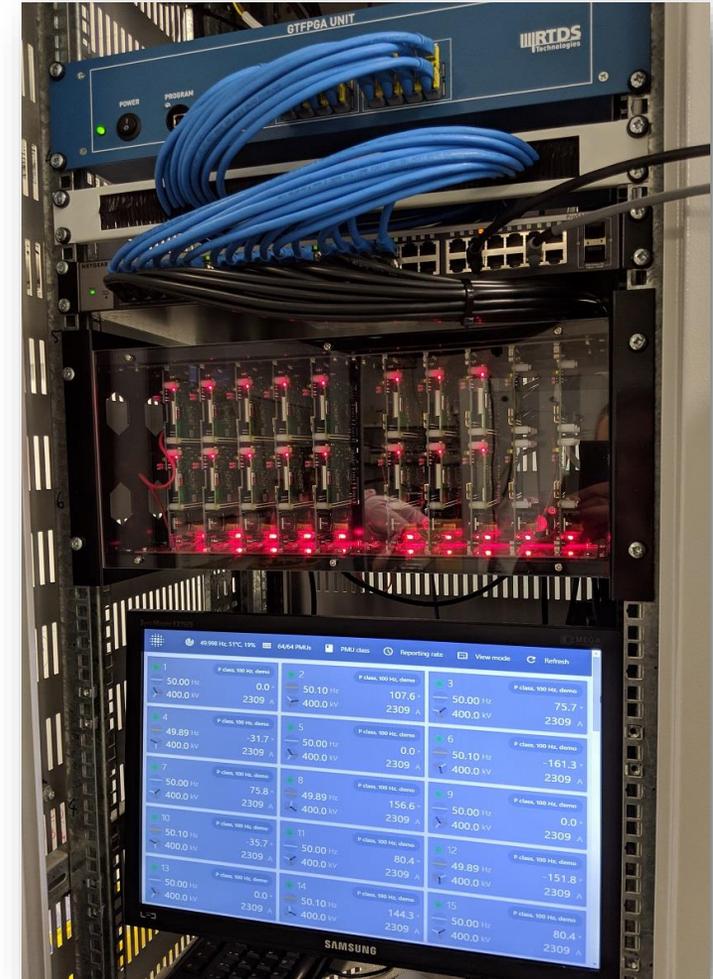


A new platform for validating real-time, large-scale WAMPAC systems

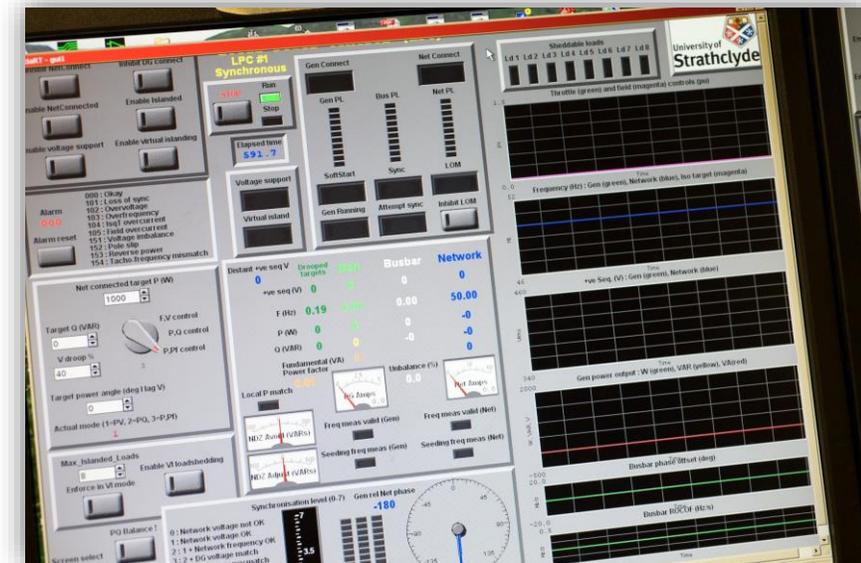
Steven Blair

University of Strathclyde, Glasgow, UK



Overview

- Industry position and challenges
 - Renewable energy trends
 - Reduced system inertia
- Using GTFPGA for 64 PMUs
- Hardware and software design
- Monitoring interface and automation
- Reporting latency analysis
- Next steps



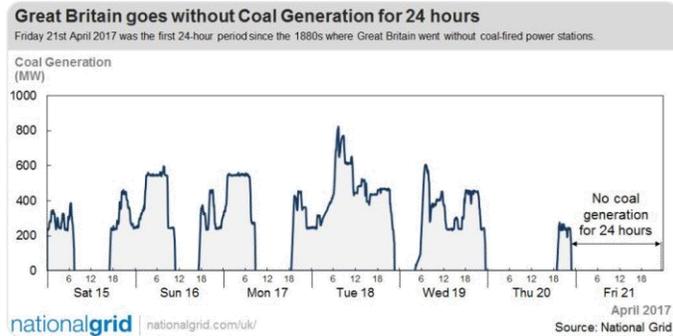
UK energy situation

Trend of reduced conventional synchronous generation



Follow

National Grid can confirm that for the past 24 hours, it has supplied GB's electricity demand without the need for #coal generation.



3:11 PM - 21 Apr 2017

1,896 Retweets 1,758 Likes

63 1.9K 1.8K

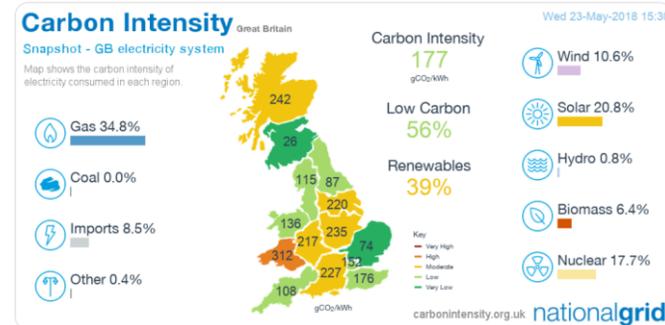
April 2017

First no-coal day since Industrial Revolution



Follow

56% low carbon and no coal generation.



7:57 AM - 23 May 2018

16 Retweets 17 Likes

16 17

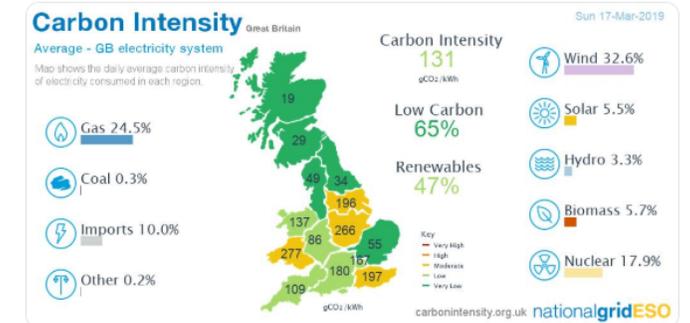
April 2018

Three consecutive no-coal days



Follow

Yesterday #wind generated 32.6% of GB electricity, more than gas 24.5%, nuclear 17.9%, imports 9.9%, biomass 5.7%, solar 5.6%, hydro 3.3%, coal 0.3%, other 0.2% *excl. non-renewable distributed generation



4:37 PM - 18 Mar 2019

4 Retweets 4 Likes

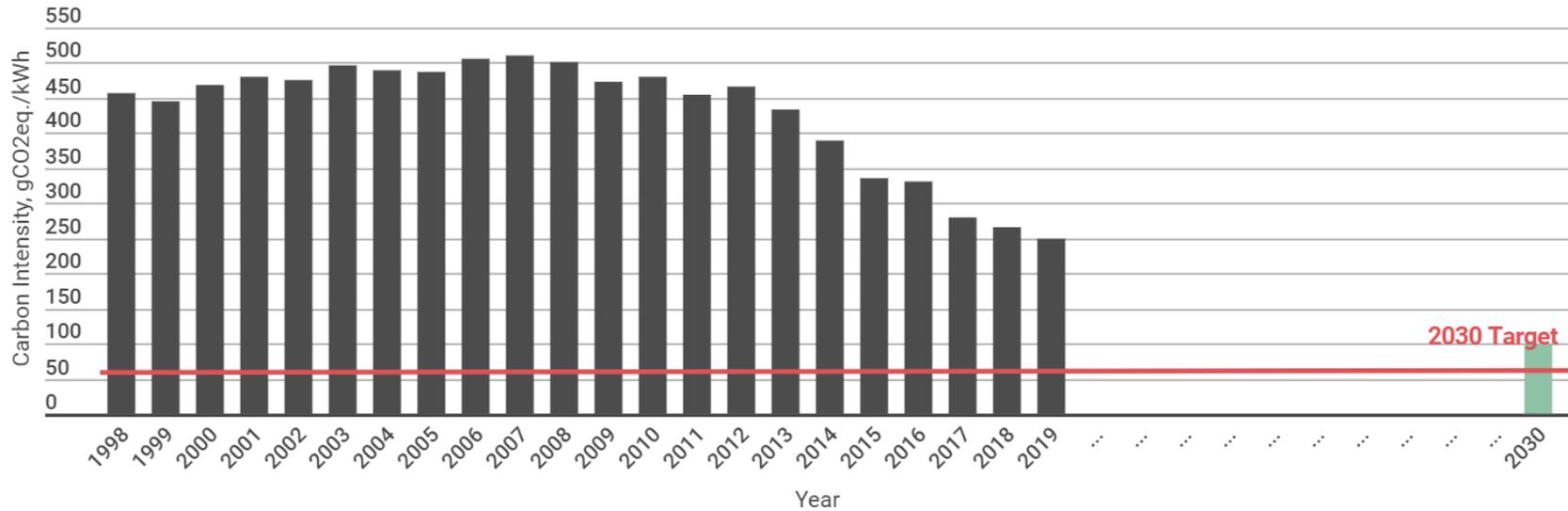
4 4

March 2019

33% wind contribution – common throughout March

Actually approaching our target...

Decarbonising British Electricity

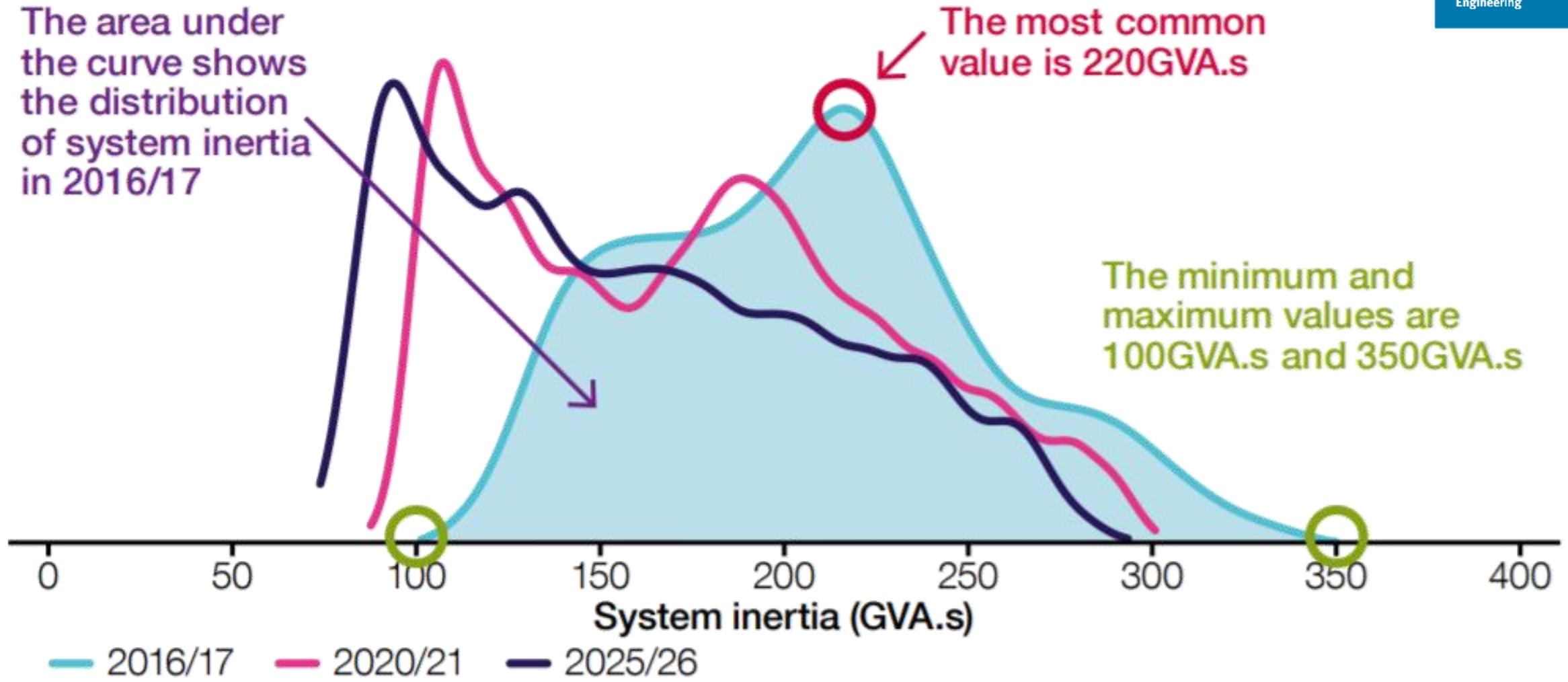


Time to 2030 carbon target:

10:07:21:23:17:45
years months days hours minutes seconds

<https://www.mygridgb.co.uk/dashboard/>

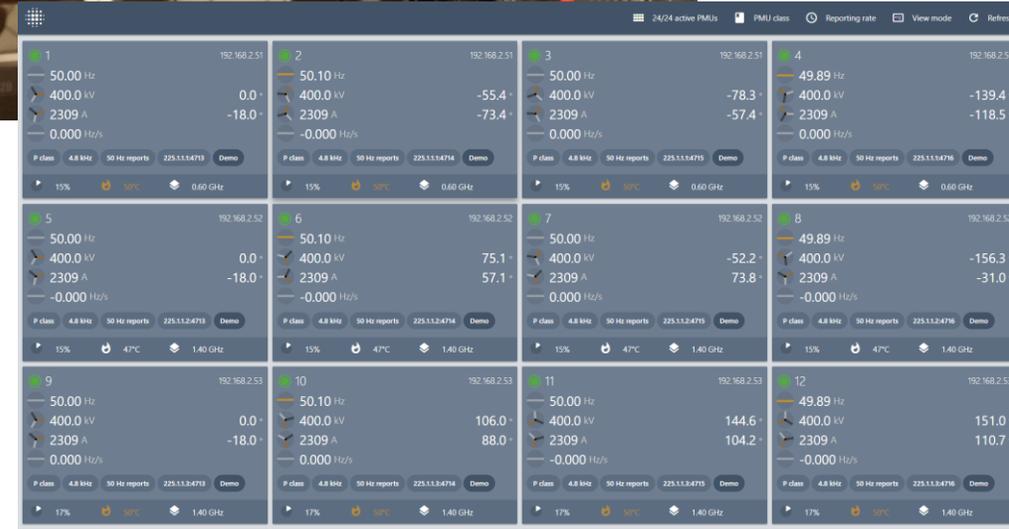
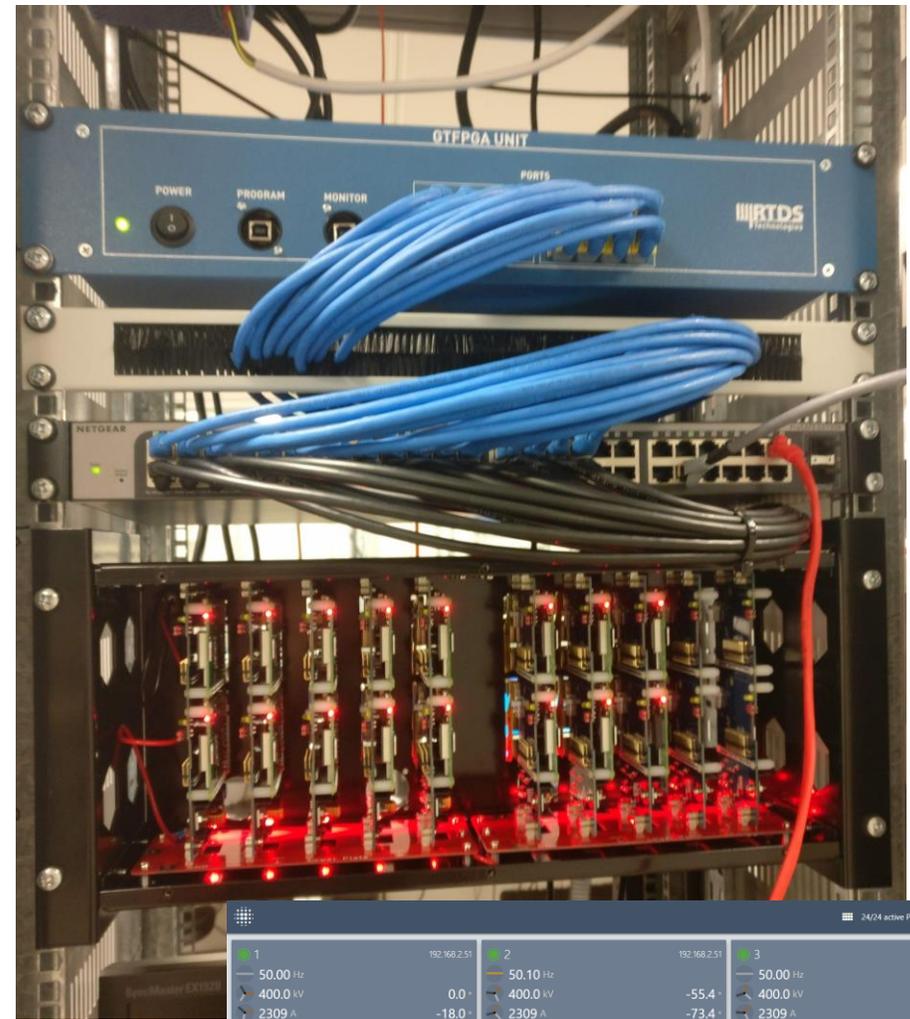
UK: reducing system inertia



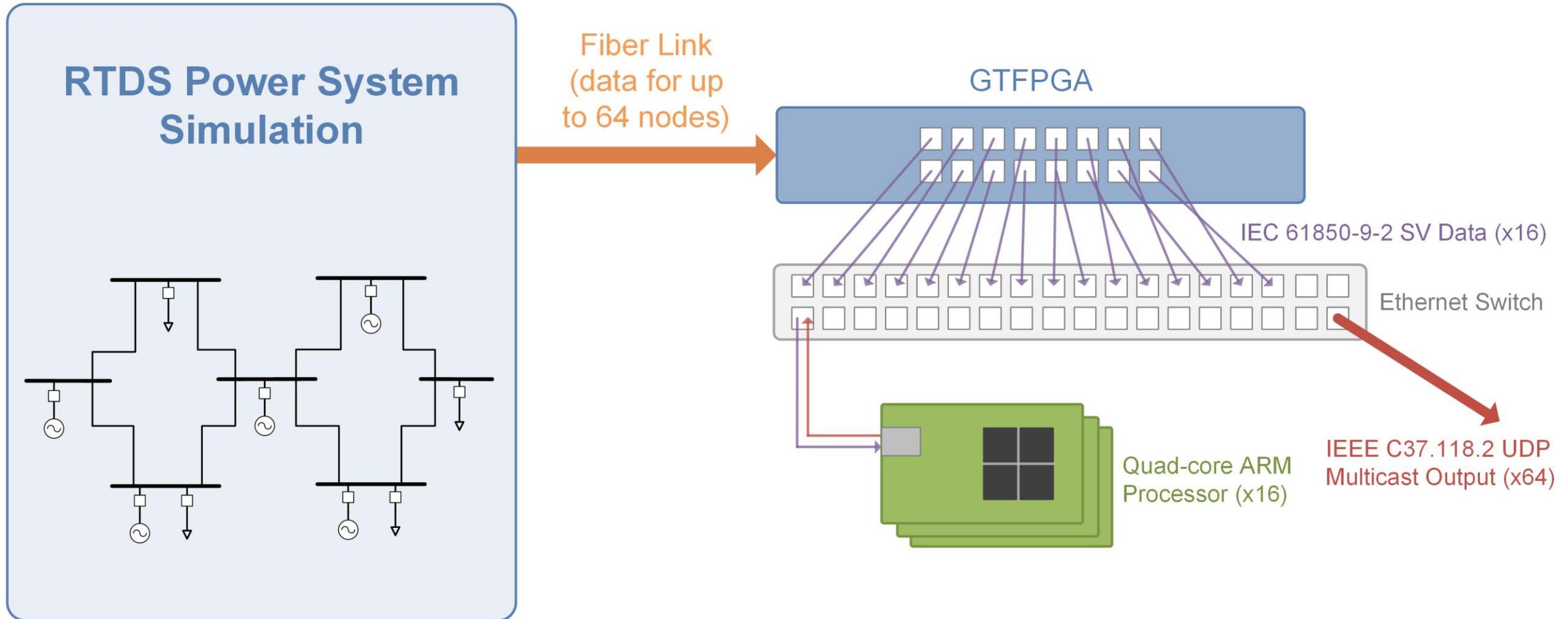
From National Grid System Operability Framework 2016

Large-scale PMU testbed

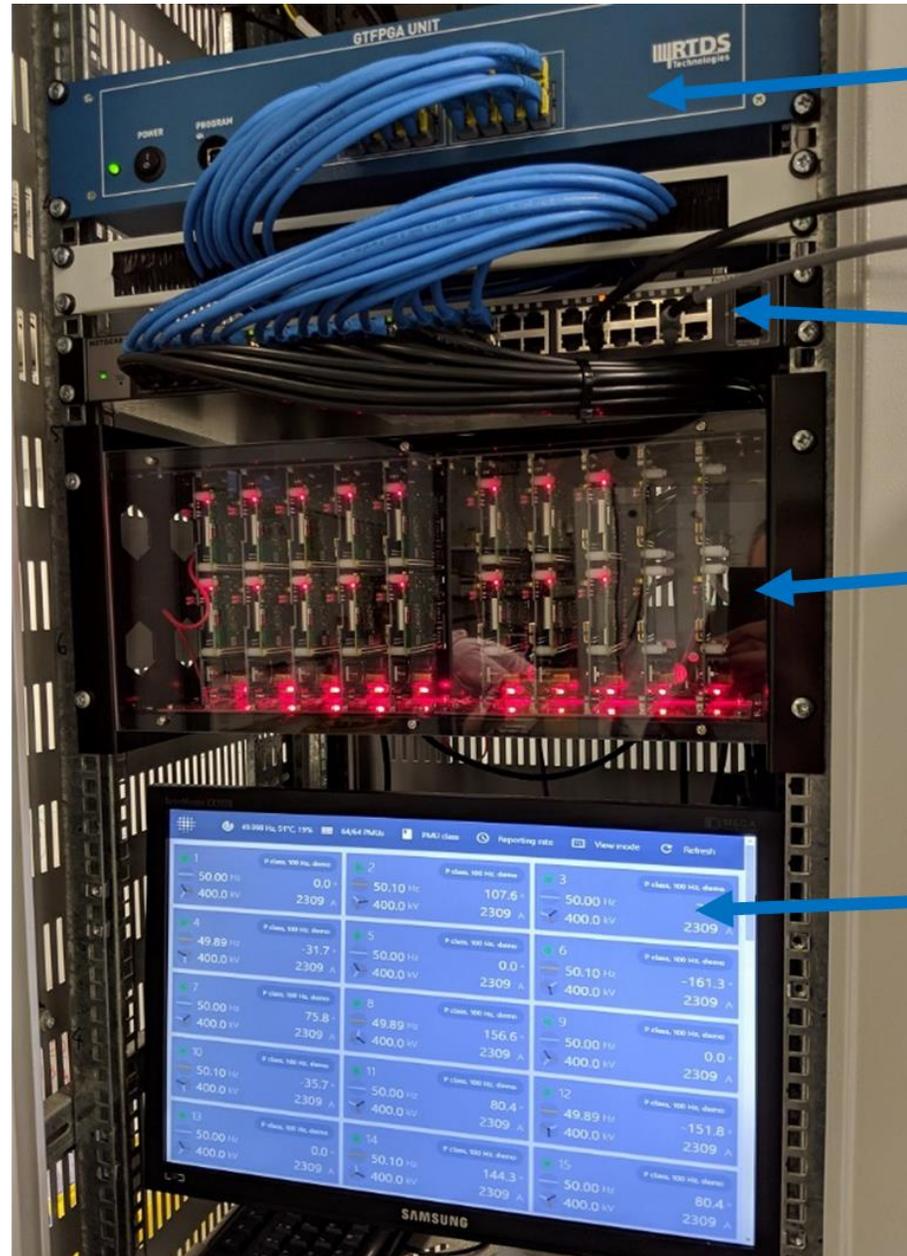
- RTDS GTFPGA
- 16x Raspberry Pis
- Strathclyde PMU algorithm
 - Adaptive filter window
- **64 PMUs in real-time**
- Dynamically change reporting rate, M or P class



Hardware design



Hardware design



GTFPGA

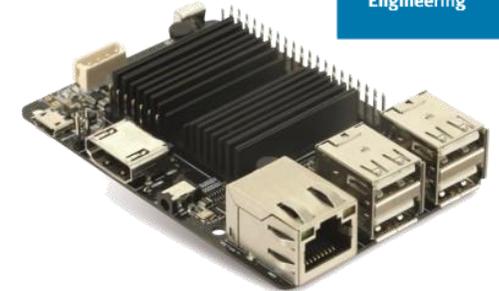
Ethernet Switch

Cluster of 16 ARM
Processors

Web-based
Management
Interface

ID	F class, 100 Hz, 4000 V	F class, 100 Hz, 4000 V	F class, 100 Hz, 4000 V	F class, 100 Hz, 4000 V	
1	50.00 Hz 400.0 kV 2309 A	0.0	50.10 Hz 400.0 kV 107.6 2309 A	3	50.00 Hz 400.0 kV 2309 A
4	49.89 Hz 400.0 kV 2309 A	-31.7	50.00 Hz 400.0 kV 2309 A	6	50.10 Hz 400.0 kV -161.3 2309 A
7	50.00 Hz 400.0 kV 2309 A	75.8	49.89 Hz 400.0 kV 2309 A	9	50.00 Hz 400.0 kV 2309 A
10	50.10 Hz 400.0 kV 2309 A	-35.7	50.00 Hz 400.0 kV 2309 A	11	50.00 Hz 400.0 kV 80.4 2309 A
13	50.00 Hz 400.0 kV 2309 A	0.0	50.10 Hz 400.0 kV 144.3 2309 A	15	50.00 Hz 400.0 kV 80.4 2309 A

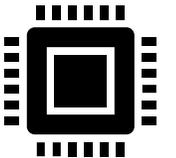
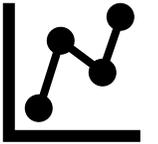
ARM processor and OS choice



Hardware	Raspberry Pi 3 B+	Raspberry Pi 3 B+	Odroid C2
Operating System	Raspbian Stretch Lite	DietPi	DietPi
CPU	Quad-core Cortex-A53	Quad-core Cortex-A53	Quad-core Cortex-A53
Maximum CPU clock	1.4 GHz	1.4 GHz	1.5 GHz
Memory	1 GB	1 GB	2 GB
Ethernet	Gigabit, but implemented over half-duplex USB interface	Gigabit, but implemented over half-duplex USB interface	Gigabit

Software design

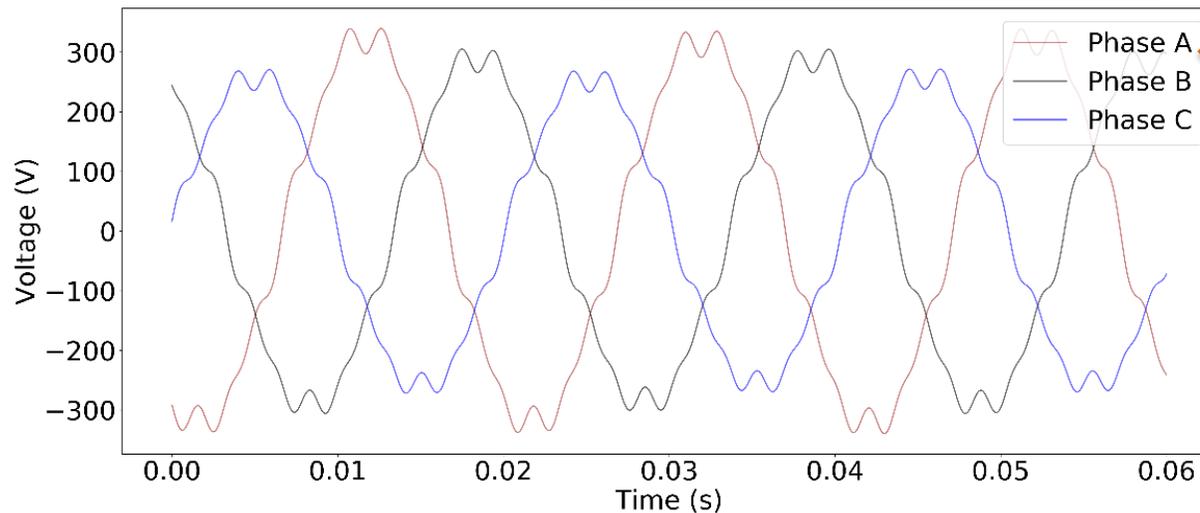
- Using **4800 Hz** sampling rate for SV data
 - Up to 24 values => 4x three-phase voltage and current (per Ethernet frame)
 - Two ASDUs (samples) per frame (so 2400 packets/s)
- One PMU algorithm running per ARM core
 - 64 cores => 64 PMUs
 - Using “rapid61850” library to decode SV
 - Using OpenMP to execute parallel code sections
- Use of VLANs to precisely control all SV and C37.118.2 data flows
- Python scripts to automate Pi configuration



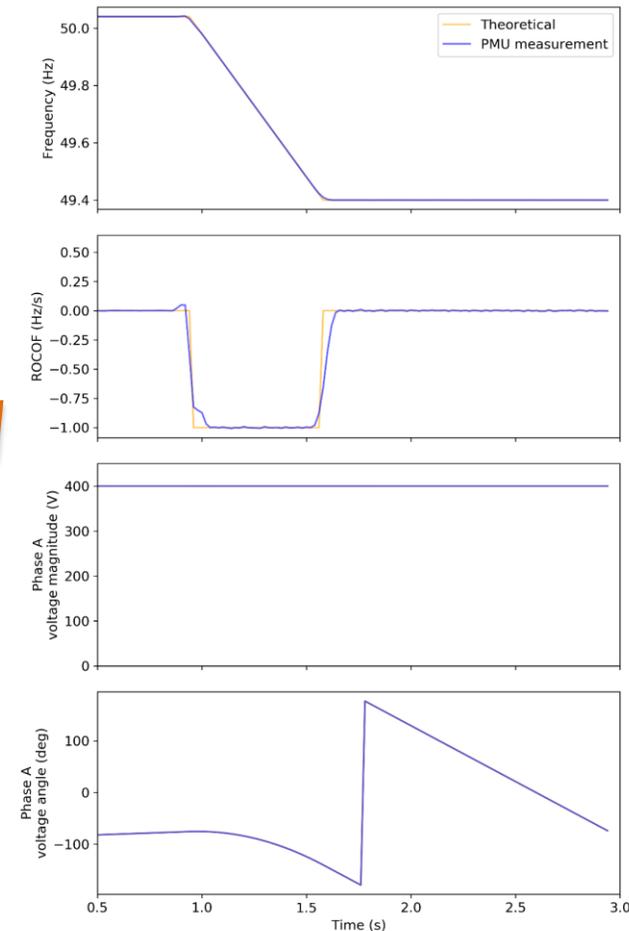
PMU algorithm choice and performance

- Highly resilient to actual grid disturbances
- 0.01% typical worst-case total vector error (TVE)
- Suited to distribution system applications
- Efficient computational performance
- M-class and P-class versions

Emulated grid disturbance



Accurate PMU response



Worst-Case M-class PMU Performance

Test	TVE (%)	FE (Hz)	DFE (Hz/s)
Frequency Range	0.007-0.012	0.00017	0.00066
Harmonic Distortion	0.005-0.013	0.000092	0.0036
Phase Modulation	0.25	0.0086	0.34
Frequency Ramp	0.12-0.13	0.000193	0.0055

~100x better than IEEE standard requirements

Test	Response Time (ms)	Delay Time (ms)	Max over- or under-shoot (%)
+ve Magnitude Step	50.5	0.758	1.11%
+ve Phase Step	66.5	-2.5	0.68%

Monitoring interface



1 192.168.2.51

50.00 Hz

399.4 kV -88.7°

371 A -86.5°

-0.000 Hz/s

M class 4.8 kHz 100 Hz reports

225.1.1.1:4713 75.414 / 78.777 ms

26% 54°C 1.40 GHz

2 192.168.2.51

50.00 Hz

399.4 kV -89.3°

143 A -91.5°

-0.000 Hz/s

M class 4.8 kHz 100 Hz reports

225.1.1.1:4714 75.269 / 78.788 ms

26% 54°C 1.40 GHz

3 192.168.2.51

50.00 Hz

399.4 kV -89.0°

71 A -116.3°

-0.000 Hz/s

M class 4.8 kHz 100 Hz reports

225.1.1.1:4715 74.839 / 78.777 ms

26% 54°C 1.40 GHz

4 192.168.2.51

50.00 Hz

399.4 kV -89.1°

576 A -90.6°

-0.000 Hz/s

M class 4.8 kHz 100 Hz reports

225.1.1.1:4716 74.545 / 78.772 ms

26% 54°C 1.40 GHz

5 192.168.2.52

50.00 Hz

400.1 kV -89.1°

66 A 100.0°

0.000 Hz/s

M class 4.8 kHz 100 Hz reports

225.1.1.2:4713 73.235 / 77.453 ms

6 192.168.2.52

50.00 Hz

399.5 kV -89.3°

280 A 101.7°

0.000 Hz/s

M class 4.8 kHz 100 Hz reports

225.1.1.2:4714 73.61 / 77.329 ms

7 192.168.2.52

50.00 Hz

399.5 kV -88.9°

144 A -90.5°

0.000 Hz/s

M class 4.8 kHz 100 Hz reports

225.1.1.2:4715 74.122 / 77.466 ms

8 192.168.2.52

50.00 Hz

400.1 kV -88.9°

130 A -82.0°

0.000 Hz/s

M class 4.8 kHz 100 Hz reports

225.1.1.2:4716 73.544 / 77.492 ms

Load shedding scenario – frequency change

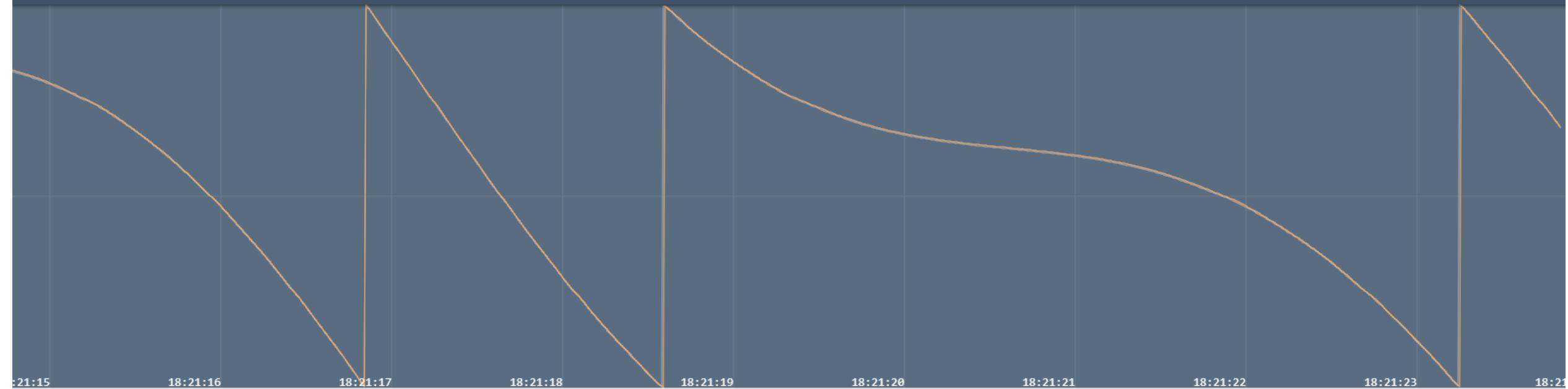


Islanding event

Load shedding activated

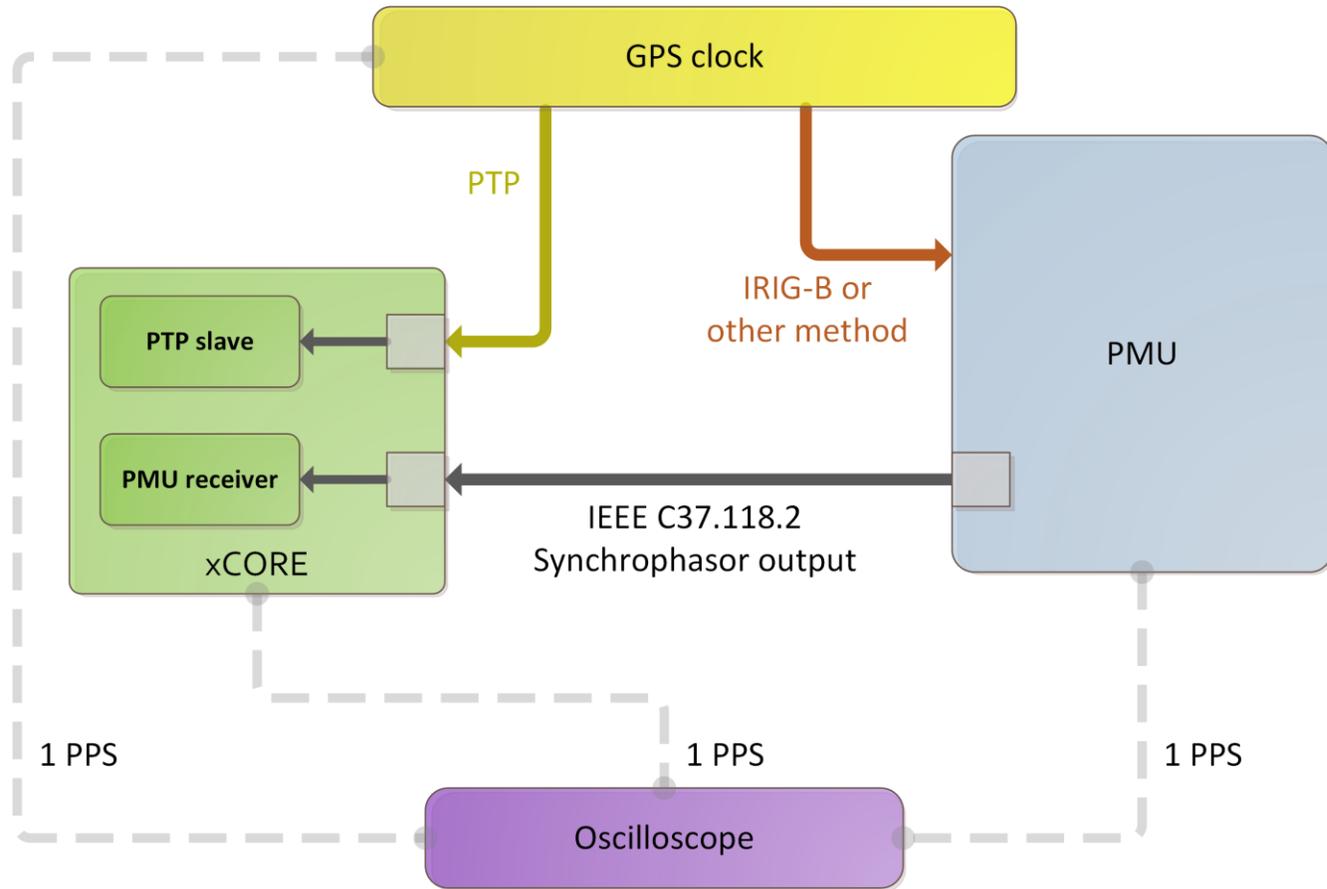
Load shedding scenario – voltage angle

49.957 Hz, 56°C, 11%, 0 ms



1	2	3	4	5
192.168.2.51	192.168.2.51	192.168.2.51	192.168.2.51	192.168.2.51
49.43 Hz	49.43 Hz	49.43 Hz	49.43 Hz	50.00 Hz
10.8 kV	10.9 kV	10.8 kV	10.8 kV	400.0 kV
86 A	324 A	79 A	79 A	2309 A
-8.2°	-9.5°	-7.8°	-8.2°	-0.000°
-49.7°	-94.5°	113.9°	113.9°	
0.024 Hz/s	0.026 Hz/s	0.025 Hz/s	0.026 Hz/s	
P class 4.8 kHz 100 Hz reports 225.1.1.1:4713	P class 4.8 kHz 100 Hz reports 225.1.1.1:4714	P class 4.8 kHz 100 Hz reports 225.1.1.1:4715	P class 4.8 kHz 100 Hz reports 225.1.1.1:4716	P class 4.8 kHz
12% 55°C 1.40 GHz	10%			

Accurate measurement PMU reporting latency



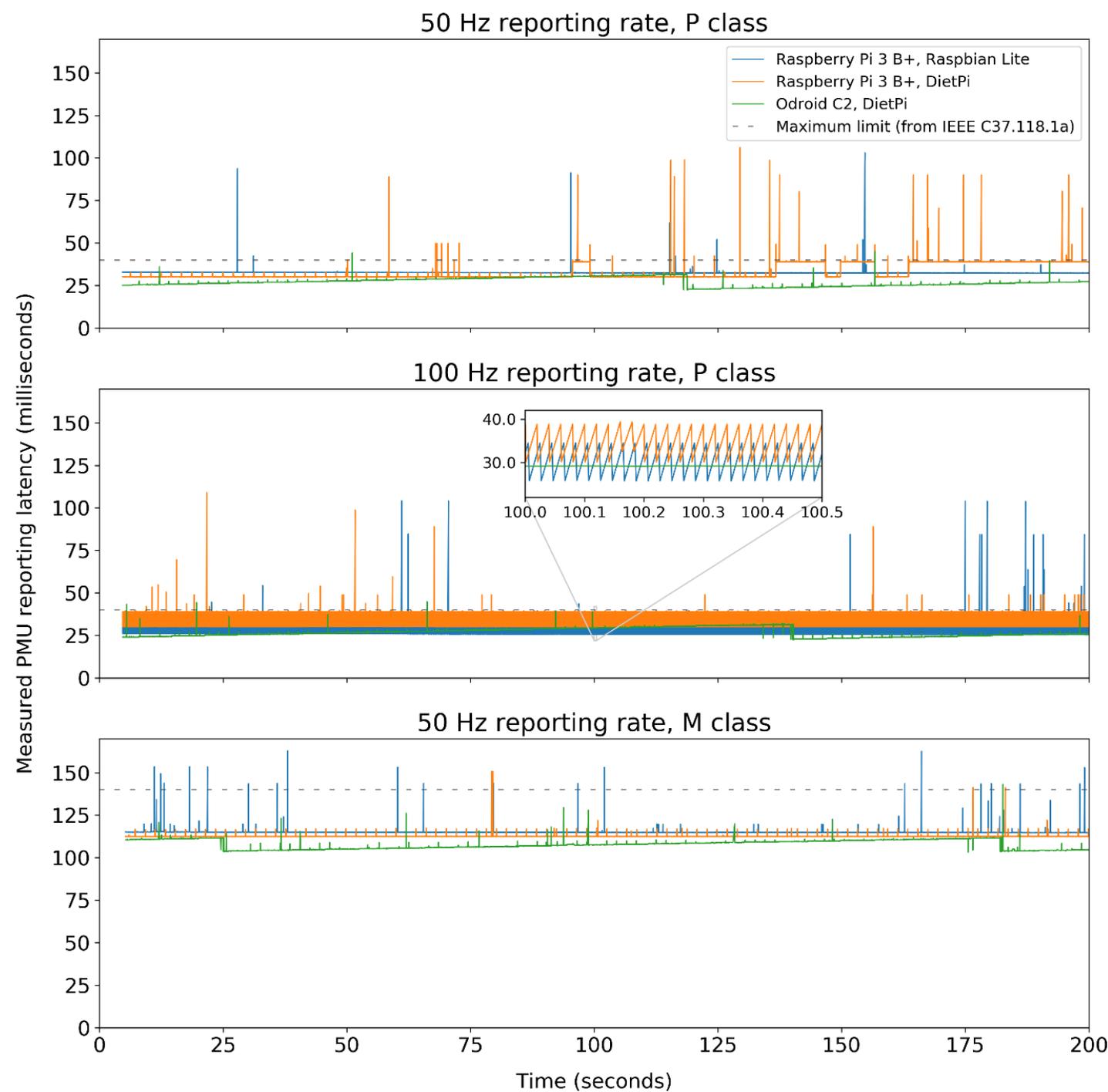
<https://github.com/stevenblair/pmu-latency-measure>

Reporting latency analysis

Synchrophasor outputs (x 64)

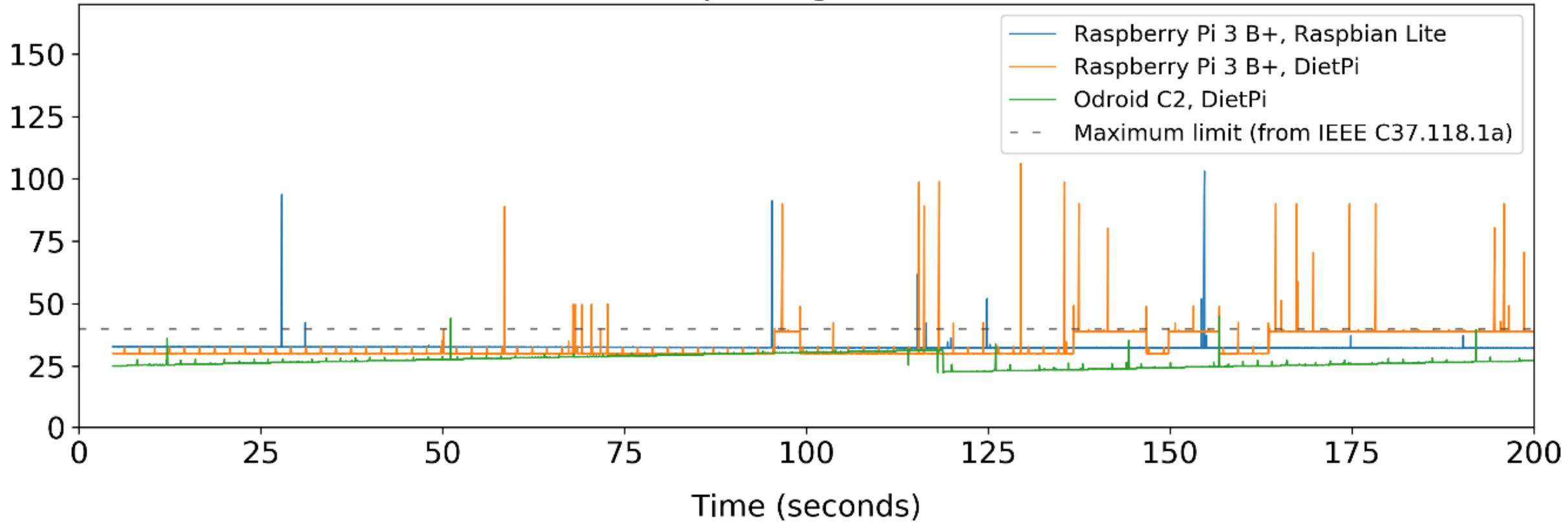


PTP time synchronisation



Reporting latency analysis

50 Hz reporting rate, P class



How long does a packet take from the UK to the USA?



Linking two laboratories

**Real-time SD-WAN
connection**



Energy Innovation Center

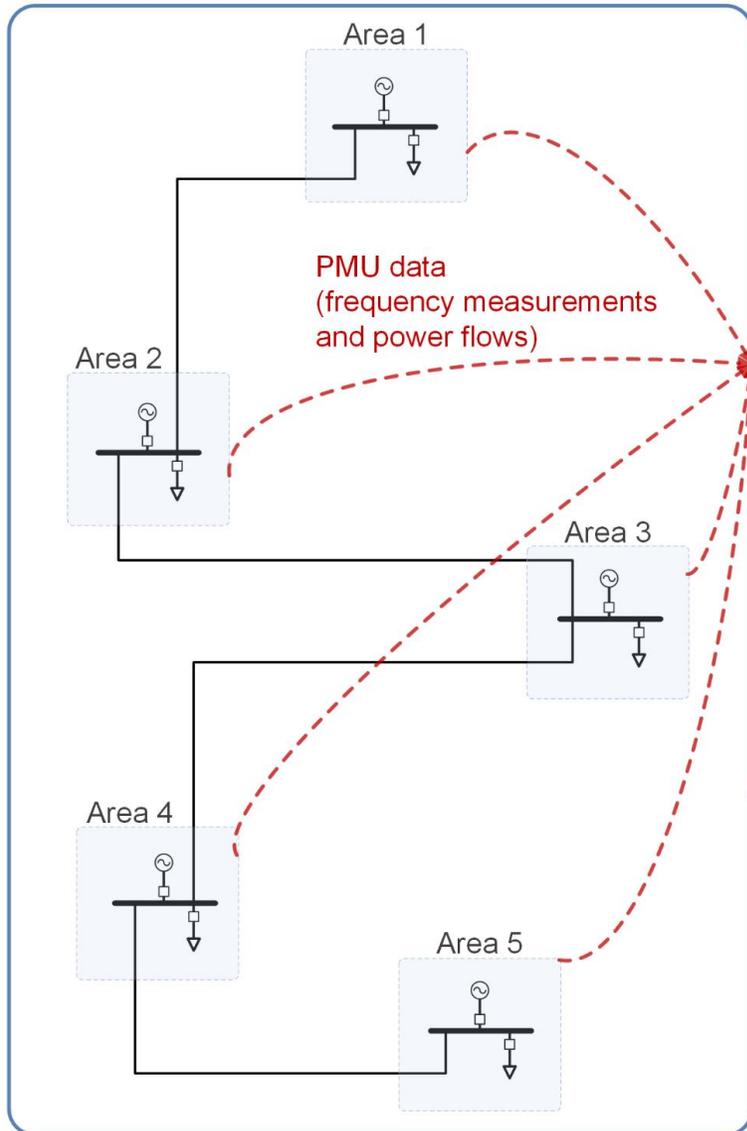
Nokia
Plano, Texas, US

Dynamic Power Systems Laboratory

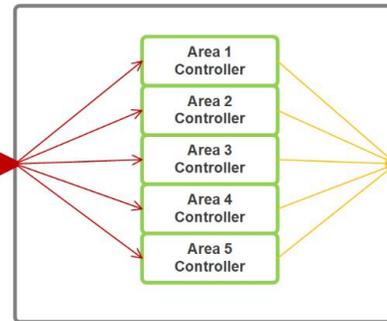
Strathclyde
Glasgow, UK

Wide-area control testbed

RTDS Simulation – Great Britain System Model



Real-time area controllers on Beckhoff CX5020 platform



5x GOOSE (layer-2)



Dynamic Power Systems Laboratory
University of Strathclyde
Glasgow, UK

Energy Innovation Center
Nokia
Plano, TX, USA

7705 SAR-8 (WAN router)



Nuage NSG-E



SD-WAN link to remote laboratory (EIC)

5x GOOSE (layer-2)

7705 SAR-8 (WAN router)



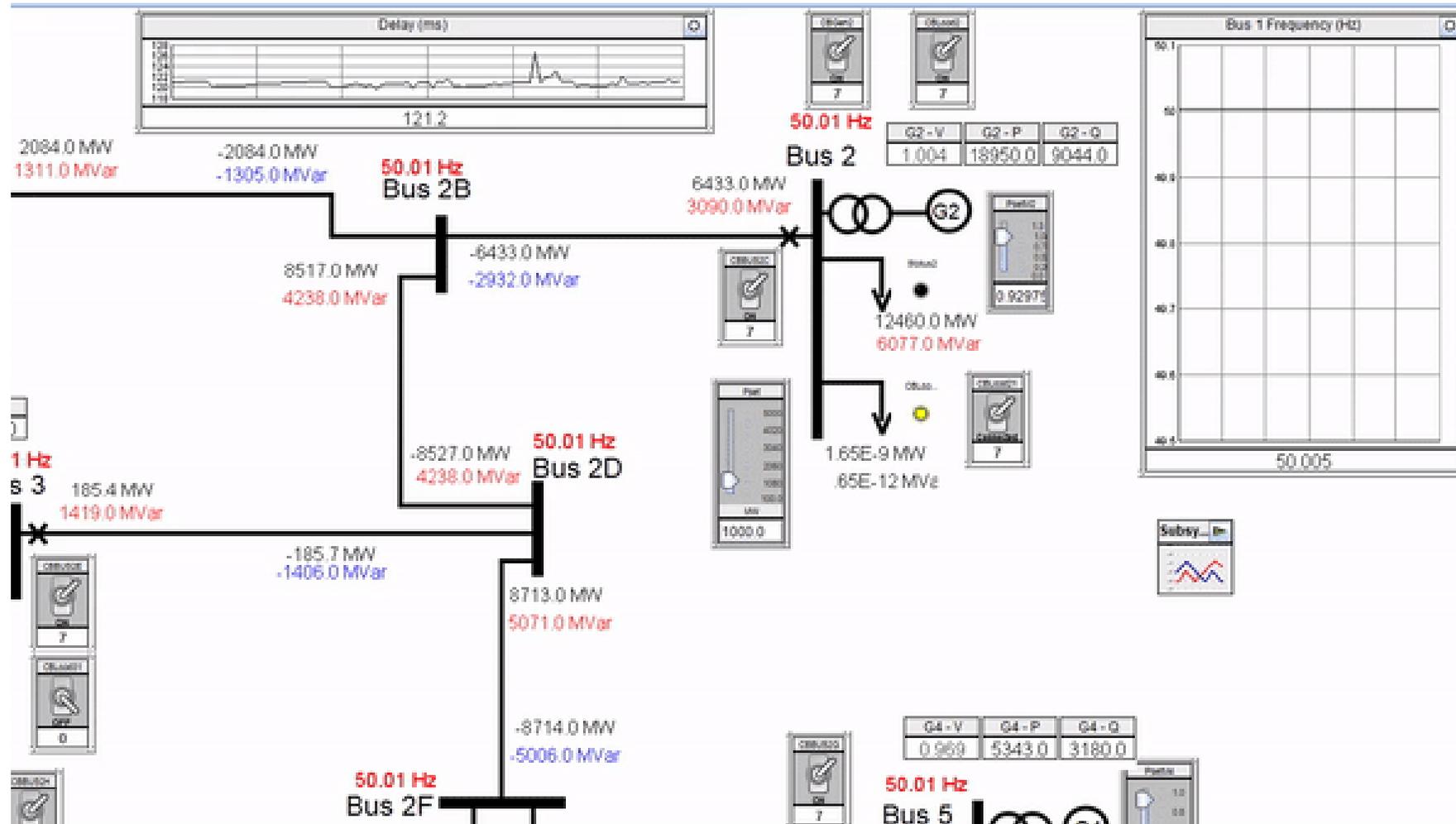
Nuage NSG-E



7705 SAR-18 (WAN router)

Frequency control demo

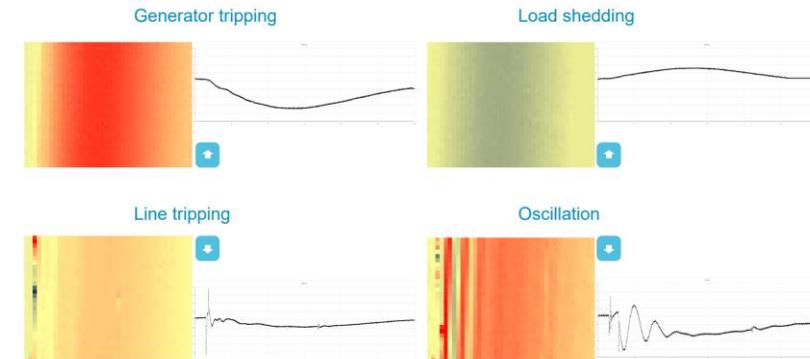
Pre-recorded



At 5x speed

Next steps

- Further performance profiling of ARM devices
- Data analytics using large-scale PMU data
- Wide-area protection and control applications
- Recreate communications delays
- Integrate SV data compression



<http://sites.ieee.org/pes-powertech/files/2017/07/PowerTech-2017-Vladimiro-Miranda.pdf>

More information

- Contact:
 - steven.m.blair@strath.ac.uk
 - <http://personal.strath.ac.uk/steven.m.blair/>
 - <https://github.com/stevenblair>
- Related publications:
 - Measurement and Analysis of PMU Reporting Latency for Smart Grid Protection and Control Applications, <https://strathprints.strath.ac.uk/67203/>
 - Real-time compression of IEC 61869-9 sampled value data, <http://strathprints.strath.ac.uk/57710/>
 - Modelling and Analysis of Asymmetrical Latency in Packet-Based Networks for Current Differential Protection Application, <http://strathprints.strath.ac.uk/61418/>
 - Automatically Detecting and Correcting Errors in Power Quality Monitoring Data, <http://strathprints.strath.ac.uk/57466/>
 - An Open Platform for Rapid-Prototyping Protection and Control Schemes with IEC 61850, <http://strathprints.strath.ac.uk/43427/>
 - A Practical and Open Source Implementation of IEC 61850-7-2 for IED Monitoring Applications, <http://strathprints.strath.ac.uk/50860/>
 - Enabling efficient engineering processes and automated analysis for power protection systems, <http://strathprints.strath.ac.uk/54545/>
 - Validating secure and reliable IP/MPLS communications for current differential protection, <http://strathprints.strath.ac.uk/55961/>
 - Demonstration and analysis of IP/MPLS communications for delivering power system protection solutions using IEEE C37.94, IEC 61850 Sampled Values, and IEC 61850 GOOSE protocols, <http://strathprints.strath.ac.uk/48971/>