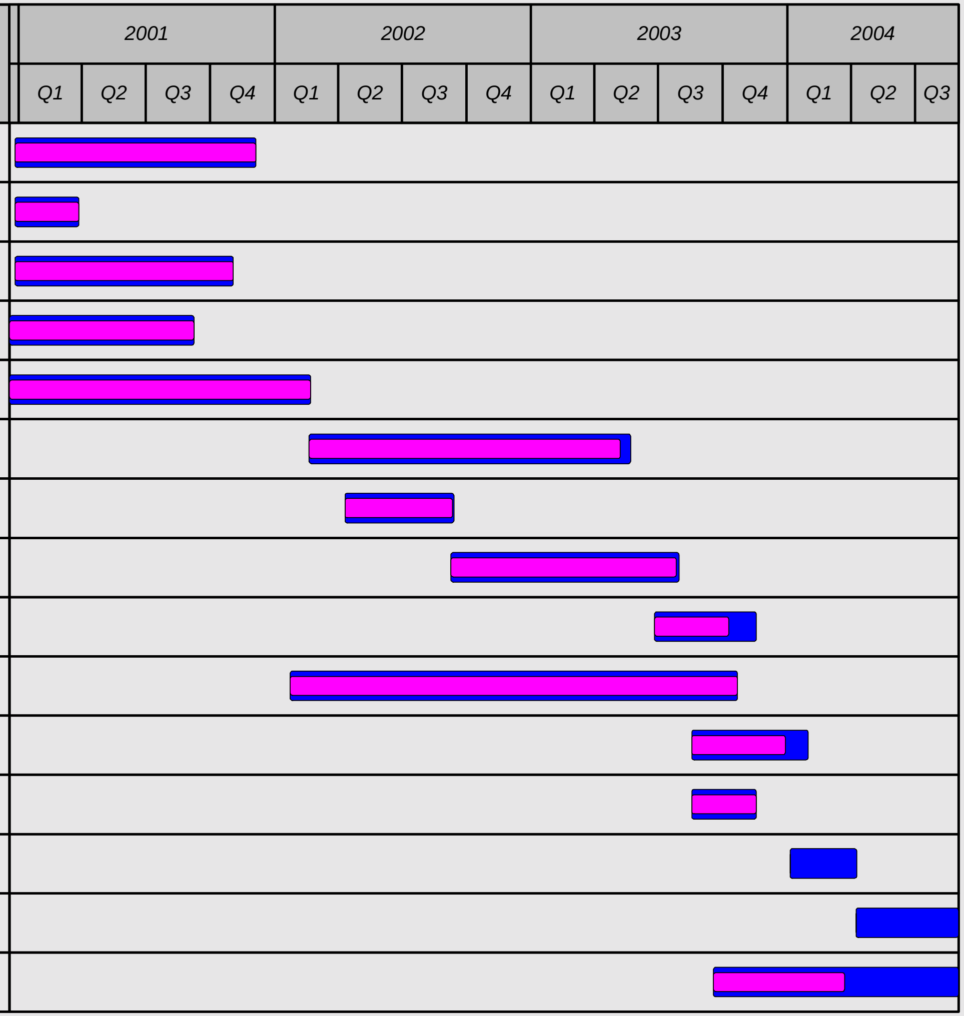
Step response of power



Voltage and current waveforms

Project Timeline

ID	Task Name
1	Development of power source emulator
2	Study of energy storage requirements
3	Demonstration of single inverter system
4	Development of DG control interface for inverter
5	Computer simulation for Tasks 1-4
6	Expansion of lab scale microgrid for utility interface and two inverters
7	Development of second PSE and inverter
8	Demonstration of islanding and reconnection
9	Demonstration of two inverters power quality transients
10	Computer simulation for Tasks 6-9
11	Expansion of lab scale microgrid to accomodate third inverter
12	Development of third PSE and inverter
13	Demonstration of 3 inverters with decentralized control
14	Demonstration of correction of common power quality problems
15	Computer simulation for Tasks 11-15



Milestones

<u>Sept 30, 2003</u>

- m-3.1.1 Complete expansion of laboratory scale microgrid. (Task 11)
- m-3.1.2 Complete fabrication of third power source emulator and inverter
- hardware. (Task 12)
- m-3.1.3 Develop computer simulation models for hardware design for Option
- year 2. (Task 16)

<u>Oct 31, 2003</u>

- m-3.2.1 Complete demonstration of three inverter decentralized control operating on the microgrid (Task 13)
- m-3.2.2 Develop updated computer simulation models for current hardware design. (Task 16)

<u>Feb 28 2004</u>

- m-3.3.1 Complete demonstration correction of power quality problems on the
- microgrid. (Task 14)
- m-3.3.2 Develop updated computer simulation models for current hardware design. (Task 16)

<u>June 30, 2004</u>

- m-3.4.1 Complete demonstration of safe system operation under faulted conditions on the microgrid. (Task 15)

m-3.4.2 Complete computer simulation models for Option Year 2 hardware design. (Task 16)

Deliverables

D-3.1	Monthly progress reports	15^{th} of every month
D-3.2	Draft Project Technical Report	June. 31, ‘04
D-3.3	Final Project Technical Report	July. 30, ’04
D-3.5	Annual Program Review Meeting	October ’03
D-3.6	Microgrid expansion report (Task 11, 12)	Oct. 31, ’03
D-3.7	3 inverters in a microgrid report (Task 13, 16)	Nov 30, ’03
D-3.8	Power quality transient report (Task 14, 16)	Mar. 31, ’04
D-3.9	Operation under faults report (Task 15, 16)	July 30, ‘04

Project budget

	Total ($K)	DOE/NREL ($K)	Subcontractor ($K)
Base Year (1 Dec 2000 – 30 Mar 2001)	**297**	**177**	**120**
Option Year 1 (1 Apr 2002-31 Aug 2003)	**238**	**142**	**97**
Option Year 2 (31 Sep 2003 - 31Aug 2004)	**248**	**149**	**100**
Total	**785**	**468**	**317**

Accomplishments '03

Hardware – Microgrid with two inverters

- Control strategy
  - ✓ Real Power-Frequency Droop Characteristics
  - ✓ Reactive Power-Voltage Droop Characteristics
  - Address short term power quality issues in control
- Operational strategy
  1. Ride through nominal amount of voltage sags and frequency deviations in a benign manner
  2. Intentionally island and feed local critical loads upon large deviation
  - ✓ Reconnect upon system recovery seamlessly

Accomplishments '03

Simulation and Analysis

- Control strategy
  - ✓ Real Power-Frequency Droop Characteristics
  - ✓ Reactive Power-Voltage Droop Characteristics
  - ✓ Address short term power quality issues in control
- Operational strategy
  - ✓ Ride through nominal amount of voltage sags and frequency deviations in a benign manner
  - ✓ Intentionally island and feed local critical loads upon large deviation
  - ✓ Reconnect upon system recovery seamlessly

Accomplishments

Publications

- B. Shi, M. Chandorkar, G. Venkataramanan, " Modeling & Design of a Flux Regulator for Three Phase PWM Inverters with Constant Switching Frequency", European Power Electronics Conference, Toulouse, 2003.
- G. Venkataramanan, M. Illindala, Dynamic Phenomena in Wind Farms with a Mix of Line Connected Induction Generators and Inverter Embedded Generators, Caribbean Colloquium Electric Power Quality, June 2003
- H. Zhang, M. Chandorkar, G. Venkataramanan, "Development of Static Switchgear for Utility Interconnection in a Microgrid," Proceedings of the IASTED Conference on Power and Energy Systems, Palm Springs, CA, 2003.
- M. Illindala, G. Venkataramanan, "Battery Energy Storage for Stand-Alone Micro-Source Distributed Generation Systems", Proceedings of the IASTED Conference on Power and Energy Systems, Monterey, CA, May 2002.
- M. Illindala, G. Venkataramanan, "Control of Distributed Generation Systems to Mitigate Load and Line Imbalances", IEEE Power Electronics Specialists Conference Record, Cairns, Australia, June 2002.
- G. Venkataramanan, M. Illindala, "Microgrids and Sensitive Loads", Panel Presentation at the IEEE Power Engineering Society Winter Meeting, New York, January 2002.

Out year activities '03

- Hardware demonstration of interconnection transients for second inverter
- Incorporate protective relaying hardware into the microgrid

Planned Activities '04

Hardware

- Incorporate third inverter
- Control strategy
  - ✓ Real Power-Frequency Droop Characteristics
  - ✓ Reactive Power-Voltage Droop Characteristics
  - Address short term power quality issues in control
- Operational strategy
  1. Ride through nominal amount of voltage sags and frequency deviations in a benign manner
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Project impact – electricity affordability

- Concept of microgrid as an affordable energy solution (integrated heat harvest)
- Develop and demonstrate technology for sensitive load applications to provide pull for technology and cost reduction in the long term
- Demonstration of concept of microgrid on laboratory scale test-bed
- Applicability to broad range of primary technologies – microturbine, wind, fuel cells, photovoltaics

Project impact – electricity reliability

- Concept of microgrid as a reliable energy solution for premium applications
- Understanding and control of dynamic interactions
- Demonstration of operating strategy to minimize process disruptions

Project impact – infrastructure security

- Inherent security of distributed infrastructure
- Development and demonstration of distributed control with no critical high speed communication needs

Project impact – infrastructure resilience

- Distributed control and operation based on local information
- Control strategies enabling quick disconnect and reconnect as appropriate

Related work and Collaborations

- Completed project on control system development for a DG vendor
- One student summer internship completed at vendor facility
- Project on standardized power electronics interfaces through CERTS funded by CEC and NSF-CPES
- Leadership in CERTS efforts on microgrid demonstration plan
- Two rounds of Future Energy Challenge – DOE sponsored fuel cell inverter competition for students
- Participation in DG protection short course at UW-Madison
- Publications at professional and technical conferences
- Procured a Capstone turbine awaiting commissioning
- Secured DG protective relays as donation to incorporate into microgrid

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