Microgrids for Renewable Energy Integration, Grid Support, and Energy Security Improvement

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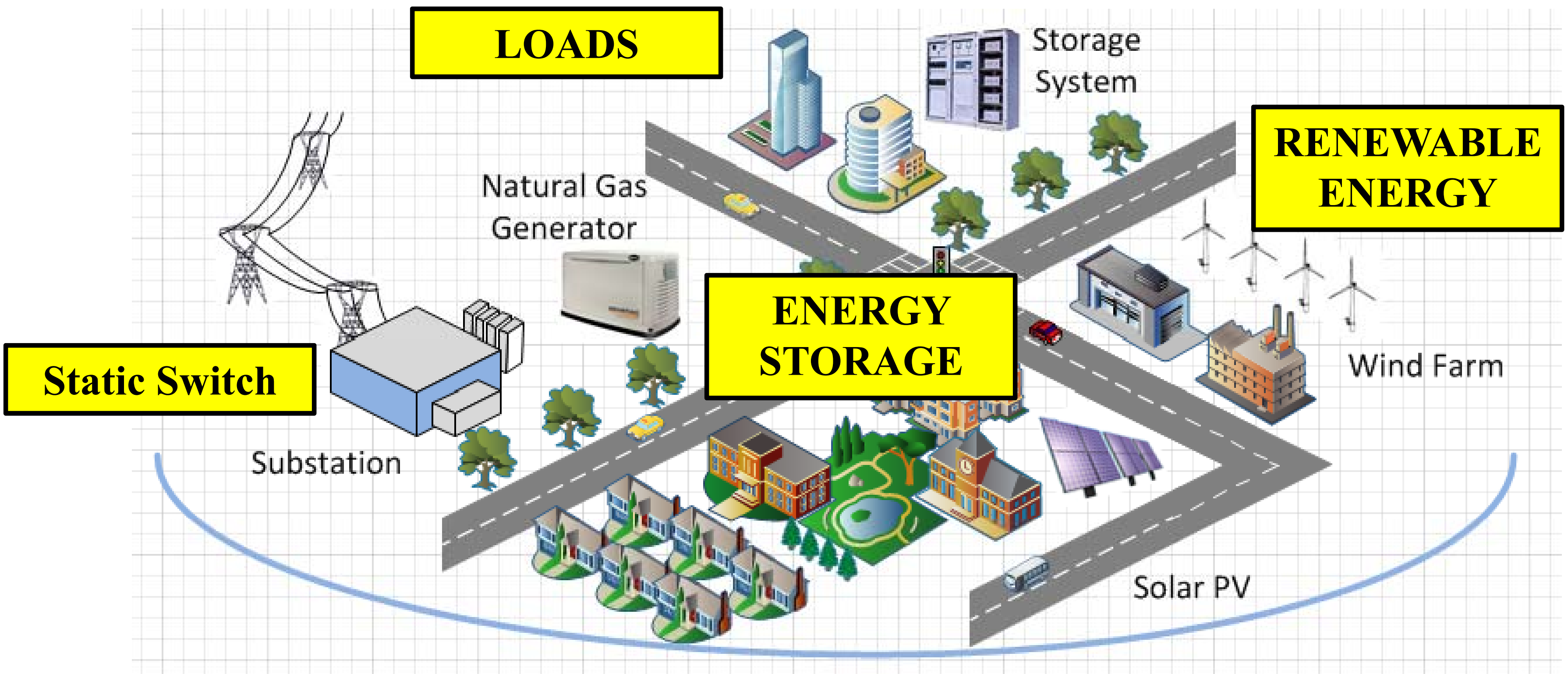
Outline

- Introduction and microgrid definition
- Microgrid components
- Energy storage modeling
- Controls for storage inverter and generator
- Controls for renewables in various modes
- System modeling results and implementation
- PGE HRZ system
- UWM microgrid update

What is a Microgrid?



- **A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid.**
- **A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.**

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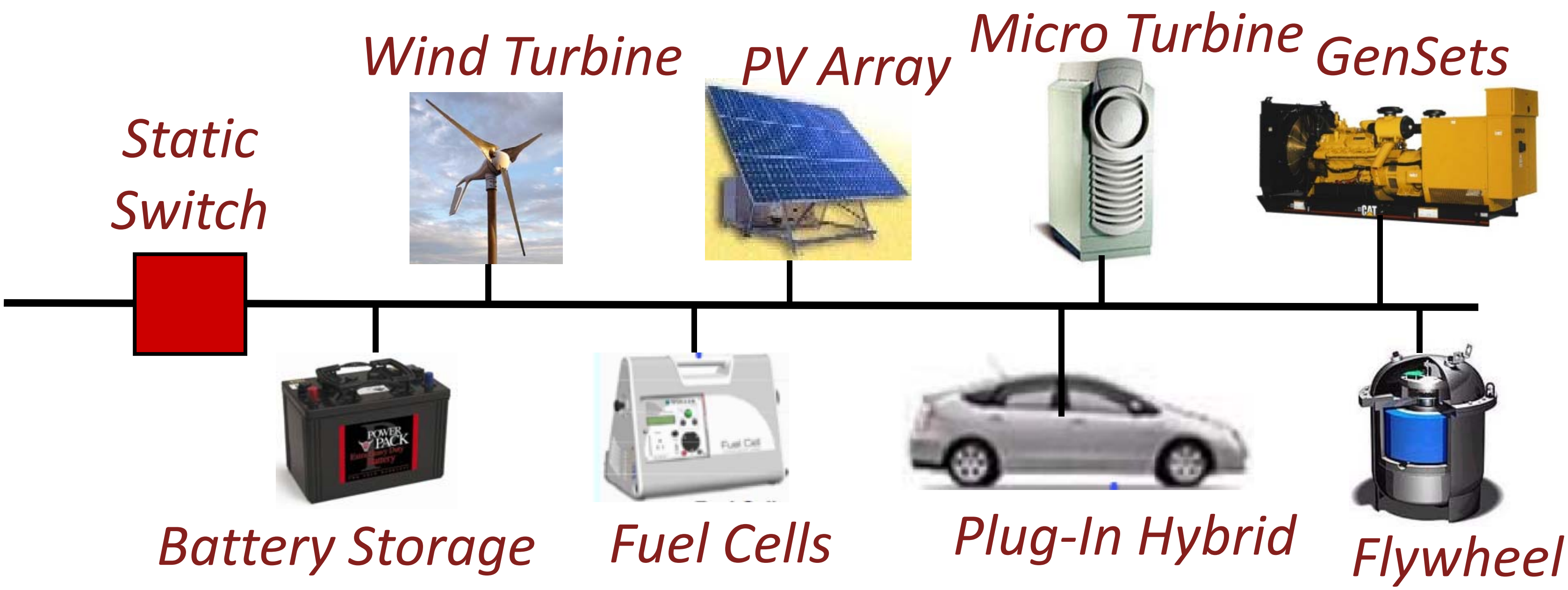
Microgrid Importance



- Microgrids provide the most promising means of integrating large amounts of distributed sources into the power grid.
  - Particularly important for renewable energy sources
- Microgrids can provide higher reliability, energy security and surety, and open the door to significant system efficiency improvements using Combined Heating & Power (CHP).

Technical Drives Behind Microgrids

- Transmission constraints requiring supplies closer to loads
- Demand for improved power reliability, efficiency, and quality
- Demand for energy security
- Integration of renewable energy and DG
- Military demand for enhanced energy security: Surety, Survivability, Supply, Sufficiency, and Sustainability.

Economical Drives Behind Microgrids

- Installed solar PV cost is estimated to fall to $1/W by 2015, making it competitive with natural gas. It is already down to $1.5/W!
- Natural gas has become as cheap as coal and is taking away the cost advantage of centralized coal plants.
- Cost of energy storage is falling dramatically and will reach $100/kW in coming years.

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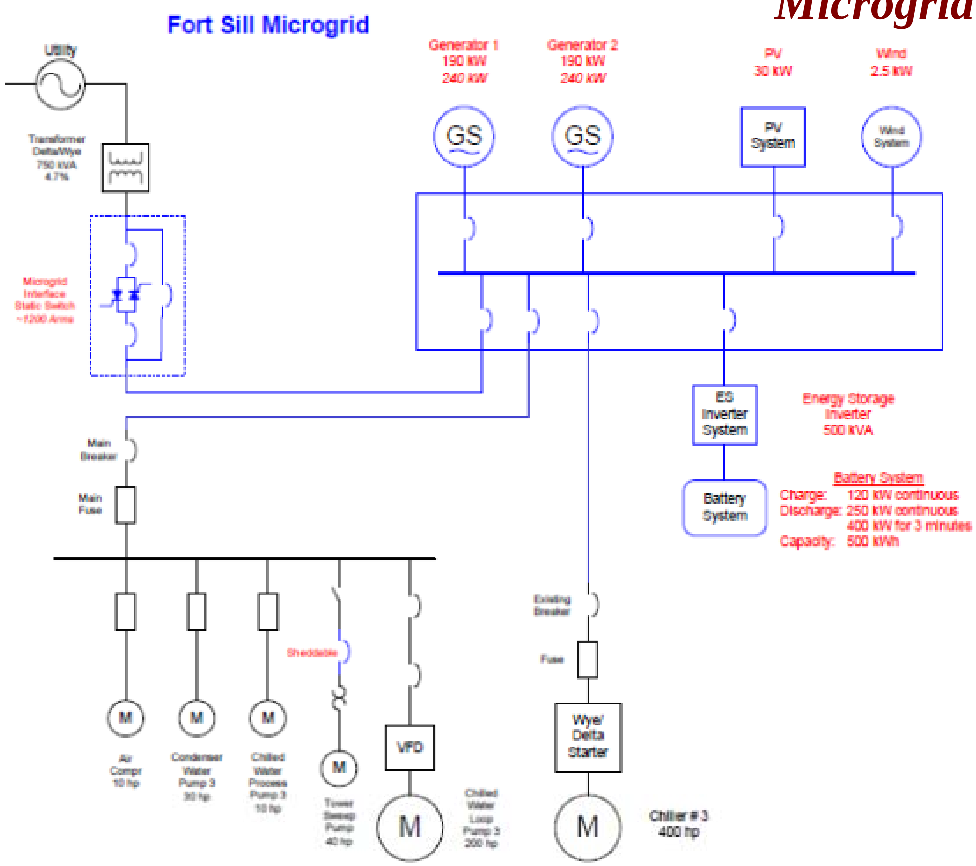
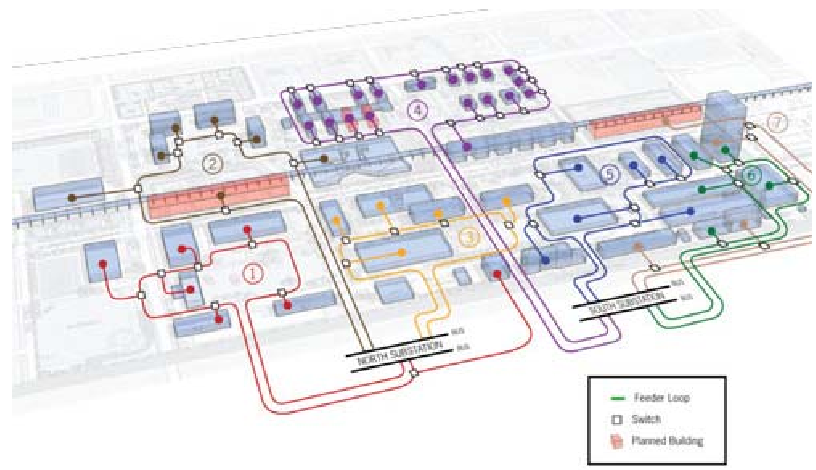
Current µgrid Technology Base



700 kW Fort Sill Microgrid Project

100 kW AEP/CERTS Microgrid Test Site

12MW IIT Perfect Power



SPIDERS: The Smart Power Infrastructure Demonstration for Energy Reliability and Security

$30M project focused on three distinct military installations: Joint Base Pearl Harbor/Hickam, Hawaii; Fort Carson, Colorado; and Camp H.M. Smith, Hawaii.

- To protect critical infrastructure from power loss in the event of physical or cyber disruptions to the bulk electric grid.
- To provide reliable backup power during emergencies by integrating renewables and other distributed generation sources into the microgrid.
- To ensure that critical operations can be sustained during prolonged utility power outages.
- To manage electrical power and consumption at military installations more efficiently, thus reducing petroleum demand, carbon emissions, and transportation costs.

SPIDERS Microgrid Implementation Plan

The goal of SPIDERS is to demonstrate a secure microgrid concept

- Maintaining 100 percent of critical load for at least 72 hours in the event of loss of grid power,
- Integrating intermittent renewable energy generation during loss of grid power, and
- Improving cybersecurity.

FY 11

HICKAM AFB CIRCUIT LEVEL DEMO

- Renewables
- Hydrogen Storage
- Hydrogen Fuel Cell
- Energy Management

FY 12

FT CARSON MICROGRID

- Large Scale Renewables
- Vehicle-to-Grid
- Smart Micro-Grid
- Critical Assets
- CONUS Homeland
- Defense Demo
- COOP Exercise

FY 13

CAMP SMITH ENERGY ISLAND

- Entire Installation Smart Micro-Grid
- Islanded Installation
- High Penetration of Renewables
- Demand-Side Management
- Redundant Backup Power
- Makana Pahili Hurricane Exercise

TRANSITION

- Template for DoD-wide implementation
- CONOPS
- TTPs
- Training Plans
- DoD Adds Specs to GSA Schedule
- Transition to Commercial Sector
- Transition Cyber-Security to Federal Sector and Utilities

RIGOROUS CYBER SECURITY IN EACH PHASE

Current μgrid Technology Base (cont'd)

- 100 kW AEP/CERTS Microgrid Test Site
  - Seamless transfer, peer-to-peer and plug-and play concepts
- 700 kW Fort Sill Microgrid Project
  - Network renewable and DGs, carbon footprint reduction, and serve critical mission power requirements in a sustainable, reliable, and secure manner
- 3 MW Santa Rita Cor. Facility Test Site
  - Initial goal for this $11M facility was to reduce energy cost, store renewable overproduction, shift loads to off-peak hours, improve grid reliability
- IIT Perfect Power
  - Sustainable power, withstand disasters, secure energy, lower cost for customers, power system approach
- UWM/M-WERC Microgrid Facility
  - **High renewable penetration, multi-bus system, storage placement and reduced size, CHP and EV systems**

Fort Sill Microgrid Configuration

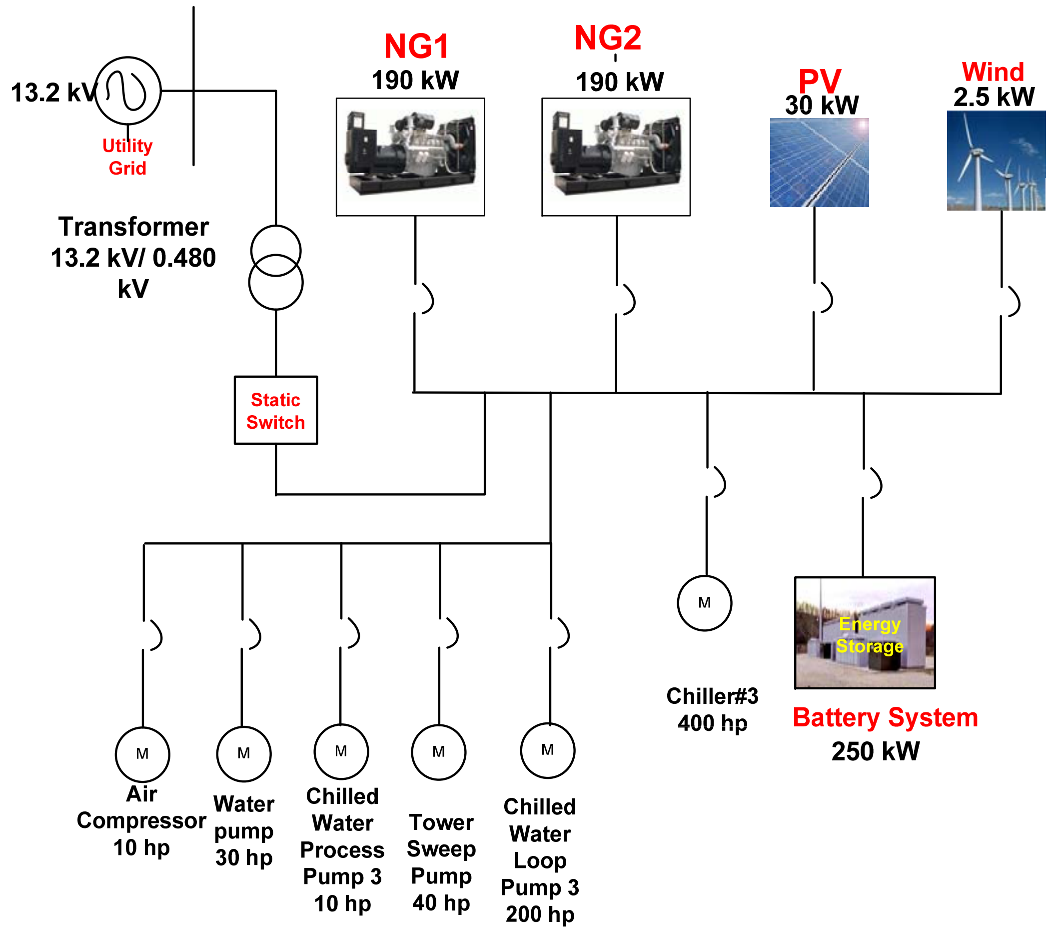
- It is rated at 0.480 kV, 60 Hz and 630 kW.
- It is connected to the utility grid through a 0.48kV/13.2kV transformer and a static switch
- The generation in microgrid includes:

  (1) Two Natural gas generators each rated at 190 kW,

  (2) 30 kW Solar PV system

  (3) 2.5 kW wind turbine

  (4) 250kW energy storage system
- The system includes various motor loads and variable loads. i.e. chillers, water pumps, air compressors.



Fort sill microgrid configuration

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Research Objectives

- Model a microgrid with high penetration of renewable energy and assess power quality
- Control and manage sources and energy storage within the microgrid to regulate voltage and frequency
- Test and study microgrid components to create a practical system model
- Size the capacity for renewable and non-renewable sources and storage to meet the demand
- Find best locations for energy storage to control voltage and frequency
- Design controls for the components and system to manage seamless islanding and reconnection
- Implement a microgrid based on emulated sources and energy storage

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Microgrids with High Penetration of Renewables

- High penetration of Renewable Energy Sources (RES), within microgrid is important to meet the energy surety requirements
- Renewable energy sources such as wind and solar are intermittent unlike fossil fuel based sources
- The problem is to manage the stability, demands, and power quality of the load while extracting maximum energy from the renewable sources
- The renewable sources are mostly connected to an inverter and this allows fast and flexible interface between the loads and the source.
- Performance of microgrids is ensured by proper sizing of capacity for projected demand
- There are no standard methods of sizing sources based on measurable indexes

Microgrid Configuration

- To study microgrids, we have adapted a standard IEEE 34-bus distribution system as a microgrid.
- The original system was 25kV, 60Hz, and 12MVA. We scaled it to 12kV, 6MVA.
- The original system was connected to the grid with no DG and with constant active/reactive power loads and constant distributed impedance loads.
- We added DG and renewables to the 34 bus system
- We provided the capability to add loads and load profiles
- Enabling islanding allowed us to model microgrids
- This system can be used as a benchmark for microgird controls, sizing and tests

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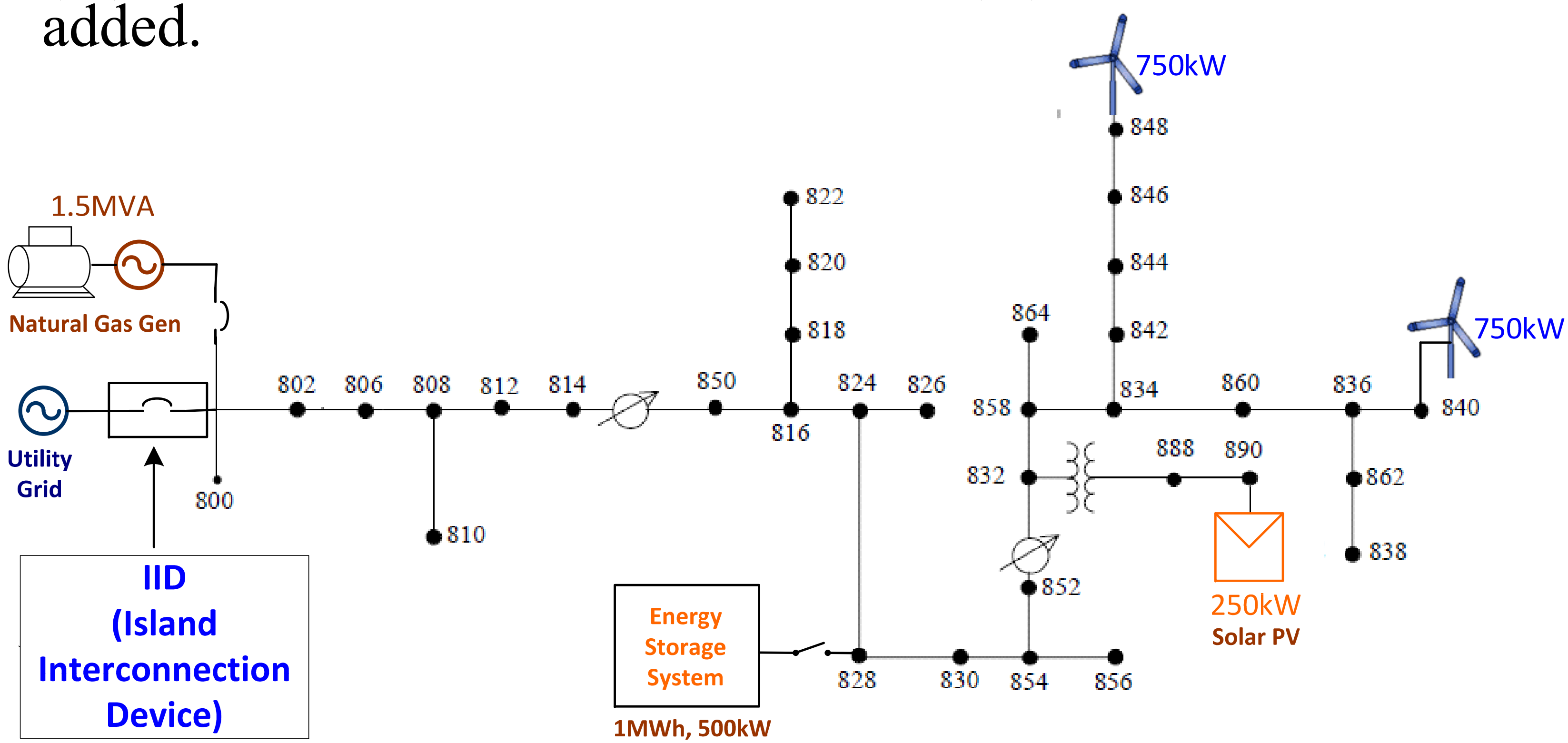
Microgrid Configuration – DG added

- (i) DG and energy storage are added (ii) Loads are scaled, (iii) Distribution lines are scaled, and (iv) Transfer switch is added.



34-Bus System with DG

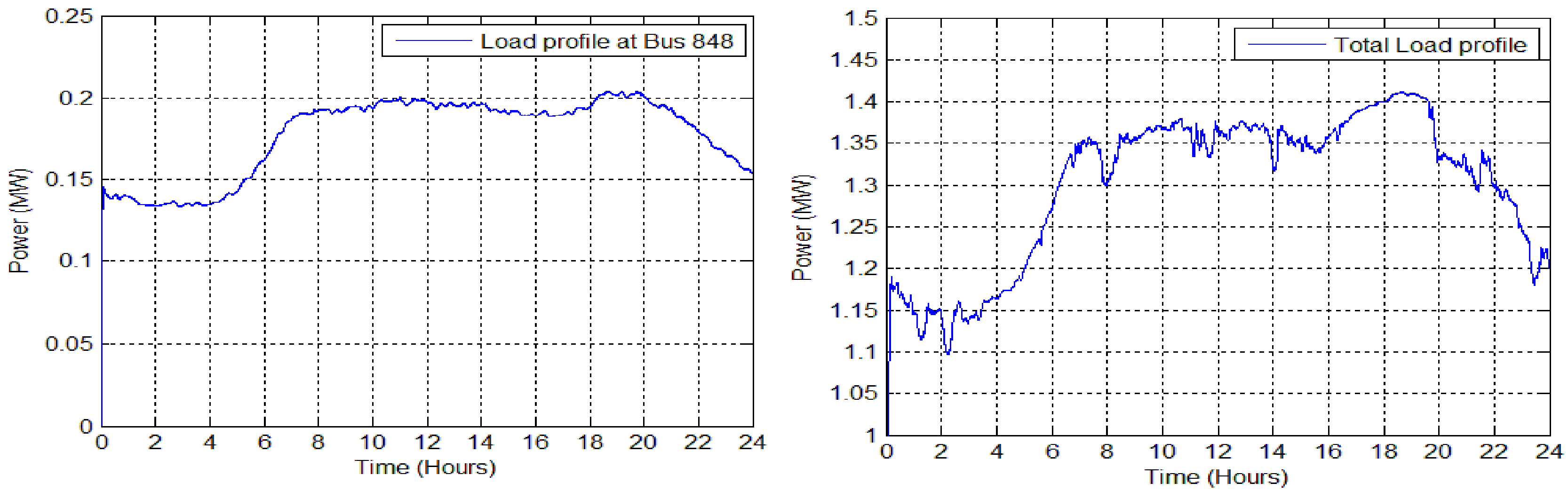
Q. Fu, L. Montoya, A. Solanki, A. Nasiri, V. Bhavaraju, and D. Yu, "Microgrid Generation Capacity Design with Renewables and Energy Storage Addressing Power Quality and Surety," IEEE Transactions on Smart Grid, vol. 3, no. 4, pp. 2019-2027, 2012.

Microgrid Components

- Loads: variable and fixed loads, impedance loads, motor loads
- Solar PV
- Wind turbine
- Natural gas (NG) generator
- Zinc-bromide battery
- Li-ion battery
- Lithium-ion capacitor
- Inverters
- Controls

Microgrid Configuration - Load Profiles

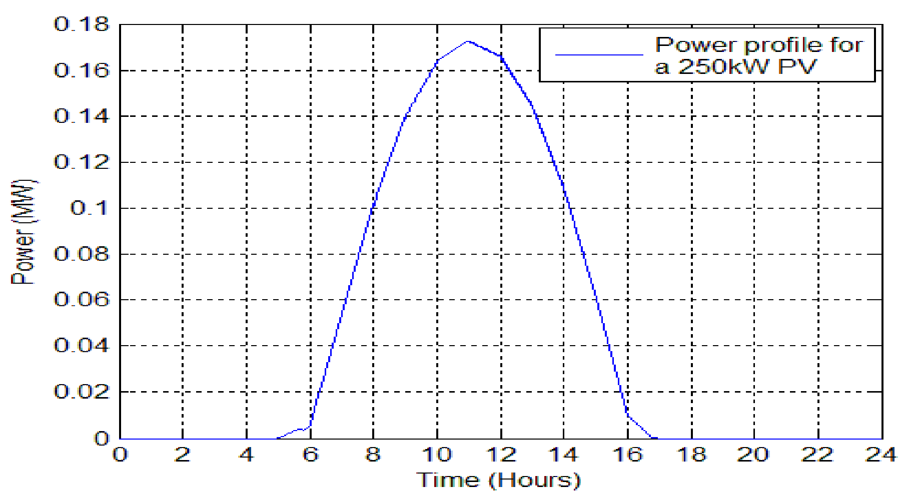
The system includes a total of 53 loads, consisting of fixed and variable PQ loads and fixed impedance loads. The load profile for a single load at bus 848 and total microgrid load are shown below. The peak load occurs at 7PM and it is 1420kW. The minimum load occurs at 2AM and it is 1120kW.

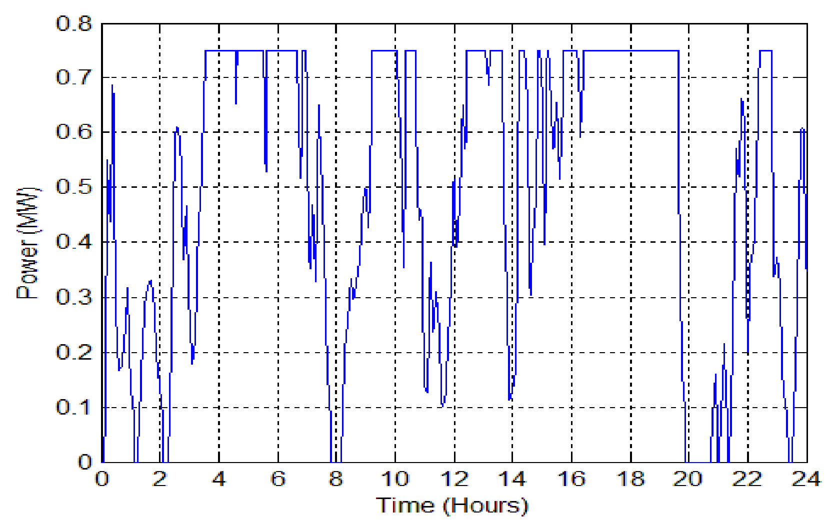


Load power profile for a single day, (a) typical load profile on bus 848 and (b) total load for the microgrid.

Microgrid Source Models - PV and Wind

- The solar PV system is modeled using solar irradiation data from Solar Advisor Module (SAM) for the city of Milwaukee, WI. All practical constraints are applied.
- The wind turbine power profile is also modeled using measured wind speed data near the city of Milwaukee WI.

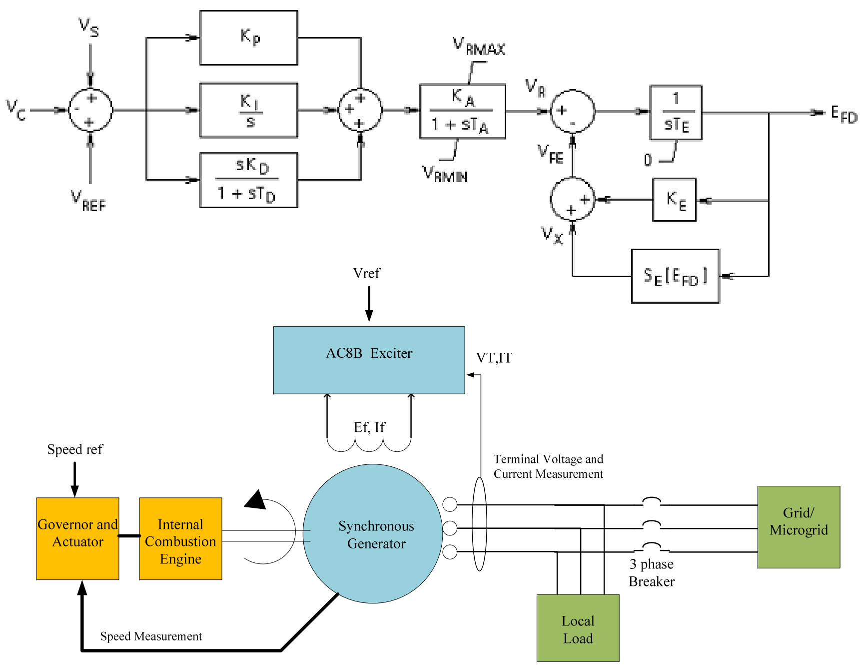




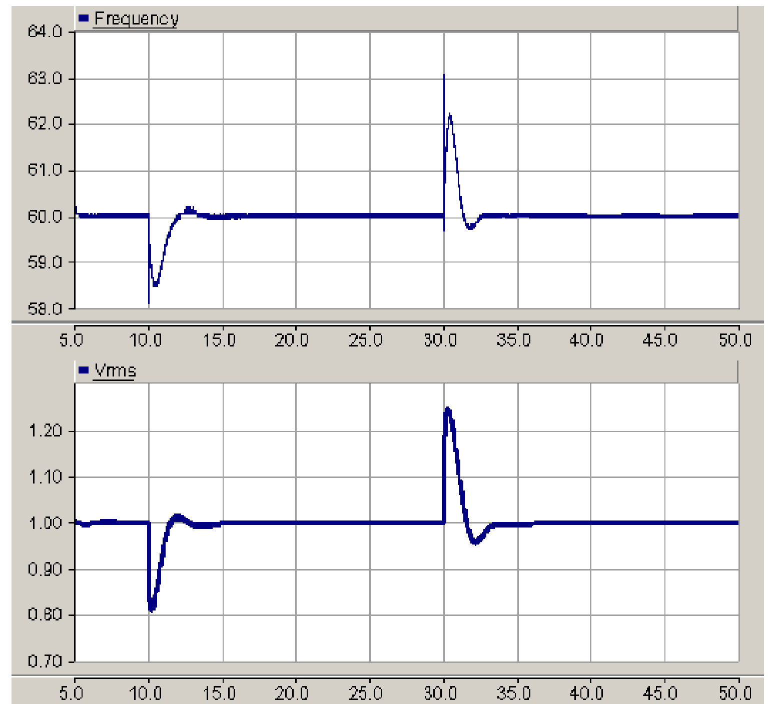
The power profile of a 250kW solar PV plant and 750kW wind turbine.

Microgrid Source Models – NG Generator

- One of the IEEE recommended exciter type systems have been modeled for a 1.5MVA generator. Practical parameters of the machine are applied to properly model the transient and step responses.



Basic block diagram of an NG generator connected to a gird/microgrid.



Simulation results for the diesel generator when load steps are applied at 10s and 20s.

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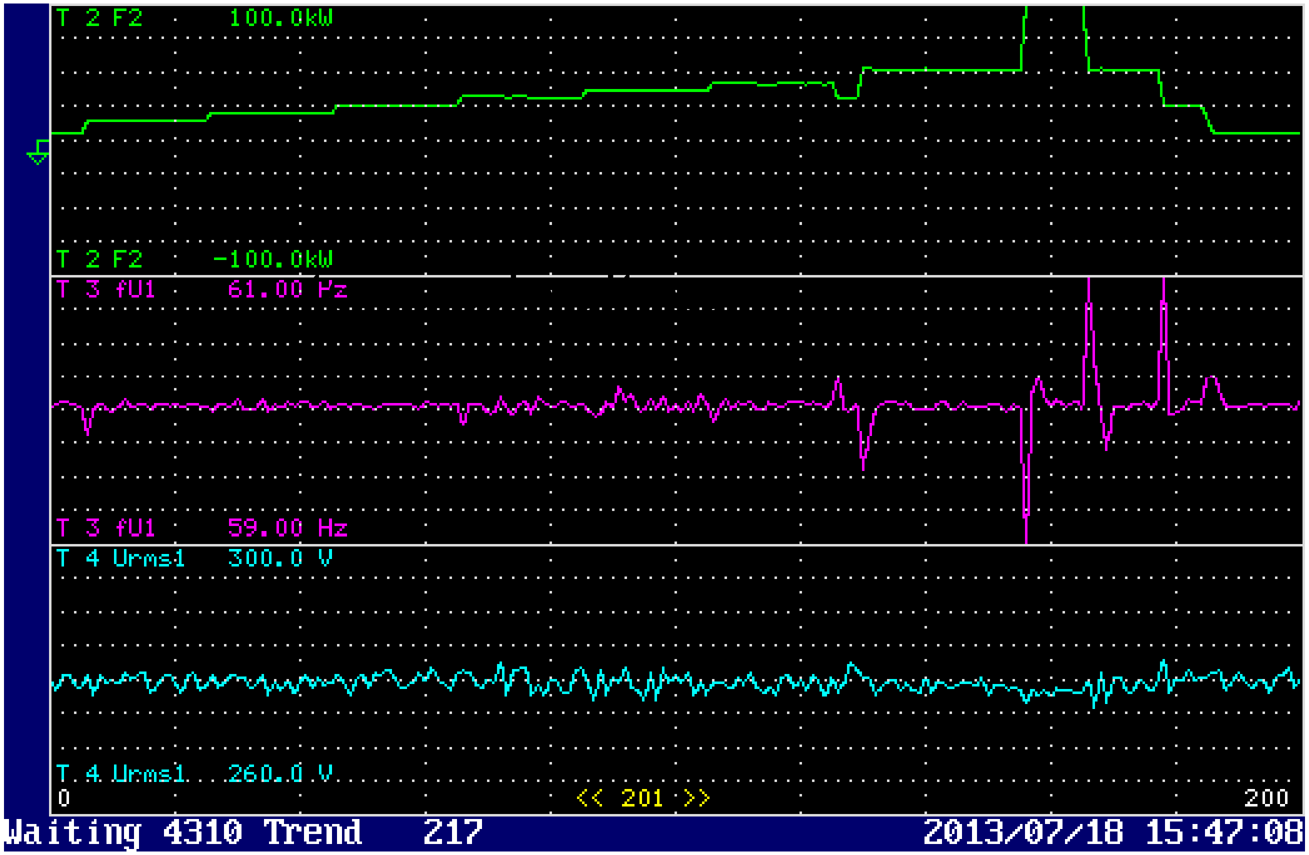
NG Generator Test Results

Figure shows the test result for a 100kW generator for different step changes in active load.

Active Power

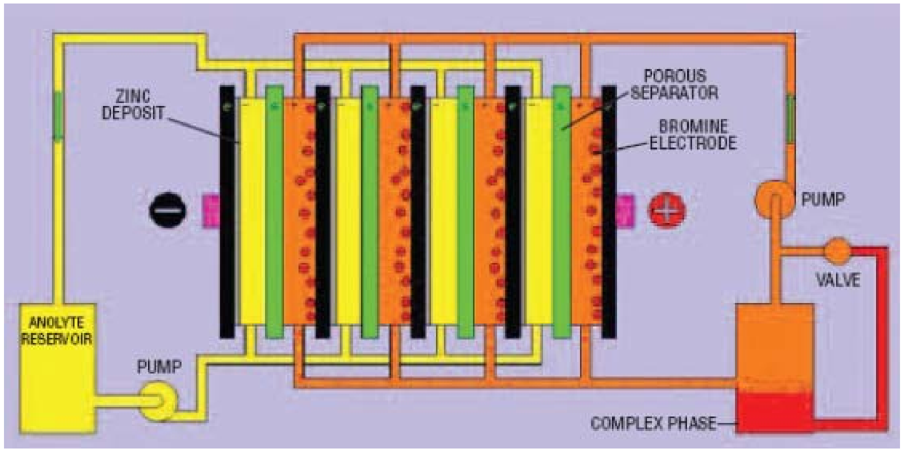
Frequency

Terminal Voltage



Microgrid Storage: Zinc-Bromide Battery

It is a flow battery with large cycle life, and good power and energy density. It is suitable for grid applications.



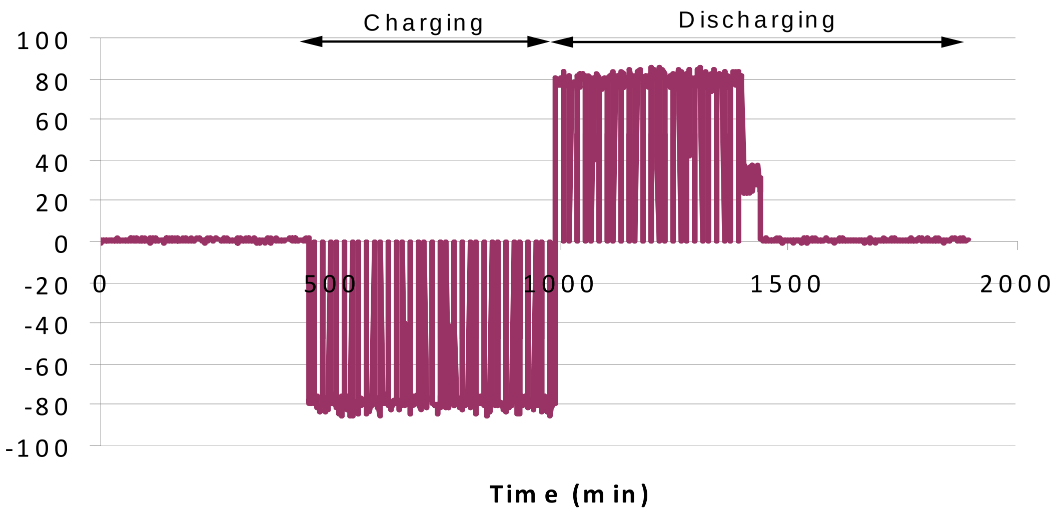
Stack Assembly and electrolyte flow in a Zinc-Bromide energy storage system.

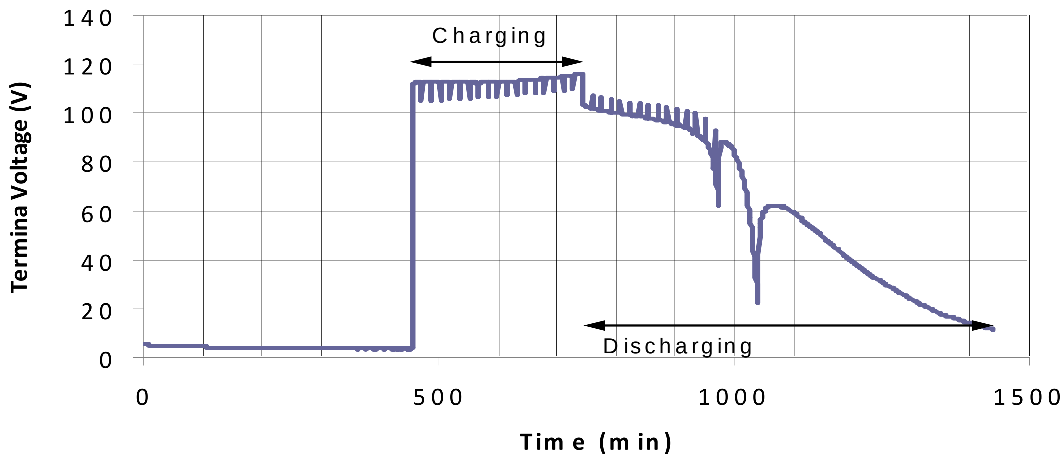
Anode: $Zn^2 + (+)\ 2e- \leftrightarrow Zn$

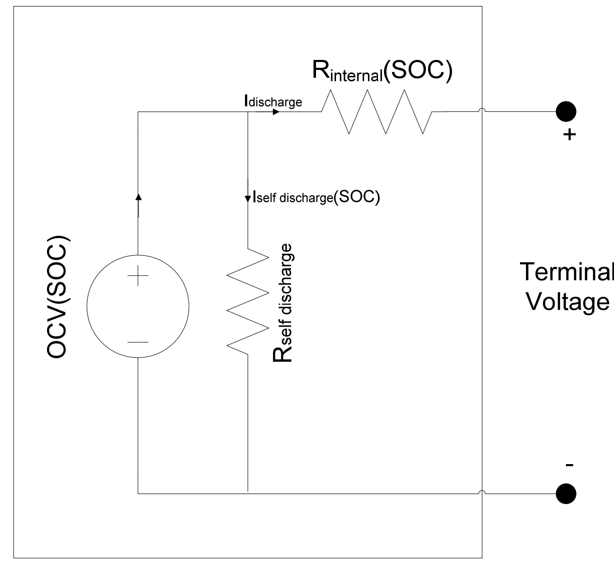
Cathode: $2Br- \leftrightarrow Br_2 + 2e-$

$ZnBr_2 + H_2O$

Zinc Energy Storage System (ZESS) Testing







Testing and modeling of Zinc Bromide battery. Components in the model are non-linear functions of SOC and temperature.

E. Manla, A. Nasiri, C. Rentel, and Michael Hughes, "Modeling of Zinc-Bromide Energy Storage for Vehicular Applications", IEEE Transactions on Industrial Electronics, vol. 57, no. 2, pp. 624-632, 2010.

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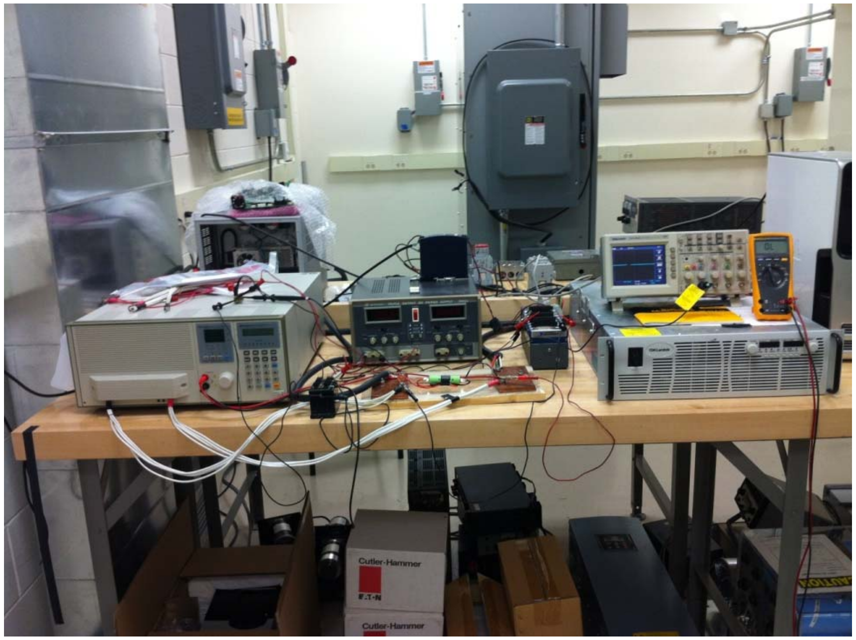
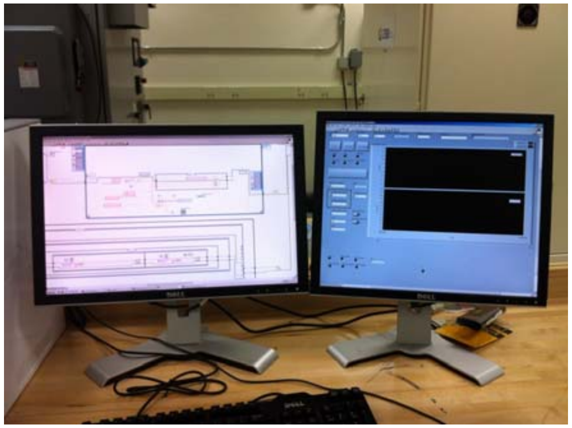
Li-Ion Battery Test System

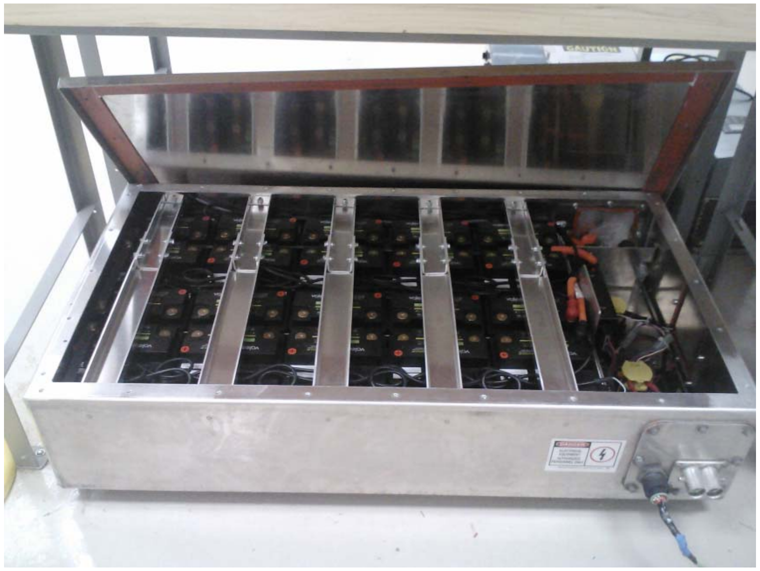
- **NI CompactRIO** and **Labview** are used for automated test procedure and data acquisition.



Battery cell test setup.

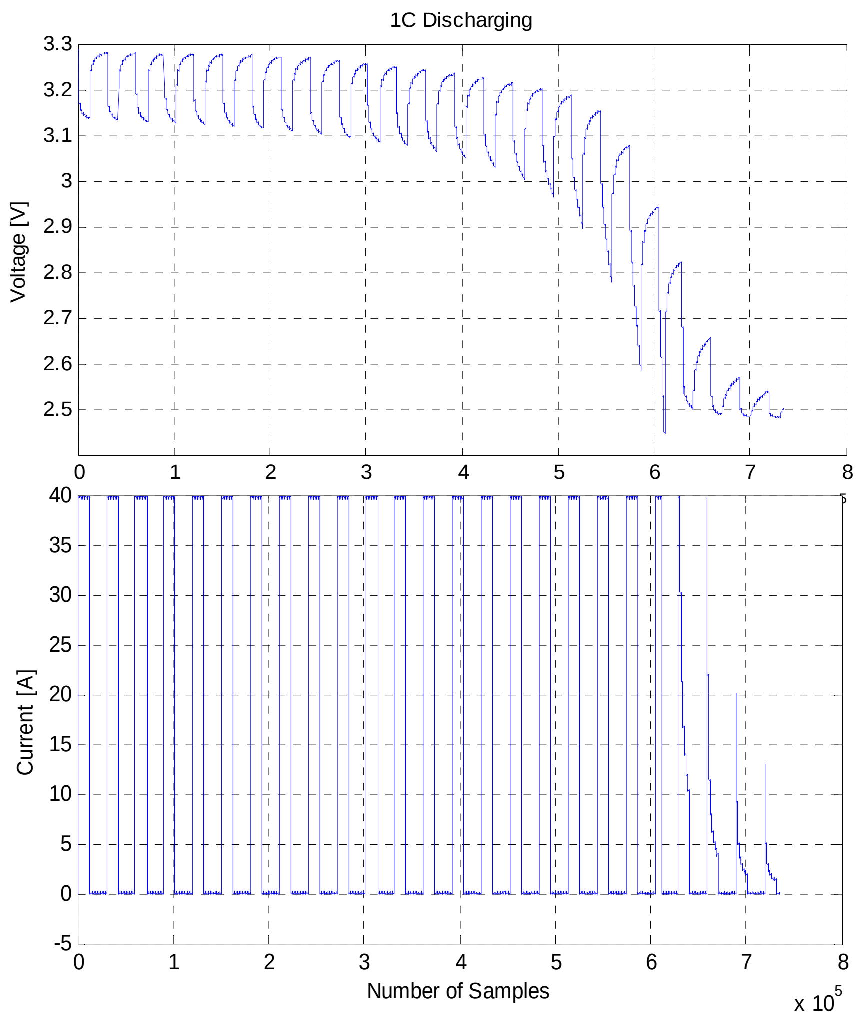


Labview interface.

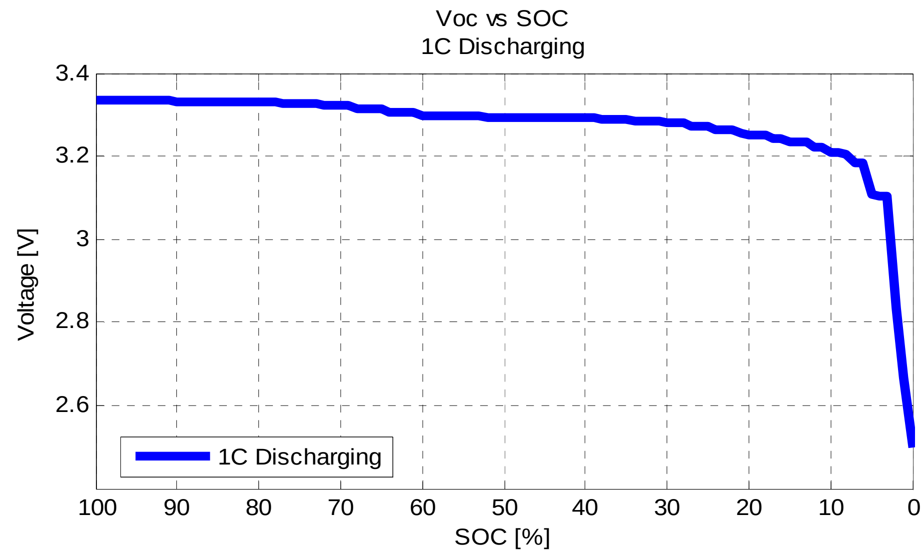


322V Li-ion battery module under testing.

Li-Ion Battery Testing



Voltage and current traces for battery discharging voltage (above) and current (below).



Battery vs. SOC traces at various discharging currents.

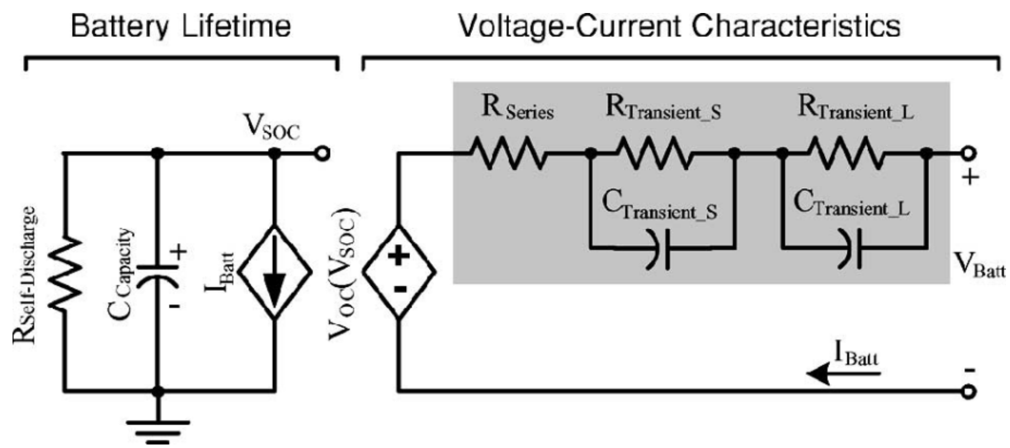
Battery testing has been conducted at various current rating and ambient temperatures. Parameters are functions of OCV and temperature.

Comprehensive Li-Ion Battery Model

- **A comprehensive battery model, combining:**
  - Transient capabilities of Thevenin-based models
  - AC features of impedance-based models
  - Runtime information of runtime-based models.

Left side :

- **A capacitor (*$C_{Capacity}$*) and a current source, model:**
  - Capacity,
  - SOC
  - Runtime of the battery

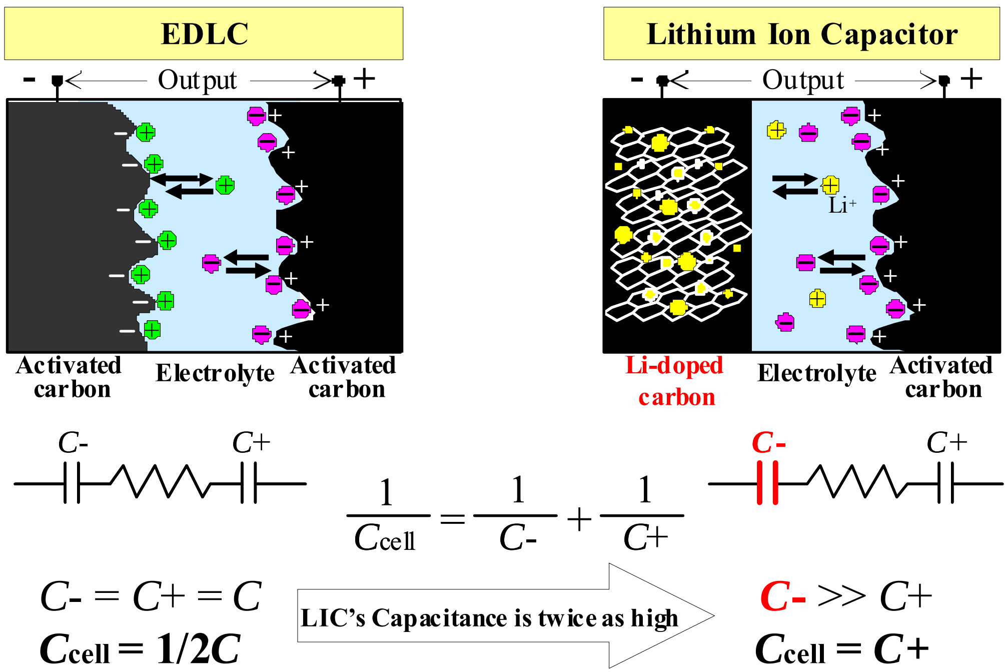


Right side:

- **The RC network**, models the transient response.
- **Voltage-controlled voltage source** is used to model the nonlinear relation between OCV and SOC.

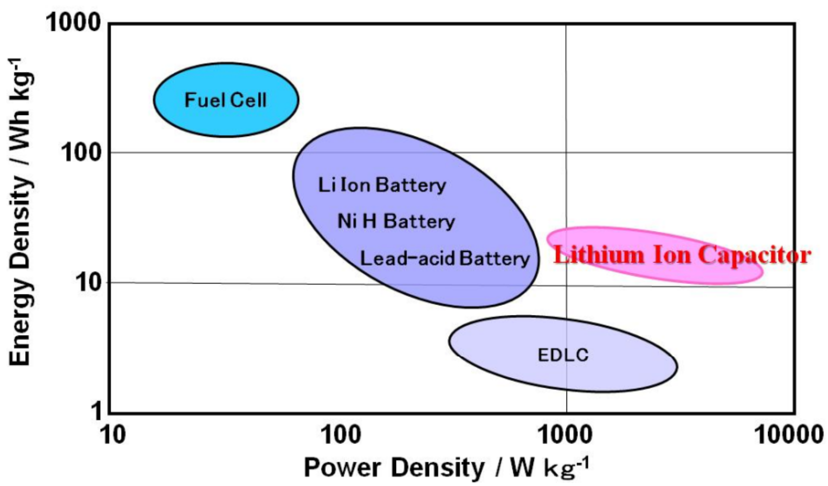
S. A. Hamidi, L. Weber, and A. Nasiri, "EV Charging Station Integrating Renewable Energy and Second-Life Battery," in Proc. International Conference on Renewable Energy Research and Applications (ICRERA), Oct. 2013, Madrid, Spain.

Microgrid Storage: Lithium-Ion Capacitor



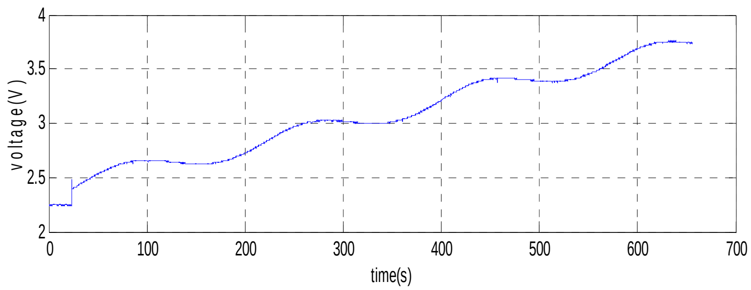
Concept of Lithium-ion Capacitor.

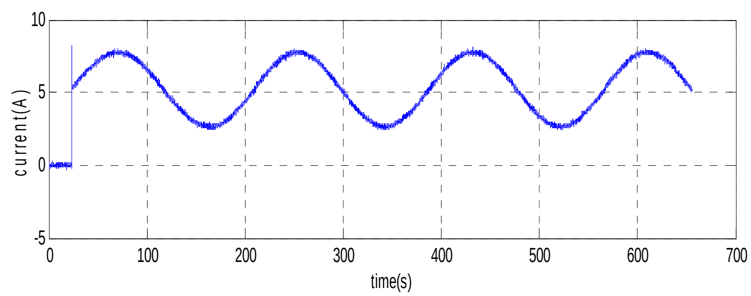
It offers very high power density and efficiency. It is suitable for systems that require large cycle life. A typical cell is rated at 2200F, 3V, and 220A.

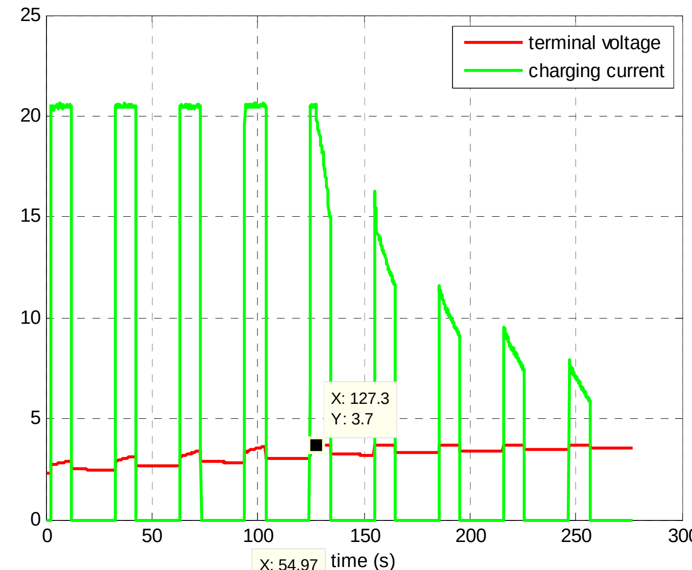


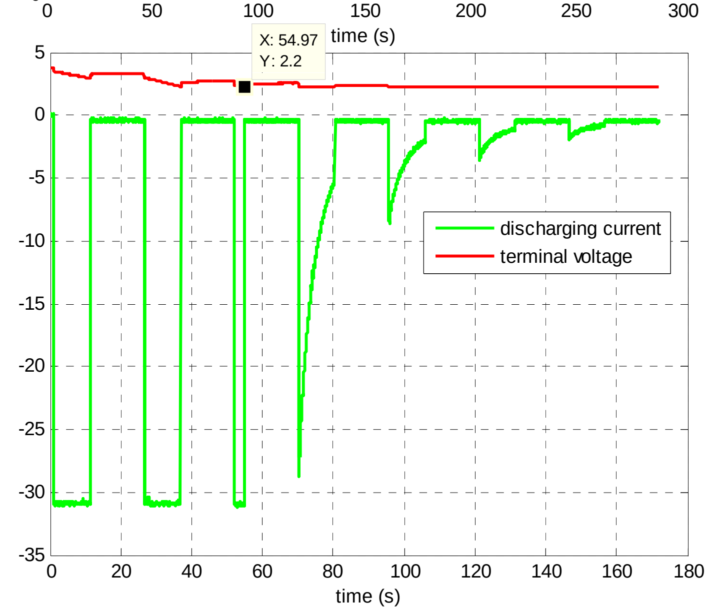
Ragone plot showing a comparison of energy and power density.

Ultracapacitor Testing



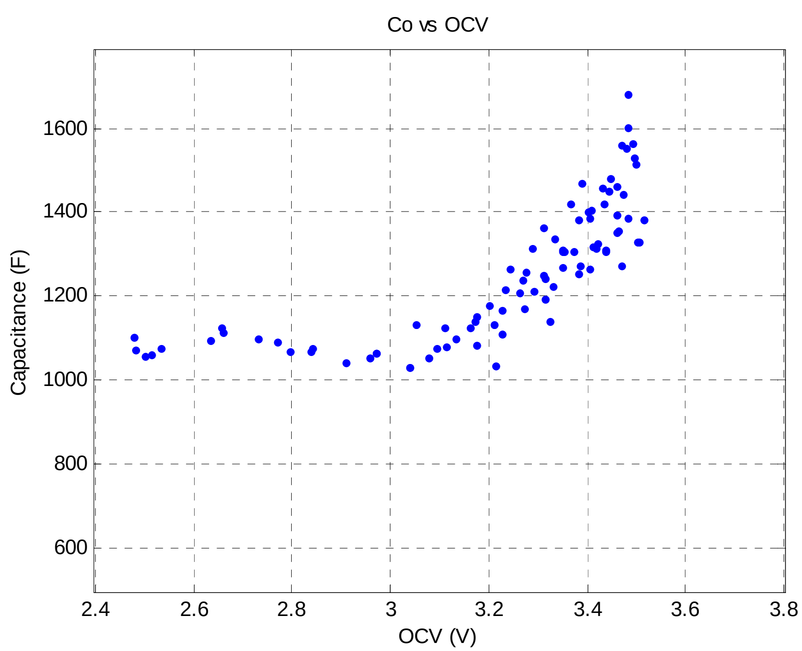






Picture of the test setup and waveforms

Ultracapacitor Model

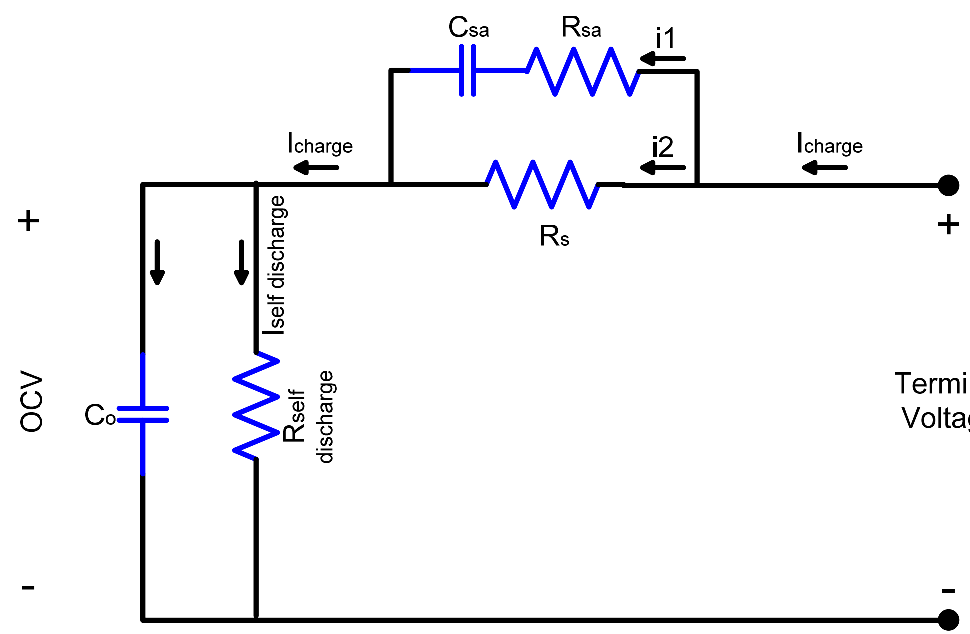


$$C_o(OCV) = a \cdot OCV^4 + b \cdot OCV^3 + c \cdot OCV^2 + d \cdot OCV + e$$

Where:

a = 745.93
b = 9975.79
c = -48536.01
d = 102318.04
e = -78004.95

$C_{sa} = 30.6$ F
$R_{sa} = 79.9$ mΩ
$R_s = 5.339$ mΩ

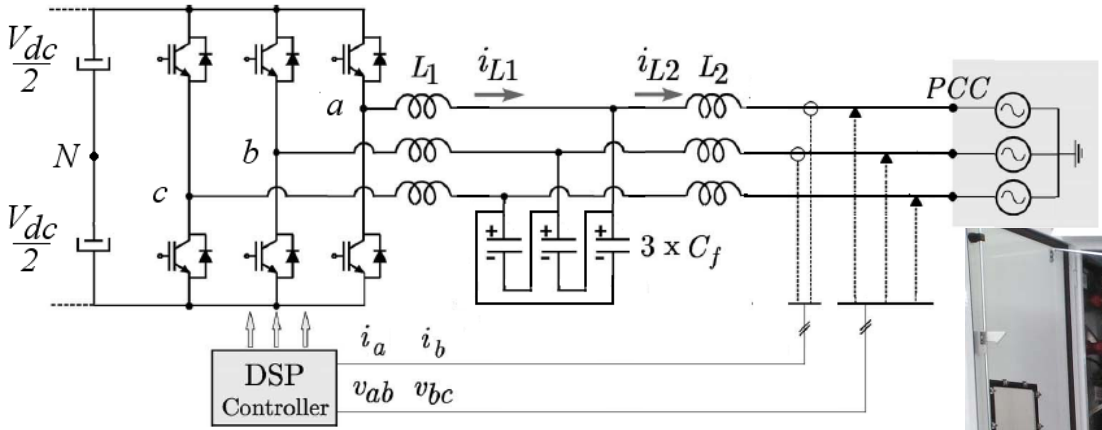


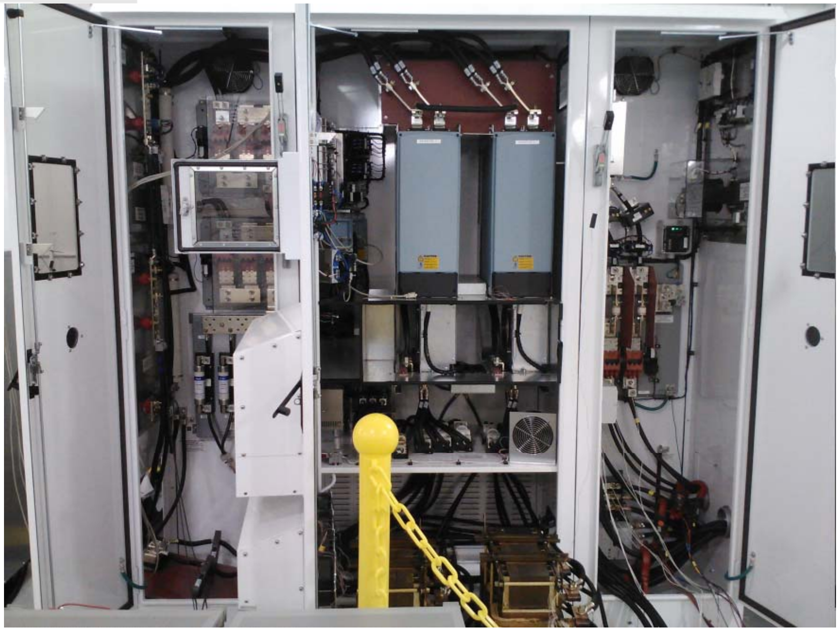
Developed model for the 1100F LIC for integration with renewable energy.

E. Manla and A. Nasiri, "Modeling of Lithium-Ion Capacitors for Renewable Energy Integration", in Proc. IEEE Energy Conversion Congress and Exposition, 2011.

Inverter Average Modeling

DC Bus Voltage (V)	Nominal Power (kW)	Rated Current (A)	Inductor (L_1) (µH)	Transformer Leakage (µH)	Grid Voltage (V)	Switching Freq (kHz)	Filter Capacitance (C_1) (µF)
300-500	500	1400	25	9	480	2-3	1600





The schematic and a picture of the 500kW grid connected voltage source inverter.

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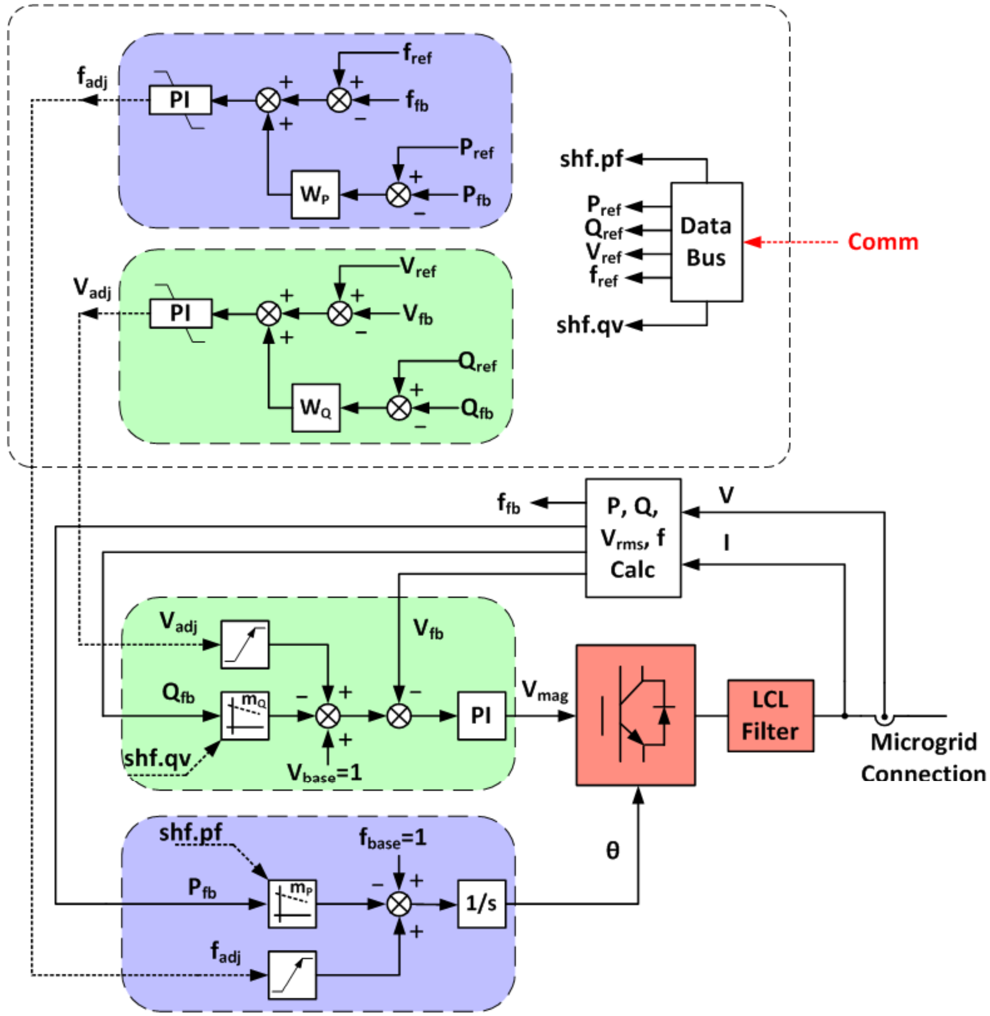
Functions for Microgrid Controls

- Inverter-based source active/reactive power control
- NG generator or microturbine control
- Voltage mode or current mode
- Power sharing between sources
- Frequency and voltage controls
- Step changes in load
- Transitions from grid-tie to island and vice versa
- Source priority
- Load management
- Black start

Controls for Storage Inverter

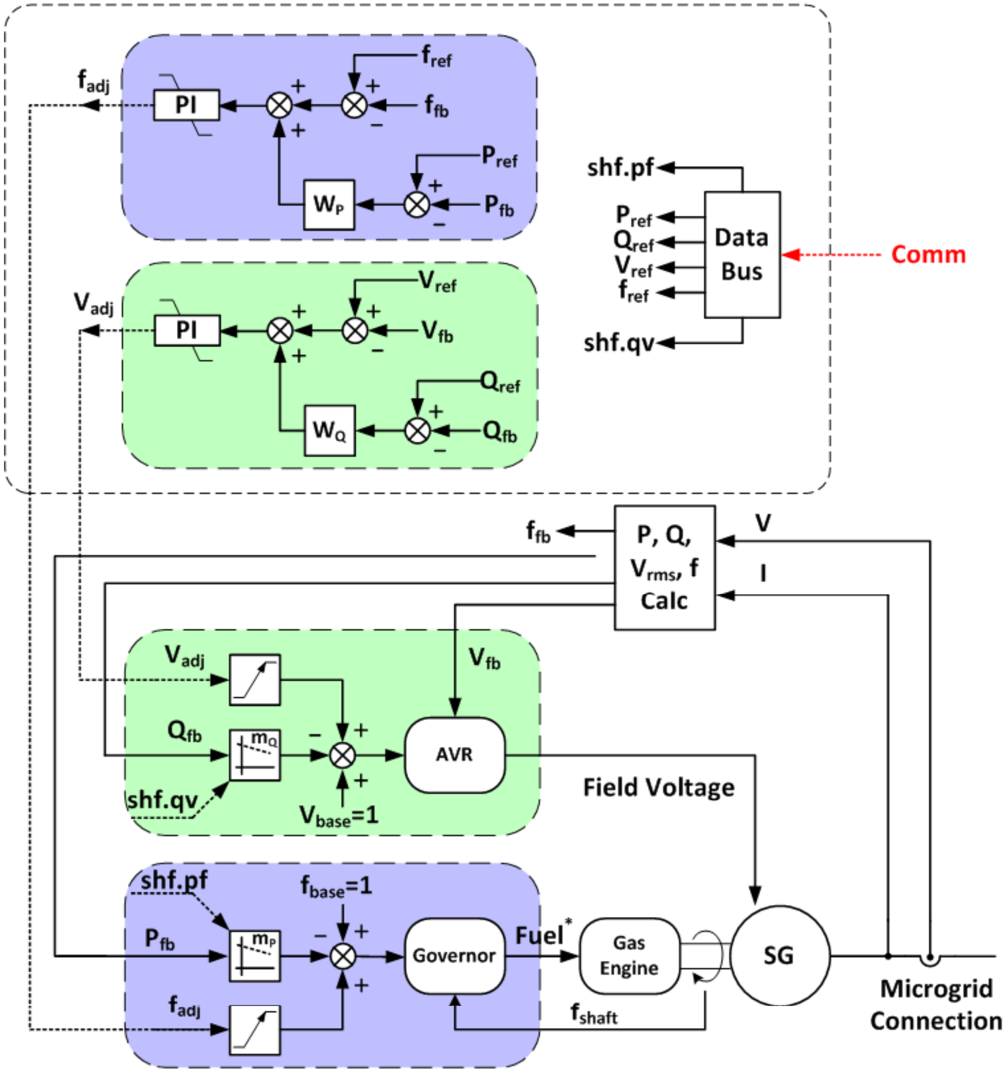
- Inverter responds almost instantaneously to the adjustment signals.
- Adjustment controller has to be smaller in order to avoid injecting large voltage and frequency transients.
- Inverter tends to initially pick up the majority of any load steps.
- If the controller tries to pass the load to the generators too quickly, undesirable transients may occur.



The block diagram of the controls for voltage and frequency of storage inverter.

Controls for NG Generator

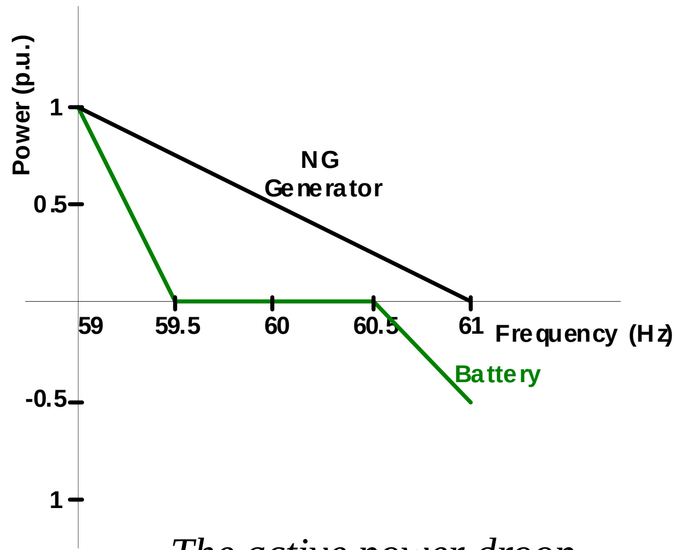
ISO communicated values are updated every 100mS while the measured values are updated every 20mS.



The block diagram of the controls for voltage and frequency of the diesel generator.

Island Mode - System Modeling

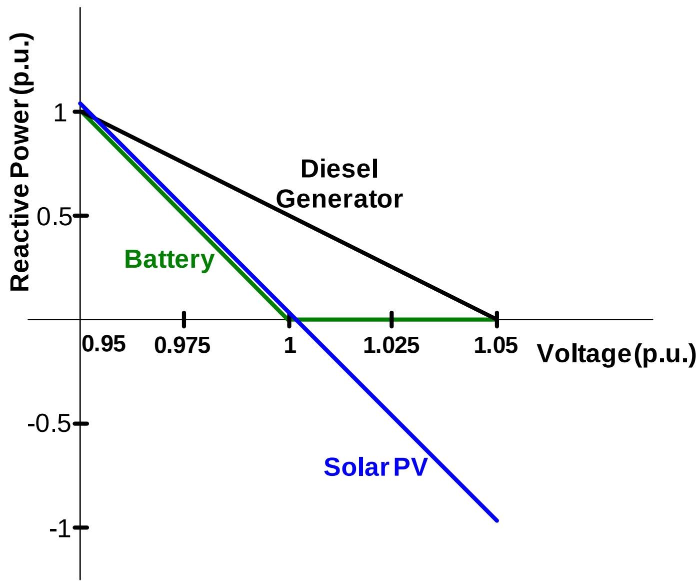
- The primary control is to adjust the active and reactive power of all the sources to regulate the system frequency and voltage.
- The secondary control is to maximize the power capture from the renewable energy sources and minimize the energy delivered by the NG generator.
- A droop control is designed for battery and NG generator to coordinate the sources in order to regulate the system frequency.
- A proportional integrator (PI) controller is designed to curtail the wind power when the frequency exceeds 60.8 Hz.
- For the solar PV, the curtailment starts at 60.9 Hz.



The active power droop mechanism for diesel generator and battery in the microgrid.

Island Mode - Reactive Power Control

- A droop control mechanism has been defined for NG generator, solar PV and battery to regulate the reactive power.
- NG generator ceases to produce reactive power when its terminal voltage reaches 1.05 p.u.
- The battery inverter and solar PV inverter will also provide reactive power when their terminal voltages drop under 1 p.u.
- The solar PV inverter absorbs reactive power to lower the voltage when it exceeds 1 p.u.
- The reactive power of the wind generator is regulated using a PI controller in order to prevent source contention.



The reactive power droop mechanism for diesel generator, solar PV and battery in the microgrid.

Constraints on P-Q Controls

- In steady state, the total delivered apparent power must not exceed the rating of the converter/source.
- To reduce the stress on the diodes of the inverter, the reactive power generation is limited to 0.5 p.u. when the active power of the sources is under 0.29 p.u. This active power level is the border line for power factor (PF) of 0.5.
- When the voltage exceeds a certain value (e.g. 1.04 p.u.), reactive power is first absorbed to the limit and then the real power is curtailed.

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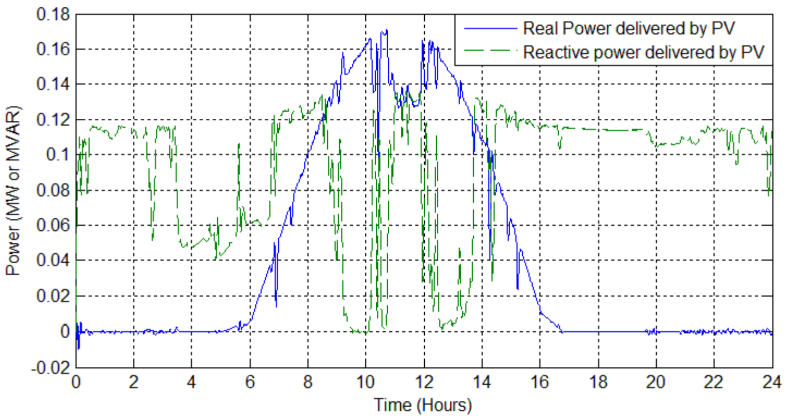
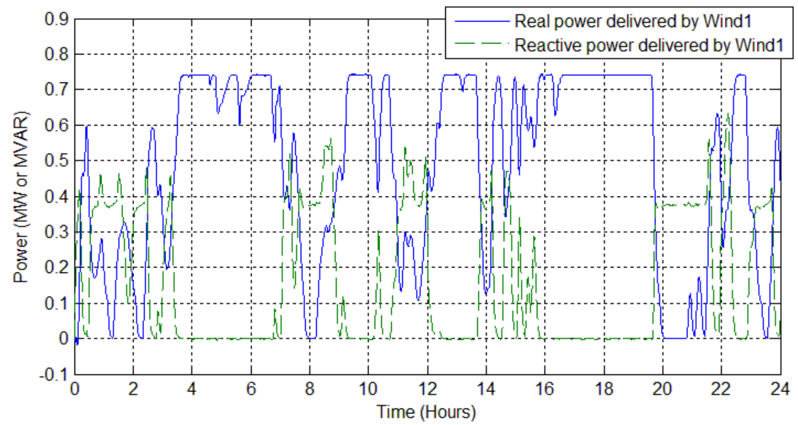
Managed Renewable Power Profiles



Active and reactive power delivered by 0.25MW solar PV.

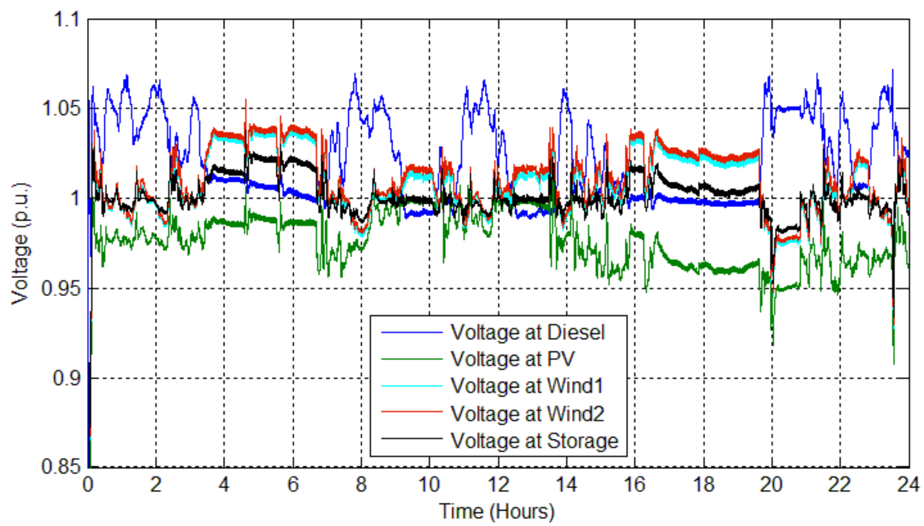


Active and reactive power delivered by one of the 0.75MW wind turbines.

Active power from wind and PV sources must be curtailed at some instances to manage the voltage profile.

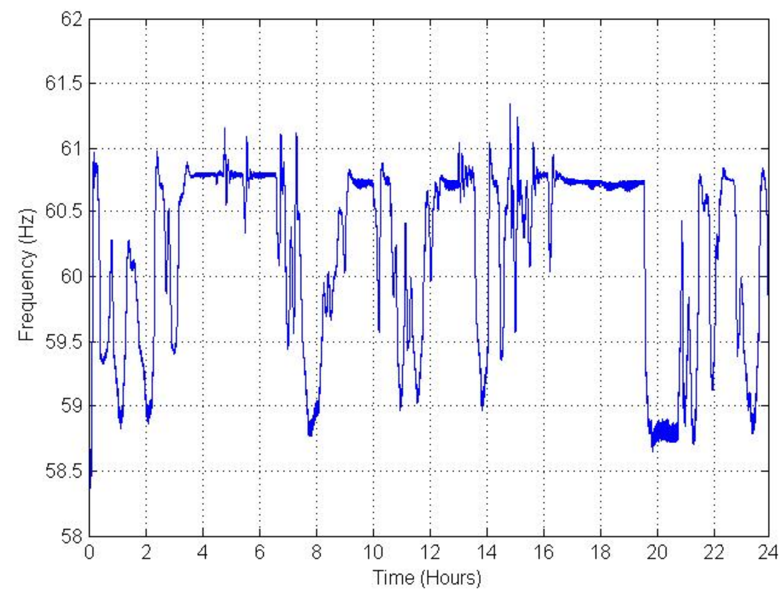
Total active and reactive power delivered by two 0.25MW battery storage systems.

Resultant Voltage Profiles



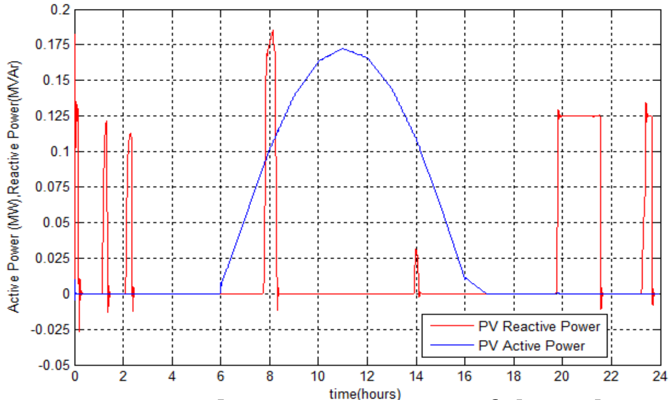
Improved voltage profile of renewable sources

The voltage at all source and load buses are in the acceptable range. The frequency swings down to 58.7Hz when wind is down.

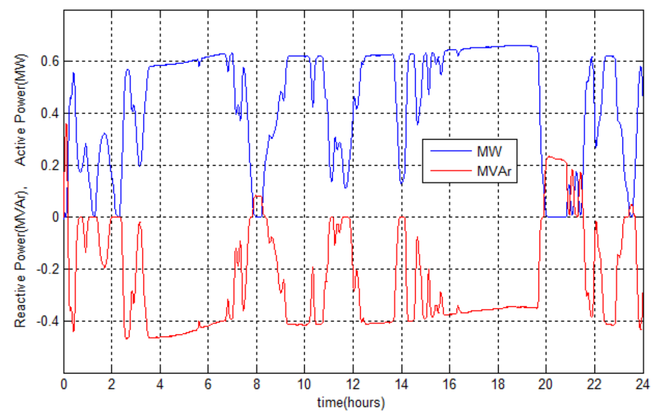


Q. Fu, A. Solanki, L. F. Montoya, A. Nasiri, V. Bhavaraju, D. Yu, T. Abdellah, "Managing Intermittent Renewables in a Microgrid," in Proc. 2012 IEEE PES Innovative Smart Grid Technologies Conference, Washington D.C.

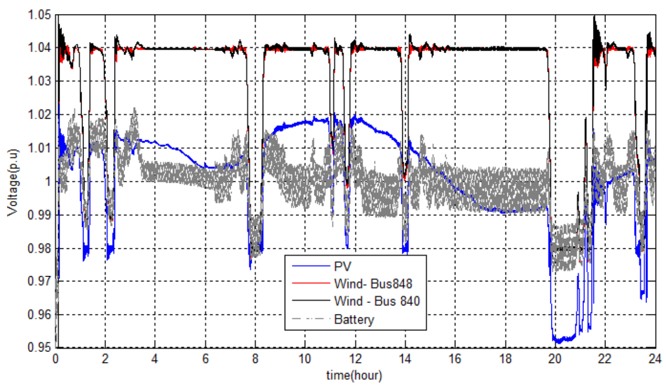
Renewables in Grid-Tie Mode



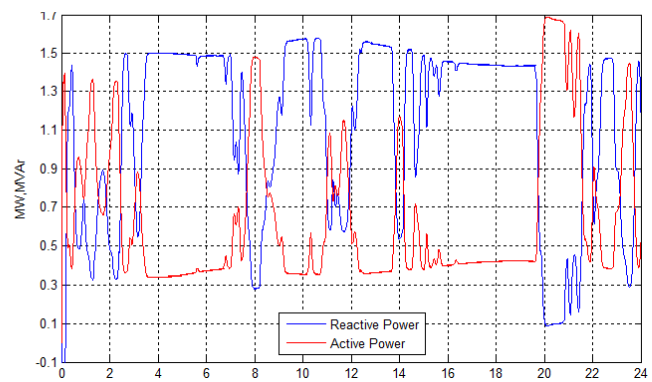
Active and reactive power of the solar PV in grid connected mode.



Active and reactive power of the wind turbine on bus 840 in grid connected mode.



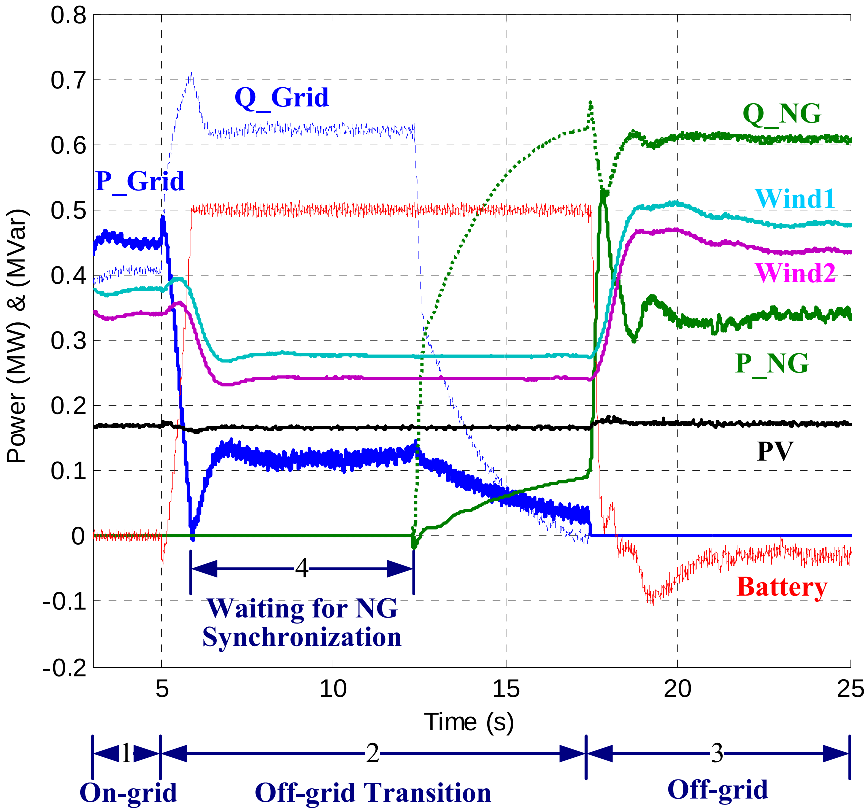
Voltages at renewable source buses in grid connected mode.



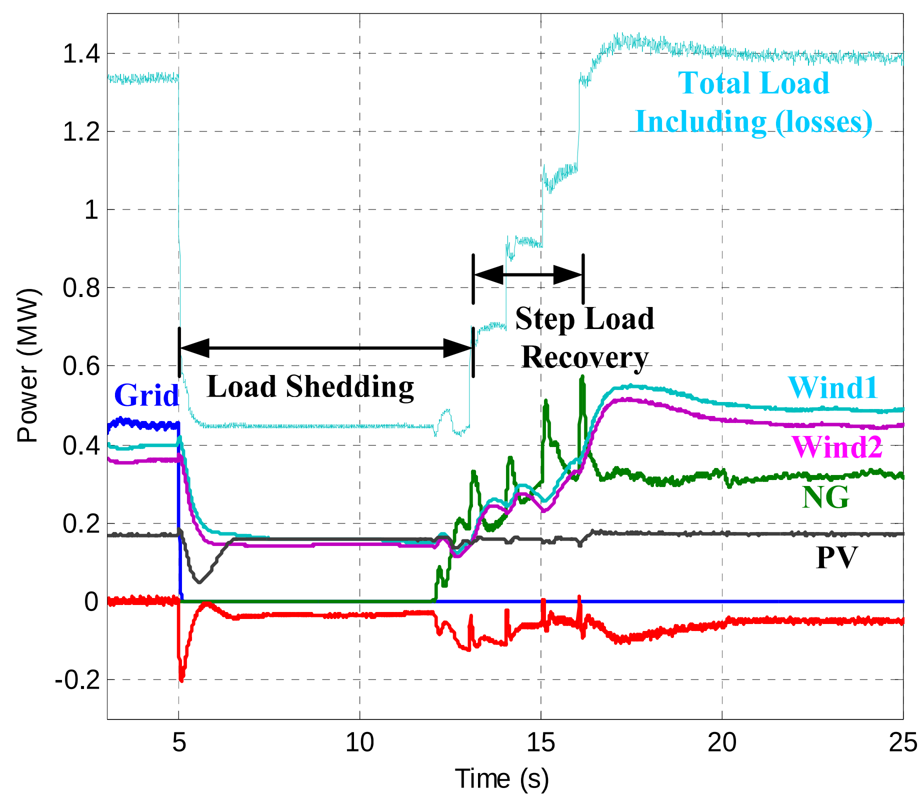
Active and reactive power delivered by the grid to the system.

Active power of the wind has been curtailed in this mode as well to mange the voltage profile.

Microgrid Islanding



Intentional islanding: real and reactive power delivered by the grid and five sources with minimum load and maximum renewables.

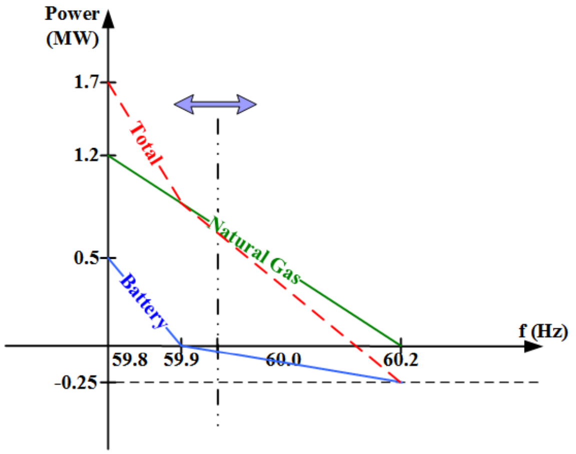


Unintentional islanding: total load and real power delivered by grid and five sources with minimum load and maximum renewables.

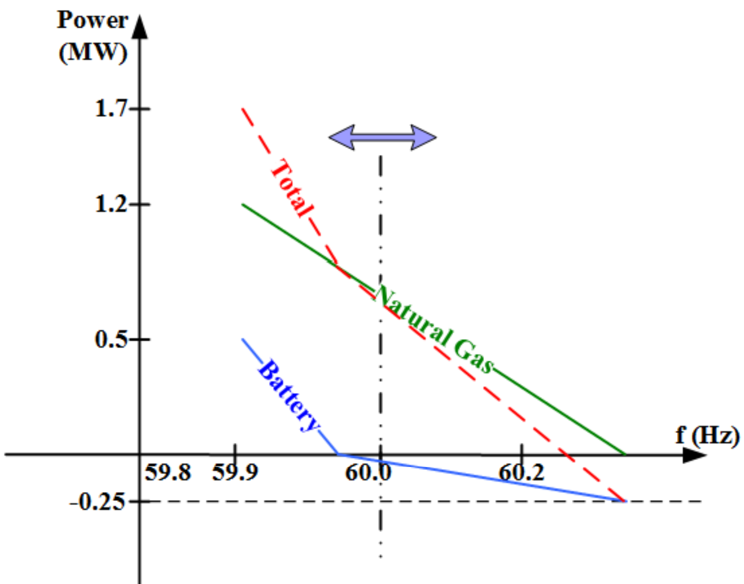
Q. Fu, A. Solanki, A. Nasiri, V. Bhavaraju, T. Abdallah, and D. Yu, "Transition Management of Microgrids with High Penetration of Renewable Energy," Forthcoming, IEEE Transactions on Smart Grid, Digital Identifier: 10.1109/TSG.2013.2286952, 2014.

Microgrid Reconnection

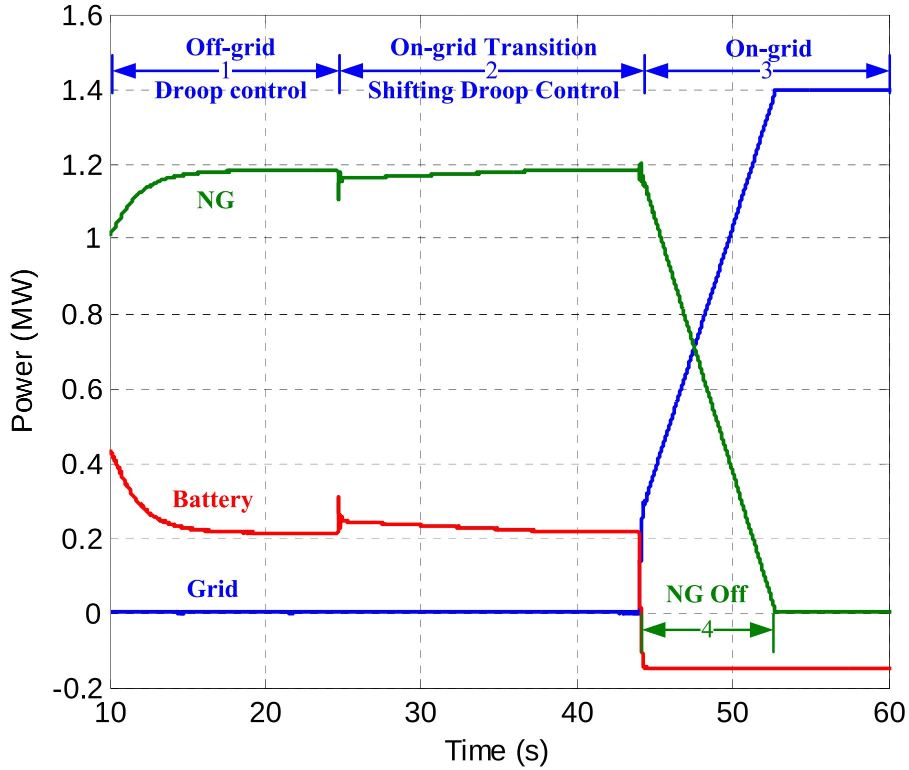
A shifting droop control is developed to minimize transients during reconnection.



The conventional droop curve



The shifting droop curve



Waveforms of power delivered by grid, natural gas generator and battery during reconnection.

Generation Capacity Sizing for Demand

- The maximum load demand of the system is 1.42MW.
- To size the NG generator and energy storage, it is suggested that they should meet the total load demand considering line losses, without renewable energy sources.
- Two energy storage systems with a total rating of 0.5MW for two continuous hours are considered for the system.
- The NG generator rating is selected at 1.5MVA considering 0.4MW line loss to meet the total demand.
- The ratings of the renewable sources are selected so that their total capacity does not exceed the total system demand.

Power Quality Assessment - Results

Utilities use the power reliability indexes namely

- **System Average Interruption Duration Index (SAIDI),**
- **System Average Interruption Frequency Index (SAIFI),**
- **Customer Average Interruption Duration Index (CAIDI) to evaluate the reliability of power provided to their customers.**

$$SAIFI = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}}$$

$$SAIDI = \frac{\text{Sum of all customer interruption durations}}{\text{Number of customers served}}$$

$$CAIDI = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customer interruptions}} = \frac{SAIDI}{SAIFI}$$

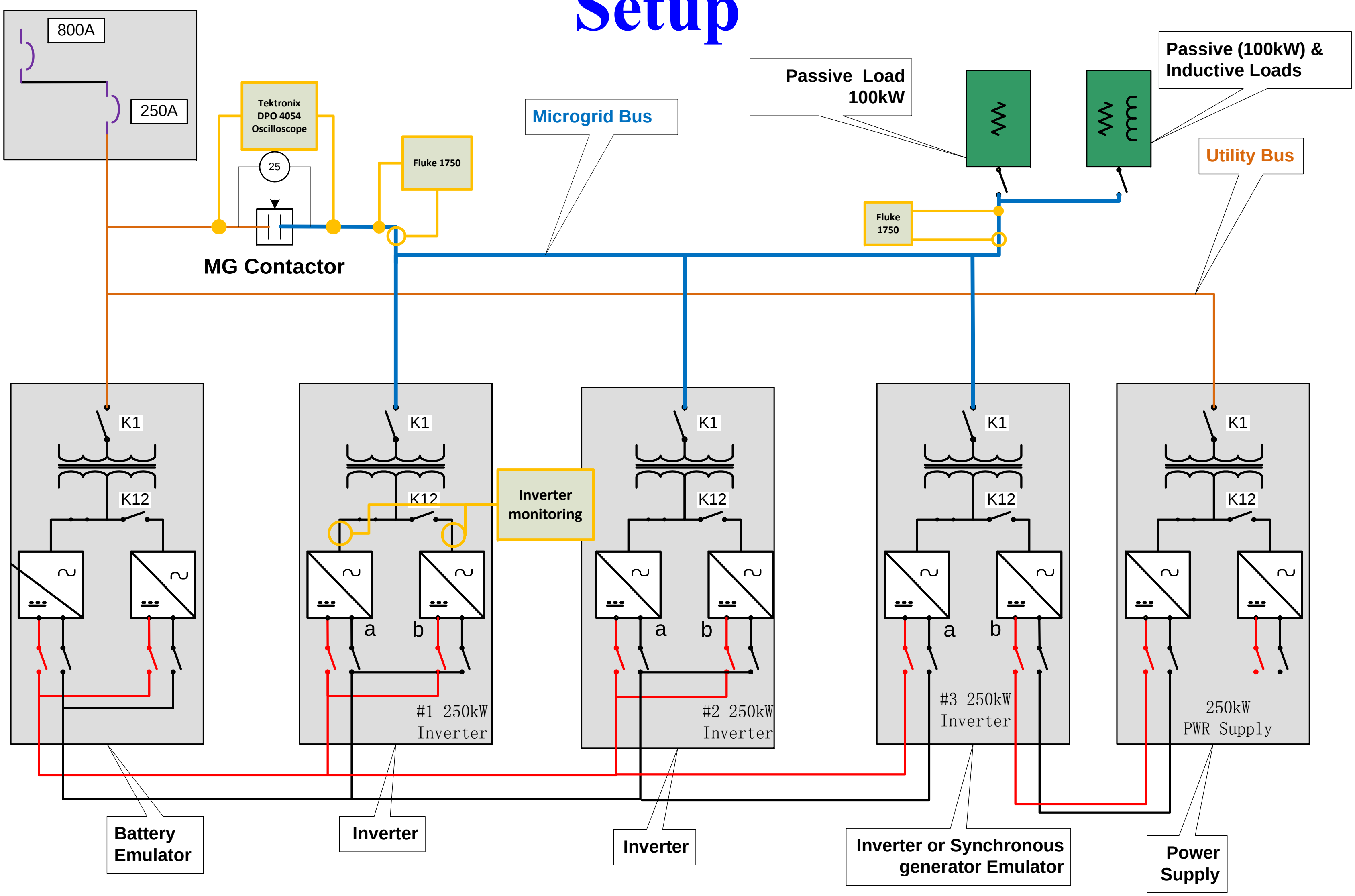
Power quality is evaluated for three cases,

- **Case-1 without regulator between buses 832 and 852 and with storage element at bus 828,**
- **Case-2 with regulator and energy storage at bus 832,**
- **Case-3 without regulator and storage at bus 832**

	Case 1	Case 2	Case 3
SAIDI (hrs)	3.25	0.91	0
SAIFI	166	796	0
CAIDI (hrs)	0.0196	0.0011	0

L. F. Montoya, Q. Fu, A. Solanki, A. Nasiri, V. Bhavaraju, D. Yu, T. Abdellah, "Generation Capacity Design for a Microgrid for Measurable Power Quality Indexes," in Proc. 2012 IEEE PES Innovative Smart Grid Technologies Conference, Washington D.C.

Schematic of Implemented Smart Feeder Test Setup



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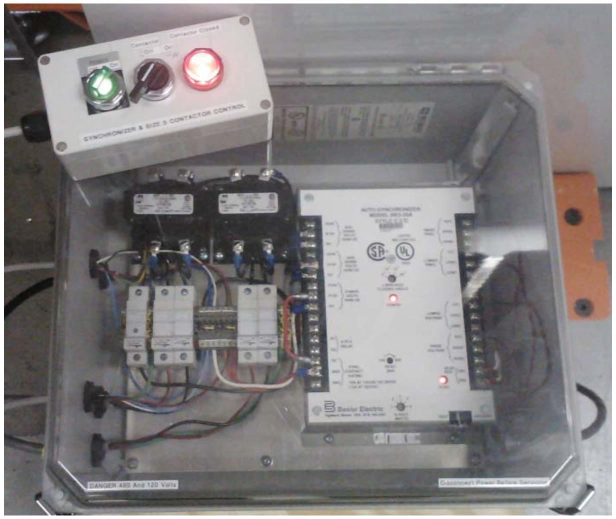
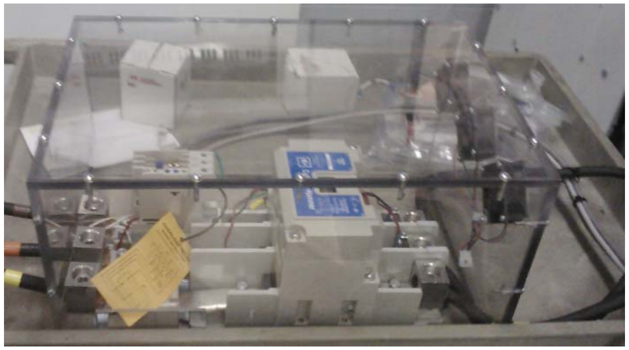
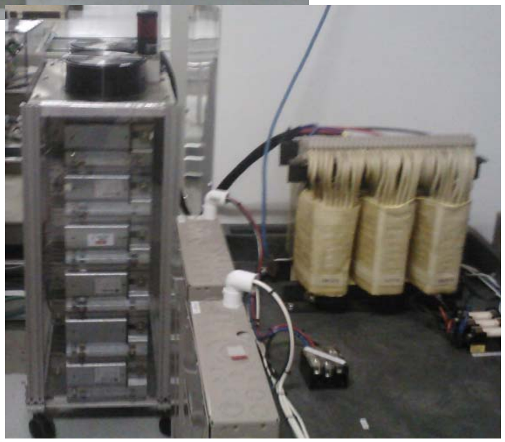
PGE Smart Feeder Implementation







5MW microgrid system that operates in grid-tie, island, and black start modes.

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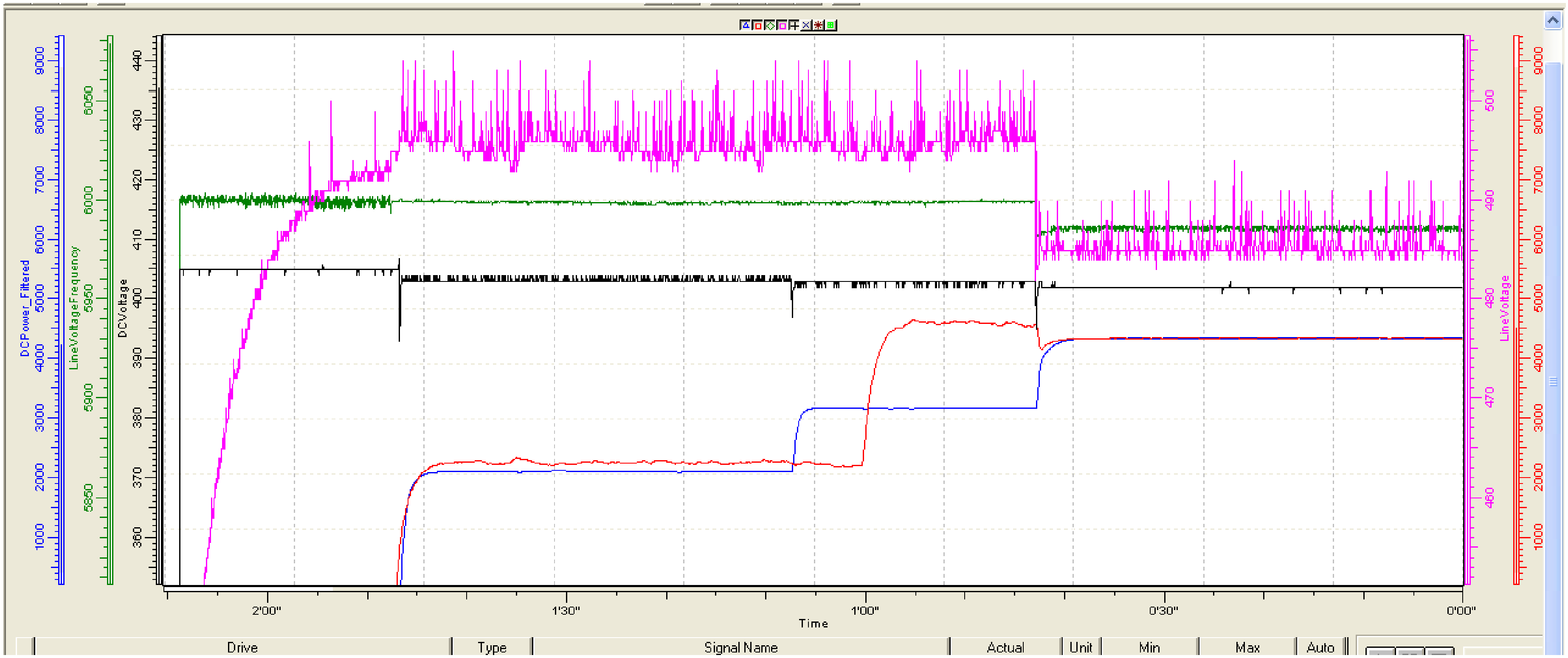
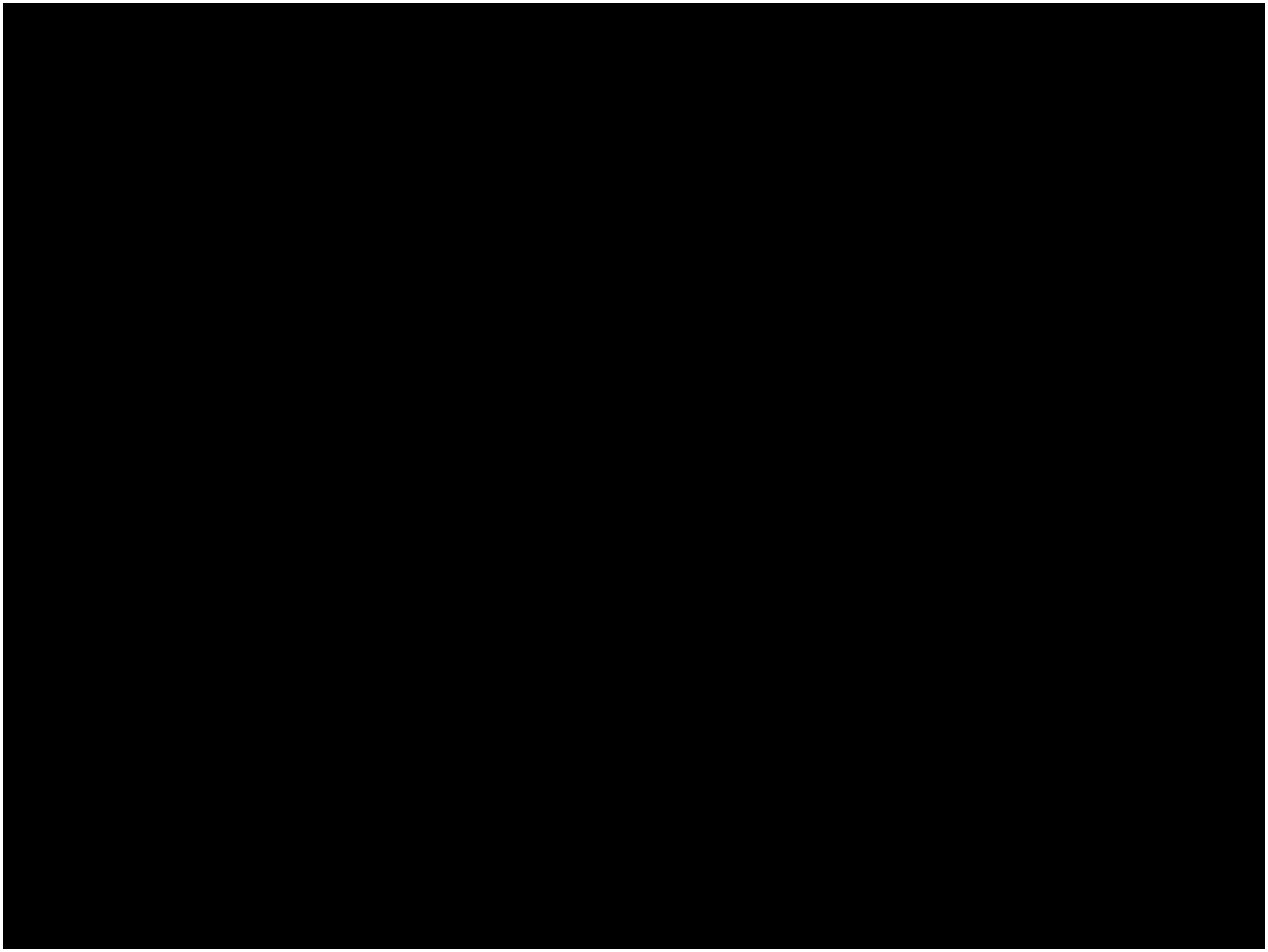
PGE HRZ Implementation Results

A screen shot of the control software, when two inverters, one in voltage mode and one in current mode are paralleled working in grid-tie and island modes. The sequence is: Synchronization, Grid-tie mode, and Island mode.



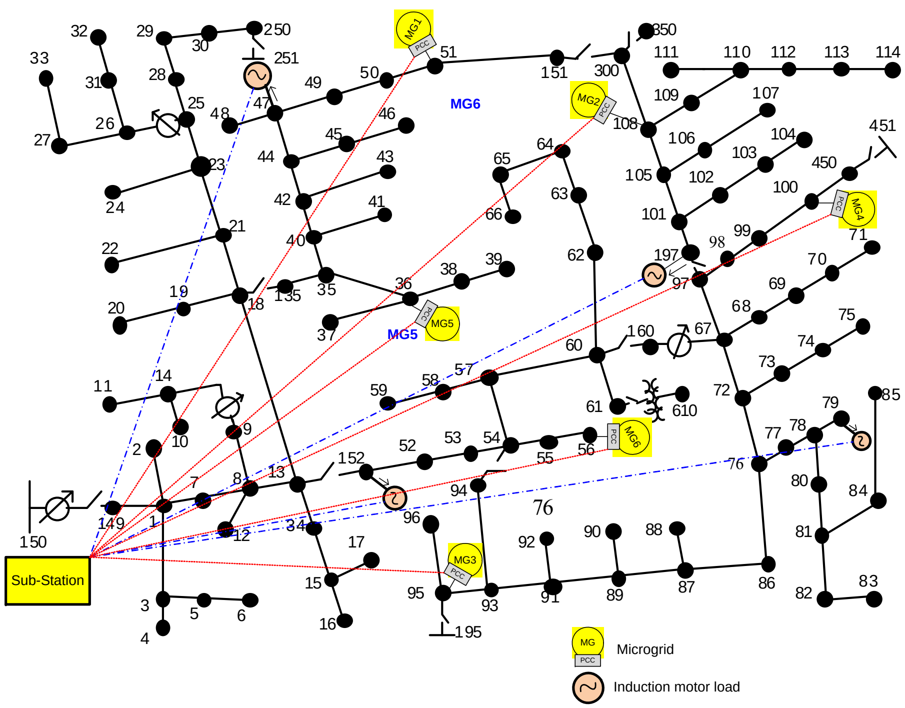
Output voltage, frequency, power, and DC bus voltage in grid-tie and island modes.

Implementation Demo

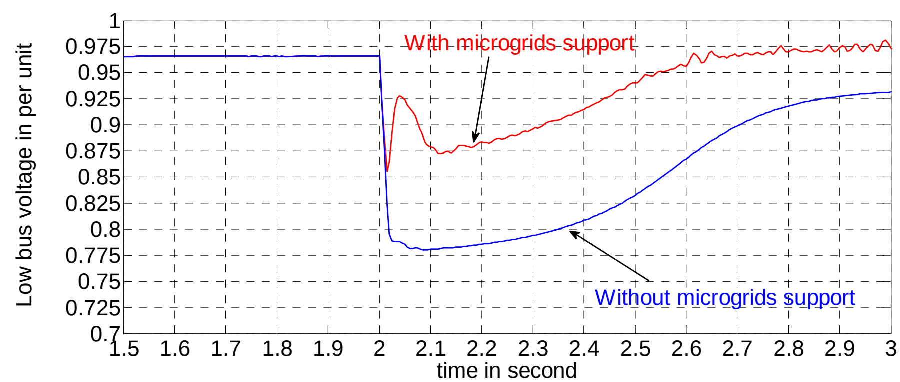


Distribution System Support Using Networked Microgrids

- **The main objective** of this project is to use microgrids to add intelligence and real-time communications and controls to distribution systems. Coupling microgrids provides benefits to the distribution system in terms of **improved voltage dynamics, frequency support, fault responses, reliability**.

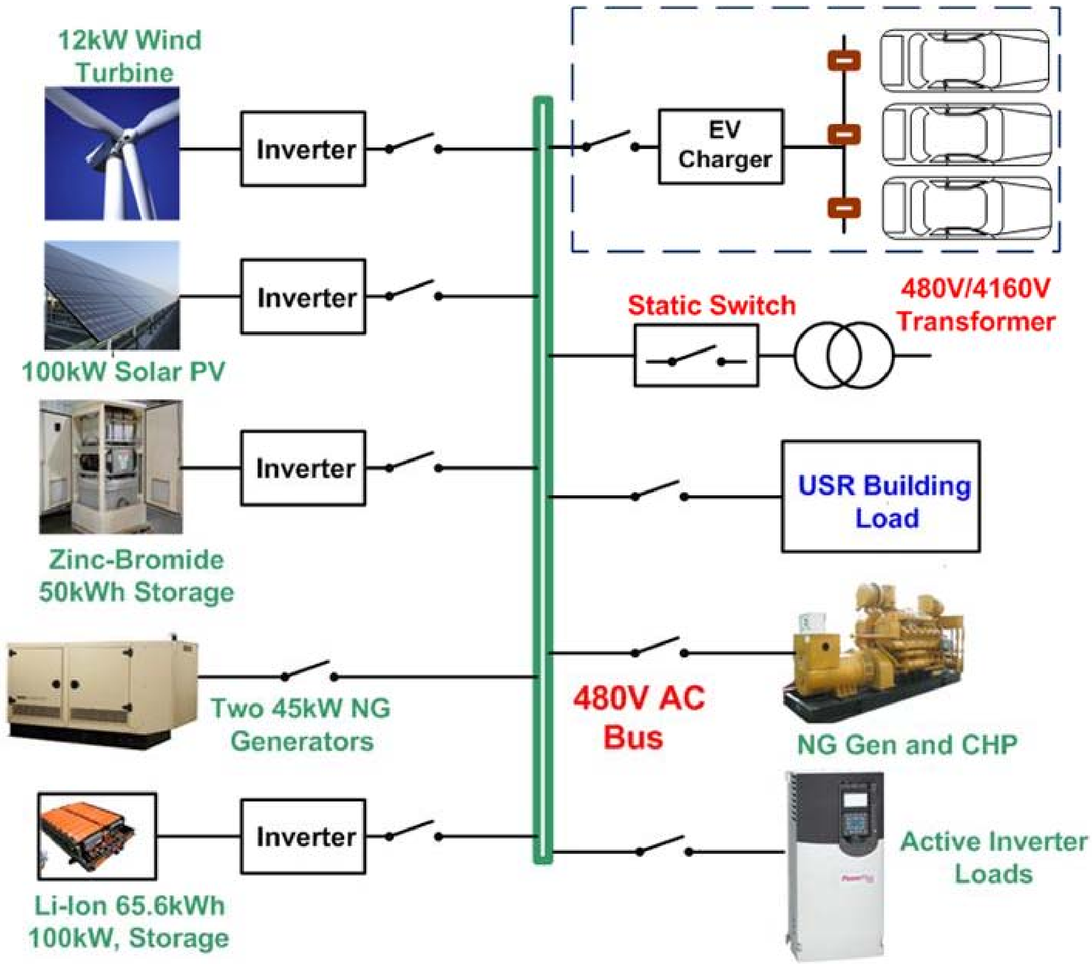


Configuration of the IEEE 123 bus test feeder with microgrds.



Bus voltage profile with and without microgrids support during induction machine starting.

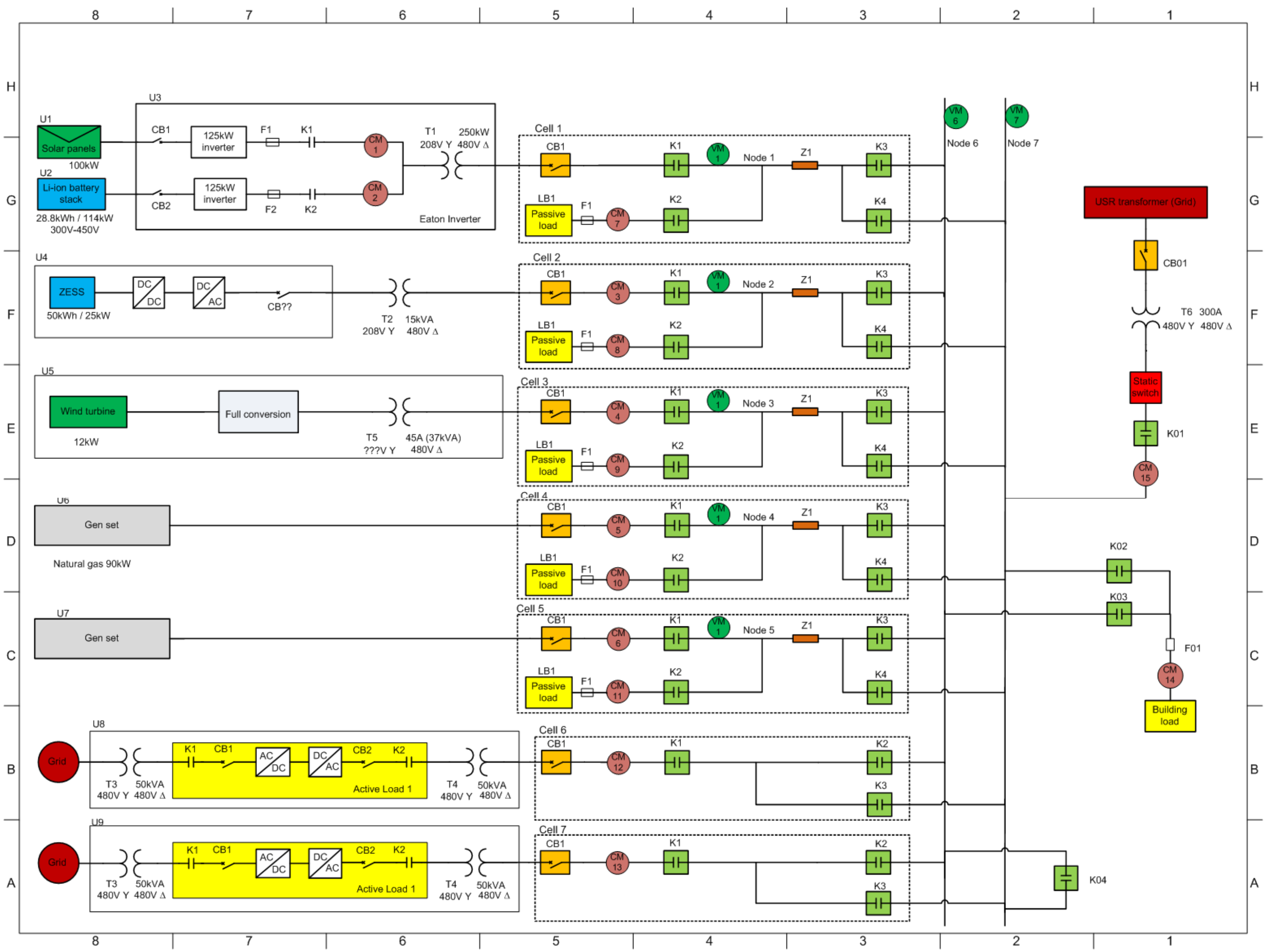
UWM Microgrid Test Bed Facility



- *100kW PV solar, with Eaton S-Max inverter in voltage and current mode.*
- *12kW wind turbine w/ PM gen.*
- *90kW and 100kW NG turbine w/ synchronous gen.*
- *50kWh, 25kW Zn-Brom. energy storage*
- *30kWh, 120kW Li-Ion Batt.*
- *Building load*

- It uses actual source hardware with controls modified for microgrid compatibility

UWM Microgrid Schematic



UWM Microgrid Testbed Update

- 12kW **wind turbine** is installed and connected, cost: $104K.
- We have signed a contract for 100kW **solar PV** system. Will be finished by Dec 15, 14, Cost $235K.
- We are bidding the implementations of **six panels** in the lab, cost $46K.
- We have purchased solar and battery **inverters**, cost $65K.
- We have a winner for **system switchgear**, cost $48K.

UWM Microgrid Testbed Update

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- We are bidding generator and battery installation, cost: ~$40K.
- We have purchased all parts for **static switch** and are building it in house.
- Kohler has provided two 45kW **natural gas generators**.
- Odyne has provided 144kWh **Li-Ion batteries**. Valance is providing technical support. We are communicating with batteries.

UWM Microgrid Testbed Update

- Rockwell has provided four 50kW drives for **active loads**.
- LEM has provided **current and voltage transducers**.
- Rockwell has provided **PLC and Ethernet switch** and expansion module.
- Have ordered **NI Compact RIO** for measurement, controls, and monitoring.
- UWM graduate school and CEAS have provided $310K of support.

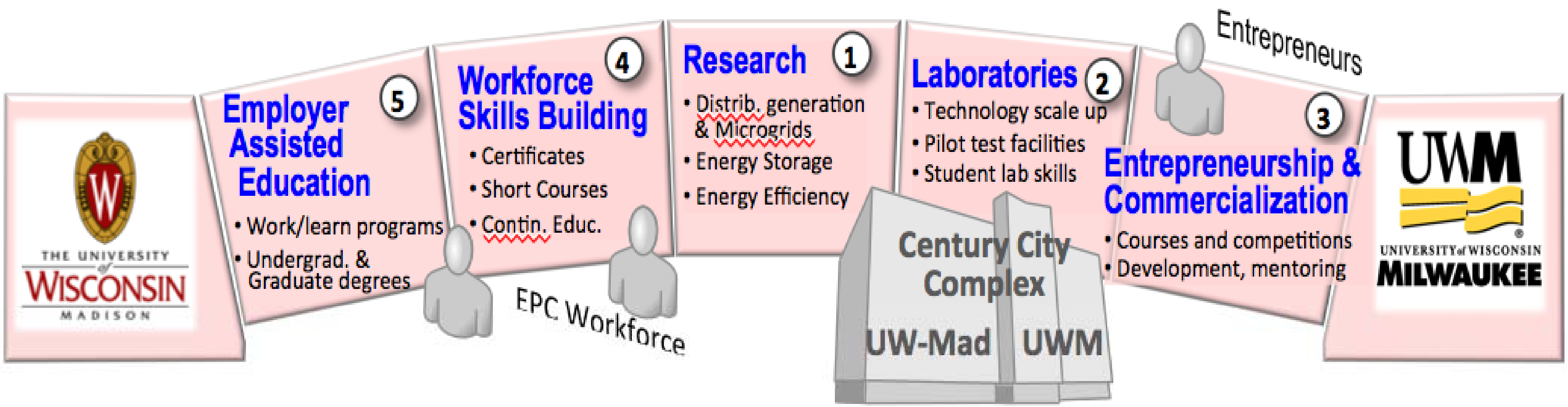
Planned UWM Microgrid Activities

- Commission 100kW solar PV system, by Dec 14
- Implement and test Static Switch, by Feb 15
- Install two 45kW NG generator, by Nov 14
- Install switchgear, by Dec 14
- Connect building loads, by Feb 15
- Commission test facilities, by Mar 15
  - Control, Data Acquisition, and Protection features
  - Microgrid controls, islanding, and reconnection
- Launch initial project work to test/exercise equipment

Research Projects Using Testbeds

- Delivery of frequency and voltage support to grid distribution system
- Energy storage sizing and placement in a microgrid to mitigate intermittency of RE sources
- Development of promising new types of energy storage for microgrid and grid applications
- Innovative inverter topologies and controls for microgrid components
- Development of technology for coupling large numbers of microgrids
- Cybersecurity for microgrids and grid

Advanced Energy Systems Center (AESC)



- An ambitious proposal was submitted to the UW System in October to establish a new multi-campus center focused on advanced energy systems, including DER and microgrids
- Center spanned a wide range from research to workforce development, continuing education, and entrepreneurship
- M-WERC was a key partner in the proposed center
- Although proposal was not successful, other opportunities are being sought to pursue key concepts

Participating Industry Partners

Contributing Participants

- ✓ Rockwell Automation
- ✓ Johnson Controls
- ✓ Regal Beloit - Marathon
- ✓ LEM
- ✓ Mercury Marine
- ✓ Kohler
- ✓ AEP
- ✓ Sauer-Danfoss
- ✓ Odyne
- ✓ Eaton Corp.

New Partners are Invited to Join Team