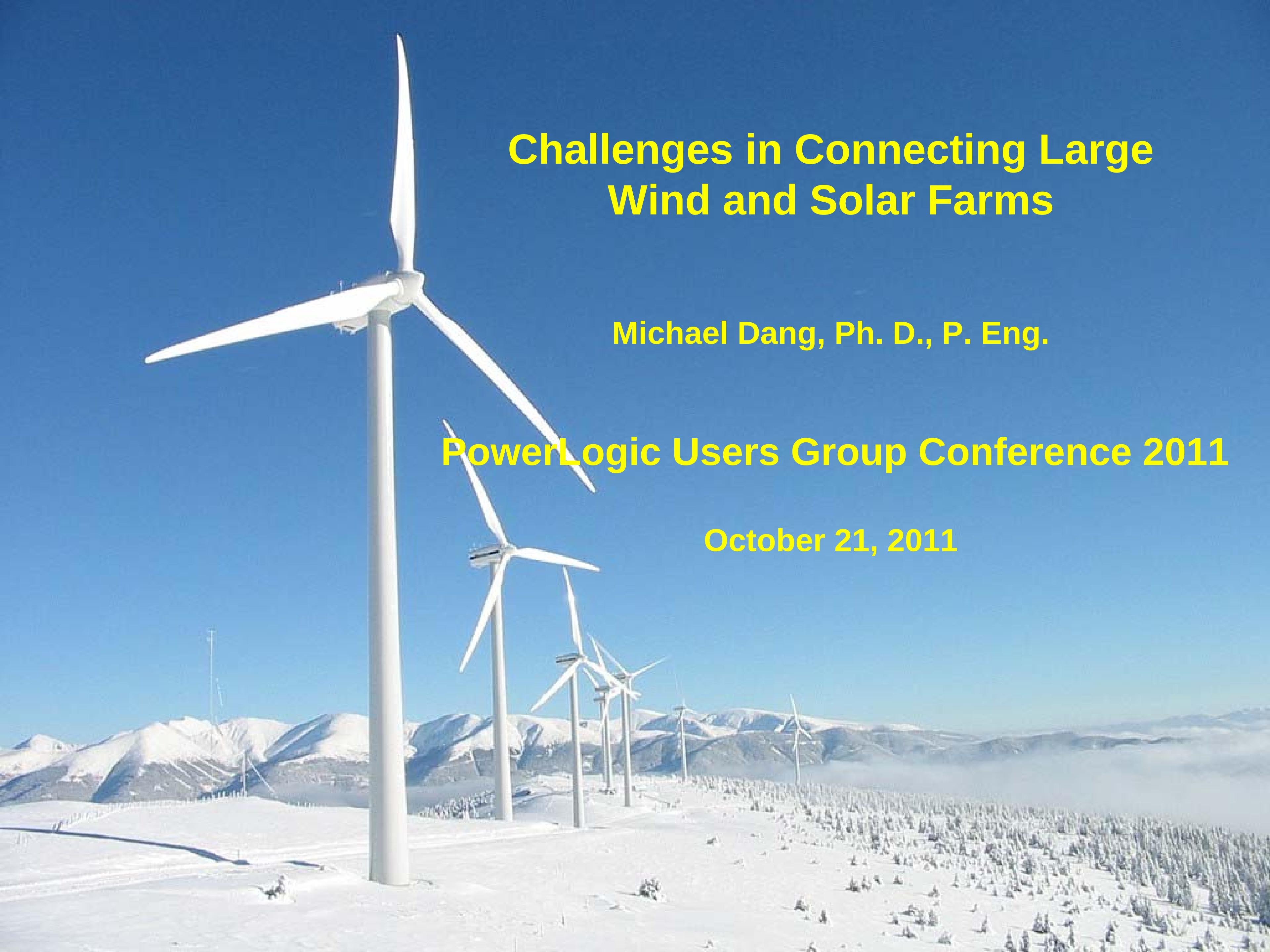


Challenges in Connecting Large Wind and Solar Farms

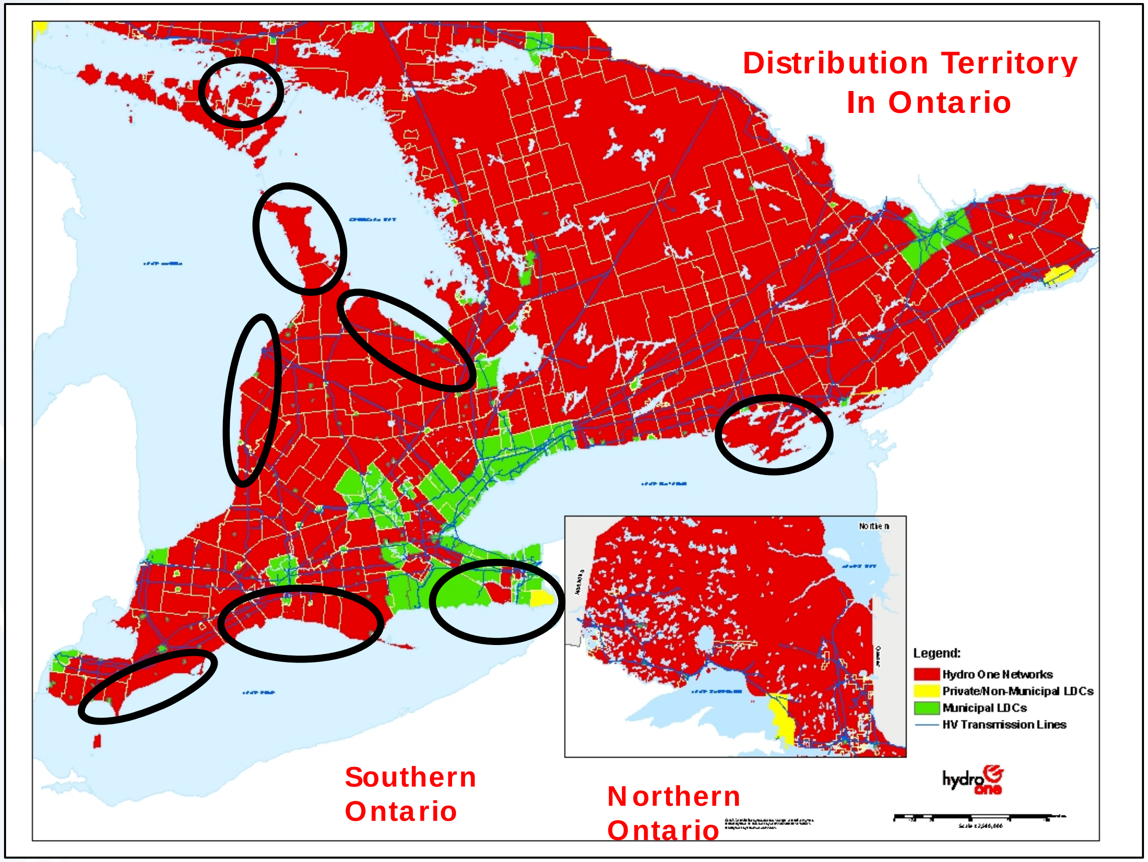
Michael Dang, Ph. D., P. Eng.

PowerLogic Users Group Conference 2011

October 21, 2011

OPA Generation Contracts

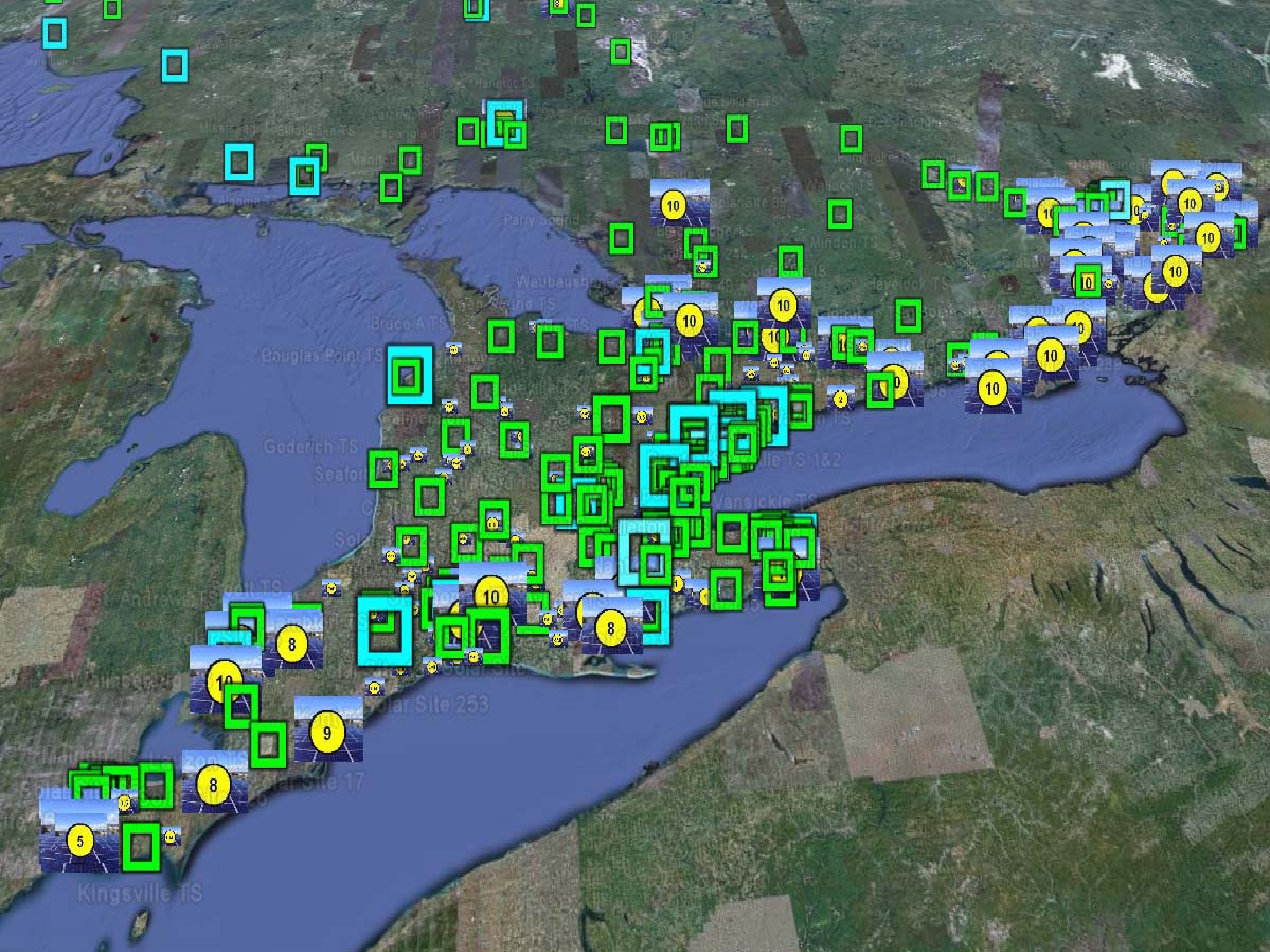
Delivery by Date and Technology Type for OPA Managed Contracts						Total
	Prior	2011 Planned	2012 Planned	2013 Planned	2014 Planned	
Wind	1527.1	833.4	497.6	1089.4	300	**4247.5**
Hydroelectric	28.2		14	507.3	54.85	**604.35**
Biomass, Landfill and Industrial By-Product Gas	55.3	15	17.8			**88.1**
Natural Gas	4153.9		673			**4826.9**
Bruce Refurbishment			1500			**1500**
Total	**5764.5**	**848.4**	**2702.4**	**1596.7**	**354.85**	**11,266.85**



<u>Good Wind Potential</u>

- **Southern Georgian Bay (Owen Sound, Collingwood)**
- **Bruce Peninsula North (tip of Lake Huron and Georgian Bay)**
- **Lake Huron shore (Goderich, Port Albert, Kingcardine, Douglas Point, Port Elgin)**
- **South shore on Lake Erie (Leamington, Port Stanley, Port Burwell, East of Nanticoke**
- **to Port Coleborne)**
- **Prince Edward County - Southeastern area**
- **Manitoulin Island**

Map of Ontario(2008)
Parry Sound TS
Muskoka TS
Bracebridge TS
Minden TS
Wallace TS
Waubaushene TS
Orillia TS
Owen Sound TS
Meaford TS
Stayner TS
Midhurst TS
Beaverton TS
Lindsay TS
Bruce A TS
Essa TS
Everett TS
Dobbin TS
Hanover TS
Armitage TS
Wingham TS
Palmerston TS
Orangeville TS
Whitby TS
Kleinburg TS
Agincourt TS
Cherrywood TS
Goderich TS
Fergus TS
Goreway TS
Rexdale TS
Scarborough TS
Elmira TS
Runnymede TS
Esplanade TS
Horner TS
Seaforth TS
Campbell TS
Hanlon TS
Cooksville TS
Detweiler TS
Oakville TS 1&2
Bronte TS
Galt TS
Stratford TS
Burlington TS
St. Marys TS
Centralia TS
Brant TS
Mohawk TS
Lake TS
Middleport TS
Vansickle TS
Thorold TS
Clarke TS
Ingersoll TS
Woodstock TS
Caledonia TS
Allanburg
Scott TS
Wanstead TS
Strathroy TS
Buchanan TS
Crowland TS
Dunnville TS
Longwood TS
Tillsonburg TS
Norfolk TS
Lambton TS 1&2
Port Colb
St. Thomas TS
Aylmer TS
Jarvis TS
Nanticoke TS
Wallaceburg TS
Kent TS
Tilbury TS
© 2008 Europa Technologies
© 2008 Tele Atlas
Image © 2008 TerraMetrics
Google
43°22'01.25" N 81°04'59.33" W
Eye alt 165.92 mi



Parry Sound TS
Minden TS
Havelock TS
Bruce A TS
Douglas Point TS
Goderich TS
Vansickle TS
Solar Site 253
Kingsville TS

Challenges in Incorporating Wind and Solar Farms

- Dynamic performance testing
- Model validation
- Low voltage ride-through requirement
- Frequency response analysis
- Steady state and dynamic model development of a solar farm

Dynamic Performance Tests in Wind Farms

Objectives of the tests are:

i. To demonstrate that the wind farm satisfies IESO and Hydro One performance requirements by carrying out the following tests:

- **Test #1**: Reactive power capability
- **Test #2**: **Voltage set point control**
- **Test #3**: Voltage step change

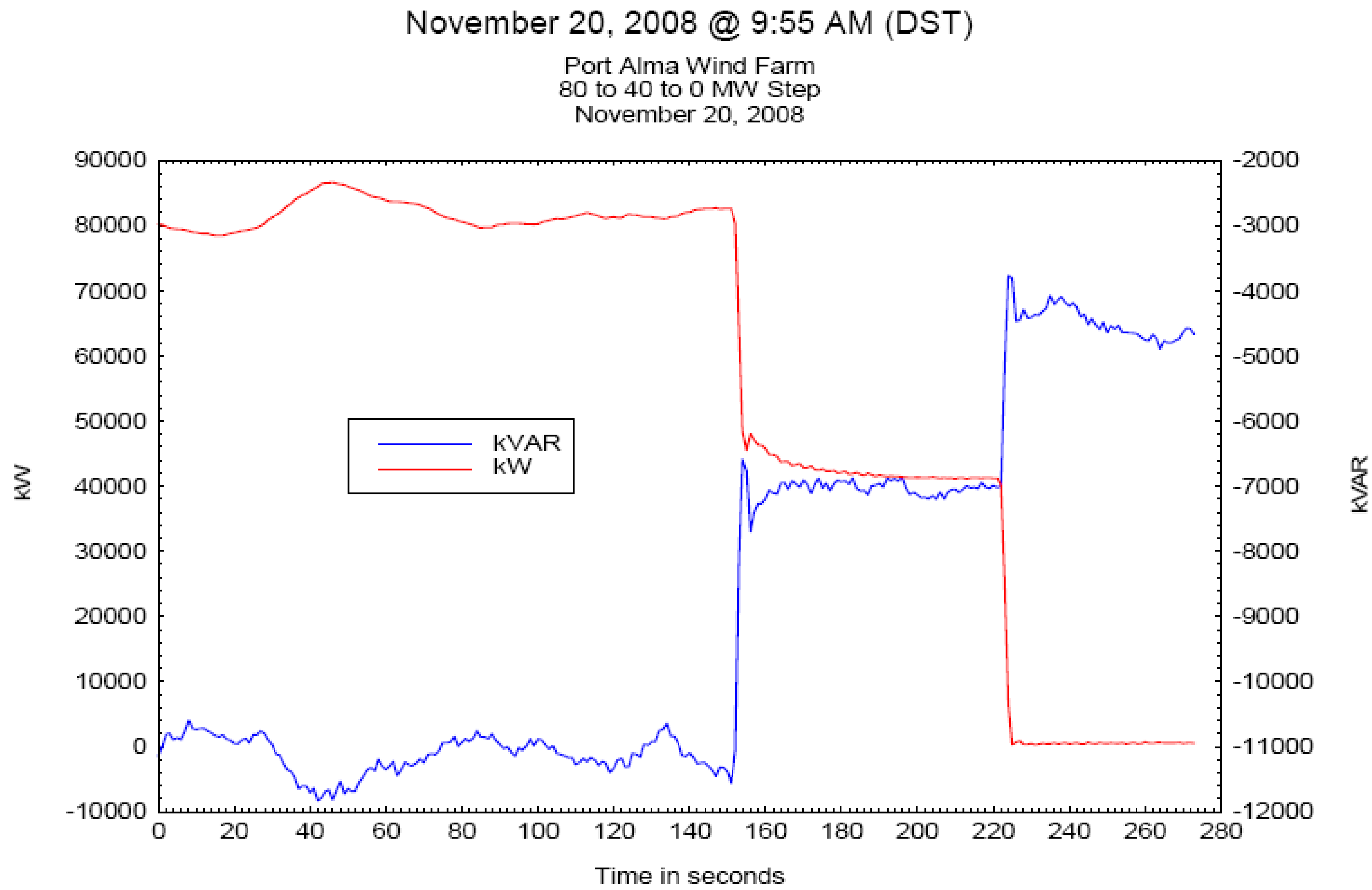
ii. To ensure that the wind farm complies with industry standards and guidelines for power quality by:

- computing voltage and current total harmonic distortions (THD) from measured waveform data
- computing voltage and current unbalances from measured waveform data.

Measurement Techniques

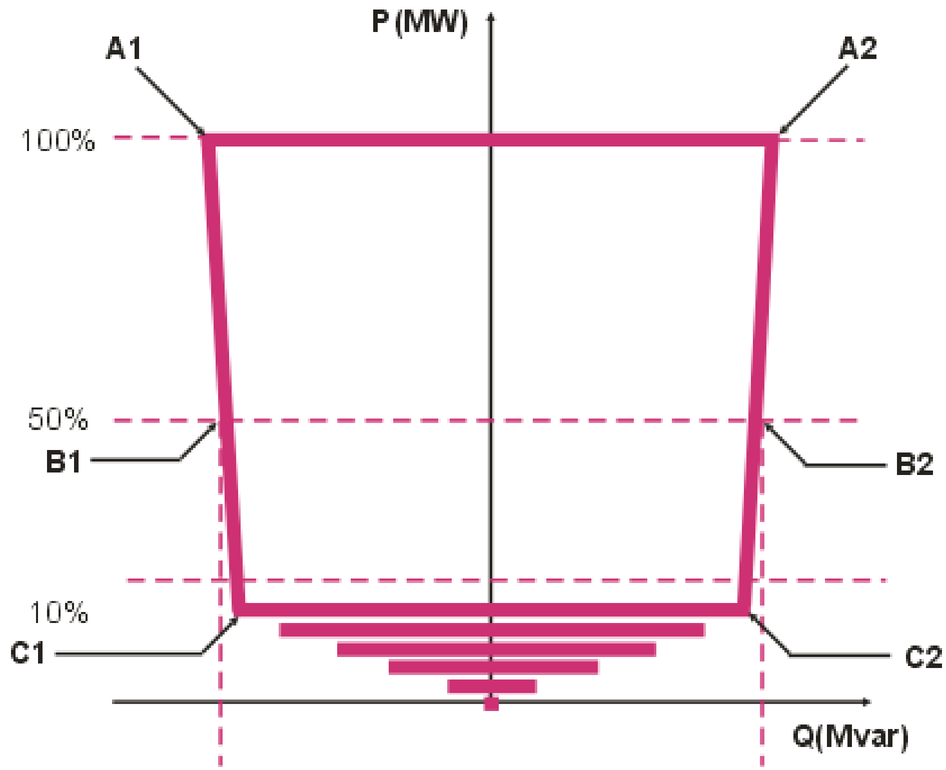
ION 7650 PQ meter connected to CVT or to PT and CT at 128 samples/cycle for 14 cycles measuring phase voltage and currents. The waveform captures could be triggered manually or automatically set to trigger at 135% of the nominal operating voltage.

Port Alma Wind Farm
Dynamic Performance Tests



Results showing power curtailment lowering power output from 80 MW to 40 MW (50% of start MW level) to 0 MW (0% of start MW level)

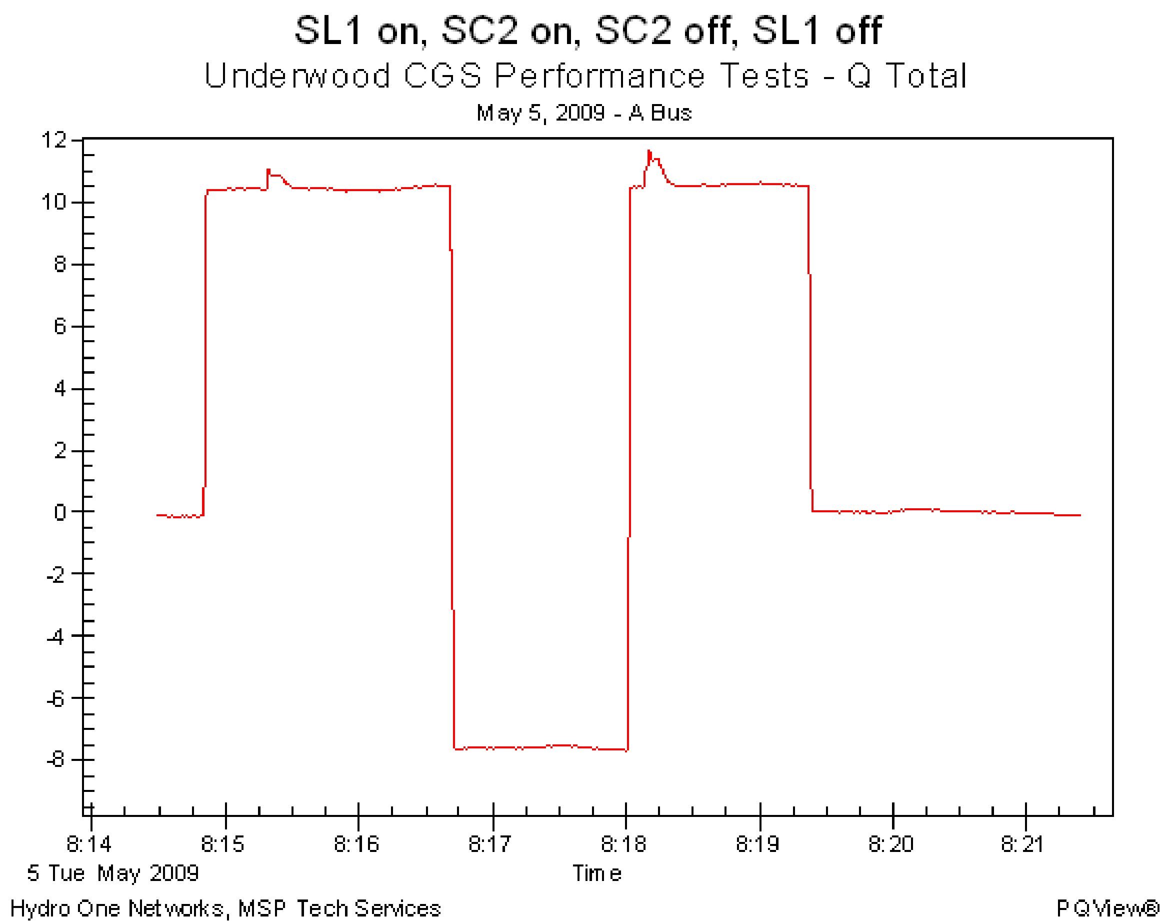
Reactive Power Capability of Wind Farm



i. A1 & A2: 100% MW generation at 0.9 lead to 0.9 lag power factor
ii. B1 & B2: 50% MW generation at 0.8 lead to 0.8 lag power factor
iii. C1 & C2: 10% MW generation; 0.3 lead to 0.3 lag power factor.

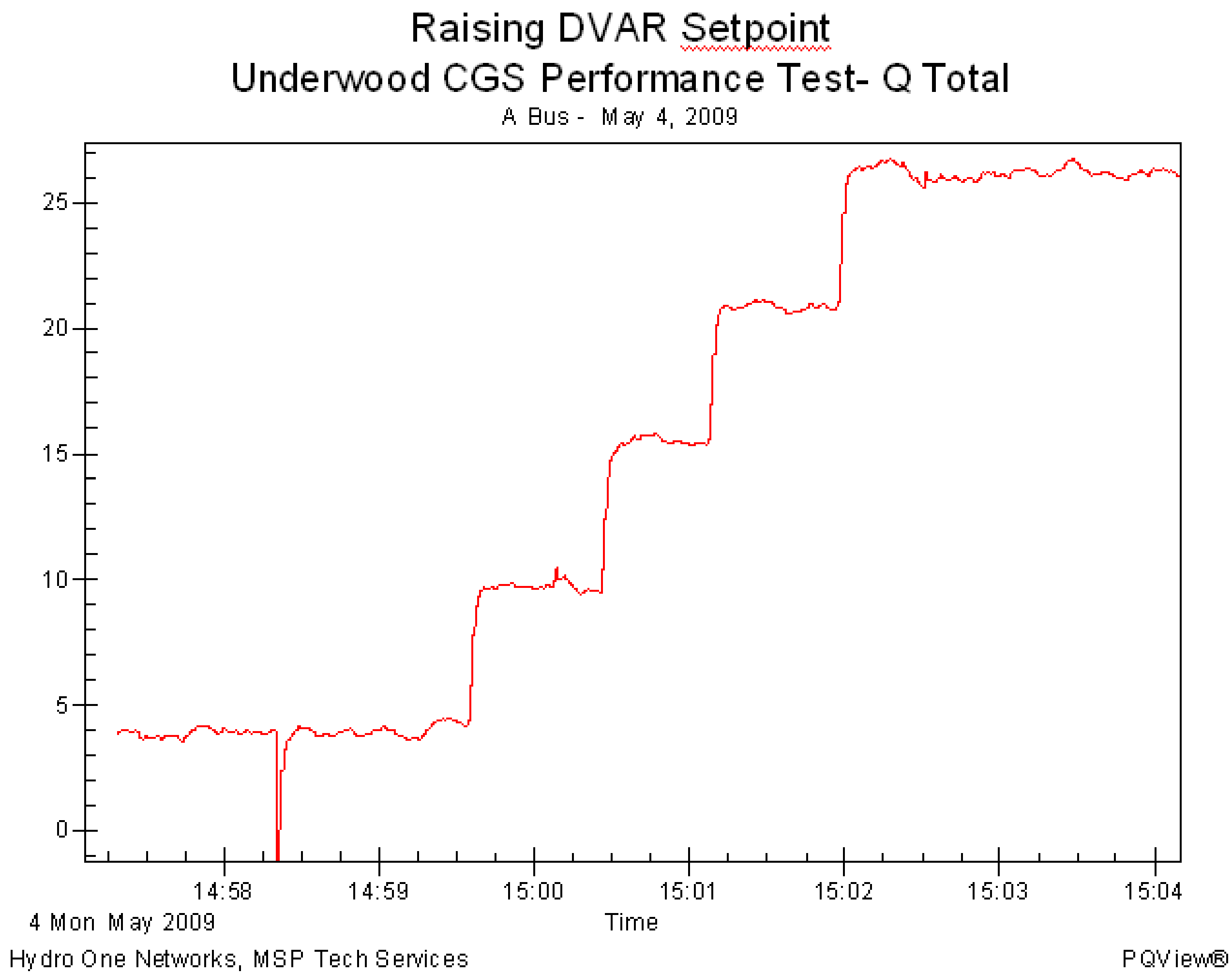
For wind farm operation below 10% of its maximum rated output, it is expected to operate within the shaded triangle.

Underwood Wind Farm
Dynamic Performance Tests



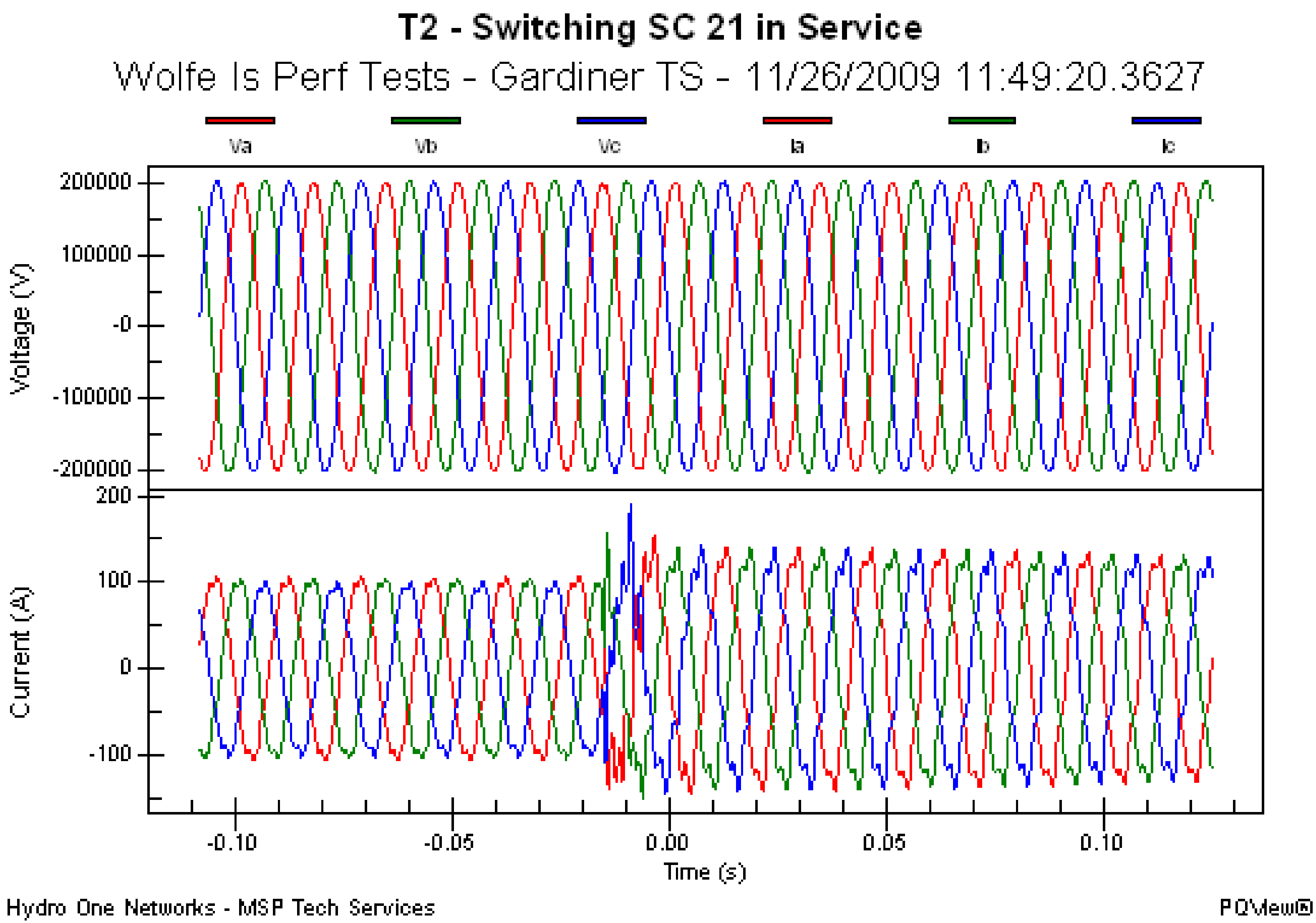
Results showing switching ON/OFF of 11 Mvar SL1 reactor and 13.8 Mvar SC1 capacitor bank at Enbridge Underwood CGS

Underwood Wind Farm
Dynamic Performance Tests



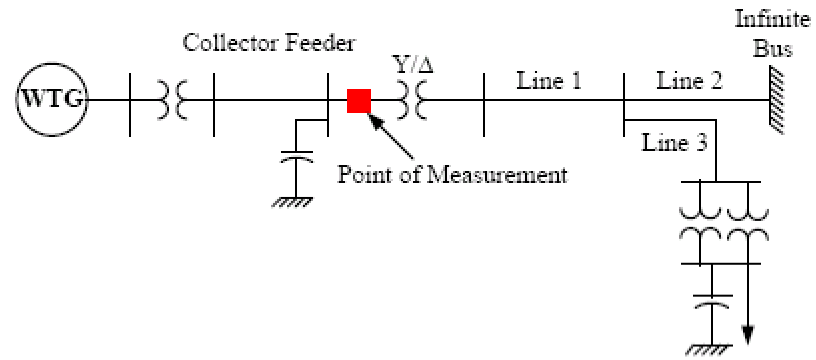
Results showing +5 Mvar set point changes at Underwood ± 4x8 MVA D-Var

Transient Waveforms



Model Validation

Simulation Studies Using Siemens-PTI PSS/E program



PSS/E Raw Data File Format

1. **Generator Data**

   7335,'1 ', 73.818, 16.024, 9999.000, -9999.000,1.01500, 0, 100.000, 0.00000, 0.01000, 0.00000, 0.00000,0.00000,1, 100.0, 9999.000, -9999.000, 1,1.0000

   90001,'1 ', 10.800, 0.000, 0.000, 0.000,1.00000, 0, 18.337, 0.00000, 0.80000, 0.00000, 0.00000,1.00000,1, 100.0, 16.500, 0.000, 1,1.0000

2. **Dynamic Data**

   90001 'USRMDL' 1 'GEDFA' 1 1 1 13 5 22 0 0.8 0.1714 2.904 0.005 0.1563 0.558 0.0 0.132853 0.02 0.02 30.0 0.1 -0.1 /

   90001 'USRMDL' 1 'GECNA' 4 0 4 26 10 10 90001 0 0 0 0.15 18.0 5.0 0.0 0.0 0.05 2.7 0.54 1.01 0.09 0.296 -0.436 1.11 0.05 0.4 -0.4 5.0 0.05 0.9 1.1 40.0 -0.5 0.4 0.05 0.05 1.0/

   0 'USRMDL' 0 'WGUSTA' 8 0 2 7 0 3 90001 '1' 9.286932 9999.0 5.0 30.0 9999.0 9999.0 30.0 /

   0 'USRMDL' 0 'W2MSFA' 8 0 3 5 2 3 90001 '1' 0 1.35 1.0 7.784 3 72.0 /

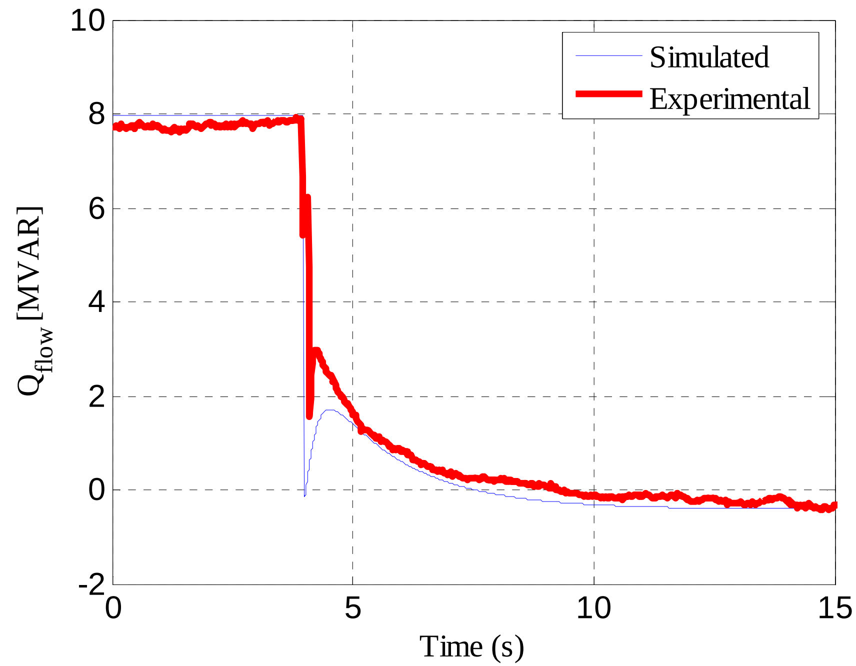
   0 'USRMDL' 0 'GEAERA' 8 0 3 12 1 4 90001 '1' 0 9.286932 20.0 0.0 27.0 -4.0 0.0 1.225 35.25 72.0 1200.0 1500.0 1.667 /

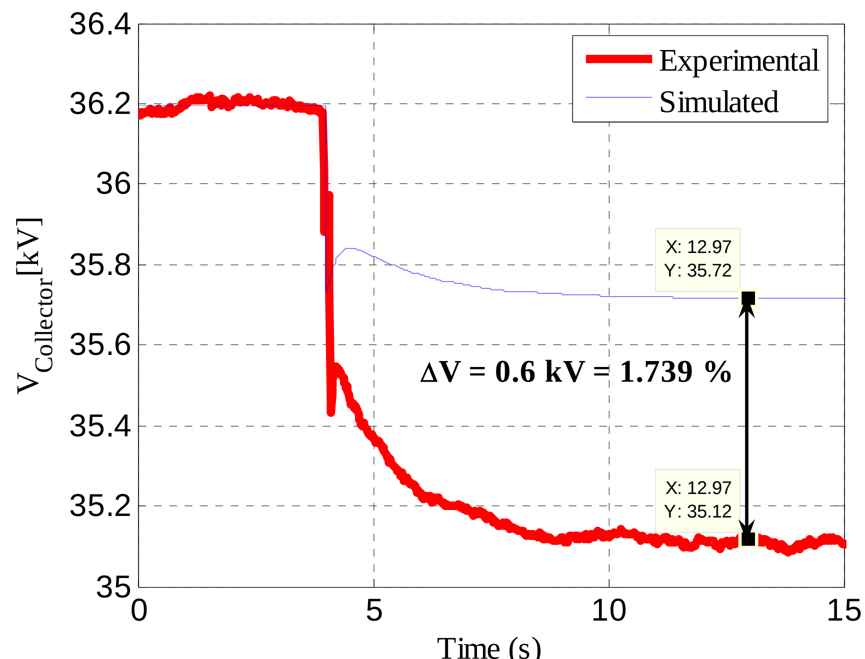
   0 'USRMDL' 0 'GEPCHA' 8 0 3 10 3 3 90001 '1' 0 0.3 150.0 25.0 3.0 30.0 -4.0 27.0 -10.0 10.0 0.91 /

   7335 'GENCLS' 1 0.0 0.0 /

Simulation Study 1

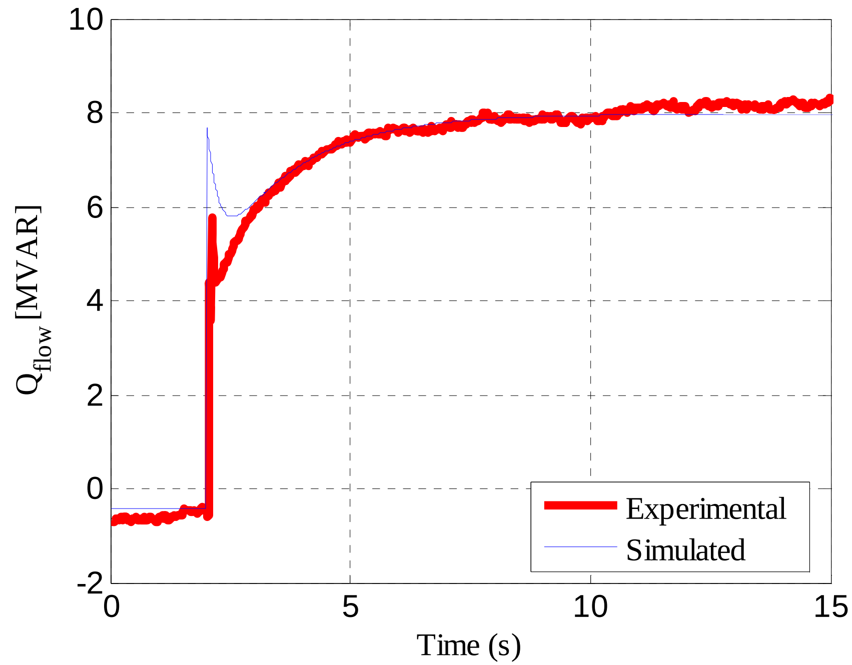
Switching OFF Port Burwell 8 Mvar capacitor bank

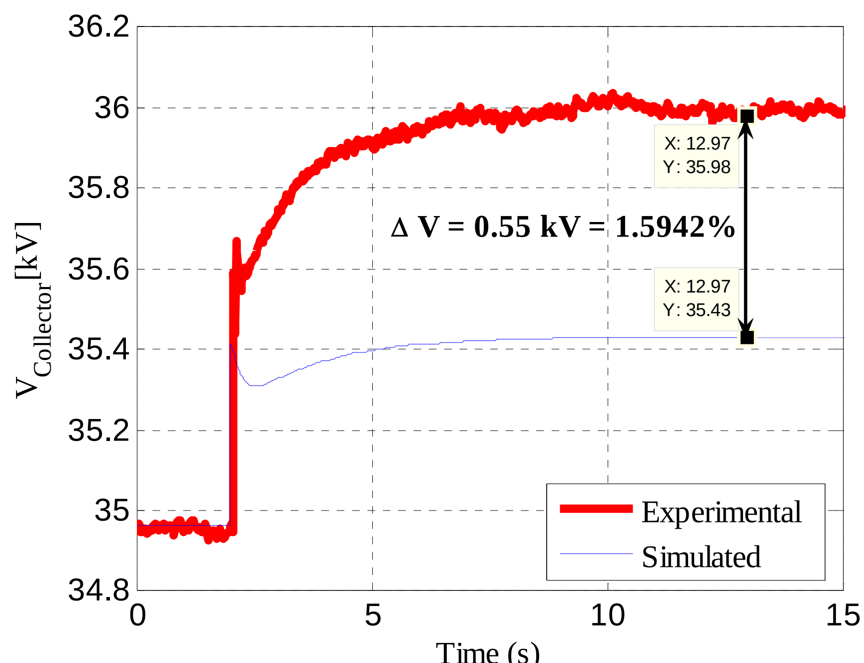




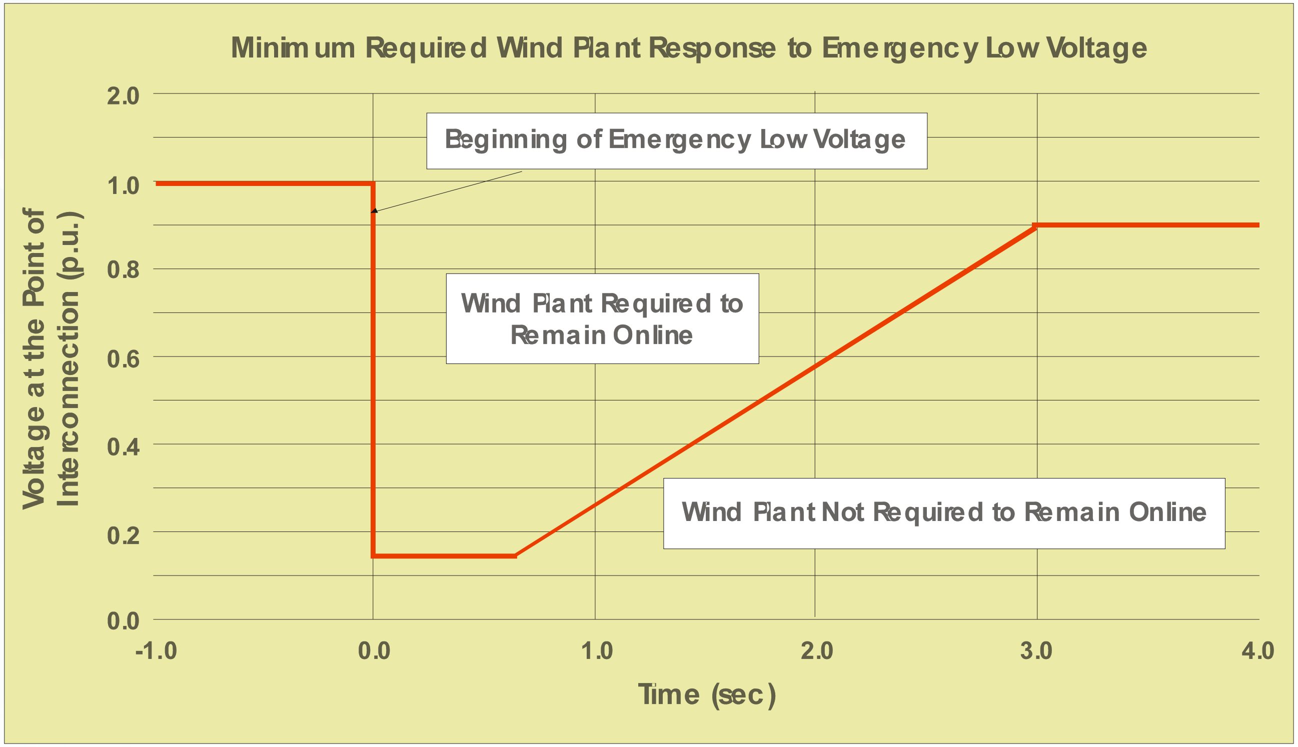
Simulation Study 2

Switching ON Port Burwell 8 Mvar capacitor bank





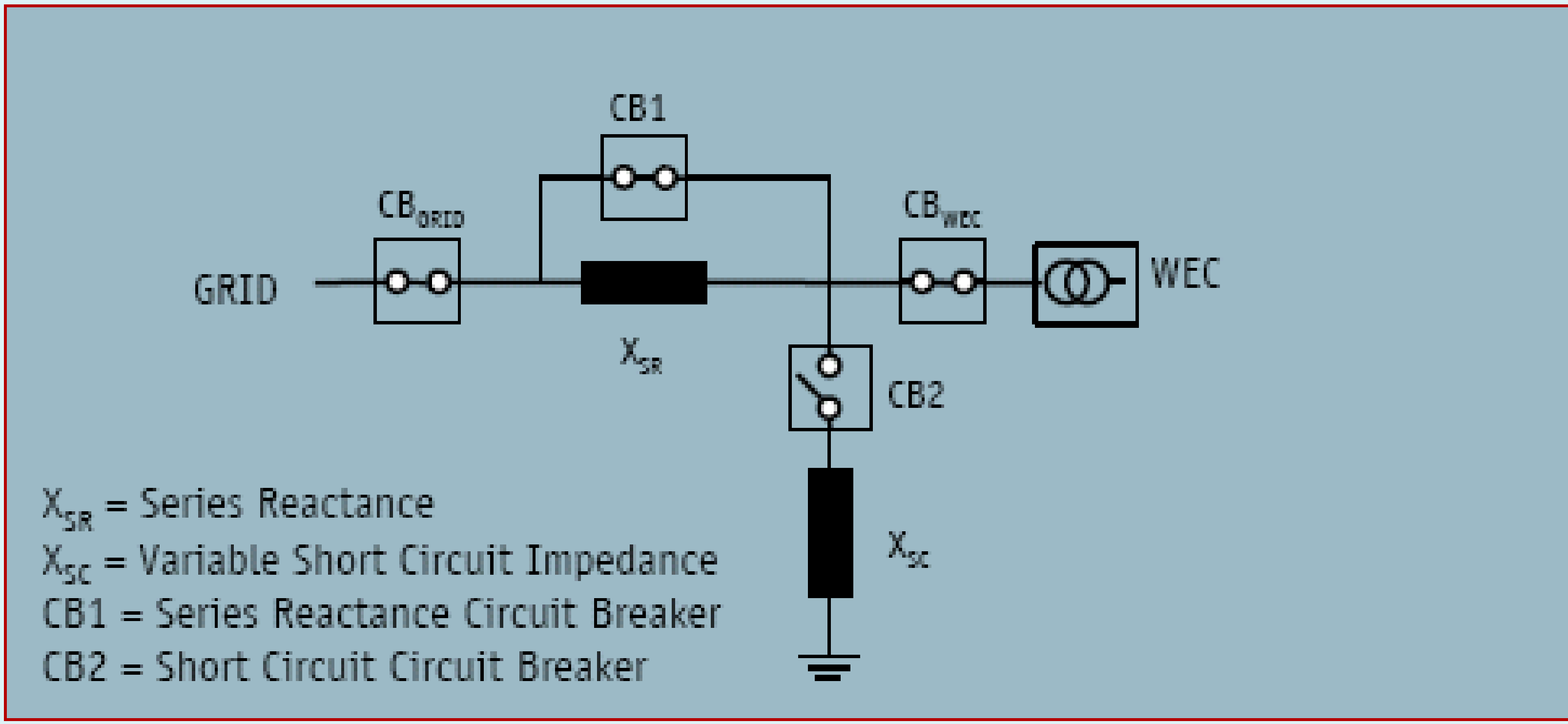
Low Voltage Ride-Through (LVRT) Requirements



FERC issued Order No. 661 on July 5, 2005 addressing low voltage ride-through capability for wind turbines - Wind turbines should stay connected for approximately 600 msec at voltages as low as 15% at the point of interconnection. This is to support transmission grid fault recovery.

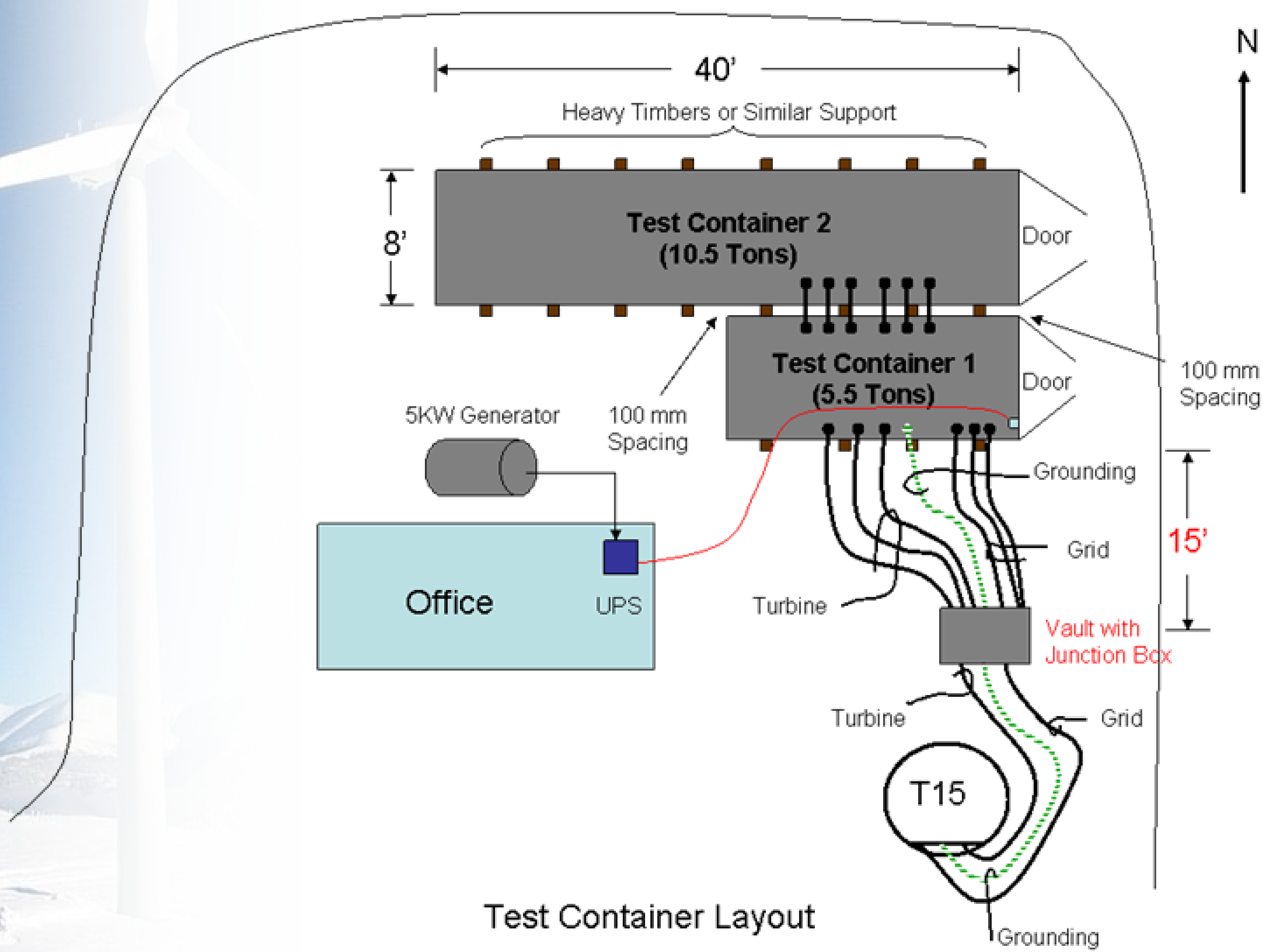
Refining LVRT Test Methodology

Vestas procures LVRT test container designed by FGH GmbH. Unique equipment provides controllable voltage dips at turbine terminals without grid disconnect of wind turbine.



LVRT testing continues using the mobile FGH LVRT test container at Kingsbridge WGS.

LVRT Test Container Setup at KWPP

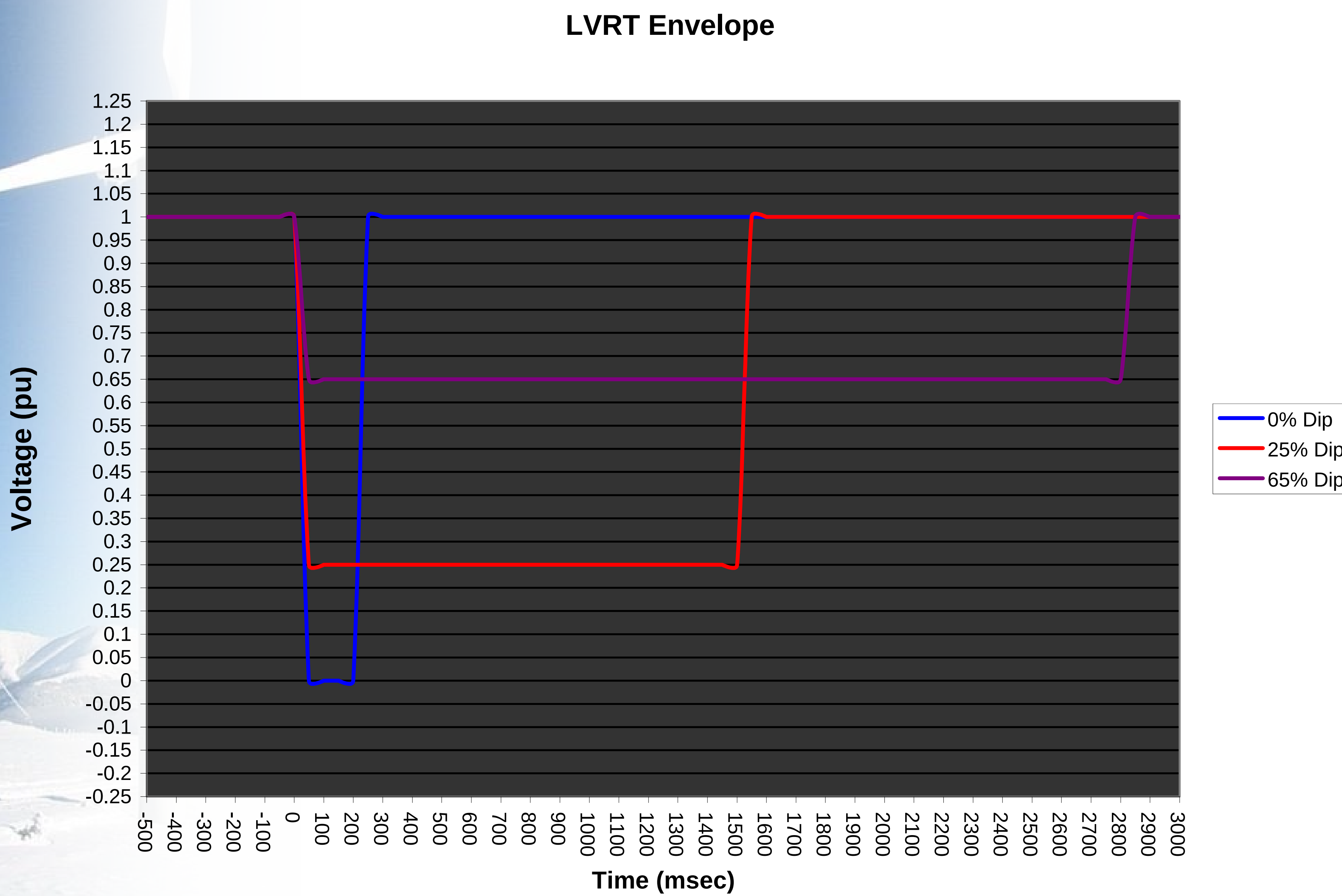


Test Container Layout

LVRT Test Container Setup at KWPP

LVRT Test Container Installation at KWPP

Example LVRT Envelopes Tested at KWPP



Frequency Response Analysis
Steady State THD Calculation

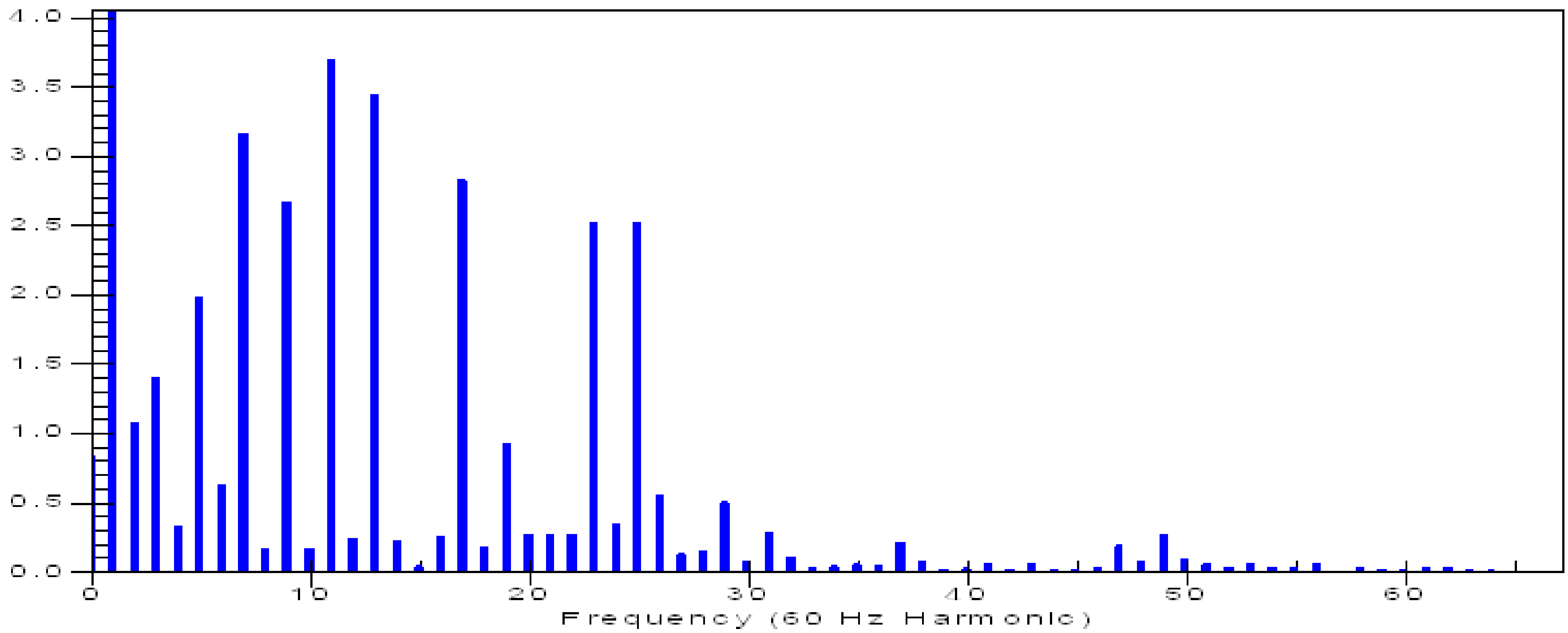
Appendix B: Steady State THD Summary

THD (% of fundamental, 1 cycle FFT)								
	Location	November 16, 2009	Va	Vb	Vc	Ia	Ib	Ic
T1 @ 0 MW	Wolfe Is	9:38:41.420 AM	0.79	0.86	0.85	3.85	3.53	4.21
	Gardiner TS	9:38:43.539 AM	0.97	0.95	0.95	13.15	14.57	12.28
T2 @ 0 MW	Wolfe Is	9:33:40.578 AM	0.79	0.82	0.84	3.39	3.43	3.79
	Gardiner TS	9:33:42.258 AM	0.90	0.96	0.87	7.36	8.21	7.28
T1 @ 16 MW	Wolfe Is	9:35:13.562 AM	0.69	0.74	0.73	3.09	2.79	3.09
	Gardiner TS	9:35:14.604 AM	0.93	0.97	0.92	7.69	8.14	7.44
T2 @ 15 MW	Wolfe Is	9:47:51.107 AM	0.65	0.71	0.72	2.74	2.69	2.93
	Gardiner TS	9:48:18.387 AM	0.88	0.96	0.88	3.78	4.03	3.42

1 cycle FFT performed on captured waveform data.

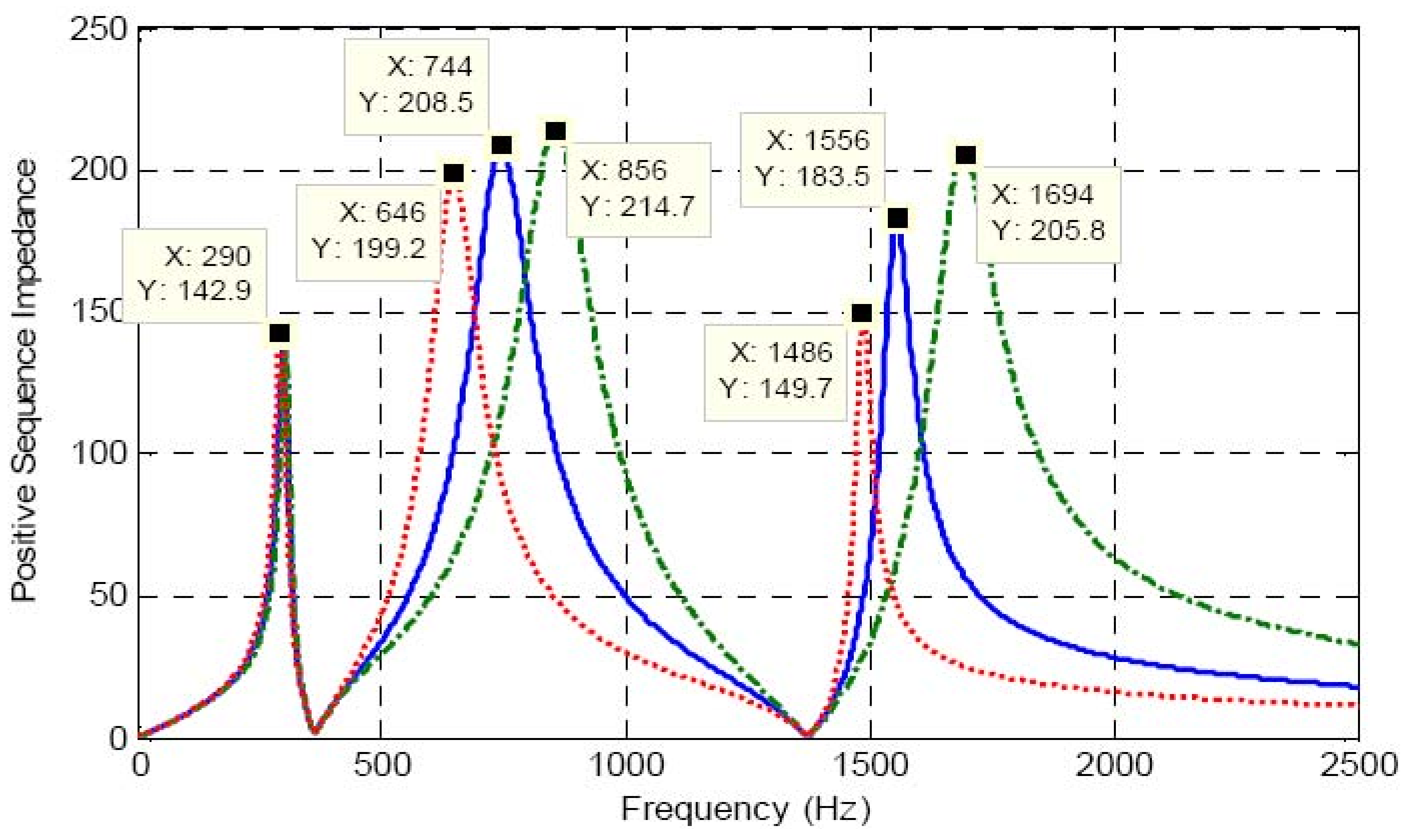
IEEE 519 establishes harmonic limits on voltage as 5% for total harmonic distortion and 3% of the fundamental voltage for any single harmonic.

Harmonic Spectrum Analysis



Spectrum analysis plot of the measured waveform taken at St. Andrews M14 27.6 kV feeder on Dec 2, 2009

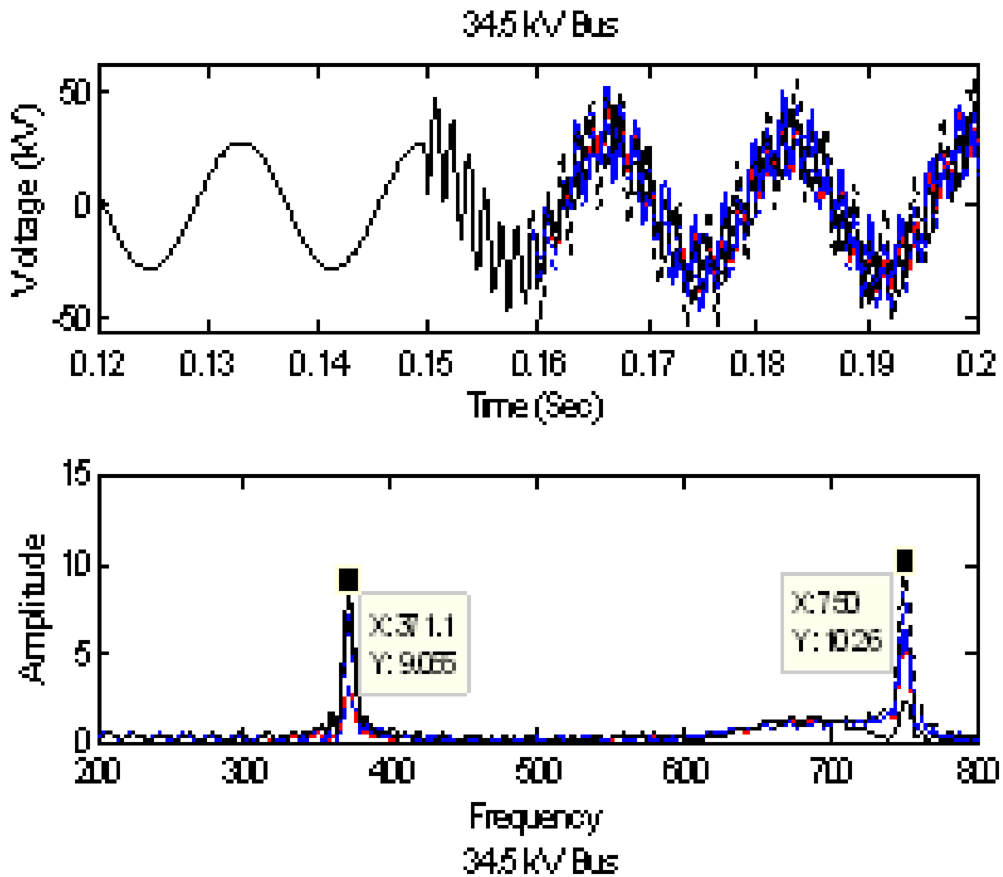
Network Resonance and Harmonics



i. **Harmonic resonances in the network can significantly amplify the impact of even small harmonic currents**

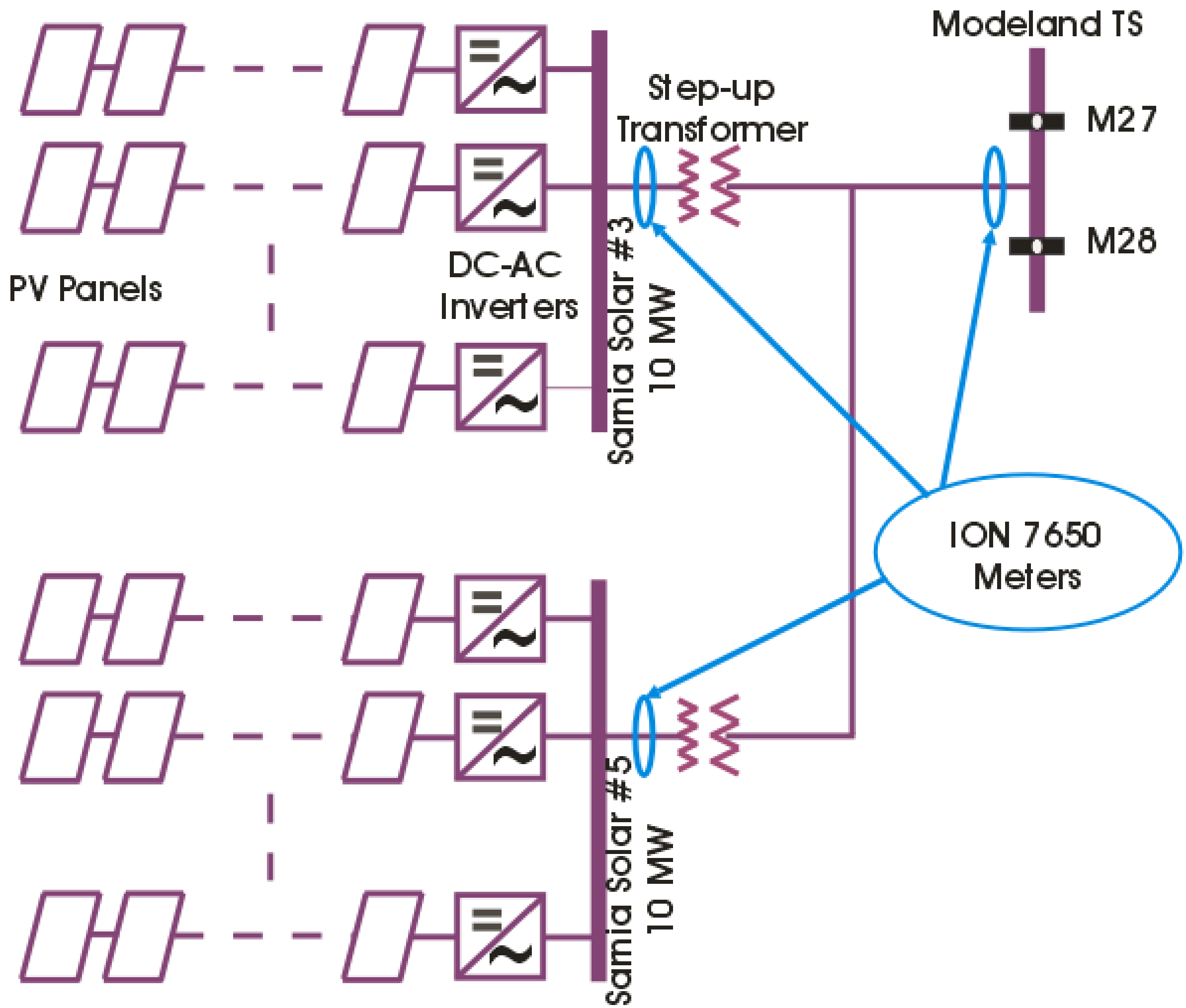
ii. **Short-circuit levels tend to shift the resonance peaks making them particularly susceptible to tripping wind turbines on transient overvoltage**.

Unsynchronized Switching of Ph-C of Chatham SC22 Capacitor Bank



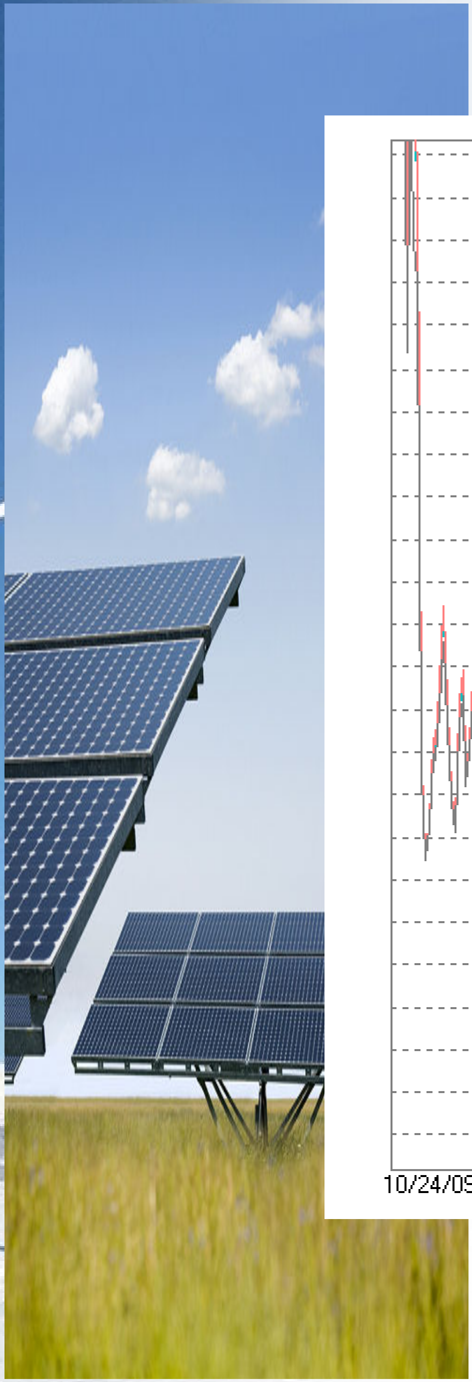
i. The first resonant frequency varies between 219-426 Hz (3rd to 7th harmonic)
ii. Second resonant frequency varies between 749-757 Hz (12th -13th harmonic)
iii. Mal-operation/ faulty SCU caused transient over voltage that resulted in tripping of wind turbines at Port Alma Wind Farm
iv. Corrective measures consisted of Increasing the threshold voltage.

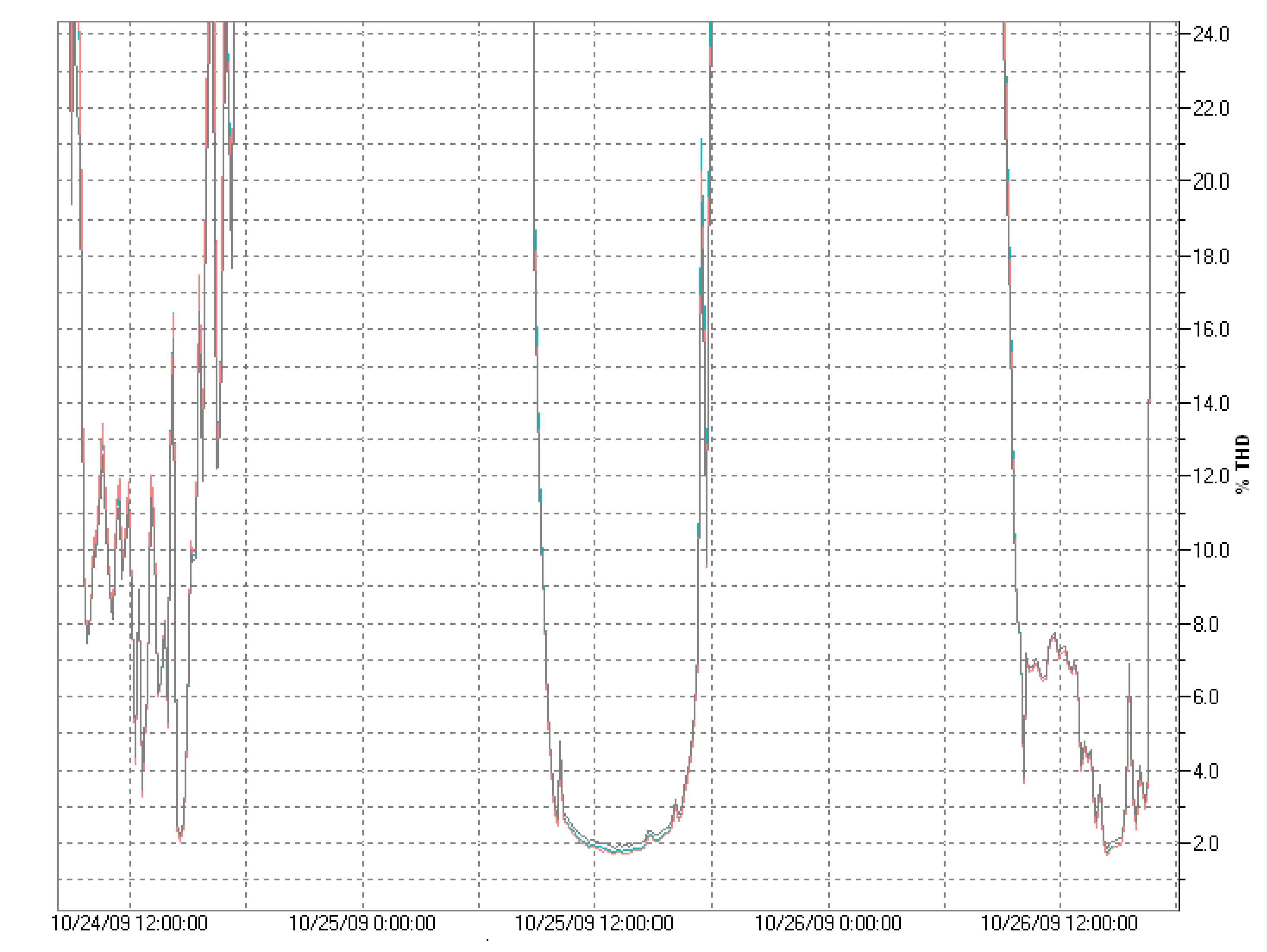
Test Equipment Connection Points at Sarnia Solar #3 and #5



The ION 7650 meter could be configured to capture data under various solar activities

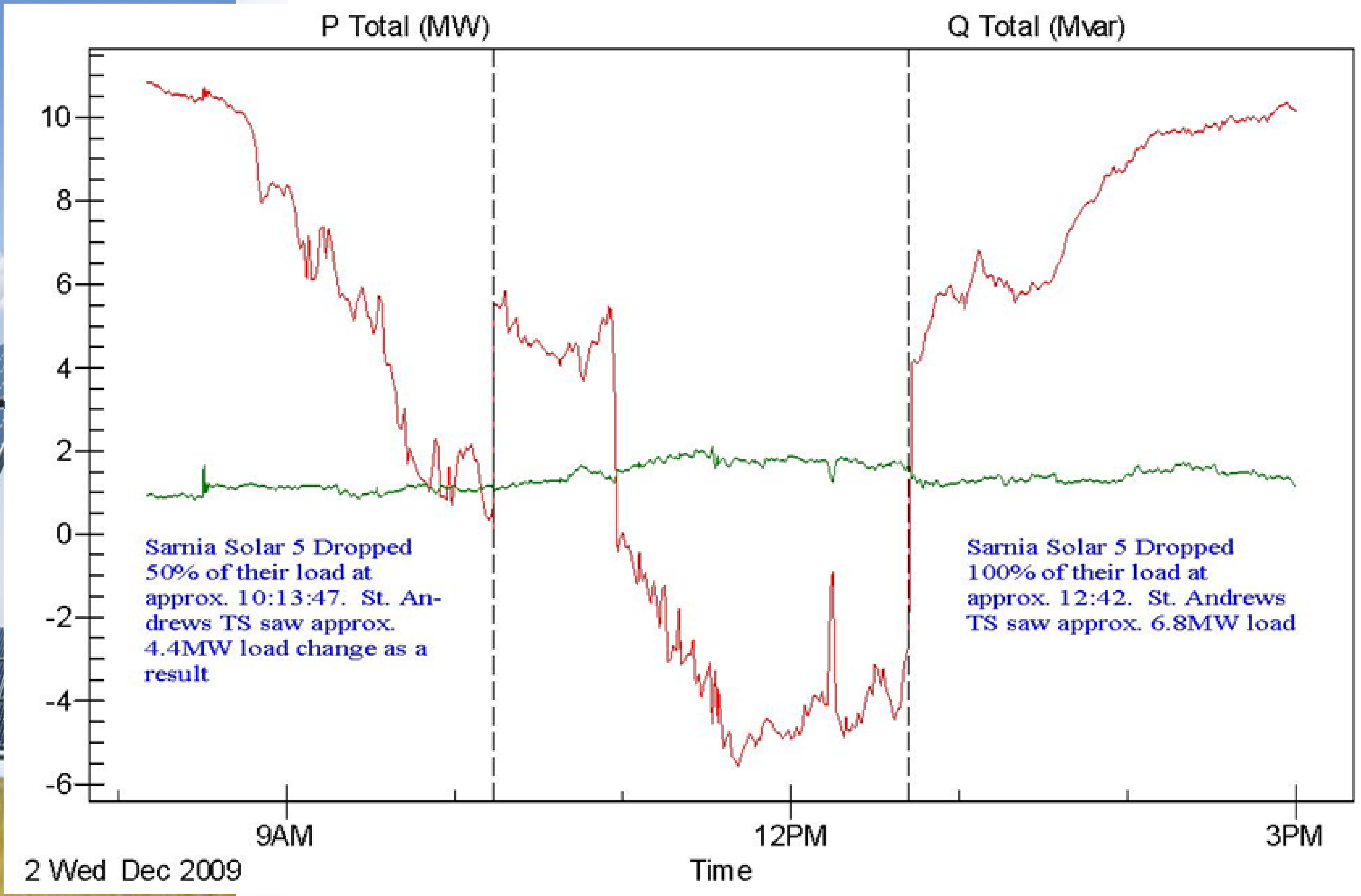
Solar Intensity Measurement at a Solar PV Farm





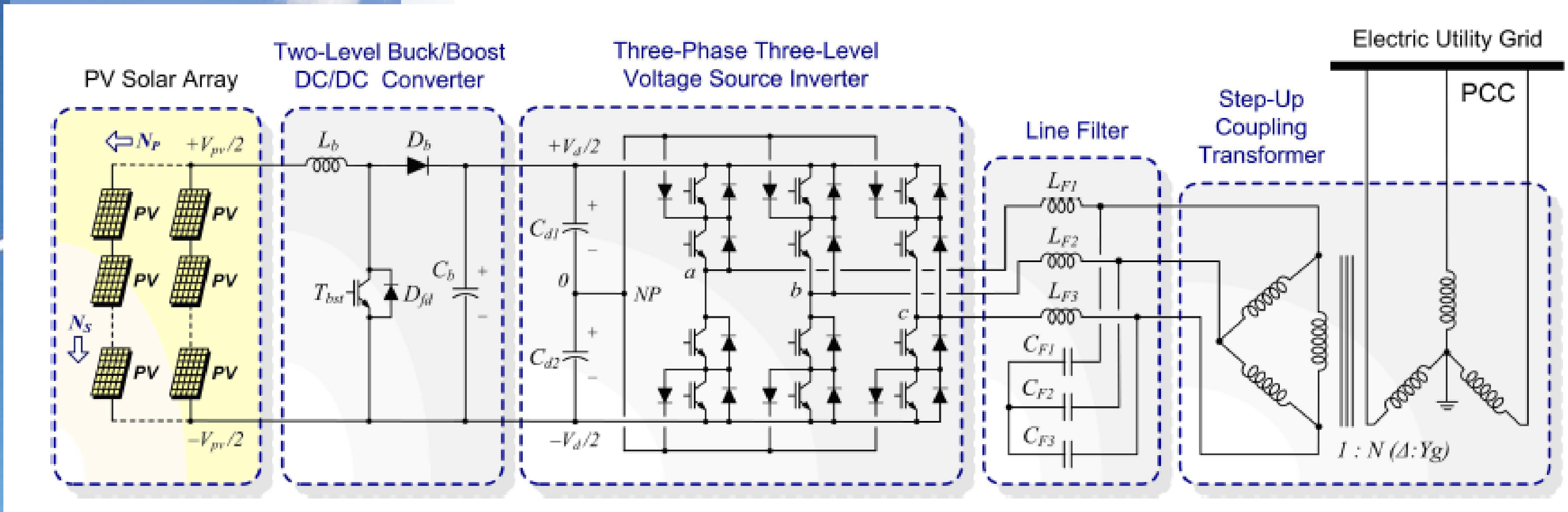
Solar intensity at a Solar PV Farm can vary a lot depending on cloud coverage conditions

Monitoring Harmonics at St. Andrews M14 27.6 kV Feeder



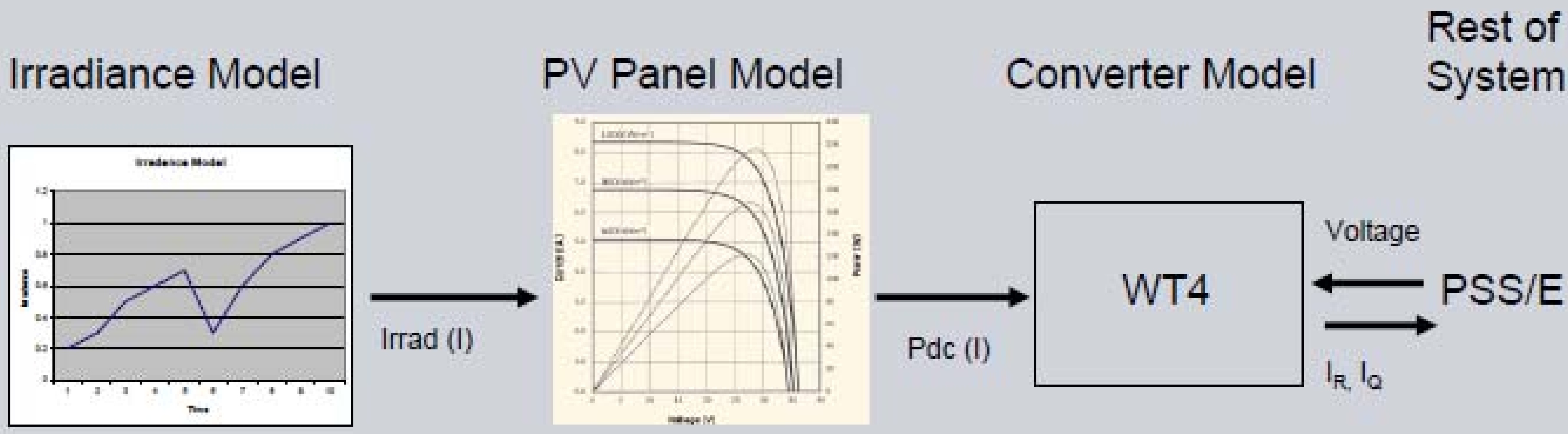
Solar intensity as seen at St. Andrews TS from Dec. 1-3, 2009

Proposed Steady-State Solar PV Model



The proposed steady-state model consists of the PV array, voltage-source inverter with semiconductor devices having turn-off capabilities, coupling transformer and corresponding line filter. This model allows power to be injected at the Point of Common Coupling (PCC).

Proposed Dynamic Solar PV Model



- Standard irradiance model allowing solar irradiance data point entry
- Standard PV panel I-V curves
- Full converter model with voltage control, Q=control and pf control

Present and Future Renewable Projects

i. Validate the steady-state and dynamic models of a solar farm
ii. Impact of harmonics on dynamic Var (D-Var) equipment
iii. Impact of harmonics during power reversal flows
iv. Interaction between Siemens, Enercon, GE and Vestas wind turbine generators during starting/stopping sequences