Microgrid Controllers
2014 T&D User Conferenc

Presented by **Chuck Wells**

Definition of Microgrid

- The term “microgrid,” is defined as a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid, operate in grid-connected or island mode.

DOE, FOA 0000997

Key drivers for microgrids

- Provide higher power quality for customers
- Reduce cost of energy
- Sell ancillary services to ISOs and area EPS
- Help support higher renewables (up to 100%)
- Sell carbon credits (California Cap and Trade)

Target performance of Microgrids

- Reduce outage time of critical loads by >98 percent
- Reduce emissions by > 20 percent
- Improve system energy efficiency by > 20 percent

Market for Microgrids in CA/USA

- In CA
  - 429 Hospitals
  - 100 + Wastewater plants
  - 100 + Water treatment plants
  - 1000 + High PV distribution circuits (PGE,SCE,SDGE)
- In USA
  - 49,059 buildings 200k to < 500k ft2
  - 11,502 buildings > 500k ft2
  - 6,753 hospitals

Past approach

- Voltage sourced DERS (CERTS)
  - University of Wisconsin and LBNL
  - Frequency droop control
  - Constant source voltage
- Examples
  - SPIDERS-Ft Carson
  - Santa Rita Jail
  - 29 Palms
  - University of Bologna (Paolone)
  - AEP test site (Columbus, OH)

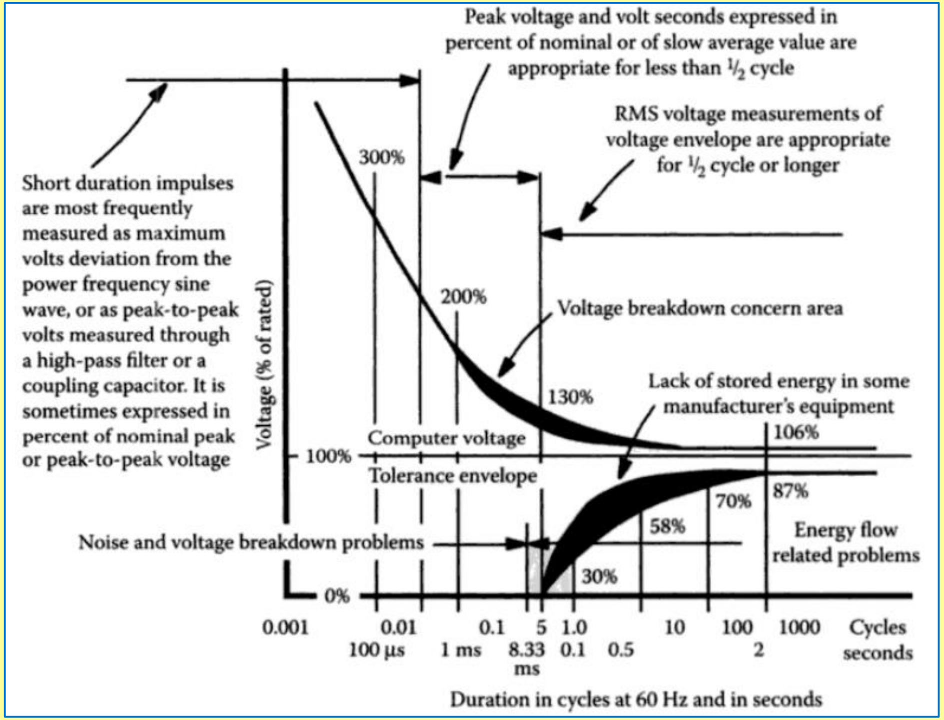
Current research direction:

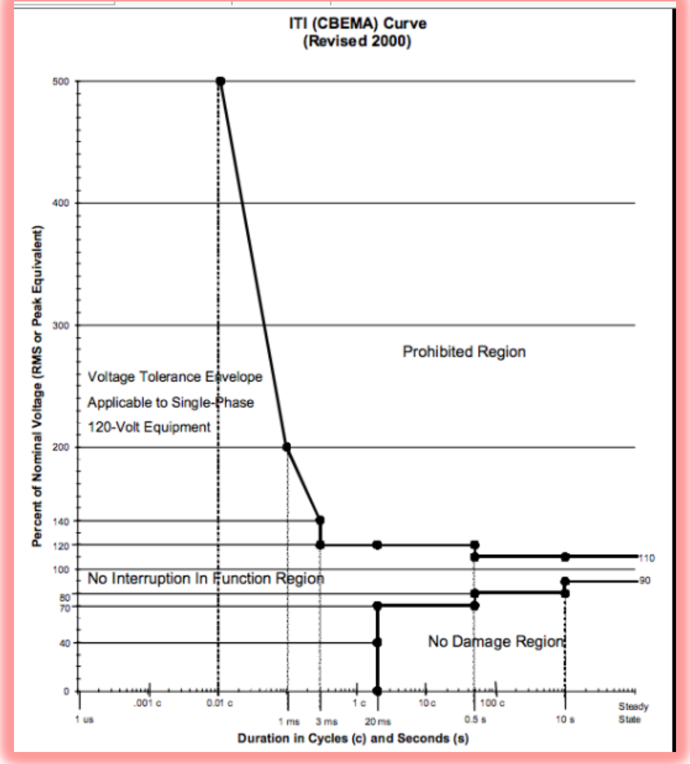
- DOE moved microgrid research to ORNL
  - NREL (switching, renewable injection lab)
  - Sandia (microgrid lab)
  - ORNL (microgrid lab)
  - DOE funded FOA-0000997 for $7 million
  - CEC funded PON-14-301 for $26.5 million
  - DOD is funding Spiders II..

Problems identified in IEEE 1547.4

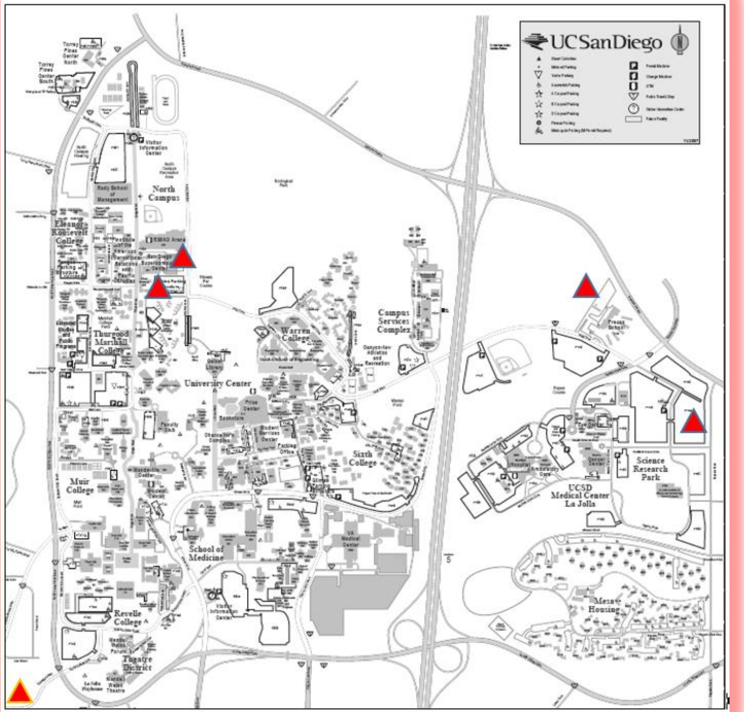
- Small signal stability
- Phase imbalance
- Voltage stability
- Frequency and voltage control
- Bumpless transfer
- Harmonic distortion (fictitious power)
- Protection
- Motor starting
- System management

Power Quality requirements (CBEMA/ITI)





UCSD Microgrid

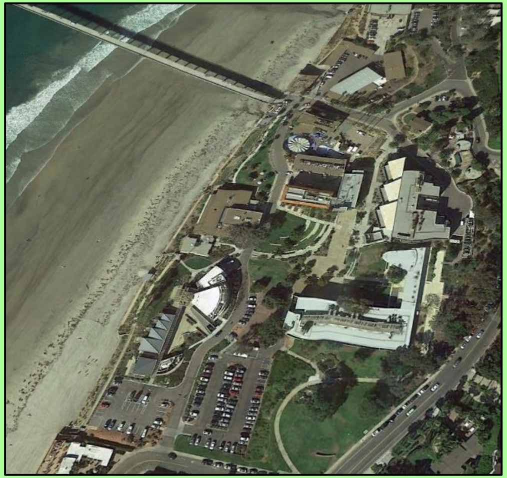


PMU Locations

Substation

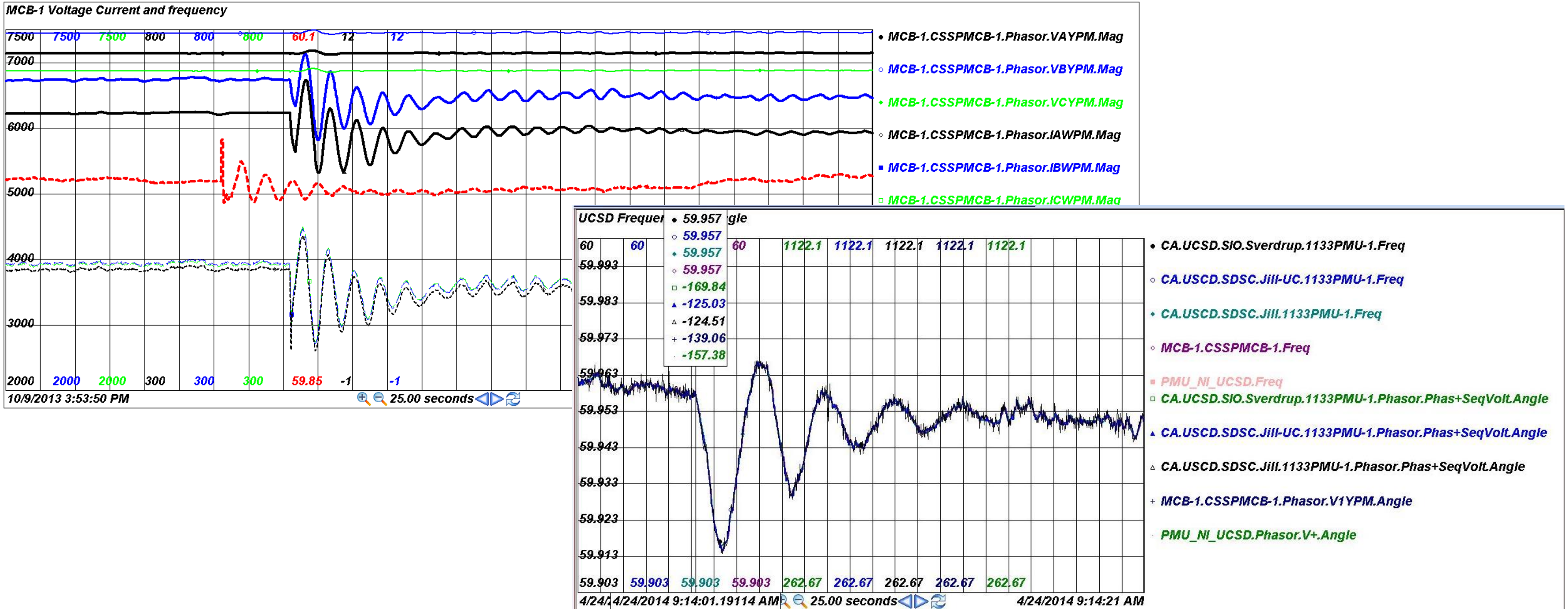
Super Computer

Scripps Institution

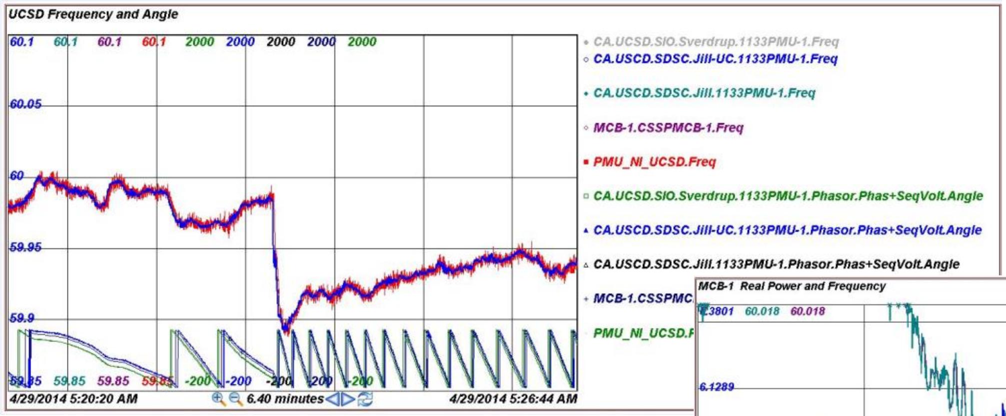


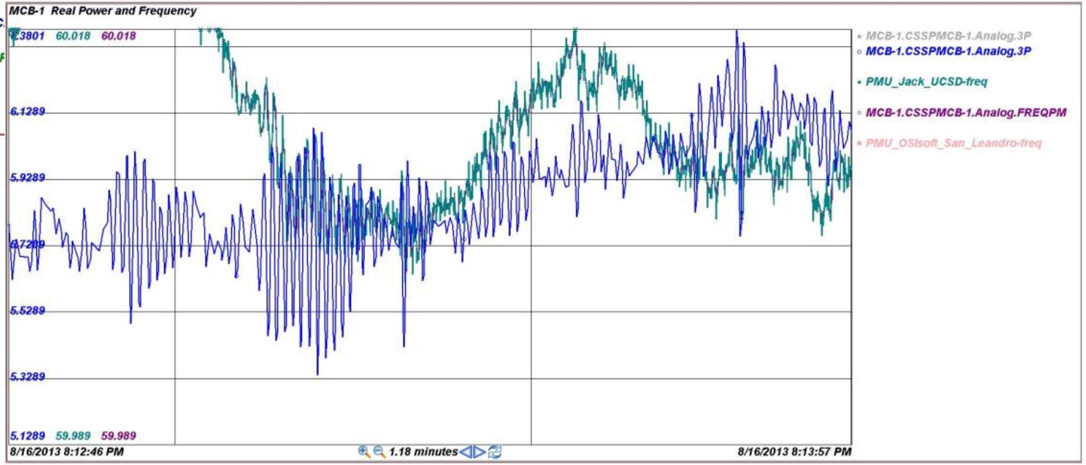
Fuel cell, solar, battery

Example of transient behavior

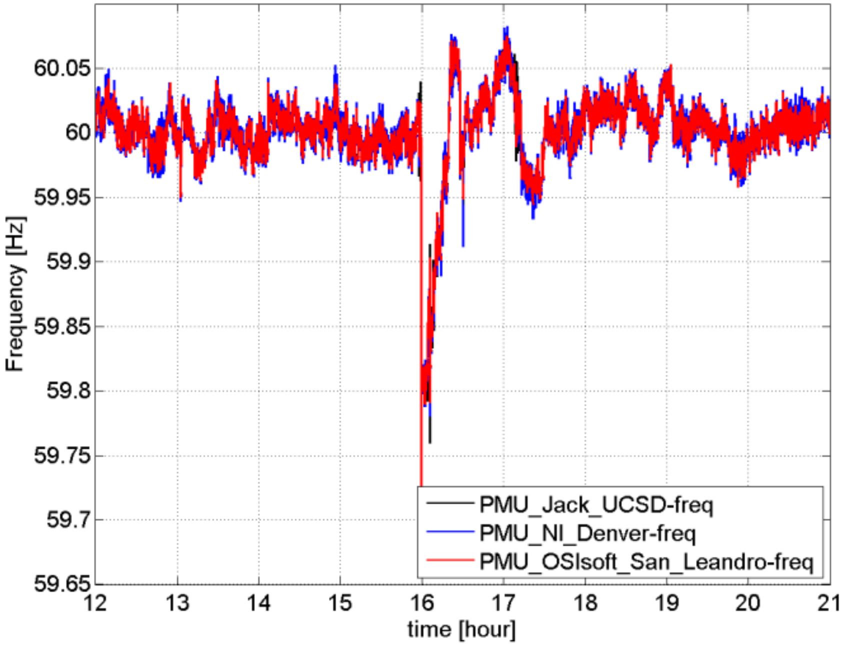


A few more examples

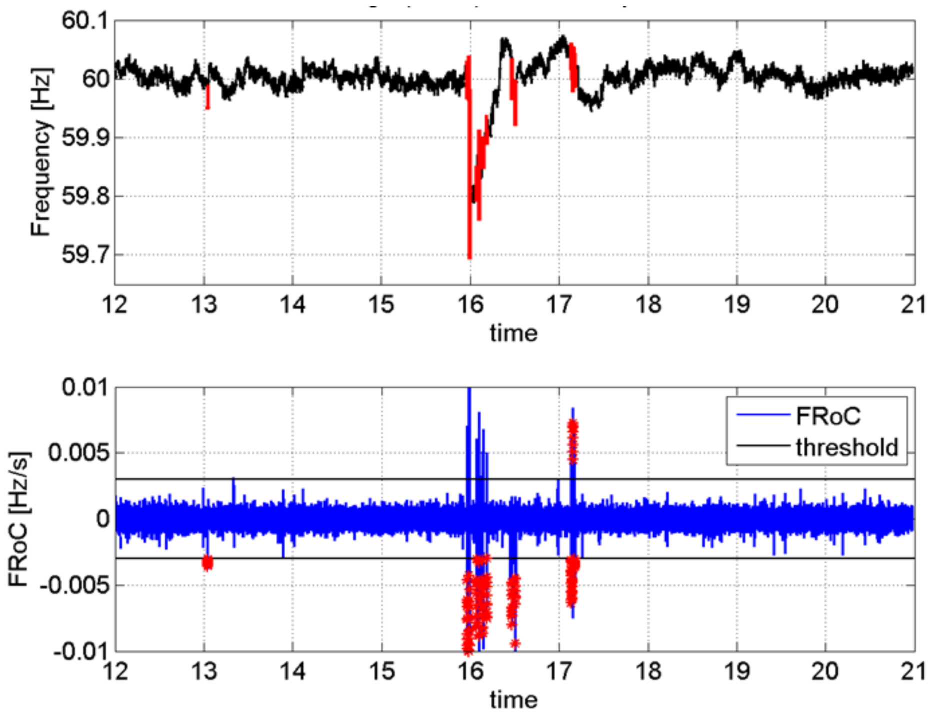




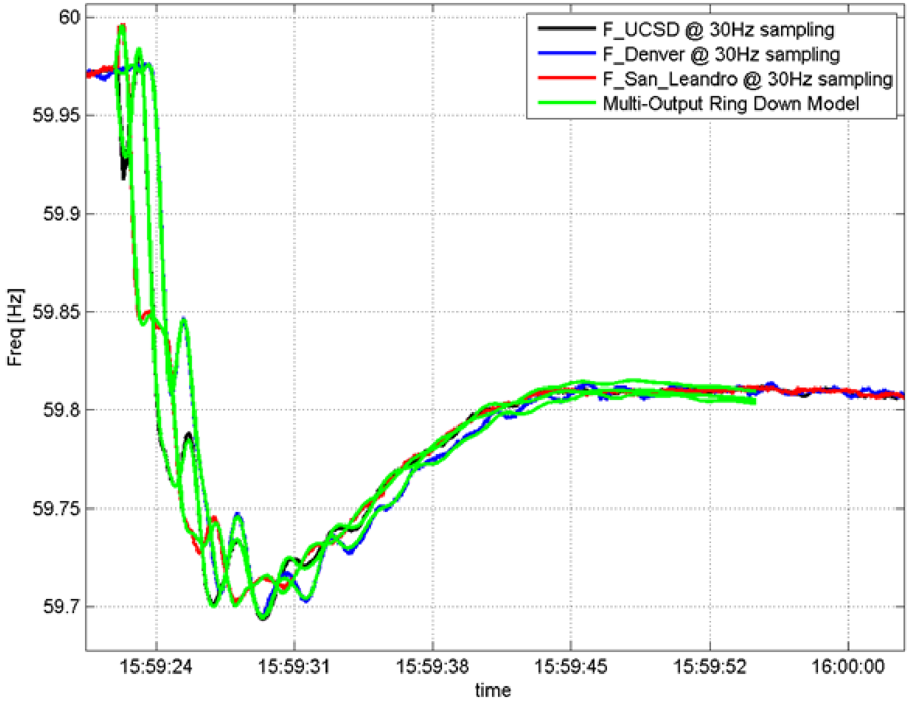
Event detection



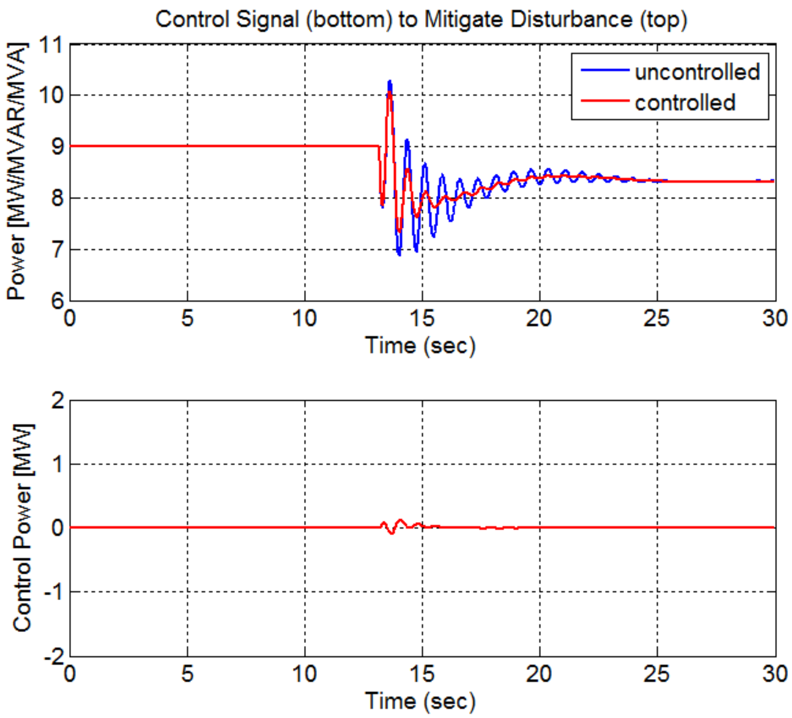
Example


60.1
60
59.9
59.8
59.7
Frequency [Hz]
12 13 14 15 16 17 18 19 20 21
time
0.01
0.005
0
-0.005
-0.01
FRoC [Hz/s]
FRoC
threshold
12 13 14 15 16 17 18 19 20 21
time

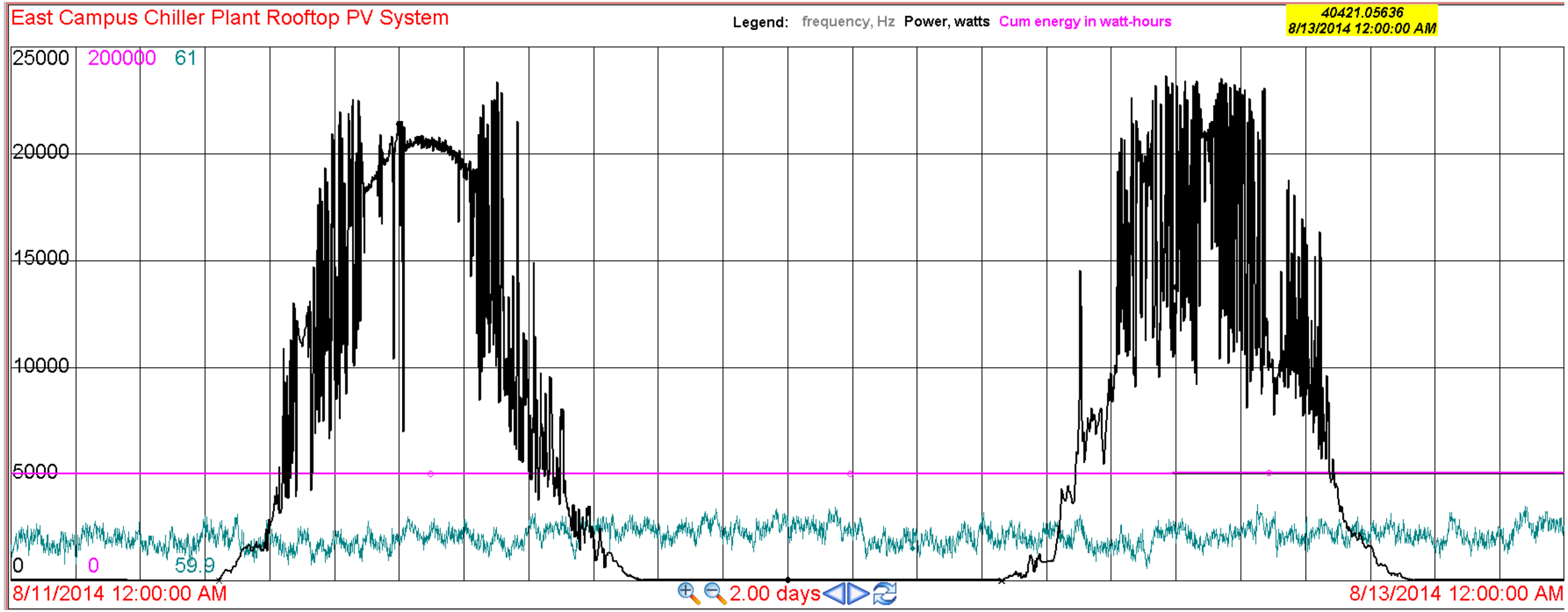
Realization



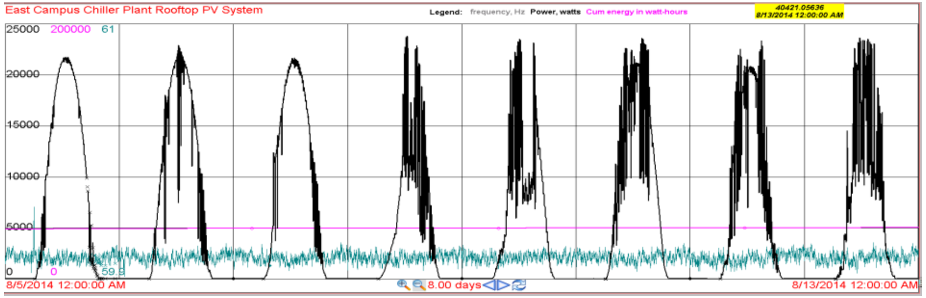
Oscillation mitigation

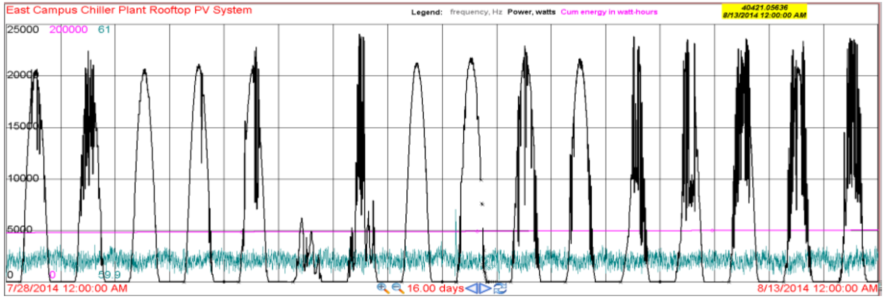


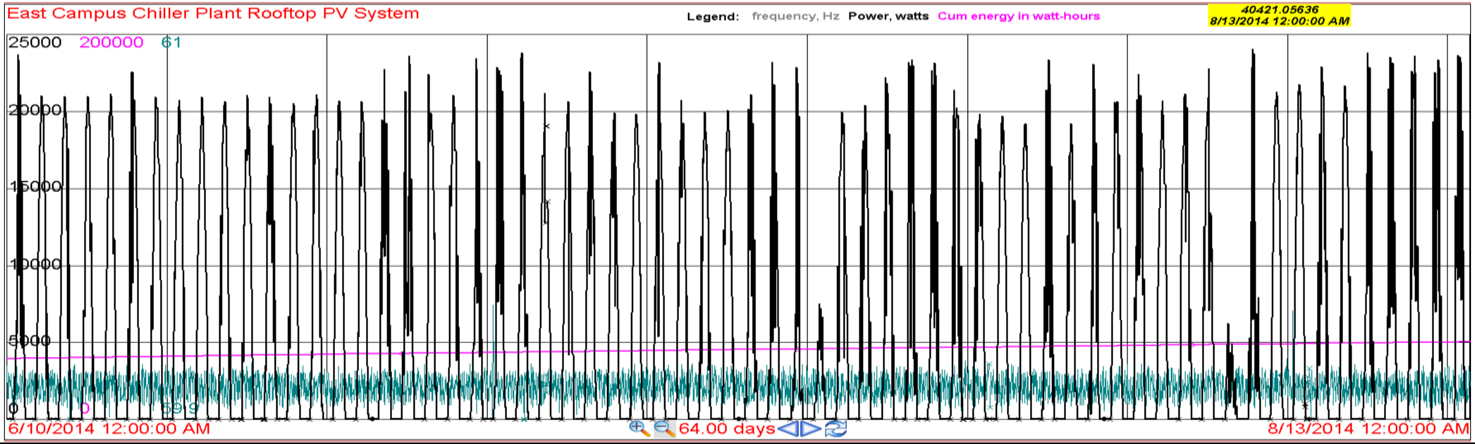
Solar intermittency in microgrids (summer)



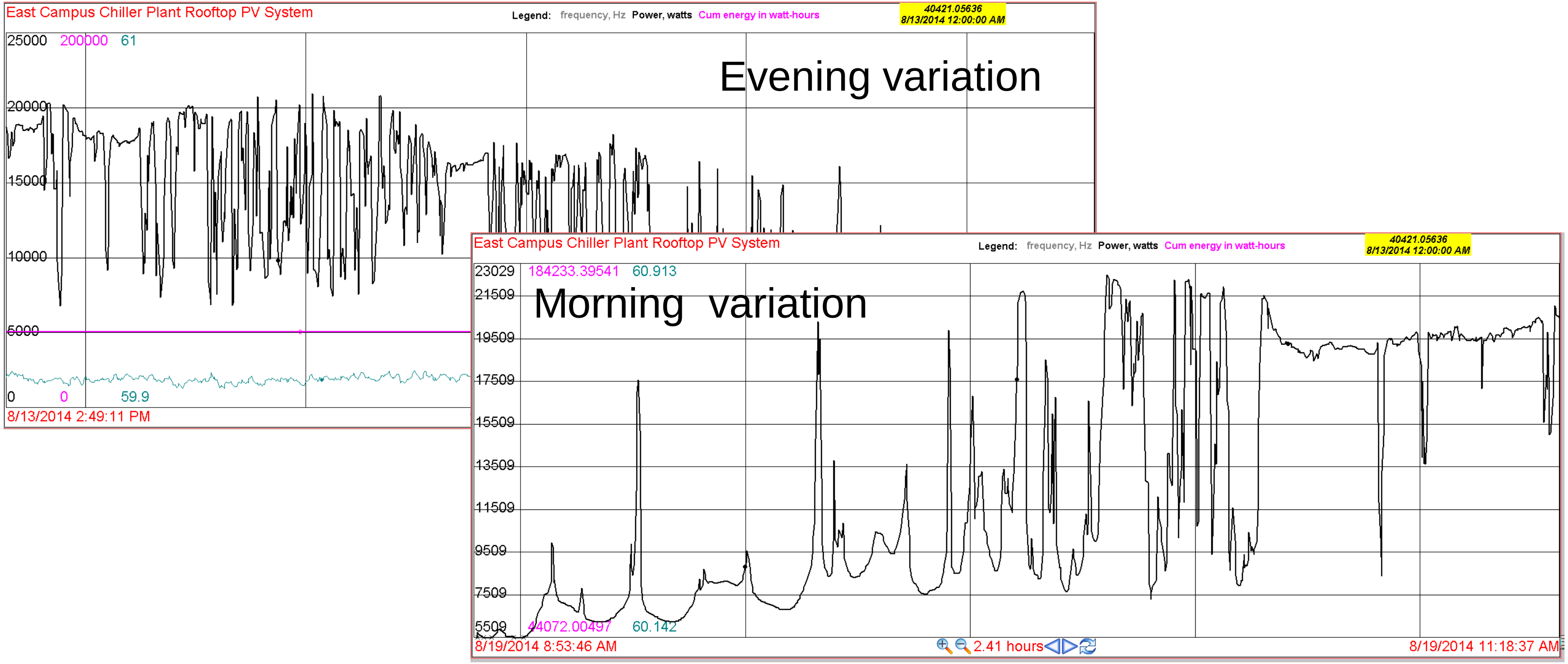
Summer-continued





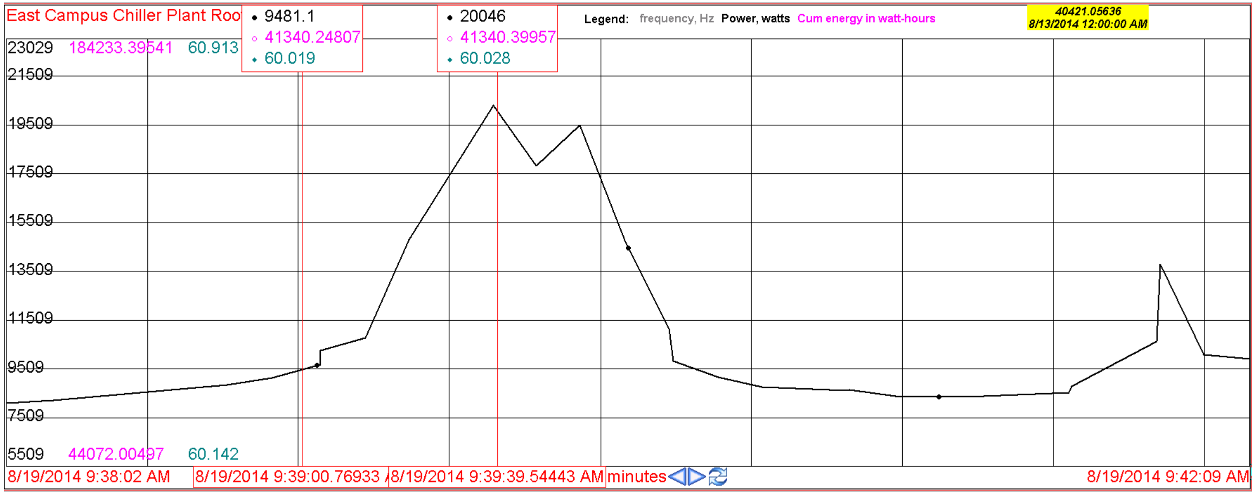


Summer-zoomed in

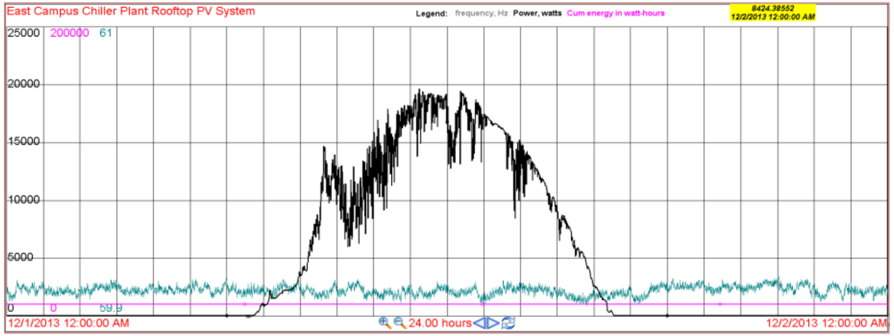


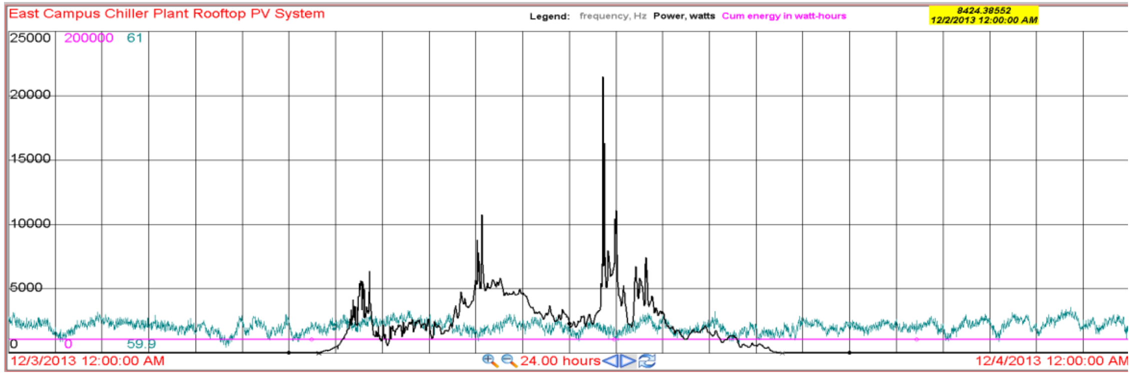
Rate of change: of output

- Up and down variation exceed 270 W/second

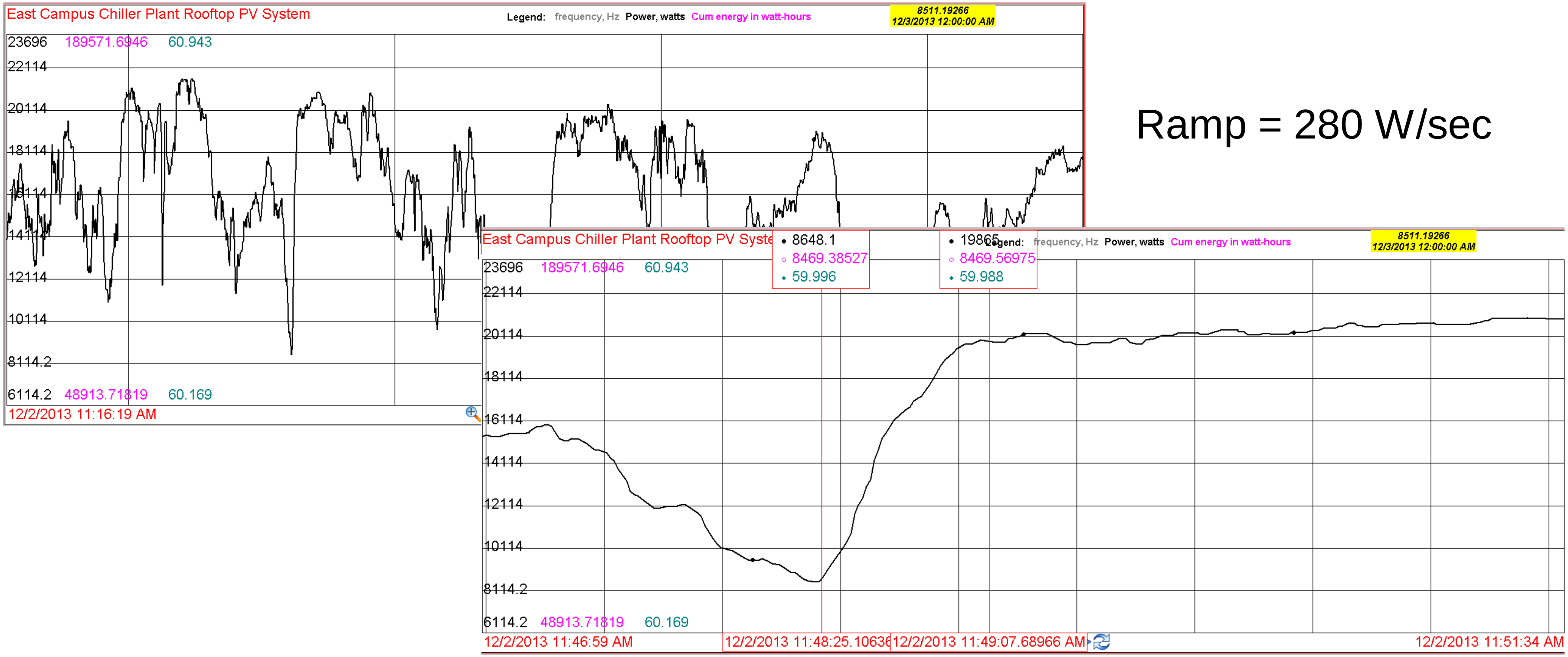


Winter variation



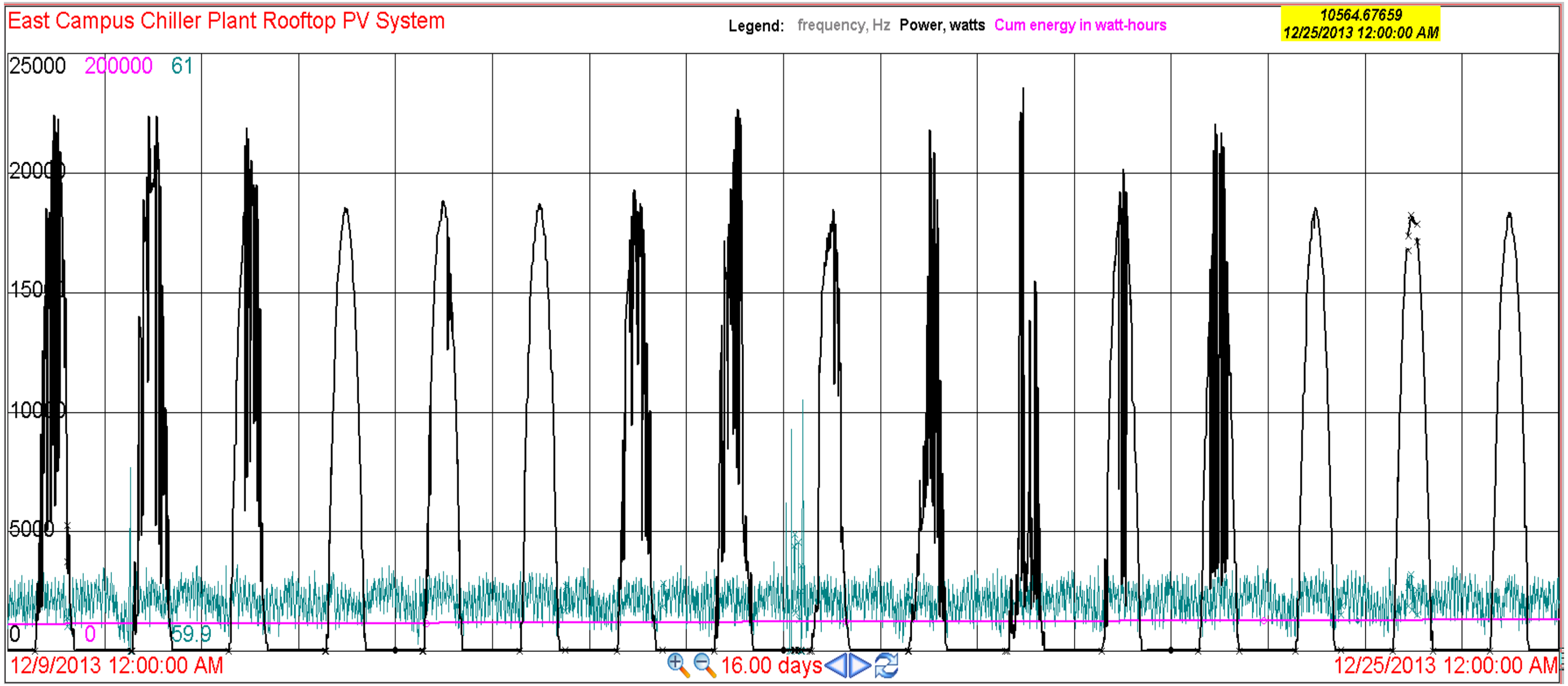


Ramp rates-winter



Ramp = 280 W/sec

Winter variation continued



OSIsoft,LLC approach

- Extensive measurement with PMUs
- Three phase dynamic models
- Low order approximate models for control
- Decoupled frequency and voltage control in island mode
- Adaptive protection settings
- Advanced warning and load shed to meet internal generation

Frequency and Voltage Control

- Current practice
  - Independent droop control for frequency
  - Independent droop control for voltage
- Basic problem
  - These control loops interact with each other
    - Why?

AC Power Flow

Consider the following model depicting the transfer of AC power between two buses across a line:

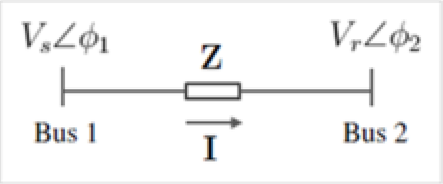


Figure 1. Simple AC power transmission model

Where $\boldsymbol{V_s} = V_s e^{-j\phi_1}$ is the voltage and phase angle at the sending end

$\boldsymbol{V_r} = V_r e^{-j\phi_2}$ is the voltage and phase angle at the receiving end

$\boldsymbol{Z}$ is the complex impedance of the line.

$\boldsymbol{I} = \dfrac{\boldsymbol{V_s} - \boldsymbol{V_r}}{\boldsymbol{Z}}$ is the current phasor

The complex AC power transmitted to the receiving end bus can be calculated as follows:

$$\boldsymbol{S} = \boldsymbol{V_r} \boldsymbol{I}^*$$

At this stage, the impedance is purposely undefined and in the following sections, a few different line impedance models will be introduced

Line transfer

RL Line

The lossless (L) line model can be made more realistic by adding a resistive component, i.e. $\boldsymbol{Z} = R + jX = Ze^{j\theta}$. The power transfer across the line is therefore:

$$\begin{aligned} \boldsymbol{S} &= \boldsymbol{V_r}\left[\frac{\boldsymbol{V_s} - \boldsymbol{V_r}}{R + jX}\right]^* \\ &= \frac{V_r e^{-j\phi_2}(V_s e^{j\phi_1} - V_r e^{j\phi_2})}{Ze^{-j\theta}} \\ &= \frac{V_s V_r}{Z} e^{-j(\phi_2 - \phi_1 - \theta)} - \frac{V_r^2}{Z} e^{j\theta} \end{aligned}$$

From the above equation, the active and reactive power transfer can be shown to be:

$$P = \frac{V_s V_r}{Z}\cos(\delta - \theta) - \frac{V_r^2}{Z}\cos\theta$$

$$Q = -\frac{V_s V_r}{Z}\sin(\delta - \theta) - \frac{V_r^2}{Z}\sin\theta$$

Frequency and Voltage Coupling

RL Line

The lossless (L) line model can be made more realistic by adding a resistive component, i.e. $\boldsymbol{Z} = R + jX = Ze^{j\theta}$. The power transfer across the line is therefore:

$$\begin{aligned} \boldsymbol{S} &= \boldsymbol{V_r}\left[\frac{\boldsymbol{V_s} - \boldsymbol{V_r}}{R + jX}\right]^* \\ &= \frac{V_r e^{-j\phi_2}(V_s e^{j\phi_1} - V_r e^{j\phi_2})}{Ze^{-j\theta}} \\ &= \frac{V_s V_r}{Z} e^{-j(\phi_2 - \phi_1 - \theta)} - \frac{V_r^2}{Z} e^{j\theta} \end{aligned}$$

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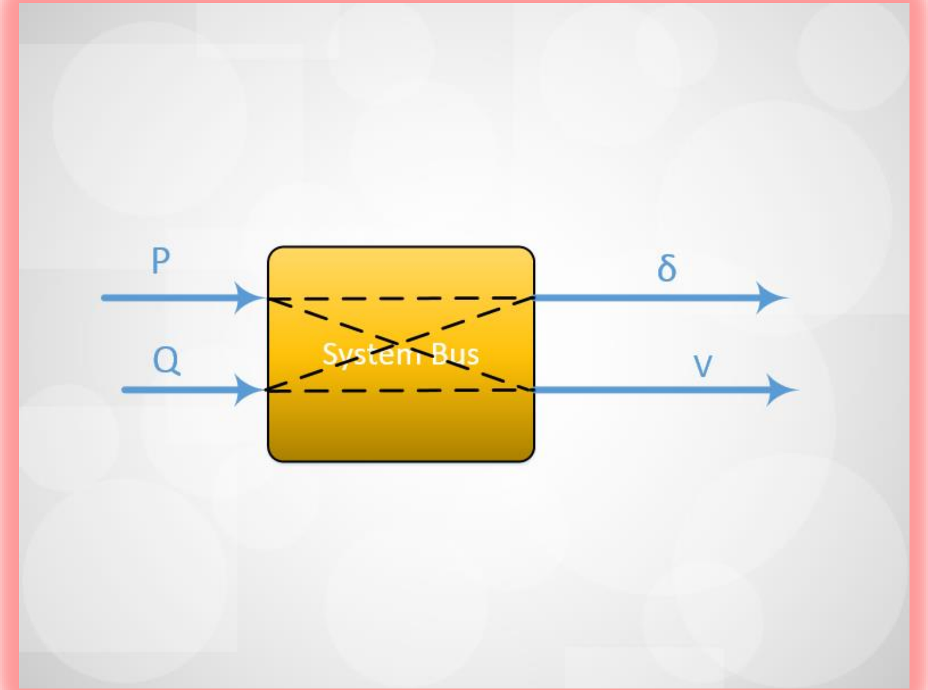
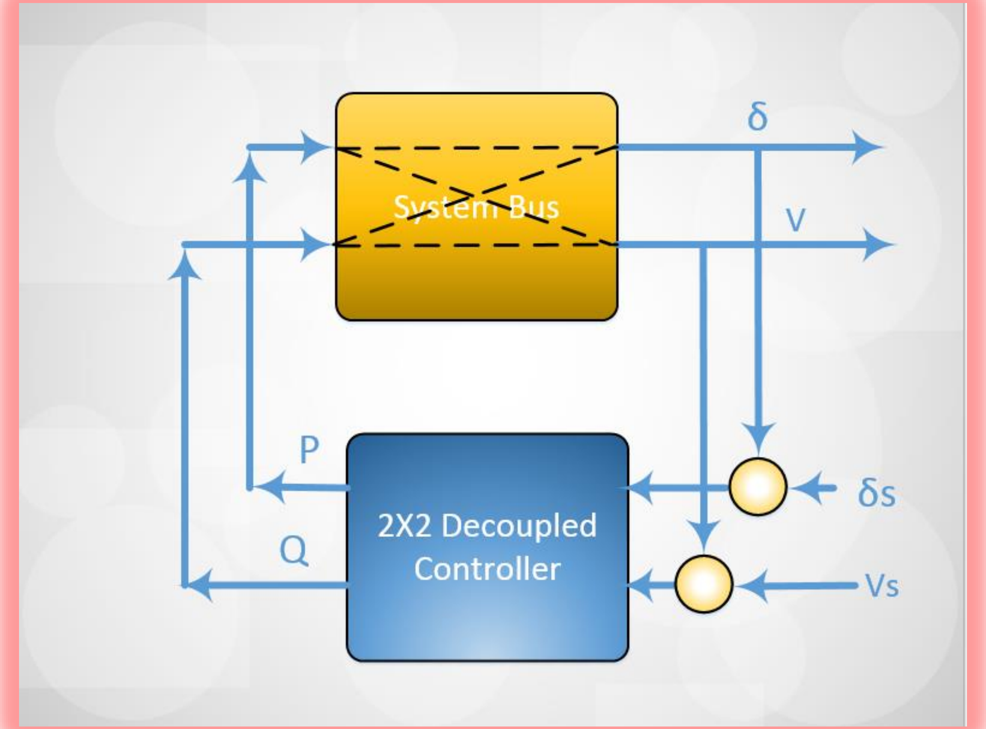
Decoupled Control



Decoupled Control

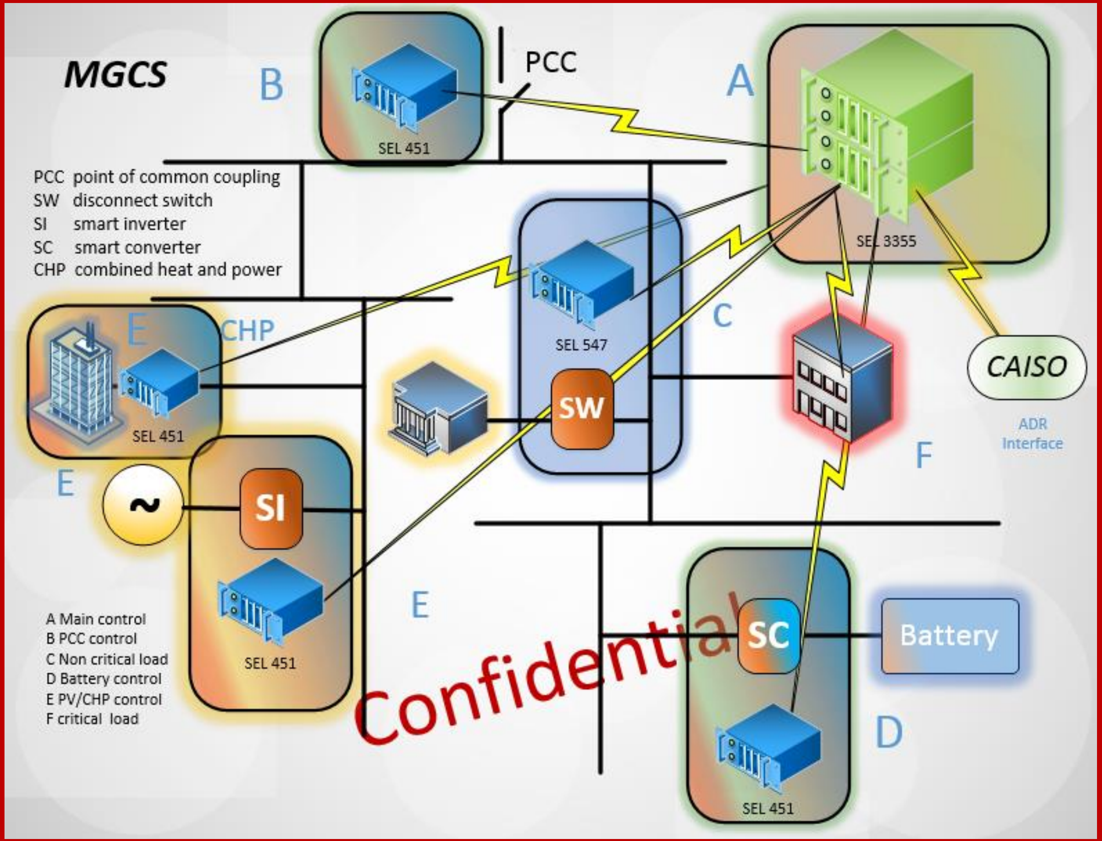


OSIsoft Patents in Microgrids

Number	Title
8,498,752	Decoupling Controller for Power Systems
8,457,912	Unwrapping Angles from Phasor Measurement Units
7,961,112	Continuous Condition monitoring of transformers
7,755,371	Impedance measurement of a power line
7,498,821	Non-linear observers in electric power networks
7,490,013	Power grid failure detection system and method

Suggested approach for Microgrids

- Multi-level hierarchical controller
- Handles arbitrary number of:
  - DERs (Solar PVs with smart inverters)
  - Batteries (with 4 quadrant converters)
  - Non-critical load shedding switches
- One PCC automated switch
- One CSSP Microgrid controller
- Secure PI-Cloud Connect to CAISO using ADR
- Secure NOC connection to Commercializer


MGCS
B
SEL 451
PCC
A
SEL 3355
PCC point of common coupling
SW disconnect switch
SI smart inverter
SC smart converter
CHP combined heat and power
E
CHP
SEL 451
SEL 547
SW
C
CAISO
ADR Interface
F
E
SI
SEL 451
E
A Main control
B PCC control
C Non critical load
D Battery control
E PV/CHP control
F critical load
Confidential
SC
Battery
D
SEL 451

Software in the CSSP

- (a) HA Enterprise PI,
- (b) 2x2 for high side of PCC,
- (c) Line impedance,
- (d) transformer impedance,
- (e) Luenberger Observer,
- (f) area EPS failure

Level 2 Regulation and Mitigation

- Low order realization models
- MPC control subject to constraints
- de Callafon mitigation controller

Level 3 Network modeling software

- Plug and play with any network modeling system
  - ETAP,
  - Cyme,
  - Synergee,
  - ISM,
  - GridLab-D,
  - OpenDSS, …

Building network model

- CIM model built using CIMTool
- CIM model imported to PI-AF (Sisco product)
- Network model used for:
  - Optimal load flow
  - Load shedding and restoration
  - Economic dispatch

Level three controls

- Implemented via MatLab executables
- Uses PI-Direct Access Toolbox
- Control technology (Model Predictive Control)

Fast regulation market

- Receive ADR commands from CAISO at 4 seconds intervals
- Respond in 4 seconds
- Get payment based on sum of up and down “power” movements (Mileage)

Hardware costs

- SEL 3355 $4500
- SEL 451 $4200
- SEL 351 $2380
- SEL 547 $1000
-

Business Model

Microgrid Business Model		
SQFT	500000	square feet
EnergyCost	0.1418	$/kWH
EnergyIntensity	19.61	kWh/ft2
CarbonFactor	0.000283	Mt/kWh
CarbonValue	11	$/Mt
DemandCharge	25	$/kW
Demand	500	kW
EnergySavings	0.3	percent
Annual Energy Cost	$1,390,349	per Year
Energy Savings	$417,105	per Year
Demand Charge Avoidance	$150,000	per Year
Saved Energy	2,941,500	kWh per year
MT carbon saved	832.4	tonnes
Carbon Credits	$9,157	per year
Total Energy Savings	$576,262	per year
Ancillary Service	$0	TBD
Total Savings	$576,262	per year

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Thank you

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