IEEE ENERGY CONVERSION CONGRESS & EXPO | PITTSBURGH, PA, USA | SEPTEMBER 14-18, 2014

Harmonic Interaction in High Populations of Distributed Power Resources

Johan H Enslin

Director, Energy Production & Infrastructure Center (EPIC)

Duke Energy Distinguished Chaired Professor

UNC Charlotte, NC, USA

JEnslin@uncc.edu; http://epic.uncc.edu

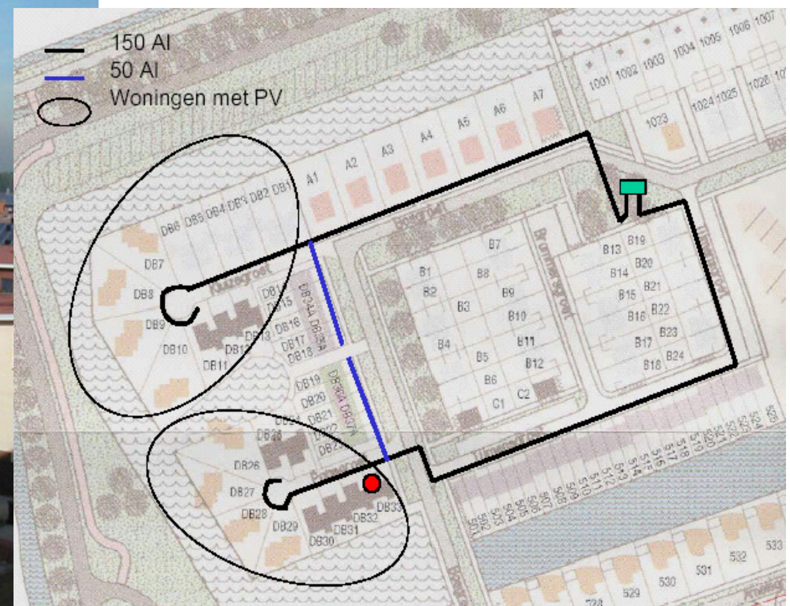
UNC CHARLOTTE

ENERGY PRODUCTION AND INFRASTRUCTURE CENTER (EPIC)

Outline

- Interconnection of DER at Dense Populations
- Mechanism of System Resonance with DER
- Analysis with High Density PV Inverters
- Advanced DER Converter Controls
- Harmonic Mitigation of Smart Inverters
- Real-time HiL Testbed for Harmonic Evaluation
- Conclusions and Recommendations

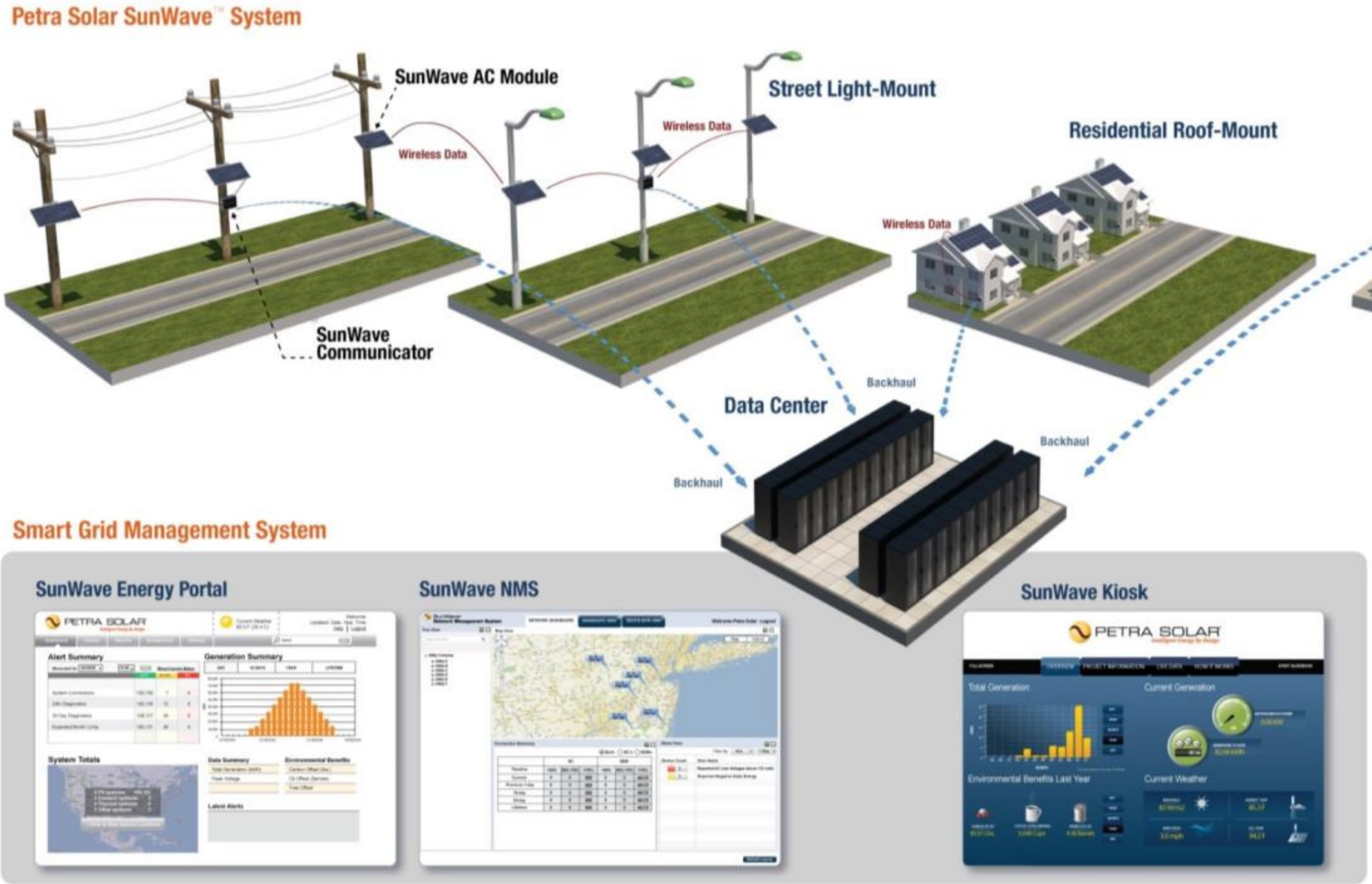
Interconnection of DER at Dense Populations



Ouddorp, The Netherlands

UNC CHARLOTTE
EPIC

The Emerging Virtual Power Plant



Source: Petra Solar, NJ USA

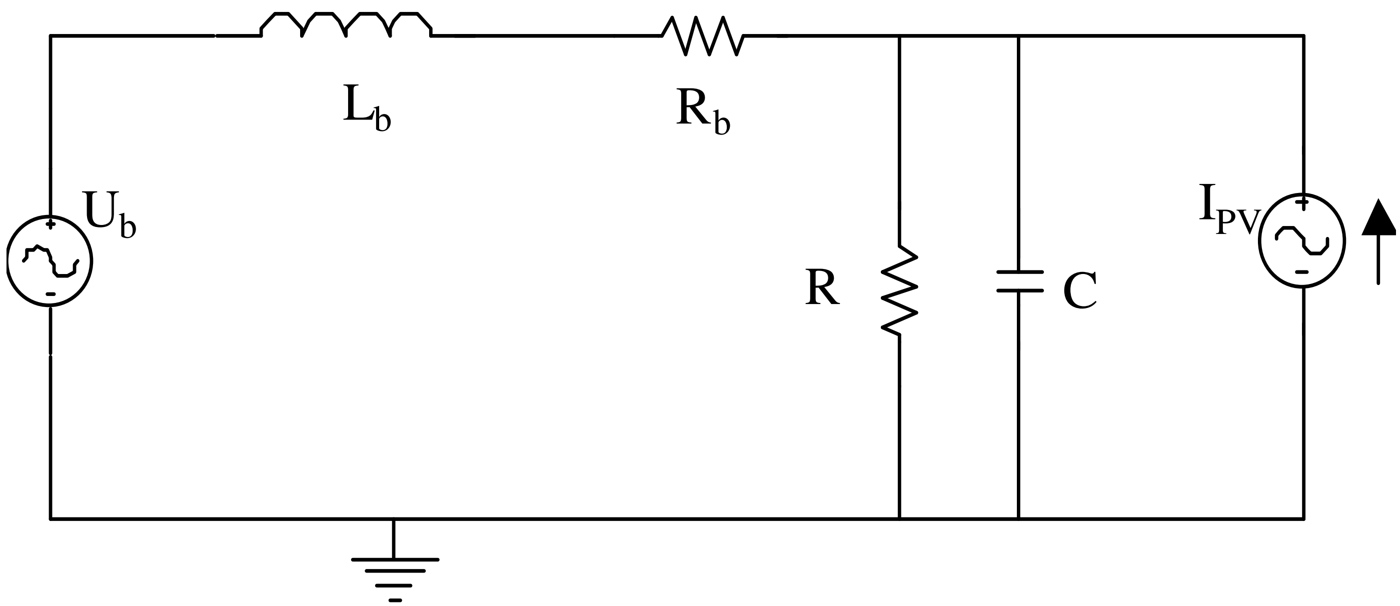
Interconnection Issues

IEEE ENERGY CONVERSION CONGRESS & EXPO
PITTSBURGH, PA, USA | SEPTEMBER 14-18, 2014

- Voltage Regulation and Flicker:
  - May exceeding voltage limits and inverters trip
  - Voltage fluctuations and flicker due to intermittency
- Harmonics:
  - Inverters individually satisfy PQ standards
  - PQ standards can temporarily be exceeded.
  - Inverters trip unexpectedly
- Attention Points on Standards and Interconnections
  - Effect of background supply distortion
  - Increased distortion due to a system resonance
  - Micro-grids and weak networks
  - Islanding times and algorithms
  - Natural damping

UNC CHARLOTTE
EPIC

Mechanisms of DER Inverter Interactions

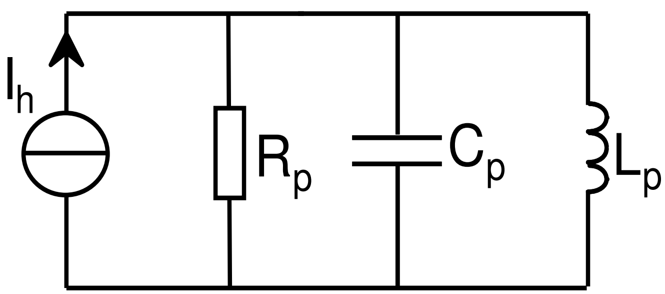


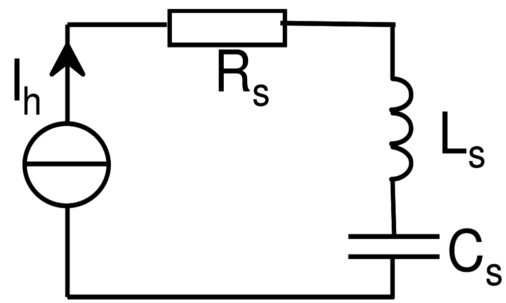
Simple electrical network with one inverter.

UNC CHARLOTTE
EPIC

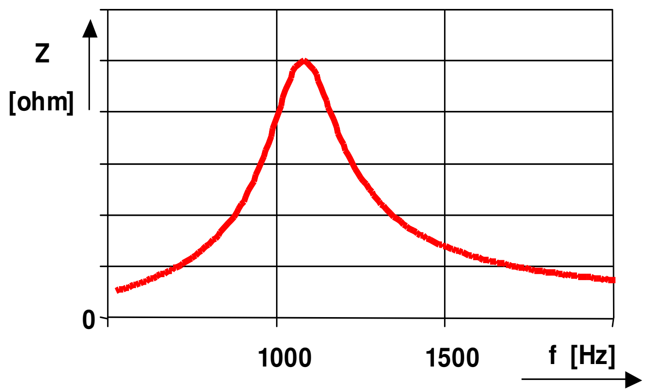
Analysis of DER inverter resonance

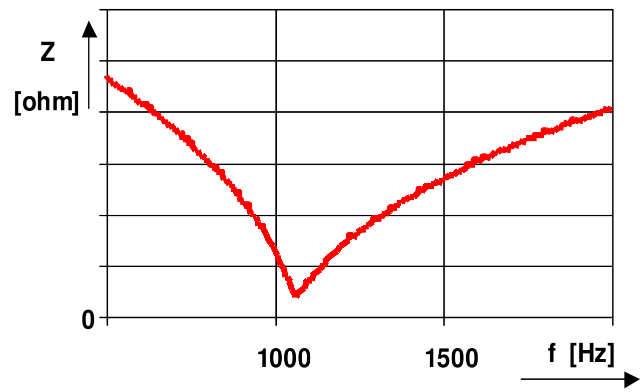
Mechanism of Parallel and Series Resonance





$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

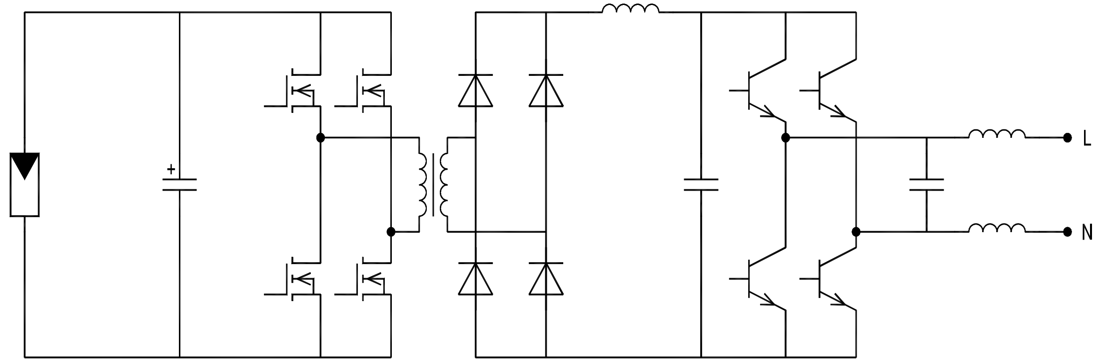




- **Small current harmonics from large population of DER inverters excite parallel resonance in networks.**
- **Supply voltage harmonics increase with DER inverters due to series resonance.**

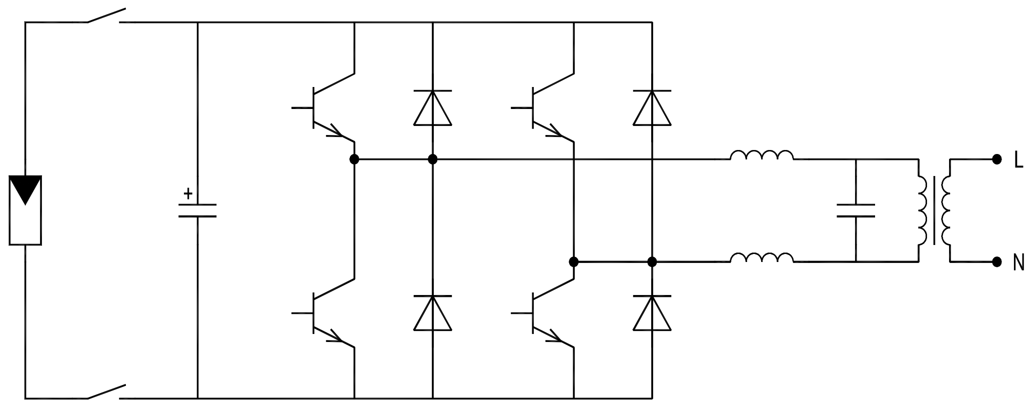
UNC CHARLOTTE
EPIC

Effect of DER Inverter Topology on Power Quality



Type A

Multi-stage PWM converter and high frequency link and transformer with 60 Hz unfolding bridge (3µF output capacitor)



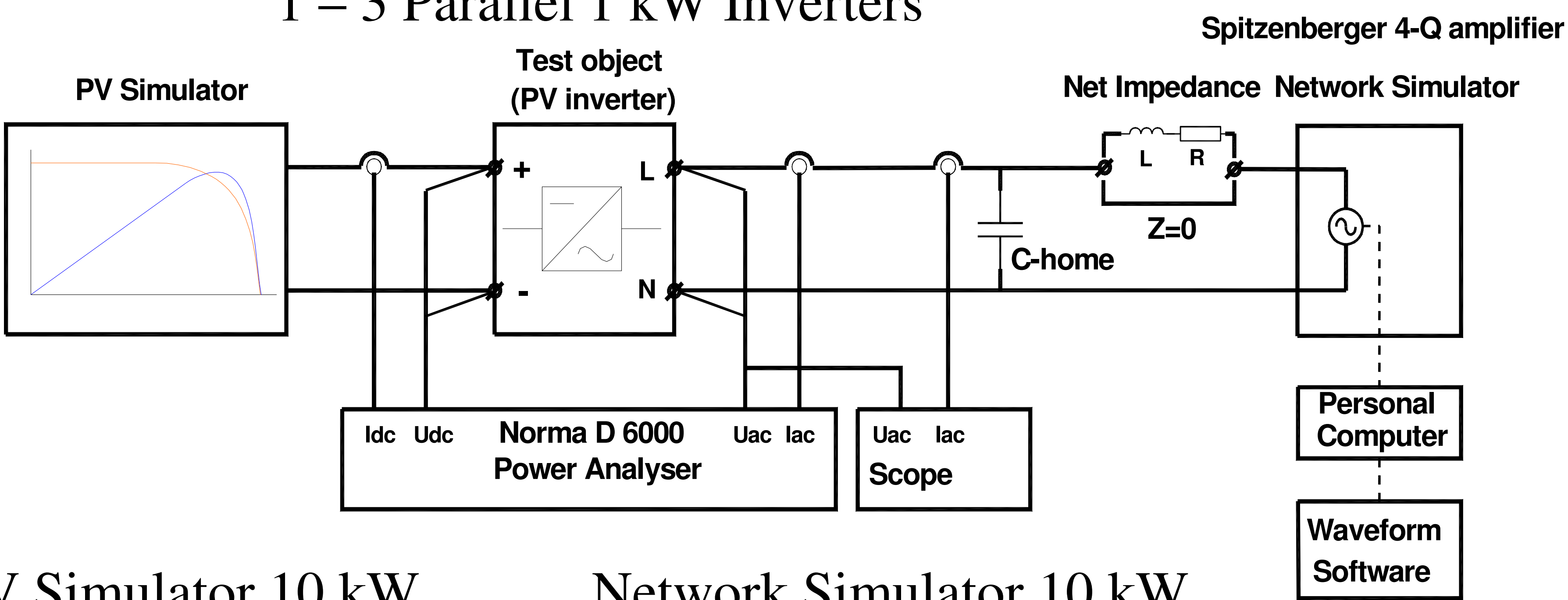
Type B

Single-stage H-bridge PWM converter coupled to the grid with a low frequency (LF) isolation transformer (6 µF output capacitor)

UNC CHARLOTTE
EPIC

PV Inverter Test Installation

1 – 3 Parallel 1 kW Inverters



PV Simulator 10 kW

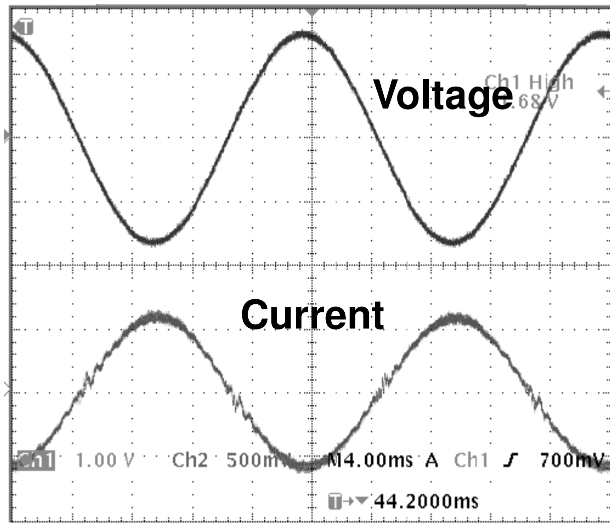
Network Simulator 10 kW

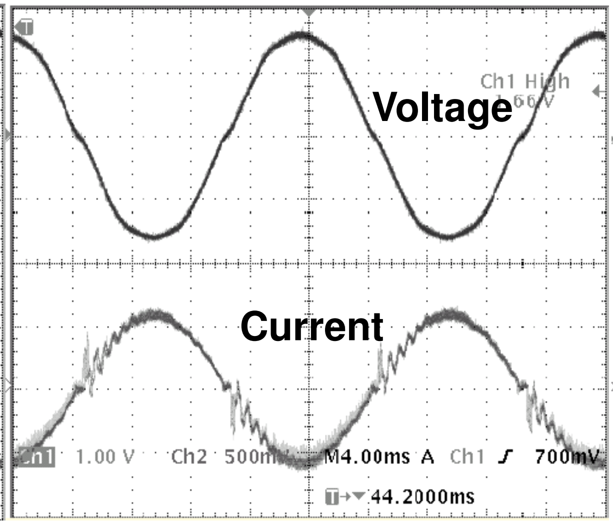
UNC CHARLOTTE

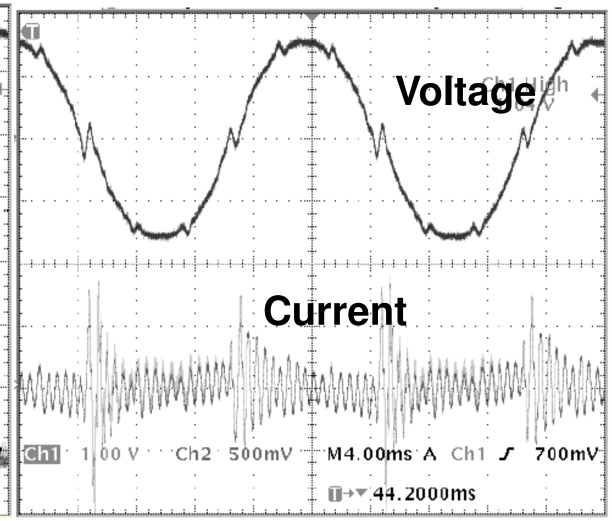
EPIC

Measurement Results
HF Link Inverter – Type A

2014 ECCE
IEEE ENERGY CONVERSION CONGRESS & EXPO
PITTSBURGH, PA, USA | SEPTEMBER 14-18, 2014





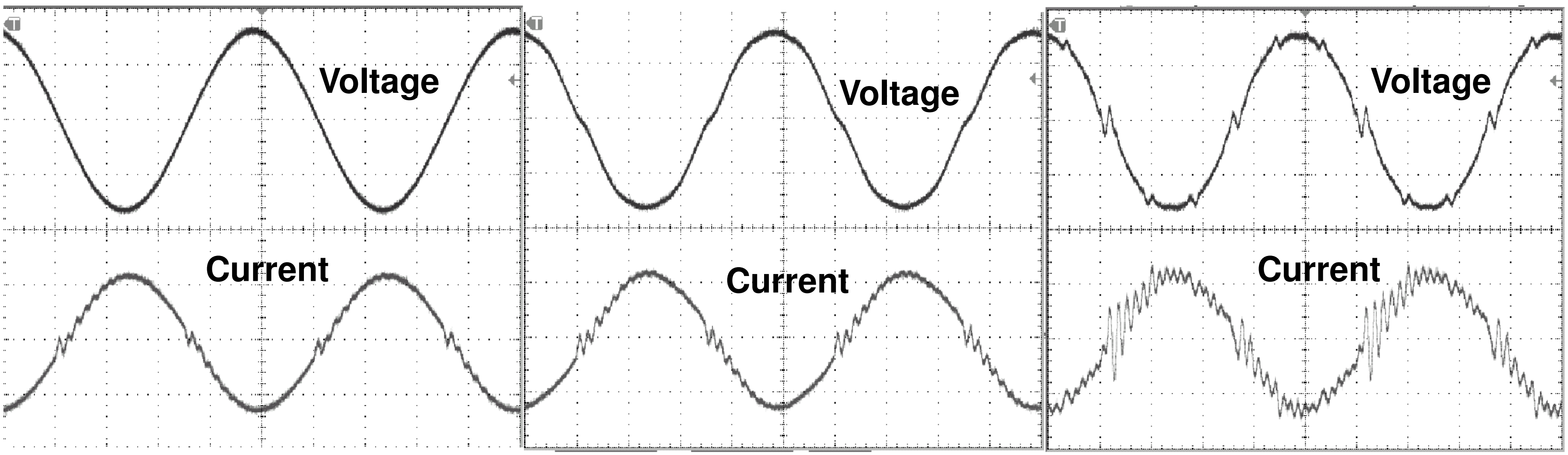


Sinus Supply: L = 1 mH R = 0,3 Ω **NL(3%) Supply: L = 1 mH R = 0,3 Ω** **EN50160 (8%): L = 1 mH R = 0,3 Ω**

Voltage:- 200 V/div; Current:- 5 A/div
Time:- 4 ms/dive
C-home = 3 µF

UNC CHARLOTTE
EPIC

Measurement Results
LF Link Inverter – Type B

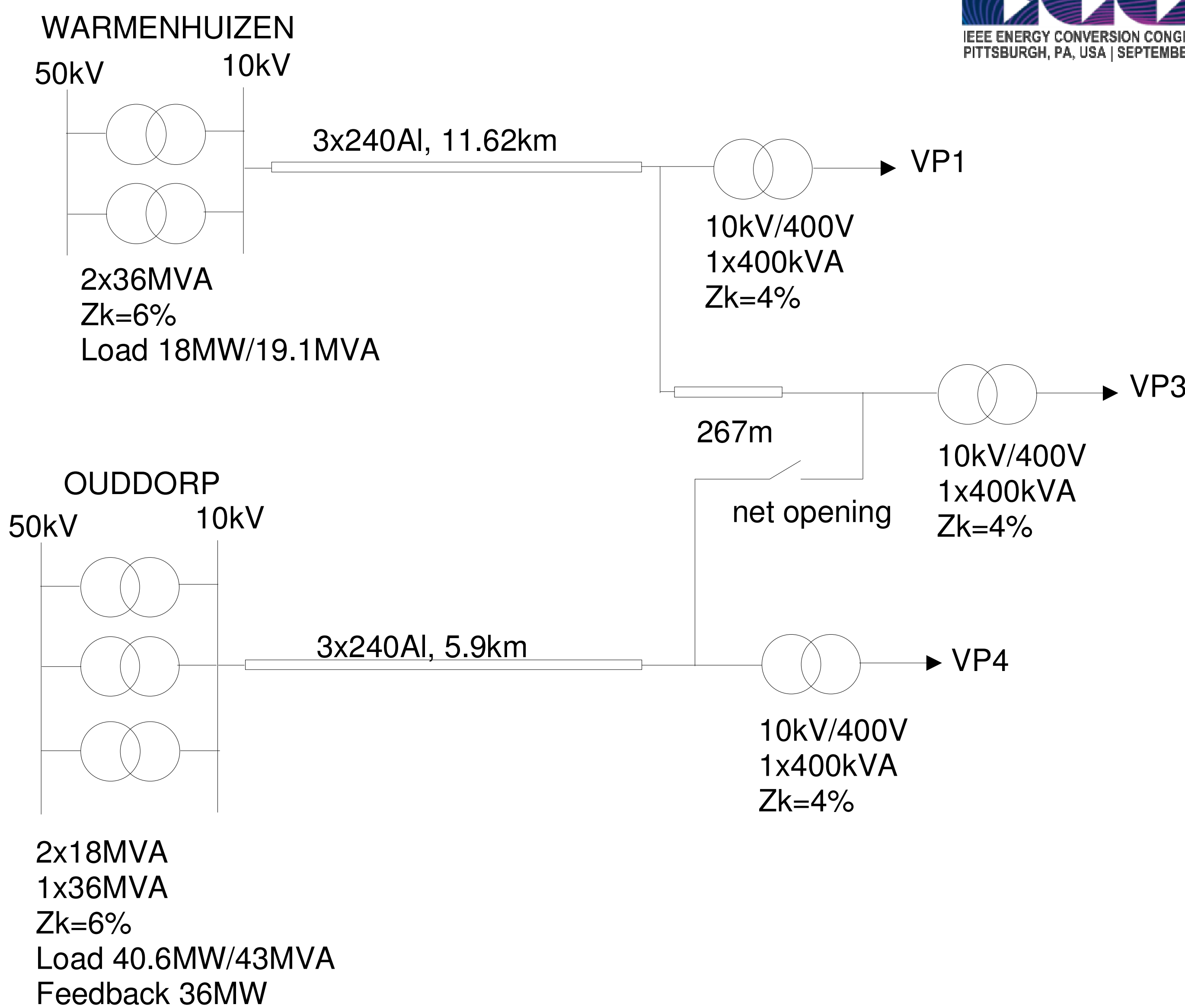


Sinus Supply: L = 1 mH R = 0,3 Ω **NL(3%) Supply: L = 1 mH R = 0,3 Ω** **EN50160 (8%): L = 1 mH R = 0,3 Ω**

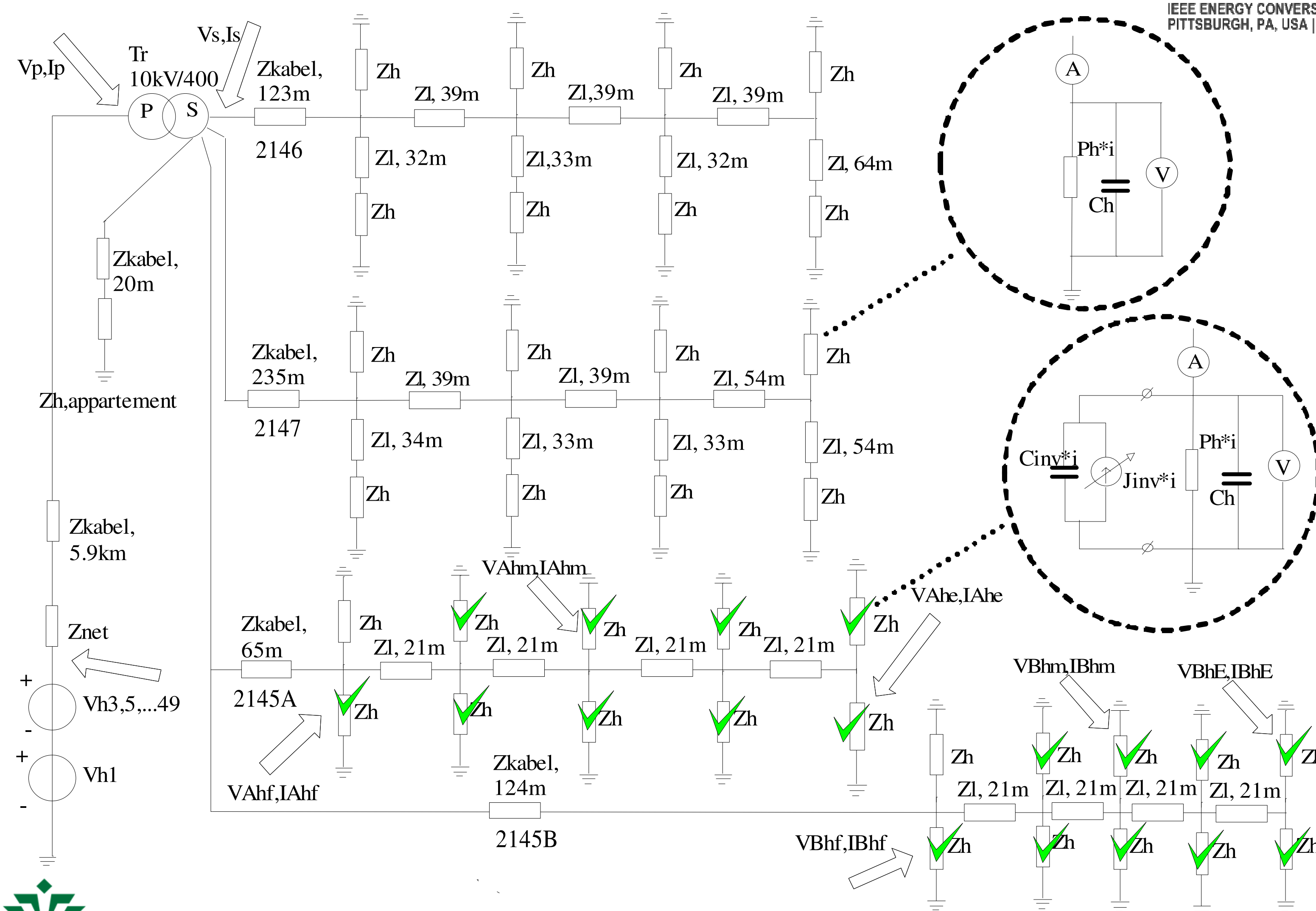
Voltage:- 200 V/div; Current:- 5 A/div
Time:- 4 ms/dive
C-home = 3 µF

UNC CHARLOTTE
EPIC

System Analysis Configuration

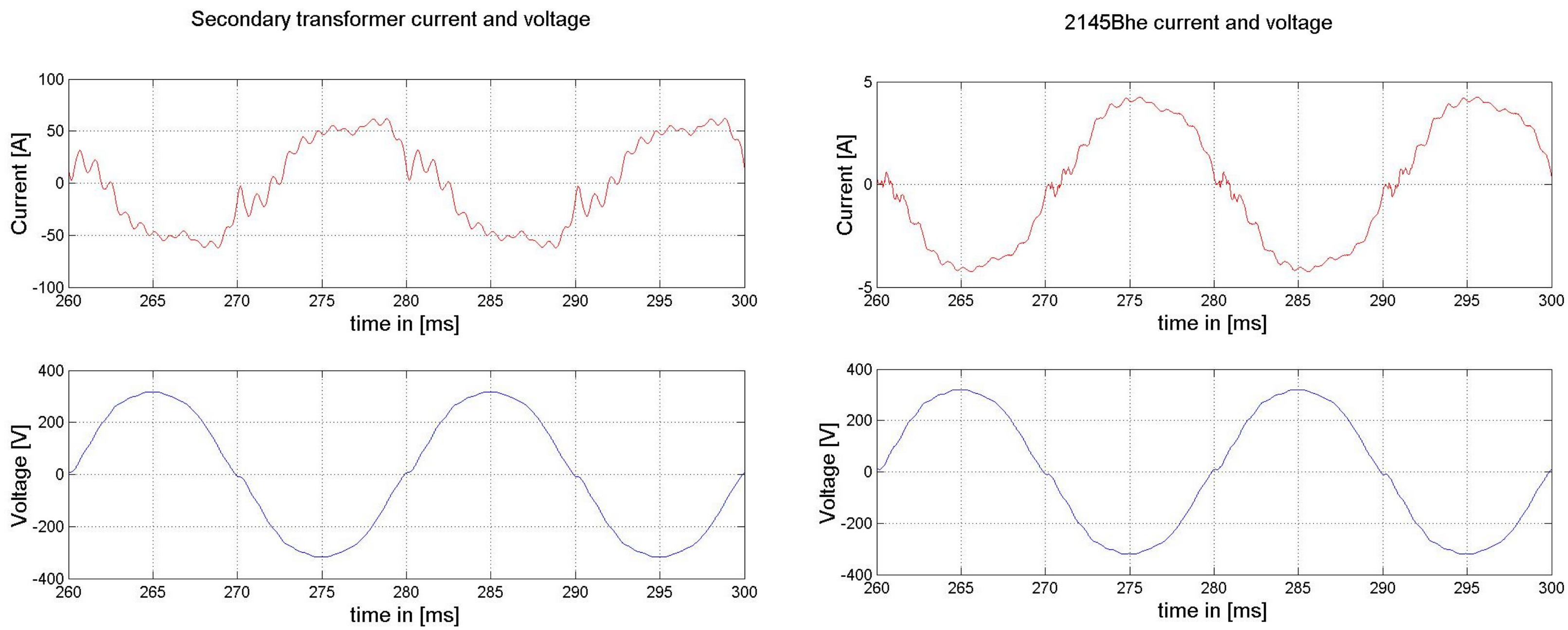


Network Simulation Model VP4



Simulation Results VP-4

Average Dutch (3%) Supply

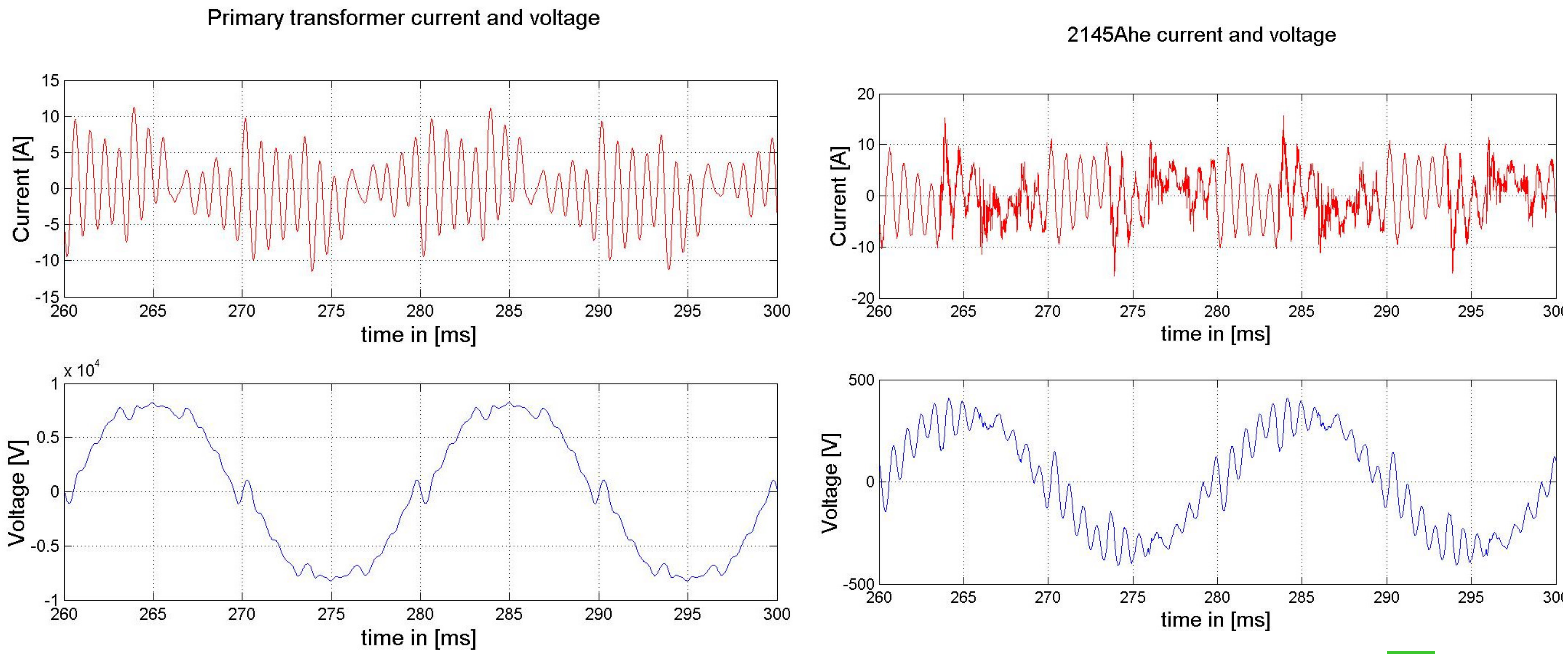


Simulated waveforms at two locations for the VP4 network section with average background distortion (V_{main} – 2%)

UNC CHARLOTTE
EPIC

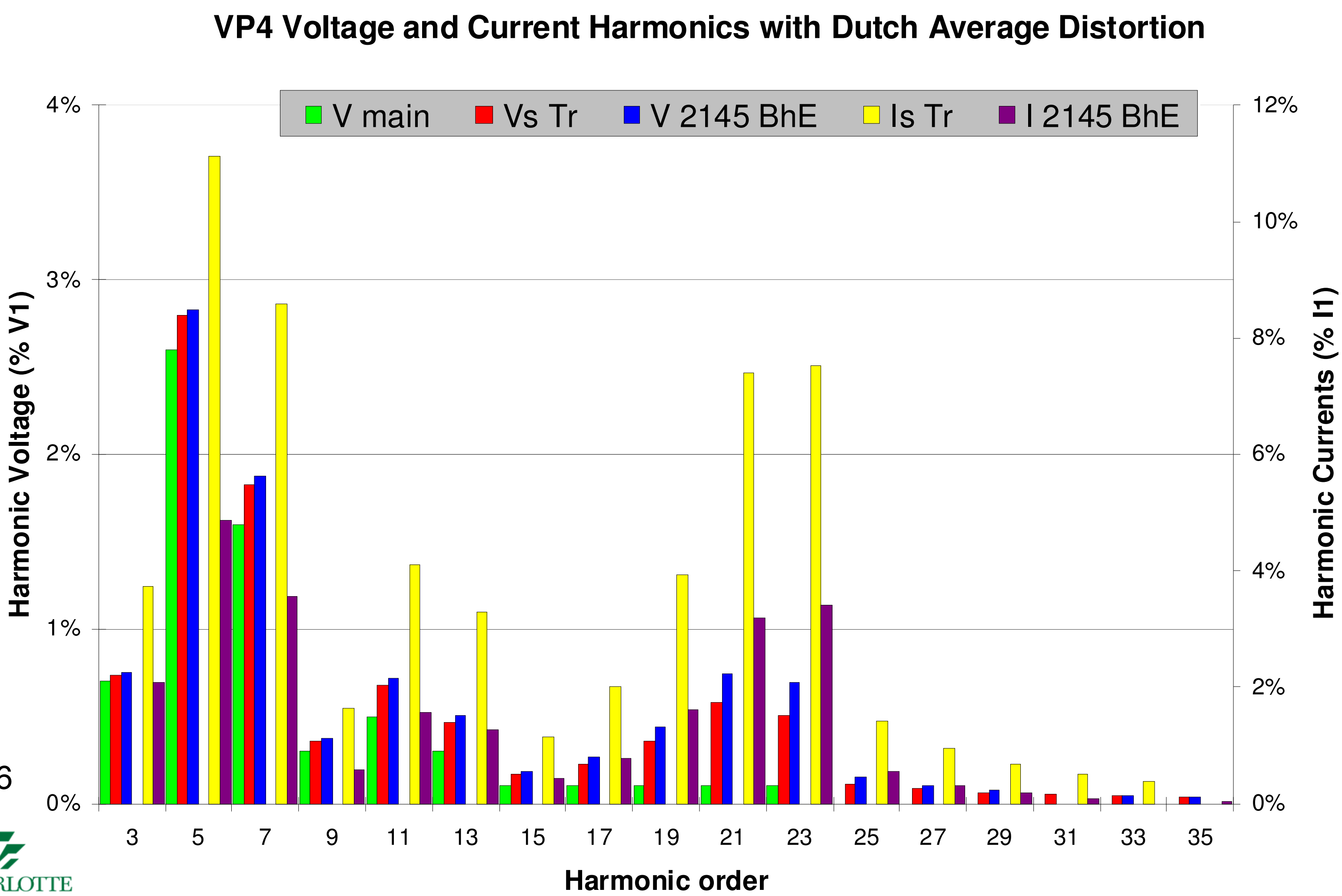
Simulation Results VP-4

Maximum EN50160 (8%) Supply Distortion



Simulated waveforms at two locations for the VP4 network section with maximum allowable distortion

Harmonics VP4 average pollution



UNC CHARLOTTE
EPIC

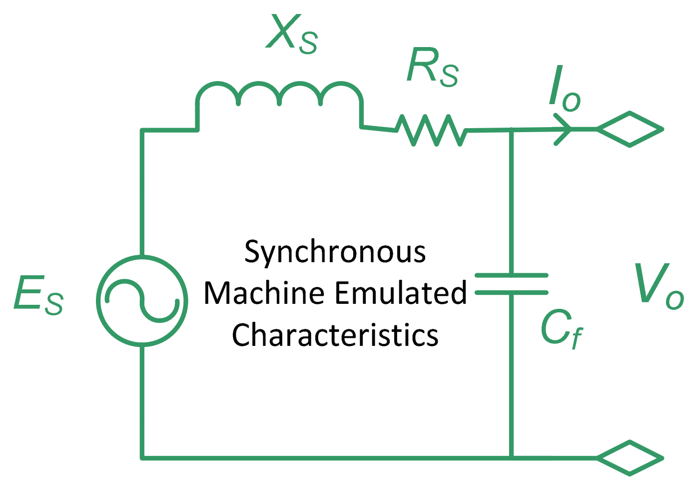
Advanced Smart DER Converter Controls

Generator Emulation Controls (GEC)

- Control PV inverters in a manner that emulates characteristics and behavior of traditional synchronous generators

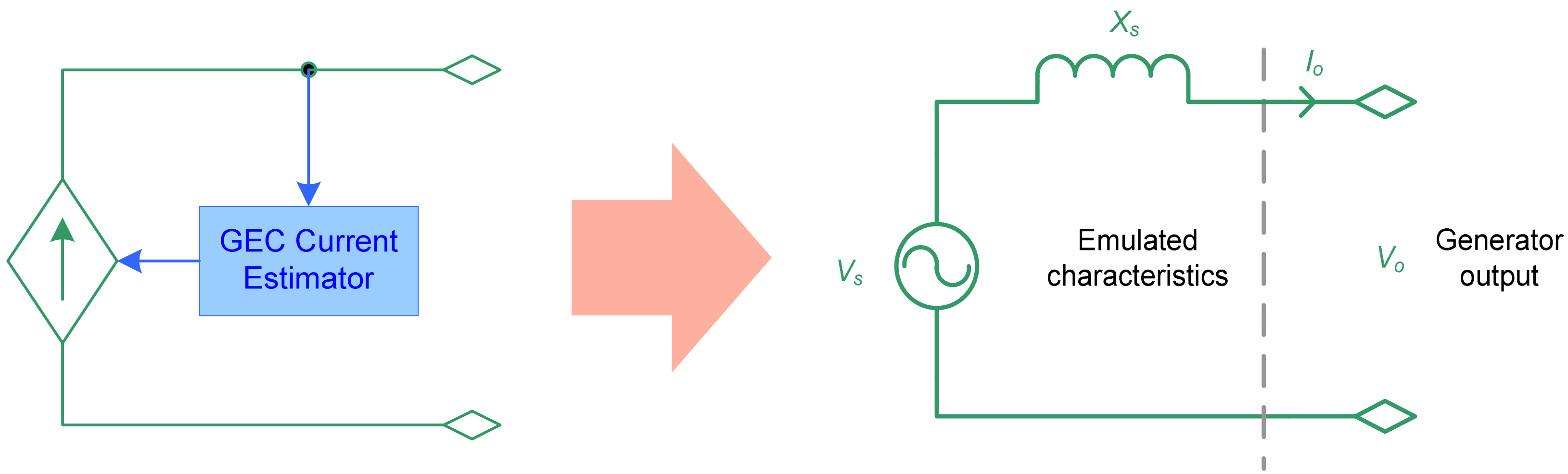
GEC allows PV inverters to:

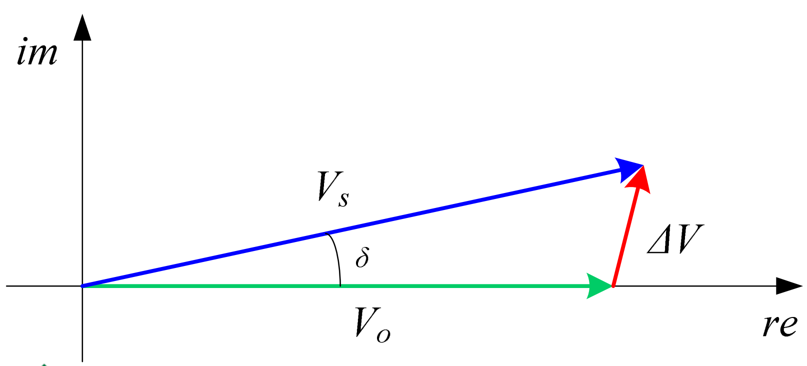
- Supply reactive power
- Active Power Filtering
- Support voltage stability through Volt / VAr control
- Perform voltage ride-through (VRT)
- V-f regulation for Micro-grid operation



UNC CHARLOTTE EPIC

GEC Concept Overview



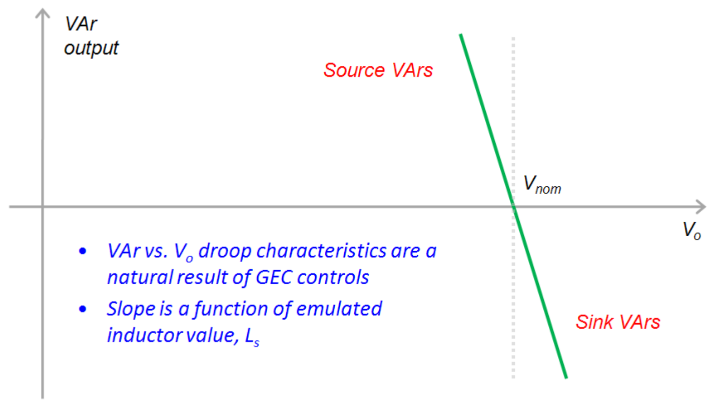


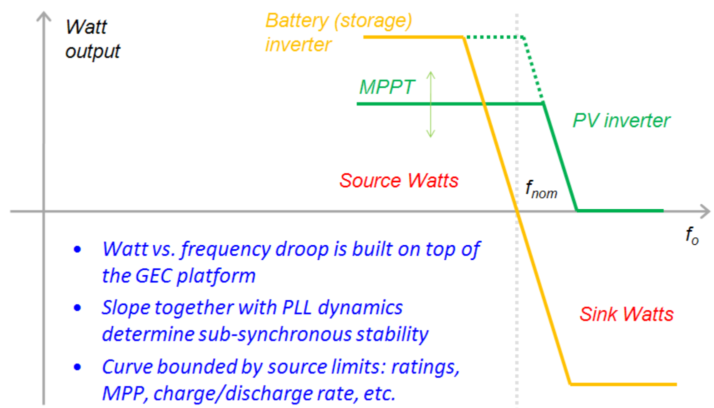
$$P_o = \frac{V_0 \cdot V_s \cdot \sin\delta}{X_s}$$

$$Q_o = \frac{V_0 \cdot V_s}{X_s}(1 - \cos\delta)$$

GEC Multi-Mode Operation

- Legacy Tie
  - UL1741-compliant grid-tie operation
  - Active Harmonic Filtering
- Smart Tie
  - Voltage Regulation support
  - Programmable V-f windows
  - Low-voltage ride-through
  - Reactive power injection
  - Ramping control and curtailment
  - Active Harmonic Filtering
- Islanded - MicroGrid
  - Voltage and frequency regulation
  - Automatic load sharing
  - Black Start support
  - Seamless transition to and from grid-tie
  - Energy storage integration
  - Active Harmonic Filtering

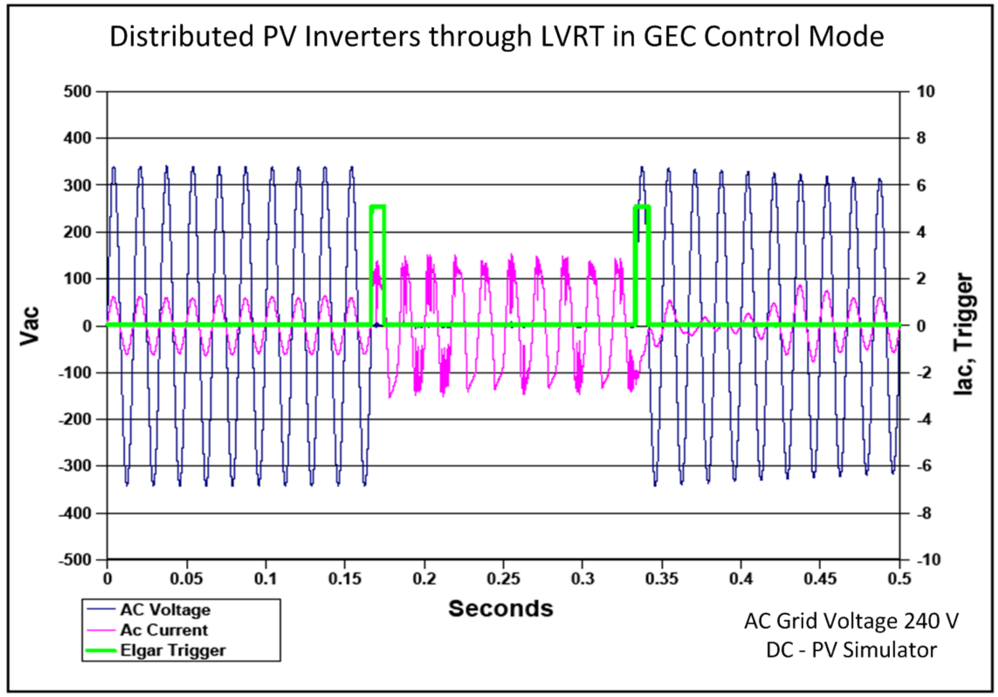




UNC CHARLOTTE
EPIC

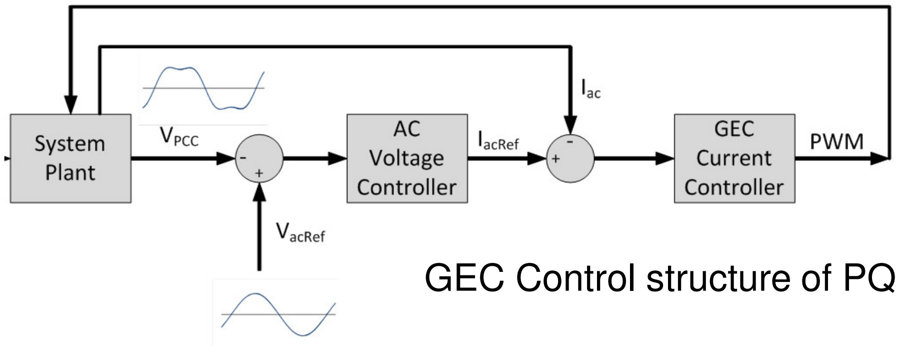
LVRT Operation

- GEC control is implemented into grid connected and micro-grid applications
- DER units stay connected through a low voltage transient and inject reactive power until voltage stabilize
- Units inject active power as soon as voltage is stable for a few cycles

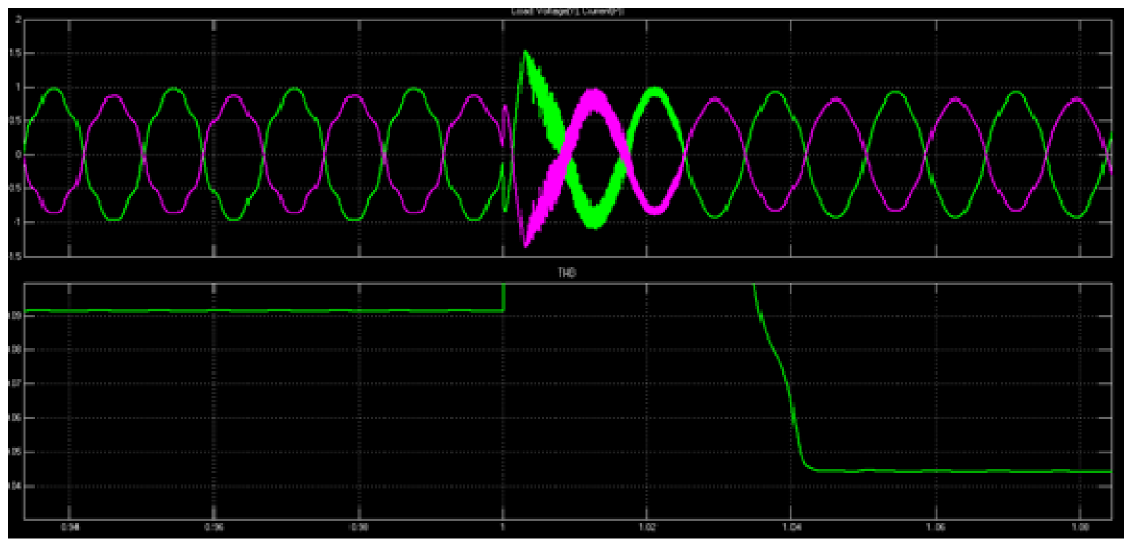


UNC CHARLOTTE
EPIC

Harmonic Mitigation with GEC-based Smart PV Inverter



GEC Control structure of PQ mitigation algorithm



Voltage THD at PCC is reduced from 9.2% to 4.3% by connecting the PV AC string with PQ mitigating algorithm

UNC CHARLOTTE
EPIC

Duke Energy Smart Grid Lab

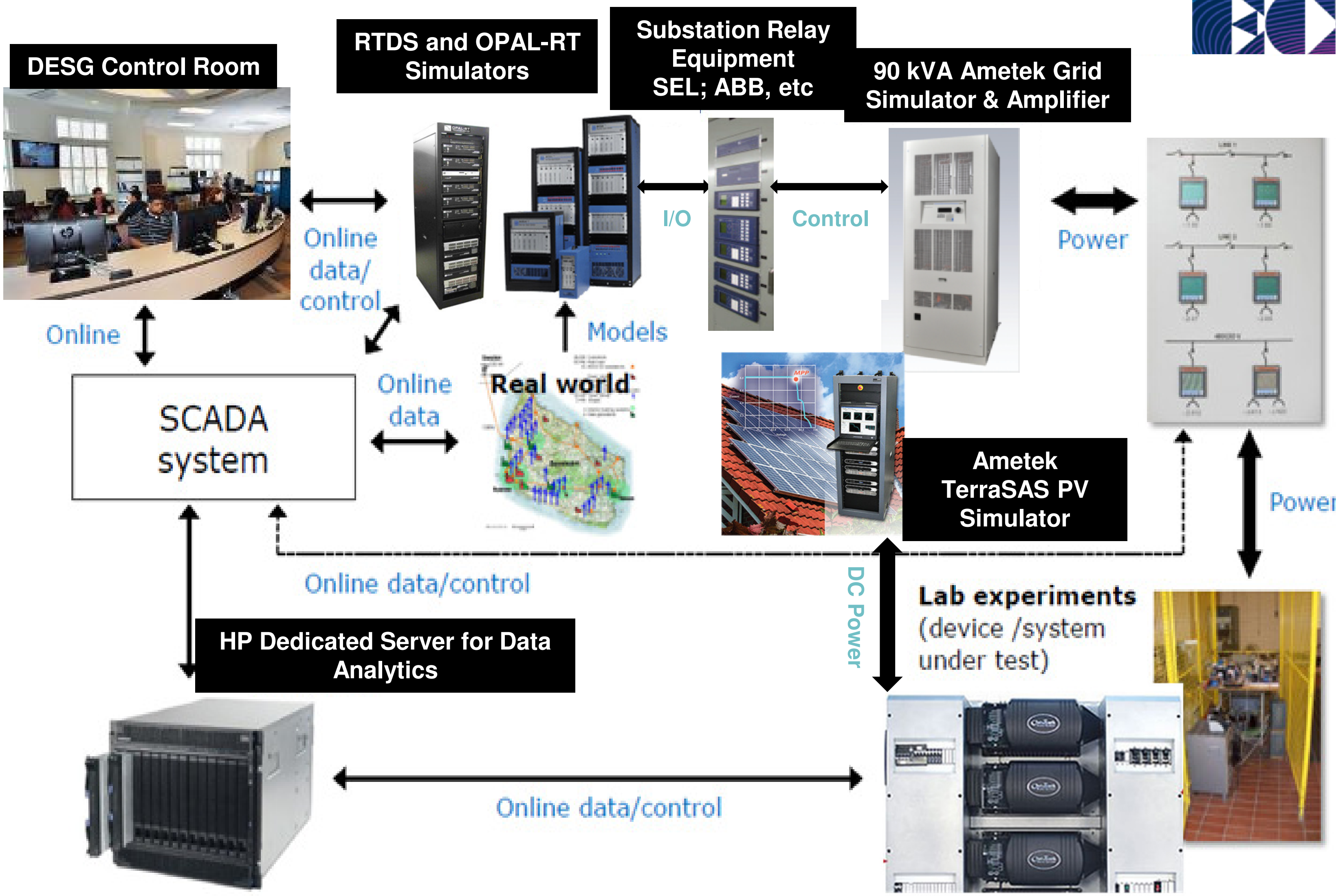
2014 ECCE
IEEE ENERGY CONVERSION CONGRESS & EXPO
PITTSBURGH, PA, USA | SEPTEMBER 14-18, 2014

- Real Time Digital Simulator (RTDS) – 3 enhanced racks
- 32 core OPAL-RT real-time power simulator
- 90 kVA Ametek Grid Simulator and Amplifier
- 150 A with 120V, 208V, 480V 1&3 phase power supplies
- Amatek TerraSAS 10 kW PV SImulator
- High speed fiber connections between labs and server room
- Dedicated and secured private LAN for external data streams
- Raised floor access for power, communication and control cables
- 6 fast response large LCD Screens and image control
- Data storage devices and SCADA gateways
- Communications - Private HP Server for data analytics
- HP X820, 16-Core, Dual Processor Xeon Workstation
- Simulation tools including - PSS/E; ETAP; EMTP-RV;
- RSCAD; PSCAD; Hypersim, RTLAB, etc.

UNC CHARLOTTE
EPIC

UNC CHARLOTTE
EPIC

Duke Energy Smart Grid Lab.



Conclusions & Recommendations

- Small current harmonics from large population of DER inverters excite resonance in distribution networks.
- Background voltage harmonics increase with DER Inverters due to series resonance.
- Household and cable capacitance together with short-circuit inductance can be dominant in resonance circuit
- Smart Inverters, emulating synchronous machine characteristics, can mitigate power quality issues
- Evaluate and test inverters with real-time HiL Testbeds
- Need to develop guidelines and standards for weak, Micro-grid or islanded network operations with variable impedances.

References

- Enslin, JHR: “Integration of Photovoltaic Solar Power – The Quest towards Dispatchability”, IEEE Instrumentation & Measurement Magazine, pp. 21-26, April 2014.
- Campanhol, L.B.G; da Silva, S.A.O; Sampaio, L.P; Junior, A.A.O: “A grid-connected photovoltaic power system with active power injection, reactive power compensation and harmonic filtering”, Power Electronics Conference (COBEP), 2013 Brazilian, pp. 642 - 649, Oct. 2013.
- Lee, C-.T.; Chu, C-.C.; Cheng, P-.T., "A New Droop Control Method for the Autonomous Operation of Distributed Energy Resource Interface Converters," Power Electronics, IEEE Transactions on , vol.28, no.4, pp.1980,1993, April 2013.
- Alatrash, H; Mensah, A; Mark, E; Haddad, G; Enslin, JHR: “Generator Emulation Controls for Photovoltaic Inverters”, IEEE Transactions on Smart Grid, Special Issue: Application of Smart Grid Technologies on Power Distribution Systems, Vol. 3, No 2, pp. 996-1011, June 2012.
- Sun, J: “Power Quality in Renewable Energy Systems - Challenges and Opportunities”, International Conference on Renewable Energies and Power Quality (ICREPQ’12), Spain, 28-30 March 2012.
- Liserre, M.; Teodorescu, R.; Blaabjerg, F., "Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values," Power Electronics, IEEE Transactions on , vol.21, no.1, pp.263,272, Jan. 2006.
- Enslin, JHR; Heskes, PJM: “Harmonic interaction between a large number of distributed power inverters and the distribution network”, IEEE Transactions on Power Electronics, Vol. 19, No. 6, pp. 1586 - 1593, Nov. 2004.