Agenda for today

10:35	Welcome address	Colin Taylor	SPEN
10:40	SP Energy Networks Experience	Priyanka Mohapatra	SPEN
11:00	System Operator Experience	Phil Ashton	NG SO
11:20	National Grid Experience	Mark Osborne	NG TO
11:40	***Break***		
12:00	SHE Transmission Experience	David Wang	SSE
12:20	Monitoring and Analysis Applications	Stuart Clark	GE
12:40	Research Activities and Findings	Peter Wall	UoM
13:00	***Lunch***		
14:00	Visualisation software demonstration	Alan McMorran	Open Grid Systems
14:20	Round Table session		
16:00	Roadmap development and findings	Bryan Gwyn	Quanta Technology

VISOR Stakeholder Event 2016

IET Savoy Place, London, 6 July 2016

Priyanka Mohapatra

SPEN VISOR Project Manager

Introduction: Project Partners

	PROJECT TEAM	STEERING BOARD
SPEN:	Priyanka Mohapatra Jamie Campbell Finlay MacLeod	James Yu Colin Taylor
NGET:	Mark Osborne Phil Ashton Nick Hird Sanjeev Gopalakrishnan	Duncan Burt John Haber Martin Bradley Ray Zhang
SSE:	Chris Nendick David Wang	Stewart Reid
UoM:	Vladimir Terzija Peter Wall Papiya Dattaray	**Academic Partner**
Alstom:	Richard Davey Stuart Clark Douglas Wilson	**WAMS Supplier**

Presentation Agenda

Emerging Challenges

- The evolving transmission network
- NETS SQSS requirements

Infrastructure

- Monitoring & Comms req.
- Data quality
- Data sharing

Applications

- PhasorPoint: Monitoring and analysis

Why and who invests?

- GB Roadmap
- Sandbox

Emerging Challenges

- The changing energy landscape and the evolving electricity network
- Changing dynamic behaviour, increasing uncertainty
- Generation changes
  - A ‘lighter’ system, especially in Scotland
- More diverse transmission equipment
  - Increased Europe- interconnection, intra-network HVDC, Series Compensation
- TO’s required to adhere to NETS SQSS

Wind

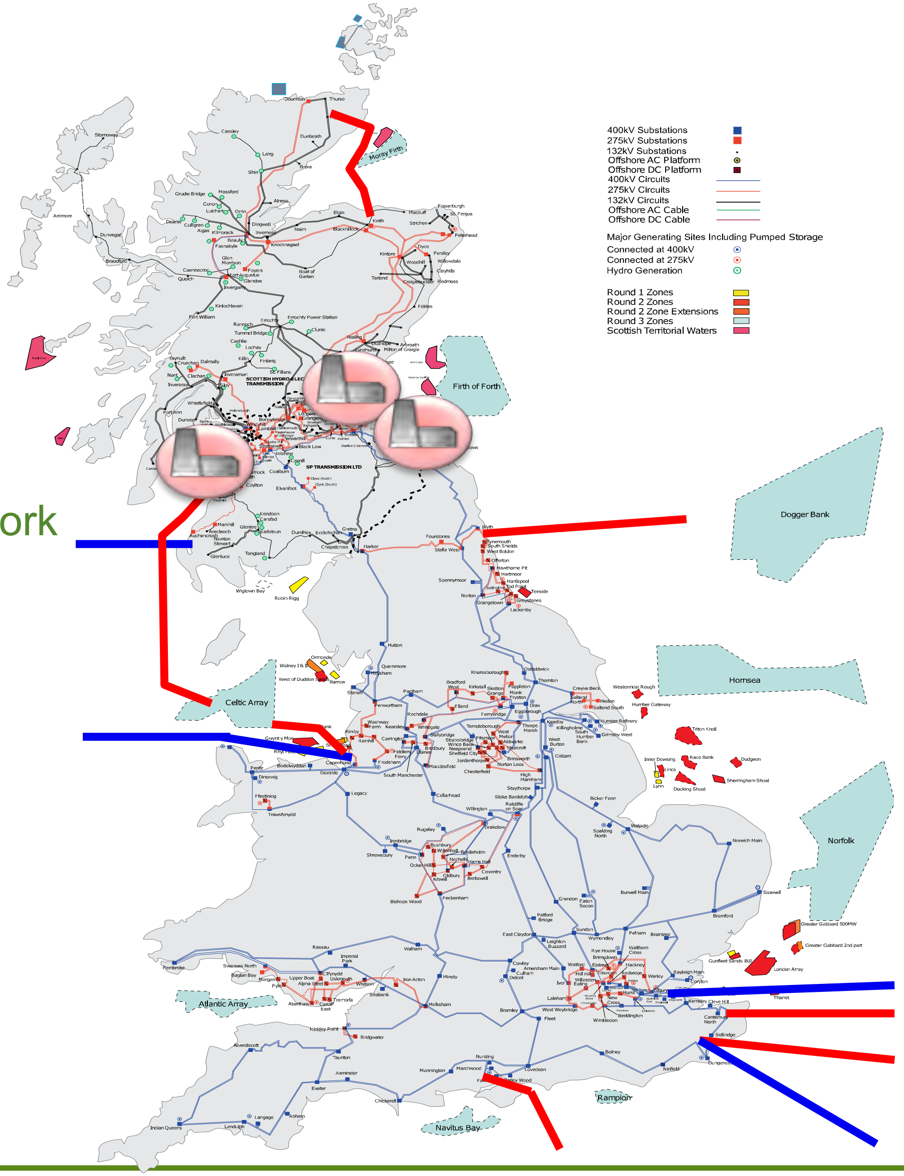
~5GW

2.5GW

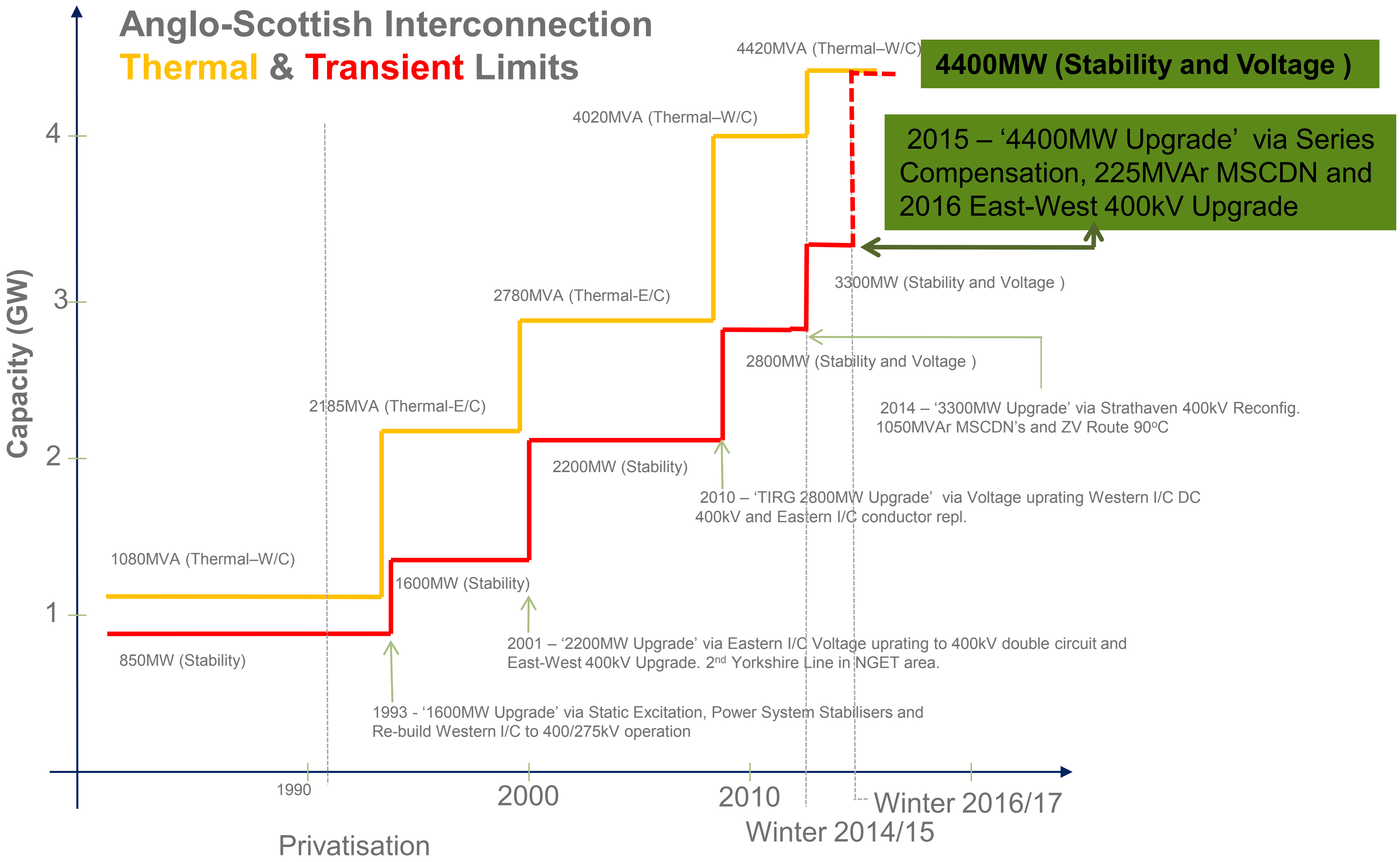
By 2021,
2011 forecast = 2.5GW
2015 contracted 5GW

Thermal

Closure of big generators
> Longannet
> Torness
> Hunterston



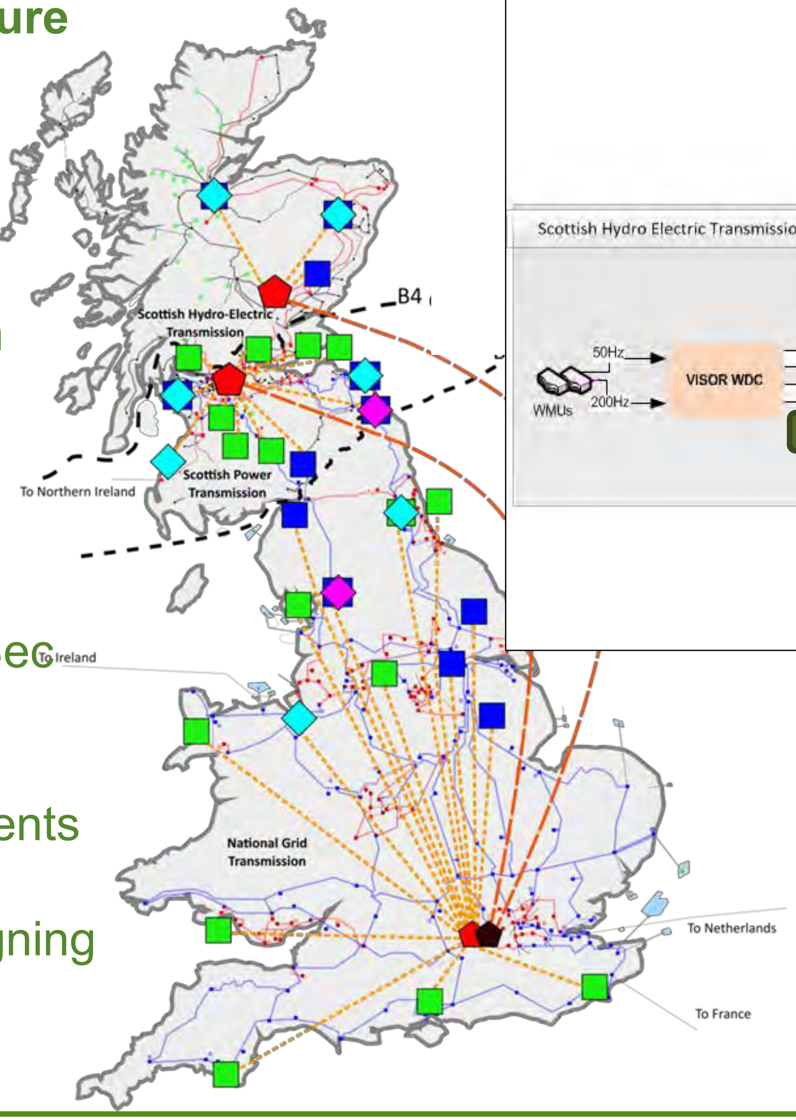
Emerging Challenges: B6 Export Upgrades

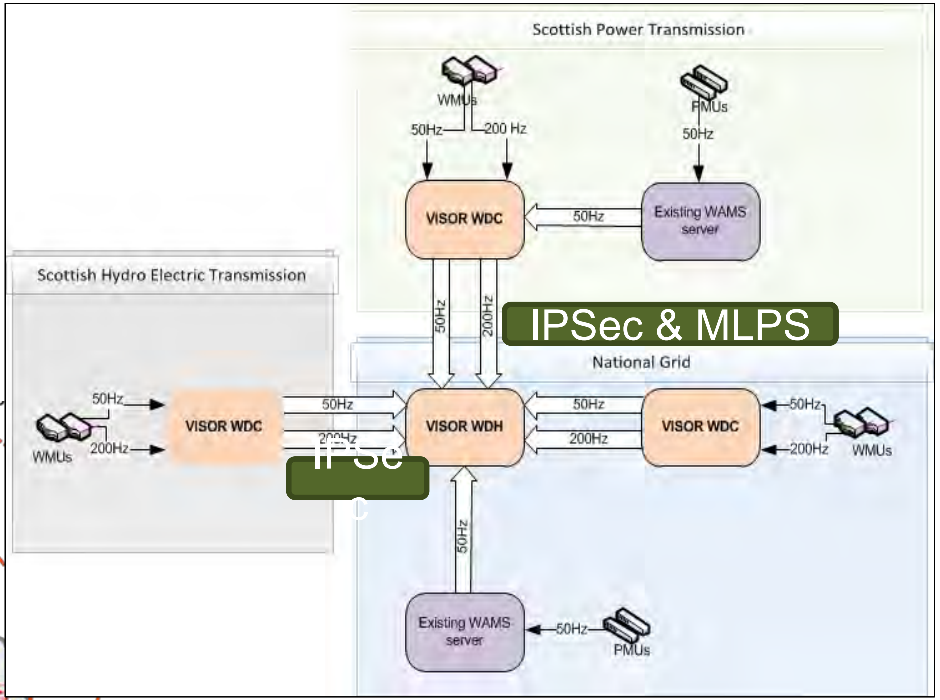


VISOR Infrastructure

Monitoring infrastructure

- PMUs/WMUS
- Data Centres
- PhasorPoint platform





Comms infrastructure

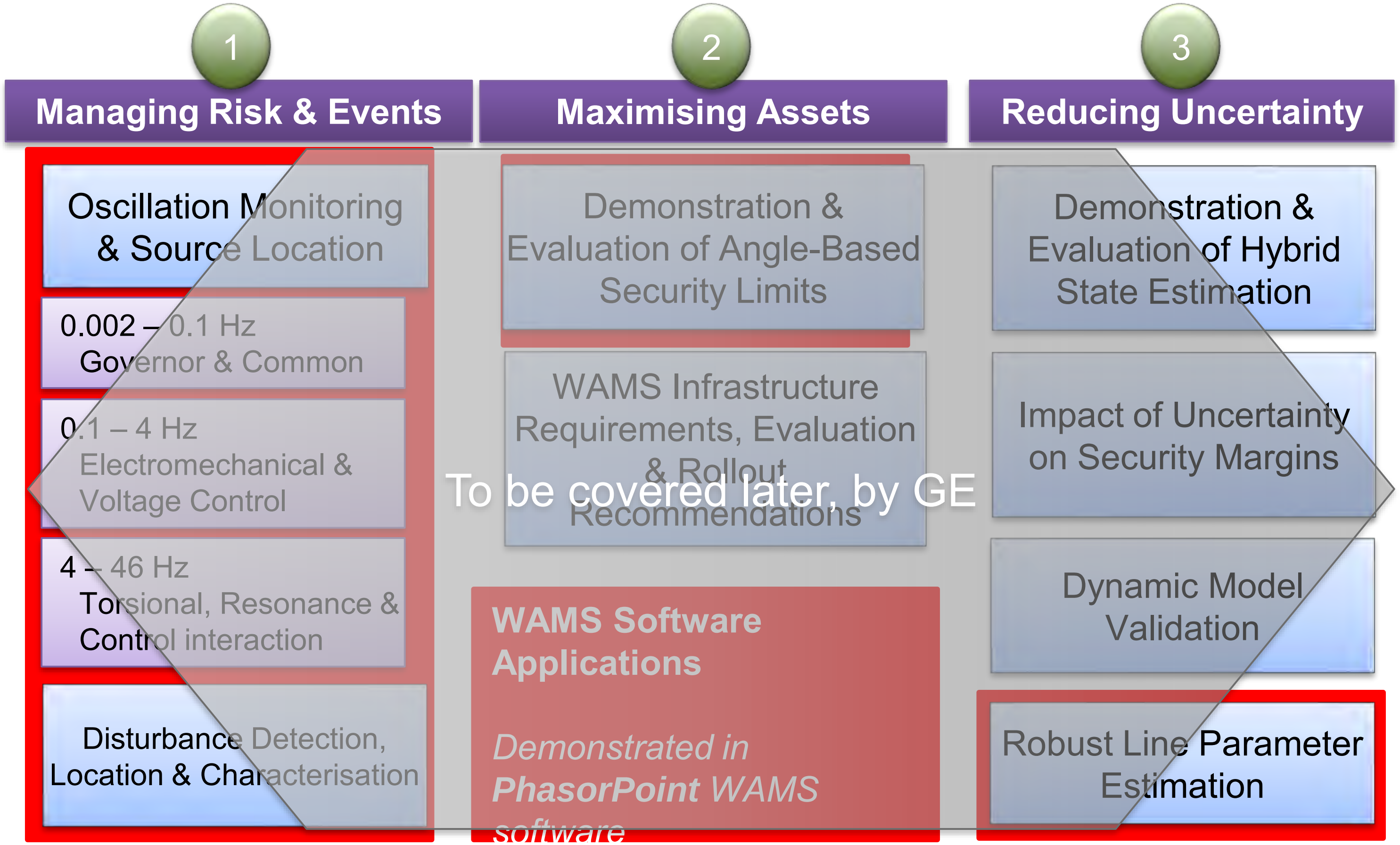
- Data to NETSO (IPSec and MPLS)
- Bandwidth requirements
- Cyber Security – aligning with NETSO

VISOR Applications

PMU/WMU Data collected by PhasorPoint within each TO region

New PhasorPoint applications address three main areas:

- Market-leading SSO detection & location
- Prove operation - Minor SSO detected in 2015
- Various benefits for TO & SO



Emerging Challenges

- The evolving transmission network
- NETS SQSS requirements

Why and who invests?

- GB Roadmap
- Sandbox

Infrastructure

- Monitoring & Comms req.
- Data quality
- Data sharing

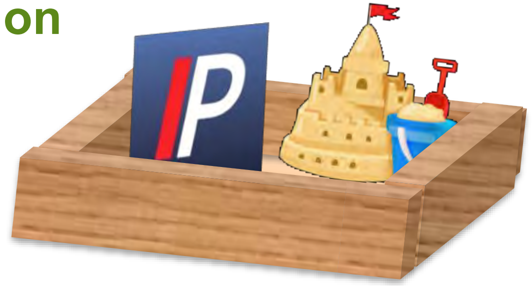
Applications

- PhasorPoint: Monitoring and analysis

The hard bit!

VISOR: Why and who invests?

WAMS Sandbox for EMS Interface and Business Integration



Stakeholder engagement introduced significant value gained from trial, integration & training facility:

- PhasorPoint **interfacing** with EMS
- **Trialling** applications in ‘real environment’
- Building **necessary confidence** to bridge the gap from **Pilot-to-Production**
- Demonstrate **WHY to invest**

Necessity of a <u>GB Roadmap</u>: determine WHO & HOW to invest

- PhasorPoint value for TO and SO
- Integration with existing EMS

APPLICATIONS

+

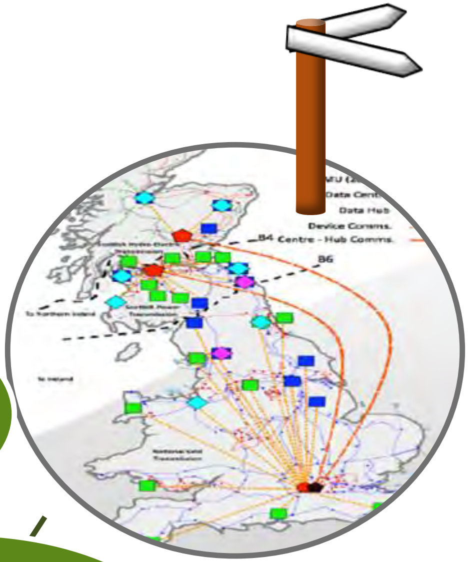
- PMU requirements & coverage
- Comms req. from PMU to PDC
- TO/SO data sharing

INFRASTRUCTURE

+

- Procedure
- Training
- Standards

PROCESS



- Assess findings of VISOR
- Learning from international experience
- Evaluate various business benefits
- Develop business cases
- Design infrastructure specification
- Determine roll-out strategies for **<u>TOs and SO</u>**

Priyanka Mohapatra,
pmohapatra@spenergynetworks.co.uk

Thank you

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WAMS Development – NETSO Perspective

Dr Phil Ashton – Future Control Strategy

Wednesday 6th July 2016

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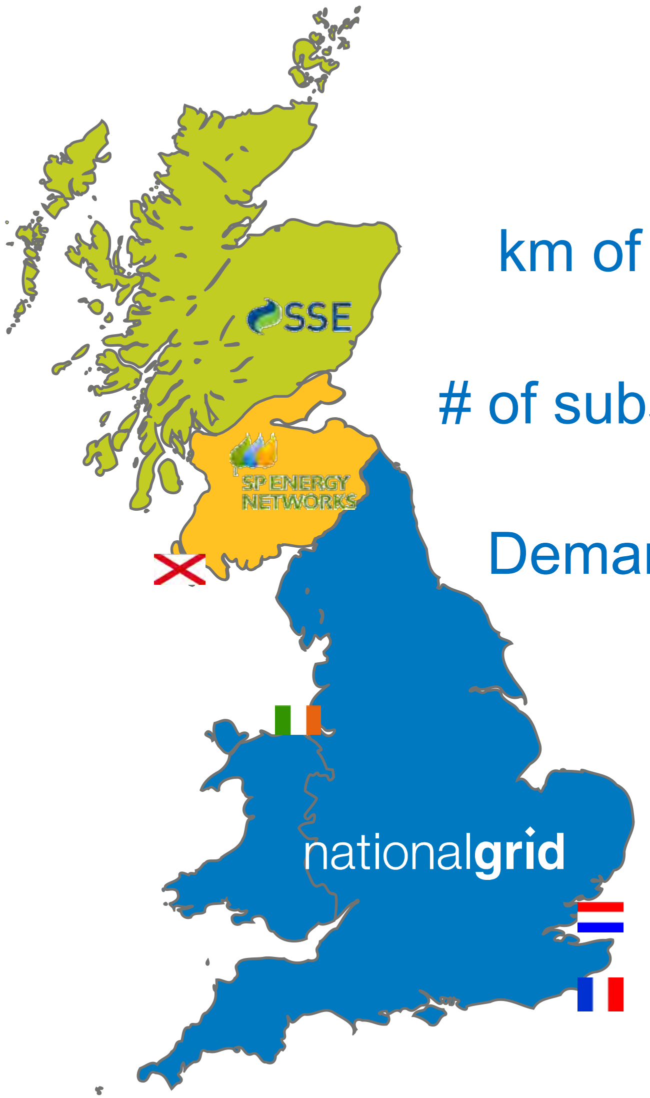
Presentation Overview

- Introduction to National Grid
- Future Challenges
  - Motivation for Enhanced Monitoring Applications
- Experience of PMUs to date
  - Applications
  - Key Challenges
- What is Proposed Through VISOR
  - Key Work Packages
- Strategy and WAMPAC Roadmap

GB Transmission Network



	nationalgrid	SP ENERGY NETWORKS	SSE
km of circuit	14,000 400kV and 275kV	4,000 400kV 275kV and 132kV	5,000 400kV 275kV and 132kV
# of substations	340	80	40
Demand (GW)	54.3	4.39	1.65

Operational View		GB Interconnectors	
Winter Peak Demand	~ 60GW	France	2GW
Generation Capacity	~ 80GW	N. Ireland	0.5GW
		Ireland	0.5GW
		Netherlands	1GW

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Changing Energy Landscape

Power Station Closures

≈25%

of total capacity by 2020 vs 2010 levels

Decarbonise Electricity

80%

CO_2 reduction by 2050

Energy from Renewables

≈15%

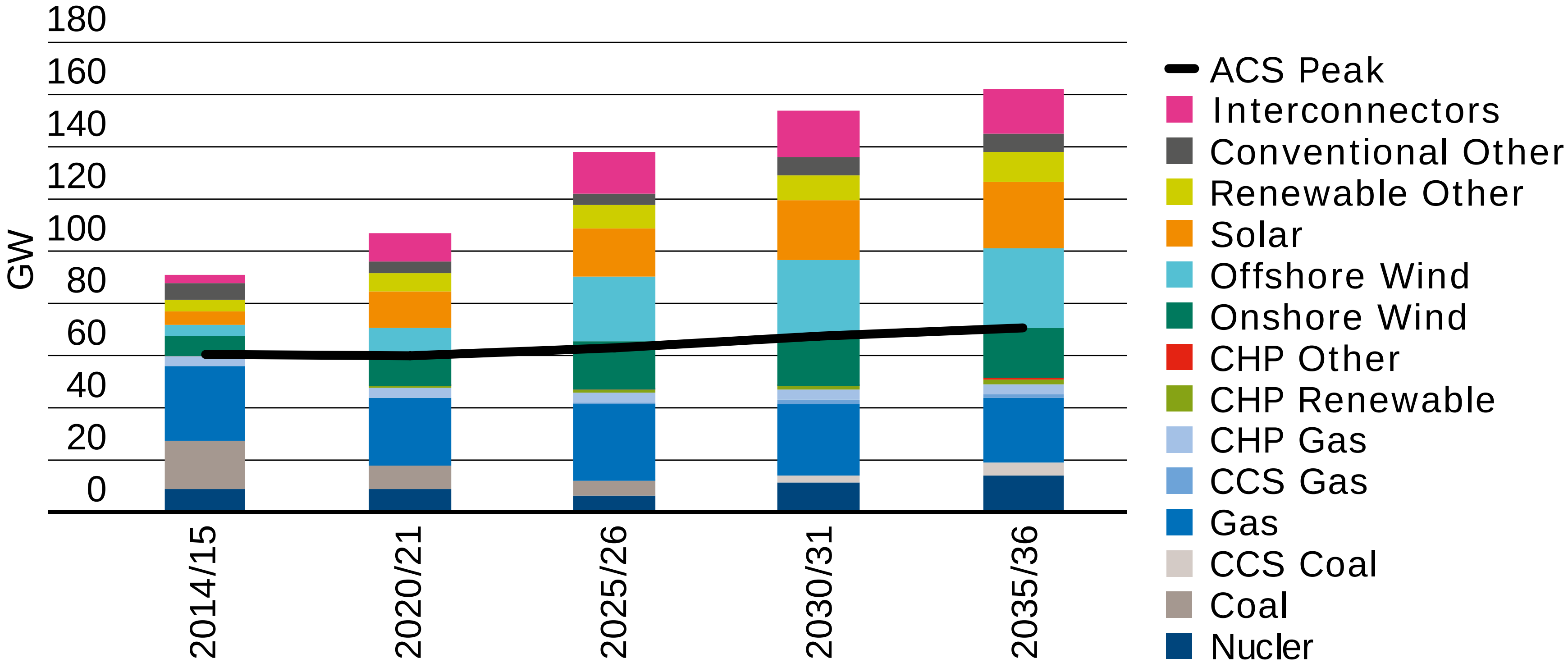
of total supplies by 2020

Energy needs based on Stakeholders views of the future energy landscape

Challenges and Opportunities. Developing measures to ensure the operability of future networks

Changes in Supply and Demand

- Generation Mix
  - *Closing Synchronous Generators, Increased Wind, PV and Interconnectors*
  - *Variable Power flows, Largest Loss, Storage*
- Increasingly Complicated Network

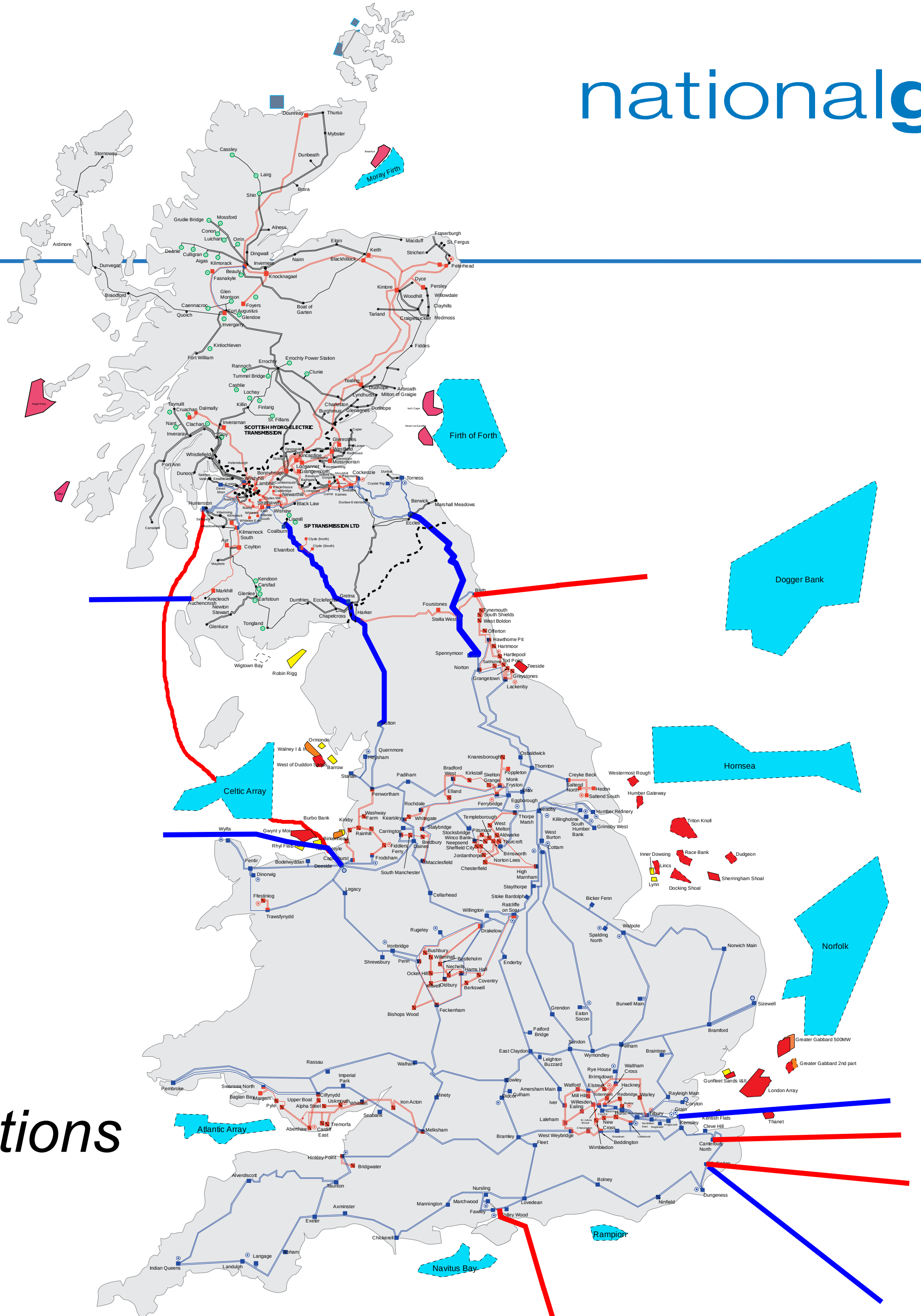


Growing requirements for WAMS and increased system visibility!

Future Energy Scenarios 2015, National Grid. http://fes.nationalgrid.com/fes-document/

Network Reinforcement

- Network Changes to 2020
  - *Increased Interconnection*
    - ELEC Link 1000MW
    - NEMO 1000MW
    - IFA2 1000MW
    - NSN 1400MW
  - *Series Compensation*
    - *TCSC and FSC*
    - *B6 Increases to 4.4GW*
  - *Intra-Network HVDC*
    - *Western Link*
    - *B6 Increase to 6.6GW*
- *Increased Dynamic Interactions*
  - *System Stability Issues?*



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Project VISOR: January 2014 – March 2017

First WAMS for the whole GB Network

Enhanced System Monitoring Applications

Increased Visibility of System Dynamics

Specification for a “Production Grade” System

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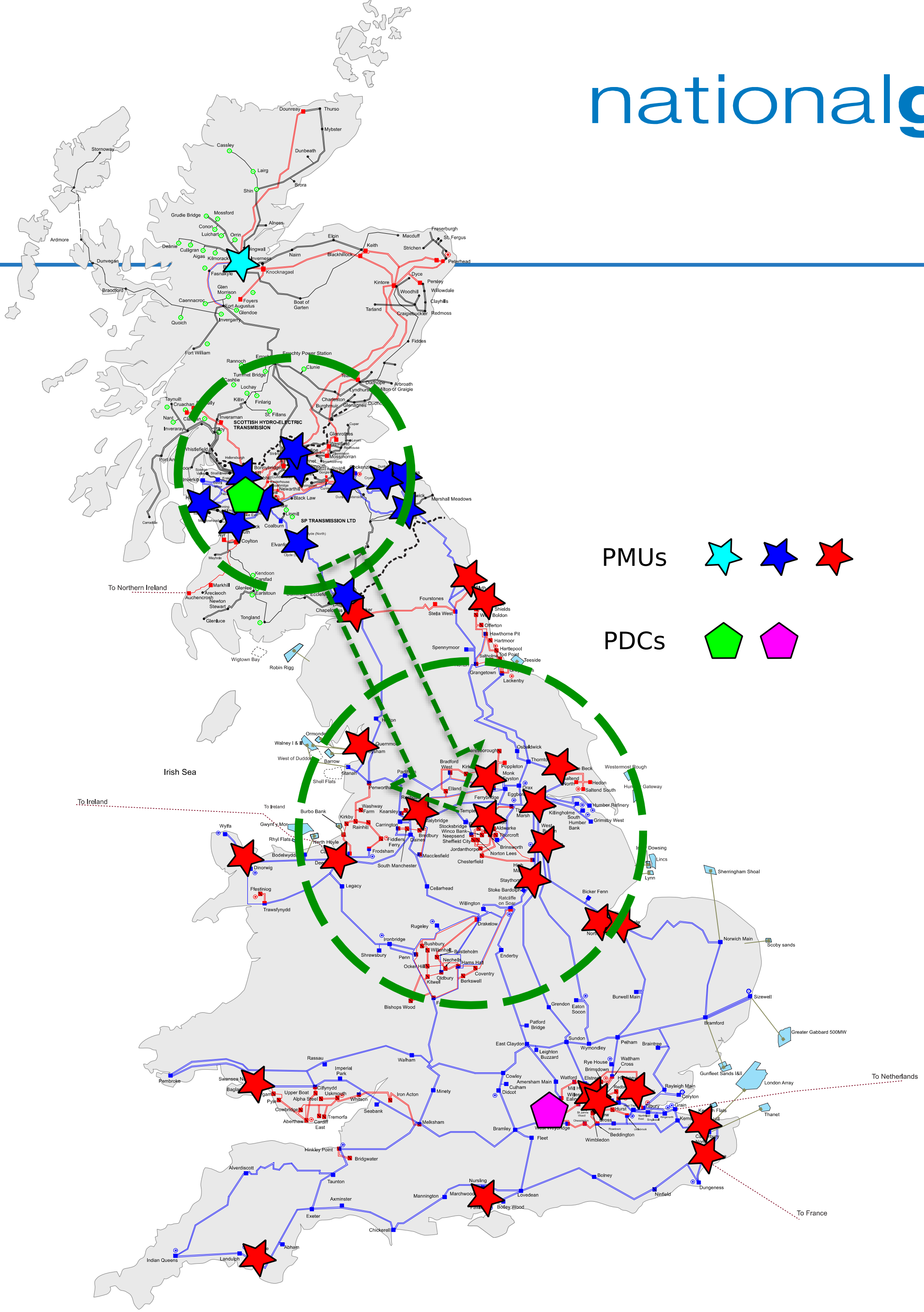
PMU Experience

- No initial problems to solve…
- Bottom- up approach
  - Upgraded DFRs
- PMU based Oscillation Monitoring
  - Alarms to EMS
- Post-event analysis
- Comparisons with offline model
- Challenges
  - Communication Issues
  - Data Accuracy and Availability
  - Building Requirements

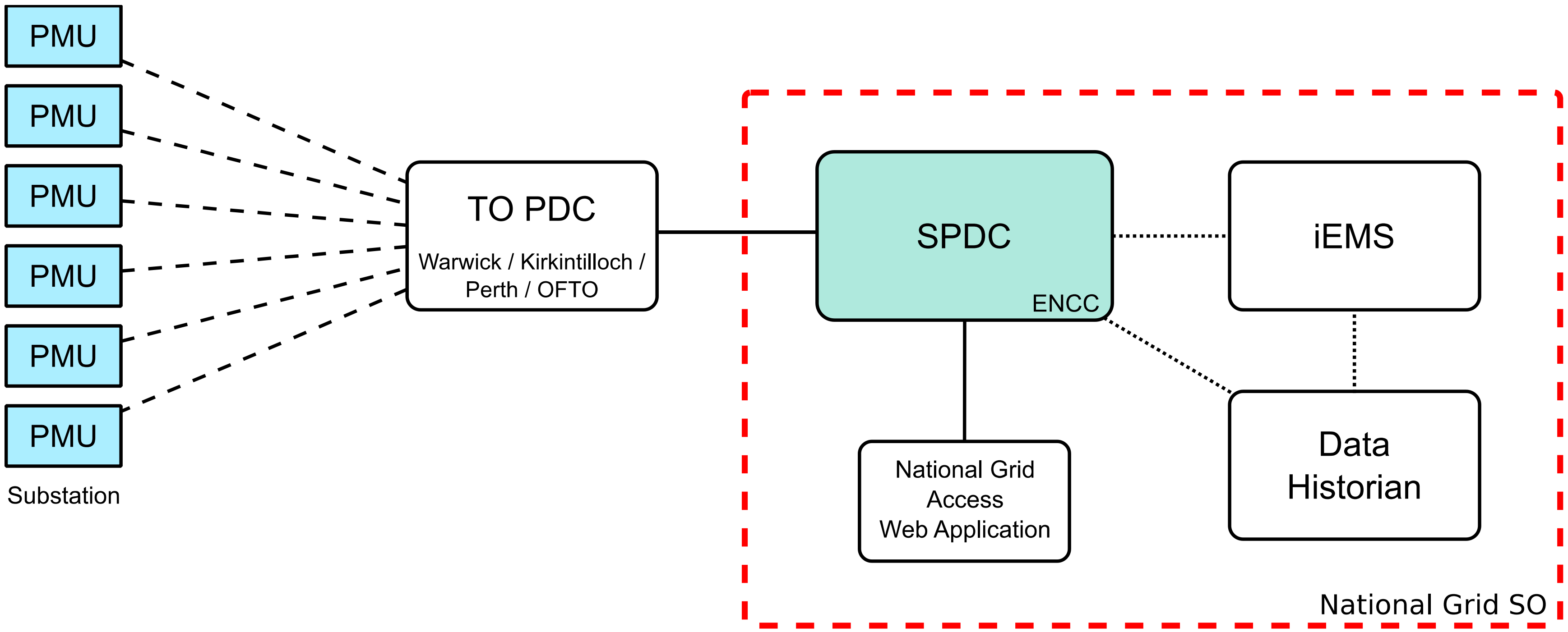


VISOR Work Packages

- WP1 – Enhanced Oscillation Monitoring
  - LF (0.1 – 4Hz) + Sub-Synchronous (4-46Hz), VLF (0.005-0.1Hz)
  - Source location
- WP2 – System Model Validation
  - Line Parameter Estimation
  - Dynamic Model Validation
- WP3 – Management of Stability Constraints
  - Hybrid State Estimation – SE drives internal systems
  - B6 Boundary Transfer – Angle Based
- WP4 – Supporting Infrastructure – **Vital!**
  - Servers, Comms
  - How to integrate into the business…

WAMS Architecture

- Visibility at various levels
  - How many PMUs and where + redundancy requirements
  - TO PDC's
  - Regional? / Substation
- Application Specific Information



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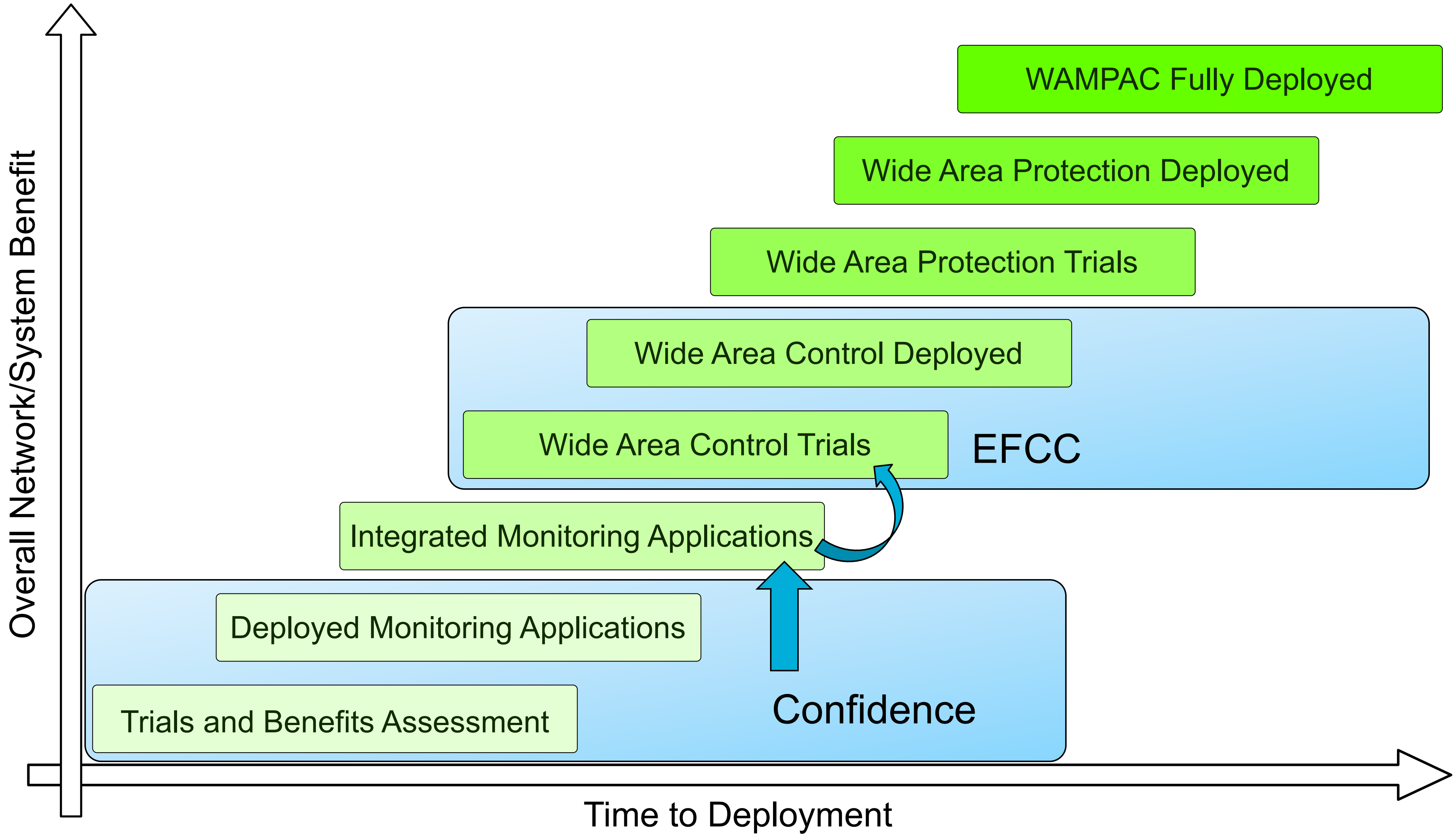
Experience to date…

- Bottom-up Approach since 2011 – CR
  - *Early warning system for B6*
- VISOR 2014 – 2017
  - *Leading to Application Specific Installations*
- EFCC 2015 – 2018
  - *Building on VISOR, leading to WAMC (frequency response)*
- Motivations for WAMS
  - *Increased system visibility*
  - *Post-Event requirements*
    - *To develop frequency response requirements/capabilities*
    - *To develop potential for WAC - POD*
- Roadmap – Points to Consider
  - *Applications and there owners (CR/Planning/Network design)*
  - *No' of devices and specifications (50Hz/200Hz, IEC/IEEE 60255-118-1)*
  - *IEEE 1588, concern over reliance on GPS*
  - *Comms' requirements*
  - *Big Data Challenges*
  - *TO & SO Visibility*
  - *Timescales for deployment, based on similar sized systems (Nordic example)*

WAMS / WAMPAC Roadmap



In Summary

- Growing Complexities on the GB System
  - *Network Changes*
  - *Generation Mix*
  - *Potential for Increased Interactions – System Dynamics*
- Increased Monitoring now Required
  - *Existing Systems becoming unsuitable*
  - *Greater Visibility of System Dynamics + SSO*
- Motivation for WAMS
  - *Increased Visibility*
  - *Real-time / Post Event Applications*
- WAMPAC Roadmap
  - *Confidence in monitoring applications*
  - *Release the benefits of Wide Area Control / Protection*

WAMS Development – NETSO Perspective

Dr Phil Ashton – Future Control Strategy

Wednesday 6th July 2016

VISOR: Transmission Owner Experience

Mark Osborne
National Grid Electricity Transmission

Introduction

- Background
  - Growing need for network observability
- Experiences & Issues
  - PMUs
  - Infrastructure
- Ambitions
  - Role for SM in Future Network Development
- Summary
  - WAM strategy

Background for System Monitoring

Why do Transmission Operators need system monitoring?

- Networks are changing faster than utilities can respond
- Quantify the phenomena (harmonics, sub-synchronous oscillations, unbalance & control interactions)
- Drive to characterise generation & demand response to perturbations
- Validate network modelling and prediction assumptions
- Changes in regulation and grid code requirements may require the networks to be managed differently "Connect & Manage"
- Observe the impact of changing network conditions on asset performance.

System Monitoring

How will Transmission Owners use system monitoring?

- Improve network observability to measure and monitor the performance of an increasingly complex system
- identify opportunities for marginal capacity improvement
- Underpin the control philosophy for network automation to address transient & voltage stability issues
- Improve post-event analysis, including accurate fault location
- Improve asset monitoring and protection
    - Optimising asset maintenance
    - Facilitate Risk and criticality strategy

VISOR Trial Installations

- Installed Waveform Monitoring Units (WMU) at 3 sites with a 4^{th} planned for this summer
  - Hutton, Stella-West, Grain, Deeside*
  - PDC located at Wokingham – will be relocated to Warwick
- Utilising the RAMM network until fully proven
- Establishing Settings & Configuration files
- Also utilise existing PMU population
- Connection to 110V Dc supplies

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Lessons Learned

- Installation taken longer than anticipated
  - Piggy backing onto outage restrictions
  - Internal design assurance and commissioning checks
- Instrument transformers
  - Availability of 3 phase VT signals
  - Availability of spare cores
- UDP vs TCP requirements -
- GPS antennae performance affected by rain
  - Being replaced
- Firmware upgrades
- Existing PMUs not designed to output to multiple PDCs
- Smartgrid applications are not low cost
  - Exchange primary equipment costs for IS related ongoing costs
  - Change management – more frequent generally driven by external factors to Energy industry

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Management of WAM solutions

Functionality & Performance	■ Adaptability to change ■ Mal-operation & 'Fail safe' modes ■ Proving reliable operation
Interfaces & interoperability	■ Control interaction ■ Managing Third Party access ■ Interoperability with legacy systems
Testing & commissioning	■ Proving the design ■ Cyber security ■ How to safely 'un-install
Lifecycle management	■ Long term product support ■ Replacement/modifications

WAMS enduring Asset Management

- Need to define the Service Level required
  - Resilience
  - Bandwidth and timescale
- Data management
  - Storage strategy
  - Accessibility
- Communication services
  - Migration to OPTEL from RAMM
- Cyber security
  - Applications in time will become critical national infrastructure
  - Need to be hardened
- Asset maintenance & replacement strategy
  - Replace on fail
  - Looking at required redundancy levels
  - Multiple function system monitoring

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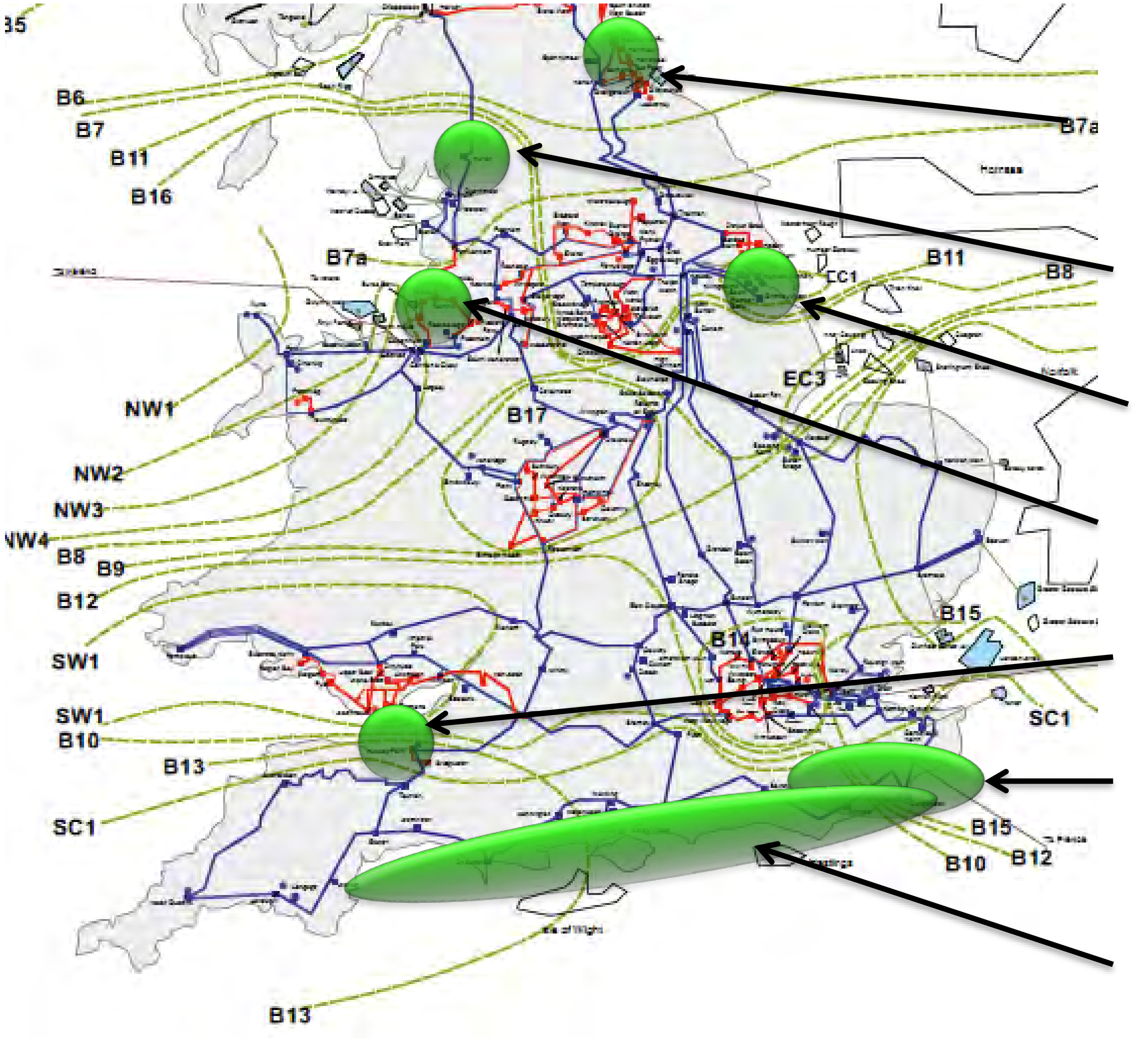
Potential Applications for WAM



Blythe 400kV substation NSN HVDC - 2023
Hutton Series Compensation - 2015
Humber OTS replacement
Western link HVDC 2016
Hinkley Point to Seabank double circuit - 2024
Voltage stability Static & dynamic reactive compensation - 2018
Sellindge OTS upgrade

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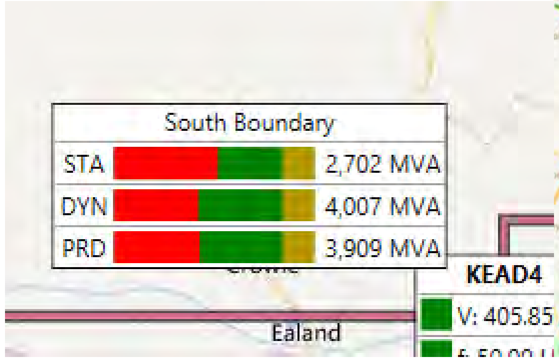
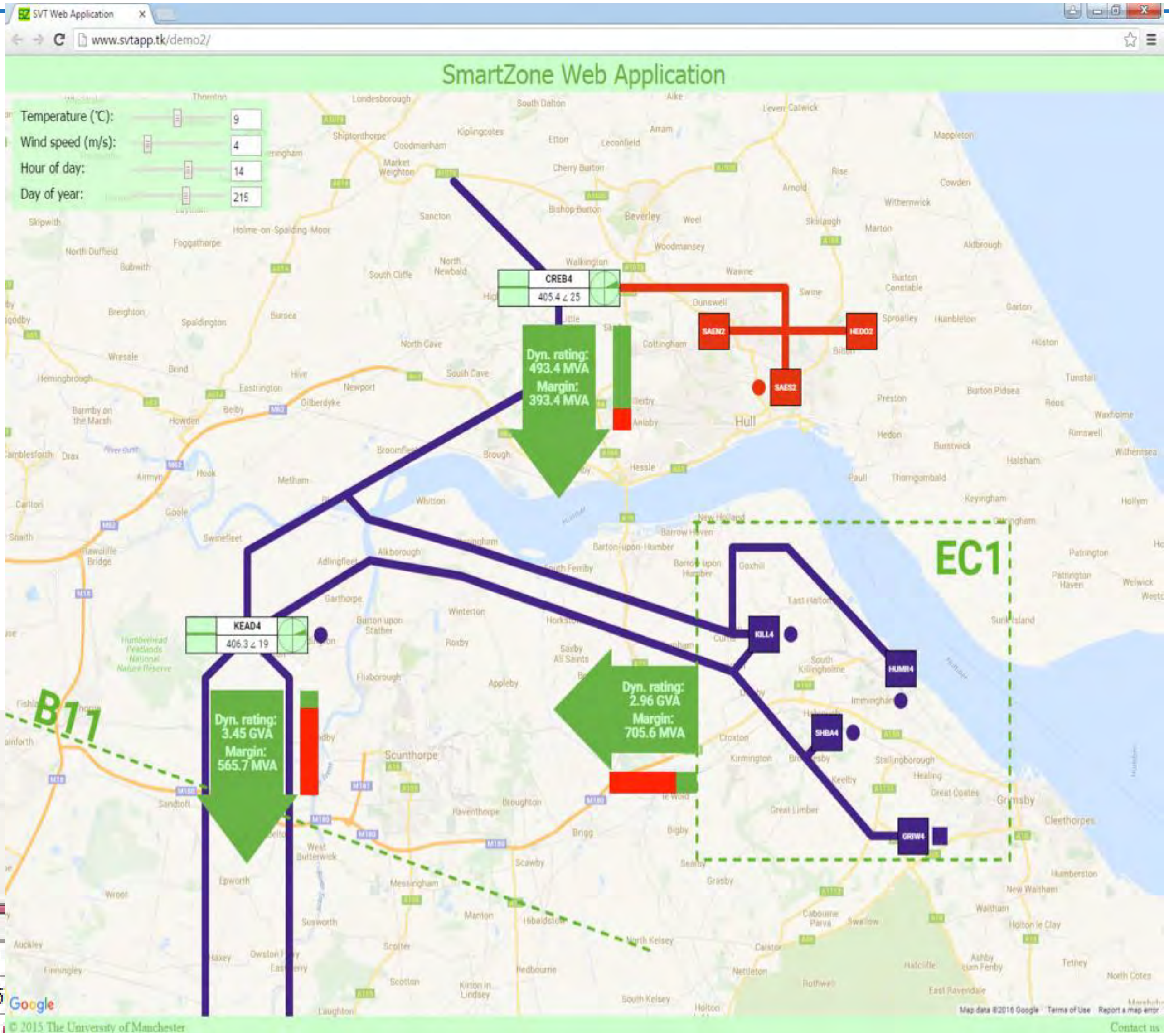
Humber Smartzone Project

- Visualising real time and predicted Boundary capacity
- Compares Dynamic, real-time and predictive ratings.
- Evaluate marginal boundary capacity using situational awareness data
- PMU derived.





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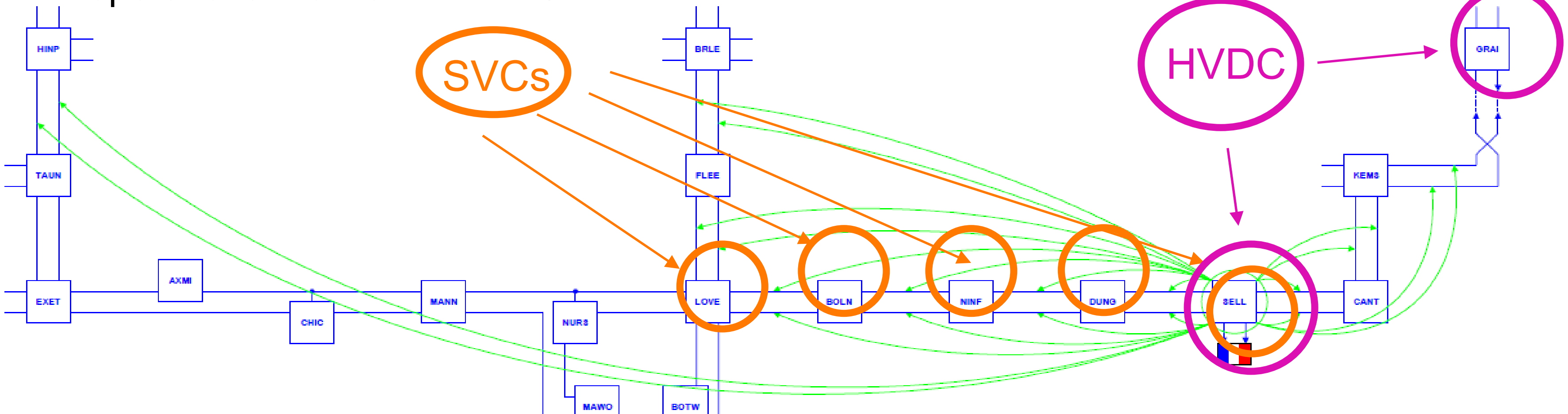
South East Voltage Stability

- WAM scheme to measure voltage profile across the SE region
  - Post fault analysis
- Defer capital build (new line)
- Coordinate voltage support equipment
  - HVDC converters
  - Dynamic reactive compensation
  - ARS (including ATCC & MSCDNs).
- Longer term wide area control strategy

Sellindge Operational Tripping Scheme

- Facilitating coordinated control
- Operational tripping scheme
- Reactive control scheme - voltage
- Multiple HVDC control schemes
- Very difficult to commission & test in an operational network – RTDS?



HVDC Link to France,
Power import/export reliant on how intact the surrounding UK network is.

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Summary - Emerging strategy for WAM

'Fit for Purpose' Network	■ Optimising asset utilisation ■ Improving system access ■ Enhancing capacity. ■ Protecting Critical National Infrastructure
Timely provision of information to inform decisions	■ Better network modeling and prediction ■ Improved planning & operational flexibility ■ Enhanced Asset Management capability ■ Managing Risk & Criticality
Develop services to deliver energy securely and efficiently	■ Intelligent network automation ■ More System balancing tools ■ ICT Skills & resources for Energy ■ Coordinate with Demand side management.

SP ENERGY NETWORKS

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sse

MANCHESTER 1824

The University of Manchester

VISOR Stakeholder Event 2016

IET Savoy Place, London, 6 July 2016

VISOR

Exploiting WAMS Technology in North Scotland Transmission System

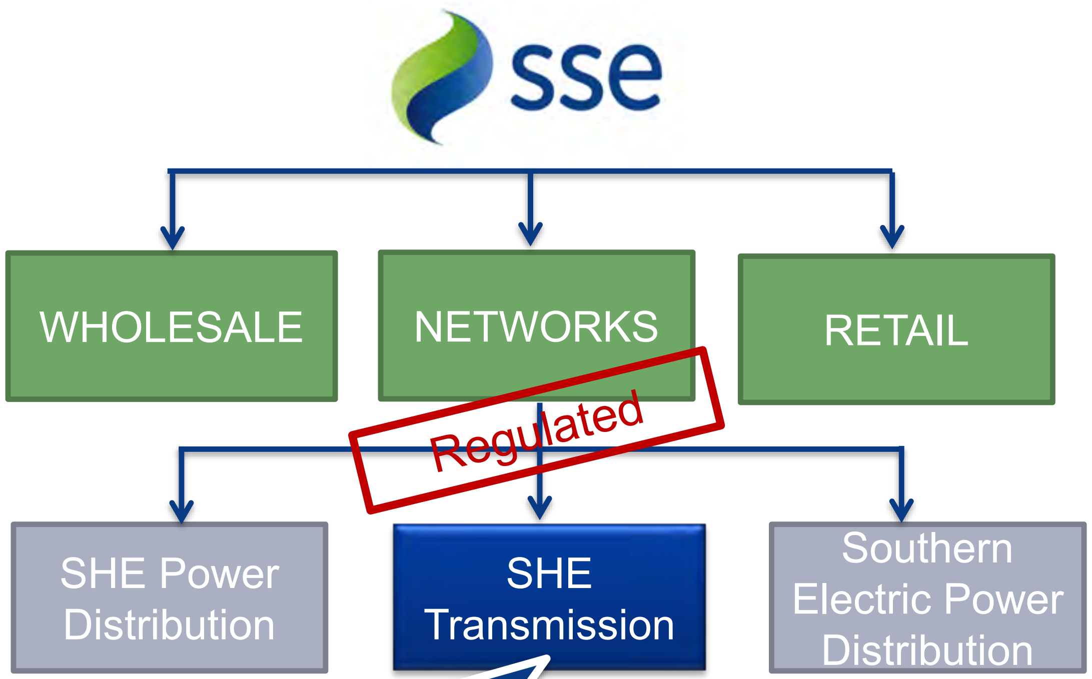
Dr David Wang
(david.wang@sse.com)
Scottish Hydro Electric Transmission
06 July 2016

Scottish and Southern Energy
Power Distribution

Presentation Overview

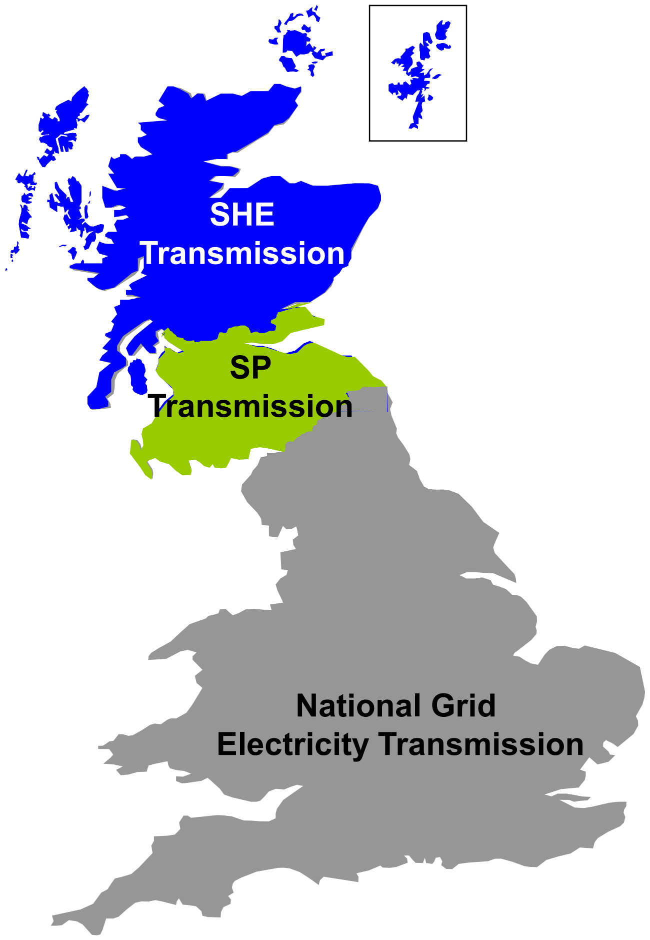
- **Scottish Hydro Electric Transmission**
  - a brief introduction
- **Recent network reinforcements**
  - Kintyre-Hunterston subsea cables
  - Caithness-Moray HVDC
  - Beauly-Denny 400kC circuit
- **VISOR**
  - purpose of network monitoring
  - our role
  - progress update

Scottish Hydro Electric Transmission PLC (SHE Transmission)



Transmission Owner in the North of Scotland

- 132kV - 400kV networks
- 4,900km overhead/underground cables
- 117 Substations
- Covering a quarter of the GB landmass



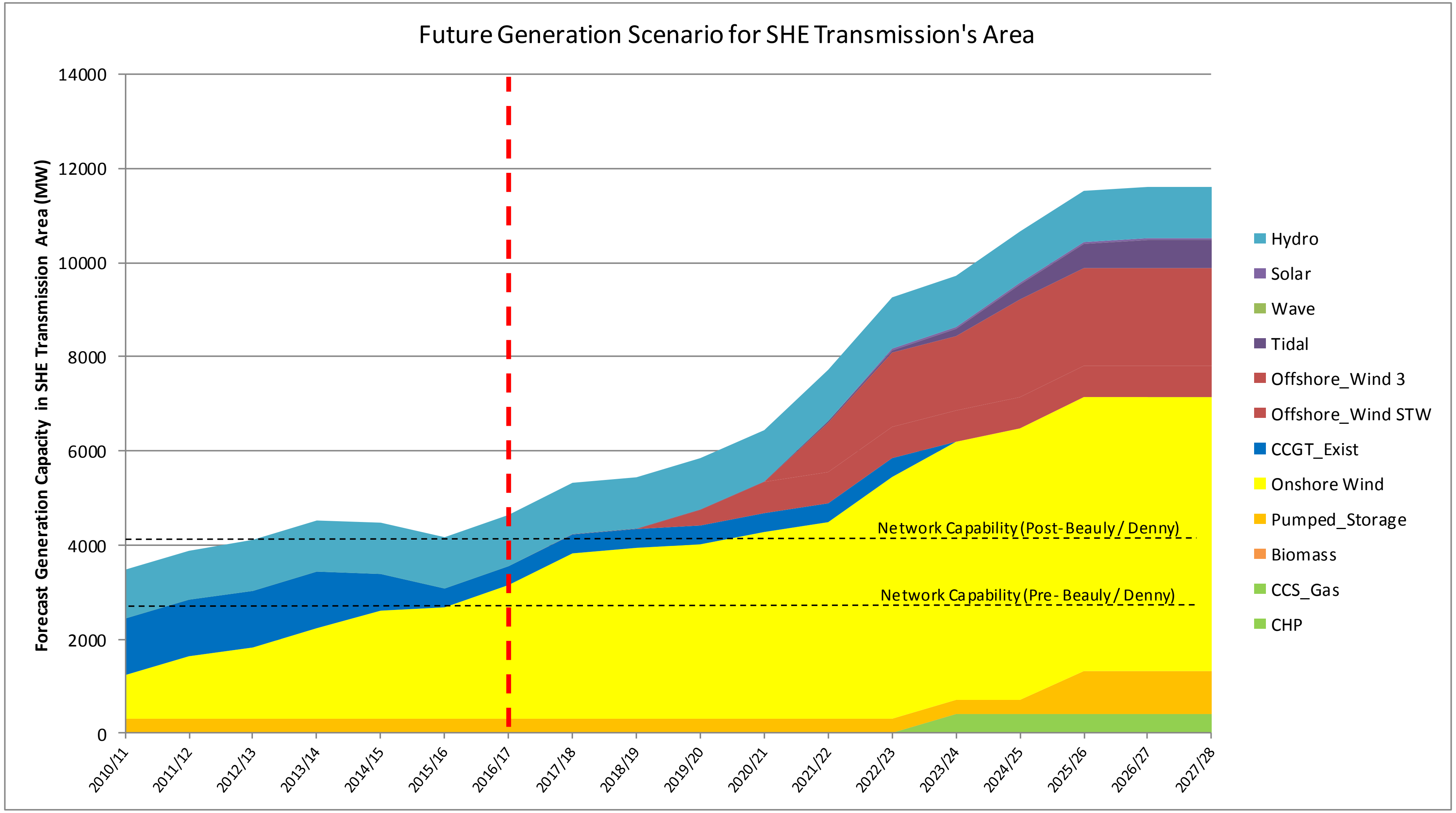
Scottish and Southern Energy Power Distribution

SHE Transmission Network

- **High generation, low demand:**
  - Total generation to-date: 4,200 MW
    - Renewables: 3,500 MW
  - Total demand to-date: 500 – 1,600 MW
- **Future network outlook:**
  - Generation:
    - 6 GW by 2020, 11GW by 2025
  - Demand:
    - Increasing capacitive Q seen at GSPs
- **Challenges:**
  - No straightforward upgrade solutions
    - limited space
    - uncertainties
  - Even more difficult on islands

Scottish and Southern Energy
Power Distribution

Future Generation Growth



Scottish and Southern Energy Power Distribution

Beauly-Denny Reinforcement

- **Key Facts:**
  - energised in late 2015
  - joint project with SPT
  - 220 km line, 800 towers
  - 2800MVA winter capacity

Scottish and Southern Energy
Power Distribution

Kintyre-Hunterston Subsea Link

- **Key Facts:**
  - Joint project with SPT
  - 2 x 220kV subsea cables
  - Crossaig 220/132 substation + QBs

Caithness-Moray Reinforcement + HVDC

- **Key Facts:**
  - 1200 MW 165km HVDC
  - Substation upgrade at Spittal (275kV), Blackhillock (400kV)
  - Expected completion 2018

Scottish and Southern Energy
Power Distribution

SHE Transmission Network Monitoring User Group

- **Identify use-cases:**
  - system performance
  - network model validation
  - regulation compliance
  - asset health-check

- **What to monitor:**
  - faults/disturbances
  - power quality: i.e. harmonics, voltage flickers
  - partial discharge monitoring
  - transformer monitoring (dissolved gas analysis, SF6 etc)

VISOR – Main Objectives

- **Exploit WAMS/PMUs benefits to GB transmission system:**
  - oscillation detection (LF, VLF, SSO)
  - disturbance localisation
  - network model validation
  - increase boundary flow (i.e. B6) with real-time monitoring

Scottish and Southern Energy Power Distribution

VISOR – SHE Transmission's Scope

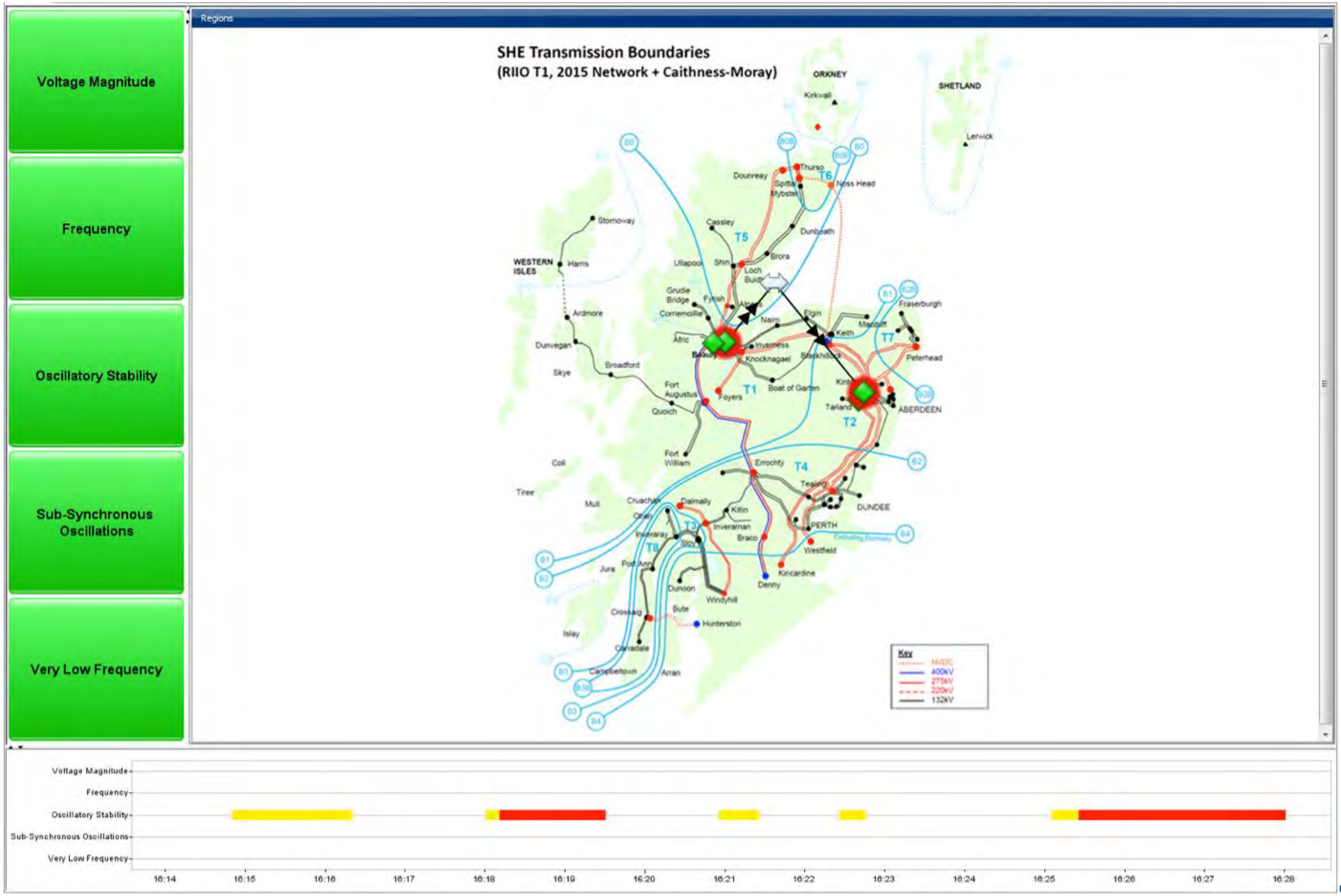
- **Install PMU/WMU pair at Beauly & Beauly sub**
- **Install data centre at SSE's headquarter, Perth**
- **Establish comms links between PMU/WMU pairs and DC**
- **Sending data from SSE DC to a data hub at GBSO**
- **Historical/live data review**

Data centre

PMU/WMU

Scottish and Southern Energy
Power Distribution

VISOR – Progress Update



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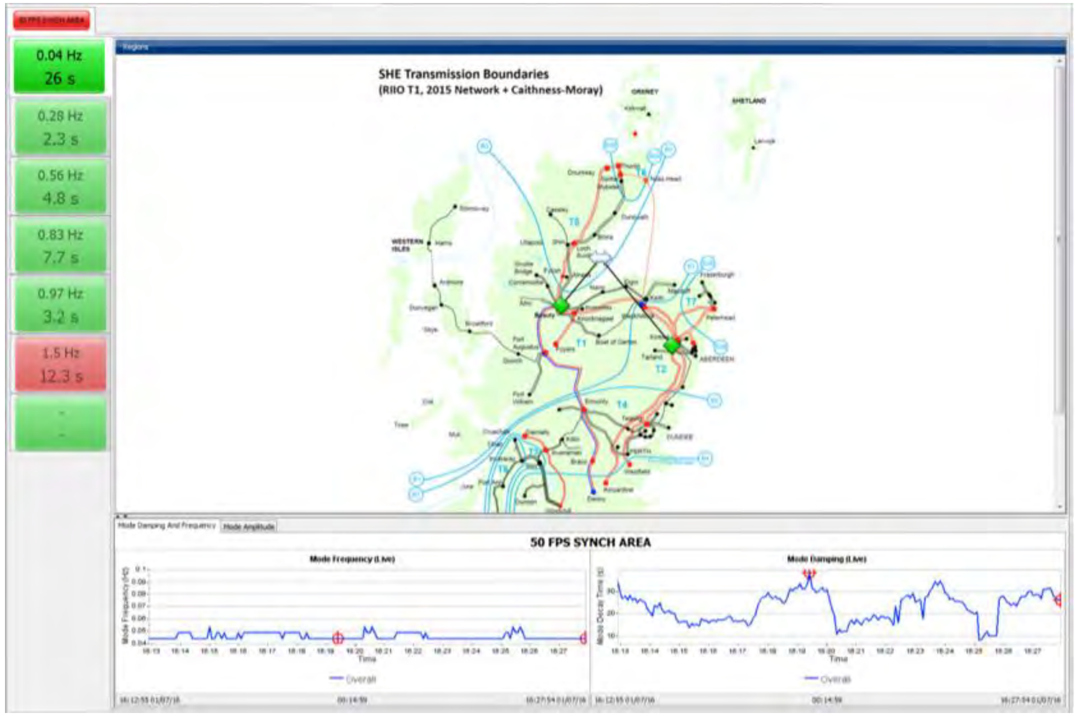
ution

Oscillation Events 01/June – 01/July 2016

- **Oscillation events**
  - 0.04 – 0.1 Hz
    - 3 events
    - amplitude 20 – 21 mHz
    - decay time: 20 – 25s
  - 0.62 – 0.9 Hz
    - 1 event
    - decay time: 27s
  - 1.05 – 1.7 Hz
    - 216 events
    - decay time: 25-38s
    - amplitude: < 10 mHz



Scottish and Southern Energy
Power Distribution

Summary

- **Evolving network**
  - driven by growth of renewable generation
- **Improvement in network monitoring necessary**
  - understand our network better
  - Asset-health check
- **Experience of WAMS technology to-date**
  - high resolution data desirable
  - more business cases needed to trigger roll-out
  - main challenge: IT security

Scottish and Southern Energy
Power Distribution

Any Questions?

VISOR Applications

Stuart Clark, Dr. Douglas Wilson
GE Grid Solutions

VISOR Stakeholder Event, London

6th July 2016

VISOR Project: Visualisation of real time system dynamics using enhanced monitoring

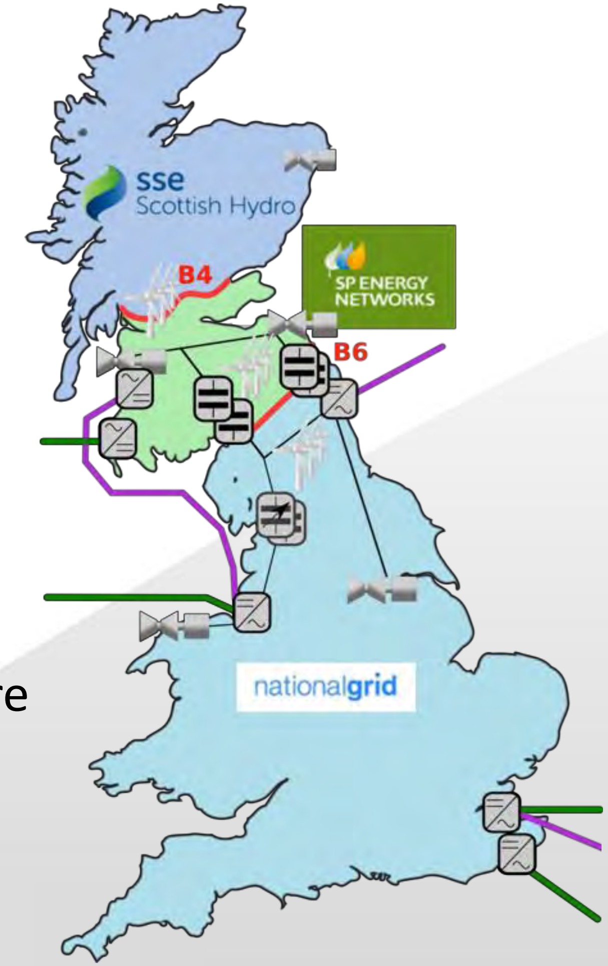
Outline

- **Recap:** VISOR motivation & components
- **VISOR applications:**
  - **Recap:** motivation & function
  - **What has been done** so far
  - **Initial learning**
  - **Benefits** demonstrated
- **Progress** & next steps
- **WAMS Infrastructure:** deployment experience

Recap: The VISOR Problem

The GB power system is changing:

- **Generation**
  - Closure of large synchronous generation
  - Increased wind generation
- **Network**
  - Intra-network HVDC link, new HVDC interconnectors
  - Series Compensation (Fixed & Thyristor-Controlled)
  - Heavily constrained boundaries (B6 Scotland-England)



This creates a need for enhanced monitoring, to:

- **Clear the fog:** Give operators a more confident picture of the system operating state and true limits
- Give **early warning** of emerging problems
- Aid in **event diagnosis & response**
- **Provide study data** to improve models & understanding

VISOR Project: Visualisation of real time system dynamics using enhanced monitoring

Recap: VISOR Components

Managing Risk & Events	Maximising Assets	Reducing Uncertainty
Oscillation Monitoring & Source Location	**Angle-Based Constraints** Demonstration & Evaluation	**Hybrid State Estimation** Demonstration & Evaluation
Governor & Common — 0.002 Hz	**WAMS Infrastructure** Requirements, Evaluation & Rollout Recommendations	**Impact of Uncertainty** On Security Margins
Electromechanical & Voltage Control — 0.1 Hz		**Dynamic Model Validation**
Resonance, Control & Torsional interaction — 4 Hz		
46 Hz		
Disturbance Detection, Location & Characterisation	**WAMS Software Applications** Demonstrated in GE's e-terra*phasorpoint* software	**Robust Line Parameter Estimation**

OSCILLATIONS

Oscillations : Background

Governor Modes	Electro-Mechanical Modes	Control Modes / Torsional Modes / Grid LC Resonant Modes

0.1 Hz *2 Hz* *4 Hz* *50 / 60 Hz*

Well-known & monitored ***Less well-known, not monitored***

<u>Reliable</u> Observability

50/60 fps PMU data

~10 Hz

Tools & Capabilities pre VISOR

Monitoring

Source Location

Oscillations: VISOR Motivation

RIIO NIC NETWORK INNOVATION COMPETITION

- **Risk of Sub-Synchronous Oscillation (SSO)**
  - New Series Compensation
  - Proliferation of Power Electronic Controllers (HVDC, wind)
- **Changing system dynamics**
  - Loss of generators with a Power System Stabilising role
  - Reduced inertia (less synchronous generation, more wind & PV)
  - New plant, of increasing complexity and non-traditional behaviour (HVDC, wind, FACTs)
- **Existing monitoring limited**
  - Covers only “LF”: Electromechanical & Voltage Control modes (0.1–4Hz)
  - Identifying of sources of oscillations is complex and cumbersome (offline / many PMUs)

Need enhanced monitoring to <u>compliment</u> studies, design & protection

- **Extended visibility** to include SSO & governor modes (0.002–46Hz) — **Mitigation**
- **Practical Source Location** information for operators and engineers — **Response**
- **Long-term observation** to baseline behaviour and validate models — **Confidence**

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OSCILLATIONS: SSO

Oscillations: SSO

Recap: *what is SSO?*

Torsional Modes

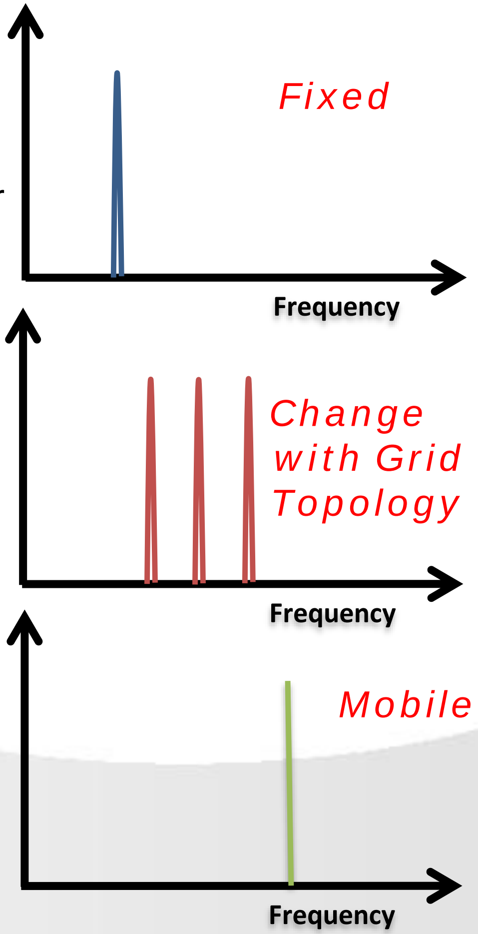
Generator Shaft

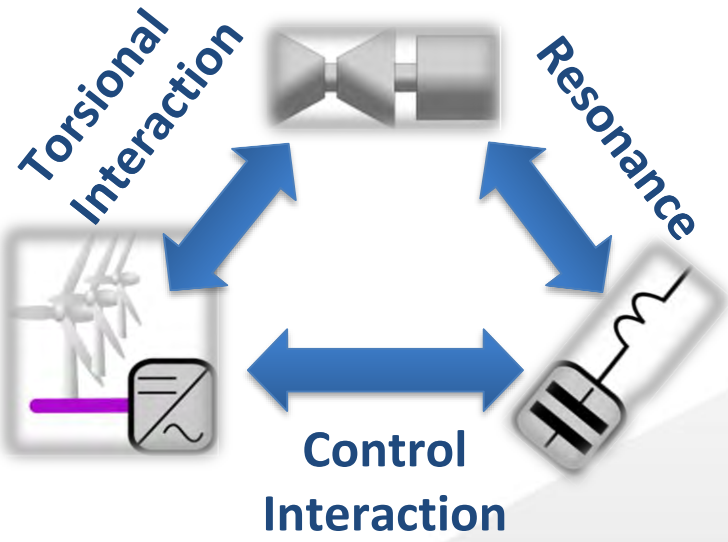
Grid Resonances

Network RLC Circuit

Control Modes

Power Electronic Converters





Plant wear & stress

Network disruption

Generator damage

Bruce English, "Reactive Power Solutions, Subsynchronous Oscillations (SSO): Risk Analysis, Protection, and Mitigation Techniques", GE Digital Energy. Available: http://www.slideshare.net/GEEnergyConsulting/v5-ssr-ssciwebinar

Hole burnt in shaft after SSR event: Mojave desert, USA 1970

Oscillations: SSO

***Recap:** why SSO?*

- Present **SSO mitigation measures:**
  - **Model studies** *to check for possibility of interaction*
  - Careful **design**, with **filters & controllers**, *to avoid interaction*
  - **SSO protection** *to trigger if interaction occurs*

- **Need for SSO monitoring:**
  - To **validate models** (network, generator, control modes) and **studies**
  - To **detect low-level interactions**:
    - That could escalate to larger levels

      avoiding drastic protection action
    - That cause increased plant wear

      avoiding reduced lifetime & unscheduled outages
  - To **tune protection thresholds** and **frequency bands**

Oscillations: SSO

What VISOR has done

- **Demonstration of real-time, continuous, wide-area SSO monitoring:**
  - New data acquisition device: **Waveform Measurement Unit (WMU)**
    - **11 WMUs** (8 sites) now deployed in GB under VISOR (+3 WMUs, 2 sites pending)
    - **+12 WMUs** (+2 sites) from follow-on **Series Compensation project**: includes generator speed monitoring
  - **SSO Application** (analysis & visualisation) **deployed across all TOs and SO**
- Provided **real-time commissioning support** for Series Compensation
- **Long-term reviews conducted:**
  - **Numerous modes observed**: triggering some further investigations
  - **Generator modes visible** in grid measurements
  - **Frequency bands** and **alarm thresholds tuned**

Oscillations: SSO

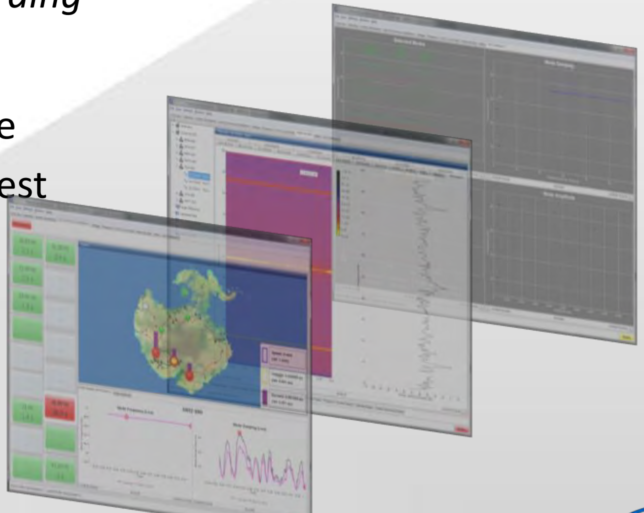
The 1st Real-Time Wide-Area SSO Monitoring System

Practical observable bandwidth of PMU WAMS: up to ~10Hz
Due to anti-aliasing filtering, window for accurate phasor calculation

- **"Waveform Measurement Unit"** for SSO visibility
  - **New:** 1st demonstration under VISOR
  - Streams time-synchronised **waveforms at 200 samples/s**
  - Sent via **IEEE C37.118** ("PMU protocol"), as Analog measurement type
  - **200fps** transmission rate is **atypical but fully compliant** and encouraged
  - Implemented within **GE Reason RPV311**
    simultaneous PMU, WMU, DFR and 800fps continuous recording
- **SSO Management Application** for analysis
  - **Frequency, amplitude & damping** of SSO modes in real time
  - **Custom Frequency Band Sorting** singles out modes of interest
  - Analyses **Voltage, Current & Shaft Speed**
  - **Unified presentation** of electrical and mechanical modes
  - **Alarming** on high amplitude or poor damping
  - Geographic view to **identify interacting locations**
  - **Results stored** for long-term study

RPV311
Central Unit

RA33x
Acquisition Unit



VISOR Project: Visualisation of real time system dynamics using enhanced monitoring

Oscillations: SSO

WMU: Waveform Measurement Unit

GE Reason
RPV311 DFR

- Uses **standard hardware:** PMU / DFR platform
- Uses **standard protocol:** IEEE C37.118
  200fps rate is atypical, but encouraged by standard
- **New signal processing** is **straightforward to standardise**
  Simple downsampling: filter requirements easy to define
  "Clever bit" is in single phase conversion, bad data detection, etc.
- **Uses existing infrastructure:** PDCs, communications networks
  Increased communications bandwidth and PDC enhancement may be needed for 200fps

Device	Bandwidth		Storage
	Device -> PDC	PDC -> PDC (20 device system)	
PMU (50fps, +ve seq)	34 kbps UDP	200 kbps TCP	1.0 GB/week/device
PMU (50fps, 3-phase)	50 kbps UDP	460 kbps TCP	1.9 GB/week/device
WMU (200fps, +ve seq)	125 kbps UDP	470 kbps TCP	2.9 GB/week/device

Oscillations: SSO

SSO Application

Spectrogram for detailed investigation with **diagnostic visibility of 4-96Hz**

Frequency band sorting to single-out key modes

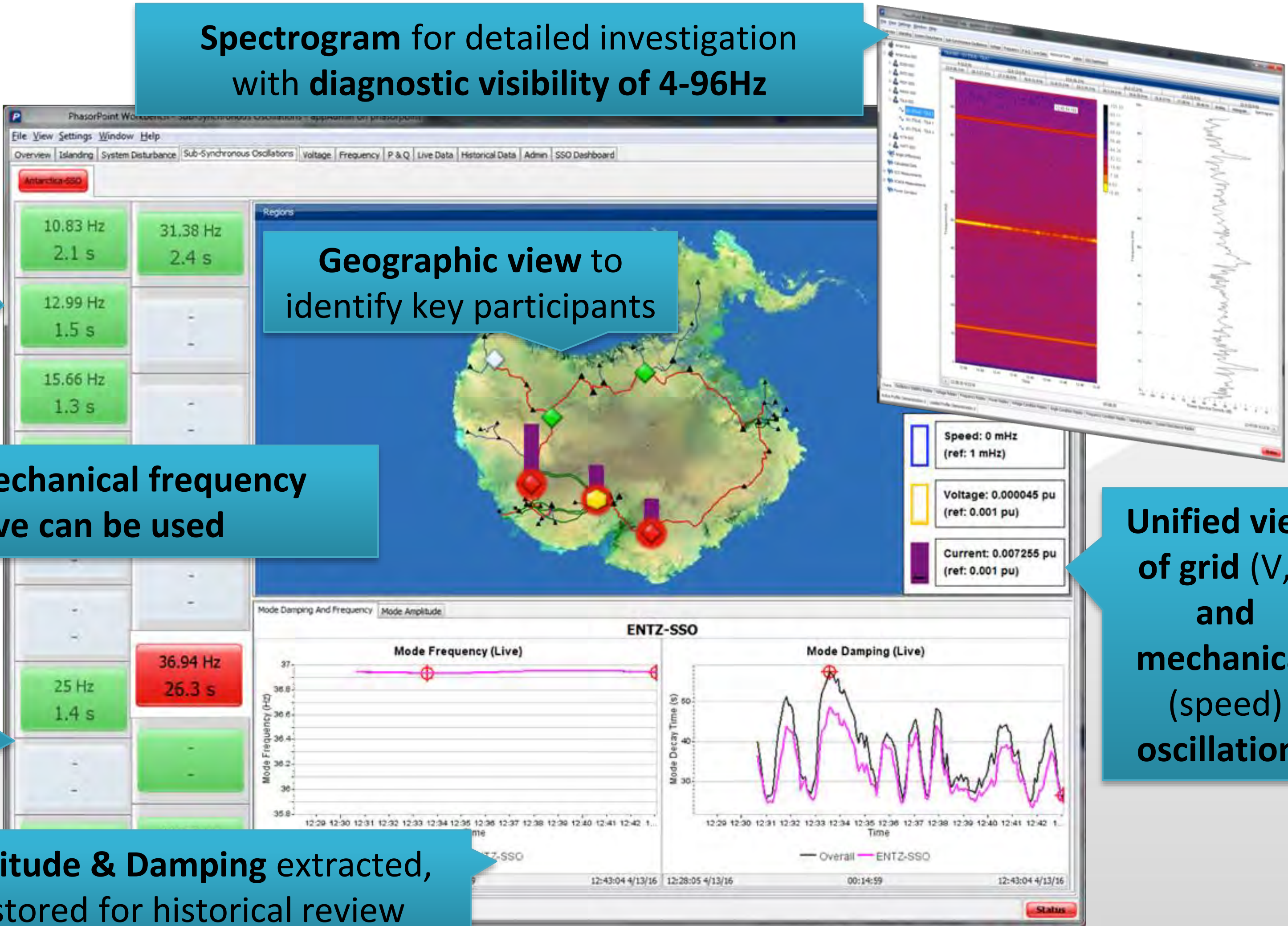
Geographic view to identify key participants

Electrical or Mechanical frequency perspective can be used

Alarms on high amplitude / poor damping

Unified view of grid (V,I) **and mechanical** (speed) **oscillations**

Frequency, Amplitude & Damping extracted, displayed, and stored for historical review



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Oscillations: SSO

Tangible benefits of SSO monitoring demonstrated during VISOR

Complimentary to model studies and SSR protection

Wide-area visibility → **Identify main participants** → **Effective & efficient response**
Targeted action & investigation

Continuous visibility → **Detect intermittent behaviour** / **Detect low-level Interactions** → **Early warning** of potential SSO problems → **System security** / **Asset protection** / **Maintenance**

Real-time visibility → **Real-time operator alarms** → **Early warning** of potential SSO problems; **Mitigate risk** when commissioning new plant

Historical visibility → **Model validation**
Shaft, network, PE control → **Reduce risk:** catch unpredicted modes
Confidence in models & studies

Historical visibility → **Baseline behaviour** → **Optimised protection & alarms**
Operational procedures

Series Compensation Project

Generator speed → **Directly observe mechanical behaviour** → **Confirmation of interactions and torsional modes**

Oscillations: SSO

Initial learning

Torsional modes visible in grid measurements

Numerous other modes observed (all **low amplitude**): *likely PE control*

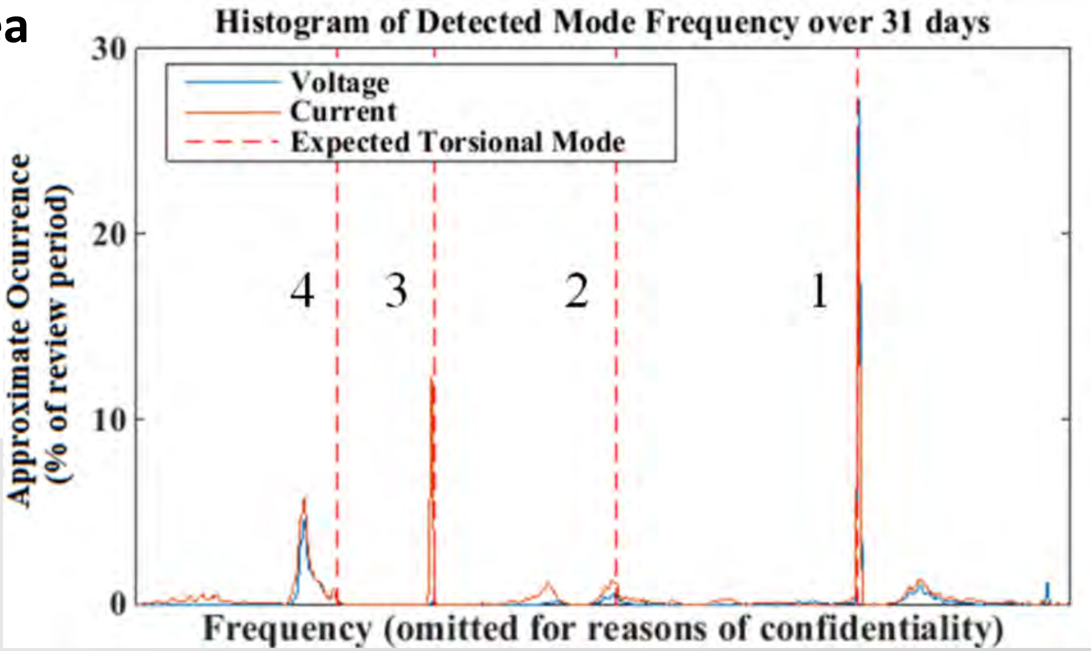
- Some **mobile in frequency**, a few **occasionally close to torsional modes**
- **Most modes well-behaved** and localised
- A few showed **poorer damping** periods
- A few observable over **wide area**
- Some **investigations triggered** as prudence

Mitigated Risk: supported SC commissioning (no issues observed)

Early warning
Identified PE modes

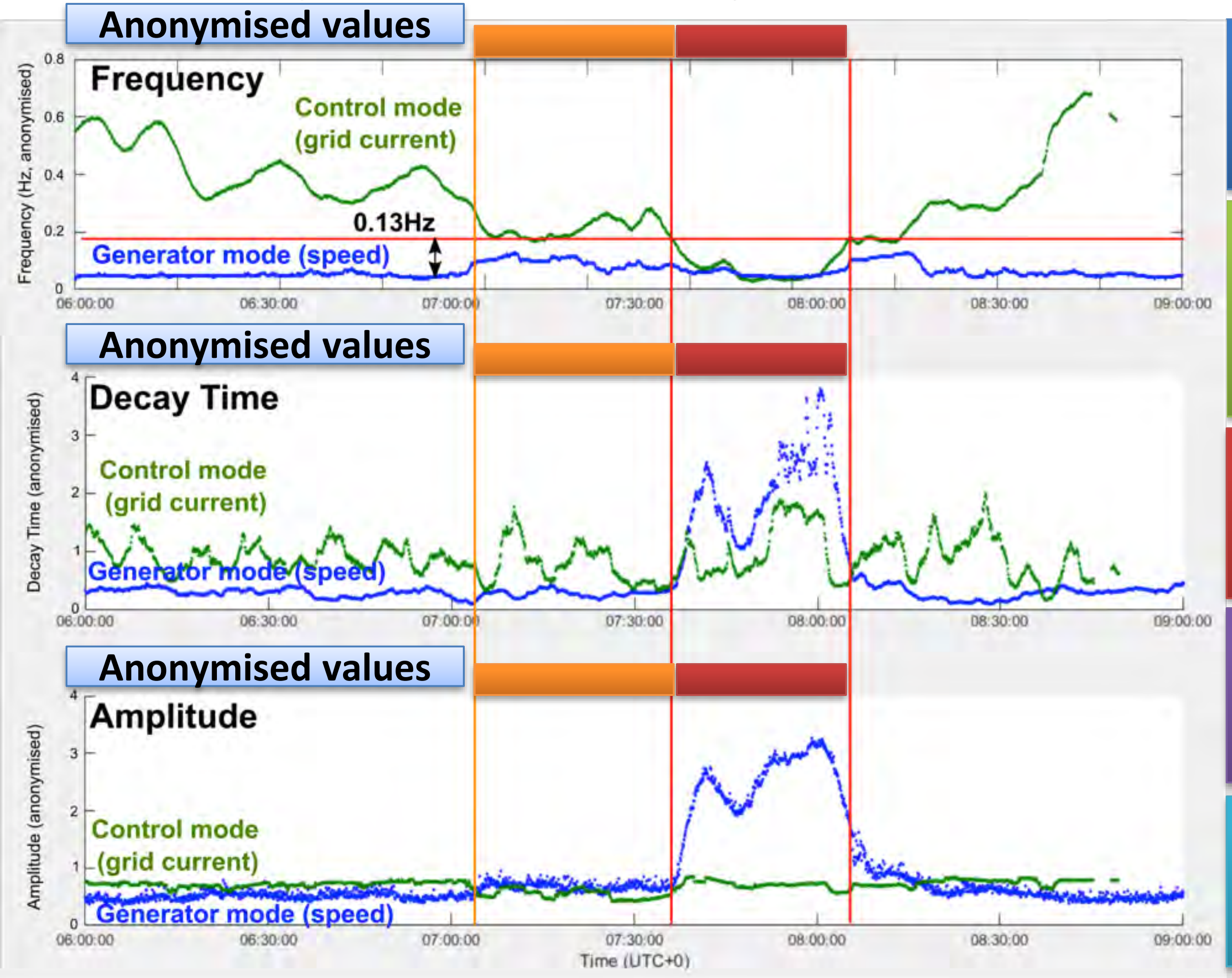
Targeted investigation

Optimised protection & alarms
Tuned thresholds & bands



Oscillations: SSO

Case Study: low level sub-synchronous torsional interaction detected



Known torsional mode
- Visible in grid
- Speed data from SC project

Suspected control mode
- Seen over a **wide area**
- **Sporadic** occurrence
- **Mobile frequency**

Signs of interaction
When control mode close to torsional mode: **low amplitude**

Monitoring fed investigation:
- **Location** from mode shape
- **Timings** of occurrence

Suspected source identified
End user equipment malfunction
Monitoring for recurrence

OSCILLATIONS: VLF & LF

Oscillations: VLF & LF

***Recap:** why source location?*

- **Oscillation monitoring long established** (LF 0.1-4Hz)
  GB was the first to implement real-time oscillation monitoring, in 1998
  (GB inter-area 0.5Hz mode)
- **However management of oscillations is complex:**
  - **Many participants** (plants, loads, controllers) over a wide area
  - **Not always replicable in models** e.g. control malfunction, interaction
- **Mitigating action most effective**, efficient & safe **when targeted** at sources
- **Source location** analysis is **challenging**:
  - **Largest amplitude ≠ Source:** not obvious
  - **Existing methods impractical:** power tracing or historical pattern identification

VISOR solution: **new source location analysis & displays**

Uses oscillation phase in voltage to identify sources: **works with sparse visibility**

Present results to operators & other users **in a simple way**

Oscillations: VLF & LF

***Recap:** why VLF?*

- **Existing tools focus on LF range** (0.1-4Hz)**:** electromechanical, voltage control
  VLF requires different algorithms, previously most interest was in LF range
- **VLF mode in GB** at ~0.035-0.045Hz, **mainly low amplitude**
- **"Wobbles" often visible** but no context for operators: *"Is this a problem?"*
- **Need to:**
  - **Establish normal characteristics** (providing reassurance)
  - **Highlight abnormal events** in real time and historical review
- **More important as generation mix & inertia changes** in coming years

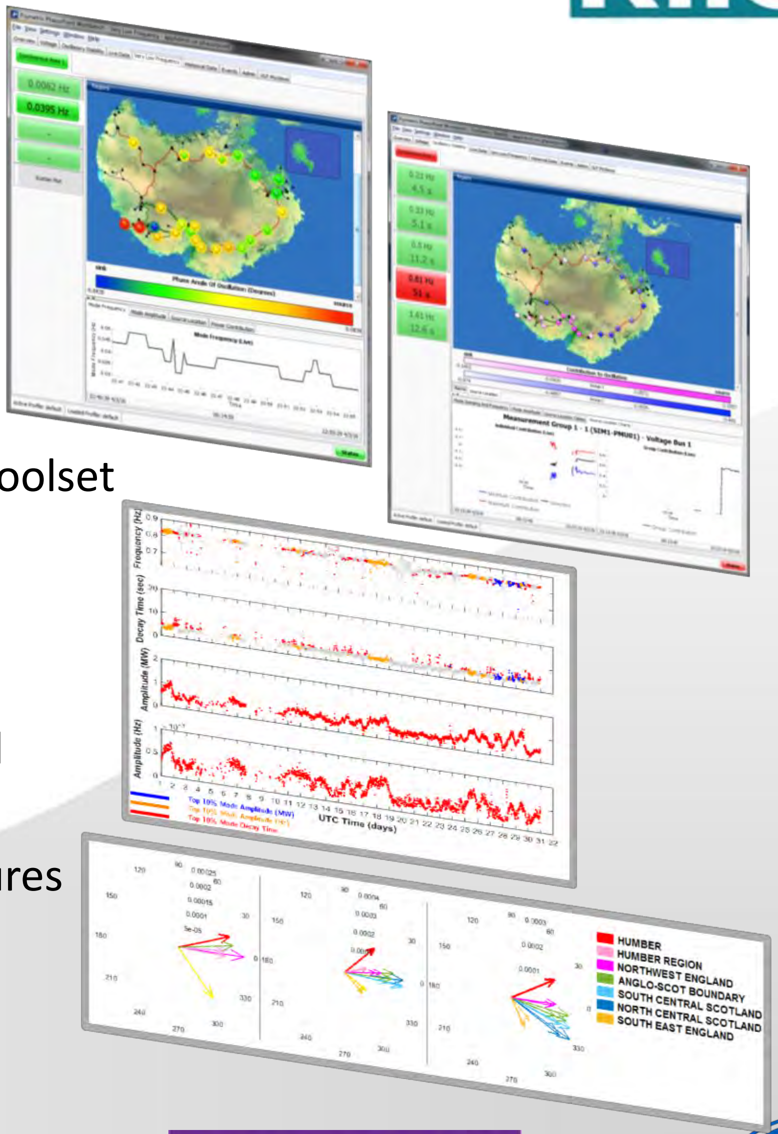
VISOR solution: **new VLF application module**

Detection, **monitoring** and **source location** of VLF oscillations

Oscillations: VLF & LF

What VISOR has done

- **Demonstration of new VLF & LF oscillation management tools:**
  - **VLF application module**
    Detection, monitoring & source location
  - **LF source location enhancement:**
    Adds source location analysis & display to LF toolset
- **Long-term reviews conducted:**
  - **Numerous modes observed**
    Triggering some further investigations
  - **Frequency bands** and **alarm thresholds tuned**
  - **Source location analysis applied**
    Has helped investigations, will inform procedures



Oscillations: VLF & LF

Tangible benefits of Oscillation Monitoring demonstrated by VISOR

Visibility	Capability	Benefit	
Continuous visibility	**Detect intermittent behaviour**	**Early warning** of potential problems	**System security**
Real-time visibility	**Detect low-level behaviour**		**Compliance**
	Real-time operator alarms		**Maintenance**
		Mitigate risk of unexpected behaviour **Confidence to push system harder**	
Source Location	**Identify contributors**	**Effective & efficient response** Targeted action & investigation	
	Operational procedures knowledge & understanding	**Mitigate risk** Preparedness for events	
Historical visibility	**Model validation**	**Mitigate risk** of model errors **Confidence to reduce constraints**	
	Baseline behaviour	**Optimised alarms** Tuned thresholds and frequency bands	

Oscillations: VLF & LF

Very Low Frequency

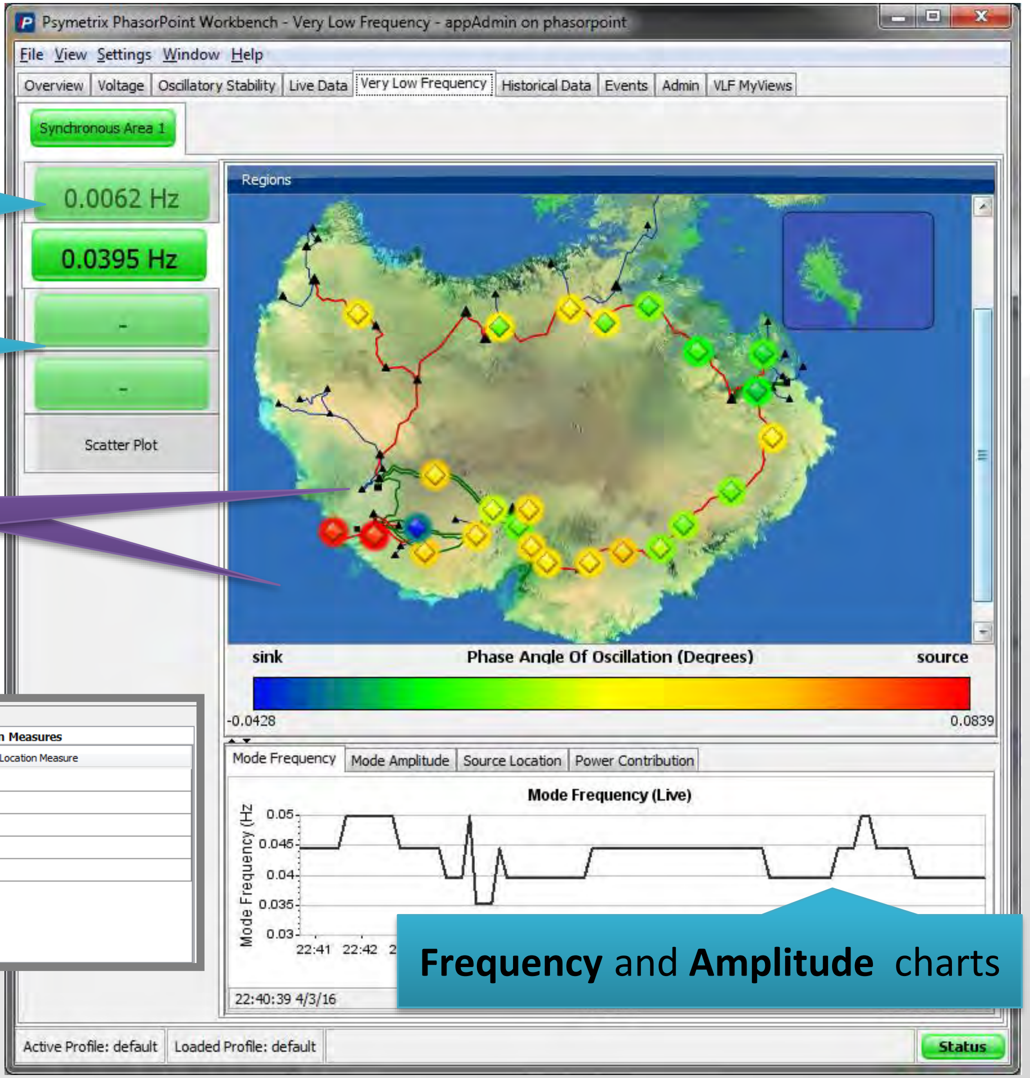
New application module

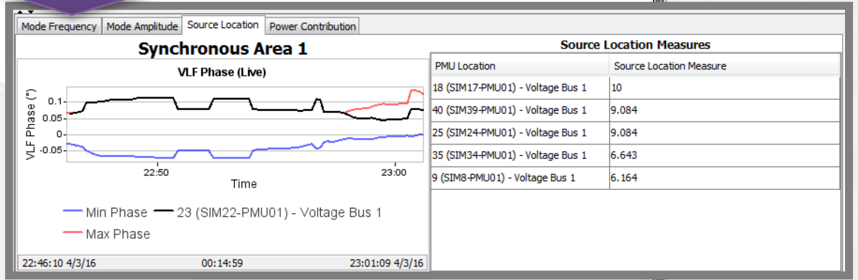
Frequency band sorting to single-out key modes

Alarms on high amplitude

Oscillation **sources & sinks** shown as **Colour gradient map:** fast, intuitive

Detailed identification: source location charts, tables & power flow contributions





PMU Location	Source Location Measure
18 (SIM17-PMU01) - Voltage Bus 1	10
40 (SIM39-PMU01) - Voltage Bus 1	9.084
25 (SIM24-PMU01) - Voltage Bus 1	9.084
35 (SIM34-PMU01) - Voltage Bus 1	6.643
9 (SIM8-PMU01) - Voltage Bus 1	6.164

Frequency and **Amplitude** charts

Results stored for later review

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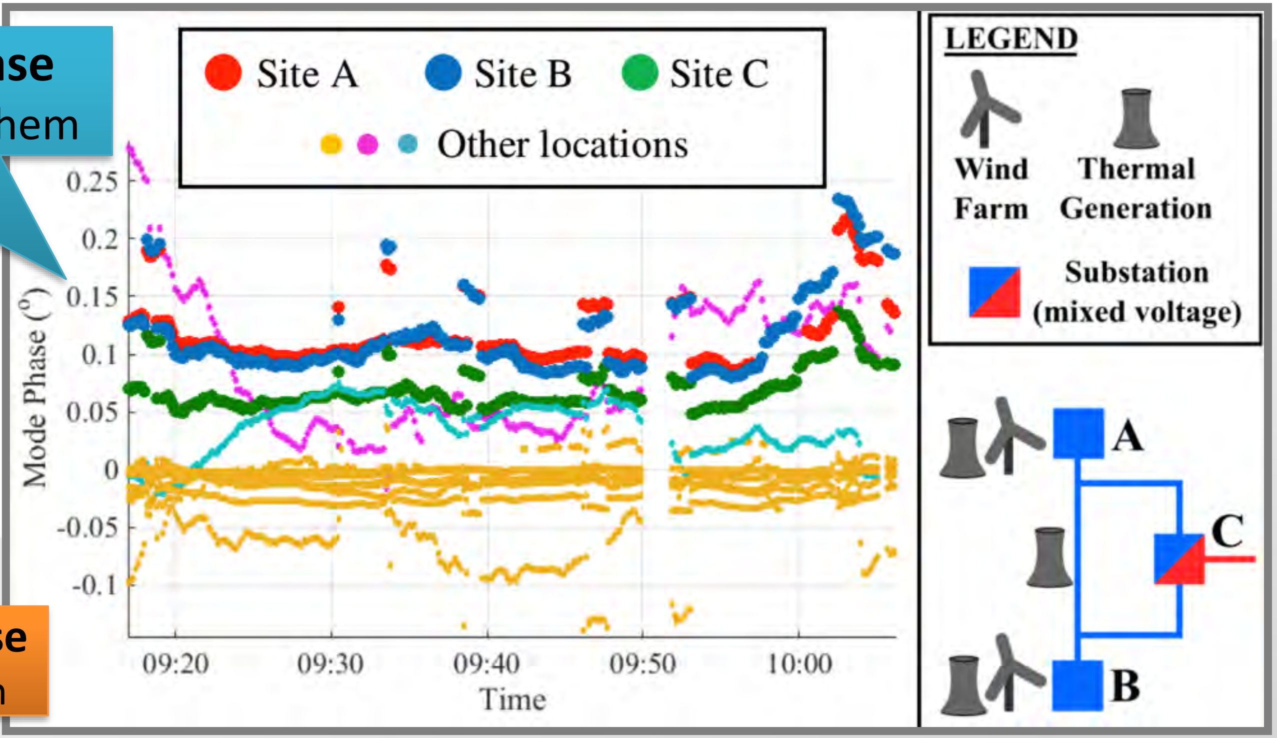
Oscillations: VLF & LF

***Initial Learning:** Case Study – VLF Monitoring & Source Location*

- **0.035-0.045Hz common mode** regularly detected in GB
- **Mostly well behaved**, but **some sustained oscillations**
- **Source location applied offline**

Sites A & B leading phase
Suggests source between them



Effective & efficient response
Targeted action & investigation

Oscillations: VLF & LF

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LF Source Location

Additional analysis & display for existing LF module

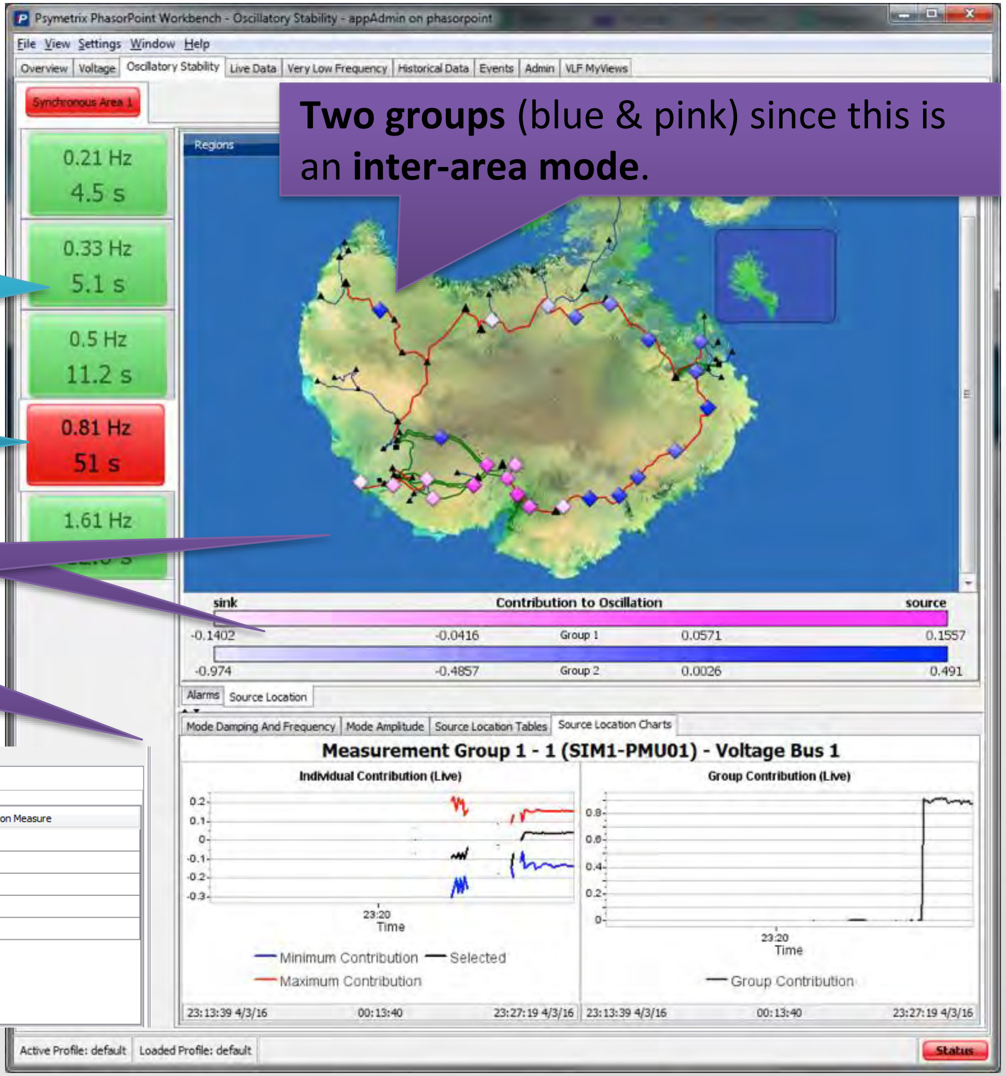
Frequency band sorting to single-out key modes

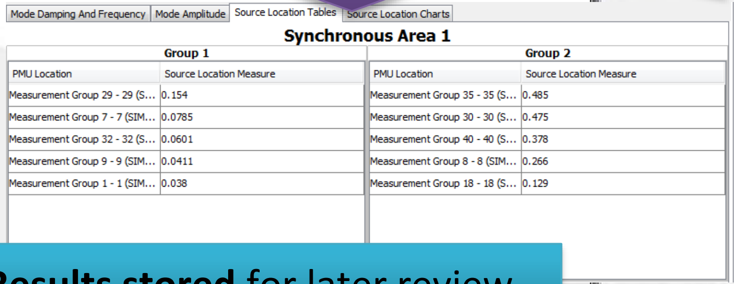
Alarms on high amplitude / poor damping

Oscillation **sources & sinks** shown as **Colour gradient map:** fast, intuitive

Detailed identification Source location charts and tables

Two groups (blue & pink) since this is an **inter-area mode**.





Mode Damping And Frequency | Mode Amplitude | Source Location Tables | Source Location Charts

Synchronous Area 1

Group 1		Group 2	
PMU Location	Source Location Measure	PMU Location	Source Location Measure
Measurement Group 29 - 29 (S...	0.154	Measurement Group 35 - 35 (S...	0.485
Measurement Group 7 - 7 (SIM...	0.0785	Measurement Group 30 - 30 (S...	0.475
Measurement Group 32 - 32 (S...	0.0601	Measurement Group 40 - 40 (S...	0.378
Measurement Group 9 - 9 (SIM...	0.0411	Measurement Group 8 - 8 (SIM...	0.266
Measurement Group 1 - 1 (SIM...	0.038	Measurement Group 18 - 18 (S...	0.129

Results stored for later review

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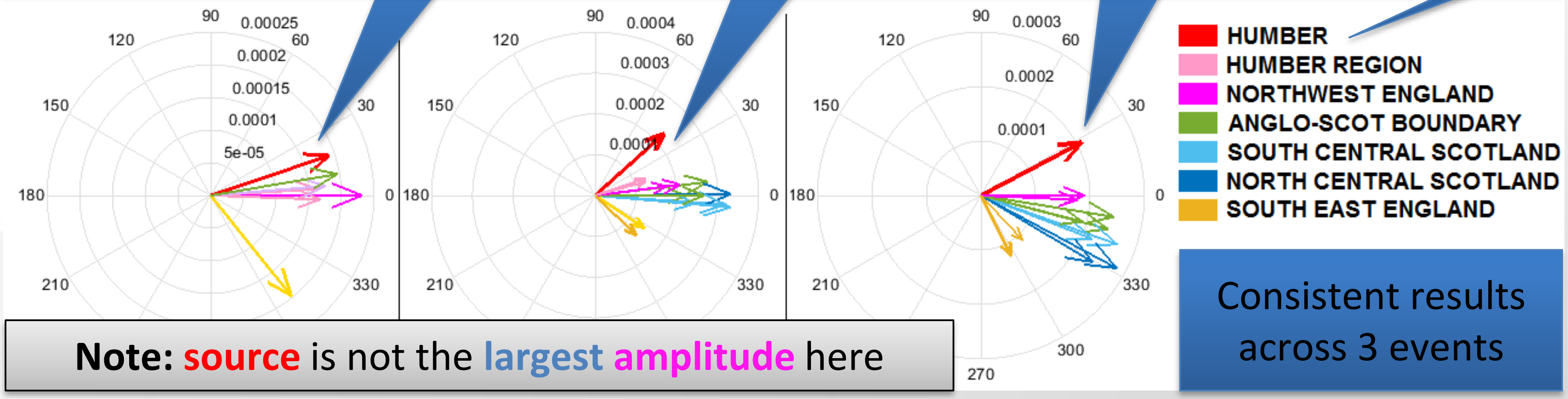
VISOR Project: Visualisation of real time system dynamics using enhanced monitoring

Oscillations: VLF & LF

***Initial Learning:** Case Study – LF Source Location*

- **0.7-0.8Hz mode**: previously observed but difficult to diagnose.
  Not <u>presently</u> an issue
- **Source location was applied offline**
  Provided useful results, based on available measurements

Leading oscillation phase = source: results suggest generation-rich Humber area



Note: source is not the largest amplitude here

Consistent results across 3 events

Effective & efficient response
Targeted action & investigation

Operational procedures
knowledge & understanding

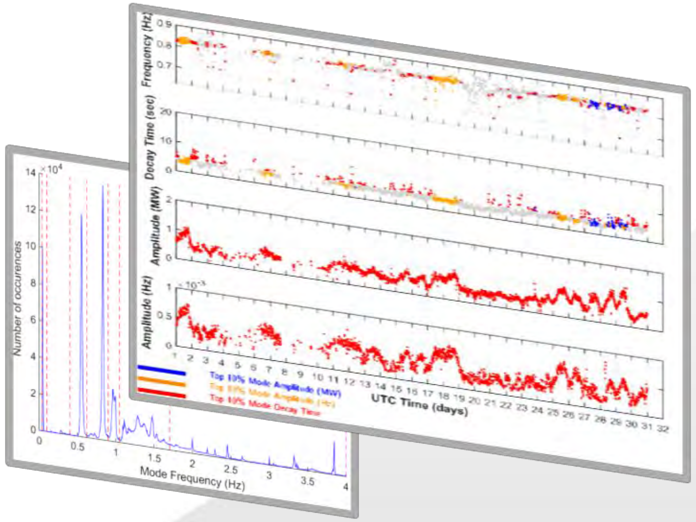
Mitigate risk
Preparedness for events

Oscillations: VLF & LF

***Initial learning:** Oscillatory behaviour reviews*

- **Annual reviews** and **monthly reviews** conducted
- **Major modes characterised**

Identify contributors	**Effective & efficient response** Targeted action & investigation
Operational procedures knowledge & understanding	**Mitigate risk** Preparedness for events
Model validation	**Mitigate risk** of model errors **Confidence to reduce constraints**
Baseline behaviour	**Optimised alarms** Tuned thresholds and frequency bands



- **Other modes identified**
  - Local or limited-occurrence
  - Some further investigations
  - Others noted for future reference

Early warning of potential problems → **System security** | **Compliance** | **Maintenance**

- **Learning from this will inform future processes:**
  Oscillations reports (content, frequency, audience), follow-up processes, etc.

DISTURBANCE MANAGEMENT

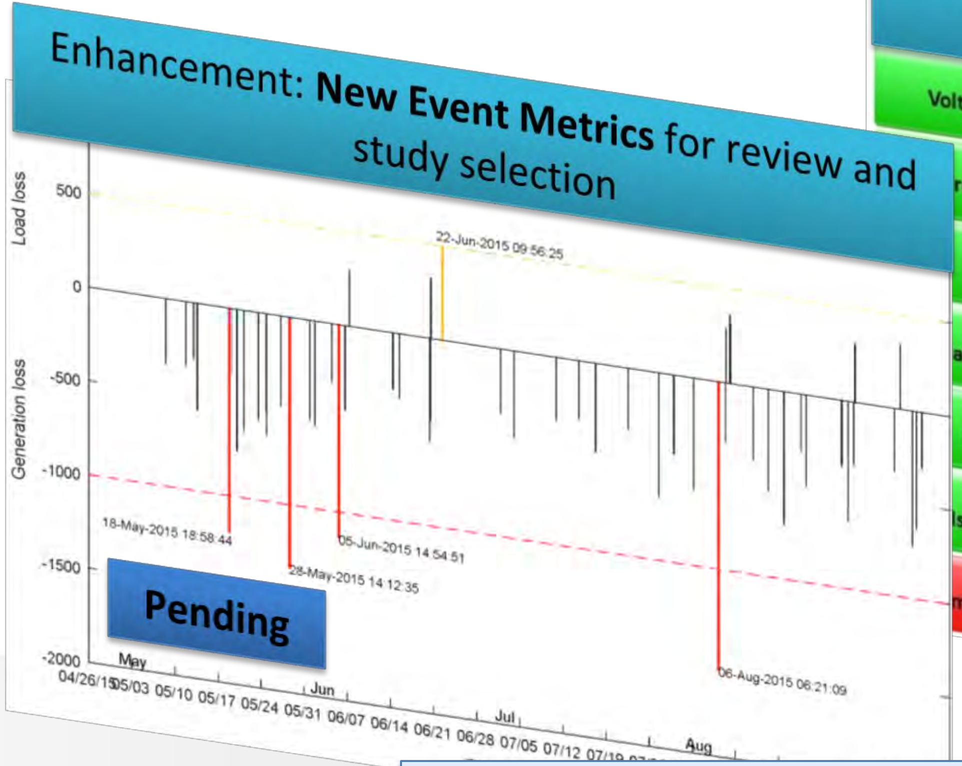
Disturbance Management

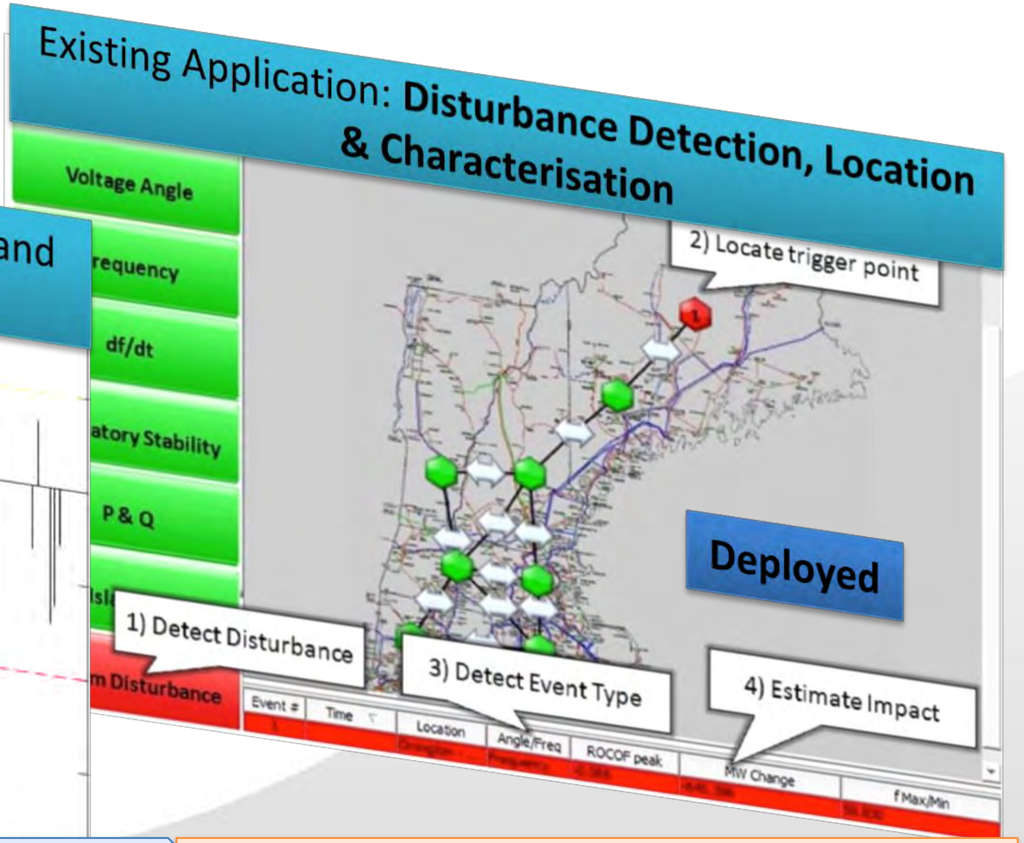
Why use WAMS in Disturbance Management?

- Modern **SCADA & DFR** driven **automated analysis** can be **quick to diagnose faults**
- **However TOs do not have visibility** of external faults
  - Risk of further events
  - *“Will this affect my network?”* e.g. heavier loading
- **Also, need to easily identify significant disturbances** for studies and reviews
  - **Not just faults:** e.g. breaker opening / closing on a stressed network
  - **Metrics for comparison:** dynamic impact (e.g. ringdown) and static (e.g. voltage dip)

Disturbance Management

What VISOR is doing



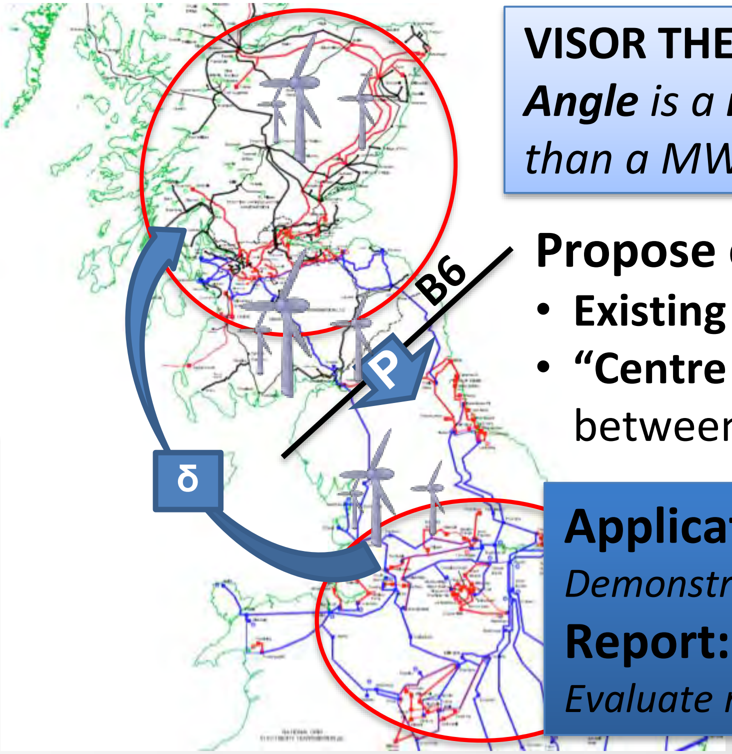


Event information without SCADA	**Improved risk awareness (TO)**
Identify significant events (not just faults)	**More Efficient & effective model validation**
	Highlight potential plant/model issues

POWER-ANGLE BOUNDARY CONSTRAINT

Power-Angle Boundary Constraint

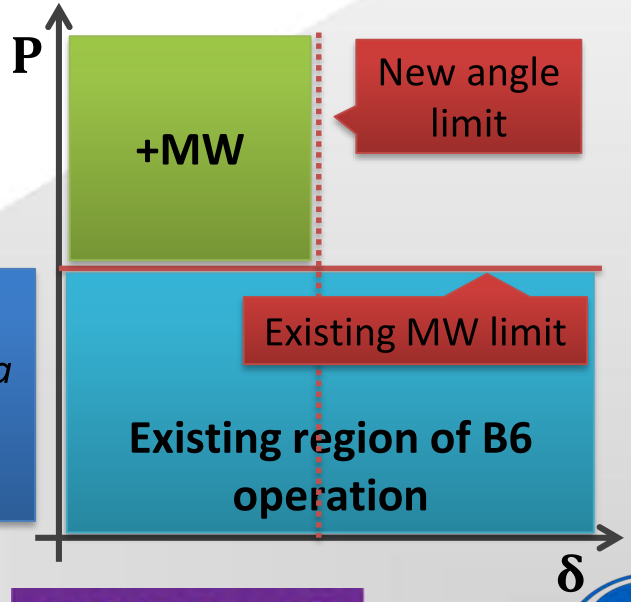
- *Scotland-England "B6" Boundary* currently limited by **Transient Stability**, **expressed as** a **MW limit**
- **Large amount of wind generation** especially close to boundary
  Adds to MW flow but less effect on stability



VISOR THESIS
***Angle** is a **more direct measure** of distance to **stability limit** than a MW cut-set*

Propose composite constraint:
- **Existing MW limit**
- **"Centre of Angle" difference**
  between Scotland and N. England

Application: Deployed
Demonstrate real-time CoA on real data
Report: 2016
Evaluate reliability & robustness



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ROBUST LINE PARAMETER ESTIMATION

Line Parameter Estimation (LPE)

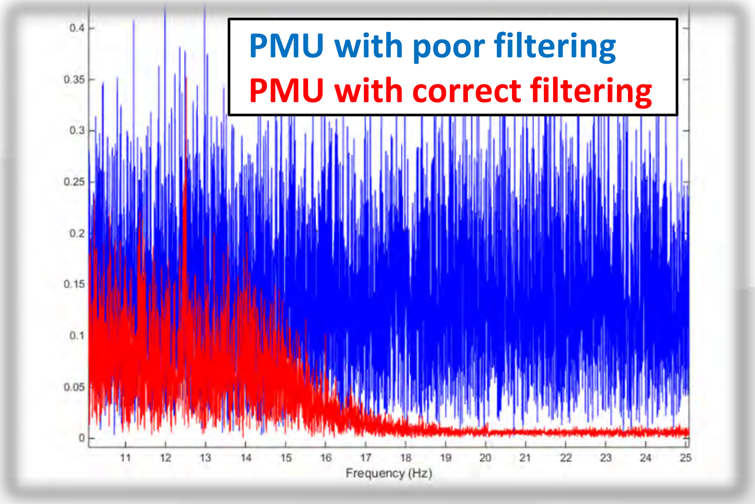
Motivation:

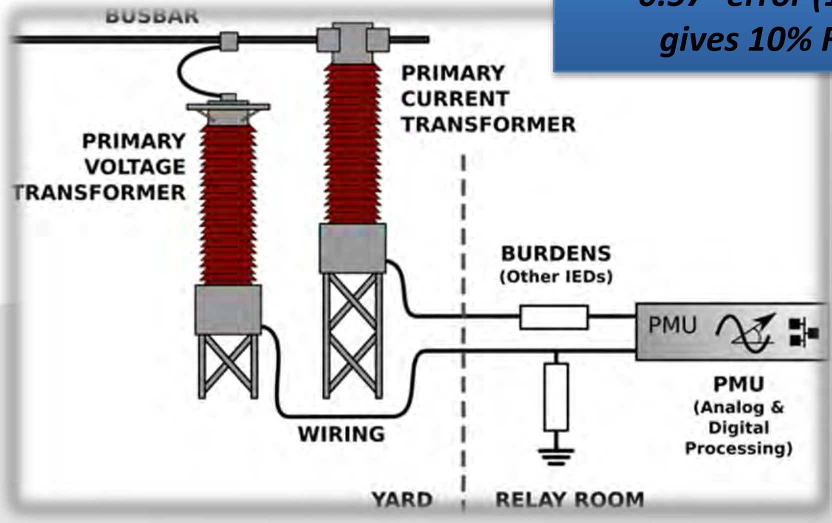
- System limits are determined using assumed parameters
- Measurement-based estimation of parameters provides:
  Validation of network models, visibility of parameter variation: scope for dynamic ratings

Theory: V & I phasors from both line ends allows LPE

Challenge: Compensating for measurement errors
*Primary CT/VT, wiring, PMU – noise **and** systematic*

For a typical line, X/R ≈10, 0.57º error (1% TVE) gives 10% R error





Line Parameter Estimation (LPE)

Solution: Robust Line Parameter Estimation

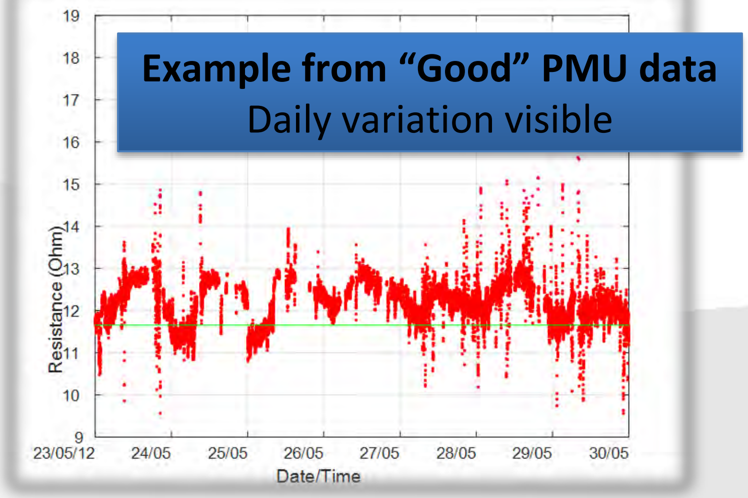
To mitigate errors where possible

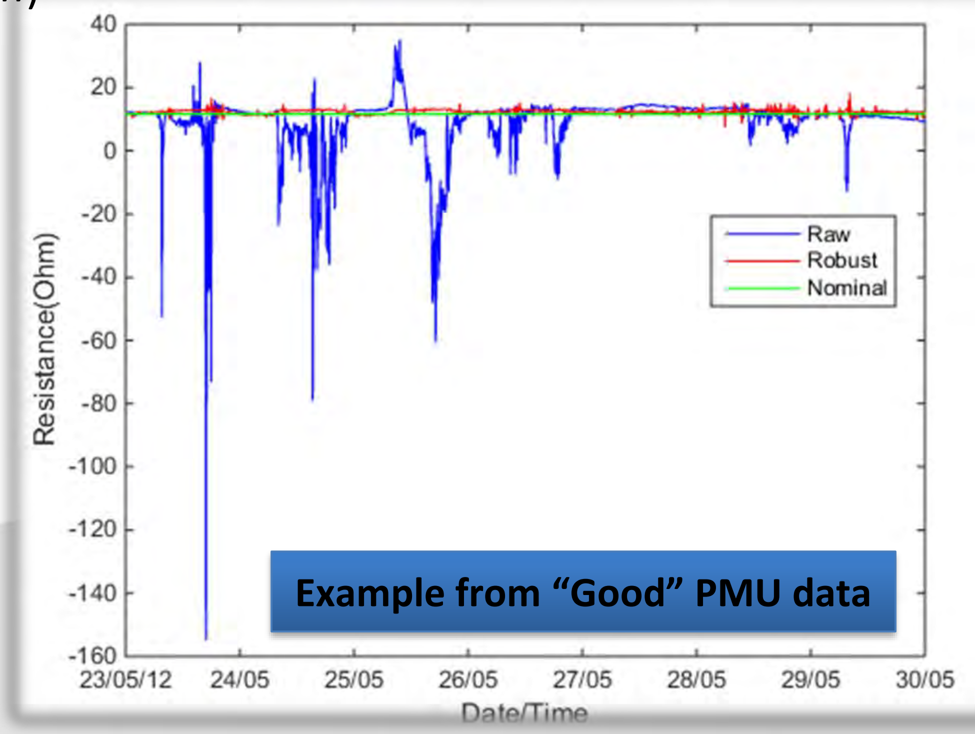
Results so far: Initial study & report – offline Robust LPE

- Highlighted impact of data quality issues *(clock drift, filtering)*
- Improvement on raw calculation (*~90% SD reduction*)

Next steps:

- Robust LPE application
- Addressing data quality issues





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Conclusions

RIIO NIC NETWORK INNOVATION COMPETITION

VISOR goal: *to demonstrate WAMS applications & their benefits*

Oscillation Monitoring & Source Location (0.002 – 46 Hz)

- **Very Low Frequency** – **Application**
- **Electromechanical & Control** – **+ Source Location Feature**
- **Sub-Synchronous** – **Application**

System Disturbance Management

- **Detection, Location & Characterisation**
- **+ Additional Event Metrics**

Power-Angle Boundary Display

- **Prototype**
- **Evaluation Report**

Robust Line Parameter Estimation

- **Offline Analysis & Report**
- **Application**

Power System & WAMS Performance Reviews *Data Quality, Oscillations…*

- **2014**
- **2015**
- **2016**

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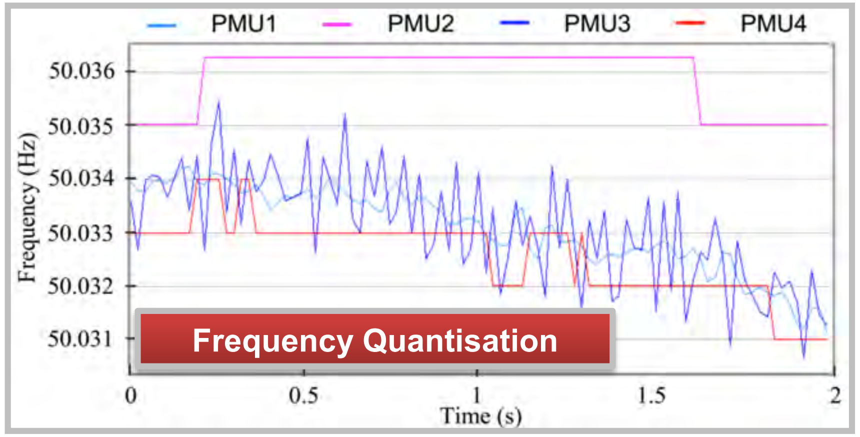
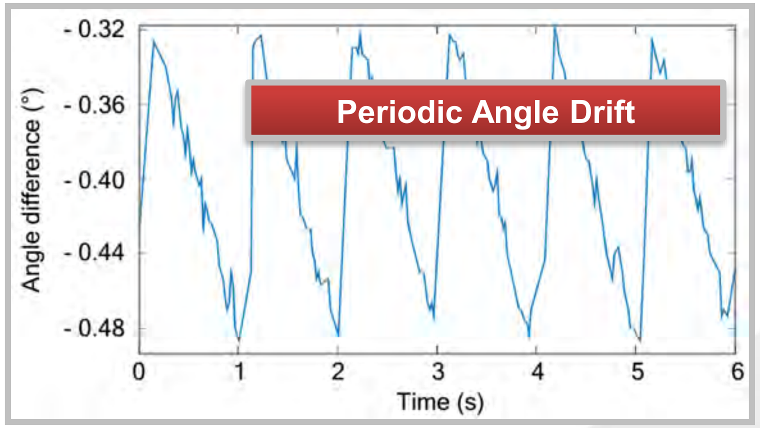
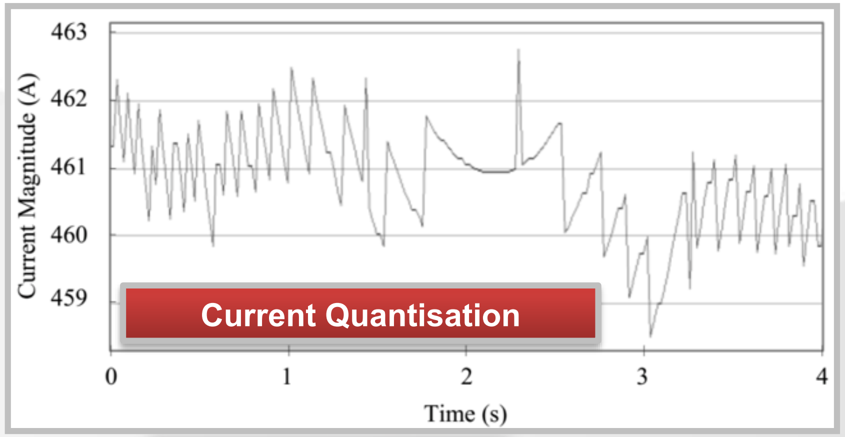
WAMS INFRASTRUCTURE

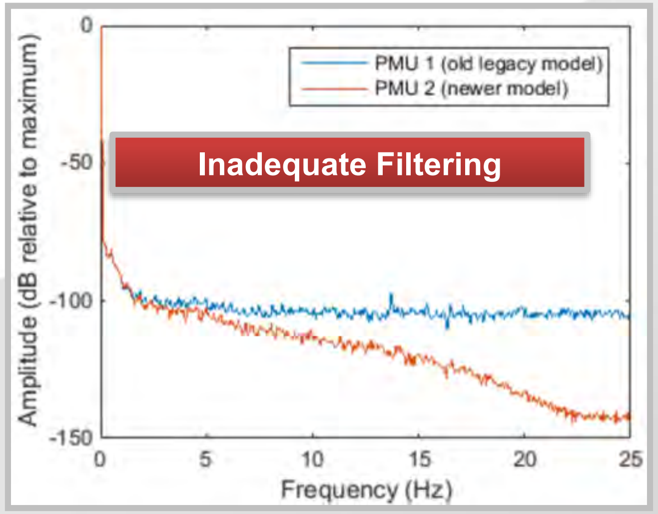
Assessing GB WAMS Performance

VISOR integrates separate **legacy systems** incorporating **older PMUs**, as well as **deploying new devices**. As a result, **WAMS Performance assessment** has been important.









VISOR Stakeholder Event 2016

IET Savoy Place, London, 6 July 2016

The University of Manchester

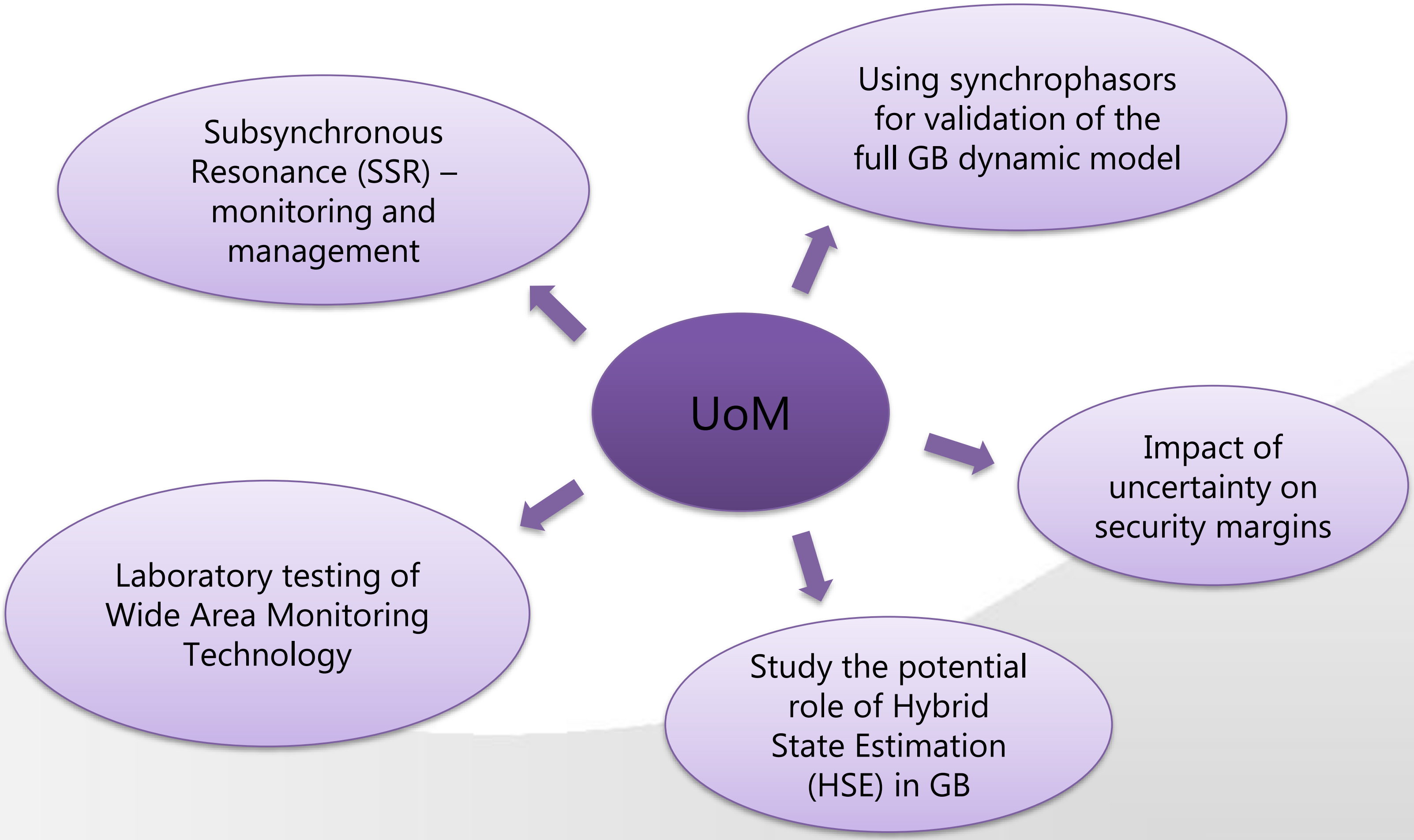
VISOR Stakeholder Engagement

The University of Manchester
Research Activities and Findings

Peter Wall
Papiya Dattaray
Zhaoyang Jin
Prof. Vladimir Terzija (The University of Manchester)
peter.wall@manchester.ac.uk

Helicopter View – Study Areas

RIIO NIC NETWORK INNOVATION COMPETITION



Focus: use offline simulations and WAMS data to perform work with lower technical readiness

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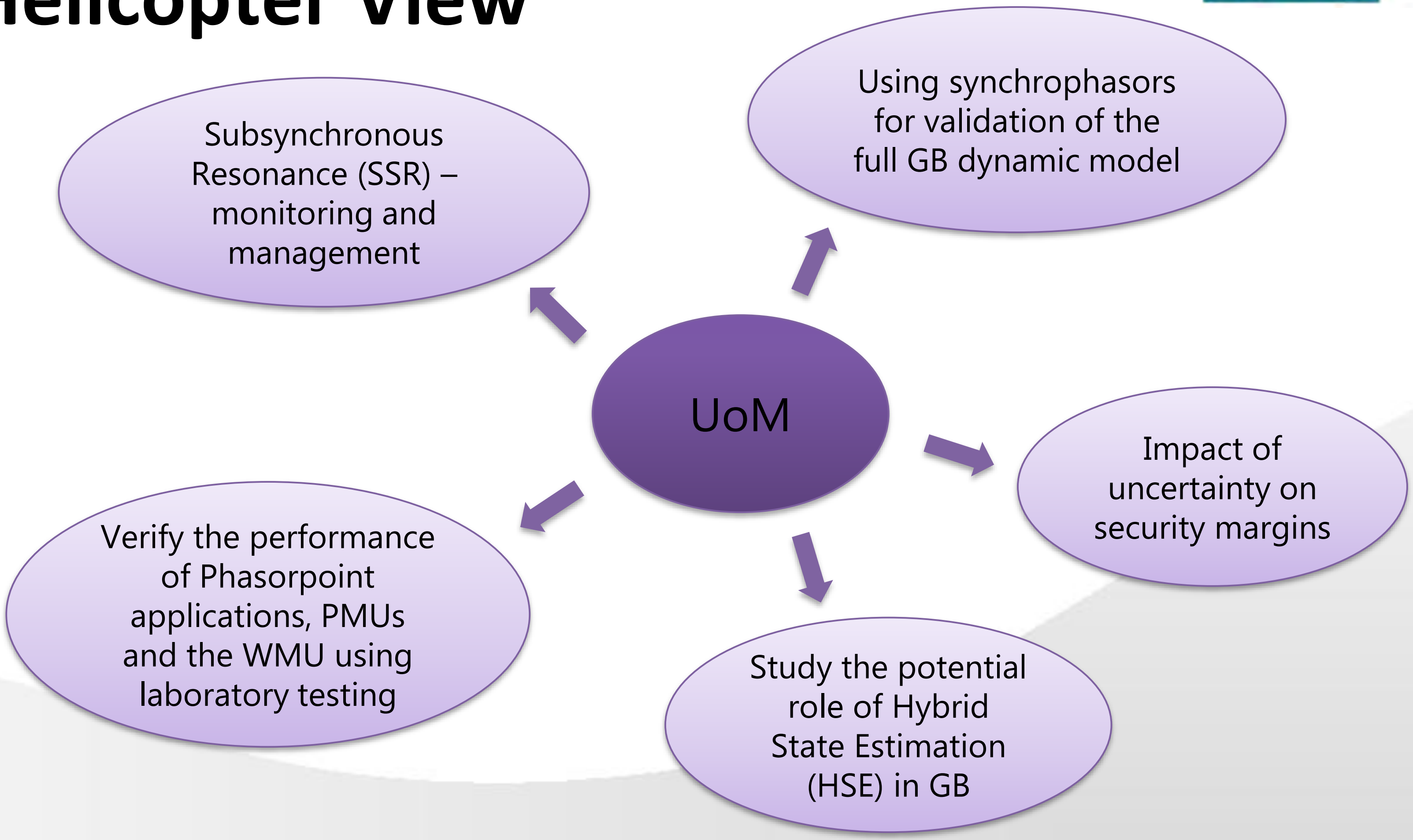
VISOR Project: Visualisation of real time system dynamics using enhanced monitoring

Helicopter View



Subsynchronous Interactions

- Inter-area oscillations – less than 1 Hz
- Local plant oscillations – 1 to 2 Hz
- Intra-plant oscillations – 2 to 3 Hz
- Control mode oscillations
- Torsional mode oscillations – 10 to 46 Hz

Bruce English, "Reactive Power Solutions, Subsynchronous Oscillations (SSO): Risk Analysis, Protection, and Mitigation Techniques", GE Digital Energy. Available: http://www.slideshare.net/GEEnergyConsulting/v5-ssr-ssciwebinar

Hole burnt in shaft after SSR event: Mojave desert, USA 1970

Exchange of Energy between system components

Subsynchronous Resonance (SSR): Series Compensation vs Generator Shaft

Subsynchronous Torsional Interactions (SSTI): Power Electronic Controls vs Generator Shaft

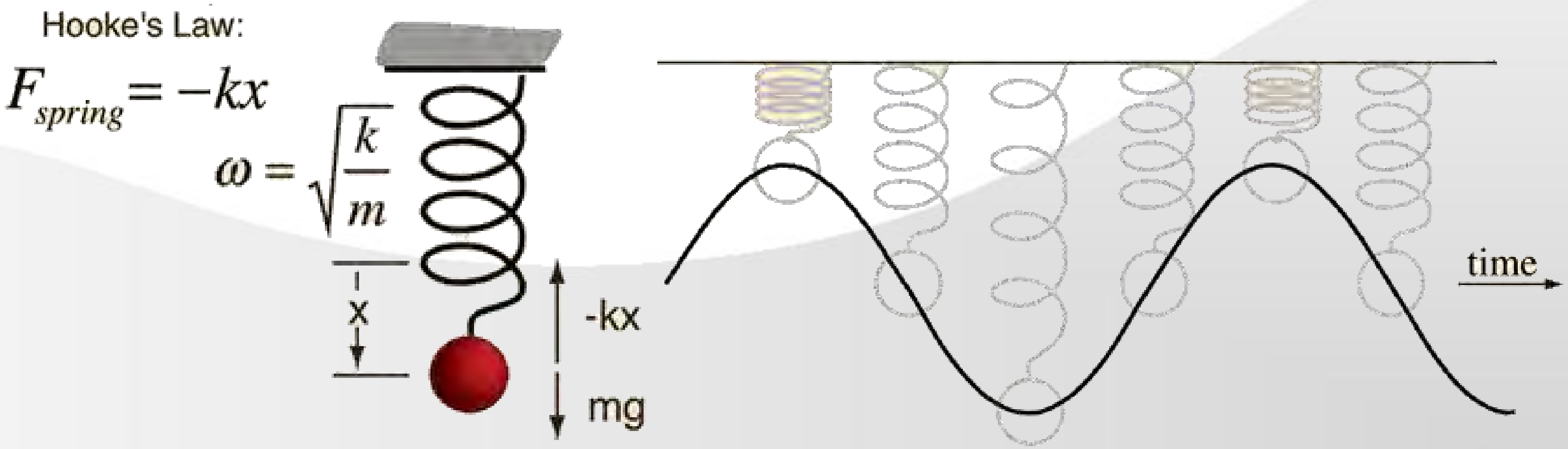
Subsynchronous Control Interactions (SSCI): Series Compensation vs Power Electronic Controls

Subsynchronous Resonance

- Exchange of energy between Generator Shaft and Fixed Series Compensation
- Unstable exchange will result in increasing power flow and voltage

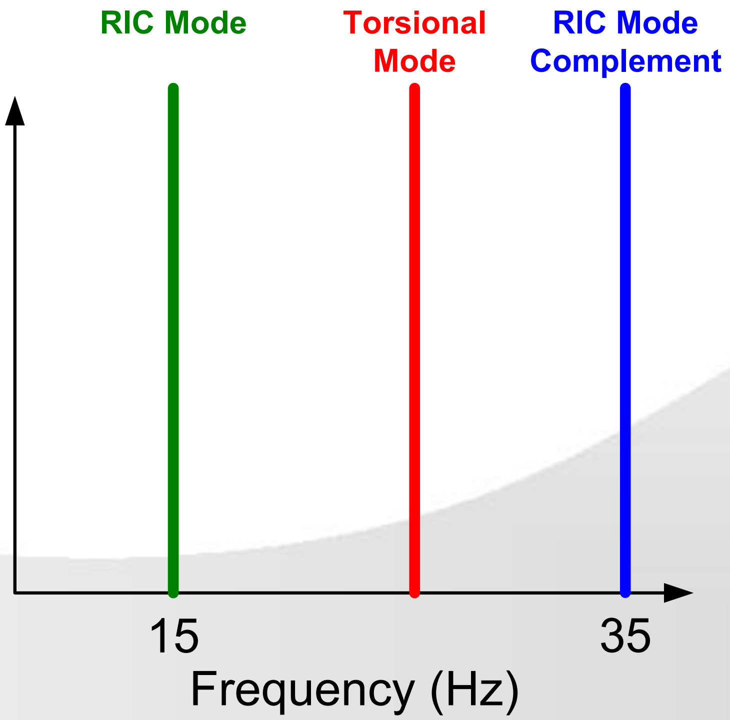
Fixed series compensation introduces a natural resonant subsynchronous mode at $1/\sqrt{LC}$

- Why do they exchange energy?
  - Natural resonant modes interact with one another
  - If this interaction is constructive and poorly damped, it will be unstable



Subsynchronous Interaction Band

- When studying SSR the electrical mode 'complement' should be used
  - 15 Hz electrical mode appears to the generator shaft as 35 and 75 Hz modes



Subsynchronous Resonance

- Under which conditions, exactly, will SSR occur in a power system
- Can we define a Subsynchronous Interaction Band (SRIB) that defines the exact range of frequencies for which a certain mode will experience unstable SSR

Constructive

Poorly damped

How Close is too Close?

Coincident

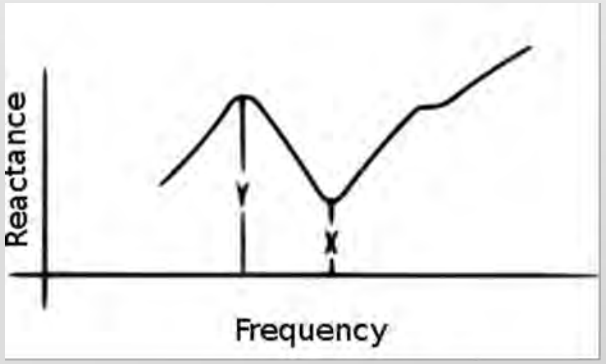
Interact

Only thing close to a band in the literature

Frequency Scan

5% reactance dip within 3 Hz of a 50/60 Hz complement of the modal frequency [1].

$$\%dip = \frac{(Y - X)}{Y} \times 100$$

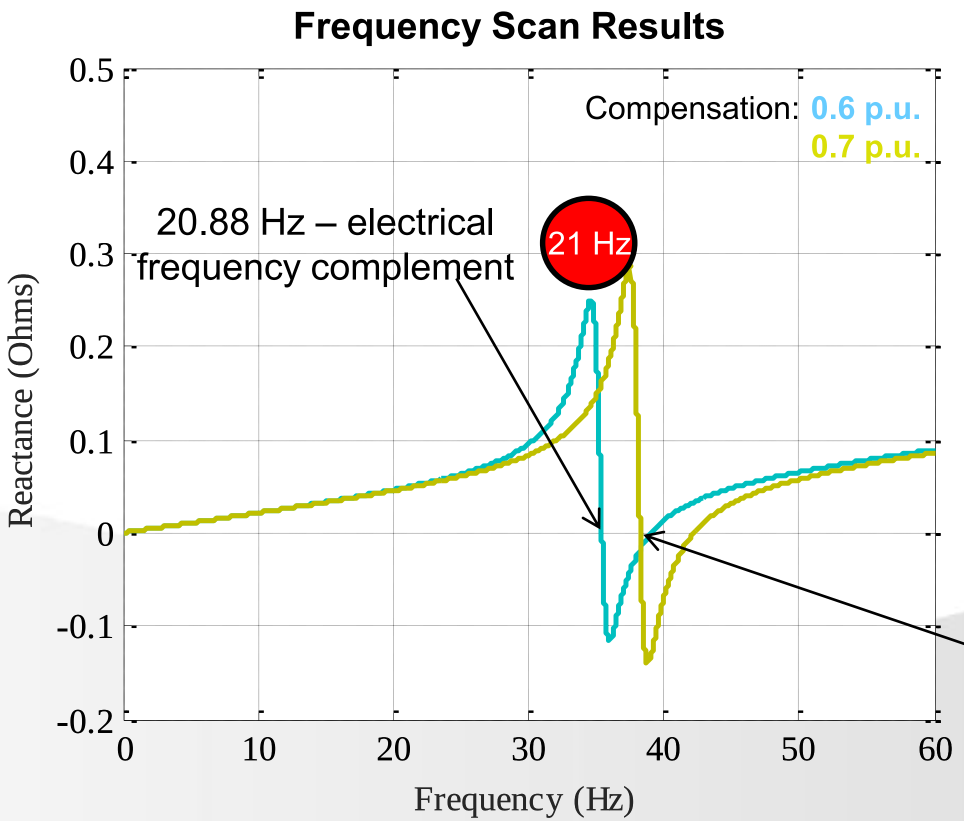


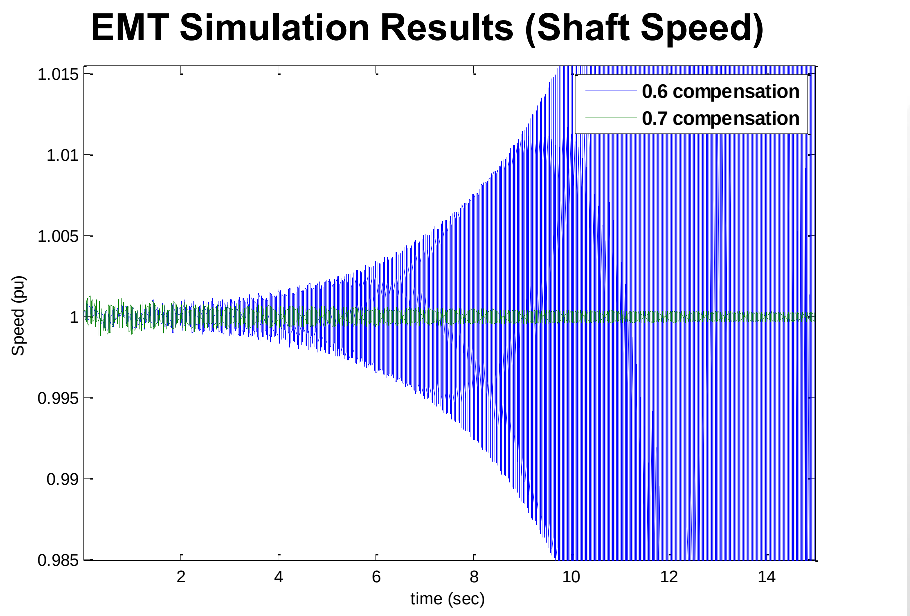
[1. B. L. Agrawal and R. G. Farmer, "Use of Frequency Scanning Techniques for Subsynchronous Resonance Analysis," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-98, no. 2. pp. 341–349, 1979]

Subsynchronous Interaction Band

Two of the dips are greater than 5 % and within 3 Hz of a torsional mode complement

However, transient response is profoundly different





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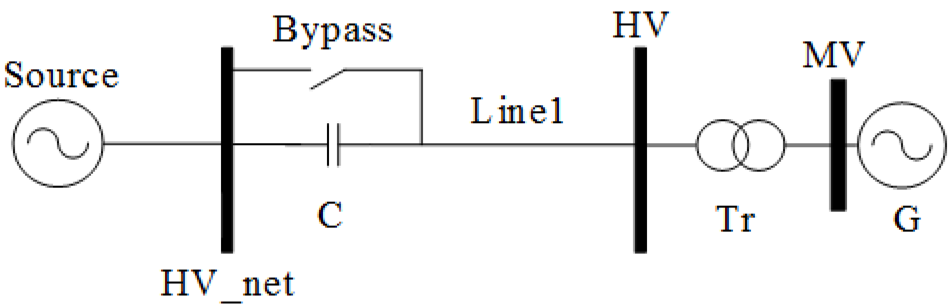
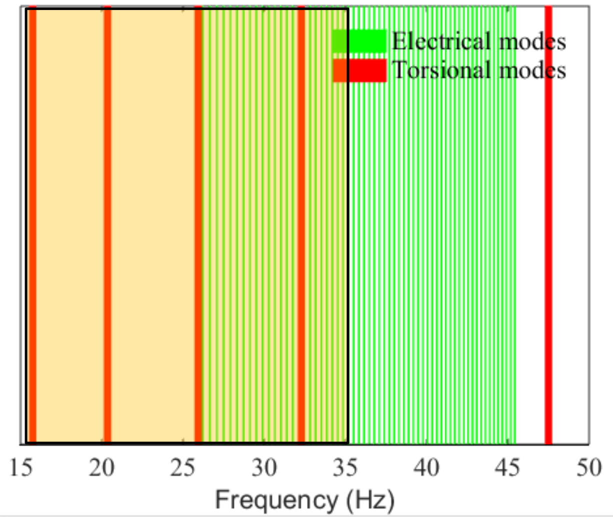
Subsynchronous Interaction Band

- EMT simulations and undamping calculations used to identify the SRIB for the IEEE First Benchmark System



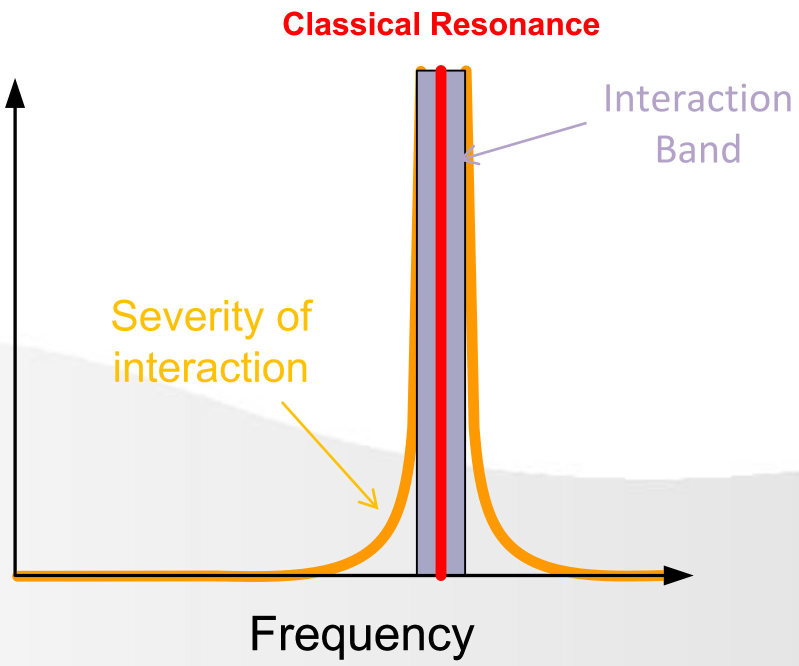


- Compensation level varied from X to Y % to vary the electrical mode complement
- Interaction simulated in DIgSILENT Powerfactory and analysed using FFT

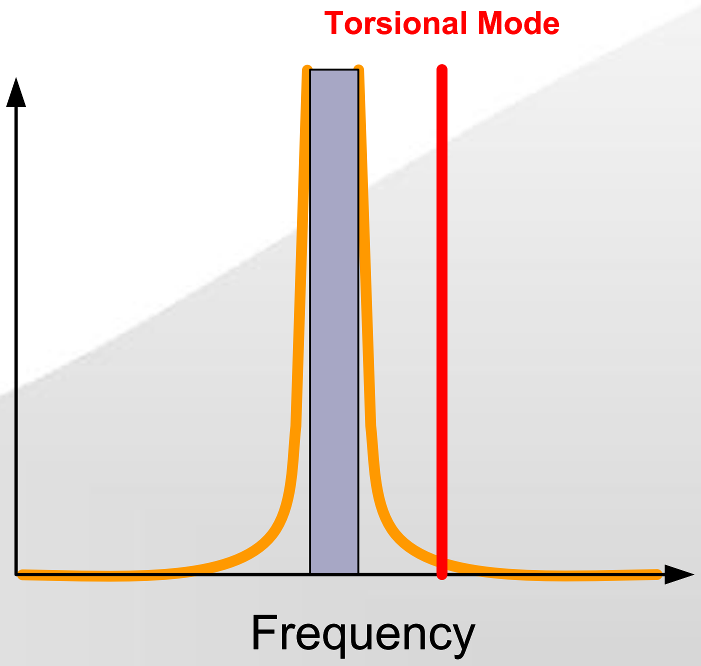
Subsynchronous Interaction Band

- SRIB describes the range of frequencies for which an unstable interaction occurs

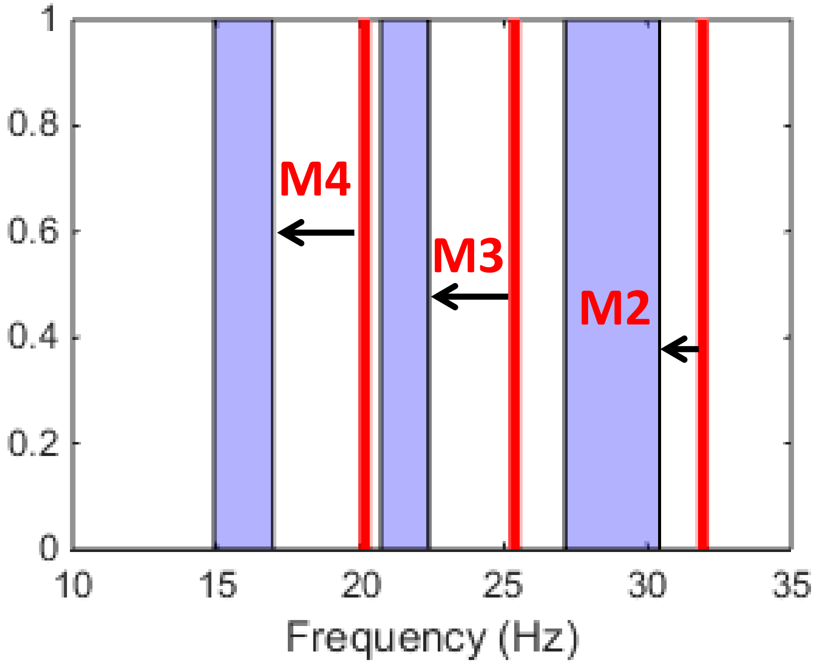
For Example



Actual Result



Subsynchronous Interaction Band



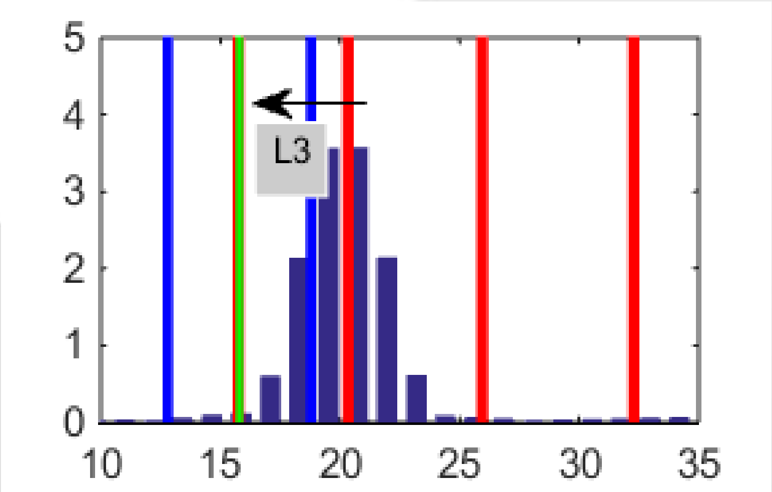
Mode not in its own SRIB

SRIB of mode is closer to other modes

Width of the SRIB is not constant

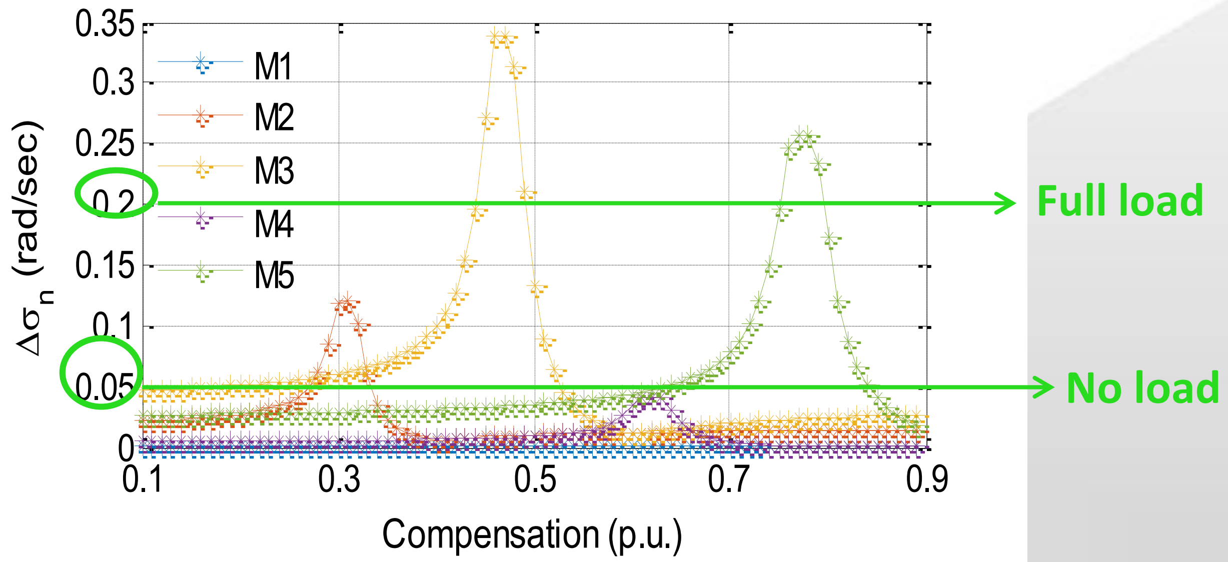
The SRIB of lower frequency modes is further away from the mode

Why?



Subsynchronous Interaction Band

- For Torsional Interaction to occur:
  - Generator Mechanical Damping
    Good thing, but tends to be low Increases with machine loading
  - Electrical Undamping
    Bad thing, and it varies with compensation and topology



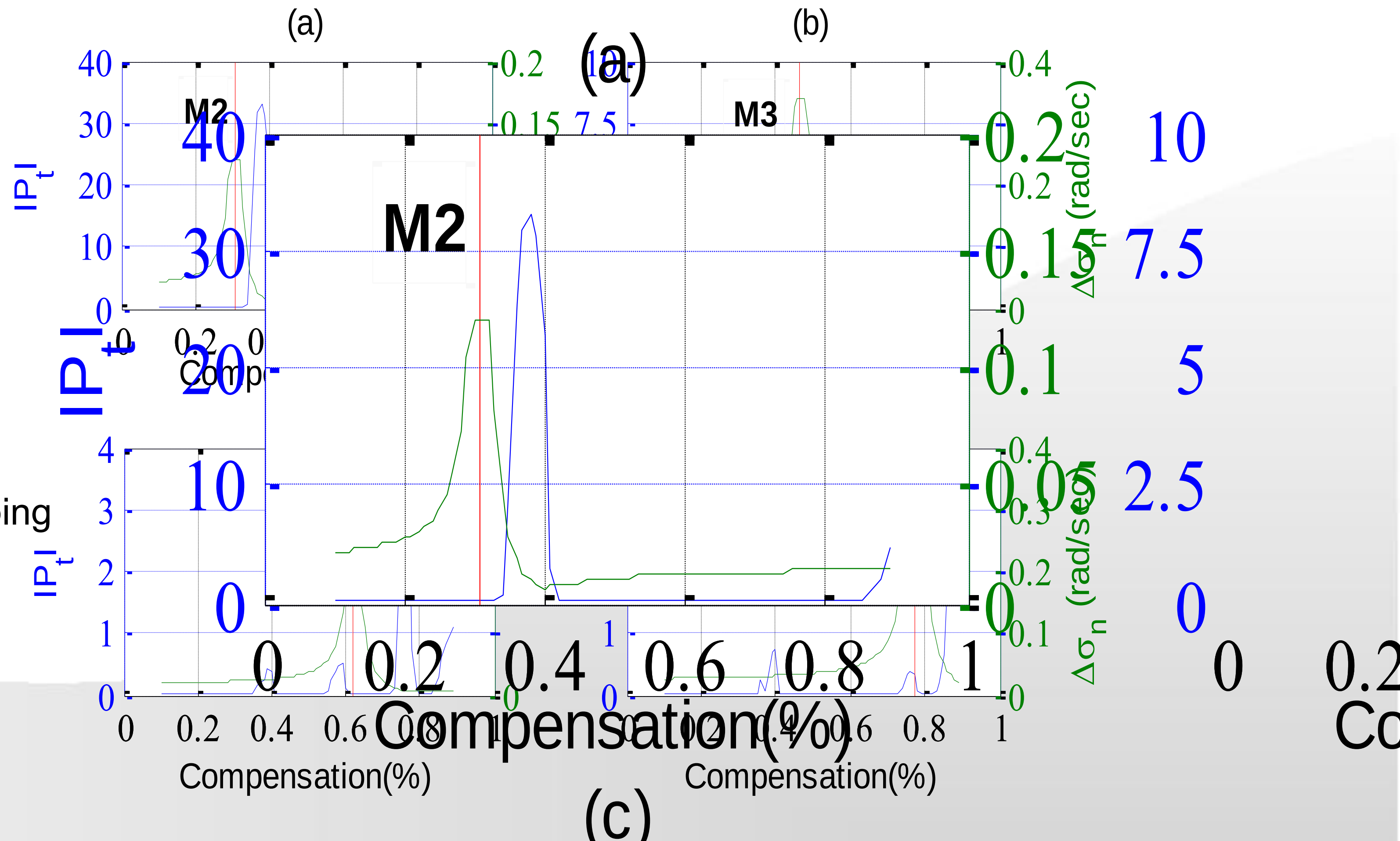
Subsynchronous Interaction Band

Peak SSR does not coincide with the peak undamping

Unstable SSR does not occur for the peak undamping

Unstable SSR is a non linear function of proximity and damping

What is this Function?



Load Modelling for SSR Studies

RIIO NIC NETWORK INNOVATION COMPETITION

- EMT studies to define the SRIB used a 6 mass machine model
- The load in the simulations was modelled as........ nothing
- SSR studies use no load models or Z load models

Z load – Load modelled as a resistor where $P \propto V2$

Is this Approximation Acceptable?

How similar is the dynamic behaviour of a resistor and a direct drive motor or variable speed drive?

- Studied the impact of the load model in the system on the results of SSR studies

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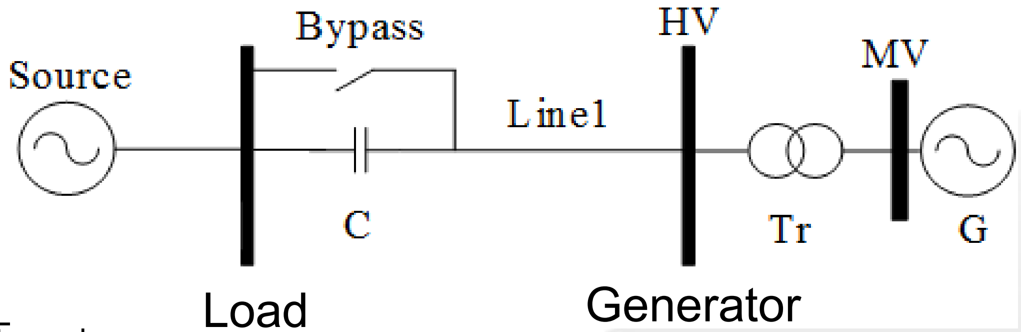
Load Modelling for SSR Studies

- IEEE FBM model was used, load was connected in at bus X and Y in turn
- Study created new aggregated load models for EMT studies in PowerFactory

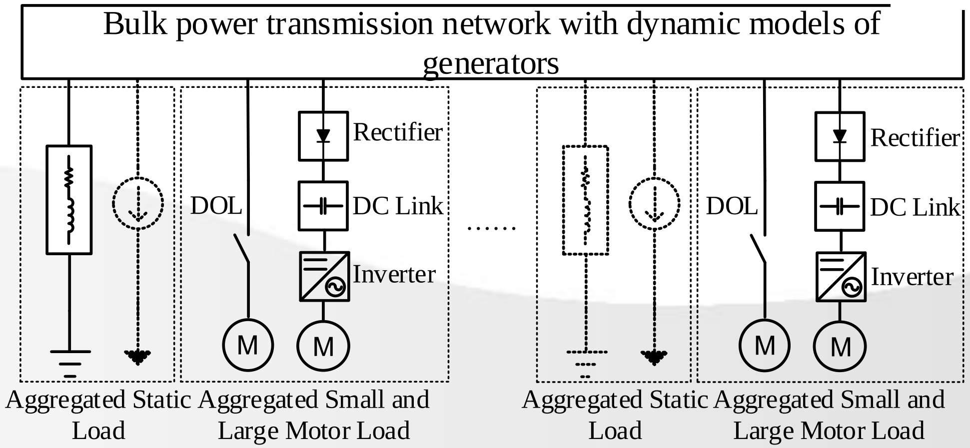
Study Impact of load location

- Load Bus
- Generator Bus



Load Bus

Generator Bus



Aggregation of loads at the transmission level

Study Impact of load composition

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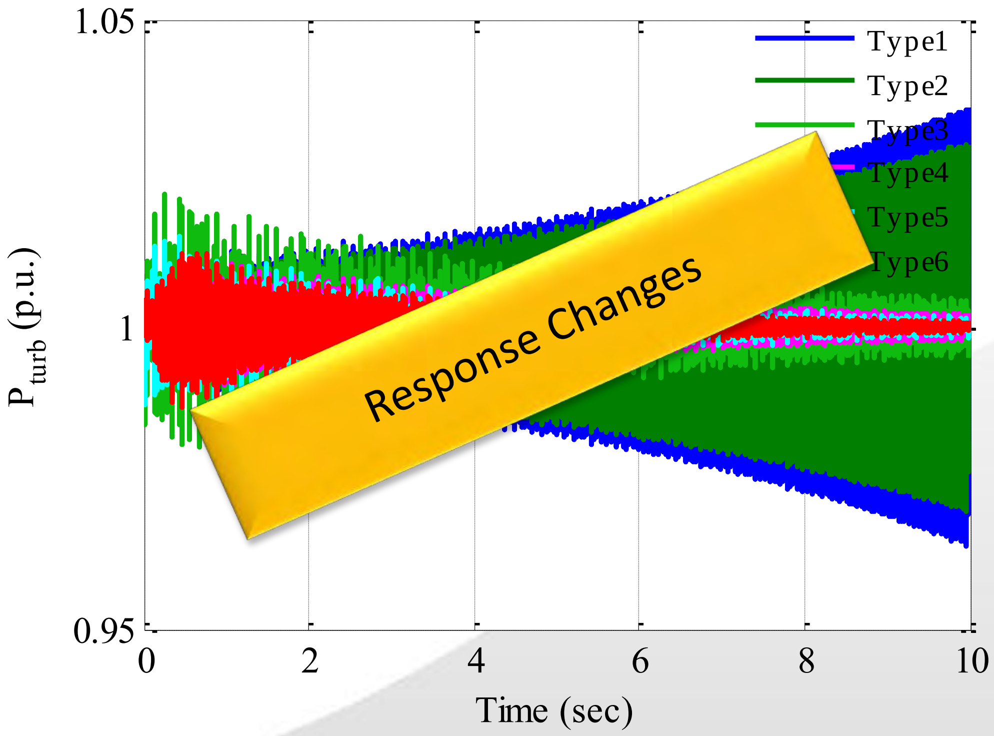
Load Modelling for SSR Studies

Load Type	Description
Type 1	Loads neglected
Type 2	100% Const. Impedance
Type 3	50% DOL and 50% VFD based Motor loads
Type 4	100% DOL connected Motor load
Type 5	30% Const. Impedance 30% Const. Current 40% DOL connected Motor load
Type 6	50% Constant Impedance 50% DOL connected



unstable for Type 1 and 2
stable for Types 3, 4, 5 and 6

Can loads play a role in mitigating SSR?

Conservative results impact decisions

Planning – Location and/or degree of compensation

Operation – reduced use of assets, failure to recognize opportunities and improper alarm settings

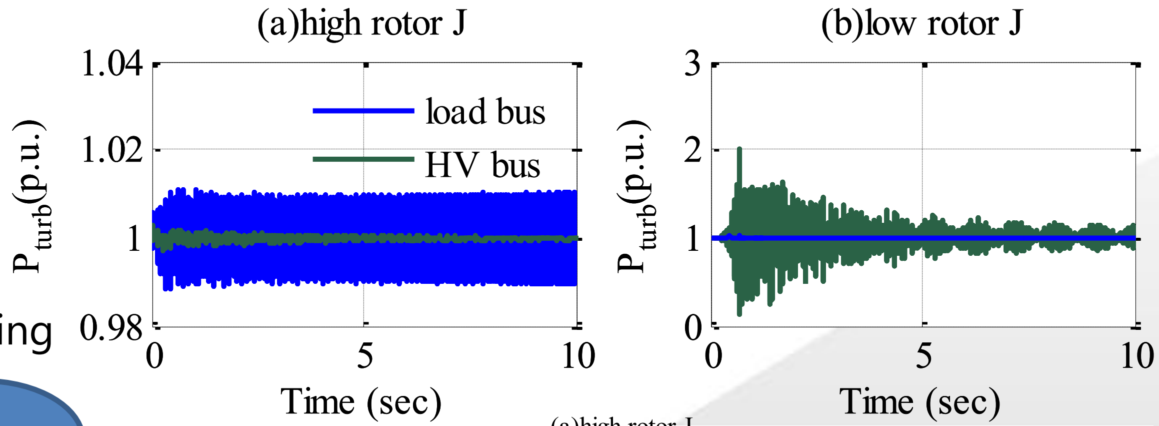
Load Modelling for SSR Studies

An interesting observation was made during this work with regard to the different behaviour of high inertia and low inertia motors

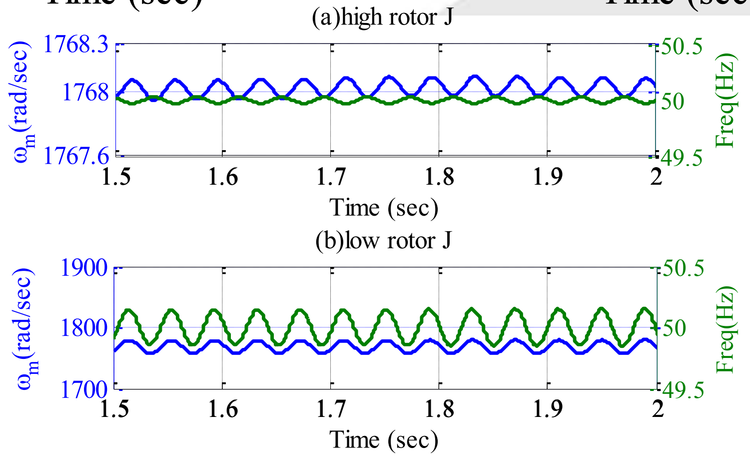
Best damping varies by location

- High Inertia – HV Bus
- Low Inertia – Load Bus

A well placed low inertia motor can be an effective source of damping

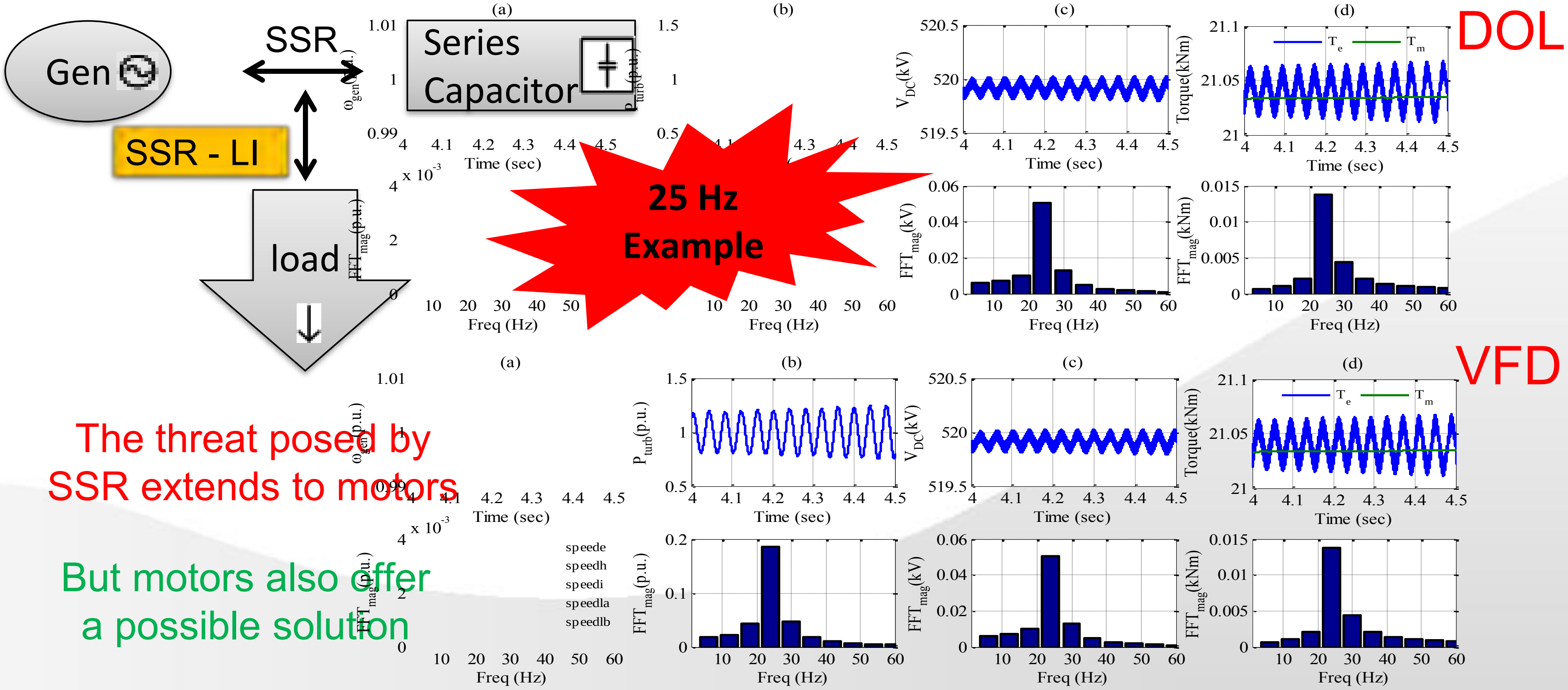


Explore opportunity for novel damping controllers for motors



Subsynchronous Load Interactions

- A new form of interaction was identified: **Subsynchronous Load Interactions**



The threat posed by SSR extends to motors

But motors also offer a possible solution

In the presence of SSR – DOL and VFD loads exhibit sympathetic oscillations

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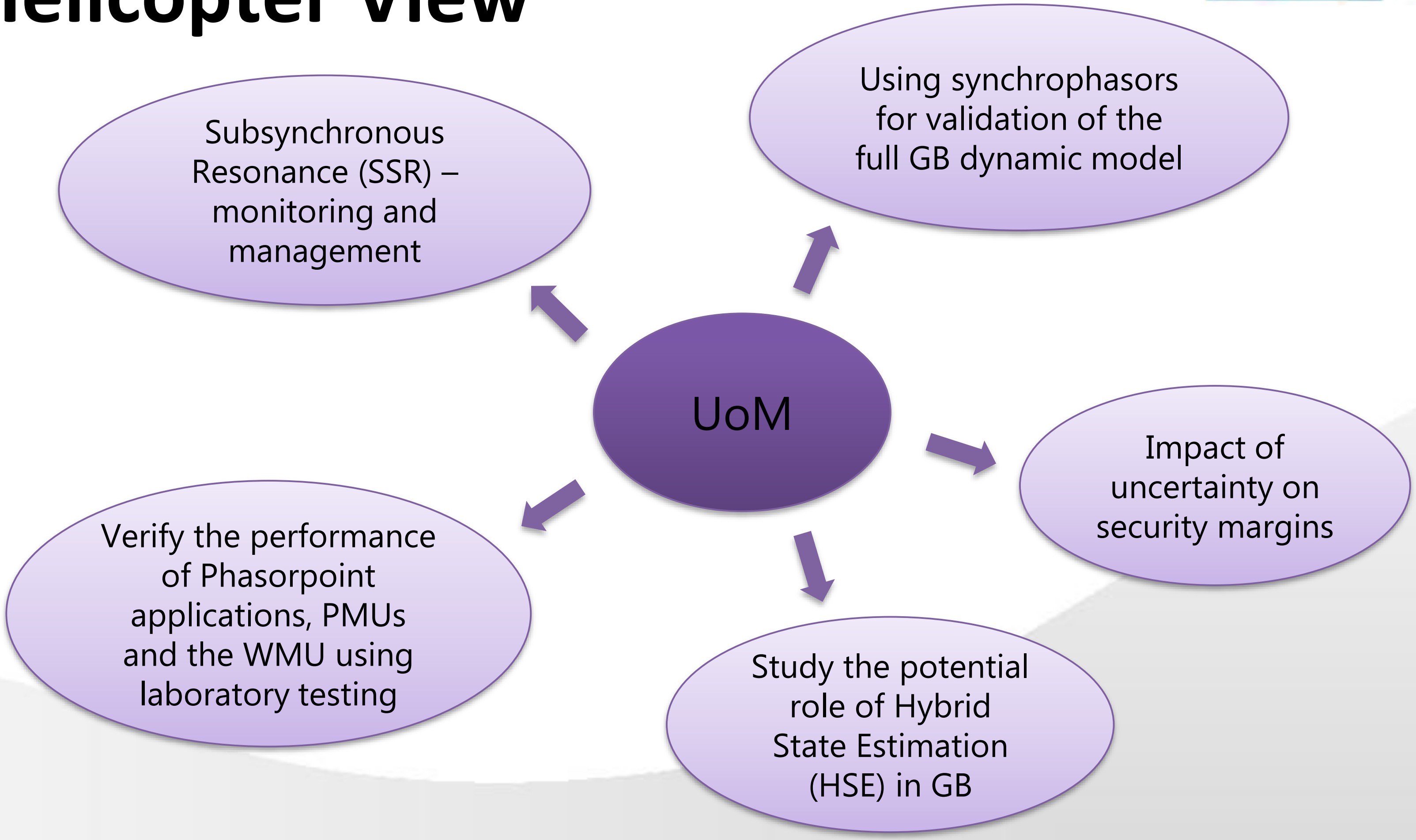
Helicopter View



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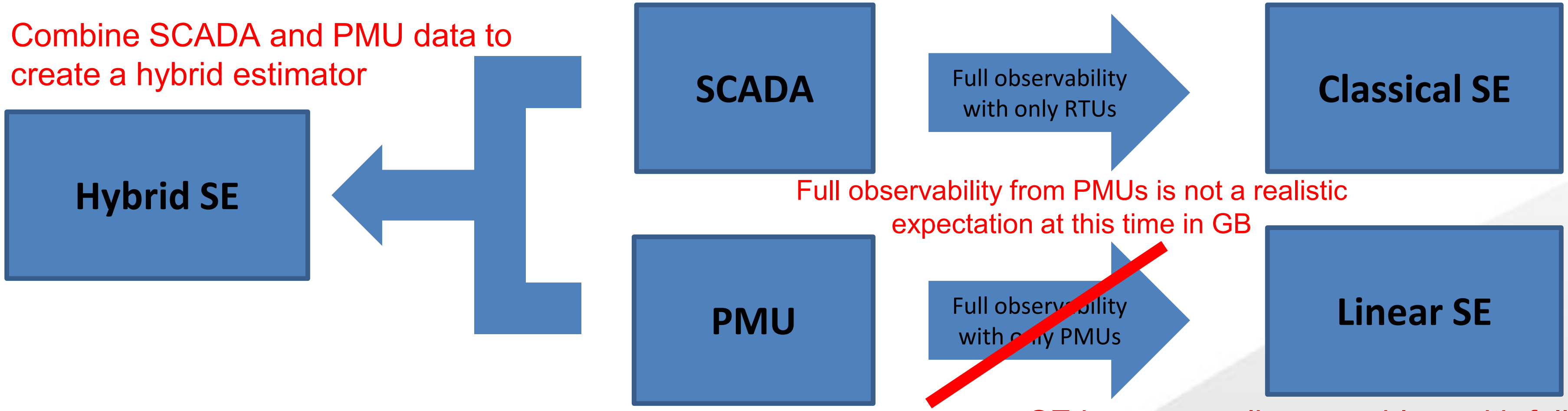
Hybrid State Estimation (HSE)

RTUs produce unsynchronised measurements of Voltage Magnitude and the P/Q flows and injections

SW is a non-linear problem that is solved recursively

Combine SCADA and PMU data to create a hybrid estimator



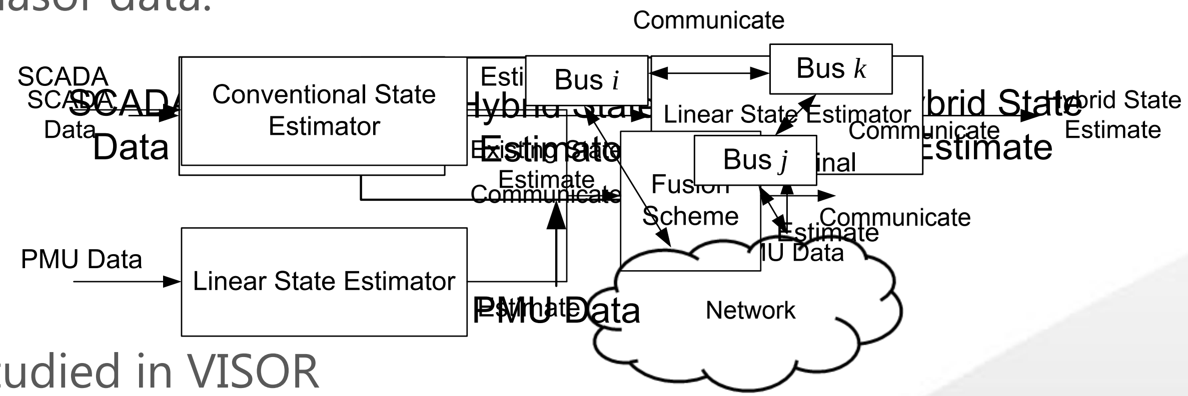
SE becomes a linear problem with full observability from PMUs

PMUs produce synchronised measurements of the system state (voltage and current)

- HSE is a middle ground between classical SE and LSE and helps the system realise the benefits of PMUs for state estimation with only partial observability of the system from PMUs

Forms of Hybrid State Estimator

- Several different approaches have been proposed for combining the SCADA measurements and phasor data:
  1. Post processing
  2. Fusion
  3. Distributed
  4. Integrated

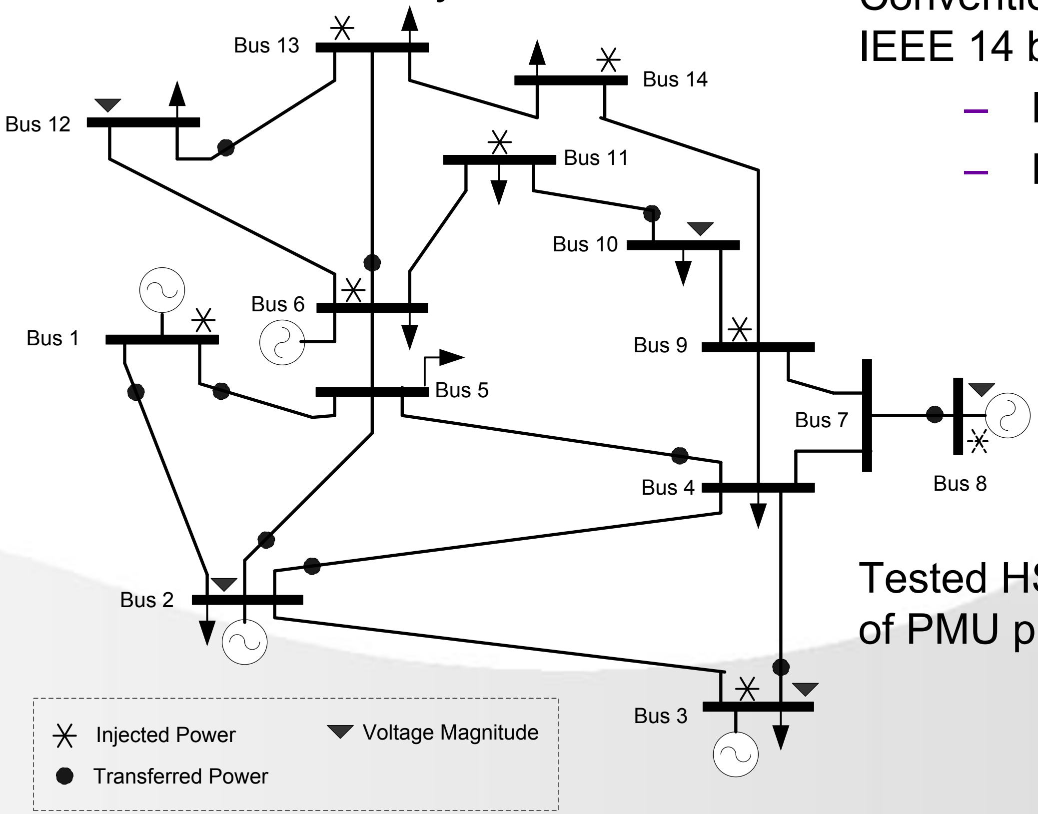


- Integrated HSEs are studied in VISOR
- These combine the traditional measurements with the synchronised PMU data into a single calculation, four types exist:
  1. Rectangular Current
  2. Pseudo Flow
  3. Pseudo Voltage
  4. Constrained Formulation

The challenge faced by integrated HSE is including the current phasors into the state estimator

Comparison of HSEs

IEEE 14 Bus Test System



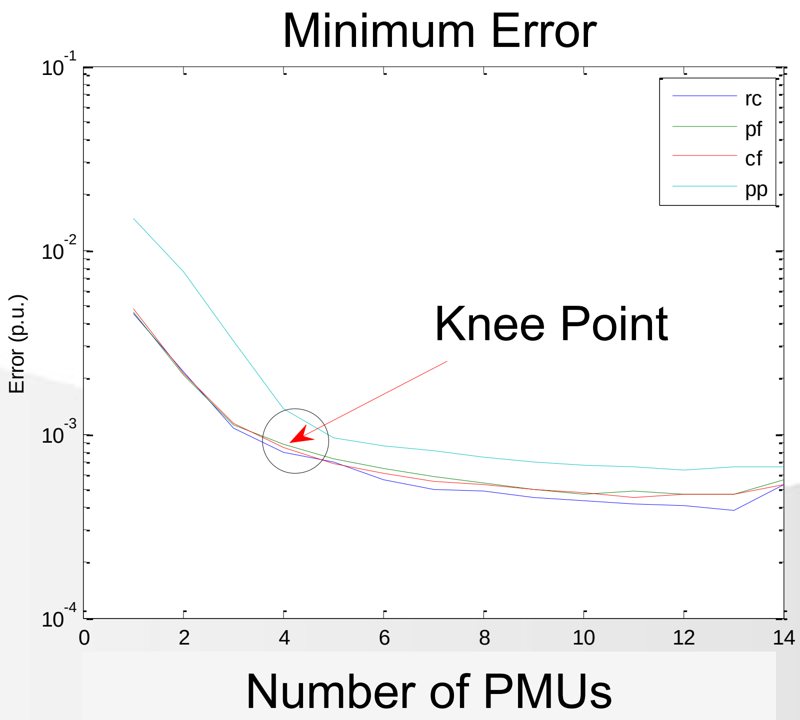
Conventional measurement placement in IEEE 14 bus test system:

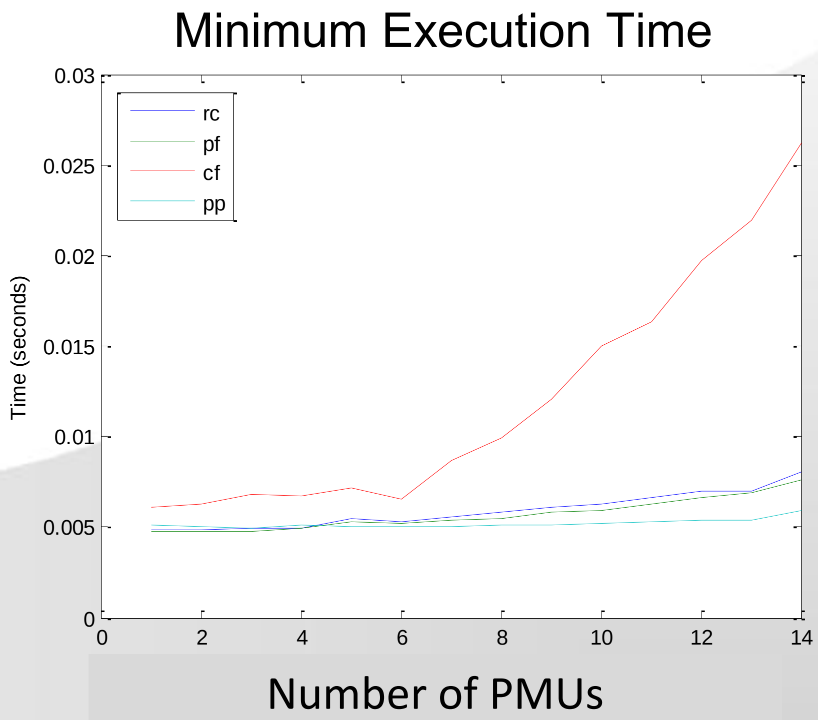
- Injection Measurements
- Flow Measurements

Tested HSEs for all possible combinations of PMU placements in this system

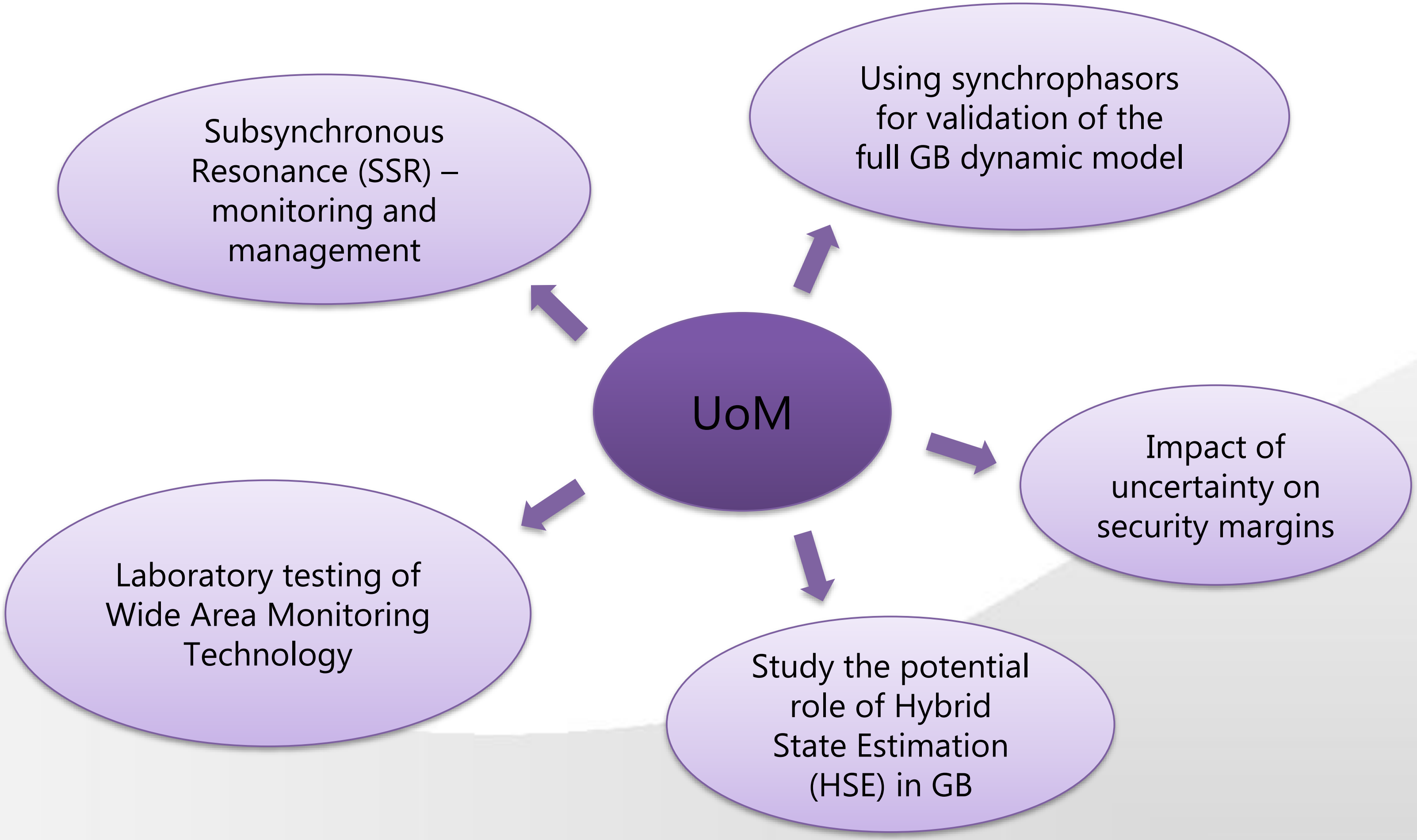
Comparison of HSEs

- The minimum error of HSEs with PMU number is characterised by a knee point
- This knee point occurs when the majority of the system is observable with PMUs
- Execution time of constrained formulation HSE increases rapidly, as this formulation includes the PMU current measurements as states





Helicopter View – Study Areas



Focus: use offline simulations and WAMS data to perform work with lower technical readiness

VISOR Project: Visualisation of real time system dynamics using enhanced monitoring

Helicopter View – Key Questions

UoM

- Can enhanced understanding of SSR and monitoring reduce the cost of installing fixed series compensation
- What benefits can synchrophasors from the VISOR WAMS offer to dynamic model validation in GB?
- Quantify the impact of uncertainty and how synchrophasors can be used relieve it
- Is the deployment of HSE in GB feasible and worthwhile in the near term?
- How accurate and reliable are the sensors and applications on which VISOR depends?

Focus: use offline simulations and WAMS data to perform work with lower technical readiness

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VISOR Stakeholder Engagement

The University of Manchester
Research Activities and Findings

Peter Wall
Papiya Dattaray
Zhaoyang Jin
Prof. Vladimir Terzija (The University of Manchester)
peter.wall@manchester.ac.uk

VISOR Stakeholder Event 2016

IET Savoy Place, London, 6 July 2016

Round table

Discussion questions, please!

VISOR Stakeholder Event 2016

IET Savoy Place, London, 6 July 2016

Visualisation software demonstration

Alan McMorran
Open Grid Systems

VISOR Stakeholder Event 2016

IET Savoy Place, London, 6 July 2016

Round table

Agenda

SP Energy Networks Experience	Priyanka Mohapatra	SPEN
System Operator Experience	Phil Ashton	NG SO
National Grid Experience	Mark Osborne	NG TO
SHE Transmission Experience	David Wang	SSE
Monitoring and Analysis Applications	Stuart Clark	GE
Research Activities and Findings	Peter Wall	UoM
Visualisation software demonstration	Alan McMorran	Open Grid Systems
Round Table session		
Roadmap development and findings	**Bryan Gwyn**	**Quanta Technology**

SYNCHROPHASOR TECHNOLOGY DEPLOYMENT – GLOBAL TRENDS AND VISOR ROLLOUT

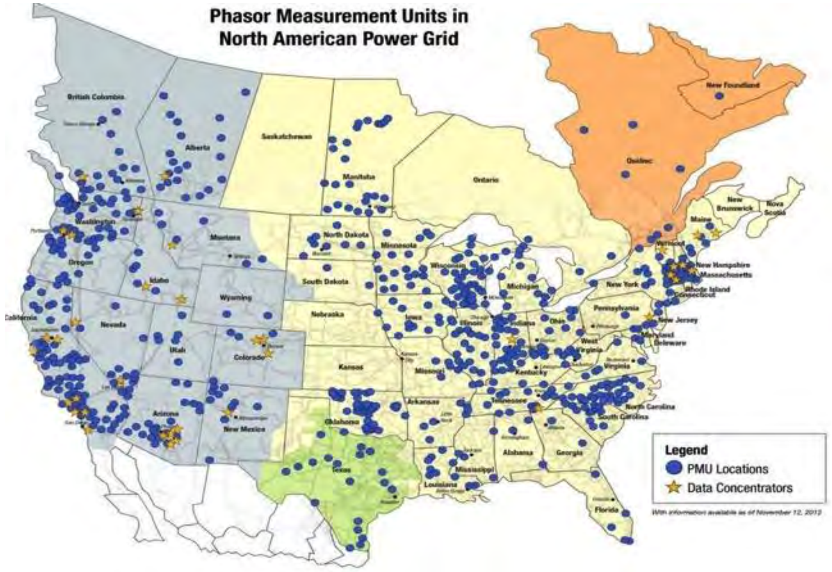
Dr. Ralph Masiello
July 6, 2016



Agenda

- Global Deployment Status and Benchmark
- Business Benefits and Operational Use
- Examples with Success Factors and Lessons Learned
- VISOR Plans and Initial Findings

International Synchrophasor Deployment



Source: US DOE 2016 Advancement of Synchrophasor Technology Report

- In the US, over 1,000 substations with ~1,700 installed PMUs and the number continues to grow
- China has installed PMUs in over 1,700 750/500/330/230 kV substations by 2013 and the number is fast growing
- India installing 1,732 PMUs
- Latin America
  - Colombia – Deployed applications for improved grid observability and reliability
  - Ecuador – Deployed System Integrity Protection Scheme using PMUs
  - Brazil – ONS is procuring the PMU system
- Many European countries have installed PMUs

Variety of applications benefit from using the same infrastructure

International Projects Benchmark

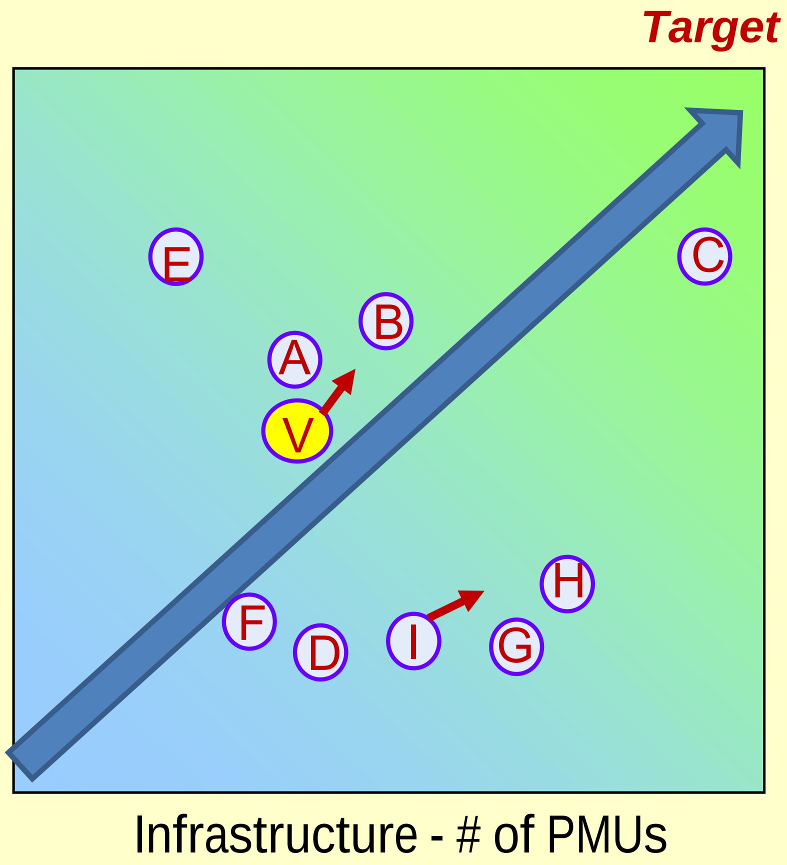
Applications

Big bang – all real-time closed loop control, protection, operation & other applications

Control room functions; some real-time applications

Data visualization and operation analysis in control room

Monitoring; visualization & operation analysis outside of control room



VISOR infrastructure enables piloting new synchrophasor applications

- Stability assessment
- Enhanced oscillation and Subsynchronous Resonance detection
- Post event analysis
- NETSO control room display of phase angles & "traffic lights"

X = PMU Projects

Major efforts are required to get VISOR to a full operational use stage at both TOs and SO

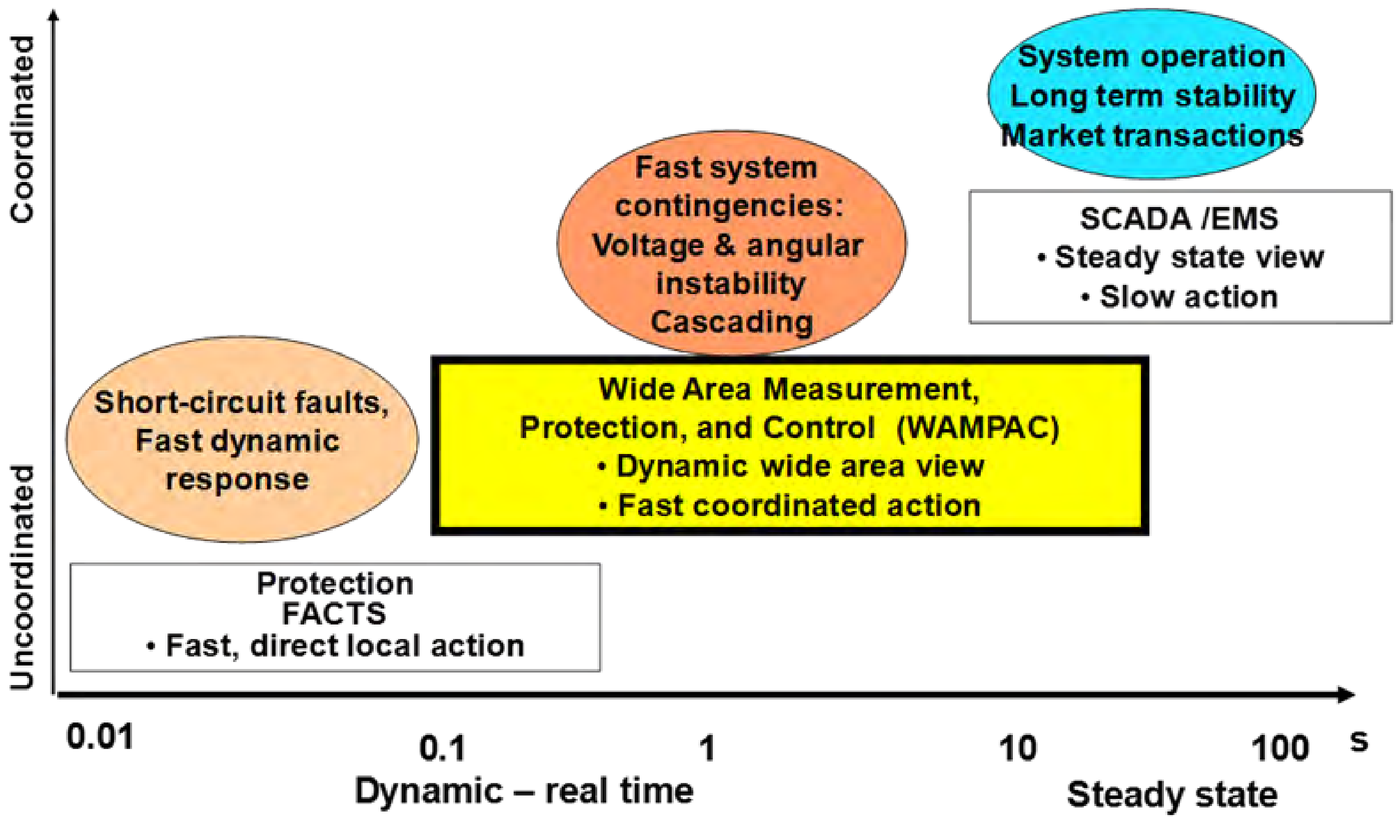
Slide 129

Bridging the Gap with Synchrophasors

1 µs precise grid measurements GPS signals

Dynamic wide-area network view at high speed (60 -120 observations/s) for better indication of grid stress

Timeframes of Grid Management using Wide Area Measurements, Protection, and Control



Business Benefits and Operational Use

KEY BUSINESS BENEFIT AREAS

- Data Analysis, System Planning and Modeling
  ➔ Significant benefits achieved already
- Monitoring of Fast Phenomena
  ➔ Control System Failures Detected
- System Visualisation and Operations Analysis
  ➔ Deployed Today
- Real-Time System Control and Protection for Reliability Improvements
  ➔ Applications being Piloted
- Renewable Integration and Market Operations (Congestion Mgt.)
  ➔ Market and Emissions Benefits

ON THE VERGE OF WIDESPREAD OPERATIONAL USE

- Applications either in use or under development
- Baselining with historical data and simulations
- Data quality or data sharing
- Key technical standards in place
- Engineering and Operator Training

WHAT'S NEXT

- Included in business processes, supported by needs roadmaps
- Identify new applications, e.g. those supporting integration of renewables and markets

More Suppliers Today

A short-list of vendors

- There are more vendors than the list can show here and the number continue to grow

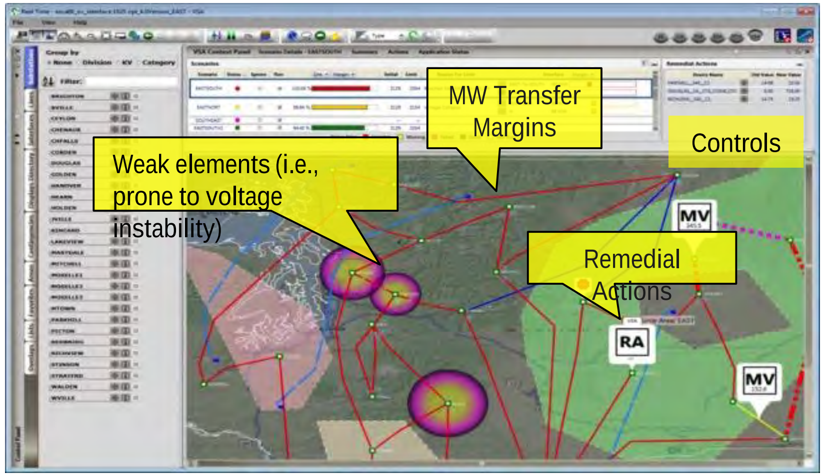
Vendor	PMU	PDC / Gateway	Real-time applications	Off-line applications	Protection & Control	Historian
ABB	X	X	X	X	X	
Beijing Sifang Automation Co. Ltd	X	X	X	X	X	
Electric Power Group		X	X	X		X
ErlPhase Power Technologies	X					
GE/Alstom	X	X	X	X	X	
Grid Protection Alliance (open-source)		X				X
Kalkitech		X				
NR Electric Co. Ltd	X	X	X	X	X	
OSIsoft			X	X		X
Schweitzer Engineering Laboratories	X	X	X	X	X	
Schneider Electric/InStep						X
Siemens	X	X	X	X		
Space-Time Insight			X			
V&R Energy System Research			X	X		

SO Example: NYISO Operational Use

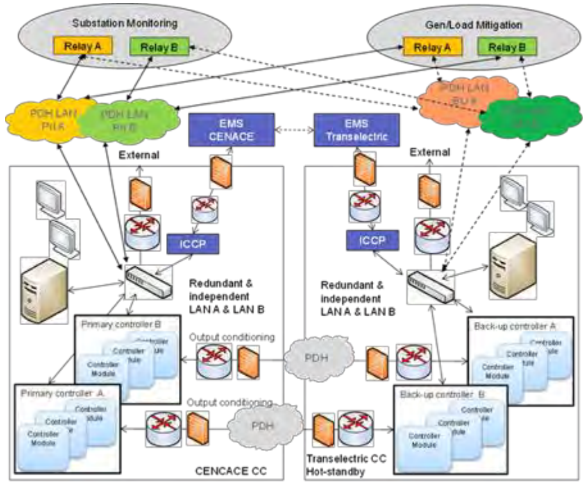
- Voltage angle differences across 4 regions (NYISO, PJM, MISO, IMO)
- The traffic lights representing the key metric elements
  - Left is internal NYISO control area
  - Right is external control areas – Angle difference under the Health column should be equaled to zero and lights up if the sum of the four angles exceeds a certain threshold
- Violation message indicator also appears on the EMS SCADA system

TO Example: PG&E Applications

- Situational Awareness, Visualization and Alarming (angles and voltages; overloads and oscillations)
- Voltage Stability Management – Combined Model and Measurement Based
- Enhanced Energy Management Systems
  - Adding synchrophasor measurements to existing SE
  - Tracking dynamic changes & contingency analysis
- System Restoration
- Post-Disturbance Event Analysis, including Fault Location
- Operator and Engineering Training
- Provide interfaces with EMS and with third parties



Ecuador: A Successful Deployment Experience



The need:

- Rapid generation expansion & demand growth lead to stressed grid operations - Double contingencies can cause a system collapse

The solution:

- PMU-based System Integrity Protection System - A fully redundant system involves 2 control centers, 12 monitoring and 11 mitigation substations, and a training system

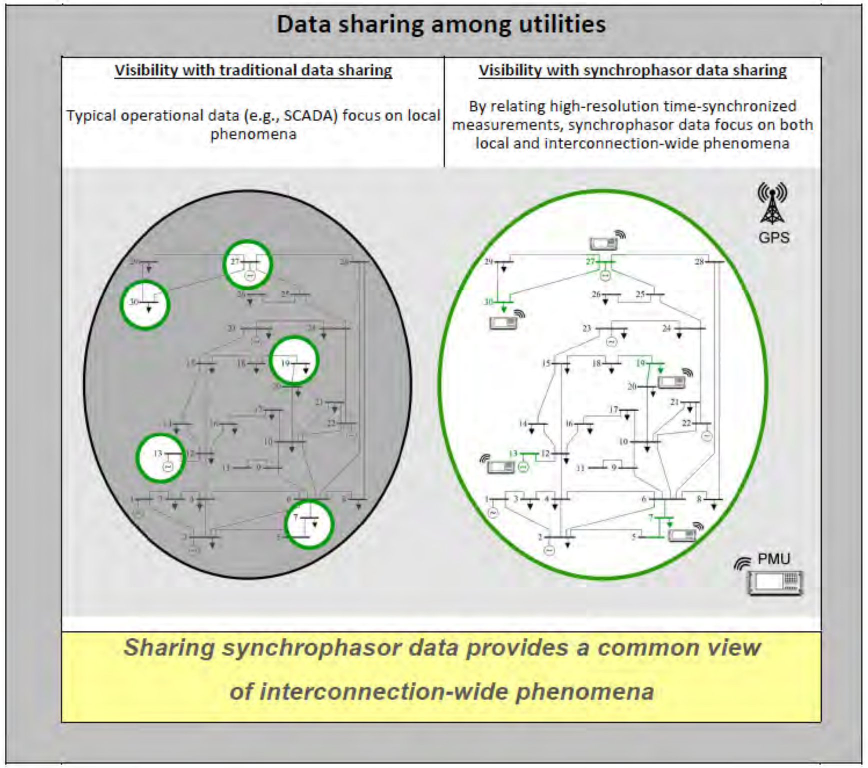
The process (completed < 3 years):

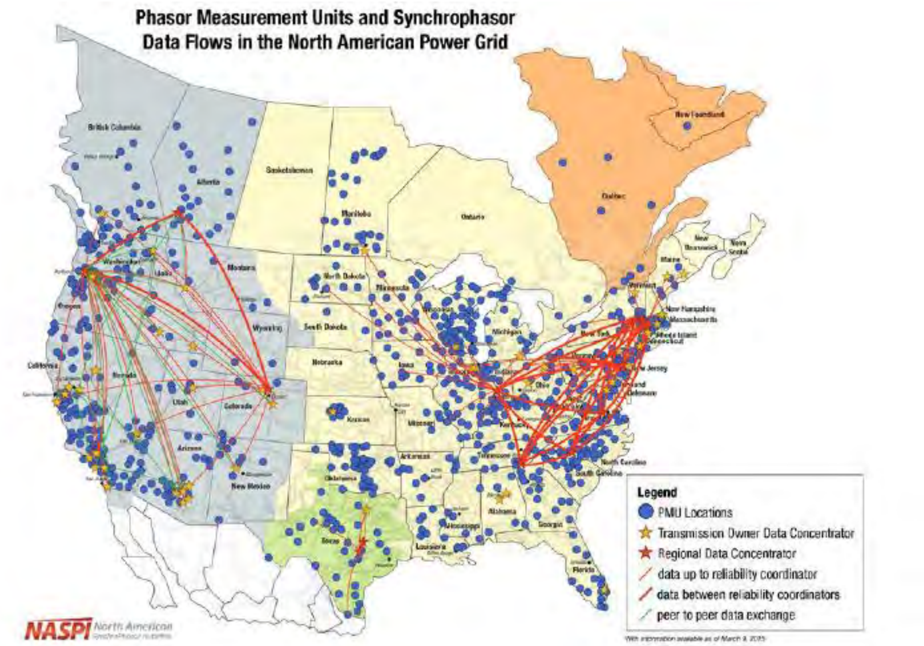
- System studies to identify problem areas and develop mitigation solutions
- Proceeded to system design and requirements specifications
- Deployed the SIPS through rigorous procurement, installation, testing and commissioning processes

The results:

- In operation since January 2015
- Correctly operated on May 6, 2015 – Realised USD $1.1M economic savings

Data Sharing is Extensive Regionally





ll PMUs displayed are connected to their local network. Major data paths for sharing information among operating entities are shown here.

Source: US DOE 2016 Advancement of Synchrophasor Technology Report

Post the 2011 SW blackout, individual entity legal concerns can slow down data sharing agreements

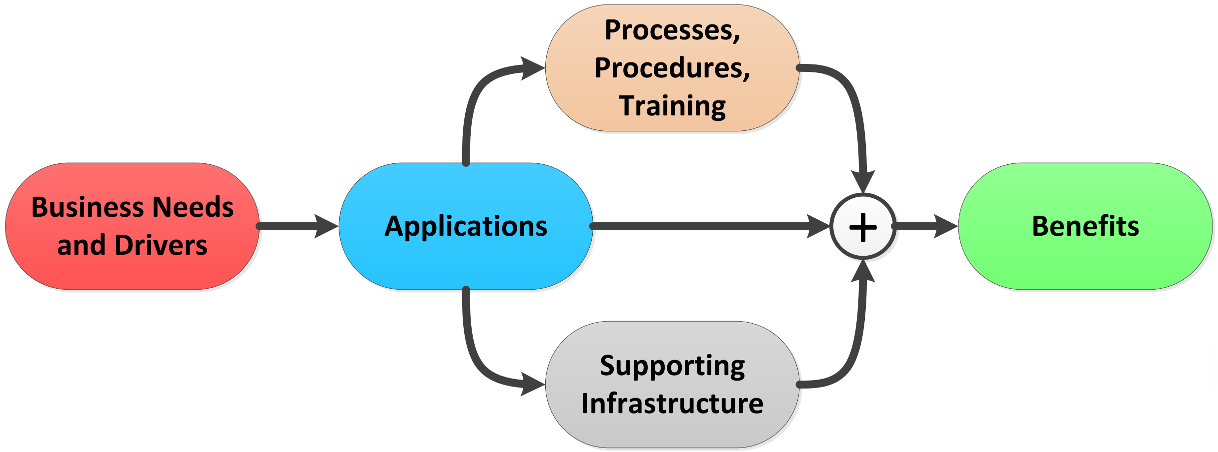
VISOR Rollout Roadmap Development

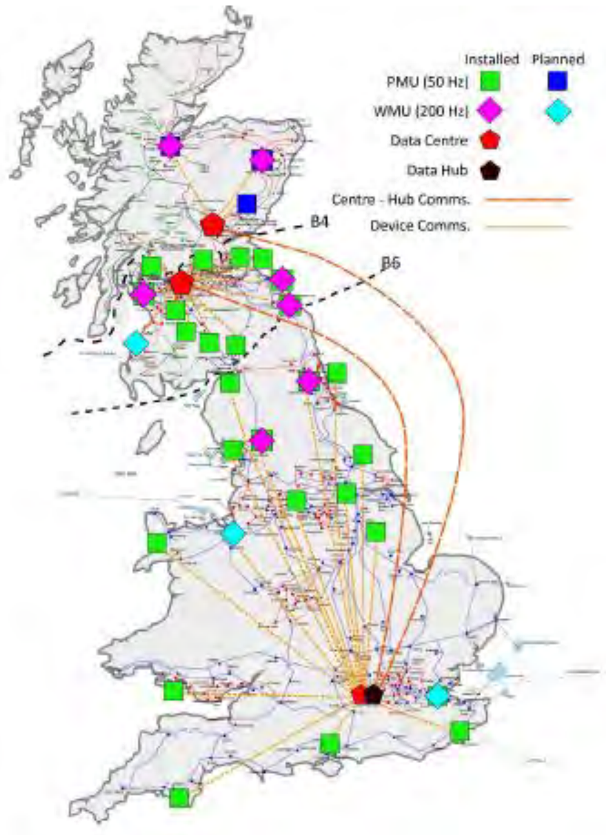
1st step: Fact Finding – Current State and Current Plans

- Deliver an Information Summary document – under review

Following activities:

- Identify Business Needs and Drivers to build business cases - underway
- Select priority Applications for Development
- Plan Architecture to fulfill applications needs
- Build the Roadmap considering priorities and constraints





Findings (so far)

VISOR collaboration project (NETSO, NGET, SPEN, SSE) includes synchrophasor pilot projects and applications, including a few in use in control room.

Need to fully deploy those applications in operations and add new applications, as well as additional PMUs.

Benefits will largely be driven by changes in system environment – high renewables, new interconnectors, coal retirements.

Future case – reduced inertia, reduced governor response, higher variability.

Business case observations:

- Interviews and document review identified a number of potentially significant applications to include in the business case, both ones already included in VISOR and new.

- UK has enjoyed quite good transmission system performance (not had major blackouts so far), but the risk is increasing.

Benefits of a common VISOR infrastructure apparent: Interoperability, standards driven, common functionality, cost reduction, etc.

Common infrastructure to optimally realize benefits of deploying multiple applications for a better business case

Thank You!

Quanta Technology, LLC
4020 Westchase Blvd., Suite 300
Raleigh, NC 27607 USA
(919) 344-3000
www.quanta-technology.com

Appendix

Applications Deployment 2016

CAPABILITIES	ATC[1]	CCET	Duke Energy	Entergy	FPL	Idaho Power	ISO-NE	Lafayette	Midwest Energy	MISO	NYISO	PJM	WECC / Peak Reliability
REAL-TIME CAPABILITIES													
Phase angle monitoring	In Development & Testing	Fully Implemented	Fully Implemented	In Development & Testing	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Planned	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
Oscillation detection and monitoring	In Development & Testing	Fully Implemented	Fully Implemented	In Development & Testing		In Development & Testing	Fully Implemented			Fully Implemented	Fully Implemented	In Development & Testing	Fully Implemented
Voltage stability monitoring	In Development & Testing	Fully Implemented		In Development & Testing	Fully Implemented	In Development & Testing	In Development & Testing	Planned		Fully Implemented	Fully Implemented		Fully Implemented
Event detection, management, restoration	In Development & Testing	Fully Implemented	In Development & Testing	Fully Implemented			In Development & Testing		Planned	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
Islanding detection, management, restoration	In Development & Testing			In Development & Testing						Fully Implemented			Fully Implemented
Equipment problem detection	Fully Implemented	Fully Implemented	Fully Implemented		Fully Implemented		Fully Implemented			Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
Wide area situational awareness	In Development & Testing	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	In Development & Testing	Planned	Planned	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
STUDY MODE CAPABILITIES													
Model validation and calibration	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented		Planned	Fully Implemented	Fully Implemented	In Development & Testing	Fully Implemented
Post-event analysis	Fully Implemented		Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented	Planned	Fully Implemented	Fully Implemented	Fully Implemented	Fully Implemented
Renewable resource integration		Fully Implemented	Planned	Planned		Fully Implemented							Fully Implemented
Operator training		Fully Implemented		In Development & Testing						In Development & Testing	Fully Implemented	Fully Implemented	Fully Implemented

KEY to status of capabilities development: Planned | In Development & Testing | Fully Implemented (real-time or study mode)

Note 1: ATC had two projects: a PMU project and a Communications project. The Communications project supports capabilities listed for the PMU project.

Sample of US ISO and TO installations.

Source: US DOE 2016 Advancement of Synchrophasor Technology Report

USA: Model Validation

August 10, 1996

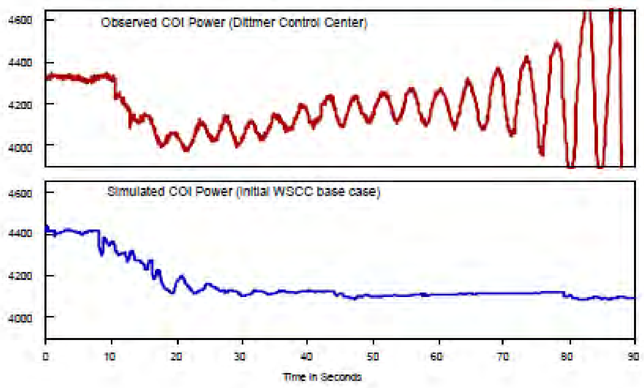
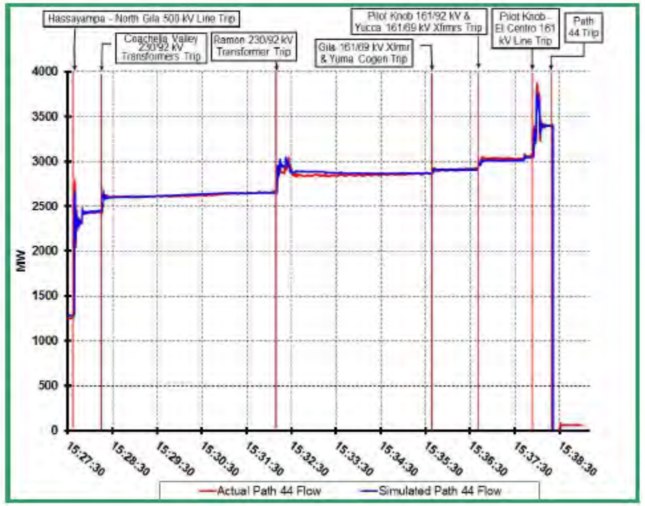


Figure 1: Comparison of Actual and Simulated Path 44 Flows



Source: FERC and NERC April 2012 Report

The need:

- The system models failed to reproduce the observed system behaviour for a 1996 blackout in the Western Interconnection
- Major interties were temporarily de-rated by 33%

The solution

- All models for generators > 20 MVA must be validated

The efforts

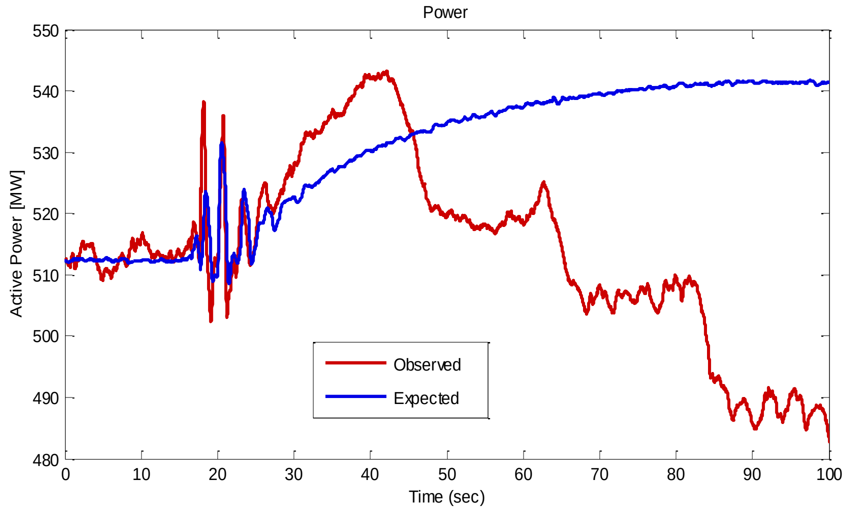
- Large number of PMUs have been installed in US through government (e.g. Department of Energy) and private funding since 1996
- PMU measurements are used for generator model validation and calibration

The result

- The simulation results for a 2011 blackout in the Southwest US could closely mirror the observed system behaviours
- High confidence in the accuracy of the system model
  - Avoid overly conservative
  - Ensure sufficient security margins are maintained

TO Example: BPA Applications

- Engineering Analysis
  - Event analysis,
  - Model validation,
  - Performance baselining
- Control Room Focus
  - Displays on dispatcher video wall
    (Oscillation Detection, Mode Meter,
    Islanding Detection, MW flow, Frequency disturbance)
  - State estimation
- Wide-Area Controls, RAS/SIPS - Control algorithm assess stability risk to switch shunt reactors and capacitors



Unexpected action from plant MW controller

Deployment Success Factors

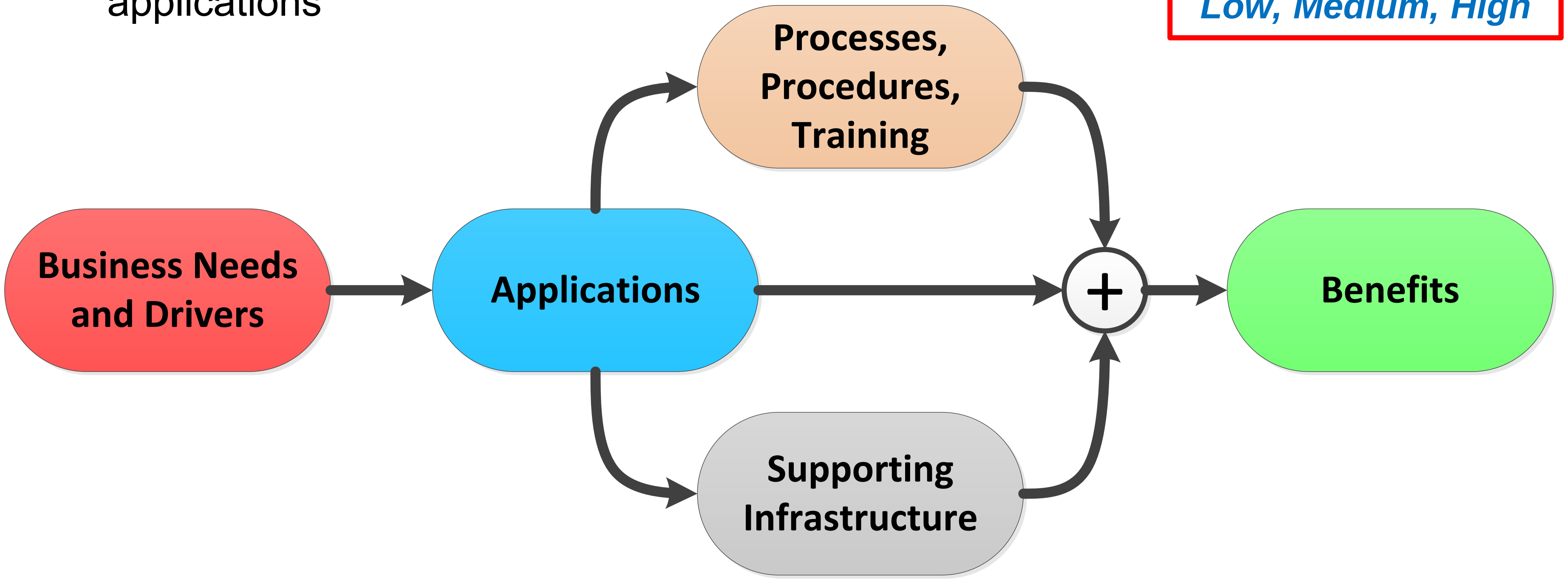
- Based on sound business cases – identify business needs and drivers, and benefits of adopting synchrophasor applications
- Buy-in and early involvement by all stakeholders
- Clearly defined system requirements for selecting a right system architecture
- Have a well-developed roadmap or rollout plan
- Follow proven acquisition processes for large production IT systems in procurement, installation, commissioning, and continued support

Following a systematic approach with a well-developed roadmap is critical for a successful deployment

Roadmap Development Approach

- Applications are determined by business needs & drivers
- Applications dictate the infrastructure requirements and deployment
- Users need processes, procedures, and training to take the full advantage of the deployed system and applications

Cost-benefit analysis to develop **Near-, Mid- and Long-term** plans with an impact level: ***Low, Medium, High***



Fact Finding

- Interviews with National Grid SO (NETSO), TO (NGET), and ScottishPower Energy Networks TO (SPEN) stakeholders
  - VISOR project team members
  - System Operations – Control Room
  - Operations Planning
  - System Planning
  - Asset Management
  - IT
- Meet with GE
- Review documents either available publically or supplied by VISOR project team

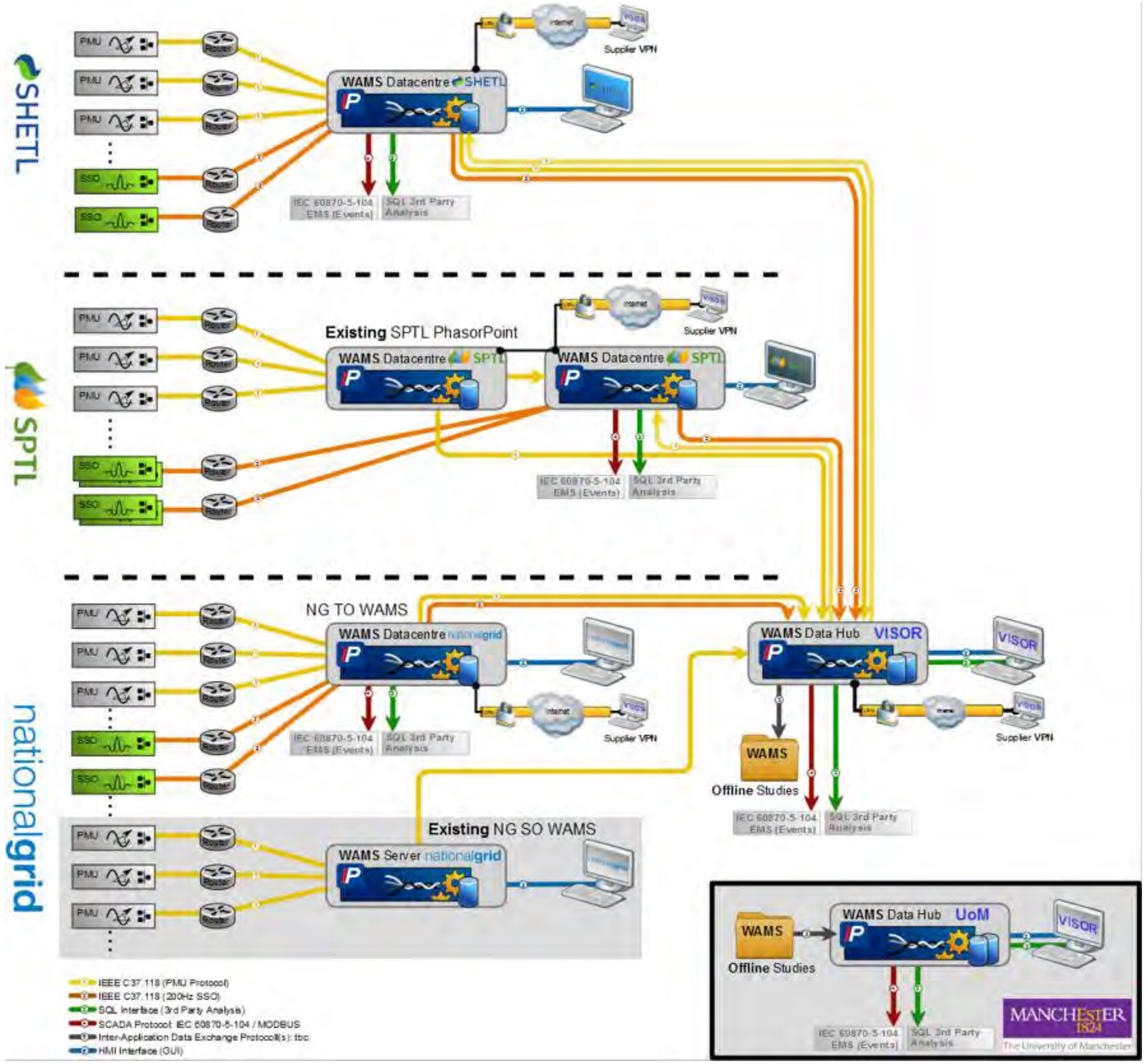
Draft Information Summary is currently under review

Project VISOR Work Packages

- WP1 – Enhanced Oscillation Monitoring
  - Sub-Synchronous (4-46Hz)
  - VLF (0.005-0.1Hz)
  - LF (0.1 – 4Hz) + Source location
- WP2 – System Model Validation
  - Robust Line Parameter Estimation
  - Oscillation Analysis Validation
  - Transient Stability Simulations
- WP3 – Management of Stability Constraints
  - HSE – Manchester University
  - B6 Boundary Transfer – Angle Based
- WP4 – Supporting Infrastructure – **Vital!**
  - Servers
  - Comms
  - WMUs

QUANTA TECHNOLOGY

VISOR ARCHITECTURE TODAY



Observations

GLOBALLY

- US ARRA (Stimulus) program jump started major PMU deployment with DOE funding toward operational use of the technology
  - Transition from a deployed system (infrastructure + applications) to operational use proved to be quite challenging – data quality, process / procedure development, operator training, data sharing, cyber security, etc.
  - 8 Years after ARRA program started, full operational use still a work in progress for many
- *PMU Installation and Applications Development becoming Mainstream*
- Regions globally that "have the problem" (i.e. business needs and drivers) are early adopters
  - History of blackouts
  - Long transmission to remote generation and stability issues
  - Regions with already high renewables
  - Heavily constrained transmission paths
- Market economics and real time operations benefits hardest to quantify and realise
  - Requires changes in how limits are set / congestion is dispatched
  - Thus requires complete credibility
- Improved visualisation and analytics for operations and reliability enhancement has made some progress
- Use in post-event analysis, oscillation detection, voltage stability, model validation is wide-spread and benefits have been realised

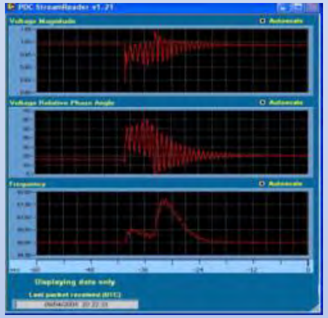
Synchronized Meas. Progression

Before

First PMU

Analog Displays

Products Now



2015

Standard feature (relays, DFR, controllers, monitors)

On major interconnections and generators

Standard SW tools included in EMS/SCADA

Primary use for monitoring, event analysis

Interoperability standards deployed

Some distribution PMUs

Improvements in communication infrastructure

2020

Thousands of synchronized measurements world-wide

Integrated in standard business and operational practices

Fully integrated with EMS/SCADA or Independent system

Higher data rates

Fully in Distribution

Distributed comm. and processing architecture

Fast Control and Adaptive Protection

Today's events

SP Energy Networks Experience	Priyanka Mohapatra	SPEN
System Operator Experience	Phil Ashton	NG SO
National Grid Experience	Mark Osborne	NG TO
SHE Transmission Experience	David Wain	SSE
Monitoring and Analysis Applications	Stuart Clark	GE
Research Activities and Findings	Peter Wall	UoM
Visualisation software demonstration	Alan McMorran	Open Grid Systems
Round Table session		
Roadmap development and findings	Bryan Gwyn	Quanta Technology

Closing remarks

Thank you very much for attending