2014 Smart Grid R&D Program
Peer Review Meeting

Microgrid Testbed

Aleks Dimitrovski
Oak Ridge National Laboratory

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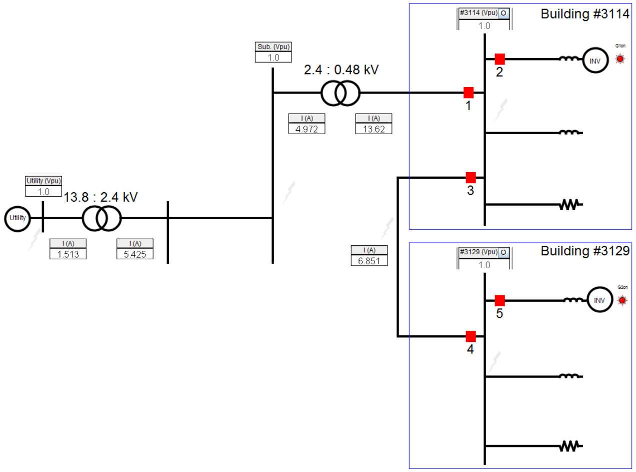
Microgrid Testbed

Objective

Facilitate standardized microgrid testing at system and device level:

- Flexible and reconfigurable
- Standardized interconnections and communication protocols
- Standardized testing procedures with automated operation cases and scenarios



Life-cycle Funding Summary ($K)

Prior to FY 14	FY14, authorized	FY15, requested	Out-year(s)
	175	200	

Technical Scope

Real Time Digital Simulator-based Hardware-in-the-loop system with high resolution in real-time to test:

- Energy management
- Operation and control
- Communication
- Protection

Challenges & Needs

- Frequency vs time domain:
  - Power system simulator: both frequency and time domain
  - Communication system simulator: time domain
- Continuous vs event-based:
  - Power system requires continuous time simulation
  - Communication system is based on discrete events
- Differences in time scales
  - Power system response in ms
  - Communication and control system response in μs
- Separate professional simulators available, but no convincing co-simulation results

Significance and Impact

Flexible platform for testing, verification, and assessment of microgrid components and controllers for system operation, energy management, and protection under different operation scenarios. Allows to:

- Provide standardized and independent testing
- Reduce deployment cost for new devices and solutions
- Perform research
- Investigate safety issues
- Facilitate standards development

Technical Approach – ORNL Microgrid Testbed

- DECC microgrid system modeled in RTDS
  - Complete system model with detailed inverter models
  - Relay-in-the-loop protection test bed
  - Communication-power co-simulation model being built

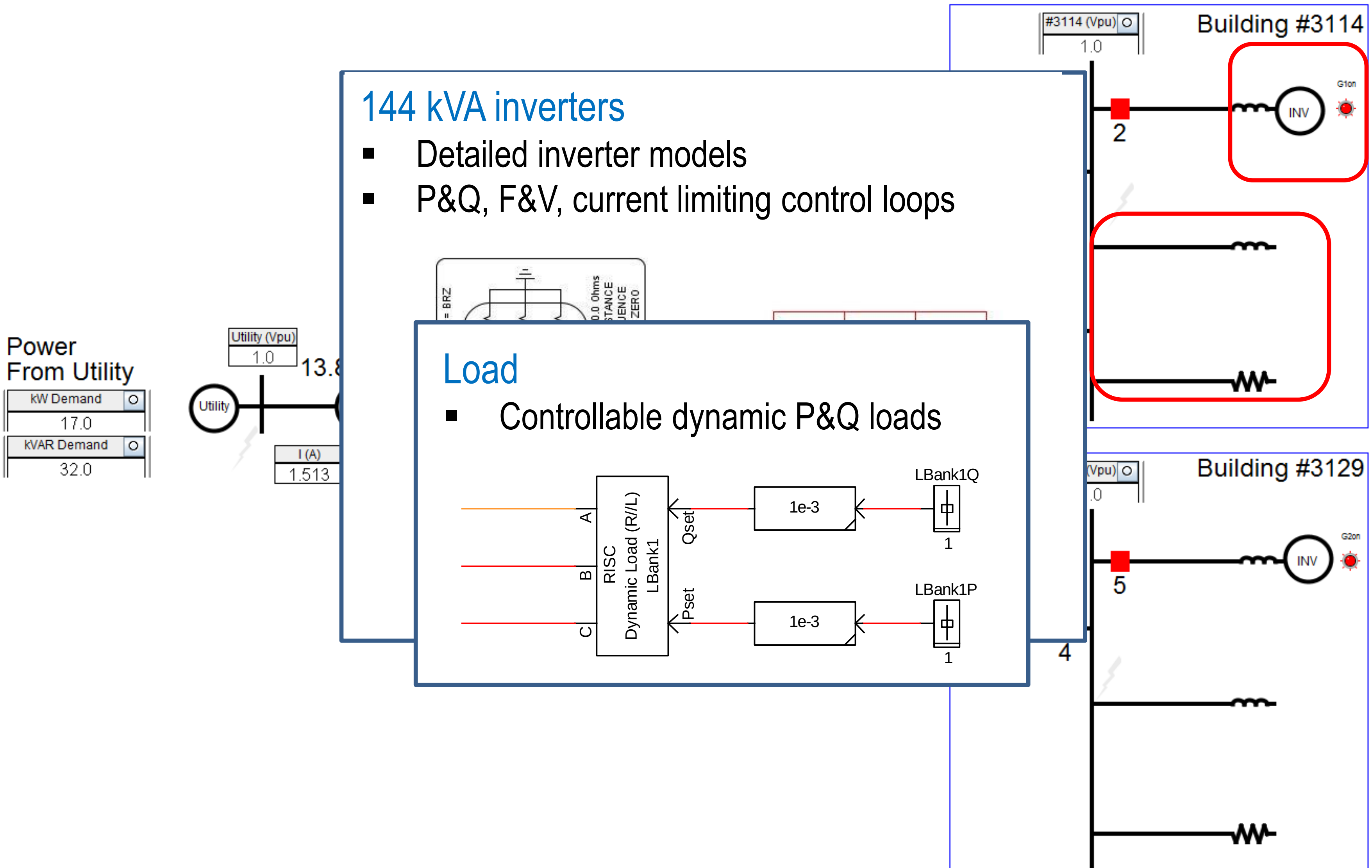
ORNL Microgrid System Modeling

144 kVA inverters

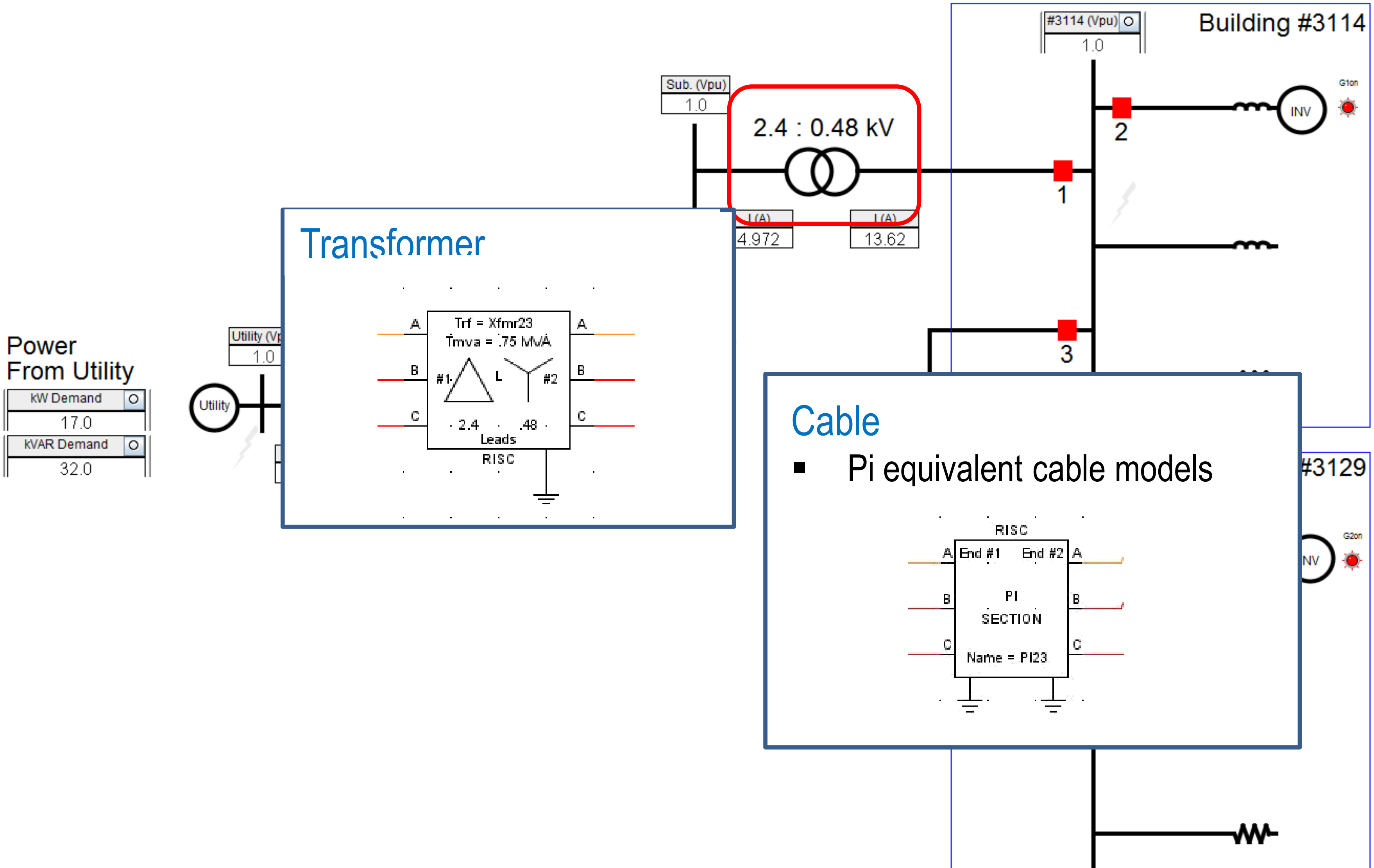
- Detailed inverter models
- P&Q, F&V, current limiting control loops

Load

- Controllable dynamic P&Q loads



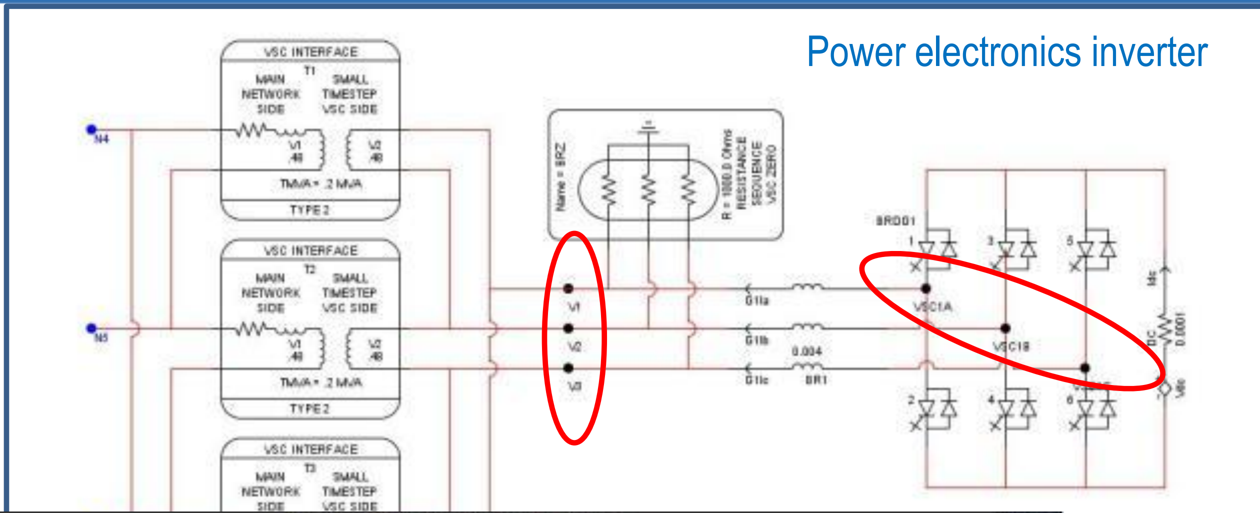
ORNL Microgrid System Modeling

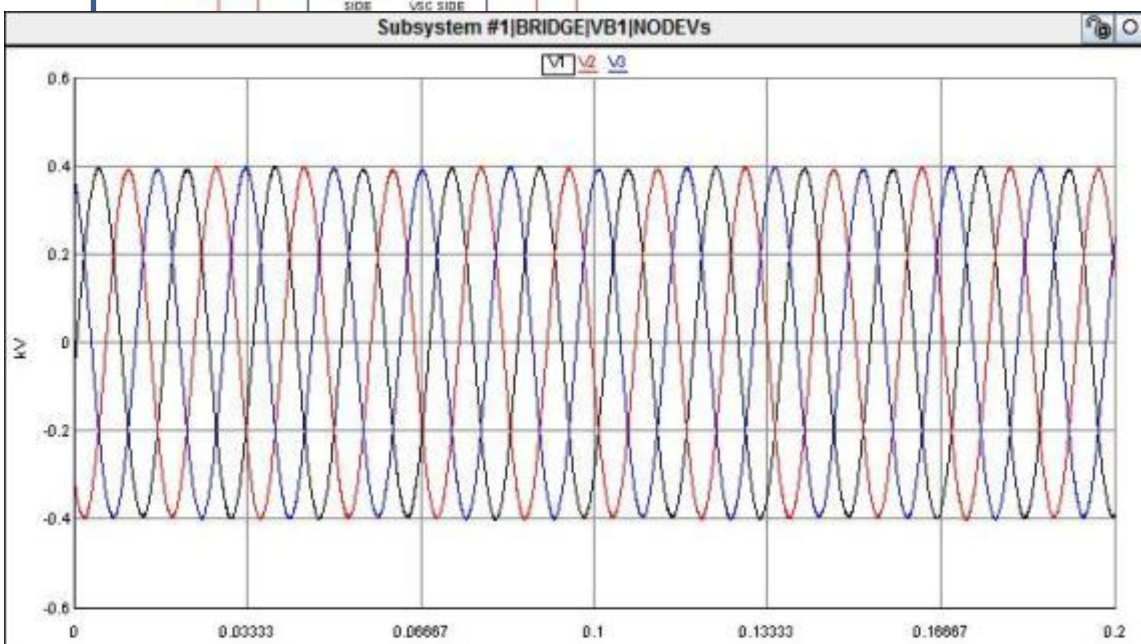


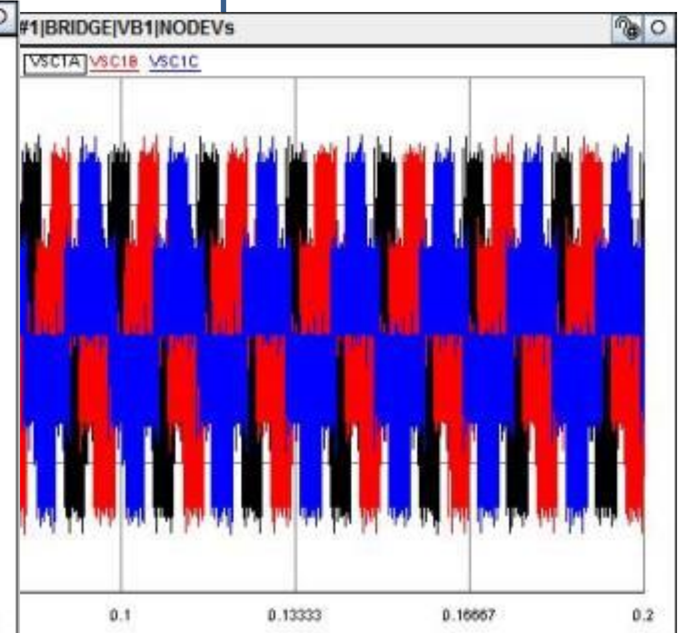
Microgrid Cable Parameters

Cable	From	To	Cable Model	Length (ft)	Ground Length (ft)	Z1 (ohm)	Z0 (ohm)	C (uF)
1	PPA1	300 A Contactor	Cobra XFLEX	20	20	0.0013272+0.00069588i	0.0078965+0.0091801i	0.0014894
2	300 A Contactor	200 A Fuse Block	Cobra XFLEX	3	3	0.00019908+0.00010438i	0.0011845+0.001377i	0.00022341
3	200 A Fuse Block	4 mH Inductor	Cobra XFLEX	7	7	0.00046451+0.00024356i	0.0027638+0.0032131i	0.00052129
4	4 mH Inductor	PowerEX PP150T120	Cobra XFLEX	7	7	0.00046451+0.00024356i	0.0027638+0.0032131i	0.00052129
5	PPA1	MTD 1000-150	Cobra XFLEX	33	33	0.0035127+0.00121i	0.014706+0.015222i	0.024781
6	PP3	500 kW Resistive Load Bank	Cobra XFLEX	125	125	0.013306+0.0048469i	0.053001+0.039889i	0.19955
7	PP3	375 kVAR Inductive Load Bank	Cobra XFLEX	125	125	0.013306+0.0048469i	0.053001+0.039889i	0.19955
8	PP3	125 A Motor Starter	Cobra XFLEX	25	25	0.0042326+0.00096616i	0.012026+0.014937i	0.022361
9	125 A Motor Starter	30 A Fuse Block	Cobra XFLEX	35	35	0.0059257+0.0013526i	0.016836+0.020912i	0.031305
10	30 A Fuse Block	Motor Variable Sizes	Cobra XFLEX	7	7	0.0011851+0.00027053i	0.0033672+0.0041823i	0.006261
11	PP3	45 kVA xfmr	Cobra XFLEX	25	25	0.013349+0.0010184i	0.019977+0.01787i	0.0048166
12	PP3	250 A Contactor	Cobra XFLEX	3.5	3.5	0.00037256+0.00012833i	0.0015598+0.0016144i	0.0026282
13	250 A Contactor	200 A Fuse Block	Cobra XFLEX	16	12	0.0017031+0.00058667i	0.0071303+0.0073802i	0.012015
14	200 A Fuse Block	2 mH Inductor	Cobra XFLEX	13	13	0.0013838+0.00047667i	0.0057934+0.0059964i	0.009762
15	2 mH Inductor	APS IAP150T120	Cobra XFLEX	7	7	0.00074513+0.00025667i	0.0031195+0.0032288i	0.0052565
16	Building 3114	Building 3129	Southwire Quadraplex	750	750	0.0255+0.0144i	0.05845+0.17445i	0.0133

Detailed Inverter Modeling







Microgrid with detailed inverter models

- Tested in grid-connected mode, islanding mode, and resynchronization.
- Grid-connected mode

Near Bus:

Inverter 1: P_{gen} = 80 kW ⟶ 40 kW, Q_{gen} = 20 kVar

Load 1: P = 50 kW, Q = 10 kVar

Far Bus:

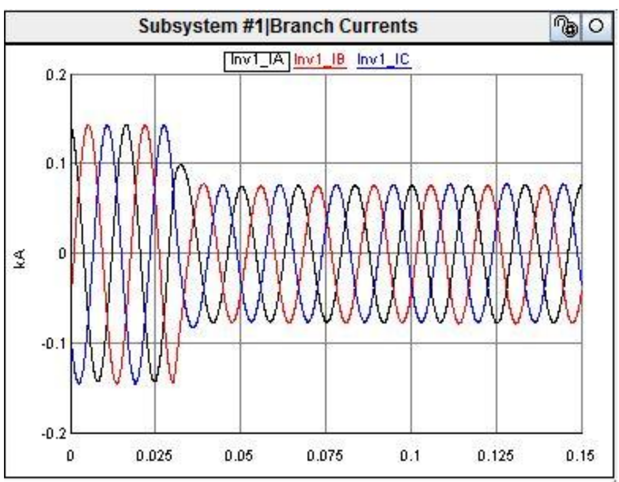
Inverter 2: P_{gen} = 20 kW, Q_{gen} = 0

Load 2: P = 50 kW, Q = 10 kVar

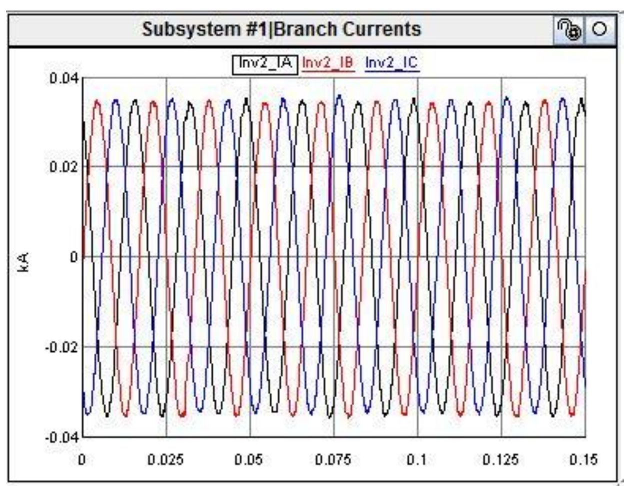
Microgrid totals:

P_{gen} = 100 kW ⟶ 60 kW, Q_{gen} = 20 kVar, P_{load} = 100 kW, Q_{load} = 20 kVar

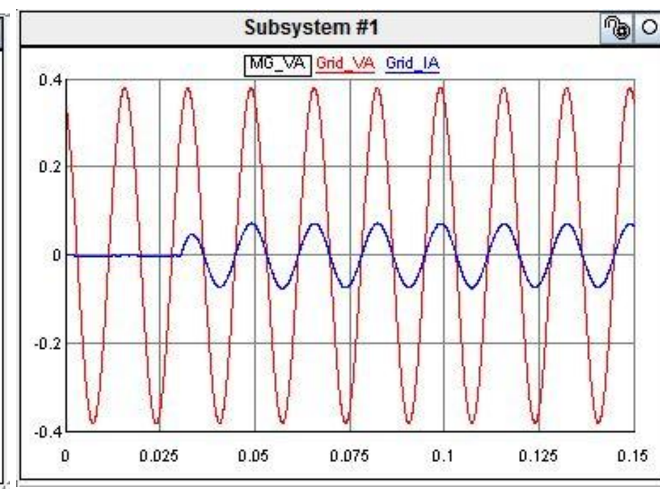
Inverter 1 output current



Inverter 2 output current



Microgrid voltage, Grid voltage and current

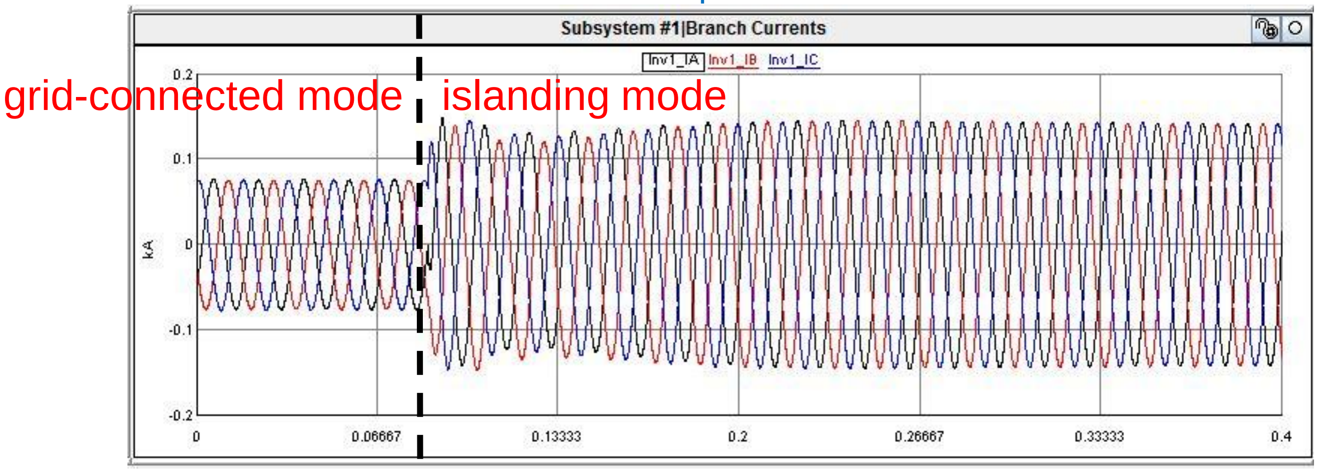


Microgrid with detailed inverter models

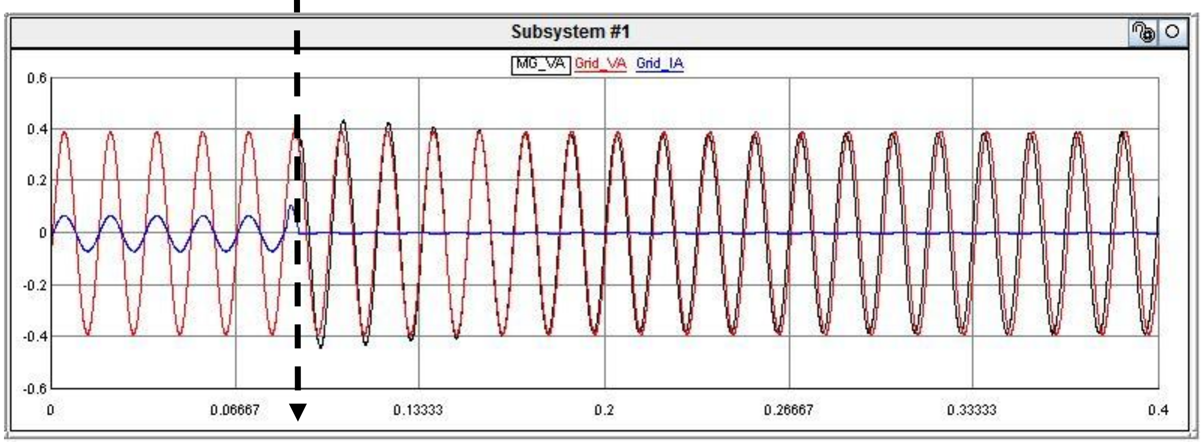
- Transition between grid-connected mode and islanding mode

Near Bus: Inverter 1, from P&Q mode to V&f mode

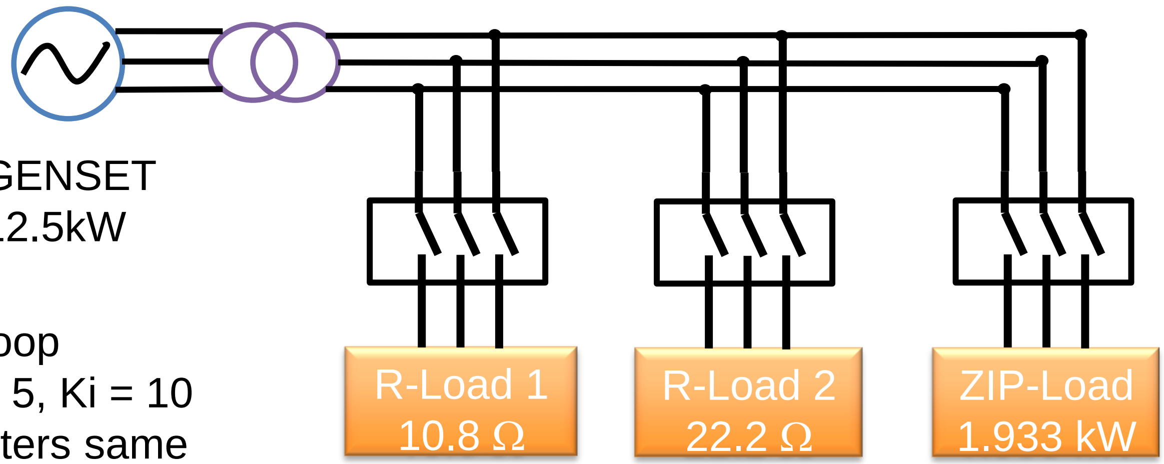
Inverter 1 output current



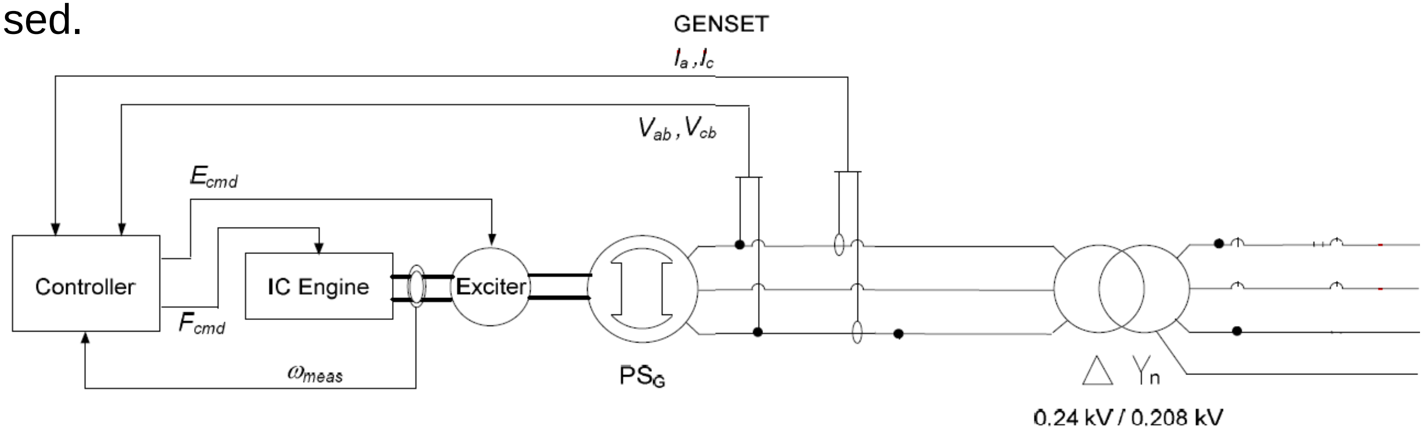
Microgrid voltage, Grid voltage and current



IC Engine driven Synchronous Machine



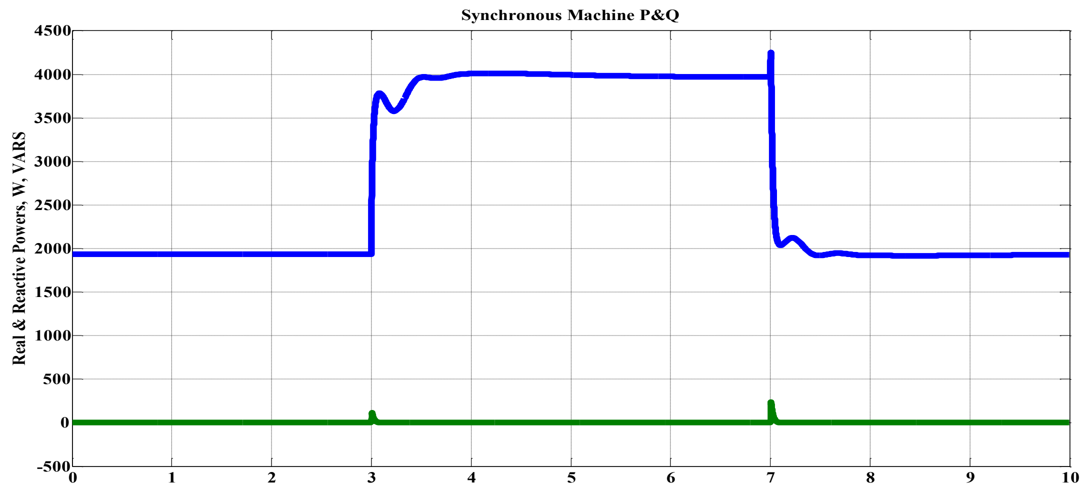
PI of excitation loop changed to Kp = 5, Ki = 10
All other parameters same
No Cables used.



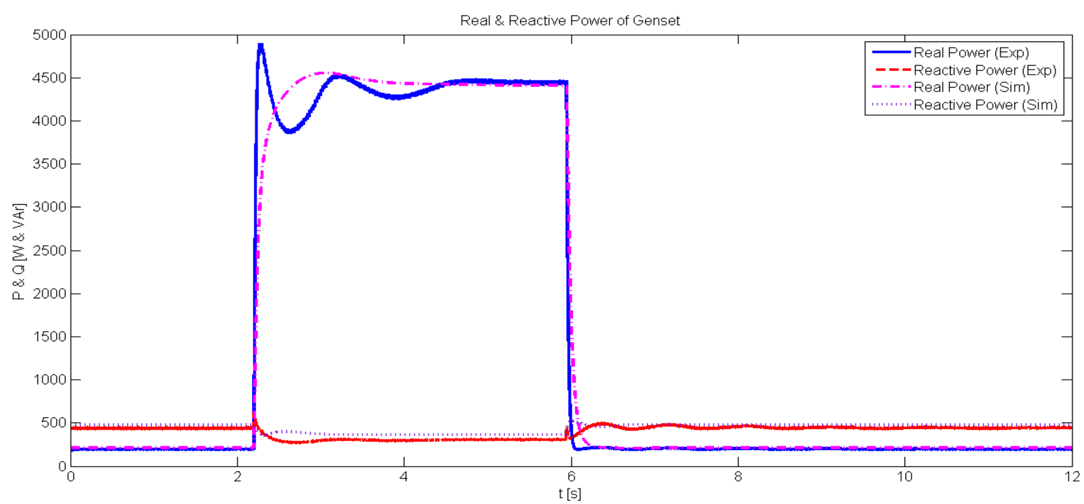
MC parameters and controller structure same as UW GENSET 12.5kW
Voltage is regulated at the machine terminals instead of transformer.
Controller parameters are tuned.

Load Step Up and Step Down – P&Q

R-Load 2 is initially supplied and ZIP Load OFF.
Step up: R-Load 1 ON and R-Load 2 OFF at 3s
Step down: R-Load 2 ON and R-Load 1 OFF at 7s.

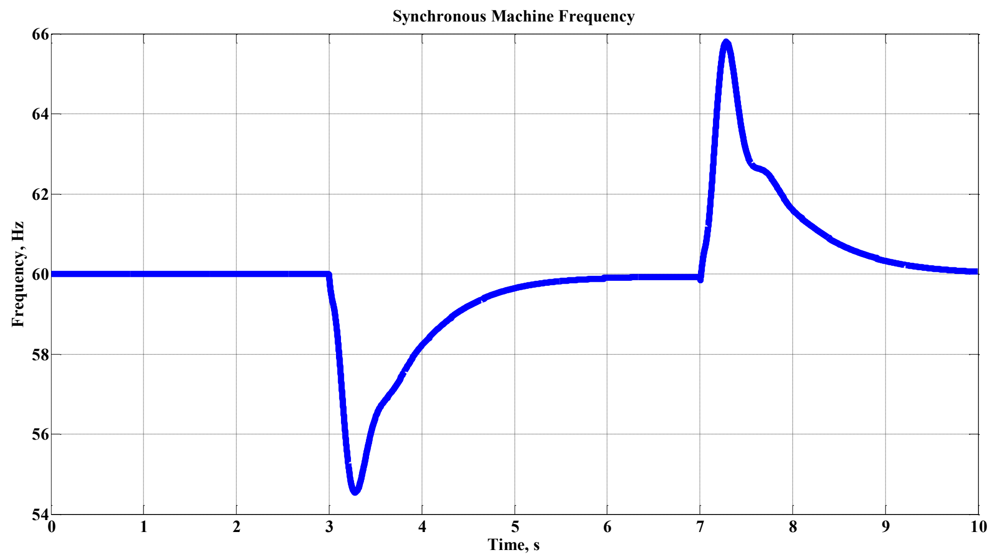


RTDS

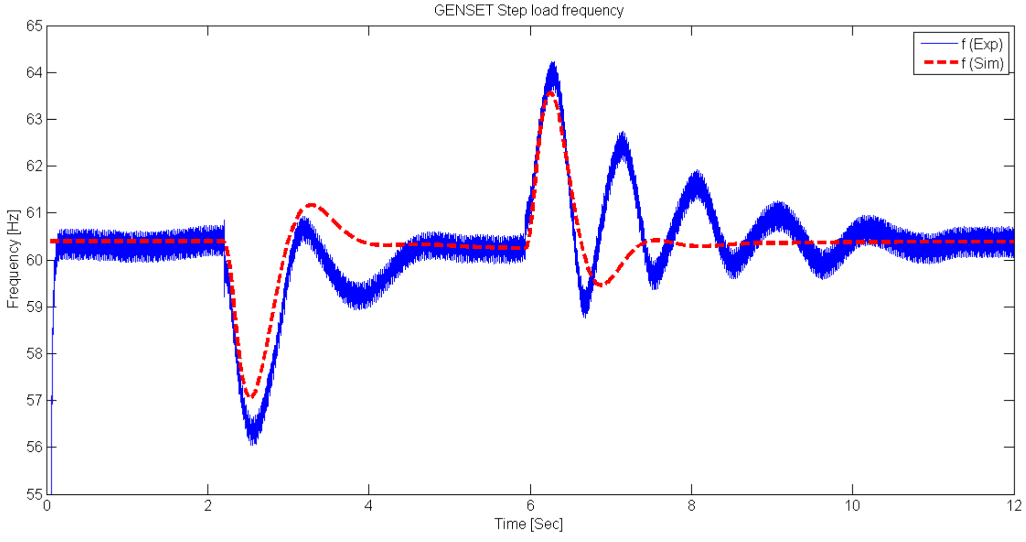


Actual load used in simulation is different from the UW specs

Load Step Up and Step Down – Frequency

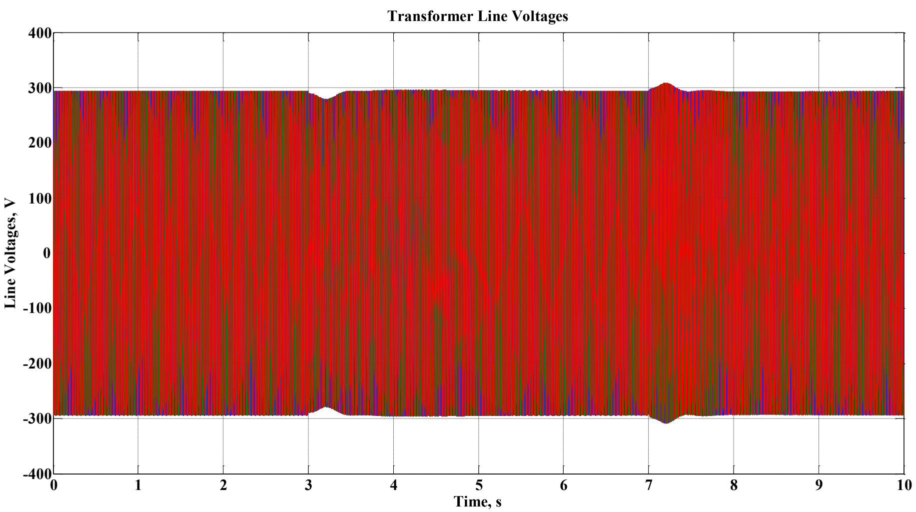


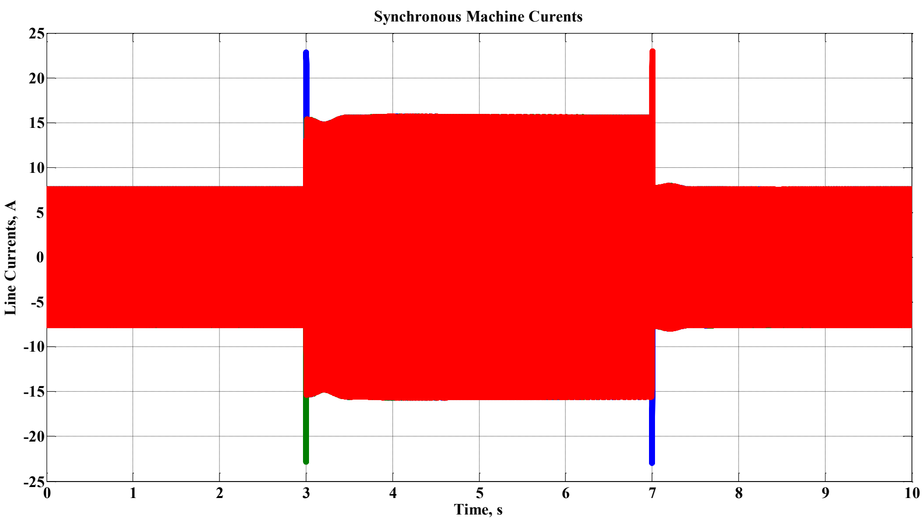
RTDS

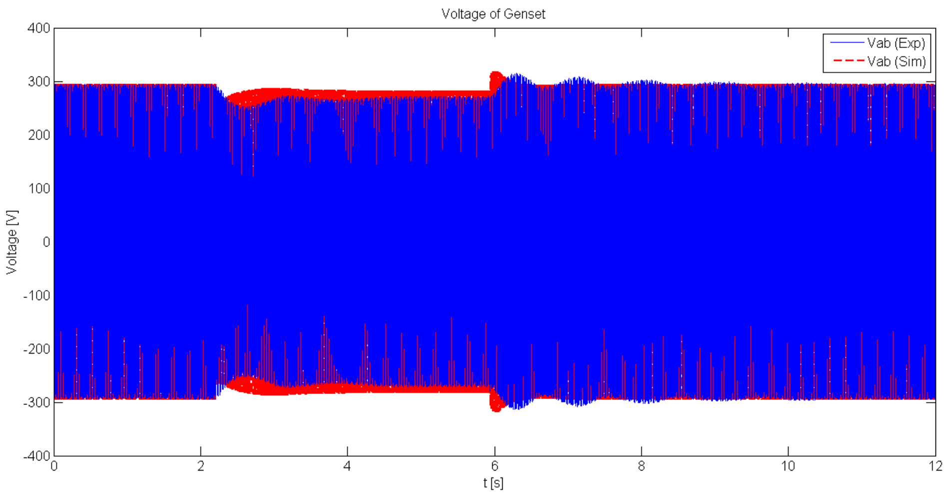


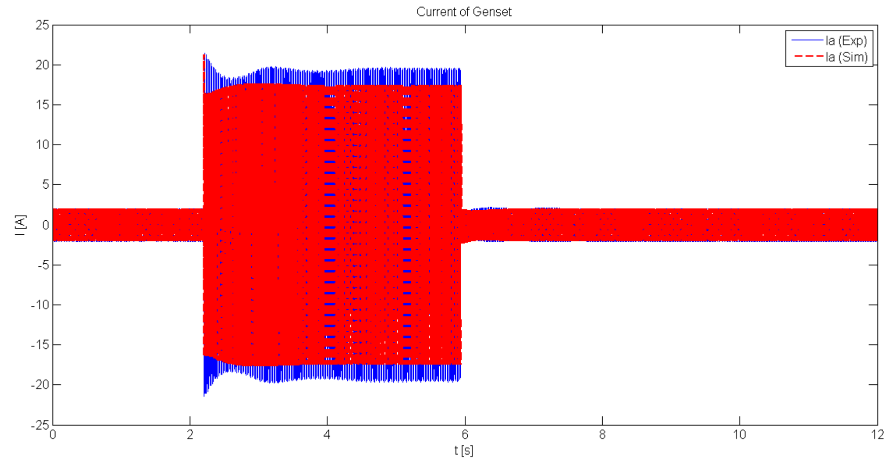
UW specs

Load Step Up and Step Down – V & I





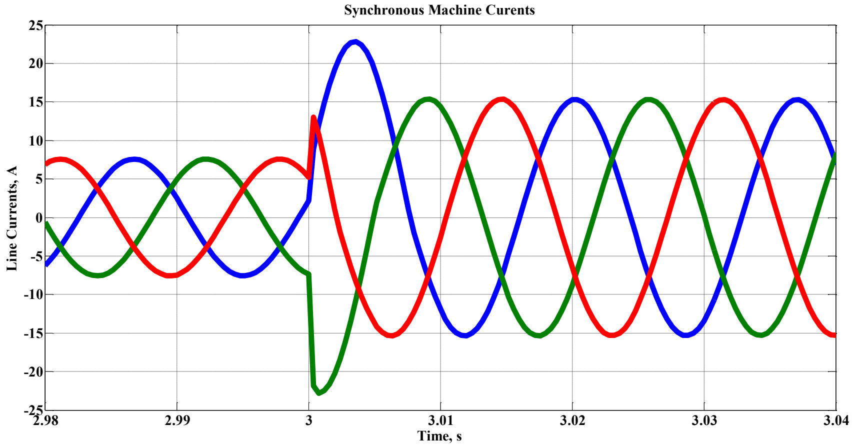




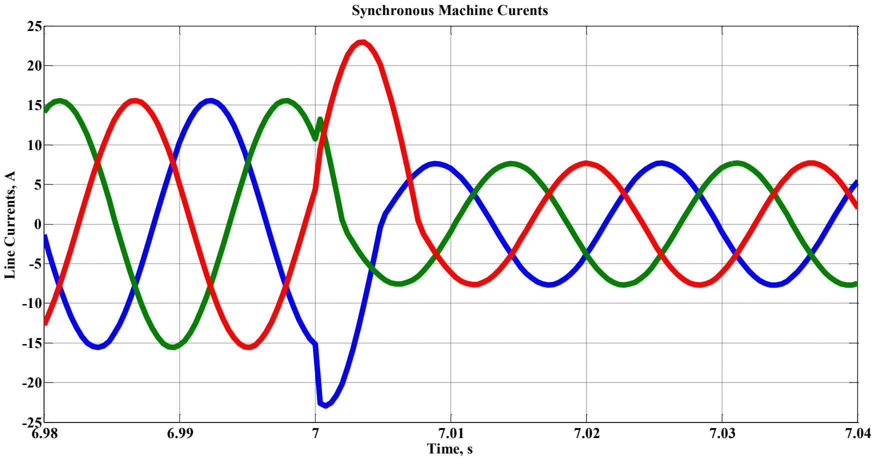
Line Voltages

Line Currents

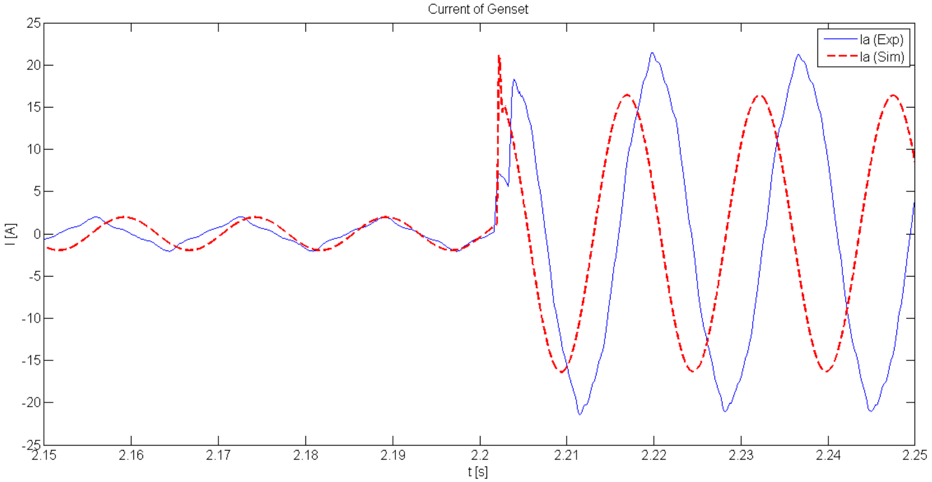
Load Step Up and Step Down – I zoomed



Load increase



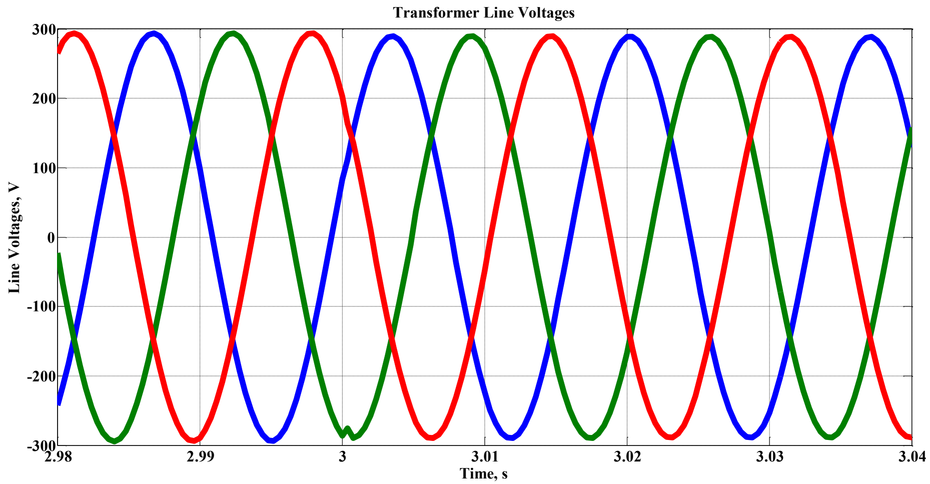
Load decrease



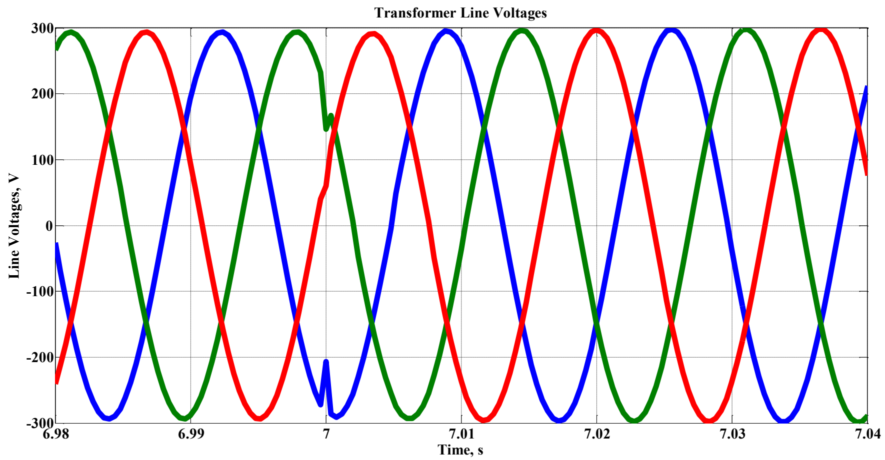
Load is well regulated

Current peak depends on the switching instant

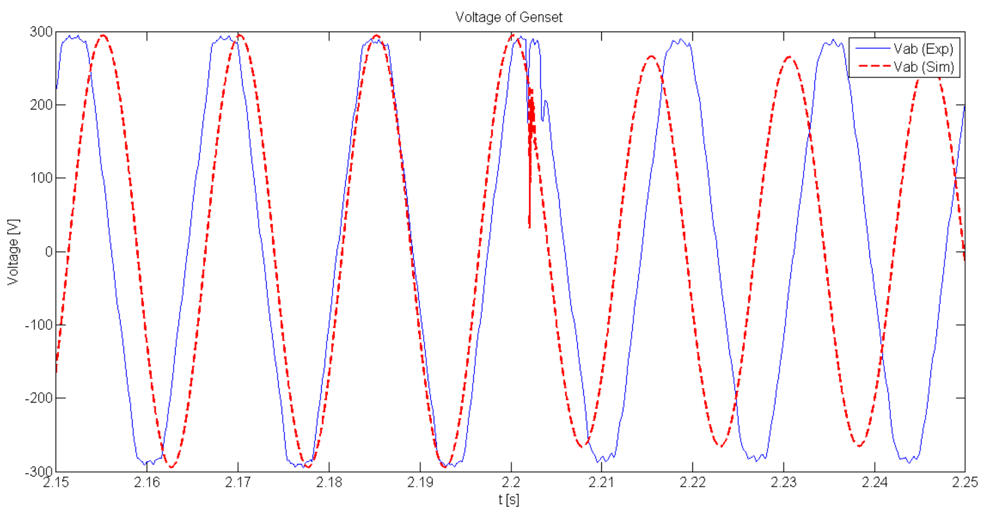
Load Step Up and Step Down – V zoomed



Load increase



Load decrease



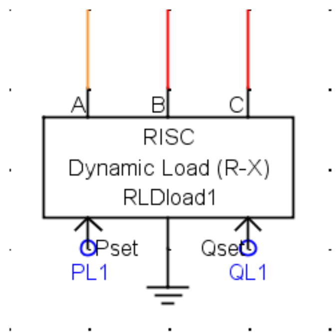
Voltage is well regulated

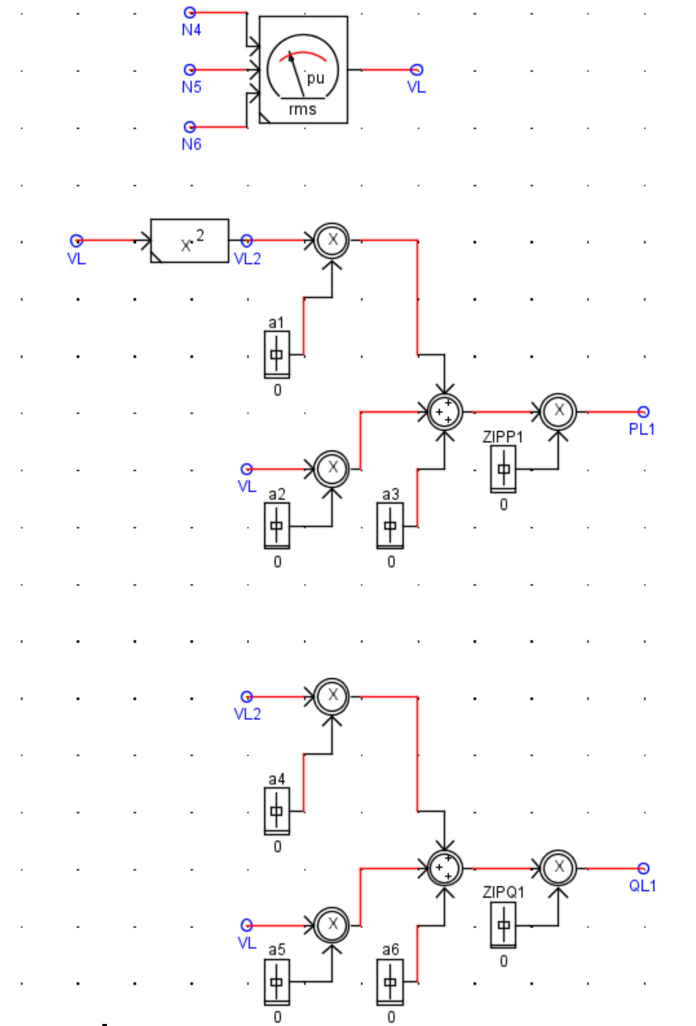
ZIP Load Model

$$P = P_0\left[a_1\left(\frac{V}{V_0}\right)^2 + a_2\left(\frac{V}{V_0}\right) + a_3\right]$$

$$Q = Q_0\left[a_4\left(\frac{V}{V_0}\right)^2 + a_5\left(\frac{V}{V_0}\right) + a_6\right]$$

$V_0,\ P_0$ and Q_0





Coefficients a_1 – a_6 specify the composition of constant impedance, current and power loads

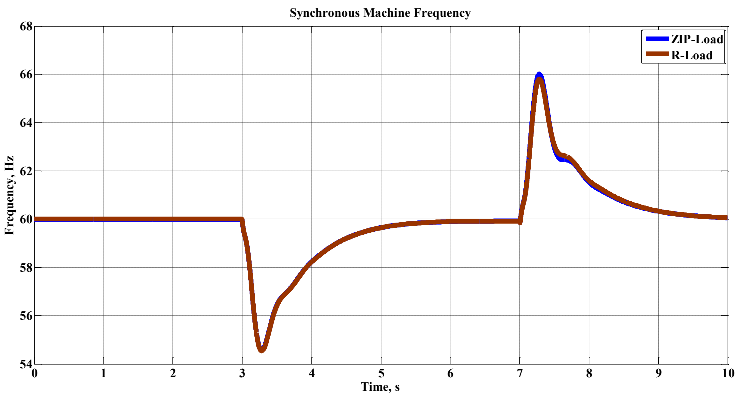
$a_1+a_2+a_3$ = 100% $a_4+a_5+a_6$ = 100%

RTDS dynamic load model is used
All parameters can be specified in run time

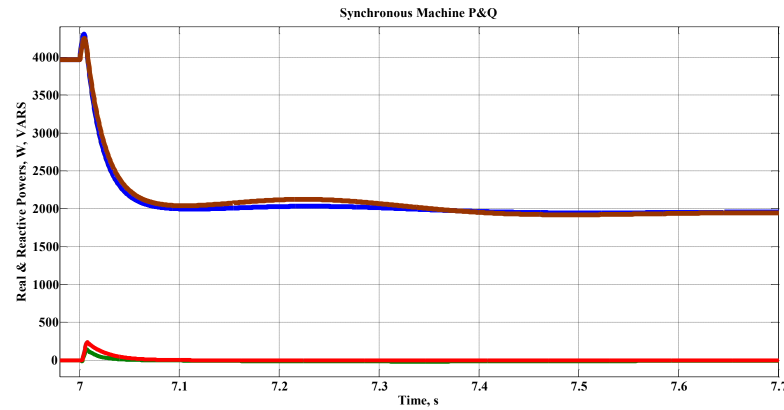
Load Step Up and Step Down – ZIP Load

ZIP-Load is initially supplied and R-Load 2 is OFF.
Step Up : R-Load 1 ON and ZIP-Load OFF at 3s
Step Down : ZIP-Load ON and R-Load 1 OFF at 7s

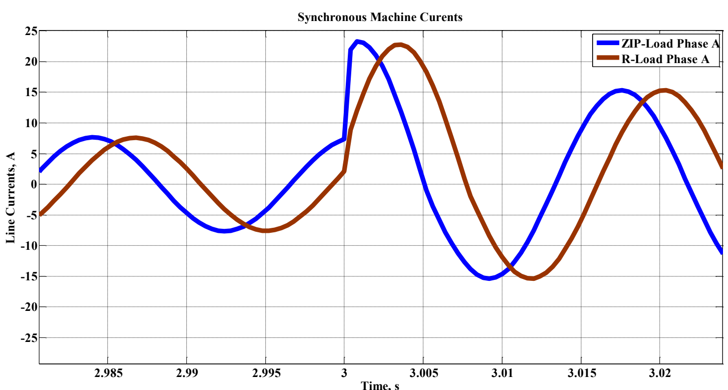
a1 = 0.2; a2 = a3 = 0.4
a4 = 1; a5 = a6 = 0;
Po = 1.933kW; Qo = 0; Vo = 208V;



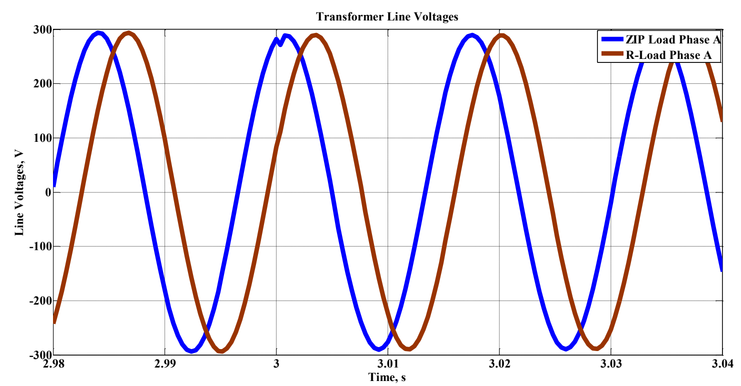
Frequency



P & Q



Current Phase A

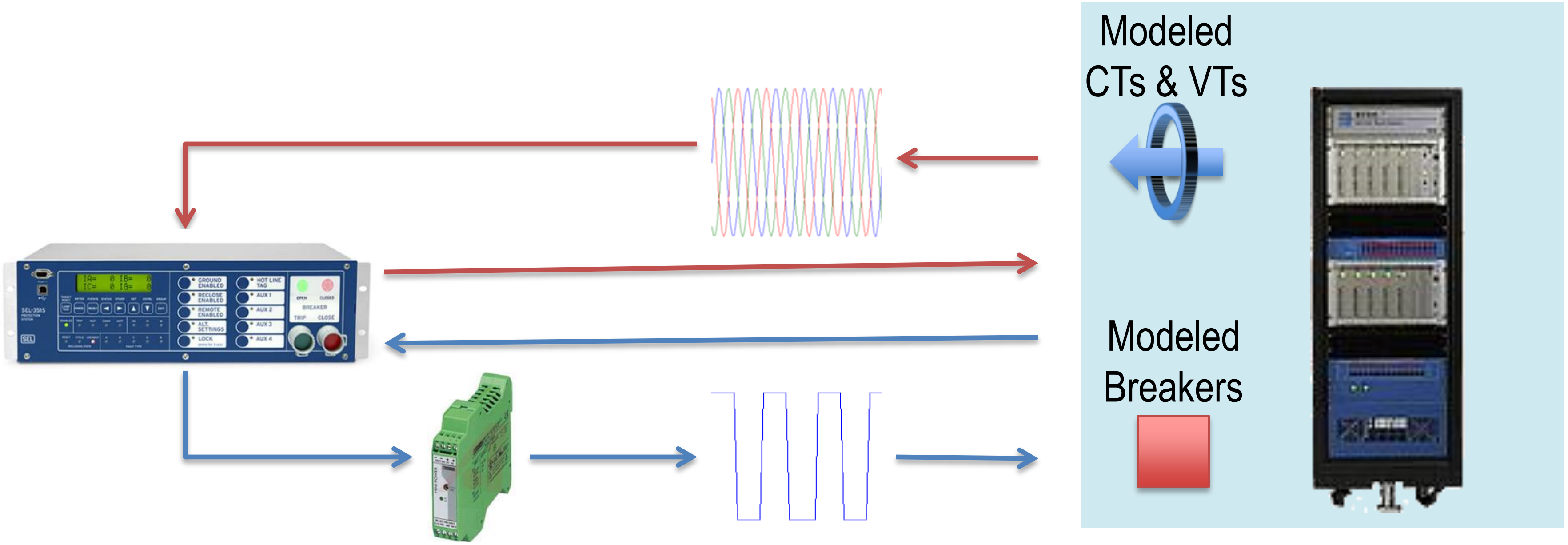


Voltage Phase A

Some differences observed during step down

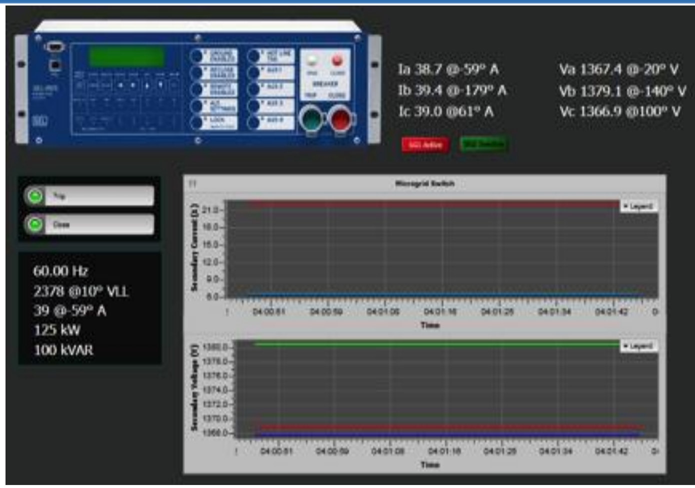
Relay-in-the-loop protection test

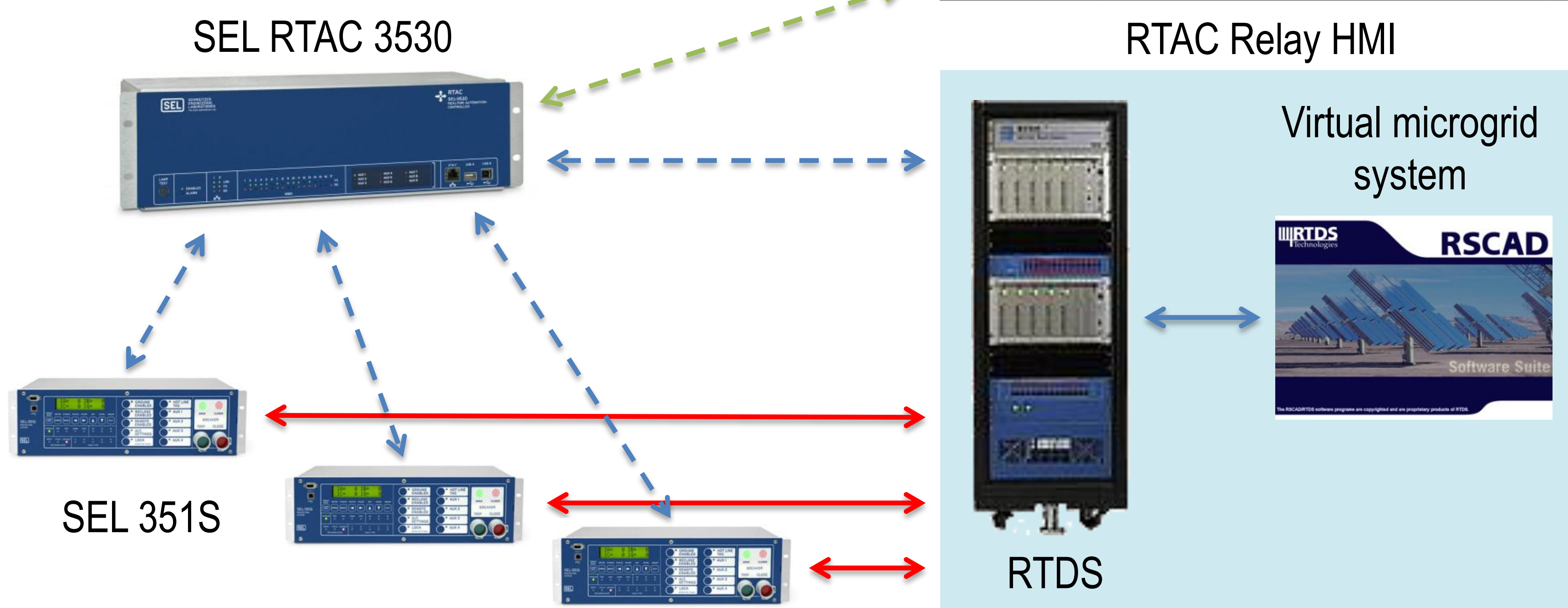
- SEL 351S relays interfaced with RTDS
  - Microgrid system simulated in RTDS
  - CT and VT measurements sent to relays
  - Circuit breaker control outputs from relays interfaced with RTDS
  - Circuit breaker status signals routed through RTAC



Relay-in-the-loop protection test

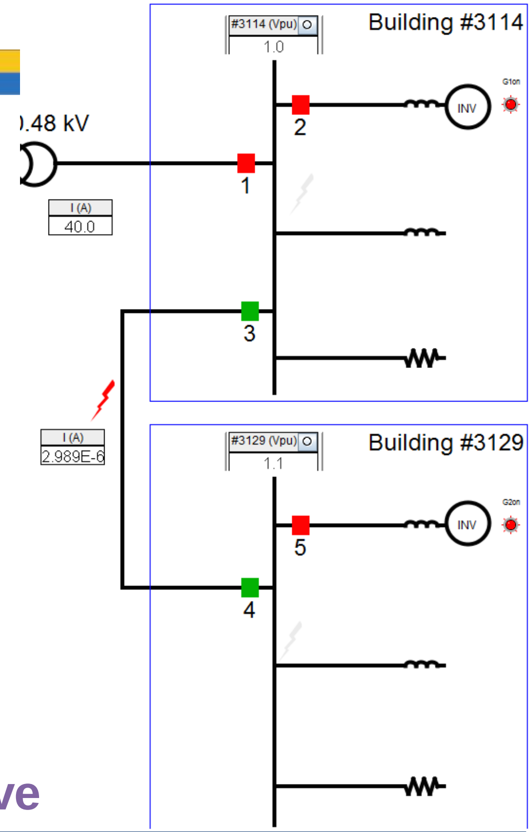
- Real Time Automation Controller
  - Monitor circuit breakers in RTDS
  - Monitor and coordinate relays
  - Dedicated HMI for physical relays
  - Web interface
  - Remote relay setting changes





Differential overcurrent protection

- Microgrid connected to utility
  - Differential protection implemented with overcurrent protecting DERs
  - Inverters injecting P&Q into microgrid
- Using either U5 short time or instantaneous overcurrent characteristics
  - Grid connected faults inside the microgrid are very effectively isolated



Differential protection is very fast and very effective

Three-Phase Fault		Protection Operation Delay (Cycles)				
Status	Location	Relay #1	Relay #2	Relay #3	Relay #4	Relay #5
On Grid	External	-	19.8	-	-	16.8
	Bldg. #3114	3.6	3.6	3.6	-	-
	Bldg. #3129	-	-	-	2.6	2.6
	MG Cable	-	-	3.5	3.5	-

FY 2014 performance and results, against objectives and outcomes

- FY14: microgrid testbed development for testing and assessment of microgrid operation and control system
  - RTDS-based with HIL capabilities
  - DECC lab system model
  - Standardized testing procedures
- Milestones are met or on track

Due Date	Milestone Type	Milestone Description
12/31/2013	Process Milestone	DECC system model with complete circuit topology and parameters.
03/31/2014	Process Milestone	Basic operation and protection functions with simplified component models.
06/30/2014	Process Milestone	Complete and detailed models of fundamental microgrid components.
09/30/2014	Final Deliverable	Integrated scenario testing with the ORNL microgrid controller. Final annual report.

FY 2015 Plan

1. CSEISMIC
   - Complete development of the microgrid controller – EMS implementation, communication standardization, microgrid controller development for field demonstration.
   - Participation on Technical Advisory Committee.
   - Standards – collaborate with NIST on microgrid standardized test bed, microgrid controller standard development.
2. Hardware-in-the-loop microgrid test bed completion
3. Networked microgrids, collaborate with Chattanooga Electric Power Board
4. DC microgrid & communications
5. De-coupled microgrid control, collaborate with OSIsoft

Collaborations

- **NIST**: Microgrid standardized test bed, microgrid controller standard
- **Hydro-Quebec IREQ**: microgrid protection
- **Chattanooga EPB**: networked microgrids
- **National Instruments**: microgrid control for field implementation
- **OSIsoft**: de-coupled microgrid control