Visualisation of Real Time System Dynamics using Enhanced Monitoring (VISOR)

In collaboration with

Project Progress Report

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1 Executive Summary

SP Transmission (SPT), supported by the other transmission licensees and the academic partner, made a full proposal submission for the project: Visualisation of Real Time System Dynamics with Enhanced Monitoring (VISOR), under the Network Innovation Competition (NIC) mechanism in 2013. Ofgem approved the proposal and issued the Project Direction on the 19th of December 2013. The project commenced in January 2014 and is due to conclude in March 2017.

The VISOR project aims to showcase the role of an enhanced Wide Area Monitoring System (WAMS) in overcoming the challenges facing the GB power system as it moves toward a low carbon future. It has created the first integrated GB WAMS and has also marked the first deployment of new Waveform Measurement Units (WMUs), which generate 200 frames per second data for the detection of sub-synchronous oscillations (SSO), anywhere in the world.

The VISOR WAMS is the first to collate, store, visualise and analyse synchronised measurements in real-time across all three of the GB Transmission Owners (TO's). The WAMS incorporates wide area synchronised phasor measurements produced at a rate of 50 frames per second that provide unparalleled monitoring and understanding of the dynamic behaviour of the GB system, when compared to unsynchronised SCADA data that is sampled at one frame per second or less.

VISOR will focus on the following key areas that are expected to be of the most benefit to the GB system in the short to medium term:

- Real-time monitoring and alarming of oscillations in the range 0.002Hz to 46Hz - from low frequency generator governor behaviour, to inter-area oscillations, to sub-synchronous resonance introduced by series compensation,
- The use of WAMS data to aid and enhance post-event analysis and network & dynamic model validation,
- Hybrid state estimation using Phasor Measurement Unit (PMU) and SCADA data, and,
- The potential use of angle based security limits to relieve power flow constraints across the B6 boundary between Scotland and England.

The PhasorPoint and technology supplier for VISOR, Psymetrix, part of Alstom Grid, was acquired by General Electric as of November 2015. The company name has subsequently changed to GE Grid Solutions and referred to as "GE" within this report.

1.1 Project Highlights

This is the fourth progress report and covers six months of the project delivery June 2015 - December 2015, "the reporting period".

The project delivery is in line with the original proposal regarding project programme, resources, budget, risk management, intellectual property rights (IPR) and knowledge sharing, and over the reporting period, supporting evidence for the following elements contributing to the Successful

Delivery Reward Criteria (SDRC) have been delivered on schedule with some restrictions as described later in this report:

SDRC 9.4.1:

- ✓ *Display incorporating power, angle and associated thresholds (WP 3.3, Dec 2015)*

SDRC 9.5.1:

- ✓ *System commissioning report (WP 4A, Dec 2015)*
- ✓ *Visualisation of data in SPT, NGET, SHE TL Transmission including real-time and historic (WP 4A, Dec 2015)*

SDRC 9.6.1:

- ✓ *Presentations and show-casing at the annual innovation conferences (WP 5.4, Dec 2014, Dec 2015, Dec 2016 and June 2017 for Close-down report dissemination)*

The Project Delivery Team (PDT) has successfully undertaken the following activities during the reporting period:

- Four WMU installations have been successfully completed at the following locations:
    - Torness (SPT)
    - Stella West (NGET)
    - Kintore, Beauly (SHE TL).
- Plans to install further WMUs in 2016 at
    - Auchencrosh (SPT)
    - Deeside/Connah's Quay[1], Grain (NGET)
- Established the following communication links between Data Centres and the Data Hub:
    - SPT and NGET communication link, IPSec commissioned as an interim mitigating solution to overcome delays with BT in delivering the Multiprotocol Label Switching (MPLS) link between Kirkintilloch Phasor Data Concentrator (PDC) and Wokingham Data Hub.
    - SHE TL and NGET communication link, IPSec between Perth PDC and Wokingham Data Hub awaiting commissioning in December 2015.
- WAMS Phasor Data Concentrator server installed and commissioned at Perth (SHE TL).
- Successfully development of two new PhasorPoint applications, *B6 boundary display* and *System Disturbance Monitoring Disturbance Characterisation (SDM:DC*), showcased at the Application Demonstration Workshop on 19 November 2015, at GE, Edinburgh.
- Second Annual System Report completed by GE in November 2015.
- Approved specification for VLF (Very Low Frequency) oscillation application and LF oscillation source location enhancement.

[1] Deeside is in the process of being replaced by a new substation, Connah's Quay, scheduled for completion in 2018, upon which the WMU will be transferred from Deeside onto the new circuits at Connah's Quay.

- Key new project initiatives currently in delivery to support progression into business as usual, including
    - Identified [redacted] as suitable partners to support the System Roll-out report. Expected to commence in Q1 2016, pending contractual arrangements.
    - Identified [redacted] as suitable partner for the development of new open-source phasor data visualisation platform. Expected to commence in Q1 2016 pending contractual arrangements.
- Successful knowledge dissemination activities:
    - Two dedicated VISOR Stakeholder events hosted by the VISOR project team
    - Comprehensive presence at LCNI 2015 - including presentations, workshop and soapbox presentations
    - Intra business workshops and meetings highlighting objectives
    - Production of explanatory videos for website and other knowledge sharing activities
    - Enhanced functionality of VISOR website, including videos and FAQ

The following reports were produced by GE, based on actual system data from NGET and SPT

- The second System Performance Review incorporating:
    - WAMS Infrastructure performance
    - Power System Oscillatory behaviour: baseline & events covering:
        - 0.002-0.1Hz Very Low Frequency (VLF) or governor oscillations
        - 0.1-4Hz Electromechanical (e.g. inter-area) oscillations
        - 4-46Hz “Sub-Synchronous Oscillations” including power electronic control modes, generator torsional modes and series capacitor resonances.
    - Power System Disturbances

These reports were thoroughly reviewed by the PDT and forwarded to project steering board for approval. External versions of these reports will be published on the website in January 2016.

During the reporting period, knowledge dissemination has been conducted through the following highly successful and high-profile events, organised and hosted by members of the VISOR team:

1. First External Stakeholder Event, 18 August 2015, London.
   Hosted by SP Energy Networks
2. First Internal Stakeholder Event, 24 September 2015, Wokingham.
   Hosted by National Grid
3. Second Annual System Review workshop, 17 – 18 November, Edinburgh.
   Hosted by GE
4. Demonstration event (B6 display and System Disturbance Monitoring), 19 November, Edinburgh.
   Hosted by GE
5. LCNI 2015, 26 – 28 November 2015, Liverpool.
   Sponsored by SP Energy Networks

In addition to the knowledge dissemination dedicated events organised and hosted by the project team, the knowledge gained by the project has been shared with the wider industry through the following activities:

1. Paper and presentation at PAC World Glasgow, 29th June – 2nd July 2015
2. Presentation at IEEE General Meeting, Denver, 26th – 30th July 2015
3. Paper and presentation at APAP Conference, Nanjing, 20th – 26th Sept 2015
4. Paper and presentation at Cigre Study Colloquium B5, Nanjing, 20th – 26th Sept 2015
5. Presentation and Workshop at EPSRC-NSFC Project Meeting, Chengdu, China 12th – 15th Oct 2015
6. SGTech Europe Smart Grid conference, Amsterdam, 22nd – 24th Sept 2015
7. EPRI International User Group conference, Dublin, 23rd Sept 2015
8. Alstom User Group meeting, Cannes, 28th Oct 2015.

In addition to the above, to ensure the project not only disseminates but also draws in the wider experience of WAMS, a number of international experts and leading research institutions in the WAMS area have been engaged through all possible avenues, particularly drawing upon learning in the Americas and China.

Within the reporting period, working relationships have been established and nurtured with noteworthy international experts in WAMS and wide area monitoring, protection and control (WAMPAC):

Quanta Technology

An expertise-based consultancy based in North America, providing strategic supporting to utilities and have, in particular, vast experience in supporting utilities deploy WAMS solutions as part of day-to-day operation and offer a wealth of synchrophasor expertise, business acumen and highly valuable experience that may provide vital in overcoming the leap from innovation to business as usual. Key personnel include

- Dr. Damir Novosel, a global leading figure in synchrophasors and wide area monitoring, President of Quanta Technology, and President-Elect of IEEE Power & Energy Society, and
- Dr. Bryan Gwyn, 30 years' experience in the power industry in UK and USA, former Director of Protection and Control at National Grid UK.

Pacific Gas and Electric (PG&E)

- Vahid Madani, Director of Protection and Control at Pacific Gas and Electric, and Chairman of North American Synchrophasors Standards at NERC.

The University of Manchester and GE have submitted the following papers seeking to represent VISOR at key international conferences:

PSCC Conference 2016

- *Impact of Load Dynamics on Torsional Interactions*
- *Optimal PMU Placement in the Presence of Conventional Measurements*
- *Addressing Emerging Network Management Needs with Enhanced WAMS in the GB VISOR Project*

IEEE PES General Meeting 2016

- *Placement of SSO Monitoring Devices for Maximum Visualization of Torsional Interactions*
- *Transient Torque Amplification in Meshed Power System Networks*
- *Creating a WAMS for the GB Power System and the Lessons Learned So Far*

Cigre 2016

- *Advances in Wide Area Monitoring and Control to address Emerging Requirements related to Inertia, Stability and Power Transfer in the GB Grid.* Abstract.

In terms of future knowledge dissemination and sharing events in 2016, the significant events will be held:

- Innovation day at Kirkintilloch, February 2016
- Seminar and strategic consultation with PG&E at Kirkintilloch/Glasgow, February 2016
- Innovation day at Warwick, Q1 2015
- Second dedicated stakeholder event, location to be confirmed, June 2016.

In addition to the dedicated events above, representation of VISOR at the following international events is planned:

- NASPI Work Group meeting and first International Synchrophasor Symposium, March 24-26, Atlanta, USA.
- All Energy Conference, May 4-5, Glasgow, Scotland
- CIRED Conference, June 14-15, Helsinki, Finland
- PAC World Conference, June 13-16, Ljubljana, Slovenia

1.2 Project Risks

There are currently no uncontrolled risks that could impede the achievement of any of the SDRCs outlined in the Project Direction, or which could cause the Project to deviate from the Full Submission. We monitor risks on a continuous basis with regular review at monthly progress meetings. The key risks are summarised below, with more details in Section 4.

1.2.1 Technical and Roll-Out Risks

The following technical risks were encountered during commissioning and system analysis for project VISOR in the reporting period:

- A significant technical risk stems from the commissioning of the Multiprotocol Label Switching (MPLS) link which, although itself not a technical risk, has many implications on other technical aspects of the project, in particular inhibiting the centralised online GB-wide monitoring. The real-time data is stored within each Data Centre but must then be manually transferred and collated to the central server to replay historical events. This issue has not significantly impeded the ability to complete the System Performance Review but does increase complexity and technical resource required to undertake the same task, whilst also restricting the GB-wide real-time view of the system.
  The mitigating action has resulted in the commissioning of an IPSec link between SPEN and NGET. An upshot of this, however, is that it will eventually provide additional benefit by enabling a comparative assessment with the MLPS link, once both are online, to inform and define the specifications for the future WAMS communications infrastructure.
- The VISOR PhasorPoint server at SPT Kirkintilloch has suffered a number of crashes of software. It is believed this is due to a combination of the storage hardware and configuration (RAID 1 Array) and the large quantity of dropped/invalid packets and connections from SPT PMUs. GE Grid Solutions are investigating the issue and trialling potential solutions.
- A few incidents have raised a question of WMU performance that is currently under investigation. Engineers at both SPT and NGET have reported three incidences where WMUs monitoring parallel circuits were observed to be 90 degrees out of phase. This issue has been raised with GE Grid Solutions and is under investigation.

1.2.2 Project Management Risks

The key project management risks that have been encountered during the reporting period are listed below. Project Managers at each of the project partners have ensured that these risks are continuously monitored and actively managed to ensure the project milestones are not jeopardised:

- Project delivery delays incurred by SHE TL. This issue was highlighted in the previous reporting period whereby the commissioning of the SHE TL WMU, PDC and communications link with NGET was behind schedule. This has persisted through this current reporting period and poses a risk to a number of milestones. The issue has been raised with senior personnel and additional resource has subsequently been deployed to advance the commissioning of SHE TL's infrastructure.
- A significant project management risk has been the commissioning of the MPLS link which has suffered severe delays from which a number of project milestones are dependant. BT is responsible for the delay, which is due to insufficient availability of resource on their part. The decision was made in October to execute the contingency plan to mitigate the risk by installing an IPSec link as an interim measure. The IPSec link is due for commissioning in December 2015, and will enable a continuous stream between SPT and NGET.

Further details of Risk Management including Technical Risk and Project Management Risk can be found in Section 4 of this document.

Summary of Learning Outcomes

The main learning outcomes over the reporting period are summarised as:

System Commissioning Learning

- **Complexity of MPLS link**
  The project has suffered extensive delays in commissioning the MPLS link, although the issues have been escalated as far as possible, deadlines are repeatedly missed and delayed further. Subsequently, a separate IPSec link has been implemented to mitigate further impacts.
- **Data quality and uncertainty volumes from PMU and new WMUs**
  Initial estimates of traffic volumes were based upon theory and were a bit low. Add to this the increased number of WMUs and the initial bandwidth calculated for the NG to SPEN WAN link would not be sufficient for the duration of the project. There have been ad-hoc firewall changes to incorporate the data streams identified as part of the 200Hz data transfer, as the network support is outsourced then each change has a time and cost impact.
- **Consideration of wider business plans**
  There is a trade-off between trying to get an innovation project up and running as soon as possible, and keeping strategic options in consideration. This can lead to innovation decisions being purely tactical as a proof of concept, but would require complete reengineering for a strategic implementation.

Research - University of Manchester

- **Investigation of Planning Rules for the Mitigation of Sub-synchronous Resonance**
  The role of WAMS in the mitigation of SSR is to complement, not replace, the existing planning based studies and measures. Therefore, an aspect of the research in VISOR has been the study and evaluation of the existing planning based methods and tools for the assessment of the threat of SSR. The research summarised in Section 6.1.2 has found that it is possible for an electrical mode to interact with a torsional mode that is outside of the +/- 3 Hz recognised 'safety band', even when another torsional mode is within the +/- 3 Hz band. A key outcome of this research is that the electrical damping should be considered in more detail as part of SSR studies and during the creation of screening rules.

- **Optimal Placement for Monitoring Sub-synchronous Oscillations**
  To ensure that the monitoring required is provided at the lowest cost, methodologies must be developed for the optimal placement of synchronised measurement devices for monitoring SSO. The research has used 68-bus IEEE test network to evaluate the various methodologies to optimise the placement of devices. The methodology, set out in Section 6.1.3, use a combination of linear and non-linear studies and various outage scenarios (i.e. cases where a combination of lines are removed from the system) to identify critical generators that may be vulnerable to SSR based on frequency scan studies (a generator is deemed to be critical if it

has a reactance dip of more than 5 % in any case). The learning generated using the IEEE network will be applied to the full GB model in 2016.

- **Comparison of Hybrid State Estimators (HSE)**

  The existing GB state estimator is a classical state estimator that uses measurements of voltage magnitude, and active/reactive power flows and injections from the Supervisory Control and Data Acquisition (SCADA) system to estimate the power system state through an iterative procedure. The goal of this comparison is, through collaboration with the GB system operator and transmission owners, to attempt to create an index that balances the various measures of HSE performance (e.g. accuracy, convergence time and number of PMUs) to effectively score the performance of each HSE for a given number and placement of PMUs.

  If successful this should provide a useful tool for investigating the potential role of HSE in the GB system, but require extensive study for larger test systems and collaboration between the partners because, by their nature, indexes are heuristic in nature will only be of value if they are designed properly.

2 Project Manager's Report

This section highlights the VISOR projects' key activities, milestones, risks and learning over the reporting period (June 2015 – December 2015).

2.1 Project Progress Summary

VISOR remains on course for a satisfactory delivery over this reporting period regarding the project programme.

The significant achievements during the reporting period are:

- Successful installation and commissioning of WMUs at Torness (SPT), Stella West (NGET), Kintore, Beauly (SHE TL).
- Two new PhasorPoint applications successfully developed and showcased at the Application Demonstration Workshop on 19 November 2015, at GE Edinburgh
    - B6 boundary display
    - System Disturbance Monitoring Disturbance Characterisation.
- IPSec link between Kirkintilloch PDC (SPT) and Wokingham Data Hub (NGET) commissioned in December 2015.
- System Performance Review report based on actual system data from NGET and SPT (Jan15-Nov15) released by GE in November 2015.
        - WAMS Infrastructure Performance
        - Power System Oscillatory Behaviour: baseline & events
        - Power System Disturbances
- Key additional project initiatives have been identified, and are in delivery, to strengthen the progression into business as usual, including:
    - Literature and industry review of VISOR WAMS infrastructure and comparison with international experience
    - Commission a study to develop systematic roadmap for the progression of WAMS technology into BaU
    - Development of independent and universal phasor data processing and visualisation application
    - Active engagement/contribution to IEEE Synchrophasor standard committee
- Selected recognised industry experts, Quanta Technology, as suitable partners to support the System Roll-out report. Contractual arrangements underway.
- Two <u>dedicated</u> VISOR Stakeholder events held to disseminate learning, engage with key stakeholders outside the deliver team, and demonstrate potential benefits:

- The first dedicated External Stakeholder Event held at the Park Plaza Hotel, London, on 18 August 2015.
- The first dedicated Internal Stakeholder Event held at National Grid Electricity National Control Centre (ENCC), Wokingham, on 24 September 2015.

- A multitude of VISOR knowledge dissemination and promotion activities to internal and external stakeholders and the wider industry within the UK and overseas, including:
  - Presentation at Alstom User Group meeting, 28 October 2015.
  - Presentation at EPRI International User Group, 23 September 2015.
  - Comprehensive presence at LCNI conference, 24-26 November 2015.
  - Discussions with SPT Control Room personnel to highlight desirable objectives.
  - Production of educational videos for knowledge dissemination activities.
  - Enhancements to VISOR website to accommodate the download of previous project progress reports and presentations.

The University of Manchester have continued their highly valuable input into project with the following noteworthy contributions during the reporting period:

- Initial assessment and recommendation study of Hybrid State Estimation methods.
- Investigation and presentation of Optimal PMU placement study based on IEEE test network. To be modelled on the whole GB model in 2016.
- Presentation of findings at many UK and international events.
- Contribution to presentations and author of highly regarded and comprehensive video explaining stability limits.
- Promotion of VISOR objectives and investigation of other WAMS research and experience through many international events.

Other achievements include:

- The conclusions from the November System Performance Review and subsequent follow-on actions were discussed in detail at a workshop held on 17 – 18 November 2015 at GE, Edinburgh.
- Approved specification for VLF (Very Low Frequency) oscillation application and LF oscillation source location enhancement.
- The last of the originally planned WMU installations at Auchencrosh (SPT) has been planned for 2016.
- An additional four WMU circuits have been selected for inclusion in VISOR WAMS
  - Hunterston East (two circuits) to monitor circuits to HVDC (SPT)

- Connah's Quay (replacing Deeside substation) and Grain (NGET)

- Finalist for Engineering Excellence at the Scottish Green Energy Awards 2015.

The project is entering its second phase, the *operational stage*, whereby the continuous flow of new data gathered by the project is collated, analysed, and translated into new information; shedding light on the real-time system dynamics of the GB system that will provide significantly valuable for Transmission Owners and System Operator alike.

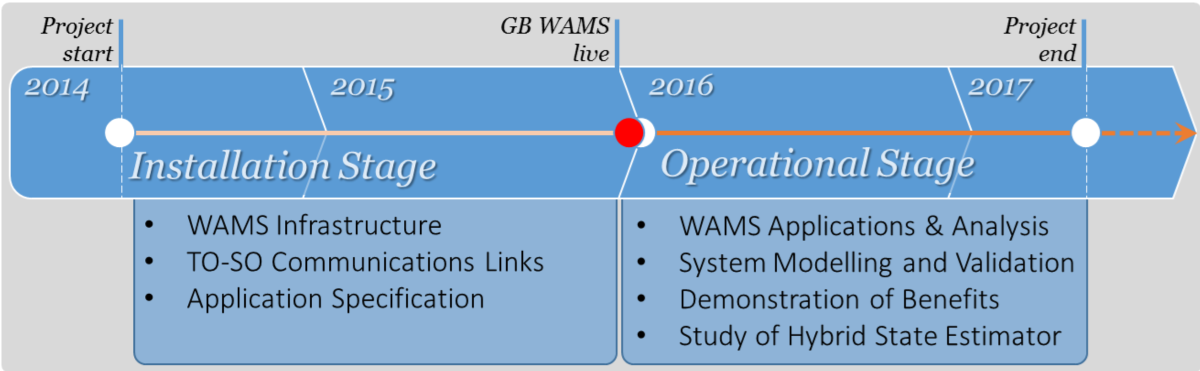


Figure 1. VISOR high-level timeline

2.2 VISOR WAMS infrastructure update

A total of ten "Waveform Measurement Units" (WMUs), three localised *Data Centres,* and one centralised *Data Hub* were originally intended to be installed under VISOR to provide phasor measurements and monitor Sub-Synchronous Oscillation (SSO) across the breadth of the GB. To date, nine of these WMUs have been fully installed and commissioned across GB collecting new data on SSO behaviour in the system.

In light of the new valuable information gathered by this new WMU technology, and a reflection of the business commitment to WAMS, further provisions have been made to purchase additional WMU units to be installed onto the VISOR WAMS. One of these additional four units has already been installed at Deeside substation which will be encapsulated by Connah's Quay substation in 2017.

The interconnector between the UK and the Netherlands has been identified by NGET where SSO is a potential issue due to interactions when operating HVDC links adjacent to wind-farms and thermal plant. A WMU is planned for installation at the primary substation Grain to further safeguard this.

In Scotland, the case to install two additional WMUs on circuits connecting the Western HVDC link, at Hunterston, is being considered which, when coupled with the WMUs on the other side of the link at Connah's Quay, will provide comprehensive monitoring of the operational behaviour of the high capacity HVDC link.

Over this reporting period, four WMUs have successfully been installed and commissioned on to the GB system at the following locations:

SPT - Torness
NGET - Stella West
SHE TL - Kintore, and Beauly

An overview of the status of the installed and proposed WMUs locations is provided below in Table 1 and Figure 1.

#	VISOR Partner	Locations (circuits)	Status
3	Scottish Power	Eccles (Stella West 2) Torness (Eccles 2) Hunterston (Inverkip 2, to be Strathaven)	Installed and operational Installed and operational Installed and operational
2	*above original scope*	Coylton (2 circuits)	2016
4	National Grid	Hutton (Harker 1) Hutton (Harker 2) Stella West (Spennymoor 1) Stella West (Spennymoor 2)	Installed and operational Installed and operational Installed and operational Installed and operational
4	above original scope	Deeside/Connah's Quay (2 circuits) Grain (2 circuits)	2016 2016
2	Scottish Hydro Electric	Kintore Beauly	Installed and operational Installed and operational
1	The University of Manchester	Manchester	Operational

Table 1. WMU outstation device locations and status

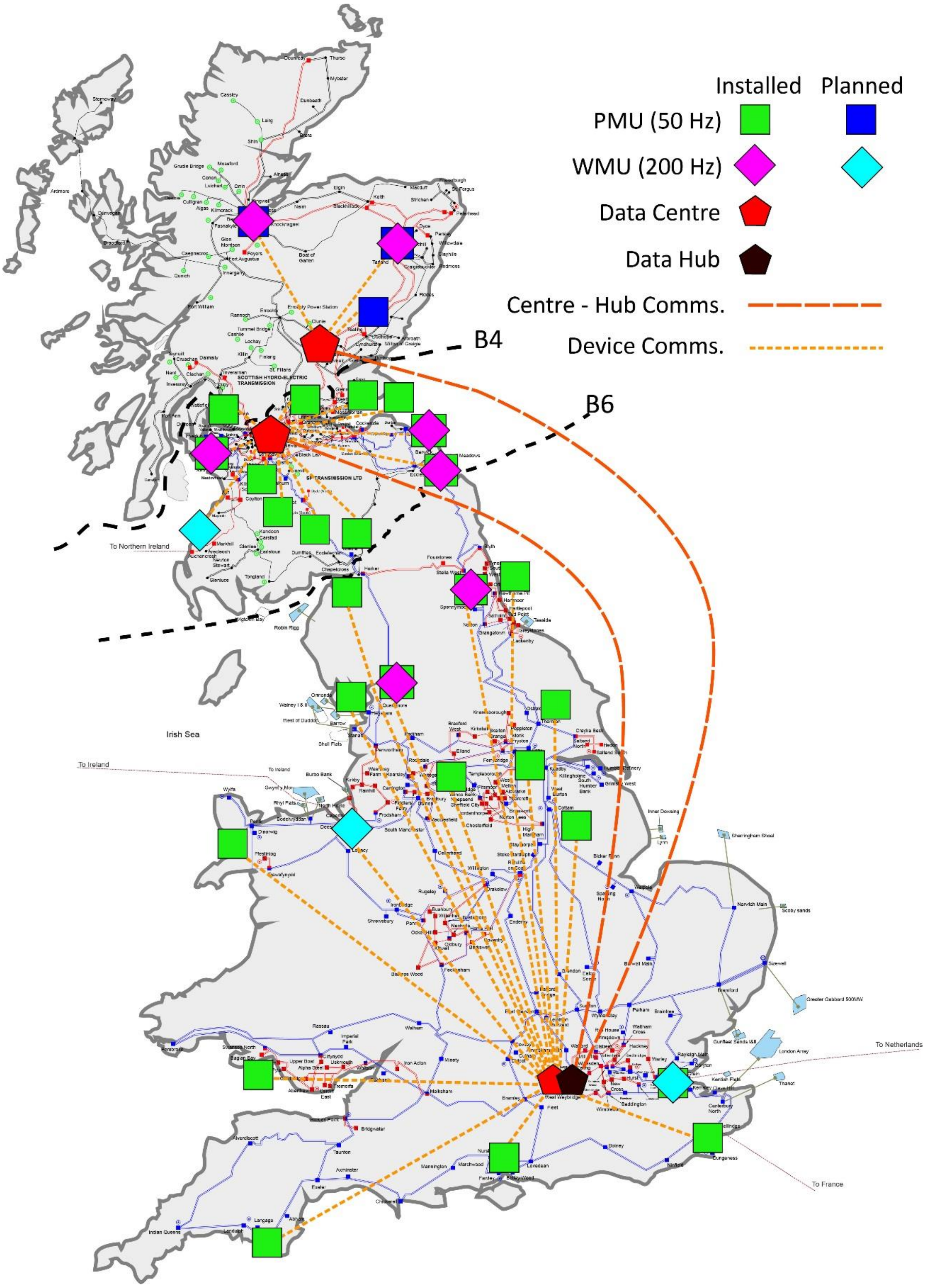


Figure 2 VISOR WAMS Deployment Overview

2.3 Monitoring and Management of Constraints

2.3.1 B6 Display PhasorPoint Application

The B6 display specification was defined in the previous reporting period and described the functions to be presented in the PhasorPoint application for monitoring the power flow across the Anglo-Scottish interconnection, referred to as the B6 Boundary - a prominent constraint boundary in the GB system.

The B6 display was successfully developed and showcased at the Application Demonstration Workshop on 19 November 2015. The figure below illustrates the newly developed application in PhasorPoint.

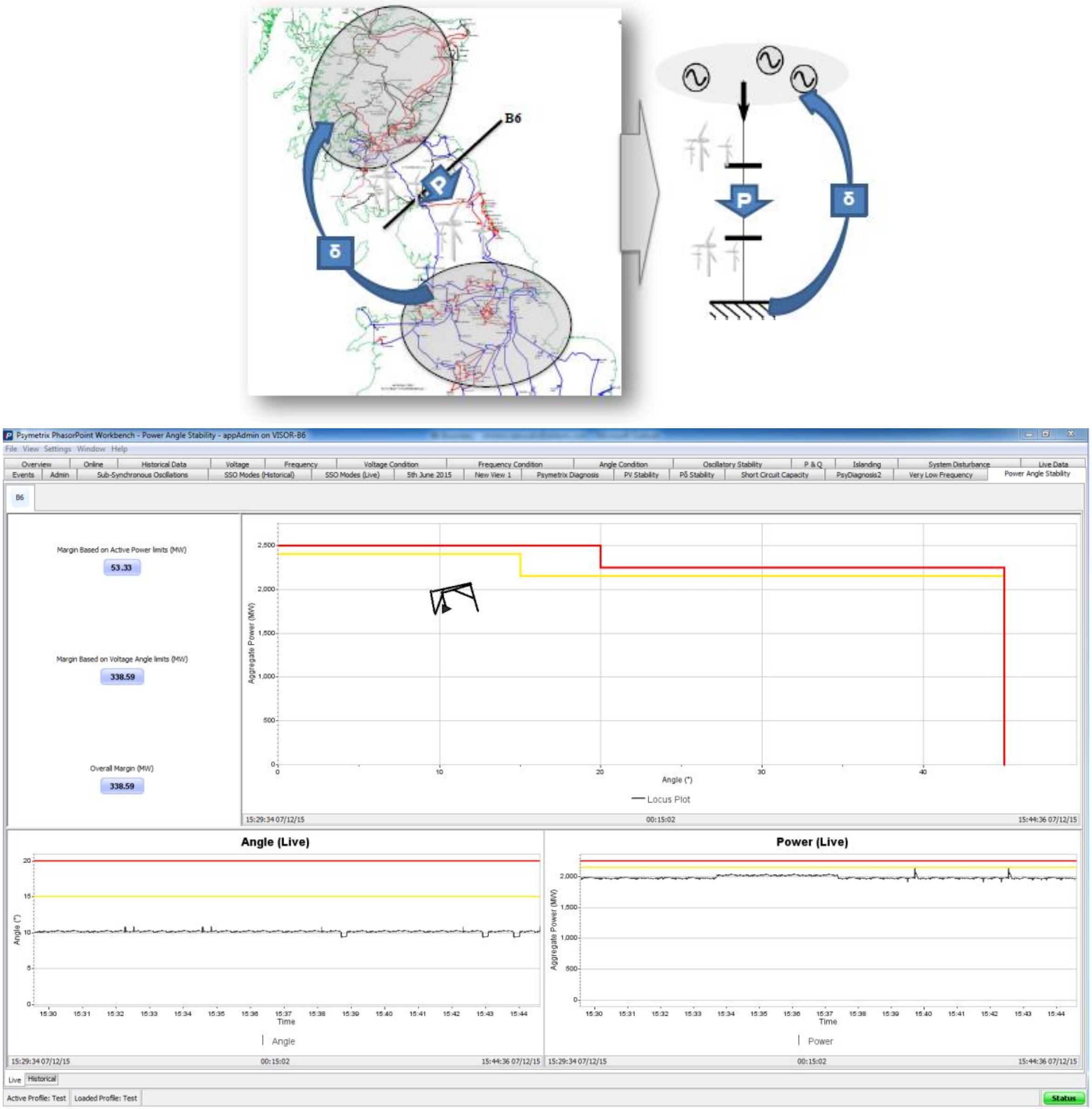


Figure 3 B6 power and angle boundary representation concept and actual

The application derives an aggregated representation of angle in each of the centres of inertia that are involved in the stability limit. These aggregated angles are calculated from PMU measured voltage angles, and user-defined inertia values. An angle limit is expressed in terms of the equivalent angle difference between the two centres of inertia. In addition to the power and angle limits, cut-off limits are also defined corresponding to secondary constraints e.g. thermal / angular separation. An alarm event is triggered if the network operation point is outside both the angle and power limits, or reaches one of the cut-off limits.

The key advantages of including angle in constraint management include:

- Dynamic limits are more closely related to the area angle movement than to the power through a cut-set. Both first-swing (transient) and damping limits are physically related to the following phenomena:
    - Effective impedance between the areas: *Angle increases with weakening of corridor between areas*
    - Loading of the interconnection lines: *Angles increase with power interchange between areas*
    - Distribution of power within the connecting areas: *Angles increase as greater proportion of power far from the boundary*

The visualisation of the B6 display will provide a representation of the aggregated phase difference across one of the system's critical circuits, potentially providing the SO with insight into the real-time operational status of the Scottish system for the first time.

In addition to the benefits to the SO, the visualisation of the angle across the B6 boundary is envisaged to be of benefit to the control centre at SPT; knowledge of the power-angle would aid control centre engineers' decision making process in operation of synchronous interrupting circuit breakers, which require a minimum degree of synchronisation to operate.

The Application Demonstration Workshop demonstrated the successful operation of the algorithms to characterise the power angle across the B6 boundary. The user interface for the display was demonstrated in a primitive form but an enhanced display will be developed to be presented to control room operators in the coming months.

The successful delivery of this functionality satisfies SDRC 9.4.1, *Display incorporating power, angle and associated thresholds*, however, the PDT is not convinced that the application, in its current state, can be used to produce tangible benefits. Further action has been planned for early next year to review the application and improve the application based on suggestions of PDT members, especially NGET SO.

2.3.2 System Disturbance Monitoring (SDM) PhasorPoint Application

The SDM Disturbance Characterisation application utilises PMU voltage angle and frequency data to detect, localise and characterise system disturbances such as line trips and generation losses. The application uses the principle that during a transient disturbance, the frequency and angle of the power system move more rapidly close to the source of the disturbance.

The SDM Disturbance Characterisation application was also showcased at the Application Demonstration Workshop on 19 November 2015. Figure 4 below illustrates the newly developed application in PhasorPoint.

The SDM tool utilises the phasor data to calculate the likely source of a disturbance informing control engineers to take remedial action, such as a ramping down/up specific generation from specific plant. By establishing an understanding of commonality of the different SSO modes, and the possible remedial actions, a severity matrix will be formulated over time, allowing observed modes to be classified as in terms of severity. Presently, no guidelines exist as to how to mitigate SSO; so this project will, through building understanding and experience of SSO, facilitate the development of mitigation actions.

The end result in the first moments after the disturbance (e.g. 0.5 seconds) is:

- Very rapid angle movement near the disturbed bus.
- Larger, faster angle movement at the station buses close to the disturbed bus.
- Smaller angle movement at generators further from the disturbed bus.
- Initial acceleration or deceleration greater close to the disturbance.

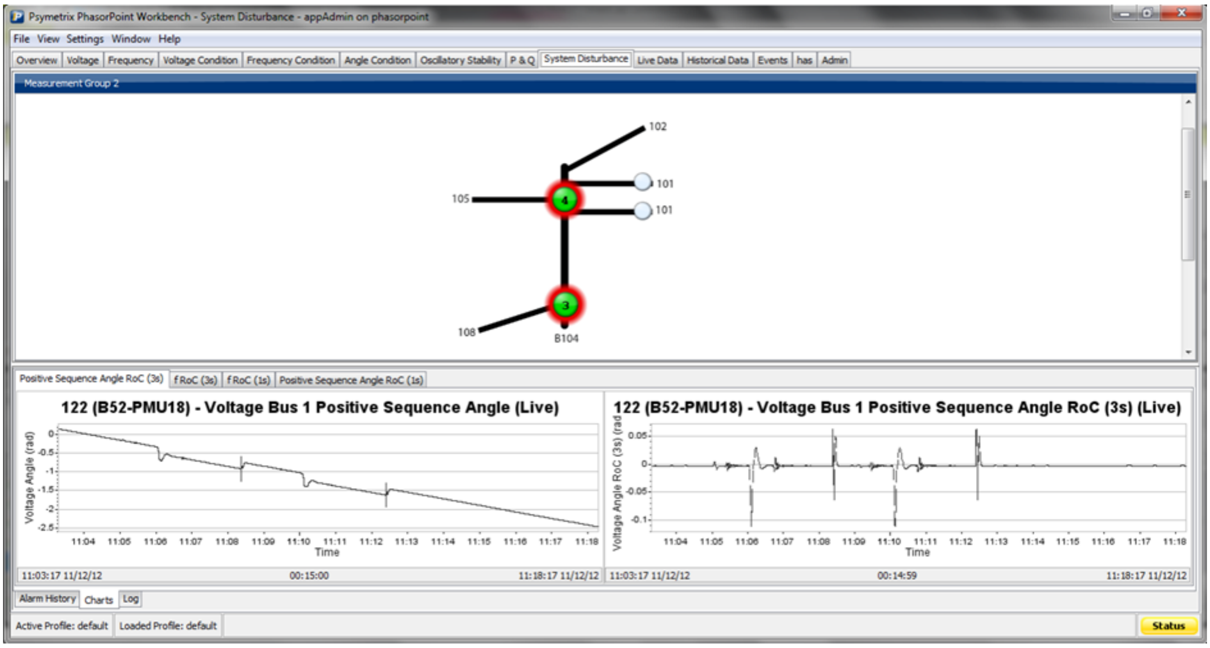


Figure 4. SDM application in PhasorPoint

2.4 System Commissioning Report

The System Commissioning Report documents the key learning generated by the project partners through planning, installing and commissioning the unified WAMS system. The report signifies the completion of each aspect of the WAMS infrastructure proposed in VISOR and satisfies an element of SDRC 9.5.1.

The system commissioning of WMUs, WAMS servers and communication links has generated significant learning regarding the processes, risks and challenges involved in large demonstration installations. The key learning outcomes of the System Commissioning Report are discussed below.

- The most significant learning has stemmed from the delays incurred by the service provider which suffered repeated delays. The order of the MPLS link was placed through NGET who placed the order with their supplier, Verizon, who in turn placed the order with BT. This supplier chain resulted in a convoluted troubleshooting procedure - debilitating SPEN and NGET's ability to query or expedite the process directly with BT.
- Installation of such communication link represents new ground for the innovation teams involved in the PDT, and as such, a full appreciation of the potential risks was not present from the outset. The lack of awareness of potential risks compounded the problem; in hindsight, an optimal plan would have to initially establish an IPSec link between SPEN and NGET whilst awaiting the MPLS link.
- The time scale of innovation projects and the nature of services required needs are challenging to predict from the outset; highlighting the importance of contingency planning and budgeting.

The VISOR System Commissioning Report captures all aspects of engineering involved, the aforementioned challenges and gives insight into the PDT's planning and risk mitigation strategies for successful project delivery.

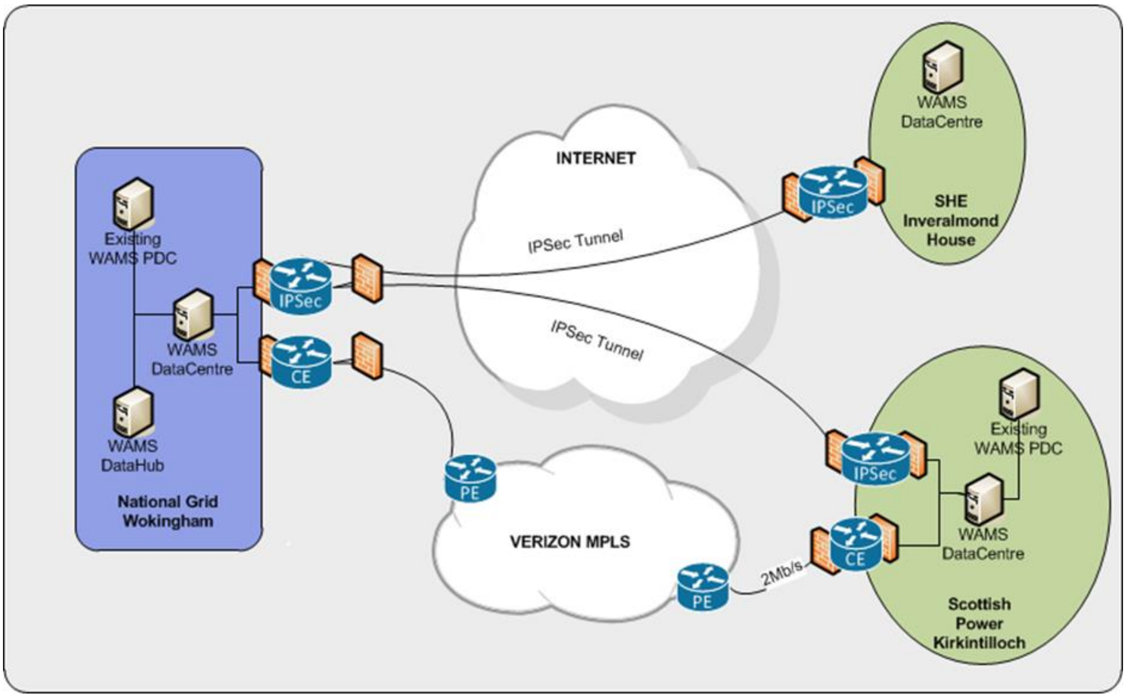


Figure 5. VISOR Communication Links between SHE TL, SPT, NGET and NGET SO

2.5 Visualisation of data in SPT, NGET, SHE TL Transmission including real-time and historic

This milestone has been partially achieved by visualisation of real time and historic data at SPT and NGET. SHE TL have recently completed the commissioning of the WAMS Server at Perth which has enabled them to visual phasor data for the first time, but none of this data has been transferred onward to NGET. Phasor data collected by PMUs and WMUs in SPEN and NGET have continued to inform the TO and SO but have relied on manual data transfer and collation.

The PhasorPoint software relies on one database to compare instantaneous phasor data. The Data Hub is unable to replay historic data from two data sources – it must be collated into one time-synchronised database. Unfortunately, the consolidation from two PDC data sources (SPEN and NGET) cannot take place until a live connection/communication link is established.

The absence of the MPLS link between SPEN and NGET has restricted the visualisation of the GB-wide system to historic data rather than real-time. The interim solution of commissioning an IPSec overcomes this problem.

2.6 Communications infrastructure between TO and SO

A key challenge of the project has revolved around the commissioning of the new communication links between the three transmission network regions. During this reporting report, a contingency IPSec link has had to be instated in place of the repeatedly delayed Multiprotocol Label Switching (MPLS) link, which is now expected for commissioning in 2016.

Whilst commissioning the hardware and communications of each outstation monitoring device requires a degree of complexity and management, any delays have been short and relatively inconsequential. However, the communication infrastructure between the PDCs and the Data Hub at Wokingham has presented a significant challenge, which is a key enabler of the VISOR project.

To accommodate the large quantity of new phasor data gathered within SPT under VISOR, a MPLS link has been selected as the most suitable medium for data transfer between SPT and NGET – providing an unobscured data channel to stream data to the Data Hub at National Grid.

The alternative method is the more conventional Internet Protocol Security (IPSec) tunnel. The key advantage of this method over the MPLS is that the IPSec uses existing infrastructure to pass through data securely across the internet. However, this advantage is also its key disadvantage; by utilising an existing internet connection the IPSec link shares the bandwidth with other services using the same connection. To use a road analogy - an MPLS link is a dedicated motorway, whereas the IPSec link shares the route with all other traffic.

In view of the delays incurred with the MPLS link, the PDT made the decision to execute the contingency plan by configuring an IPSec link between SPT and NGET as an interim solution. Although not optimal, the IPSec link will ensure no SDRC deadlines are affected.

As an added benefit, by employing both IPSec and MPLS links to perform the same task, performance comparisons can be made that will generate useful learning for future implementations. In the event that the IPSec proves incapable of handling the large quantities of PMU and WMU data, an assessment into the necessity for all PMU data will be made - allowing the team to determine a selection strategy.

The transfer requirements between SHE TL and NGET are comparatively small and therefore do not require a dedicated MPLS link. The connection between SHE TL and NGET is in the final stages of configuration and planned for commissioning in early 2016.

2.7 System SSO Behaviour Report and VISOR Workshop

The second System Performance Review and associated Technical Workshop were successfully delivered in November 2015. The Performance Review analysed collected PMU and WMU data acquired between January-September 2015. Significant learnings generated from both the report and workshop are highlighted below:

The noteworthy observations and conclusions from the latest review are summarised below.

- Significant improvement in data quality since previous review - WAMS communications and data quality performance 30-50% of devices are performing well, however the remaining devices present moderate to very poor communications performance and data availability.

- A key data quality issue – the 1mHz resolution in reported frequency – is significantly reducing the effectiveness of oscillation analysis. Various measures are recommended to address this, including re-assignment of analysis to better performing devices and hardware/firmware upgrades to equipment concerned.

- The purpose of the trial project, and the System Performance Review activity in particular, is to uncover and address the challenges that obstruct the adoption of WAMS. Whilst none of the issues identified threaten the overall implementation, the discovery and conclusions are noteworthy and are summarised below.

    - Reporting of GPS Unlock of PMUs:

        - One manufacturer, [redacted], misreporting synchronisation has been identified. Subsequent changes made in PhasorPoint to accommodate.

        - Apparent non-reporting from some devices requires further investigation.

    - Frequency quantisation of PMUs

        - Accuracy of certain devices (using integer rather than floating point) identified in previous review and remains an issue that restricts analytical of low-amplitude oscillations and effectiveness of source location.

        - Presently, only Arbiter and RPV311 devices suitable and prioritised for oscillation analysis. Upgrades to [redacted] devices to be explored further with manufactures.

    - Current stepping identified at one particular site caused by high transducer setting

- Suspicious voltage and frequency at one other particular site. The cause of these steps is unknown and will be monitored further.
- Apparent lack of anti-aliasing filter on [redacted] devices to be investigated further.
- Drift of PMU internal clock identified at number of sites causing 1-second sawtooth in phasor angles. Remedied by upgrade programme.
- Firmware issues observed in Beta version of latest firmware - voltage steps & frequency spikes, unexplained restarts and 90° phase shift. Investigate and re-test in latest release.

- Observed System Disturbances
  - Disturbances detected include three losses of the IFA (Cross-Channel) HVDC link, one loss of the BritNed HVDC link and one loss of the East-West HVDC link. In a number of cases, useful location information is not obtained due to lack of available PMU data (discussed under WAMS performance). Sharing of sparse voltage phasors and frequency values between TOs would add significant benefit, placing detected disturbances in a GB context.
- Low frequency (0.04-1 Hz) oscillatory behaviour
  - A number of oscillatory modes have been detected, including the known 0.54Hz and 0.7Hz modes previously observed. Detailed analysis of these is impaired by limited frequency resolution and availability of data (discussed under WAMS performance). In addition, a new 1.65Hz mode has been detected with poorly damped occurrences that appears to have its source in the West of Scotland. Sharing of sparse voltage phasors and frequency values between Transmission Owners (TOs) would add significant benefit, placing detected local oscillations in a GB context.
- Sub-synchronous (4-46Hz) oscillatory behaviour
  - A number of oscillatory modes have been detected, some showing power electronic characteristics and others that may well be generator torsional modes. Three suspected power electronic control modes are observed near Harestanes and Torness, with period of poor damping. Of particular interest and concern is a 13.5Hz mode that is strongest near Hunterston but visible at Hutton, Eccles and Torness. The mode is also clearly visible in current phasors at Coylton. This mode is mobile in frequency (suggestive of power electronics), and goes through distinct periods of poor damping and large(r) amplitude. It should be investigated as a priority.

2.8 Review of Hybrid State Estimation methods

The University of Manchester have begun work on a review of the benefits of Hybrid State Estimators (HSEs) by conducting a survey of the different techniques employed around the world. The report presents the results of a literature review of existing methods for Hybrid State Estimation in the open literature and their applicability to the goals of the VISOR project, and identifies Integrated HSE as the most suitable study area VISOR.

The review identified that Integrated HSEs will be the focus of VISOR, as they offer benefits to the stability of convergence without requiring infrastructure or techniques that are inconsistent with the existing approach to state estimation in GB. An Integrated HSE combines the phasor data and SCADA data into a single data set that is used for a single iterative estimation procedure. The primary challenge involved in creating an Integrated HSE is including the PMU measurements of currents into the input data set without compromising the performance of the estimator. Four different formulations of Integrated HSEs have been identified: Rectangular Current, Pseudo Voltage, Pseudo Flows and Constrained Formulation. Each of these Integrated HSEs can overcome the challenge of integrating current phasors measurements and will be considered within VISORs HSE work.

The other forms of HSE were discounted during this review for the following reasons:

- Post-Processing HSE cannot improve the stability of convergence, as it depends on the output of the existing state estimator
- Fusion HSE requires complete observability of the power system, which is not a realistic expectation in the GB system at this time, and,
- Distributed HSE performs the state estimate without depending on a centralised state estimator, which conflicts with the existing operating practices that require a centralised state estimator to support the centralised system operator.

The results of this study are being reviewing by the State Estimation experts at amongst the TOs and SO and will inform the next stage of work based on the GB model.

2.9 Knowledge Sharing and Stakeholder Engagement

The VISOR team is committed to knowledge sharing and effective stakeholder engagement to ensure that VISOR can adopt the latest technology advancements, share the lessons learned by/with other stakeholders, facilitate new entry to the market and disseminate the key learning captured along the VISOR delivery.

As the project advances from installation to the operational phase it is essential that generated learning is communicated throughout the businesses, and the wider audience, to guarantee the project is on the right path for further progression into the businesses.

During the reporting report project VISOR has increased focus on both external and internal knowledge dissemination through the following key activities.

Hosting the following dedicated events:

- External stakeholder event in Park Plaza Hotel London, 18 August 2015.
- Internal stakeholder event in the exhibition area at the National Grid Control Centre Wokingham, 24 September 2015.

Furthermore, to increase engagement and involvement with internal members of the organisations not directly involved with the project, VISOR project updates and learning has been presented at the following events:

1. Presentation at Alstom User Group meeting, 28th October 2015.
2. Presentation at EPRI International User Group, 23rd September 2015.
3. Comprehensive presence at LCNI conference, 24th – 26th November 2015.
4. Paper and presentation at PAC World Glasgow, 29th June – 2nd July 2015
5. Presentation at IEEE General Meeting, Denver, 26th – 30th July 2015
6. Paper and presentation at APAP Conference, Nanjing, 20th – 26th Sept 2015
7. Paper and presentation at Cigre Study Colloquium B5, Nanjing, 20th – 26th Sept 2015
8. Presentation and Workshop at EPSRC-NSFC Project Meeting, Chengdu, China 12th – 15th Oct 2015
9. Journal Paper describing VISOR in Special Issue of Modern Power Systems and Clean Energy (MPCE)
10. SGTech Europe Smart Grid conference, Amsterdam, 22nd – 24th Sept 2015
11. EPRI International User Group conference, Dublin, 23rd Sept 2015
12. Alstom User Group meeting, Cannes, 28th Oct 2015.

In addition to the above activities enhancements have been made to the VISOR website, with the inclusion of informative and educational multimedia and improved document sharing. Over the forthcoming periods, the website will become the focal point of stakeholder engagement and will include event tracking facilities along with the ability to access a wealth of VISOR and WAMS learning.

2.9.1 Feedback from Stakeholder Events

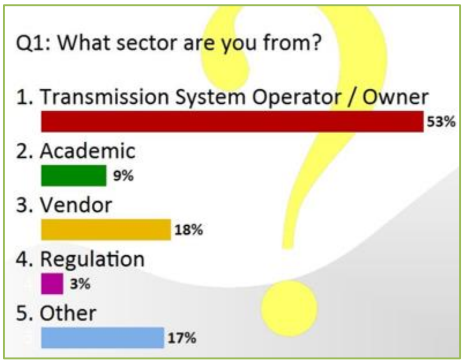
In order to ensure future stakeholder events continue to improve and deliver maximum value to the PDT and the audience alike, the first stakeholder event interweaved feedback throughout the day. The presentations slides asked questions to which the audience could respond using keypads; enabling presenters to dynamically focus on areas that are perhaps less understood or revisit some aspects. More detailed feedback was also requested through feedback forms available throughout the day.

The event was a great success in many respects:

- Prior to the event, only 30% fully understood the objectives of VISOR, with over 40% of the audience had little or no understanding of VISOR and WAMS technology. Following the day, 60% of the audience stated a full understanding with 0% having little or none.
- 9 out of 10 people said the event met all or most of their expectations

The full set of questions and answers are provided for reference in Appendix 2, but some interesting responses for consideration of the project,

- 1 out of 4 people are "not at all" confident that we have the necessary tools to meet the future challenges facing the electricity network
- With two thirds of the audience holding the belief that Wide Area Control is the future for power system operation, with the reminding third requiring more evidence to be convinced.



For continuous improvement, and to ensure the PDT deliver valuable and effective knowledge dissemination events, attendees were requested to provide overall feedback on the day. The team received some promising feedback along with some valuable input for future events.

" *Although my understanding of the system is extremely limited, I understand the importance of VISOR project to the GB Transmission community, as well as the wider international possibilities."*

" *Quite informative, was excited to learn a little bit about the European TO's and their challenges."*

" *Very good presentations! I now feel I have a much better understanding and appreciation of the VISOR project."*

" *I'm very impressed with this event. I think the content was at the right level and the presentations were well thought out and appropriately interactive. There was a clear level of expertise in the room which was helpful as interesting points and questions were raised. I'm pleased to see the progress that is being made and the collaborative nature of the project is encouraging"*

" *Well organised event, rather informative! Congratulations for the good progress, well done Team!"*

" *A very worthwhile event, thank you. Excellent presentations, with a good level of technical detail and also clearly linking the different elements of the project to the overall objectives. It was very helpful to have the overview of different work packages restated in the Q&A, and the quality of the discussion and the way participants were encouraged to contribute was particularly good.*
For future events, might be worth ensuring that a bit more time is spent introducing key

technical terms -we were fine today because the audience mainly comprised technical specialists, but maybe a point to bear in mind.
10/10, thank you!"

" *The quality of the presentations were good. Suggestions for added value - some form of news letter to capture project update to take away. Have name badges to track attendees as a fall back to record data. Rather than general SP give always have project branded. Have a video to explain what Visor is aiming to achieve.*
Positives - interactive voting and regular breaks.
Negatives - venue quite dark and oppressive"

" *Enjoyed the day, content was good. I would like to attend a demonstration day with some of my Real Time Operations Colleagues. I would also like to discuss further the specific requirements of my organisation and possibly of specifying additional VISOR functionality based on our organisational goals."*

" *Good event; well organised and structured. Outlined objectives and purpose of the project well; perhaps more clarity on stages throughout project timeline"*

" *Very good perhaps some people answering questions could have been more concise. Use of feedback questions was good but perhaps over used especially by Alstom"*

" *Good interactive well-managed event."*

" *Excellent day. Great format and diversity of presenters."*

2.10 Outlook to the Next Reporting Period

Looking ahead, the key milestones within the forthcoming reporting period are as follows, in accordance to with the VISOR project direction.

SDRC 9.1.1:

- Baseline and comparator report for SSO behaviour (WP 1, March 2015, March 2016, March 2017)

In light of the concerns surrounding the data quality and data availability in the previous report period, the regularity of SSO behaviour reports has been increased to biannual rather than annual. The next instalment of the analytical reports into the observed SSO behaviour within VISOR is expected in March 2016 and will be the third in the series. The report will draw upon the entire accumulation of SSO measurement data, building on conclusions from previous reports and potentially uncover new frequency modes that may arise during the period.

SDRC 9.2.1:

- Applications delivered and configured to include (WP 1.2, 2.3, March 2016)
  - Geographic oscillation alert presentation
  - Oscillation source location presentation for analysis & real-time
  - Disturbance detection, location identification and impact measures

To supplement and build upon monitoring and detection applications already complete, the next stage of application development will focus on source location tools for identifying contributions to oscillations, and supporting sequence and impact measures in application to provide solutions to manage the events.

SDRC 9.6.1:

- Timely delivery of project progress reports (WP 5.4, Sep 2014, Mar 2015, Sep 2015; Mar 2016, Sep 2016, Mar 2017)

As the project progresses toward completion, increasing effort will support knowledge dissemination and sharing activities to best support the onward progression into the businesses. To successfully share learning, the forecasted knowledge dissemination objectives in the forthcoming report period are:

Dedicated events:

1. Dedicated Internal Stakeholder event at SPEN Control Centre, Kirkintilloch
2. Dedicated Internal Stakeholder event at NGET Head Offices, Warwick
3. Seminar of international experience of WAMS deployment and operation from Dr Vahid Madani, PG&E

And at the following events:

4. All Energy Conference, May 4-5, Glasgow, Scotland
5. CIRED Conference, June 14-15, Helsinki, Finland
6. PAC World Conference, June 13-16, Ljubljana, Slovenia

3 Consistency with full submission

At nearly 24 months into the project delivery, VISOR remains been consistent with the original full submission with regards to resources allocation, project management and project programme.

These consistencies demonstrate the level of detail of the original submission, robust project management currently in place and set a solid foundation for the future delivery.

4 Risk Management [Confidential]

5 Successful Delivery Reward Criteria (SDRC)

The Successful Delivery Reward Criteria set out in the Project Direction links with the Project Milestones and the identified targets directly. This SDRC can be used to check the progress of the project delivery and position the progress against the original proposal. Table 4 lists all the required evidences in line with VISOR project direction for reporting period June'15 – Dec'15.

Table 4. Achieved SDRC in reporting period

Successful Delivery Reward criterion	Evidence
9.4 Successful improvement options for management of transient stability constraints **The demonstration and evaluation of a PMU-based presentation of a transient stability limit, and the assessment of the applicability to the B6 boundary constraint is an important outcome for the project. The project delivery includes:** • **Quantification of the uncertainty in transient stability calculations** • **Improvement in model initial conditions using hybrid state estimation** • **Consultation on visualisation approach for transient stability limit** • **Trial reliability of area angle measurements**	9.4.1 • Report on quantification of uncertainty in stability calculations (WP 3.1, Dec 2016) • **Display incorporating power, angle and associated thresholds (WP 3.3, Dec 2015) (Achieved with restrictions that the application requires further development to realise any tangible benefits)** • Report on findings from benefits of hybrid state estimator (WP 3.2, Dec 2016) • Report on long-term monitoring of area angle measurements (WP 3.4, Dec 2016)
9.5 Successful deployment of the supporting infrastructure of the VISOR project. **The base infrastructure required to collect, store, display and communicate phasor data is critical for the success of the project. This infrastructure should be installed and proven, with adequate performance, and the data linkages between the TO/TSOs implemented to confirm that this part of the project has been delivered. The criteria for delivery are:** • **Data centres running in SPT, NGET, SHE TL Transmission, collecting PMU data from own network, including real-time visualisation, storage, and communications (Dec, 2015)**	9.5.1 • System specification and PMU supplier contracts awarded (April, 2014) • **System commissioning report (WP 4A, Dec 2015)** • **Visualisation of data in SPT, NGET, SHE TL Transmission including real-time and historic (WP 4A, Dec 2015) (Achieved by NGET and SPT, not completed by SHE TL)** • Roll-out report (WP 4A, Dec 2016 - March 2017)

• **Central VISOR server and inter-TO data exchanges running** ➢ **Optimal GB roll-out investigation**	
9.6 Successful dissemination of knowledge generated from VISOR project. **Knowledge dissemination within the transmission network owner is a key component to transfer experience for the pre-trial training and post–trial knowledge exchange. The key objectives of this work package are to successfully achieve the following:** • **Internal knowledge dissemination** • **External knowledge dissemination** • **Influencing and updating policies and standards** • **Public Engagement**	9.6.1 • Establish on-line portal and keep up to date throughout project (WP 5.2, Sep 2014) • **Timely delivery of project progress reports (WP 5.4, Sep 2014, Mar 2015, Sep 2015; Mar 2016, Sep 2016, Mar 2017)** • Academic partner delivery of knowledge capture and publications (WP 5.2, Dec 2016 - Mar 2017) • **Presentations and show-casing at the annual innovation conferences (WP 5.4, Dec 2014, Dec 2015, Dec 2016 and June 2017 for Close-down report dissemination)**

6 Learning Outcomes

Following the Authority's formal approval in December 2013, VISOR has made good progresses regarding project partner collaboration agreement, project management and governance establishment, procurement and knowledge sharing. There are challenges and risks (as detailed in the section above and the Risk Register in Appendix 2) along the development, and lessons are derived from every aspect.

Lessons Learnt (+/-)	Lesson Learnt	Recommended Action
Positive	The presence of a contingency plan and coordination between PDT to overcoming uncontrollable delays.	By executing the contingency plan, the project milestones, and other dependant work streams, are not adversely affected.
Positive	Stakeholder engagement – both External and Internal – benefits to audience and the PDT. The stakeholder events enable the project team to engage with both the external wider industry, UK and international, and with key internal stakeholders that are not directly involved with project delivery.	VISOR will continue and improve stakeholder engagement as the project progresses and ensure key stakeholder needs are satisfied. Other innovation projects can use the stakeholder activities as a template.
Positive	Examples of challenges and benefits of WAMS, and their deployment strategy, can be drawn from discussions and demonstrations of international utilities and advisory bodies.	Ongoing engagement with external parties, through conferences and dedicated meetings, to ensure learning acquired from others, where possible.
Negative	Minimise supply chain where possible e.g. avoid intermediary bodies, which distances project team from deliver team and has reduced clarity and control of issue.	Future projects to learn from experience with placing order with BT through intermediary body, Verizon, and ensure other avenues of procurement are considered, .e.g SPEN do not have service contract and could have placed order directly with BT.
Negative	Early engagement with business IT experts important for assuring technical requirements are understood on both sides that deployment schedules are realistic. This should be done at the tendering stage.	Business IT experts should be engaged early in project delivery and specification stage to avoid potential risks and delays.
Negative	Need for greater emphasis on IS Infrastructure on System monitoring projects	Early engagement from all IS Partners from all involved parties to arrive at realistic estimates for the project

6.1 Technical Learning

6.1.1 System Commissioning Learning

The System Commissioning Report details the learning acquired throughout the planning, installing and commissioning of the WAMS infrastructure that underpins the project. The key elements of the learning generated throughout the system commissioning are summarised here.

Complexity of MPLS link

In order to support the data transfer rate from the Data Centres to the System Operator's Data Hub, SPT chose to install a direct MPLS link between Kirkintilloch and Wokingham to support large fleet of phasor measurement devices in SPT. However, with fewer monitoring devices, an IPSec link provides sufficient data transfer capacity for the link between SHE and NGETSO.

The advantage of a dedicated, unobstructed, high-performance point-to-point connection offered by the MPLS link is also its largest disadvantage. Implementing an MPLS or any Wide Area Network (WAN) that may require new cabling is not straight forward, and in this case, the work required to establish the MPLS link must be carried out by BT Openreach. Unfortunately, the project has suffered extensive delays as a result of this involvement and, although the issues have been escalated as far as possible, deadlines are repeatedly missed and delayed further. The seemingly trivial task of configuring a new WAN is currently delayed by 12 months and a separate IPSec link has been implemented to mitigate further impacts.

Data quality and uncertainty volumes from PMU and new WMUs

With respect to Innovation projects in general, the very nature of the project means there is a significant amount of uncertainty and lack of clarity, so trying to track to very tightly controlled budgets is a significant risk to all projects.

Initial estimates of traffic volumes were based upon invalid assumptions on which data would be transferred and were a bit low. Add to this the increased number of WMUs and the initial bandwidth calculated for the NG to SPEN WAN link would not be sufficient for the duration of the project. There have been ad-hoc firewall changes to incorporate the data streams identified as part of the 200hz data transfer, as the network support is outsourced then each change has a time and cost impact.

Consideration of wider business plans

There is a trade-off between trying to get an innovation project up and running as soon as possible, and keeping strategic options in consideration. This can lead to innovation decisions being purely tactical as a proof of concept, but would require complete reengineering for a strategic implementation.

6.1.2 Investigation of Planning Rules for the Mitigation of Sub-synchronous Resonance

Series capacitive compensation is a cost effective means of increasing the maximum power flow over a transmission line without reducing the transient angular stability of the system. A transmission line is primarily inductive in nature, so introducing a series capacitor reduces the effective reactance of the line. Reducing the reactance of the line allows the operator to increase the power flow on the line for a given angular separation across the line.

However, introducing a fixed capacitor in series with the inductance of the transmission line creates a series resonance circuit which will have a sub-synchronous and a super-synchronous resonant frequency.

The sub-synchronous resonant frequencies that exist in a series compensated transmission system (henceforth, referred to as the electrical modes) can interact with the torsional resonant frequencies of a long shafted generator (torsional modes) as part of the phenomena of sub-synchronous resonance (SSR). SSR entails the transmission system and the generator shaft exchanging energy back and forth between them. If not sufficiently damped, this oscillatory exchange of energy can severely damage, or even destroy generator shafts.

In a simple radial system severe SSR (like that depicted in Figure 6) is more likely to occur, as the generator is connected directly in series to the capacitor, but is also easier to mitigate, as only a single interaction must be studied, as there is only one series capacitor, and there exist a limited number of scenarios (e.g. different combinations of line outages) to study. This study system is the IEEE first benchmark model and can be used to represent the deployment of series compensation to connect a large, remote generator to the rest of the transmission system.

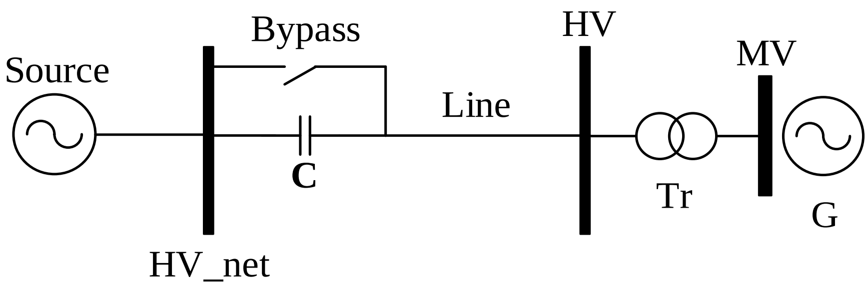


Figure 6. IEEE First Benchmark Model for the study of SSR in radial systems

However, this simple scenario is not representative of the use multiple series capacitors to increase the maximum power flow over a given transmission boundary in a meshed power system. Consider the example system presented in Figure 7 or the series compensation project to reinforce the B6 boundary in the GB system. In these meshed systems severe SSR is less likely to occur, in general; because it is less likely that a generator will find itself radially connected to a series capacitor. However, the complexity of the system, the use of multiple series capacitors and the multitude of different outage scenarios means that the study of SSR is far more complex and uncertain.

Multiple series capacitors will introduce multiple electrical modes and the different outage scenarios will cause the damping and frequency of each of these multiple modes to vary. This means that the mitigation of SSR in meshed systems must address an operating envelope rather than a single operating point.

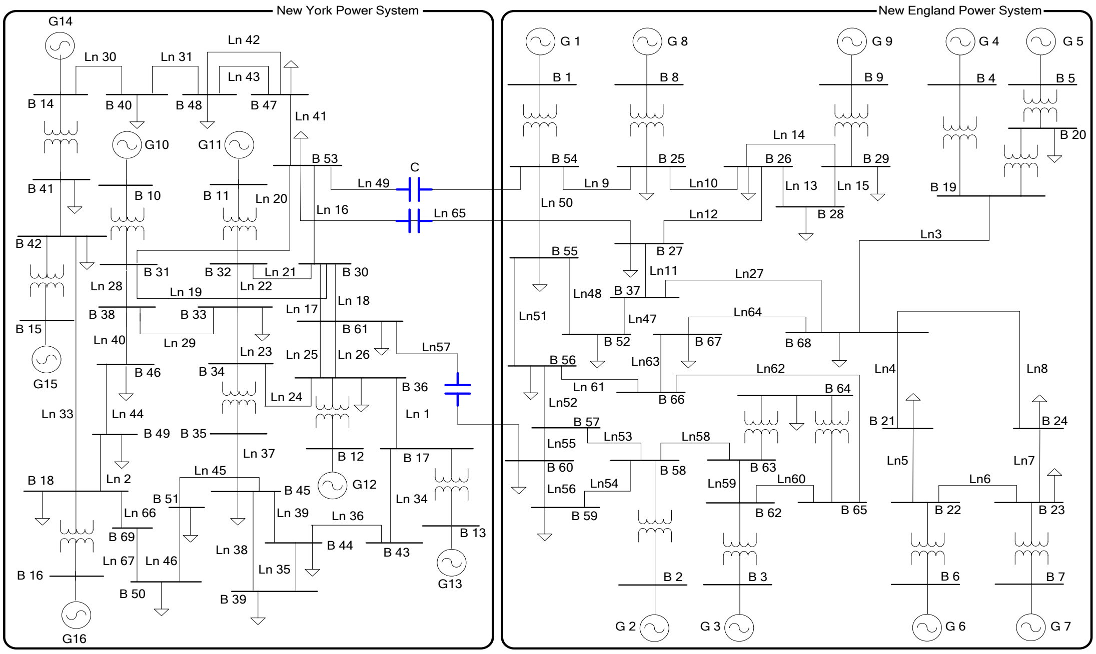


Figure 7. IEEE 68 Bus system that is representative of the New York and New England power systems and has been used for the study of SSR during VISOR, with an example of multiple series capacitors to increase the power transfer between the two areas.

The threat posed by SSR to power system plant means that the installation of any equipment that may participate in such interactions (e.g. series compensation) is accompanied by detailed network studies to design suitable mitigation actions for any probable threats. This may involve classical solutions, like Static blocking filters (BF), Static Excitation Damping Control (SEDC), or comparatively new solutions, like the installation of TCSC or HVDC converter controls. However, the development of monitoring systems for sub-synchronous interactions would allow the ongoing effectiveness of these solutions to be verified as the system evolves and would allow the development of early warning systems that could alert the system operator to emerging threats, so they may respond appropriately prior to the oscillations becoming dangerous. Furthermore, monitoring provides the ability to detect underlying low-level oscillations that will cause gradual wear of system components, shortening their lifespan, and may develop into threats during strained system conditions or major events.

Therefore, the role of WAMS in the mitigation of SSR is to complement, not replace, the existing planning based studies and measures. Therefore, an aspect of the research in VISOR has been the study and evaluation of the existing planning based methods and tools for the assessment of the threat of SSR.

An example of an existing method for the assessment of the threat of SSR to a specific generator and for a given operating condition is a frequency scan. A frequency scan consists of calculating the equivalent reactance of the power system, as viewed from the terminal of the generator under study, for a range of frequencies. An example of the output of a frequency scan is given in Figure 8. A frequency scan indicates the presence of an electrical mode through a 'dip' in the reactance. The size of this dip is assumed to indicate the potential severity of the SSR that would occur if this electrical mode were to interact with a torsional mode. Note, that due to how electrical oscillations are seen by the mechanical system, and vice versa, an electrical mode and torsional mode will interact if the frequency of the complement of the electrical mode is close to the frequency of a torsional mode, or vice versa. Where, the complement of a mode appears at a frequency equal to f_n-f_{mode}, where f_n is the nominal frequency of the power system. This approach allows simple analysis of complex systems; however, it fails to replicate certain interactions and complexities

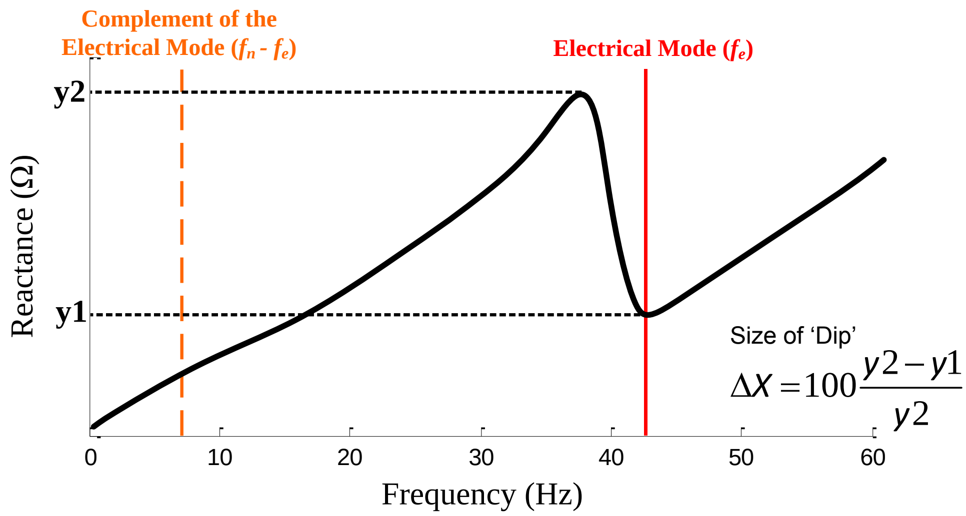


Figure 8. Example of the result of a frequency scan, the position and size of the dip in reactance caused by a resonance can be used to screen cases for the severity of, and potential for, SSR interactions

A well-established rule in the literature is that the an electrical mode poses a threat of SSR if a dip of more than 5 % is observed within +/- 3 Hz of the complement of a torsional mode. This rule is recommended as a method for screening the cases that should be considered for further study and has become widely accepted as the basis for several published approaches for the study of SSR and the calculation of indices for the threat of SSR in meshed systems.

However, whilst this rule does perform well for many cases and was originally proposed as a 'rule of thumb' rather than a rigorous screening method, studies performed during VISOR it has been found that this rule can be misleading at times, as very similar dips can lead to profoundly different responses when time domain transient simulations are performed, see an example of this in Figure 9. This is a threat, as performing electro-magnetic transient simulations for large systems is currently impractical and this screening is critical to identifying the cases that simulations will be developed for. Therefore, given the importance of this rule to the existing study of SSR further research into the flaws of this rule and potential refinements seems of great importance.

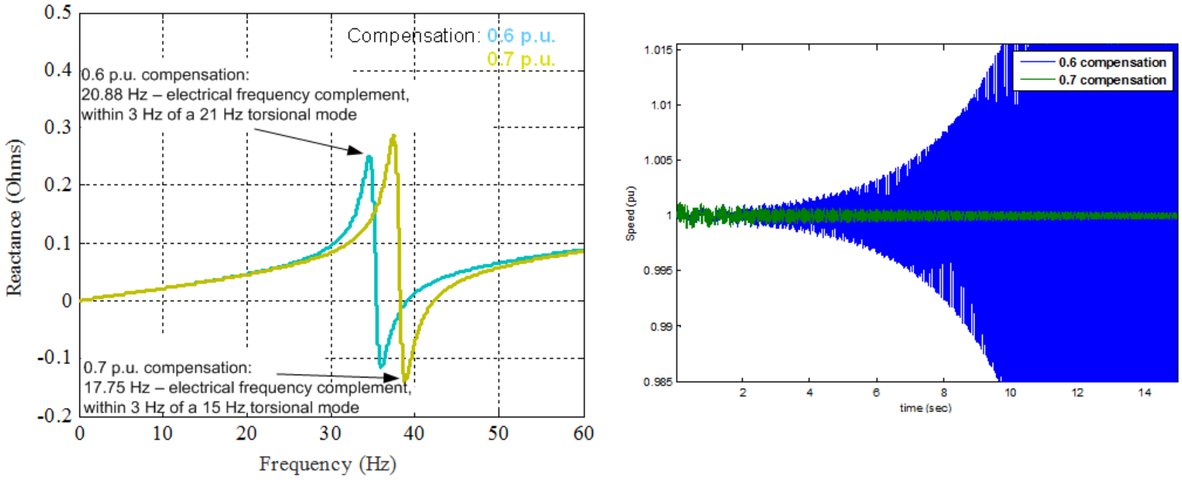


Figure 9. An example of how frequency scans can fail to accurately identify cases where SSR is a threat. Very similar dips can return very different results in time domain analysis.

Furthermore, it has been found that it is possible for an electrical mode to interact with a torsional mode that is outside of the +/- 3 Hz band, even when another torsional mode is within the +/- 3 Hz band. Figure 10 shows an example of this where despite the proximity of the electrical mode complement to the 20.728 Hz mode the interaction clearly occurs at 26.1 Hz. This behaviour could compromise the mitigation of SSR through the use of passive filtering.

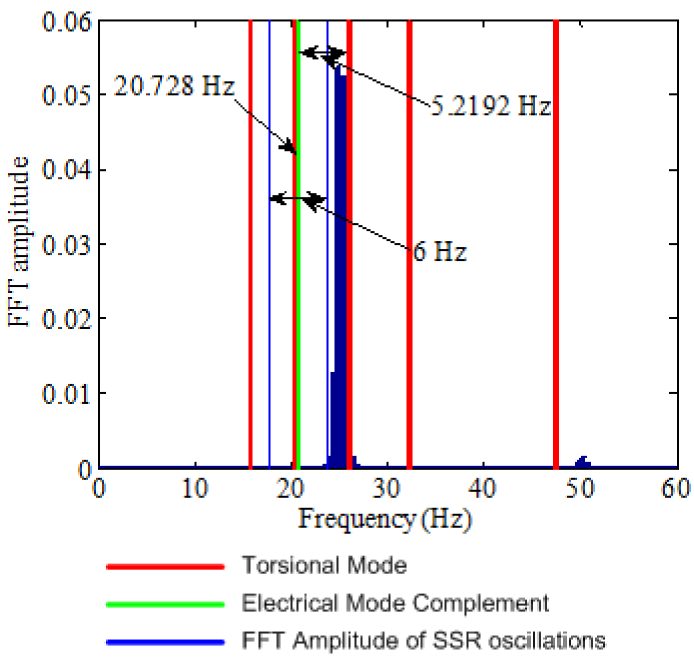


Figure 10. Example that SSR is not simply a function of the proximity of torsional modes and electrical mode complements

The relative damping of modes can allow interactions between torsional modes and electrical mode complements that are more distant than the 3Hz band. Furthermore, the FFT results show that the interaction may occur with a mode complement that is further from the torsional mode than other mode complements.

Both of these results indicate are due to the variation in the electrical damping at different frequencies; therefore, a key outcome of this research is that the electrical damping should be considered in more detail as part of SSR studies and during the creation of screening rules.

6.1.3 Optimal Placement for Monitoring Sub-synchronous Oscillations

If wide area monitoring is to provide solutions for the threat of sub-synchronous resonance (SSR), or any other sub-synchronous oscillatory threat, synchronised measurement devices must be placed in the right places in the system to provide visibility of these oscillations.

To ensure that the monitoring required is provided at the lowest cost, methodologies must be developed for the optimal placement of synchronised measurement devices for monitoring SSO.

This placement is a particular challenge for oscillations in the torsional range of 4 – 46 Hz, as this visibility is provided by the WMUs that are being deployed for the first time as part of VISOR, and not by PMUs that make up the vast majority of the measurement devices deployed in the VISOR WAMS, or any other WAMS. Therefore, the number of devices that can provide visibility of this range of oscillation will be reduced and, as such, their placement must be considered more carefully.

Furthermore, unlike those methods developed for the optimal placement of PMUs for state estimation, methods for ensuring the optimal placement of synchronised measurement devices for the monitoring of oscillations must reflect the dependence of the quality of monitoring on the relative positions of the monitoring location and the oscillation source and the signal that is monitored.

Figure 6 depicts an example of how an oscillation is observed at the MV and HV bus of a series capacitor, where the oscillation source is in the MV system. Therefore, understanding the source of any oscillation that is observed in the system will at times form a key aspect of ensuring the improved monitoring of that oscillation in the future.

Furthermore, oscillations will not be observed equally in all signals. Figure 11 shows how a 20 Hz oscillation in the IEEE First Benchmark Model is seen more clearly in turbine power than in current and voltage and that the 16.5 and 32 Hz oscillations are only seen in the turbine power.

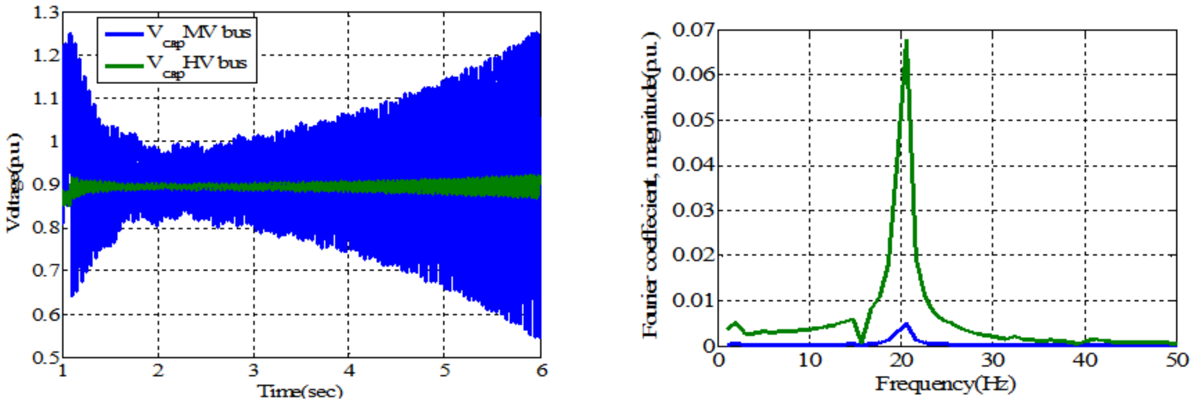


Figure 11. The relative position of a monitoring device and the source of an oscillation can impact significantly on the visibility of an oscillation. This example is for the placement of a measurement device on both sides of a series capacitor where the generator participating in the interaction is on the HV side of the bus.

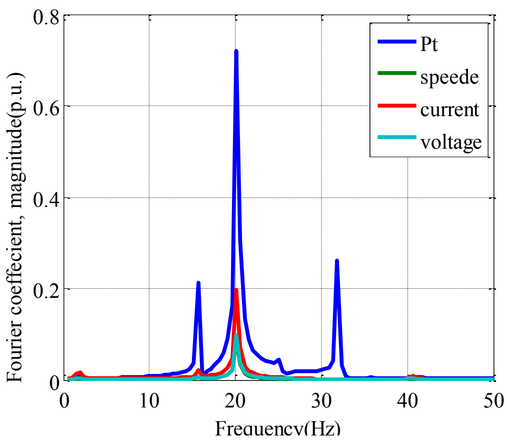


Figure 12. FFT amplitudes comparing frequency signatures in different system signals obtained from IEEE First Benchmark Model at the generator bus. Pt is turbine power, “speede” is the speed of the generator, and the voltage and current are measured at the machine

In order to contribute to the optimal placement of synchronised monitoring devices for ensuring the visibility of torsional interactions a screening methodology has been created that:

1) Identifies generators that should be prioritised for monitoring (the *critical generators*)
2) Identifies the lines that the removal of which will leave the system more vulnerable to SSR (the *significant lines*)

A summary of the results of applying this methodology to the 16-machine, 68-bus IEEE test network is presented in Figure 13. From this it can be seen that the methodology can identify significant lines and critical generators that may not be immediately apparent, e.g. G10 and Ln 20.

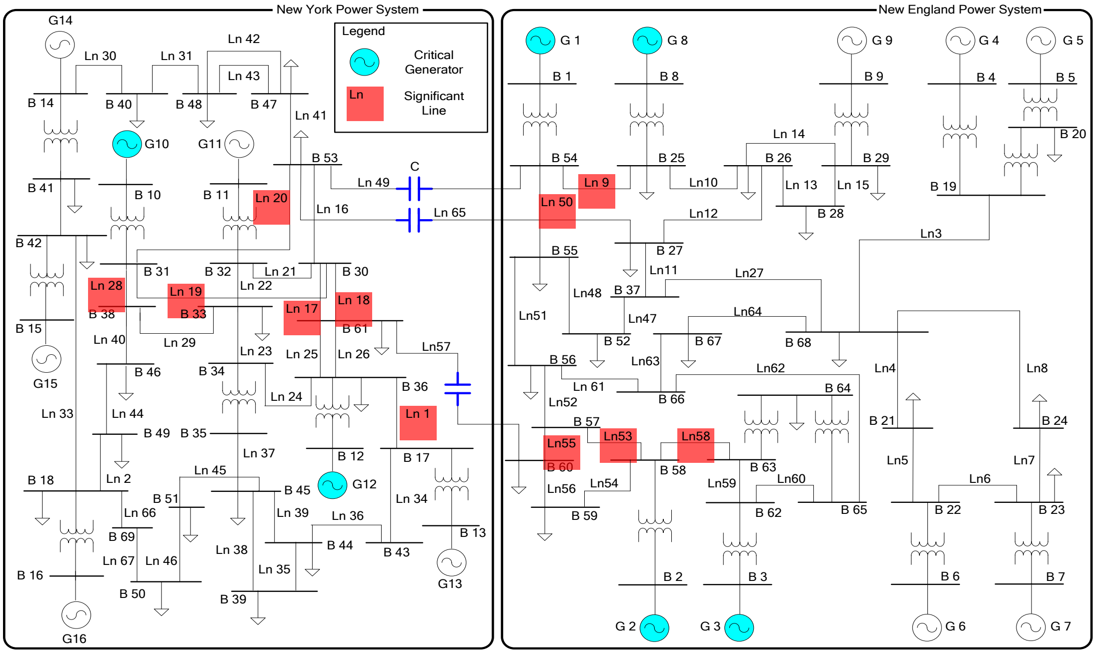


Figure 13. 16-machine, 68-bus IEEE test network. Highlighted generators and lines indicate candidates that could be considered for monitoring being electrically near to the two compensated line. This emphasizes the need for development of optimal placement

The methodology uses a combination of linear and non-linear studies and is performed as follows.

The methodology studies various outage scenarios (i.e. cases where a combination of lines are removed from the system) to identify critical generators that may be vulnerable to SSR based on frequency scan studies (a generator is deemed to be critical if it has a reactance dip of more than 5 % in any case). Examples of the severity of dip for each critical generator in the 68 bus system are given in Figure 14 for two different compensation locations.

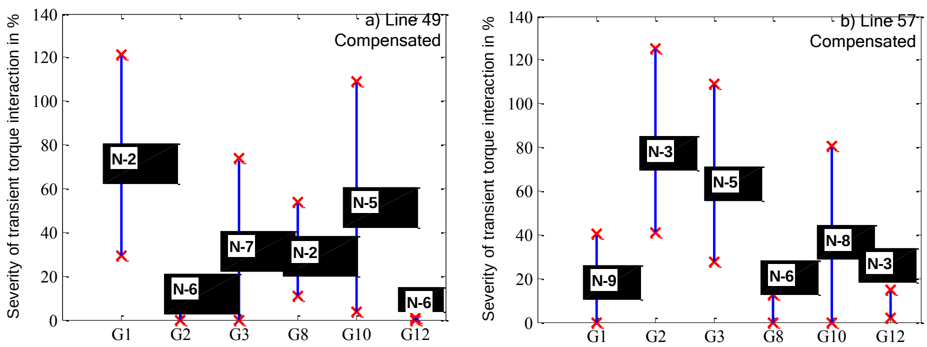


Figure 14. The severity of the interactions for the critical generators measured using the size of the dip in a frequency scan. The critical generators are those that have a reactance dip of more than 5% for a case. N is the number of line outages needed

Then the electrical damping of the modes is assessed for various line outages for each critical generator to identify combinations of line outages that will leave the generator more vulnerable to SSR. These cases are referred to as outliers, as in most cases the damping is good. Note that in SSR studies the electrical damping is treated as negative damping or undamping, so large values of electrical damping indicate a poorly damped mode.

Estimation of damping is preferred to simply using a frequency scan, as it can identify cases that frequency scan alone cannot, compare the Figure 15a and 14b,where the frequency scan results for two line outages identify only a single case that is distinct from the others but the damping estimates clearly indicate two cases as outliers. These outliers indicate the presence of lines that are not intuitive for a meshed network but are still shown to expose the system to dangerous SSR. The outlier cases have been verified using EMT. The fact that the methodology provides dual screening in the form of susceptible generators and outlier lines reduces the need for EMT simulations of numerous cases, thus saving considerable time and effort.

Awareness of these lines would allow the operator to anticipate scenarios where the system may be exposed to dangerous oscillations and create suitable solutions. For example, this information could be used to inform maintenance schedules (e.g. avoid the outage of multiple significant lines at once) or as an arming signal for some form of system integrity protection scheme.

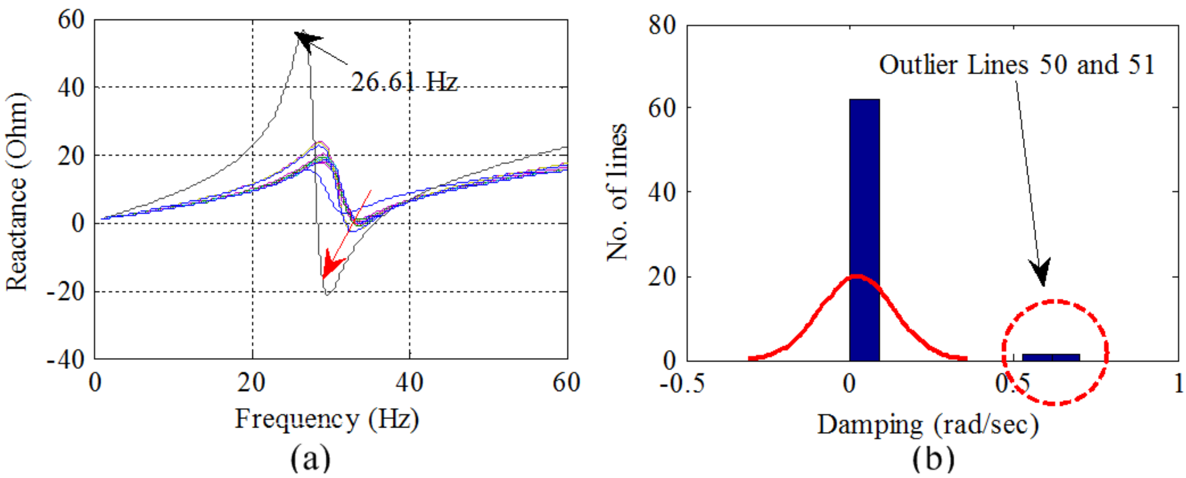


Figure 15. Frequency scan results and damping estimates for the outage of two lines. In all cases line 9 is assumed to be out and the other lines are taken out in sequence. Frequency scan only identifies one outlier (a) whilst the damping estimates correctly identify both outliers

6.1.4 Comparison of Hybrid State Estimators

The role of a state estimator is to estimate the Voltage Phasor, i.e. Voltage Magnitude and Voltage Phase, at every bus in the system (the system state). The existing GB state estimator is a classical state estimator that uses measurements of voltage magnitude, and active/reactive power flows and injections from the Supervisory Control and Data Acquisition (SCADA) system to estimate the power system state through an iterative procedure. However, Phasor Measurement Units (PMUs) directly measure the Voltage Phasors, so naturally lend themselves to supporting state estimation, either through a linear or hybrid state estimator. A Linear State Estimator (LSE) directly calculates the power system state without an iterative estimation procedure, as with sufficient PMU measurements estimating the system state becomes a linear problem. This requires full observability of the power system (PMUs at approximately 1/3 of all buses), which is not a realistic expectation in GB at this time. A HSE is so named because it combines both Phasor data and SCADA data into a hybrid estimation procedure, at least part of which is iterative. How these different forms of data are combined defines the nature of a HSE and this review has identified four main types of HSEs, namely: Post Processing, Integrated, Fusion and Distributed.

In the previous reporting period the Hybrid State Estimators (HSEs) that would be studied during VISOR were selected, these were four formulations for an integrated HSE:

- Rectangular Current (RC)
- Pseudo Voltage (PV)
- Pseudo Flows (PF)
- Constrained Formulation (CF)

Research has now begun into how best to compare the performance of these HSEs and a post processing HSE has been included to provide a reference for the accuracy and convergence speed of the integrated HSEs.

Existing publications have usually focused upon demonstrating that a new HSE, which is being proposed in the publication in question, is superior to classical state estimation in terms of accuracy. The comparison being performed in VISOR represents one of the first direct comparisons of multiple HSEs and the goal is to extend this comparison beyond simply considering accuracy.

Presented below are some of the initial results of this comparison for the IEEE 14 bus test system, depicted in Figure 16. These results are incomplete but do indicate some interesting features of this comparison that will be further studied in the future.

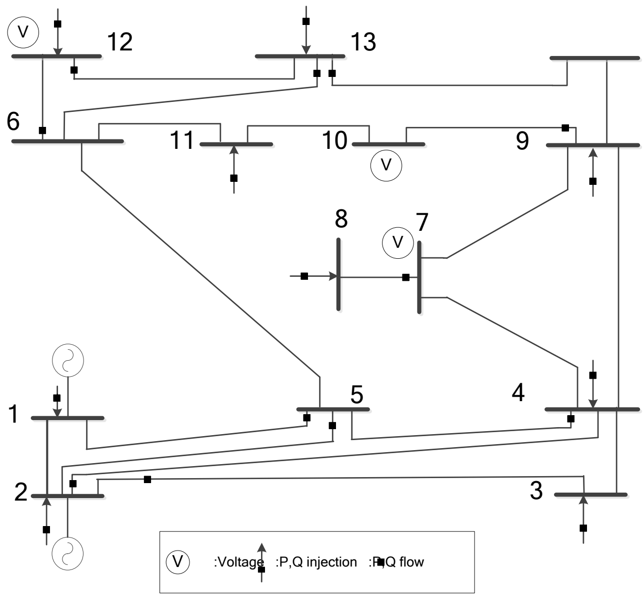


Figure 16. IEEE 14 bus tests system and conventional measurement placement

From Figure 17 it can be seen that the Pseudo Voltage HSE does not appear to perform well, in terms of accuracy when compared to the other HSEs for either a small or large number of PMUs. To verify this result two different formulations of the Pseudo Voltage HSE (a direct derivation and an unscented transform were included in the assessment).

Furthermore, the localised impact of PMUs can be observed in both Figure 17 and Figure 18. Although this localised impact is more evident for the post processing HSE, due to the nature of its formulation.

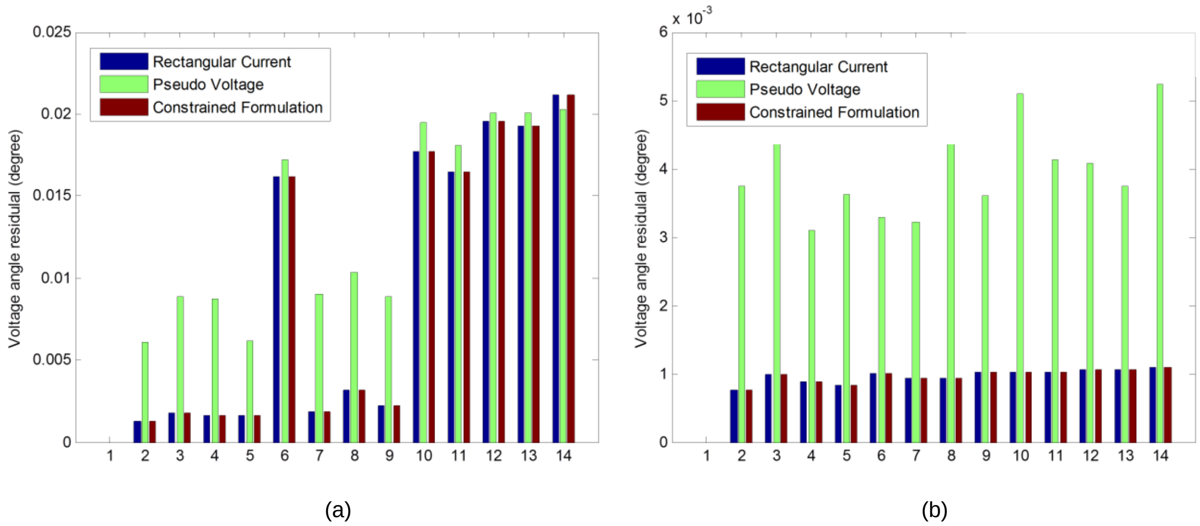


Figure 17. Estimated voltage angles for the IEEE 14 bus system with PMUs at Buses 1 and 4 (a) and the estimated voltage angles for the IEEE 14 bus system with PMUs placed at all buses (b)

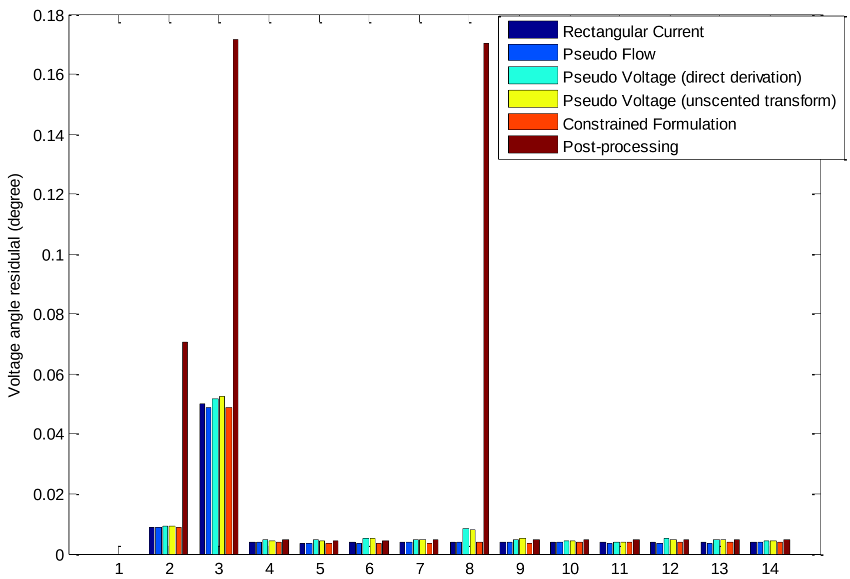


Figure 18. Estimated voltage angles for IEEE 14 bus system with PMUs placed at Buses 6 and 9

Figure 19 shows the average convergence time and variance in the states for each HSE for different numbers of PMUs. All combinations of PMU placements are considered for each number of PMUs, i.e. every possible way of placing 1 PMU in the 14 bus system is tested, so for 1 PMU 14 cases are tested.

From this it can be seen that the integrated HSEs begin to converge more slowly as the number of PMUs increases. This is more evident for the constrained formulation (cf) because it includes the current magnitudes and angles as states, so as PMUs are added the state vector increases in size and it takes longer to solve the inverse of the gain matrix.

Furthermore, it can be seen that the variance of the states decreases as the number of PMUs increases, although the benefit of each PMU is far reduced for the post processing HSE. The performance of the integrated HSEs is mostly similar, apart from the pseudo voltage HSE. The noticeable step changes in variance that occurs between 8 and 9 PMUs, exists because at this point the vast majority of PMU placements makes the system full observable using only PMUs. The improvement is most noticeable for the post processing HSE, as this means that

These results are neither conclusive nor complete, and several open questions exist. Although they do demonstrate that the comparison of HSEs and the selection of the number of PMUs that should be incorporated into an HSE is a complex task that should not be assessed in terms of only accuracy.

For example, the constrained formulation (cf) offers some of the best performance in terms of variance for all numbers of PMUs and performs best when all buses have PMUs. However, this improvement in accuracy must be balanced against the significant increase in convergence time for the constrained formulation as the number of PMUs is increased, particularly when considering larger systems. Therefore, the 'best' performance of this HSE, from the perspective of the user, will likely be achieved for a smaller number of PMUs.

As such, the goal of this comparison is, through collaboration with the GB system operator and transmission owners, to attempt to create an index that balances the various measures of HSE performance (e.g. accuracy, convergence time and number of PMUs) to effectively score the performance of each HSE for a given number and placement of PMUs.

If successful this should provide a useful tool for investigating the potential role of HSE in the GB system, but require extensive study for larger test systems and collaboration between the partners because, by their nature, indexes are heuristic in nature will only be of value if they are designed properly.

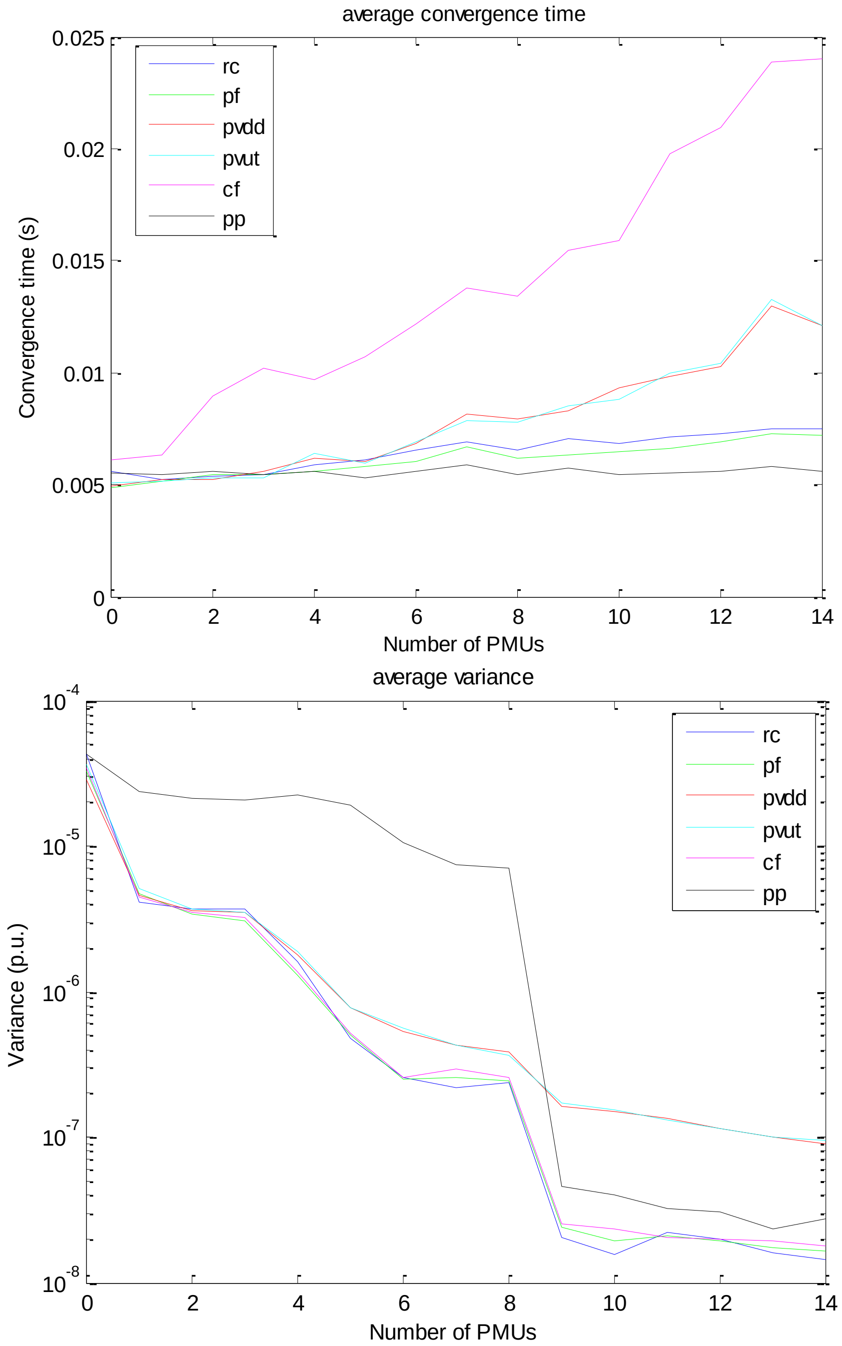


Figure 19. Average convergence times for each HSE for different numbers of PMUs for the IEEE 14 bus system

6.1.5 Enhanced Observability Analysis for State Estimation

Observability is a critical requirement for state estimation. If a system is observable it means that the system state (i.e. the voltage magnitude and angle at each bus) can be uniquely estimated based on the available measurements.

Ensuring observability of the system is essential when attempting to ensure convergence of any state estimator and VISOR has identified that one of the key benefits of synchrophasor enhanced state estimation is the potential for improved convergence. Therefore, some study has been devoted to the existing methods for observability analysis of power systems.

Observability analysis can be broken down into two stages:

1) Determine if the system is fully observable
2) If the system is not fully observable, identify the observable islands in the system and how best to restore observability

This analysis must be performed on an ongoing basis to ensure that the next execution of the state estimator will be able to converge. Therefore, observability analysis should be performed as part of online operation.

One aspect of observability analysis is identifying the observable islands, i.e. the sub-networks within the power system in which the states can still be uniquely estimated with the measurements available, like those depicted in Figure 20.

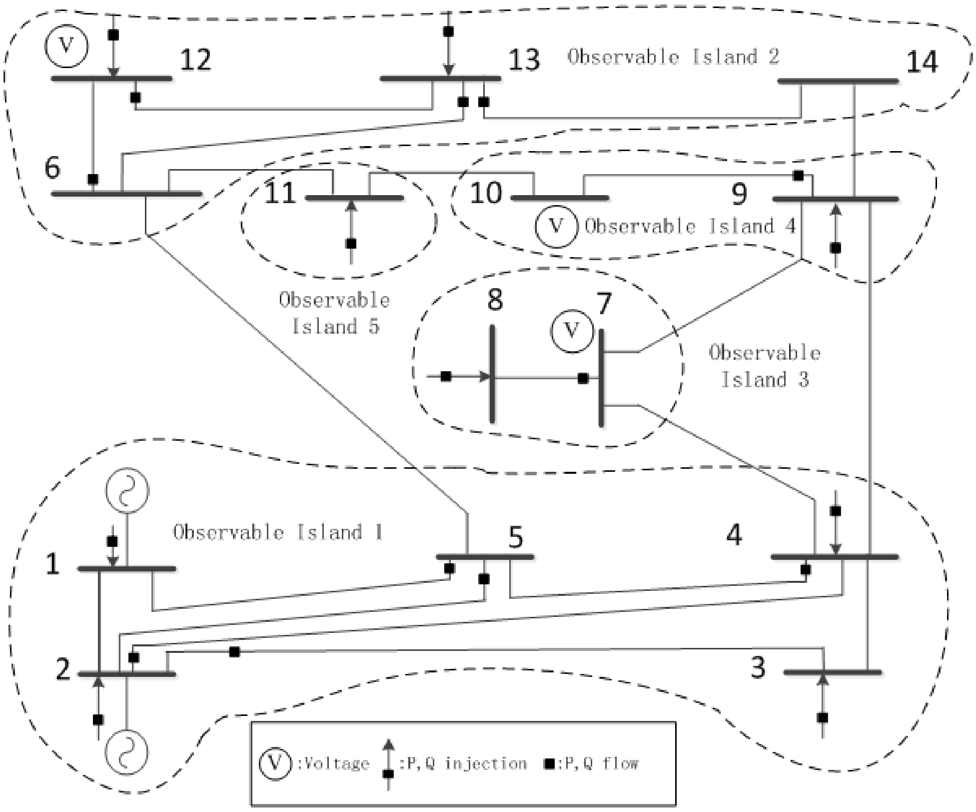


Figure 20. Observable islands in the IEEE 14 bus system for the given conventional measurement placement

The existing numerical methods for identifying observable islands are non-iterative but might fail to correctly identify the observable islands in certain 'pathological' cases.

The flaw in the underlying theorem of the existing methods that causes this problem has been identified and a new iterative method was created that overcame this flaw. However, as an online application, observability analysis is time sensitive and the iterative method proposed could significantly increase the execution time. So, a screening rule was created to terminate the iterative process when it was determined that the solution from the current iteration did not represent a pathological case.

The combination of the iterations and screening rule allows a direct island method to be created that offers 2-3 times faster execution time for a 2736 node system (see Figure 21) and can overcome the 'pathological' cases that cause other, existing methods to return an incorrect assessment of the observable islands. Furthermore, the execution time of the new direct island method is far less sensitive to the number of measurements and the composition of the measurements, which is attractive in terms of guaranteeing how long the online observability analysis will take.

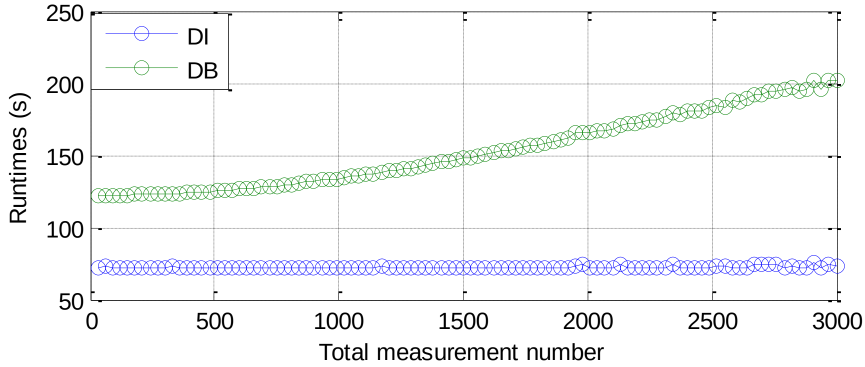


Figure 21. Runtime of the new direct island (DI) method and an existing direct branch method (DB)

7 Business Case Update

We are not aware of any developments that have taken place since the issue of the Project Direction that affect the business case for the Project.

8 Bank Account

A dedicated bank account was made available by SPT to act as the Project Bank Account in to which NGET, as the GBSO, deposited the appropriate project funds through 12 monthly transfers in the Regulatory Year commencing 1 April 2014, such that the total amount transferred equals the net amount set out in the Funding Direction.

The table below documents the breakdown of the overall spend as of December 2015. The accompanying VISOR bank statement is provided Appendix 1.

Table 5. VISOR cost breakdown, December 2015.

[redacted]

9 Intellectual Property Rights (IPR) [CONFIDENTIAL]

VISOR complies with the Ofgem default position regarding the IPR ownership.

Throughout the project, the supplier, GE Grid Solutions, generates new Intellectual Property in the form of WAMs detection and analysis applications. The supplier will retain the IPR which they independently create.

No further IPR has been generated or is expected to be generated.

10 Other

11 Accuracy Assurance Statement

I therefore confirm that processes in place and steps taken to prepare the PPR are sufficiently robust and that the information provided is accurate and complete.

Signature: ___________________

Name (Print): ___________________

Title: ___________________

Date: ___________________

Signature: ___________________

Name (Print): ___________________

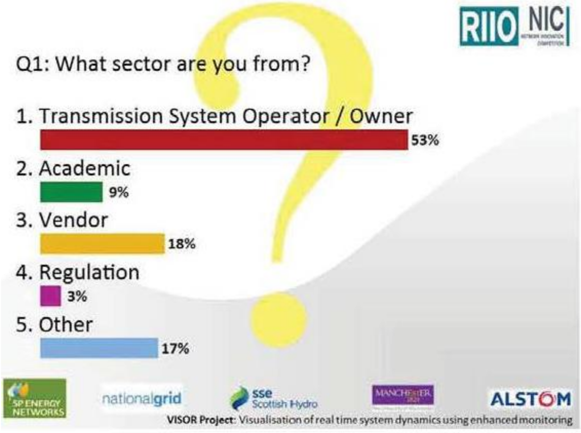
Title: ___________________

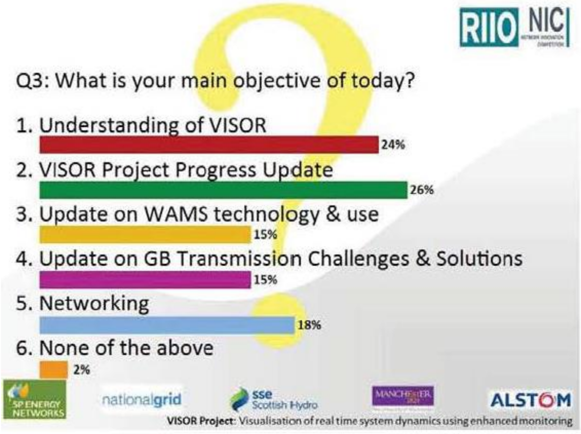
Date: ___________________

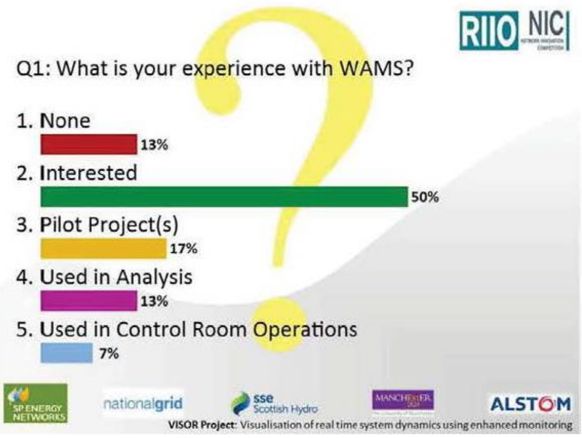
12 Appendices

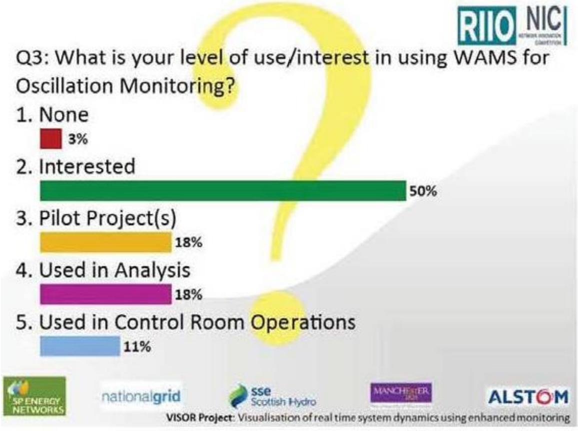
12.1 Appendix 1 Bank Statement [CONFIDENTIAL]

12.2 Appendix 2 Questions and Answers from Stakeholder Event 18 August








RIIO NIC
Q3: What is your level of use/interest in using WAMS for Oscillation Monitoring?
1. None
3%
2. Interested
50%
3. Pilot Project(s)
18%
4. Used in Analysis
18%
5. Used in Control Room Operations
11%
SP ENERGY NETWORKS
nationalgrid
sse Scottish Hydro
ALSTOM
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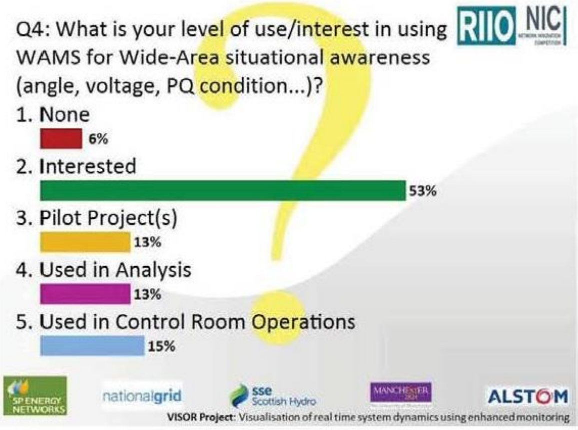
RIIO NIC
Q4: What is your level of use/interest in using WAMS for Wide-Area situational awareness (angle, voltage, PQ condition...)?
1. None
6%
2. Interested
53%
3. Pilot Project(s)
13%
4. Used in Analysis
13%
5. Used in Control Room Operations
15%
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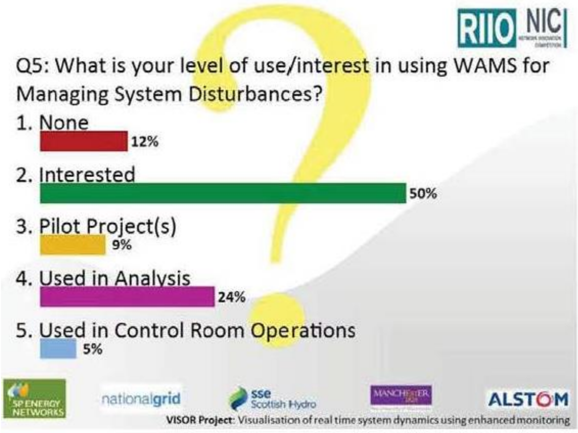
RIIO NIC
Q5: What is your level of use/interest in using WAMS for Managing System Disturbances?
1. None
12%
2. Interested
50%
3. Pilot Project(s)
9%
4. Used in Analysis
24%
5. Used in Control Room Operations
5%
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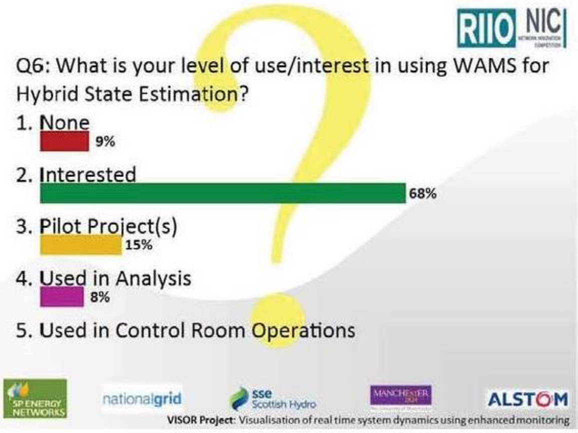
RIIO NIC
Q6: What is your level of use/interest in using WAMS for Hybrid State Estimation?
1. None
9%
2. Interested
68%
3. Pilot Project(s)
15%
4. Used in Analysis
8%
5. Used in Control Room Operations
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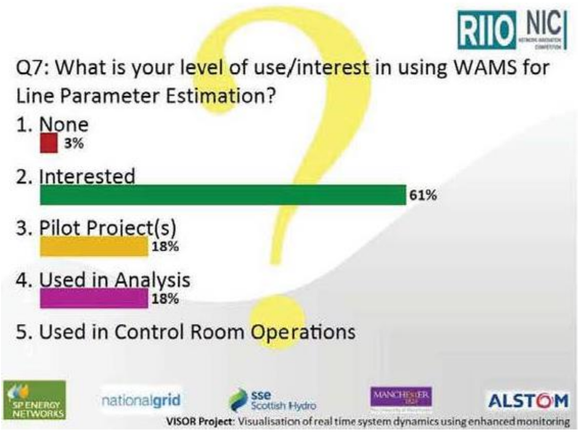
RIIO NIC
Q7: What is your level of use/interest in using WAMS for Line Parameter Estimation?
1. None
3%
2. Interested
61%
3. Pilot Project(s)
18%
4. Used in Analysis
18%
5. Used in Control Room Operations
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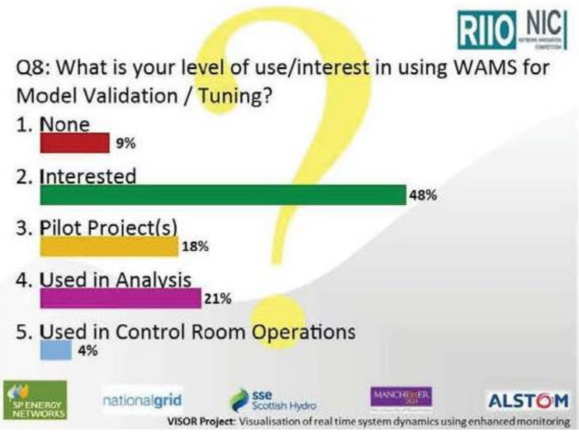
RIIO NIC
Q8: What is your level of use/interest in using WAMS for Model Validation / Tuning?
1. None
9%
2. Interested
48%
3. Pilot Project(s)
18%
4. Used in Analysis
21%
5. Used in Control Room Operations
4%
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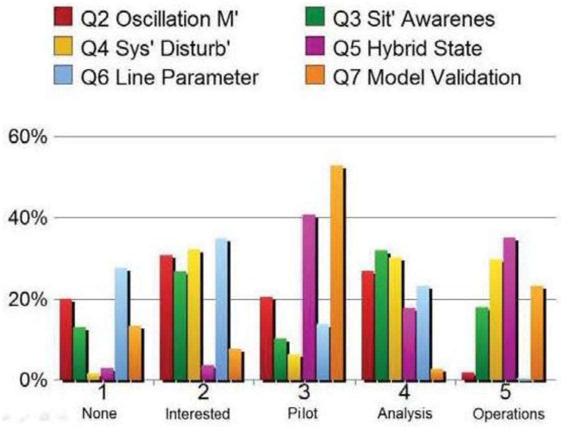
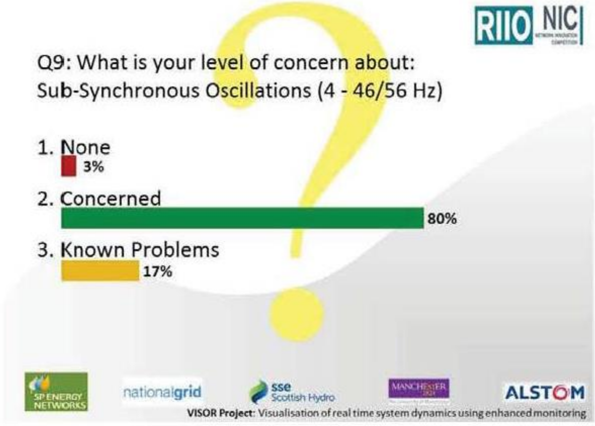

Q2 Oscillation M'
Q3 Sit' Awarenes
Q4 Sys' Disturb'
Q5 Hybrid State
Q6 Line Parameter
Q7 Model Validation
60%
40%
20%
0%
1 None
2 Interested
3 Pilot
4 Analysis
5 Operations


RIIO NIC
Q9: What is your level of concern about:
Sub-Synchronous Oscillations (4 - 46/56 Hz)
1. None
3%
2. Concerned
80%
3. Known Problems
17%
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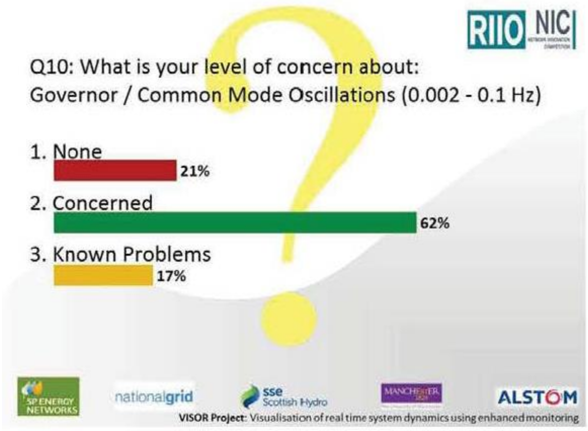
RIIO NIC
Q10: What is your level of concern about:
Governor / Common Mode Oscillations (0.002 - 0.1 Hz)
1. None
21%
2. Concerned
62%
3. Known Problems
17%
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sse Scottish Hydro
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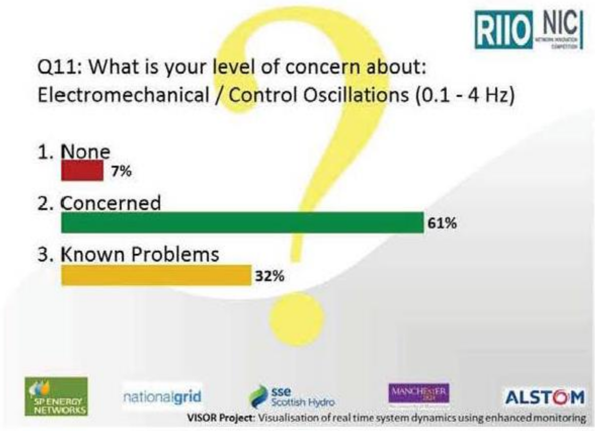
RIIO NIC
Q11: What is your level of concern about:
Electromechanical / Control Oscillations (0.1 - 4 Hz)
1. None
7%
2. Concerned
61%
3. Known Problems
32%
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sse Scottish Hydro
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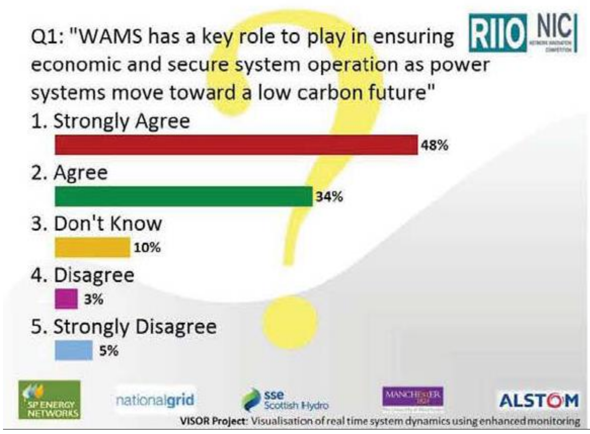
RIIO NIC
Q1: "WAMS has a key role to play in ensuring economic and secure system operation as power systems move toward a low carbon future"
1. Strongly Agree
48%
2. Agree
34%
3. Don't Know
10%
4. Disagree
3%
5. Strongly Disagree
5%
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sse Scottish Hydro
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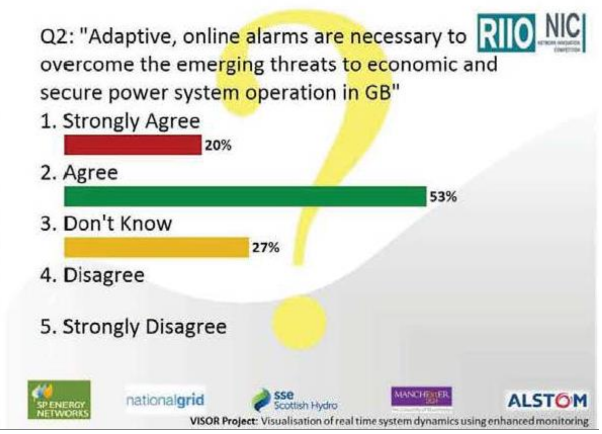
RIIO NIC
Q2: "Adaptive, online alarms are necessary to overcome the emerging threats to economic and secure power system operation in GB"
1. Strongly Agree
20%
2. Agree
53%
3. Don't Know
27%
4. Disagree
5. Strongly Disagree
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sse Scottish Hydro
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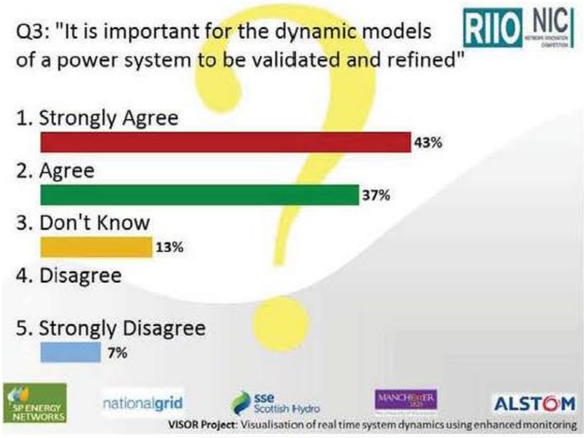
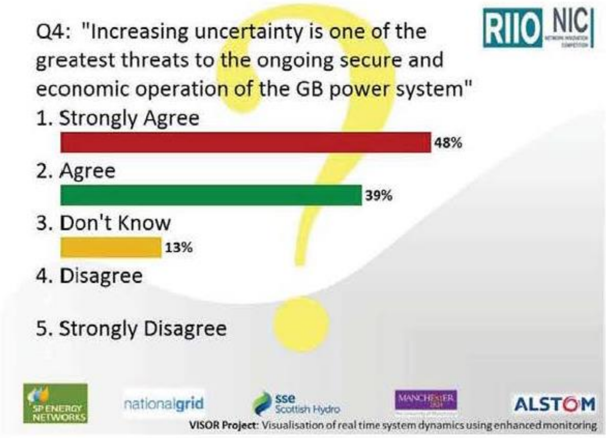

Q3: "It is important for the dynamic models of a power system to be validated and refined"
1. Strongly Agree
43%
2. Agree
37%
3. Don't Know
13%
4. Disagree
5. Strongly Disagree
7%
nationalgrid
sse Scottish Hydro
ALSTOM
VISOR Project: Visualisation of real time system dynamics using enhanced monitoring


Q4: "Increasing uncertainty is one of the greatest threats to the ongoing secure and economic operation of the GB power system"
1. Strongly Agree
48%
2. Agree
39%
3. Don't Know
13%
4. Disagree
5. Strongly Disagree
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sse Scottish Hydro
ALSTOM
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Q1: Where would you like your next VISOR event?
1. In London
55%
2. Within 2 hours of London
7%
3. Outside London
38%
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Q1: How well do you know VISOR following this event??
1. A full understanding of motivation and objectives
66%
2. A fair understanding of motivation and objectives
34%
3. Little understanding of motivation and objectives
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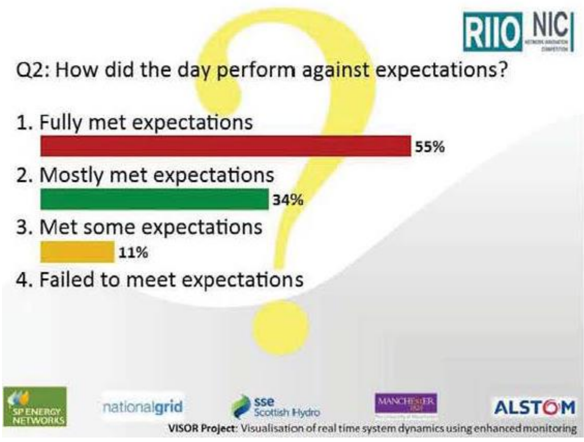
VISOR Project: Visualisation of real time system dynamics using enhanced monitoring


Q2: How did the day perform against expectations?
1. Fully met expectations
55%
2. Mostly met expectations
34%
3. Met some expectations
11%
4. Failed to meet expectations
nationalgrid
sse Scottish Hydro
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12.3 Appendix 3 Project Risk Register (Confidential)