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

In collaboration with

VISOR: Close Down Report

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Version History

Version	Date	Comments
1.0	23/01/18	First draft
2.0	10/03/18	Project delivery team revisions
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GLOSSARY OF TERMS

CNI	Critical National Infrastructure
DFR	Digital Fault Recorder
EMS	Energy Management System
fps	Frames per second
LAN	Local Area Network
NASPI	North American Synchrophasor Initiative
NIC	Network Innovation Competition
NGET	National Grid Electricity Transmission
OPTEL	National Grid's Operational Telecoms Network (operational network supporting CNI)
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
RTS	SPEN's Real-Time System (operational network supporting CNI)
SCADA	Supervisory Control and Data Acquisition
SHET	Scottish Hydro Electric Transmission
STC	System Operator Transmission Owner Code
SPEN	SP Energy Networks
SPT	SP Transmission (part of the SPEN group)
SO	National Electricity Transmission System Operator (National Grid)
SSO	Sub-Synchronous Oscillations
TCP	Transmission Control Protocol
TO	Transmission Owner
UDP	User Datagram Protocol
UoM	University of Manchester
VISOR	Visualisation of Real-Time System Dynamics Using Enhanced Monitoring
WAMS	Wide Area Monitoring System
WAN	Wide Area Network
WMU	Waveform Measurement Unit (GE 200 fps sample-on-wave monitoring device)

1 Project Background

The initial concept of Visualisation of Real Time System Dynamics using Enhanced Monitoring (VISOR) originated from the desire to better understand the dynamic behaviour of the GB power system, as it undergoes a period of significant evolution and disruption. VISOR aimed to address a number of significant changes:

- The first deployments in GB of series compensation (both fixed and thyristor-controlled)
- The first deployment of an intra-network HVDC link
- Proliferation of renewable generation
- Proliferation of power electronic converters, HVDC interconnectors and Flexible AC Transmission System (FACTS) technologies
- Closure of large synchronous generation plant, some with a power system stabilising role

These factors can all contribute to significant disruption to the GB system which drastically change system dynamics and the pattern, amount and consistency of power transfer between regions. Managing these system changes is further complicated with the connection of HVDC links and series compensation devices in close proximity to each other, this is due to the increased potential risk of introducing new modes of sub-synchronous oscillations (SSO). Of particular importance for SP Transmission (SPT) and National Grid is the “B6” boundary between Scotland and England where two 400kV AC double-circuits conventionally transferred bulk power from North to South, this power transfer capability has recently been increased by deploying series compensation and the Western HVDC link. This raised an urgent need for improved monitoring and understanding of system behaviour, to support reliable and efficient operation and development of the GB system. The VISOR project was instigated to address this need.

In 2013, SPT, supported by the other transmission licensees and the academic partner, made a full proposal submission for the VISOR project, under the Network Innovation Competition (NIC) mechanism. Ofgem approved the proposal and issued the Project Direction on the 19th of December 2013. The project was originally scheduled to run from January 2014 to March 2017, but was later extended to December 2017 to capture and analyse system dynamics following the delayed commissioning of the Western HVDC link and to utilise a new testing and training facility established at SPT’s operational control centre.

The total requested budget for the project was £7.4m to coordinate, develop, procure, commission and operate the first GB-wide Wide Area Monitoring System (WAMS) infrastructure and associated applications through the course of the project, to overcome technical challenges, build confidence in the technology and ultimately accelerate the uptake of WAMS within GB.

The project is a collaboration between SP Transmission (SPT), National Grid Electricity Transmission (NGET), Scottish Hydro Electric Transmission (SHET), National Electricity Transmission System Operator (SO) and the University of Manchester (UoM). GE Grid Solutions (formerly known as Alstom and Psymetrix) serves as technology provider of the WAMS data collection, analysis and presentation software platform, **e-terra***phasorpoint*, as well as new specialised field devices and data analysis services.

2 Executive Summary

2.1 Introduction to VISOR

VISOR is a ground-breaking collaboration project that has brought together the three mainland GB Transmission Owners and the System Operator to improve visibility of dynamic system behaviour and enhance network resilience. The Network Licensees have been supported by technology provider, GE Grid Solutions as well as research partner, the University of Manchester. VISOR has truly revolutionised the real-time monitoring of the GB system by combining synchronised measurements from all three GB Transmission Owners to provide GB-wide real-time visibility of system voltage and stability limits. The improved system visualisation also helps protect against catastrophic events that could result in a complete or partial blackout of the GB system.

Accurate time-synchronised measurements from different points of the GB system give unprecedented insight into dynamic and transient network conditions, including detection of undamped oscillations or diverging voltage angles that could lead to a blackout, faster post-event analysis and real-time replays of recent disturbances and faults. The insight given by WAMS can help to initiate corrective actions to enhance the power systems reliability. WAMS are revolutionising how power systems are operated around the world by utilising time-synchronised, high-resolution measurements of the electricity system.

VISOR has created the first integrated GB WAMS to gather, collate, visualise and analyse time-synchronised measurements in real-time taken across all three of the GB mainland TOs, using Phasor Measurement Units (PMUs), whereby each TO has visibility of measurements within their network and the SO has visibility of all measurements. The project has also marked the first deployment anywhere in the world of new Waveform Measurement Units (WMUs), which generate 200 frames per second data specifically to broaden the detection capability of SSO up to 46Hz.

VISOR focused on reducing cost to the consumer through increased system efficiency and lower network investment through:

- **Better Visibility** – providing control room operators and network planners with increased visibility and diagnostics of network operation and post-event diagnosis and recovery. It will also reduce the uncertainty in real-time of the network state to allow the network to be run closer to the true physical limits;
- **Better Understanding** – improving the characterisation of the transmission network and thus reduce model and measurement uncertainty that currently requires higher operational safety margins to be applied;

By providing:

- 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 and sub-synchronous interaction introduced by power electronic converters;
- Vital experience and understanding of both the requirements and the capabilities of WAMS, enabling networks owners and operators to evaluate the tools and practices that

provide significant value for the operation, planning and modelling activities according to their respective duties.
- Development of functional specifications for equipment and supporting infrastructure for WAMS implementation, and a GB Roadmap detailing investment options for efficient and coordinated implementation of this technology into daily network operation practices.

The project commenced in January 2014 with an initial completion date of March 2017. However, a 9-month extension was later approved by Ofgem, bringing the completion date to December 2017, in order to allow the specialist expertise developed in VISOR to capture and analyse the commissioning stages of the delayed Western HVDC, and utilise the dedicated WAMS pre-production training and testing facility situated in the SPT operational control centre.

2.2 Background - Sub-Synchronous Oscillation (SSO)

The increasing use of series compensation and power electronic converters associated with renewable generation and HVDC links, add vital flexibility and capacity to the power system and help in the move to a low carbon future. However, these control devices introduce new challenges, in particular, the potential for SSO, which is the main focus area for VISOR. SSO are oscillations below synchronous frequency (50Hz) and have been one of the main focuses of VISOR. These oscillations fall into three main categories:

- Sub-synchronous resonance (SSR): probably the most well-documented form, this involves interaction between generator shaft torsional modes and electrical resonances created by the combination of series capacitors and network impedance.
- Sub-synchronous control interaction (SSCI): interaction of power electronic converters, such as HVDC links and doubly-fed or fully-converted wind turbines, with electrical resonances created by the combination of series capacitors and network impedance.
- Sub-Synchronous Torsional Interaction (SSTI): interaction of power electronic converters with generator shaft torsional modes.

SSR is of particular concern, due to the potential risk of interactions between series compensation or power electronic controllers and generator shafts, potentially resulting in increased wear to the generator shaft, shortening its operational life, or even severe shaft damage or failure.

Before VISOR, there was very limited visibility of SSO; the geographically sparse observation capability, isolated across separate TOs, was limited to a maximum frequency of 10Hz (limit of PMU capability). As a result, this did not cover all potentially important risks, as potential interactions could occur at unobserved locations and/or at unobserved frequencies. Accurately modelling such potential interactions and oscillations is challenging due to the higher frequency simulations required and reliance on complex plant and transmission network models being accurate. Direct monitoring of such behaviour provides validation of simulations, models and studies; catches unpredicted behaviour, improved understanding and informs investigation and mitigating action where required.

2.3 Project Scope: Work Package Objectives and Outcomes

The main objective of the VISOR project has been to establish the Wide-Area Monitoring System between the GB Transmission Owners and the System Operator by commissioning the required monitoring, communication and data processing infrastructure across the country. This infrastructure provides the measurements to inform new analytical tools, which could offer enhanced information on the real-time behaviour of the system. In addition, the systems provide visibility of a wider range of oscillations and interactions that would otherwise go undetected with the potential to negatively impact the operation of the power system.

Five dedicated work packages were designed, each with their own set of objectives, to collectively achieve the overall objective, as shown below.

	Workpackages	Objectives	
1.	Enhanced System Oscillation Monitoring	•Sub-Synchronous Oscillation management	•Oscillation Analysis & Source Location
2.	System Model Validation	•Line parameter estimation •Oscillation analysis validation	•Transient stability simulations •Generator model validation
3.	Improvements for management of stability constraints	•Understanding of uncertainty •Improvement of model initial conditions	•Improved visualisation of stability limits for operators •Trial the reliability of area angle measurements
4.	Supporting Infrastructure	•Continuous analysis of oscillations •Data Storage	•Impact assessment of disturbances
5.	Knowledge Dissemination	•Internal and External Knowledge dissemination •Public Engagement	•Influencing and updating policies and standards

Figure 1. VISOR Work Packages

A dedicated work-package sought to develop visibility and understanding of new behaviour introduced by power electronic controllers associated with HVDC links and compensation devices. Furthermore VISOR was scheduled to coincide with the installation and commissioning of the Western HVDC link to provide a fingerprint of the system before and after commissioning to capture the changes in oscillation modes that are introduced by the new HVDC link. Findings from the work packages are documented in Section 4.

2.3.1 Objectives Met

All Project Successful Delivery Reward Criteria have been met, as are discussed in detail in Section 5.

SDRC 9.1 Successful delivery of Sub-Synchronous Oscillation monitoring before the start of Series Compensation commissioning.

SDRC 9.2 Enhanced stability tools delivered, including Oscillation Source Location and Disturbance Impact

SDRC 9.3 Successful model validation activity completion

SDRC 9.4 Successful improvement options for management of transient stability constraints

SDRC 9.5 Successful deployment of the supporting infrastructure of the VISOR project.

SDRC 9.6 Successful dissemination of knowledge generated from VISOR project.

2.3.2 Objectives Not Met

All SDRC and project objectives have been met and satisfied.

2.4 Key Outputs and Main Learning

VISOR has successfully demonstrated the capabilities offered by WAMS and explored the benefits in enabling the TOs and SO to improve visibility and understanding of the changing system dynamic behaviour. This serves to improve not only day-to-day network management, analysis and planning capabilities, but also the ability to identify behavioural dynamics and oscillatory modes that are introduced or exacerbated by new technologies. As the electricity system diversifies and evolves, this additional capability will help to both mitigate against potential risks of interactions and improve accuracy and capability of the network modelling and analysis used in the planning and operation of the system.

Through the implementation of WAMS technology, the project has successfully demonstrated the advantages and benefits to many areas of network management, as well as answering many questions and alleviating many concerns regarding WAMS implementation. The key outputs and learning points are summarised below and detailed further in Section 4.

2.4.1 WAMS Design and Configuration (Pre-trial)

- **The need for careful architecture design.** Plans need to be comprehensive and clear from the outset (though this can be difficult for innovation projects). Information should include data flow details including direction, ports and protocols; and should cover both data streams and the support interfaces required such as for remote configuration, debugging, and software/firmware upgrade. Access to the control room and substation networks, in particular, is strictly controlled and should be kept to a minimum.
    - **Supply Chain (Communication Link).** The order for a Multiprotocol Label Switching (MPLS) link between SPT and NGET was placed through a third-party service provider who in turn contracted the telecommunication network provider to deliver the physical fibre optics. The MPLS link was the preferred choice among the various options for the communication links between all the TO WAMS Data Centres to the SO WAMS Data Hub. However, repeated delays and an inability to query or expedite the process directly with the network provider prohibited the collation of measurement data that restricted the monitoring coverage. Following delays, which exceeded the notional maximum 6-month delivery period, an Internet Protocol Security (IPsec) Tunnel was used as the contingency plan to overcome this issue.
- **Data security:** Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are established data communication protocols with differing merits in terms of data reliability and latency. Both have been used in WAMS across the world, however, experience to date suggests that for the roll-out of WAMS as an operational tool in GB, data must be received at the control centre via TCP. However, in situations where network performance is a concern, or PMU-based control employed, UDP will likely form the first stage of the data route. Aggregation for monitoring purposes and bandwidth reduction can then be carried out at a regional or central level, followed by conversion to TCP for reliable and security-compliant delivery into the control room environment. The WMUs deployed under VISOR supported only UDP communication,

however future specifications for WMUs should include provision for TCP/IP. (Future architecture design of the GB WAMS is considered in the GB Roadmap – see link in Section 14).

- **Collaborative implementation strategy**. A degree of collaboration and coordination between TOs and SO regarding deployment and future development of WAMS applications and infrastructure will simplify integration complexity, help mitigate incompatibilities between neighbouring WAMS systems, address multi-vendor solutions and ultimately improve overall performance and management of the GB WAMS. The project findings suggest that a formal agreement will be required detailing security levels that govern communications between Network Licensees.

2.4.2 Live Monitoring Trial

- **Data stream bandwidth & firewall requirements.** Initial estimates of traffic volumes were based upon theory and the initial planned scale of deployment (with some margin). However, additional bandwidth was required to allow for incorporation of extra existing devices that were upgraded to produce WAMS data and to allow for larger than expected fluctuations in data flow and backfilling of data from dropped connections. The initial bandwidth calculated for the National Grid to SPT wide area network (WAN) link was not sufficient for the duration of the project, and so was increased.
- **Data quality and data volumes from field devices.** Monitoring infrastructure was established using new WMU devices and existing PMUs. Both used platforms that are multi-purpose Digital Fault Recorder (DFR) devices incorporating multiple functions. Issues were encountered with data quality form both existing and new devices. Firmware patches were applied to alleviate the issue.
- **Data-sharing to maximise application effectiveness**. Cross-boundary measurements are required in order for some WAMS applications to be most accurate and effective. For TOs to receive benefits from these applications, new data-sharing arrangements may need to be established. Much of these benefits can be obtained through sharing of sparse measurements that could be considered to have low confidentiality and commercial sensitivity (voltage and frequency).

2.4.3 Research Learning

- **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 SSR threat. A key outcome of this research is that the current security standards would need to be extended in order to capture this type of oscillation; and the electrical damping should be incorporated and quantified characteristically as part of SSR studies and during the creation of screening rules.

- **Optimal placement of synchronised measurement devices for monitoring sub-synchronous oscillations.** A methodology is required for the optimal placement of synchronised measurement devices to guarantee efficient and effective observations. UoM have developed an approach that prioritises monitoring locations using a combination of linear and non-linear optimisation methods to identify critical generators that may be vulnerable to SSR.

- **Comparison of Hybrid State Estimation (HSE) techniques.** Conventional State Estimation uses unsynchronised measurements of voltage magnitude and active/reactive flows and injections. HSE is a method for creating a quicker, more reliable and more accurate state estimator by including synchronised measurements of voltage and current phasors (magnitude and angle) in the state estimation procedure that has traditionally used unsynchronised measurements of voltage magnitude and active/reactive flows and injections. The main challenge faced when creating HSE is determining how to combine the synchronous and asynchronous measurements during the state estimation procedure without the loss of accuracy or robustness. UoM has studied various HSE methods such as integrated, post-processing and fusion, and found that the integrated approach provided optimum accuracy, resilience to gross errors, and reliability (relative to measurement placement). For more information, see work package 3 learning outcomes in Section 4.

2.4.4 Key Challenges for Roll-out

- **WAMS as an enabler not the solution**. Linking the increased visibility of real-time behaviour offered by WAMS with direct business case is complex. One of the primary business drivers is risk mitigation and preventative action to avoid system outages and asset damage, but without first-hand experience of major system disturbances in GB it is difficult to assert financial benefit. It is different when a major disturbance has occurred, for example following blackouts in the USA, the Recovery Act Smart Grid Investments supported the installation of 1,000 PMUs across North America, supplemented with high speed communications networks and advanced analytical applications. Twelve Smart Grid Investment Grant (SGIG) projects and two Smart Grid Demonstration Projects have installed PMUs at a total project cost of over $328 million (combined federal and private funding).
- **Robust, resilient, reliable IT system architecture.** A robust, resilient and reliable infrastructure is vital to rely on WAMS for critical decision making however maintaining complex communications and processing architecture for applications to operate at this level requires maintenance, monitoring, security and support for both software and hardware which is costly. These costs are not a one off either, IT based systems like WAMS require ongoing operational support to guarantee security, availability and performance.
- **Specialist resource.** Retaining and recruiting WAMS specialists is vital to achieving the benefits of WAMS implementation in daily operations, in particular the regular reporting, model validation and analytical skills to understand the information emerging from WAMS. In addition, information systems skills are vital to support the ‘end to end’ process.
- **Need for monitoring policy**. Policy is required around the provision of system monitoring, specifically defining the nature around PMU derived data and the level of service and resilience required by the System Operator.
- **IT Security Level**: For cybersecurity reasons, the security level of the WAMS architecture will need to be consistent between SO and TOs when data is shared. Bandwidth requirements are proportional to the number of monitoring devices, and overloading systems will have negative effects on application performance, but regional WAMS data centres can optimise data throughput to other WAMS data centres.

3 Details of the Work Carried Out

This section explains the work which was carried out by the project in order to establish the first unified GB WAMS, in particular, this section documents:

- The details of the GB WAMS infrastructure, including the monitoring and communication hardware and the overall architecture.
- The WAMS applications demonstrated and deployed through the project.
- The creation of the WAMS pre-production and training facility, located within the SPT operational control centre, Kirkintilloch.
- The established reporting mechanisms; WAMS-based disturbance and system performance reports.
- The knowledge dissemination activities to promote the technology to internal and wider external audiences.
- The development of a Roadmap for the GB WAMS, including next steps and future objectives, including the coverage and technical architecture recommendations.

3.1 GB WAMS Infrastructure Established by VISOR

The GB WAMS established by VISOR is underpinned by a foundation infrastructure comprising of measurement devices, communication channels and data centres on which the WAMS analysis layer is built. The WAMS data centres host a WAMS software platform that performs a number of functions, including a Phasor Data Concentrator (PDC) which aggregates WAMS data streams for bandwidth efficient onward transmission, together with data storage, analysis and data presentation. The three types of data centres referred to in this text are:

- WAMS Data Centre – PDC operating at TO level in each of the three TO networks, hosting the VISOR applications and TO data.
- WAMS Data Hub – PDC operating at a GB system level in the System Operator, hosting the VISOR applications and data from all 3 TOs.
- Existing WAMS Servers – legacy WAMS servers from SPT & NG's respective isolated WAMS, hosting limited legacy applications. Used in VISOR mainly for routing of data from legacy PMUs to VISOR Data Centres.

The monitoring and communication infrastructure WAMS are illustrated in Figure 3 (p.14) and Figure 4 (p.15), respectively.

A quick overview of the key aspects of the currently implemented infrastructure is provided below:

- Each TO has their own WAMS data centre. SPT and NGET have two, one is a WAMS server installed prior to the VISOR project, and one installed for the VISOR project. SHET have one data centre installed for the VISOR project.
- Data flows one-way from TOs to SO. Each TO only has access to its own WAMS data (from PMUs and WMUs), while SO has access to data from all TOs.
- Each TO hosts its own copy of all VISOR WAMS applications, which only use its own data there is no data exchange between TOs.

- SO and TOs are all using GE's **e-terra***phasorpoint* for the PDC and analysis applications. Currently, there is no data exchange between the VISOR system and the production Energy Management System (EMS).
- There is currently no redundancy in the implemented system infrastructure.
- Both SPT and National Grid had a sparse pre-existing install base of PMUs, in the form of DFRs which had been upgraded to PMU functionality. During the course of VISOR, SPT upgraded a significant number of additional DFRs to PMU functionality, increasing SPT coverage at great benefit to the project.
- Waveform Measurement Units are implemented on GE's Reason RPV311 DFR, which also acts as a PMU. Hence it produces both phasor measurements at 50 fps and analogue waveform samples at 200 fps, sent in two separate data streams via UDP protocol (TCP not currently supported, but feasible).
- SO and TOs initially deployed WAMS servers on Corporate Local Area Networks (LANs).
- Communication channels between TOs and SO were chosen as appropriate for security and bandwidth requirements.

3.1.1 Monitoring Infrastructure (PMU and WMU Devices)

One of the primary purposes of the WAMS is to observe the dynamic behaviour of the power system: oscillations present in the network, both normal and abnormal, interactions between devices connected to the network, and response of the system to disturbances such as loss of a generator. Traditional PMU-based WAMS utilise synchronised phasor measurements from PMUs, transmitted via the IEEE C37.118 protocol at up to 50 frames per second – i.e. once per cycle. Two key factors influence the observable bandwidth from PMU measurements:

- The need to ensure adequate attenuation of aliased components: this means filter roll-off must begin lower than the theoretical Nyquist limit (25Hz).
- The window employed for phasor calculation: this is typically taken over multiple cycles, which provides greater accuracy at the cost of attenuating higher frequency content. Reducing the calculation window increases bandwidth but adds measurement noise and errors.

These factors result in an observable range up to about 10Hz. This is sufficient to capture most oscillations that were previously of concern to power system operation but not the higher frequency (up to 46Hz) oscillations potentially involved in sub-synchronous resonance or interaction that are a growing concern in GB and elsewhere. To maximise learning obtained by the project and to highlight the capability of WAMS in managing SSO risk, in addition to the PMU measurements the VISOR infrastructure also incorporates new WMU monitoring devices. These provide time-synchronised point-on-wave measurements of both voltage and current at 200 frames per second, thereby extending the observable bandwidth up to 46Hz. The resultant observable bandwidth capability of the VISOR infrastructure is depicted below.

It should be noted that the basic WMU function is fairly straightforward to implement, from a signal processing point of view and it is hoped that this type of measurement function will become more widely adopted. The WMU function is fully compliant with the existing IEEE C37.118 standard used in WAMS, the data rate of 200fps is atypical, but still compliant.

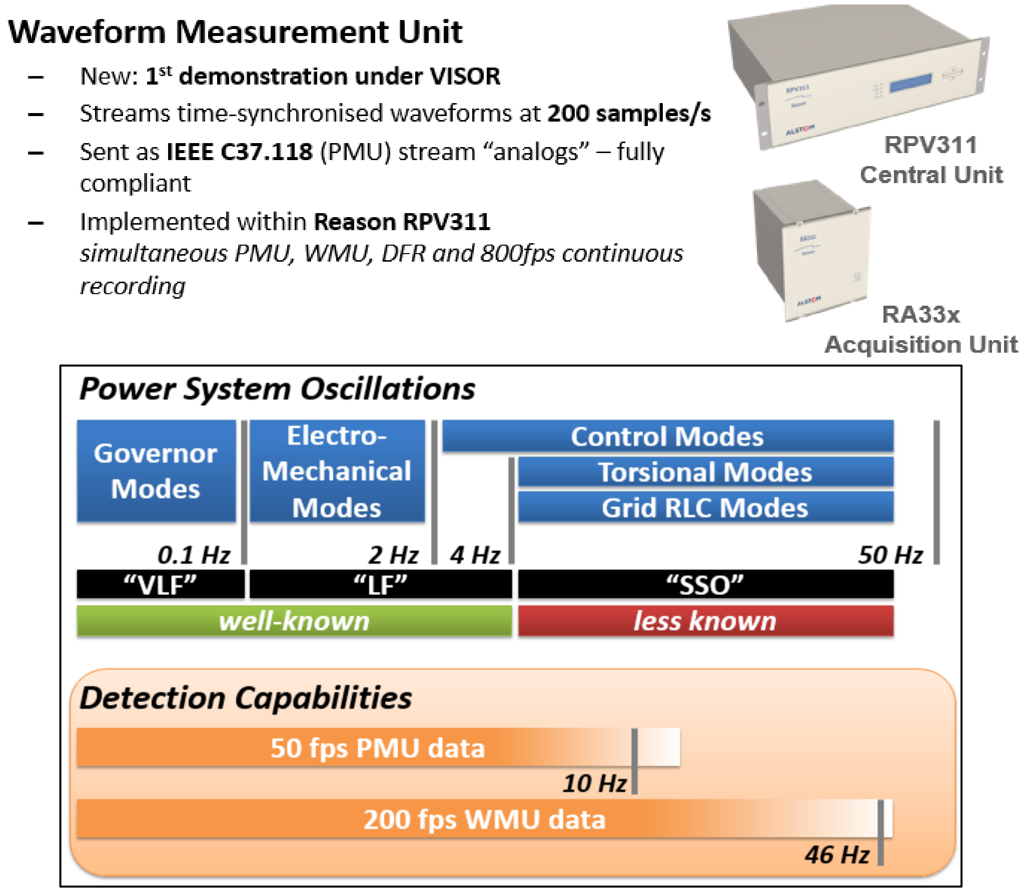

Figure 2. Frequency ranges of oscillatory modes and comparative PMU & WMU detection capabilities

For VISOR, the main focus of installing new SSO monitoring devices has been around the B4 and B6 boundaries and the Western HVDC link. To date, a total of 14 WMU (*Reason RPV311*) devices have been installed through VISOR at locations listed in Table 1. National Grid has also installed a WMU at Grain to further monitor the potential for SSO interactions when operating HVDC links adjacent to wind-farms and thermal plant. SPT has also installed additional WMUs through a different project examining oscillations across SPT.

#	VISOR Partner	Locations (circuits)
4	SP Transmission	Eccles (Stella West 2) Torness (Eccles 2) Hunterston (Inverkip 2, to be Strathaven) Auchencrosh (Coylton)
8	National Grid	Hutton (Harker 1 & 2) Stella West (Spennymoor 1 & 2) Deeside/Connah's Quay (Circuits 1 & 2) Grain (Circuits 1 & 2)
2	Scottish Hydro Electric	Kintore Beauly
1	The University of Manchester	Manchester

Table 1. Location of SSO monitoring devices (WMU) installed through VISOR

In addition to the data from these devices, phasor data is provided by a fleet of PMUs, most of which are multi-functional DFRs which have been upgraded to include PMU functionality, such as the Qualitrol IDM or Ametek TR-2000. At the time of writing, there are approximately 97 PMU data streams (55 SPT, 40 NGET, 2 SHET) providing measurements to the VISOR data servers, although this number will increase with time.

The monitoring infrastructure and communication links established by VISOR are shown in Figure 3. The image presents an indicative map of VISOR monitoring infrastructure only, and is not an accurate representation of all WAMS devices installed on the GB system that may have been installed by different projects.

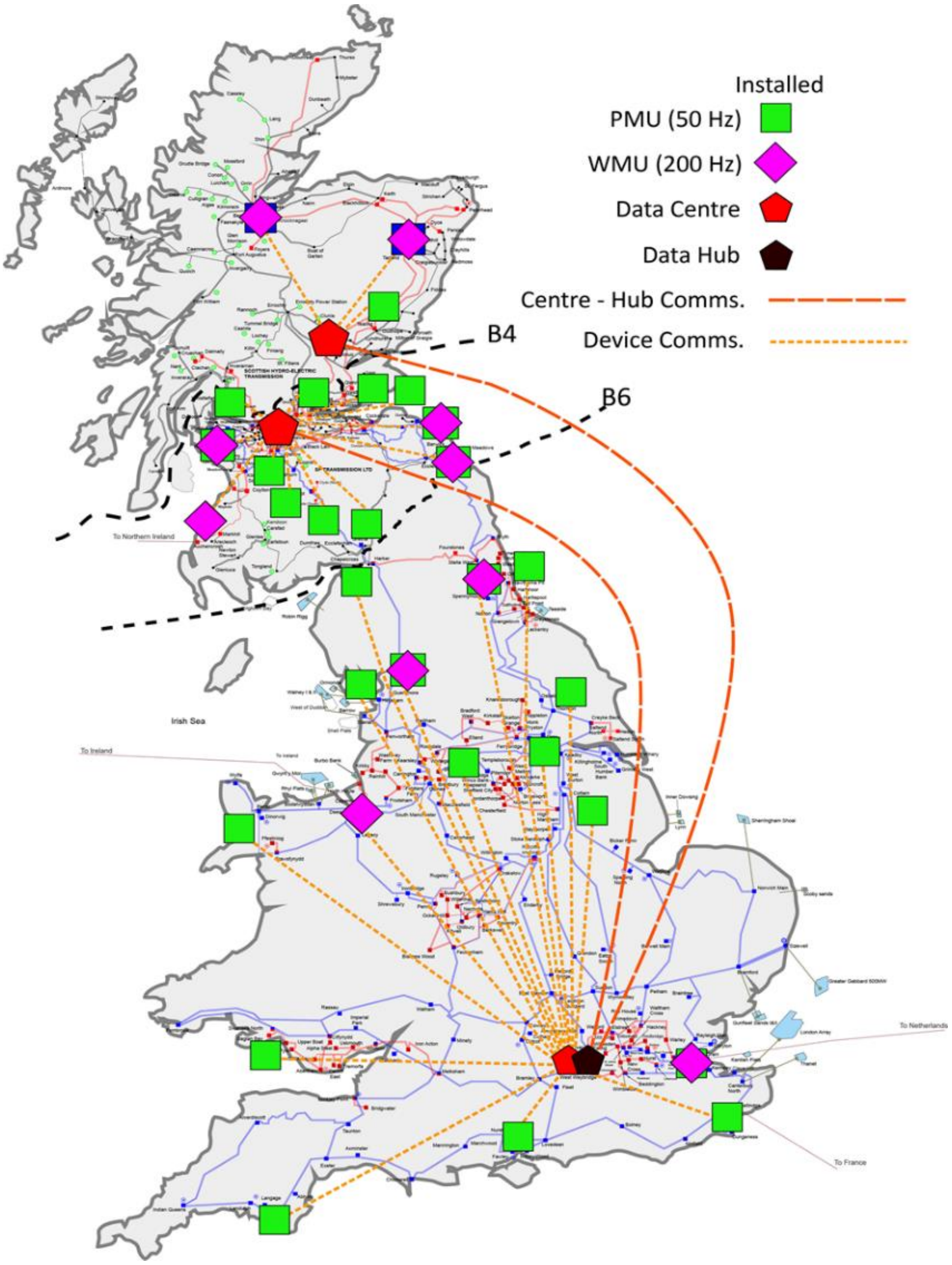

Figure 3. Location of monitoring devices and communication links of GB WAMS infrastructure established by VISOR. WMU locations chosen to provide visibility across B4 & B6 boundaries, and connection points of the Western HVDC link.

3.1.2 Communication Infrastructure

The following communication channels were established by VISOR to transfer WAMS data from TO PDCs to the SO central server, and illustrated in Figure 4:

SHET →	SO:	Internet Protocol Security Tunnel (IPSec)
SPT →	SO:	Multiprotocol Label Switching (MPLS) and IPSec
NGET →	SO:	Direct LAN

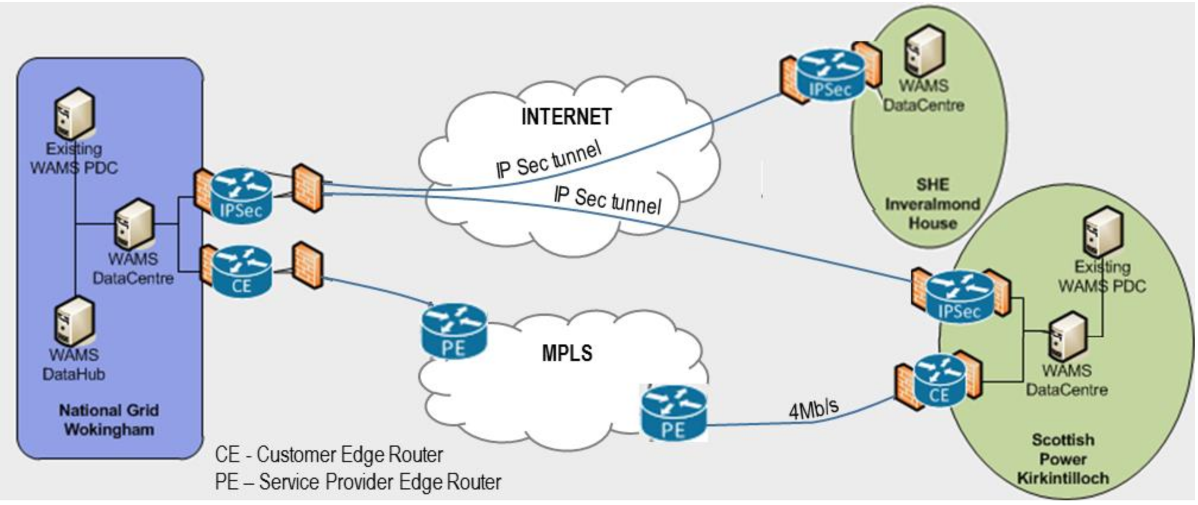

Figure 4. WAMS Server Network Interconnection

Different methods have been used for each TO to share WAMS measurement data with the SO, taking into consideration the bandwidth requirements of each link; NGET have used a direct LAN connection whereas SPT and SHET use point-to-point and internet based connections, respectively. Table 2 describes the differences between IPSec Tunnel and the MPLS link.

For SPT, an IPSec Tunnel was established as an interim solution prior to the commissioning of an MPLS optical fibre network to transfer the large amounts of PMU and WMU data acquired by SPT. At the time of writing, the bandwidth utilised is 4Mb/s to satisfy the data archiving and backup needs of the existing WAMS system. Although there is resilience within the MPLS cloud, each site has one customer edge router, so there is currently a single point of failure at each end.

Although it is possible, with changes to firewall configurations, for the SO data centre to send data back to the TO data centres, this has not been implemented. However, for the production system to achieve maximum benefit certain WAMS applications would require bi-directional data sharing between SO and TOs to achieve optimal accuracy. The extent of data sharing required will be discussed later as a key learning outcome from this project.

Table 2. Comparison of IPSec Tunnel and MPLS

	IPSec Tunnel	MPLS
Service Models	High-Speed Internet Gateway, with 256 bit encryption VPN services.	High-Speed Private Network, hosted by a service provider.
Scalability	Scalability required planning with the network capacity teams at each organisation to ensure that their Internet Gateways have sufficient capacity.	Highly Scalable WAN solution. Depending upon Customer Edge Routers, optical fibre connections are required users and service provider's network. The likely limiting factor is cost.
Place in network	Hosted in the Internet Gateways of the participating TOs/SO.	A separate network, hosted by the service provider. New Customer Edge Routers required that can be connected to any point on a network where there is a firewalled ingress point.
Security	256-bit encryption, over the internet.	No encryption of data, but running over own Virtual Private Network (not over the internet). Encryption of an IPSec Tunnel over the MPLS could be added if necessary but would require IPSec compliant routers.
Cost	Set up is a one-off fee, and has no extra operational costs over and above the normal corporate internet support.	Initial set up costs are similar to IPSec Tunnel, but also incurs monthly costs for the service. The costs will increase depending upon the level of resilience required, bandwidth and security enhancements.
Long-term suitability for WAMS	Only suitable for corporate networks. Not suitable for the operational network (which supports Critical National Infrastructure).	Suitable for both corporate and operational networks.

Operational networks offer a fast private network with exceptional reliability. The SO Operational Telecoms Network (OPTEL) services were considered when establishing the initial GB WAMS. However, as OPTEL supports the Critical National Infrastructure (CNI) it would have been problematic to connect the VISOR demonstration system to the CNI through OPTEL as existing PMUs are not connected to OPTEL.

Furthermore, while the SO OPTEL network has a connection to the SPT control room, there is currently no OPTEL path to SHET, and it would have required significant work from SHET to get their network connected to the OPTEL network, either directly or via SPT's network.

There are no technical or security issues preventing WAMS in the OPTEL environment and there are mechanisms in place to use the OPTEL network as a carrier network for non-CNI traffic, so it could be looked at as an option for a productionised system. However, migrating the existing system across would require careful coordination to ensure cybersecurity polices of all connected parties are not breached.

3.1.3 System Architecture and Data Security

The VISOR system was designed as a demonstration architecture created outside of the operational network, building on a small foundation of existing WAMS infrastructure and establishing new WAMS communication links between TOs and the SO, as shown in Figure 5. This approach was deemed most suitable for the purposes of the innovation project to demonstrate the benefits and challenges of the technology without jeopardising business-as-usual processes. A production-grade system, which requires certain high levels of reliability and redundancy, would have taken considerably more time and expense to establish.

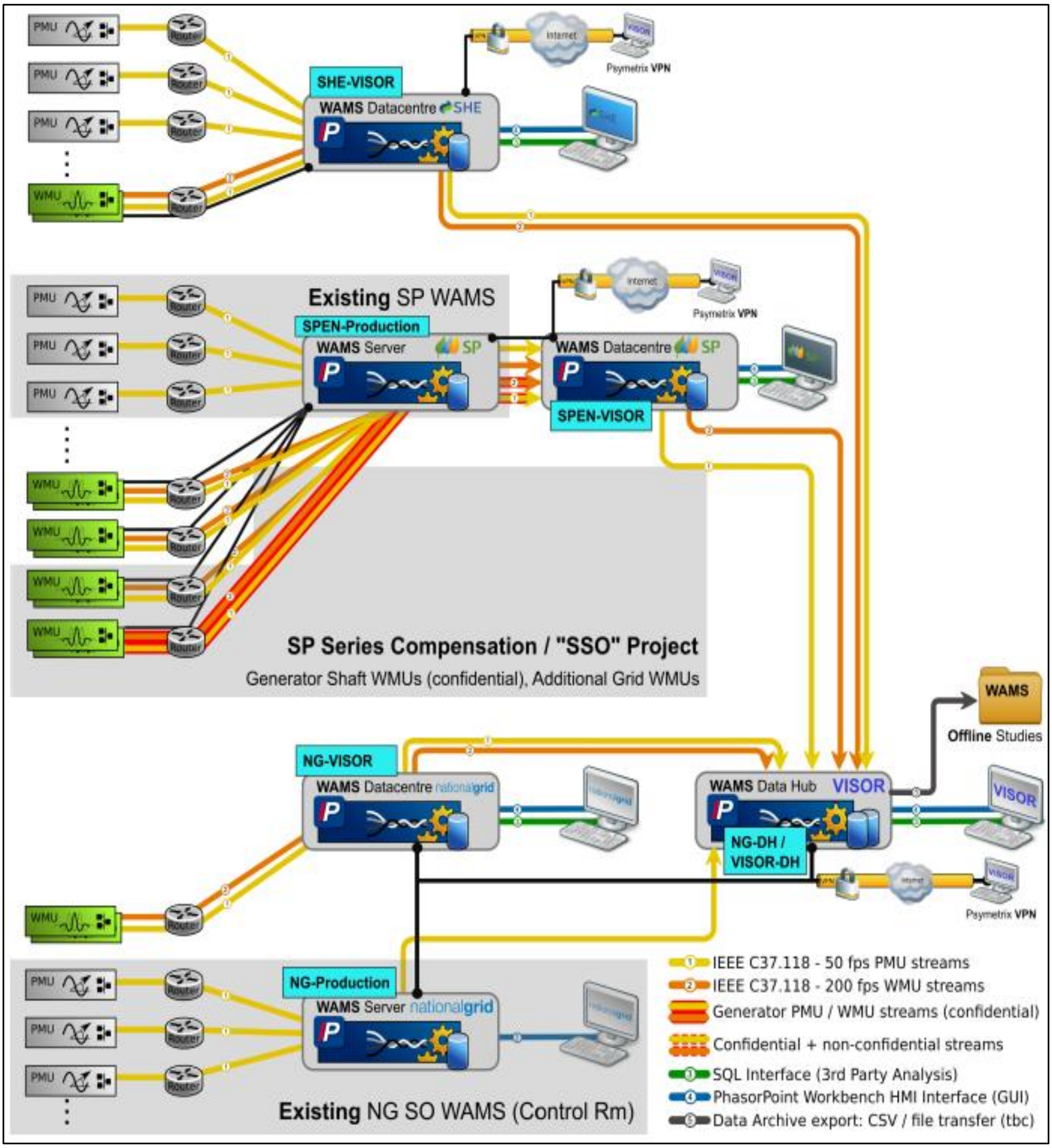

Figure 5. Overview of GB WAMS Architecture between TOs (Datacentres) and SO (Data Hub)

The introduction of WMU data highlighted a security versus performance issue; typical PMU data transfer at 50 Hz requires approximately 45 Kb/s using TCP packets, however, a WMU providing both 200 Hz and 50 Hz data streams, requires nearer 130 Kb/s using UDP packets.

UDP has performance advantages over TCP as it is a connectionless method of communication that sends data to a defined Internet Protocol (IP) address without error checking or verification of successful communication. As a result, the protocol has very little information overhead, which reduces bandwidth and latency. However, it also means that if a packet does not arrive the data is lost.

Conversely, TCP is a connection-oriented transport method that will open a socket or a connection between the two IP addresses and will provide error checking and packet receipts to ensure all the packets have arrived and resent where required. This subsequently introduces information overhead in a TCP datagram, but it does provide greater reliability in the data transmission.

The use of UDP causes an issue with the configuration of firewalls and is currently not acceptable in cases where data security is paramount. As it is a connectionless transport protocol, it means that the UDP ports need to be opened up on the firewalls so that it allows data inbound to the data centre from the substation. As TCP is connection oriented, the TCP socket can be initiated from the WAMS server out to the WMU at the substation. This is achieved by configuring firewall rules at the data centre to allow connections initiated outwards from the data centre, but not connections initiated inwards to the data centre. Figure 6 shows the basic direction of the holes that would need to be opened in a data centre firewall depending upon the type of protocol used.

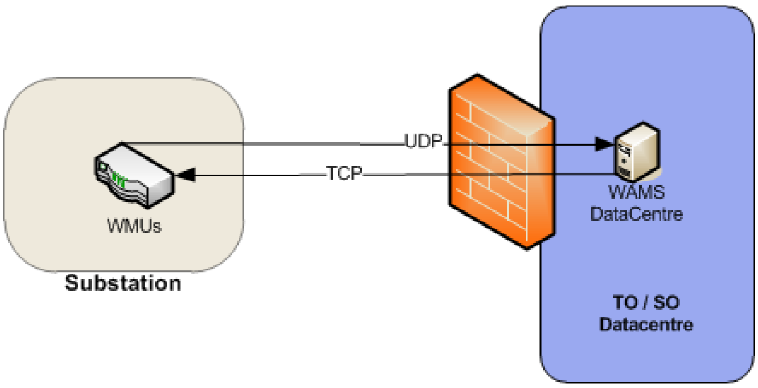

Figure 6. Port Directions

While the WMUs are communicating with systems that are outside of the critical infrastructure, UDP transmission is not an issue. However, if the project were to move the WAMS servers into the operational network area, the security would be much more rigorous, and a UDP hole in the firewall from the substations would be totally unacceptable. There are a number of potential solutions to address this, such as the use of intermediate proxy servers (this is already used in some production-level WAMS), or a mandatory requirement for TCP communications in all PMUs and WMUs. GE Grid Solutions have indicated it should be possible to develop the WMUs to transmit over TCP, but this would require further development.

3.2 Demonstration and Deployment of WAMS Applications

3.2.1 WAMS Platform: *e-terraphasorpoint*

VISOR marks the first major deployment of **e-terra***phasorpoint* in GB, in order to demonstrate and trial the new and potential WAMS-applications it facilitates. The phasorpoint platform was developed by Psymetrix, who were acquired by Alstom Grid, and subsequently acquired by GE, and is now GE Grid Solutions. **e-terra***phasorpoint* is now integrated as part of the wider GE **e-terra** product suite.

e-terra*phasorpoint* receives conventional PMU data via IEEE C37.118 at 50 samples per second, and also accommodates the new 200 samples per second WMU devices. It provides the following base functionality, in addition to the advanced analysis application modules demonstrated under VISOR, which are described in Section 3.2.2:

- PDC for stream reception, aggregation and forwarding. Automatic backfilling re-sends data missed during a connection drop between two PDCs.
- Storage of WAMS data and analysis results
- Presentation of WAMS data and analysis results in real-time and historical geographical displays (Figure 7) and charts.
- Event logging: both simple alarm thresholds and advanced application alarms
- Interfaces for data export to external applications, e.g. MS Excel, including SQL interface and CSV export.

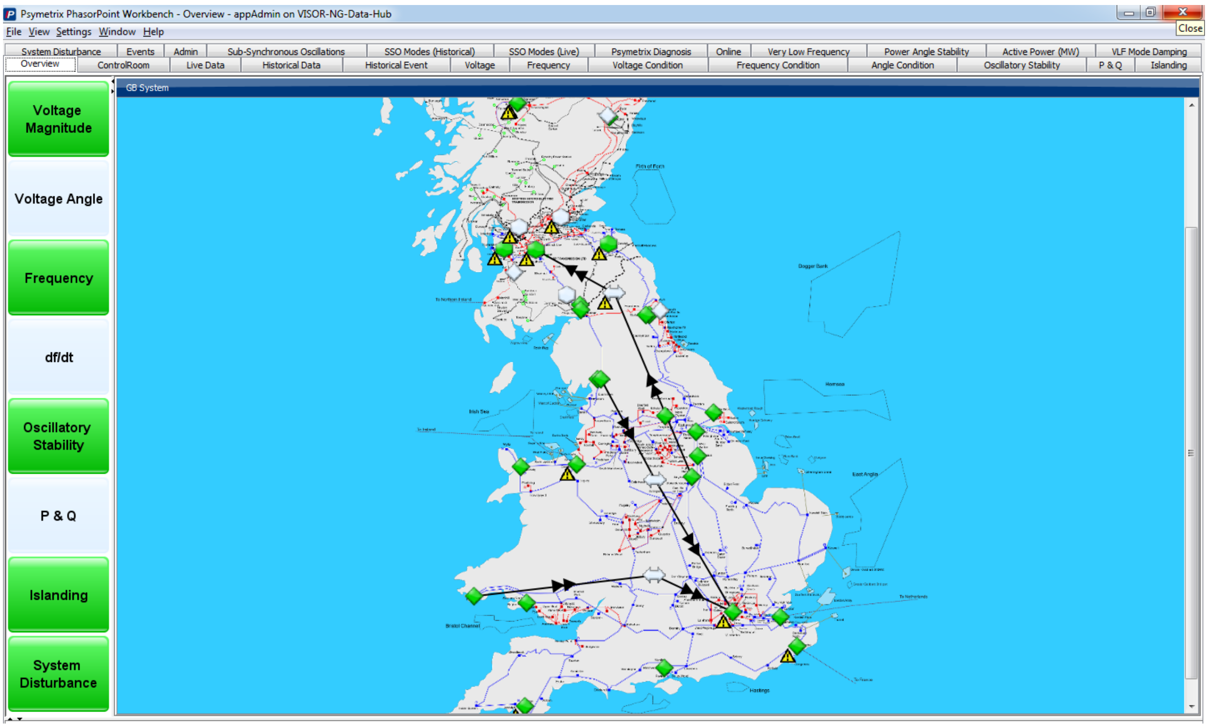

Figure 7. e-terra***phasorpoint*** **software (overview screenshot at system-level monitoring)**

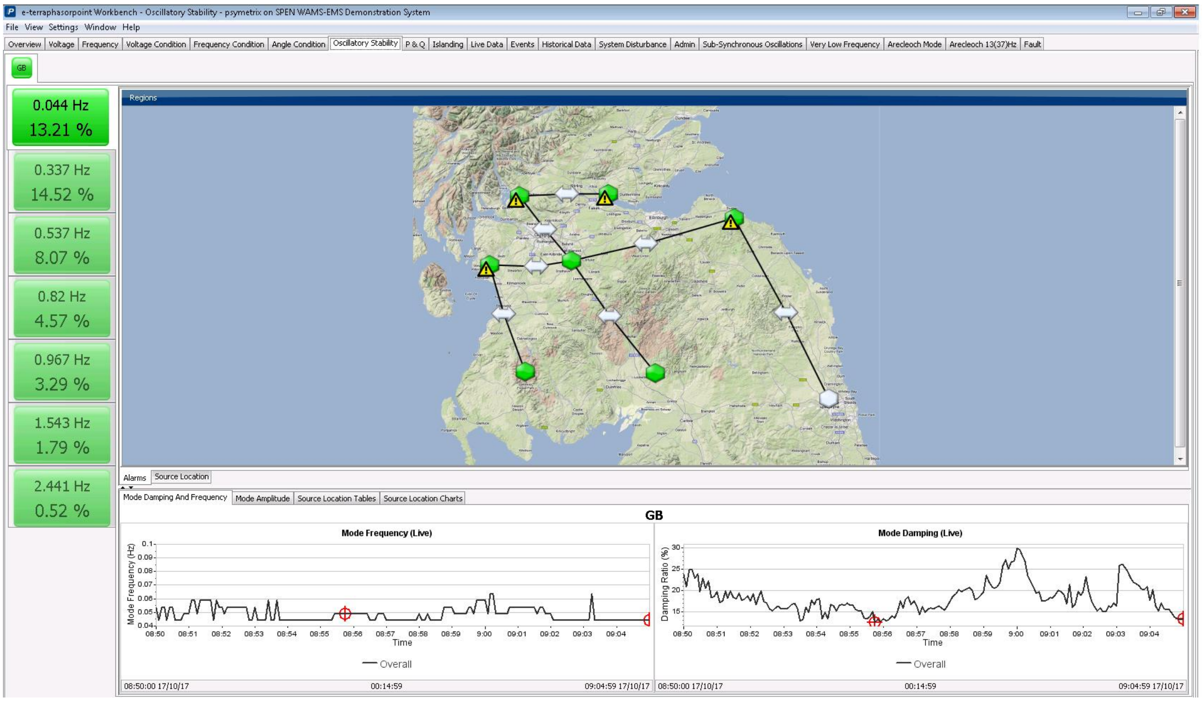

Figure 8. Oscillation Stability Management application within e-terra***phasorpoint*** **(screenshot at TO-level monitoring)**

3.2.2 WAMS Application Deployment

The same **e-terra***phasorpoint* analysis platform has been installed on each of the servers at SPT, NGET, SSE and the SO. There is a wide array of applications within **e-terra***phasorpoint*, the table below lists the applications specifically demonstrated through VISOR.

Table 3. Current suite of e-terra***phasorpoint*** **applications demonstrated through VISOR and available to GB WAMS**

#	Application	Data Rate (Minimum)	Measurement Type	Device Type
1	0.002Hz - 0.1Hz Very Low Frequency Oscillation Detection & Location	10Hz	Phasors	PMU
2	0.1Hz - 4Hz Low-Frequency Oscillation Detection & Location	10Hz	Phasors	PMU
3	4Hz - 46Hz Sub-Synchronous Oscillation Detection	200Hz	Analogs (point-on-wave)	WMU
4	System Disturbance Monitoring: Detection, Location & Characterisation	10Hz	Phasors	PMU
5	Power-Angle Boundary Constraint	1Hz (any)	Phasors	PMU
6	Line Parameter Estimation	10Hz	Phasors	PMU

With reference to the table above, Applications 1-3 form the Oscillation Stability Management (OSM) package and address oscillatory behaviour, which is a key aspect of power system performance assessed by VISOR. These **e-terra***phasorpoint* applications are capable of detecting oscillation (or modes) across different frequency ranges:

- **"Very Low Frequency" (0.002-0.1Hz) behaviour**. These typically take the form of common-mode oscillations, where the entire power system accelerates and decelerates in near-unison. They tend to be caused by generator speed governor systems, the control system which opens or closes the tap of water/steam feeding a generator, to maintain a certain speed (mains frequency). These are often termed governor modes of oscillation.
- **"Low Frequency" (0.1-4Hz) electromechanical behaviour** typically involving generators and their faster control systems, where segments of the GB power system swing against each other, resulting in see-saw like power flows across the network. These can involve the entire GB network, or be restricted to a smaller area around a particular power station. They are often termed inter-area, local and plant modes of oscillation.
  Some specific modes have been known in the GB system for some time, and are managed through the use of generator Power System Stabiliser control systems and monitored using the pre-existing isolated WAMS installed in National Grid and SPT.
- **Sub-Synchronous Interaction and Resonance (4-46Hz)**, which involve generator natural mechanical frequencies, electrical resonant frequencies introduced by series compensation, and/or oscillations introduced by power electronic converter control systems.

The visibility provided by the new oscillation source location tools has allowed these modes to be better characterised through long-term direct observation, to a level never achieved before. This has included baselining of normal characteristics and the capture and analysis of several instances of degraded behaviour (such instances are often expected, due to changes in network topology, new active technologies like HVDC or generator running arrangements). These observations can then be compared and validated against system model predictions allowing for fine-tuning, where necessary, and will also inform future operational procedures and monitoring arrangements.

The ability to characterise and assess the behaviour of these modes is considered critical as the GB system continues to evolve; becoming more complex, with new plant being connected and old conventional generators being decommissioned, and the network itself undergoing continuous development to accommodate these changes.

The capabilities of the remaining applications listed in Table 3 are briefly summarised below:

- **System Disturbance Monitoring:** this application provides detection, location & characterisation of system disturbances i.e. generator, load or transmission line disconnections. When a disturbance occurs, an alarm is raised, the closest monitoring point to the origin of the disturbance is highlighted, and the impact of the disturbance is characterised. This characteristion of the impact of a disturbance considers both the impact on system as a whole, to indicate the significance of an event or risk to the system, and at a local level to highlight those sites which might require urgent attention for post-fault recovery, or plant which might not have responded as intended.

  These capabilities are valuable in real-time operation, post-event analysis and long-term historical review. In real-time, they add to operator situational awareness, providing high-level information about a disturbance to augment or validate that from other systems such as the EMS. The automated analysis and availability of continuous, wide-area synchronised data enables more efficient post-event analysis. Finally, the long-term build-up of impact assessments of disturbances facilitates historical review and statistical analysis of system behaviour, such as identifying conditions (e.g. generation/demand profiles) under which the power system tends to be particularly affected by disturbances.

- **Line Parameter Estimation**, calculates the impedance of circuits using PMU voltage and current measurements from both ends of a circuit. This is valuable in validating network model parameters. The key challenge to line parameter estimation lies in addressing measurement noise and systematic error, so as to calculate consistent and reliable results.
- **Power-Angle Boundary Display**: a representation of the constraint and operating state of a transmission boundary. Targeted at the B6 Scotland-England boundary, this incorporates a derived voltage angle difference between the Scottish and English centres of inertia – which is more closely related to the physical stability limit than the conventional constraint on MW power flow. The representative Scottish and English "centres of angle" are derived as weighted averages of chosen bus angles in each area. A confidence measure for each highlights the impact of any measurement loss.

3.3 Creation of WAMS Pre-production and Training Environment

VISOR put WAMS analysis in front of many system operators and control engineers for the first time via the **e-terra***phasorpoint* platform, with many entirely new application modules seeing their world-first demonstration through the project. These new applications and capabilities have been demonstrated to end-users to engage, introduce and deploy **e-terra***phasorpoint*. However, limitations were met during the project as the VISOR system resided within the corporate network (away from the control room), thereby incapable of interacting with live SCADA measurements or replicating the true control room environment.

Through stakeholder engagement activities, VISOR identified the benefit and opportunity of utilising a concurrent SPT EMS upgrade programme to establish a dedicated WAMS integration and testing facility within the SPT operational control centre at Kirkintilloch. By repurposing elements of the upgrade environment, the **e-terra***phasorpoint* system could access the secure network domain, thus allowing direct interface with the EMS.

The facility provides an environment for training and evaluation of new operational tools and procedures incorporating WAMS data without interfering with, or posing cybersecurity risks to, the live operation of the real power system. As shown below, the system architecture mirrors SPT's real EMS and SPT's VISOR WAMS platform within a self-contained environment and receives both conventional SCADA data and key WAMS information including measurements, analytics and alarms.

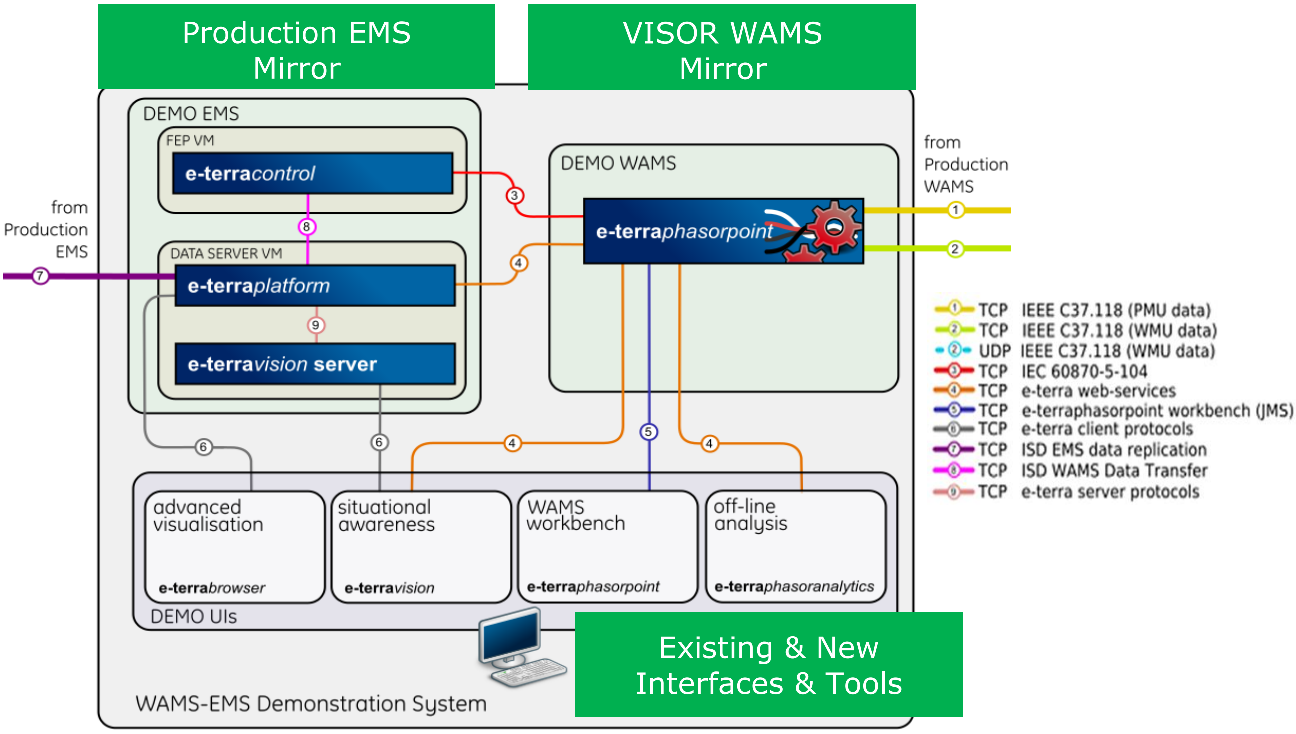

Figure 9. WAMS-EMS pre-production System Architecture

Furthermore, the facility has made WAMS more accessible to all project partners by providing a live representative environment in which operators can learn, configure and build screens to meet their needs whilst also providing a safe environment for exploring and trialling the next generations and phases of WAMS-EMS integration and visualisation capabilities.

Figure 10. WAMS-EMS Demonstration System Testing and Training Facility

The new applications and capabilities made available by this new WAMS-EMS facility include:

- **Hybrid State Estimation:** incorporation of phasor measurements into the State Estimator.
- **New situational awareness displays:** efficiently combining WAMS information with the traditional SCADA/EMS information and display screens that operators are accustomed to. WAMS information must be relevant and comprehensible to operators, displayed clearly and concisely, without extraneous detail. Two particular examples are:
    - **Voltage angle condition:** to clearly illustrate system stress, highlighting where actions such as planned line outages have led to stressed conditions that were not predicted by models e.g. large angle differences, either due to model inaccuracies or distribution system loading. Such differences can also block line restoration.

Visibility of angle across the network can assist operators in identifying re-dispatch actions to address this excess stress and enable reclosure of lines.

- **Oscillatory stability status:** whilst a powerful tool in managing problematic oscillations when they occur, the detailed picture of system oscillatory behaviour delivered by the VISOR WAMS applications is, during the typical stable state of the power system, of little interest to operators. It is vital therefore that key status information is presented clearly in operator displays to highlight conditions requiring attention and more detailed examination.

- **Hybrid WAMS-EMS Applications:** combining measurement-based analysis from WAMS with model-driven predictions from the EMS. WAMS measurements provide operators with direct visibility of stresses in their system and when combined with limits and contingency analysis driven by the EMS model, can highlight potential constraint issues in present or post-fault operating conditions. Model-derived angle difference sensitivities can then advise operators on the optimum redispatch action to return within limits.
- **Model validation & post-event analysis:** the WAMS-EMS Demonstration System includes tools for combined analysis of WAMS, SCADA, and simulation data. These tools enable:
    - System models to be validated, by comparing the response to disturbances, as captured by WAMS, to the modelled response from contingency analysis.
    - Easier and more efficient study of events by being able to view and analyse WAMS, SCADA and DFR data in one single tool.

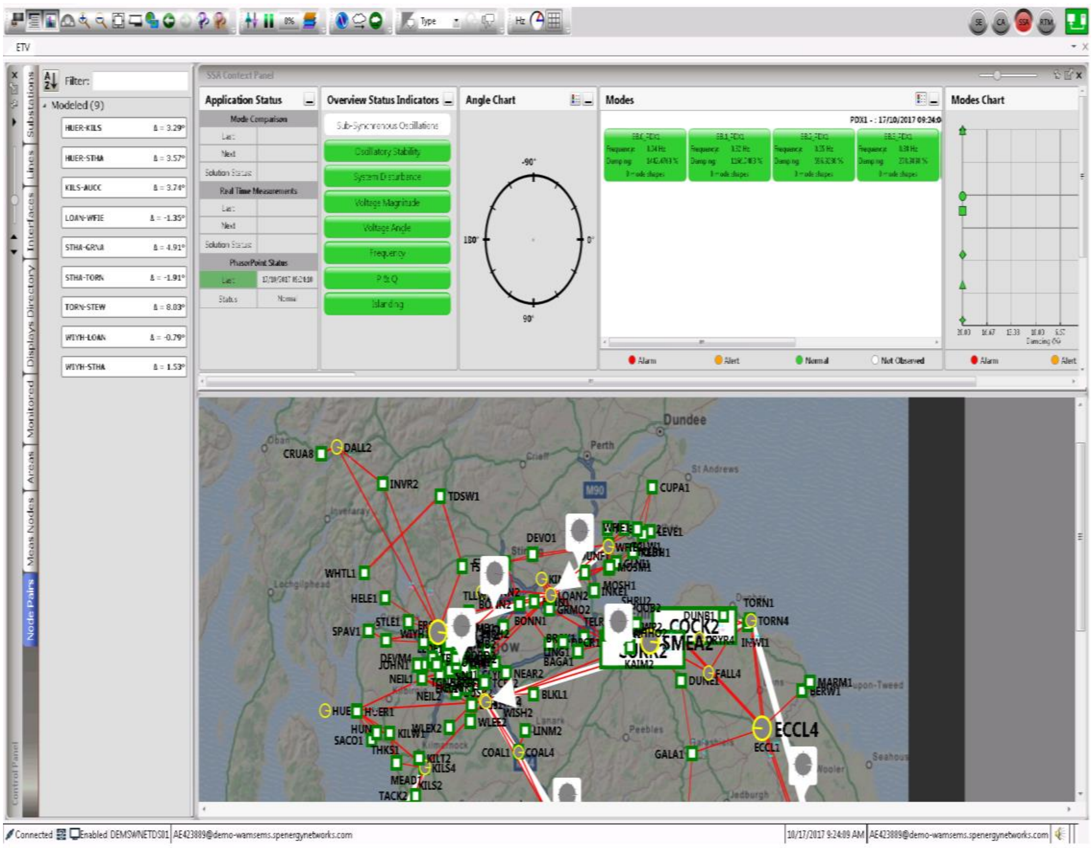

Figure 11. Example of new WAMS applications enabled in WAMS-EMS facility: contextual dashboard showing e-terra*phasorpoint* status and GIS-alarms

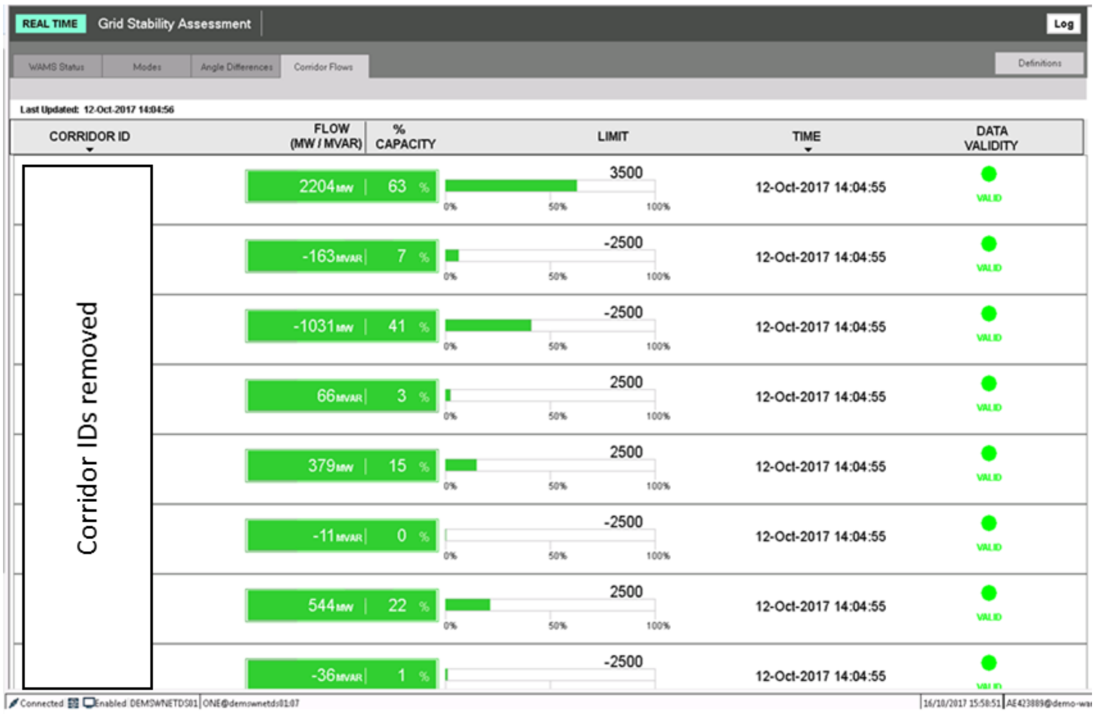

Figure 12. Example of new WAMS applications enabled in WAMS-EMS facility: Grid Stability Assessment including power corridor monitoring (bottom)

A WAMS and **e-terra***phasorpoint* training programme has been developed with the support of GE to help teach operators how to utilise the new tools and capabilities. Initial training sessions introduce the core principles, functionality and hands-on experience of the integrated WAMS-EMS platform, and a further set of dedicated training sessions covering different aspects of WAMS analysis and applications. The full list of training sessions developed through VISOR is provided in the tables below. Repeated sessions will also be held to ensure all operators and engineers receive suitable training.

Multiple sessions have been held at the new WAMS-EMS training facility and SPT Headquarters, Glasgow. The agenda for the previous training session is provided in Appendix 2.

Table 4. WAMS Training topics

Training Topic	Format	Duration	No.
Introduction to WAMS concepts	Classroom	⅓ day	3
Introduction to use of e-terraphasorpoint	Classroom and practical	⅓ day	3
Use of WAMS in improving real-time Situational Awareness	Classroom and practical	⅓ day	3
WAMS data integration using Grid Stability Assessment (GSA) tools, alarm integration and State Estimation	Classroom and practical	½ day	3
Historical phasor analytics capabilities using **e-terra**phasoranalytics	Classroom and practical	½ day	2
Training for IEC 60870-5-104 configuration for State Estimation and integration	Hands-on	½ day	2
Typical software configuration and system administration tasks pertaining to WAMS-EMS Demonstration System	Hands-on	1 day	1

Table 5. Training topics to be held at the WAMS-EMS Demonstration System facility

	Content	Audience
WAMS basics and Analysis Tools	• **WAMS Intro & Basics** • **e-terra*phasorpoint* Analysis Tools**	All (for WAMS basics), Planning & Analysis Staff
	• **Module 2 (cont): e-terra*phasorpoint* and PhasorAnalytics analysis tools**	Planning & Analysis Staff
Advanced WAMS applications	• **e-terra*phasorpoint* Advanced Applications: OSM, VLF, LF Source Location, SSO**	Planning & Analysis Staff
	• **e-terra*phasorpoint* Advanced Applications (IRB, SDM, LPE, Power-Angle boundary monitoring)**	Planning & Analysis Staff
e-terra***phasorpoint*** & PhasorAnalytics Admin and Configuration	• **PDC Admin, troubleshooting, Disaster Recovery PhasorAnalytics Admin** • **PDC and Workbench Configuration**	IT/Network Staff, **e-terra***phasorpoint* Admin, Lead engineer
Demo & Close-Out Meeting	• **Demonstrate fully configured e-terra*phasorpoint* and PhasorAnalytics (30 mins)** • **Use cases and business benefit for SPT participants**	All

3.4 WAMS-based Disturbance and System Performance Reports

The information gathered by VISOR has been collated and concisely reported across the relevant business functions using regular reports covering different aspects of power system operation and WAMS performance. These reports are designed and produced by GE to bring the learning from the continuous monitoring of oscillations and disturbances into an easily accessible format. They offer a completely new level of visibility that helps to discover the oscillatory behaviour of the system, i.e. how system dynamics vary throughout the day and under different operating conditions and in the longer term, track how these dynamics evolve in time.

Once the VISOR WAMS was fully operational, SPT trialled regular reports covering the following two aspects of power system monitoring. These reports were trialled both annually and monthly at different stages throughout the project:

- **Power System Performance reports** monitoring and reporting the oscillatory stability of the GB system, providing baseline trending of overall system stability dynamics and behaviour across the different oscillatory modes.
- **Power System Disturbance reports** presenting power system behaviour during of significant disturbances, e.g. generator loss or transmission line faults.

In addition to the reports listed above, the operational health of the VISOR WAMS itself was monitored and managed through:

- **Data Quality summaries**, providing a concise and interactive high-level timeline and statistics to identify problematic devices easily.
- **Data Stream Connection summaries**, in a similar form to the above, high-level statistics provide a quick overview to identify devices with poor communications.
- **PMU Connection Analysis reports,** identifying and investigating poorly performing data connection issues to inform remedial action to resolve issues.

The above reports ensured that the system was operating adequately, and that the vast amount of measurement data gathered by WAMS could be analysed and translated into meaningful learning for internal dissemination. Furthermore, the overall reporting process informs recommendations to effectively integrate WAMS data into business practices. Examples of procedural recommendations include what information to include in reports, the frequency of reporting, and most appropriate report recipients.

Regular WAMS system health reports were produced on a monthly basis during the initial stages of WAMS operation to ensure areas of unsatisfactory performance could be identified and investigated. The overall learning outcomes generated by these reports is provided in Section 4.3.

The above reports have been produced by GE and present highly valuable and concise overview of the performance of the system and the WAMS system itself. However, this is a manual process to extract and assemble the information from the WAMS platform and the details of the actual events witnessed. Whilst steps have been taken during VISOR to make the process more efficient and automated, this remains a task that requires manual intervention and more importantly requires suitable expert resource with knowledge of both the WAMS applications and power system analysis. The development of full or partial automated processes is recommended to form part of the enduring solution.

3.5 External and Internal Stakeholder Engagement

A proactive approach to stakeholder engagement has been undertaken to support the project in achieving its goal of accelerating the uptake of WAMS in the GB. As such, the VISOR project team has demonstrated a strong commitment to the dissemination of project progress and learning by presenting at many industry conferences and hosting dedicated knowledge-sharing events, seminars and training workshops.

Both internal and external stakeholders have been regularly engaged throughout the duration of VISOR, so that project aims and objectives are well understood, that lessons learnt and challenges overcome are shared, and also, to learn from other deployments and gather feedback from a broad audience. Furthermore, these engagement activities offered the opportunity to stay abreast of latest technology advancements, identify areas or applications for further development and discuss long-term goals of the industry across a broad audience.

An additional workstream was created to develop an open-source web-based tool to provide a high-level presentation of, and open access to, the PMU data. The tool offers read-only access to WAMS data using a web browser from anywhere; making WAMS information more open and accessible to other users outside the existing PMU analysis environment. By doing so, the tool also demonstrates alternative means of accessing and processing WAMS information and could complement detailed analysis tools such as **e-terra***phasorpoint*.

This means of accessing, visualising and interacting with WAMS information across multiple platforms, i.e. mobile phones and tablets, helped showcase WAMS to a broader stakeholder community without requiring access to **e-terra***phasorpoint*. The simplicity of this tool aided knowledge dissemination.

Figure 13. Screenshot of Phasor Data Visualisation tool

3.6 Production of WAMS Roadmap for GB, Including Coverage and Technical Architecture Recommendations

To determine the next steps and pave the way for continued operation and future expansion of the GB WAMS established by VISOR, a dedicated Roadmap report has been published through the project.

The Roadmap aims to support investment decisions regarding the continued operation and future expansion of the GB WAMS following VISOR. It examines WAMS deployments across the world and in GB commenting on the applications utilised, highlighting key learning points from both, and identifying the challenges that lie ahead. International experience of deployment has been obtained through consultation with Quanta Technology who have supported numerous utilities with the design and deployment of WAMS solutions in North, South and Central America. The objective outcomes are a list of recommendations across the three mains aspects of WAMS deployment (Application, Infrastructure, and Process) for the wide-spread implementation of the WAMS across GB, with regards to the three mainland Transmission Owners and the System Operator, including:

- A roll-out investment strategy;
- Potential operational frameworks considering degree of collaboration and coordination between TOs and SO;
- The requirements and responsibilities of each party.

<u>The conclusions from the Roadmap are listed below:</u>

Recommendations for roll-out

To support the move from demonstration to a production system, this Roadmap makes the following recommendations in relation to the three main aspects of WAMS deployment, Application, Infrastructure, and Process, each with its own set of challenges:

<u>Application recommendations:</u>

- Following the conclusion of VISOR, it is recommended that each party retains software licences for data processing and archiving applications to retain existing system monitoring coverage, and maintains the necessary infrastructure and processes to support them. Additional analysis applications should be licenced according to individual requirements;
- Significant development and deployment effort is required to unlock the full potential of WAMS applications, and should be guided by a long-term infrastructure deployment strategy;
- Facilitate and encourage the use of the GB WAMS platform to support the trial and development of new and existing applications.

Infrastructure recommendations**:**

- Each project partner to assess and upgrade accordingly:
  - To ensure the communication infrastructure achieves an appropriate Quality of Service between PMU, data centre and applications;
  - Review of communication infrastructure and data routing between TO and SO;
  - Legacy or problematic monitoring devices upgraded or replaced where required;
  - Review of monitoring coverage to identify areas of oscillation risks for immediate attention (output of review to also inform future expansion planning);
  - Assessment of computational infrastructure to identify areas for improvement, such as processing capability and server redundancy.
  - The system architecture should allow for potential WAMS expansion to one WAMS monitoring device per transmission substation.

Process recommendations**:**

- Development of the policy covering various aspects of System Performance Monitoring, defining the WAMS requirements for the provision of monitoring and analytics to the SO;
- Identify WAMS delivery team(s) or task force responsible for overseeing deployments in the immediate future and define GB system monitoring requirements for an effective and cost-efficient roll-out: this team should comprise of representatives from each TO and the SO;
- New data sharing arrangements between SO-to-TO and TO-to-TO to be reviewed, and/or trialled for specific WAMS applications, to ascertain benefits and ensure that, where necessary, suitable measures are in place;
- Establish regular reporting of power system and WAMS performance. Such reports proved highly valuable in VISOR by analysing disturbance and oscillatory behaviour, along with overall WAMS health. Currently, these reports are compiled by a skilled resource at GE but TO/SO could perform this analysis with tools currently available, and future effort should be made to automate this process, where possible.
- Resource is required to support WAMS with the translatable skills between complex power system understanding, analytics development and information systems expertise.

The full Roadmap can be downloaded from the VISOR website.

4 The Outcomes of the Project

This section documents the main outcomes and learning from the VISOR project by providing an overview of the project work packages. It lists the original objectives and the resultant learning outcomes of each, providing recommendations on future requirements and highlighting the improvements offered by WAMS applications that are now available or ready for future trial and development. Some of the key observations made by the GB WAMS to date are also presented.

4.1 Overview of Work Package Outcomes

The objectives for each work package as per the original project submission are listed below along with the outcomes achieved by the project.

Work Package 1: Enhanced System Oscillation Monitoring

Objective a) Sub-Synchronous *Oscillation management, observing and characterising the wide-area performance of the grid and identifying early warning signs of SSO. The focus of the VISOR project is the known risk of interaction between natural frequencies of series capacitors and long-shaft generators (classical Sub-Synchronous Resonance, SSR), as well as the other less-understood forms of SSO involving control system interactions with HVDC and wind farm controllers.*

(note: here SSO refers to the 4-46Hz Sub-Synchronous Resonance/Interaction range)

Outcome: VISOR has successfully deployed (what is believed to be) the world's first continuous, real-time, wide-area SSO monitoring system covering up to 46Hz. This consisted of new WMU devices, data gathering infrastructure (upgraded PDCs to take WMU data) and a new advanced SSO analysis application module. This has provided the GB TOs and SO with their first continuous, wide-area look at SSO behaviour in GB, and has provided significant insight; a number of behaviours, including some low-level interaction, have been identified for further investigation. The new capability has also been used in real-time to support commissioning of new plant, such as series compensation, and monitoring thresholds have been set to detect abnormal behaviour. Work is still ongoing to understand the precise baseline limits of the system. This will go on to further inform thresholds/stability limits for real-time monitoring. The SSO module of the Oscillatory Stability Management application is available for roll-out.

Objective b) Oscillation Analysis & Source Location to baseline the dynamic performance of the grid, identify the occurrence of early warnings as well as instability, and determine the locations of equipment that are degrading the stability of the system.

Outcome: The continuous GB-wide visibility delivered through VISOR, coupled with the new oscillation analysis and source location tools demonstrated, has allowed GB oscillatory behaviour to be closely monitored and characterised through long-term direct observation, to a level not achieved before. System modes, including GB-wide inter-area oscillations, have been characterised in terms of the key contributors and participants; a number of small localised behaviours have been identified which are of interest to system analysts, and the VISOR data and tools have provided valuable contributions to investigation and cause identification of some significant events. This is ongoing and needs to be regularly reviewed and updated.

The Very-Low Frequency (VLF) and Low Frequency (LF) modules, including source location, of the Oscillatory Stability Management application are available for roll-out.

Work Package 2: System Model Validation

Objective c) Line Parameter Estimation (LPE) where parameters derived from measurements are compared with the values used in the network model. The variability due to weather, network loading and other effects is characterised. Conductor sag on long transmission lines may have a material effect on transient stability simulations and so needs to be quantitatively assessed.

Outcome: Through VISOR, a dedicated LPE analysis application was demonstrated in **e-terra***phasorpoint* by GE. In early 2016, initial studies found insufficient data quality from multiple measurement units made LPE calculation very challenging. Since then, some monitoring improvements were made, to improve data quality. The LPE application was deployed on the VISOR WAMS, and long-term review has showed that useful results can be produced that can support network modelling and simulations. The LPE application module is now available for roll-out.

Objective d) Oscillation analysis validation where the frequency, damping, amplitude and mode shape is compared with the expectation. In cases where there is a degradation of oscillation damping, the source location can identify where there is a suspected deviation from the model of the network, generator or HVDC link.

Outcome: GE supported this objective by undertaking numerous investigations examining oscillation events observed by VISOR and produced a number of consistent cases characterising mode behaviour across GB, including source location information. The VLF and LF modules, including source location, of the Oscillatory Stability Management application are available for roll-out.

Objective e) Transient stability simulations for reconstruction of disturbances can be compared with records of measured wide-area disturbances to qualitatively assess the accuracy of the full system simulations.

Outcome: UoM supported this objective by comparing oscillations observed by VISOR with simulations based on the Offline Transmission Analysis (OLTA) model used by National Grid. The report produced valuable conclusions however the detailed dynamic model validation was limited by the absence of primary frequency response in the OLTA model as this primary response is a critical factor in determining how the system responds to a large disturbance. UoM's investigation found that, despite efforts to improve similarity between the steady-state load flow and the pre-event measurements, the active and reactive power flows in the model differ somewhat from the measured values. Furthermore, the reactive power flows in the model are far less similar to the measurements than the active power flows are, and some of the simulated reactive power flows had significant differences. Another notable finding was that subsequent event reports did not capture all of the major events that occurred in the aftermath of a 1GW bipole trip, suggesting additional support or enhancement will be required to improve similar future effort for WAMS based model validation.

Objective f) Generator model validation: where naturally occurring disturbances and control set-point changes are captured and used with synchronised generator and wide-area monitoring to identify deviations and improve generator and control system modelling.

Outcome: Monitoring devices, alarms and regular reports have ensured the wide-area monitoring platform has captured and analysed disturbances and deviations, particularly those that potentially involve power electronic controllers or encroach known generator modes, to enhance understanding of the dynamic behaviour of the transmission system. The capture of system and generator response to GB system disturbances has provided date that can be used to support validation of generator models.

To further support this objective, UoM conducted a body of research examining the torsional oscillations that occur as a result of sub-synchronous resonance in series compensated transmission systems. The research studied the impact of dynamic load on oscillation damping, torsional interactions with induction motors, and proposed methods for identifying generators vulnerable to SSR and critical circuits which, if switched out, heighten the potential risk of SSR occurring. Through this research, UoM also propose a new method for torsional oscillation mitigation using variable frequency drives, and can be found in the findings report entitled *VISOR Project: Monitoring and Management of Torsional Oscillations (Sub-Synchronous Resonance),* December 2016 (Dattaray, Wall, & Terzija, 2016).

Work Package 3: Improvements for management of stability constraints

Objective g) Understanding of uncertainty – quantify the effect of model parameter variation and how the dynamic model validation in WP2 can improve confidence. Review transient measurement records to calibrate accuracy of the simulation model. Assess the influence of generation forecast accuracy on stability limits.

Outcome: UoM conducted a study into the impact of uncertainty on stability management with the findings documented in a report entitled *VISOR Project: Impact of Uncertainty on Stability and Security Margins,* December 2016. The report examines the potential merits of developing existing “Preventive Control” stability management approaches (e.g. a power flow constraint) with “Corrective Control” which can adapt to a wide range of contingencies and operating conditions. The paper proposes an approach which incorporates probabilistic methods for risk-based management of security that provides an effective combination of preventive and corrective control. The proposed method allows the user to select a pre-determined set of preventive measures that ensure security for the most probable contingencies and conditions, based on a defined level of acceptable risk. Corrective control would be implemented to combat against less likely contingencies and conditions. Given the limitations of the system model available to VISOR, a quantification activity using the GB system model was not pursued as part of this work. However, the paper does provide a foundation of work to inform future assessment.

Objective h) Improvement of model initial conditions – trial the use of a hybrid state estimator that uses PMU data to improve reliability and accuracy of the solution. Test through on-line and off-line techniques to determine the benefit of this more sophisticated approach on the stability limit calculations. Hybrid state estimators have been shown in a USA trial to improve accuracy by between 0.5% and 2%.

Outcome: UoM led an investigation into HSE by evaluating the performance of different HSE approaches that combine SCADA and WAMS measurements in order to improve state estimation above existing practices. The investigation concluded that the Integrated type HSE approach provides optimum accuracy, resilience to gross errors, and reliability (relative to measurement placement). The newly created WAMS-EMS facility enables HSE applications to be deployed in order to assess true performance improvement. Modelling improvements are anticipated in the region of 2-3%, but these cannot be validated until HSE is fully operational on the GB system. If these improvements were realised in GB it would save millions of pounds in system balancing costs. HSE operation is contingent on further system model developments in line with current system operation in order to enable comparative assessment of HSE with current practices.

Objective i) Improved visualisation of stability limits for operators – the ability of system operators to run a system at high levels of utilisation depends on the confidence they have in their monitoring data. The trial will test a power-angle representation of the boundary state based on weighted angle differences and contrasting against conventional power-flow representation. This will consult the system operators and owners to define approaches. The benefit to transmission network owners will allow the release of incremental capacity without requiring additional primary network investment. Such benefits will be further passed onto customers in the form of carbon reduction and reduced constraint costs.

Outcome: A dedicated Power-Angle Boundary Constraint application has been trialled within **e-terra***phasorpoint*. The project has demonstrated this application and its new proposed approach to provide a measure of stability across the B6 boundary that is complementary to the existing MW constraint, which might be used to increase the power-transfer limit across the boundary under previously constrained scenarios. The boundary constraint application has been initially developed for the B6 boundary but can be applied across a different region providing sufficient monitoring data is available.

Objective j) Trial the reliability of area angle measurements – Understand the system conditions that arise and cause angle movements across the boundary, identify any that could cause difficulty in deciding actions. Determine if the signals provide good visibility of disturbances and therefore can reliably provide the observability required for control of equipment such as HVDC links.

Outcome: VISOR has trialled a new representation of the constraint and operating state of a transmission boundary. Targeted at the B6 Scotland-England boundary, this incorporates a derived voltage angle difference between the Scottish and English centres of inertia. The representative Scottish and English "centres of angle" are derived as weighted averages of chosen bus angles in each area. A confidence measure for each highlights the impact of any measurement loss. This application has been successfully demonstrated across the B6 boundary by the project but has not been deployed for real-time operation of the network. However, during VISOR, WAMS data obtained by SPT has already proven valuable in assisting the SO decision-making regarding real-time operation of the system.

Work Package 4: Supporting Infrastructure

Objective k) Continuous analysis of oscillations and retention of significant dynamic behaviour

Outcome: The continuous GB-wide visibility delivered through VISOR, coupled with the new oscillation analysis and source location tools demonstrated, has allowed GB oscillatory behaviour to be closely monitored and characterised through long-term direct observation, to a level not achieved before. System modes, including GB-wide inter-area oscillations, have been characterised in terms of the key contributors and participants; a number of small localised behaviours have been identified which are of interest to system analysts, and the VISOR data and tools have provided valuable contributions to investigation and cause identification of some significant events. Analysis results continue to be stored, and raw high-resolution data for some events of particular interest have been preserved long-term.

Objective l) Impact assessment of disturbances over a long period of time, noting the statistical distribution of occurrences of events with varying impact

Outcome: Measurement data and analysis alarms are retained to allow historical performance to be examined and events or disturbances to be replayed at a later date. All disturbances captured by the System Disturbance Monitoring module of **e-terra***phasorpoint* are characterised in terms of their impact on power system metrics (e.g. rate-of-change-of-frequency) and this information is logged. Regular power system performance reports summarise this information, and allow the observed disturbances to be cross-referenced with switching operations and outages to determine the resultant impact on cost and system performance. Such reporting can, therefore, examine historical performance to highlight potential hazardous trends that warrant further investigation and inform risk assessment. The data retention and playback capabilities have been demonstrated and should remain in service to ensure potentially valuable events are not missed. The regular performance reports are not yet automated and have been compiled by GE throughout this project.

Objective m) Data-Storage: Providing the necessary data collection, storage and retrieval facilities to facilitate the other key work packages

Outcome: A robust IT infrastructure is vital for the WAMS to operate. VISOR has successfully established a suitable data collection and communication architecture for the purposes of the project, but further actions are required to transition this architecture to a full productionised system. VISOR has initiated this process by establishing a WAMS-EMS testing facility in the appropriate production-grade network, and system architects have identified measures to create a production-grade system. However, in order to adequately transition the whole WAMS infrastructure into the same operational network, and retain the existing services (i.e. data links between TOs and SO), ongoing coordination and collaboration are required. Each project partner is considering interim and enduring architecture designs, using learning from VISOR to specify storage, processing, and data communication requirements.

Work Package 5: Knowledge Dissemination

Objective n) Internal Knowledge Dissemination

Outcome: Internal stakeholder engagement has proven highly successful in not only sharing learning and tools offered by VISOR but also gaining feedback from end-users of the system. The following activites have been undertaken to achieve this objective:

- Dedicated internal workshops and learning dissemination events. Application workshops have been held for each application released by VISOR for the purposes of review and approval. Multiple dedicated application demonstration and drop-in events have been hosted at Kirkintilloch, Warwick and Wokingham to engage with the wider internal audience and on-duty engineers.
- Seminars have been hosted with speakers with international experience of WAMS deployments in order to share learning, discuss challenges and build confidence to support overall GB deployment effort.
- Online engagement and access to project information and reports
    - The website has provided stakeholders with the project aims and objectives and access to download publicly available reports
    - Press-releases of project successes, key findings and upcoming events communicated through intranet and internal social media outlets

Objective o) External Knowledge Dissemination

Outcome: External stakeholders have been engaged through two main avenues:

- Attendance and presentation at many industry conferences on an annual basis, which have included the Low Carbon & Network Innovation (LCNI), PAC World, CIGRE, AllEnergy, and CIRED.
- Dedicated VISOR stakeholder events hosted by the project team.

A full list of these engagement activities and events is provided in Appendix 1.

Objective p) Influencing and updating policies and standards

Outcome: One of the key influence areas has been identified as the monitoring requirements placed upon TOs as determined by the SO. Collaborative effort has been made through the project to influence policy regarding monitoring requirements. This has been particularly successful with the SO as a project partner, as VISOR has demonstrated a wide range of applications and benefits cases offered by using WAMS at a system-level.

Objective q) Public Engagement

Outcome: Public engagement has focused on delivering biannual public-facing project progress reports to Ofgem and the VISOR webpage hosted on the SPEN website. The website provides a complete overall explanation of the aims and objectives of the project, a document library to download relevant project reports and presentation material, and a project contact email address to facilitate any additional enquiries.

4.2 Learning from System Commissioning

Following the installation and commissioning of the WAMS infrastructure, a system commissioning report was published to explain the installed infrastructure which underpins the project, and the learning acquired throughout the planning, installing and commissioning of the system. The two key findings from the report are summarised here.

- **Third-party commissioning the new Multiprotocol Label Switching communication link**
  In order to support the data transfer rate from the SPT Data Centre to the System Operator's WAMS Data Hub, a direct MPLS link was established between Kirkintilloch and Wokingham to support the large fleet of phasor measurement devices in SPT. With fewer monitoring devices on the SHET network, an IPSec link provided sufficient data transfer capacity for the link between SHET and SO.

  The advantage of a dedicated, unobstructed, high-performance point-to-point connection offered by the MPLS link was also its greatest disadvantage. Implementing an MPLS or any Wide Area Network that may require new cabling is not straightforward, and in this case, the work required to establish the MPLS link was contracted through a third-party service provider and carried out by the telecommunication network provider. The commissioning of the MPLS suffered extensive delays and deadlines were repeatedly missed and delayed further. In total the commissioning of the new MPLS was delayed by 18 months, and a separate IPSec link was subsequently implemented as a contingency measure to achieve related project deliverables.

- **Communications Link Bandwidth**
  Initial estimates of traffic volumes were based upon theory and the initial planned scale of deployment (with some margin). In reality, additional bandwidth was required to allow for incorporation of extra devices that were upgraded to produce WAMS data, and to allow for larger than expected fluctuations in data flow and backfilling of data from dropped connections. The initial bandwidth calculated for the National Grid to SPT WAN link was not sufficient for the duration of the project, and so was increased.

4.3 Learning from WAMS Applications and Observations

WAMS analysis applications provide the basis for new and improved insight and alarming capabilities to individual network owners and operators. Two key areas of focus for VISOR applications have centred on providing visibility of SSO and enhancing stability and capacity assessment of the B6 Boundary between Scotland and England. VISOR has successfully demonstrated both Oscillation Stability Management and B6 Boundary Constraint Management applications to support these objectives, as discussed below. In addition to these two applications, a range of other benefits to post-event, network planning and control room functions are also discussed below.

4.3.1 Power System Oscillatory Behaviour

The continuous GB-wide visibility delivered through VISOR, coupled with the new oscillation analysis and source location tools demonstrated, has allowed GB oscillatory behaviour to be closely monitored and characterised through long-term direct observation, to a level not achieved before. System modes, including GB-wide inter-area oscillations, have been characterised in terms of the key contributors and participants; a number of small localised behaviours have been identified which are of interest to system analysts, and the VISOR data and tools have provided valuable contributions to investigation and cause identification of some significant events.

VISOR has detected several oscillations in both the electromechanical and SSO frequency ranges which have been fairly localised and low magnitude. Such behaviour includes local electromechanical modes, power electronic or voltage control modes, and the torsional modes of generators. The new visibility of the 4-46Hz range has revealed many previously unseen frequencies in the system, most of which are believed to originate from power electronic converters and controls.

Due to the confidential nature of these observations, the two examples of observed events provided below have been anonymised.

This application has proven highly successful in demonstrating a level of SSO insight that would otherwise go unnoticed. Whilst many of the observations made by the Oscillation Stability Management (OSM) application have been relatively small in amplitude and resulted in no tripping events, the ability to detect reoccurring oscillations allows the severity to be monitored over time, baselining normal and abnormal events and highlighting potentially hazardous changes in trends.

i. Figure 14 shows a brief and relatively low amplitude, but still significant, oscillation observed in active power, in a segment of the GB system. This oscillation was detected in real-time, and the region containing the source was identified in the real-time display, later this confirmed to be consistent with a manual investigation using DFR data.
ii. Figure 15 shows a detected variable-frequency mode moving close to a known plant mode, and a corresponding degradation in mode damping and amplitude at the plant in question. This event was sufficiently small in amplitude that it did not cause protection to operate or DFRs to trigger but highlights an area for examination to reduce risk against future occurrences.

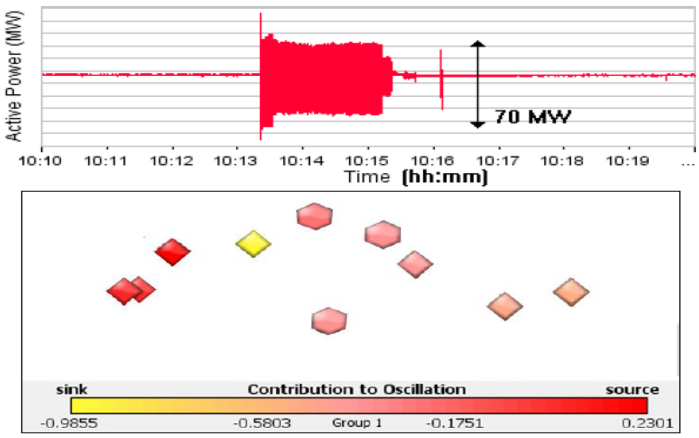

Figure 14. Example (anonymised) of a significant oscillation event observed in active power (top) and real-time source location display (bottom) for the relevant segment of the GB network.

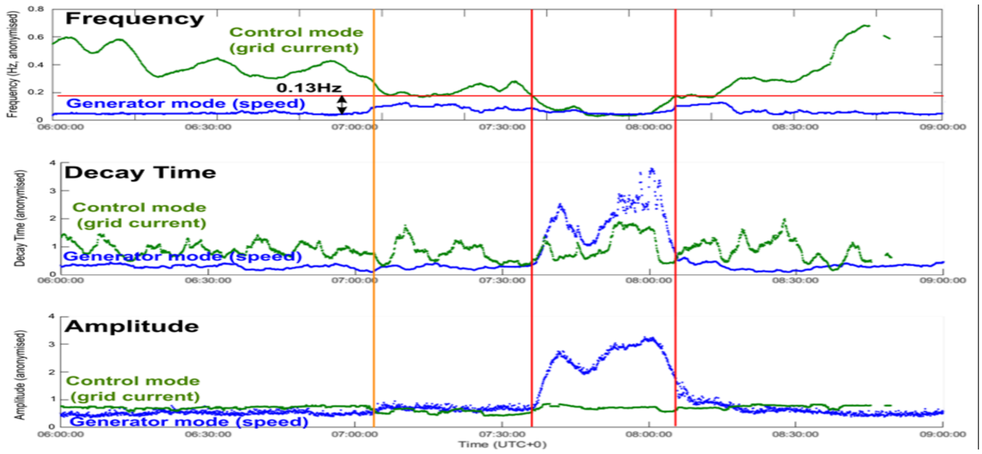

Figure 15. Example of very low-level sub-synchronous interaction observed (anonymised)

4.3.2 B6 Boundary Angle Display

Following approval of the specification, the B6 Boundary Display application was demonstrated in Q4 2015. 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.

a)

b)

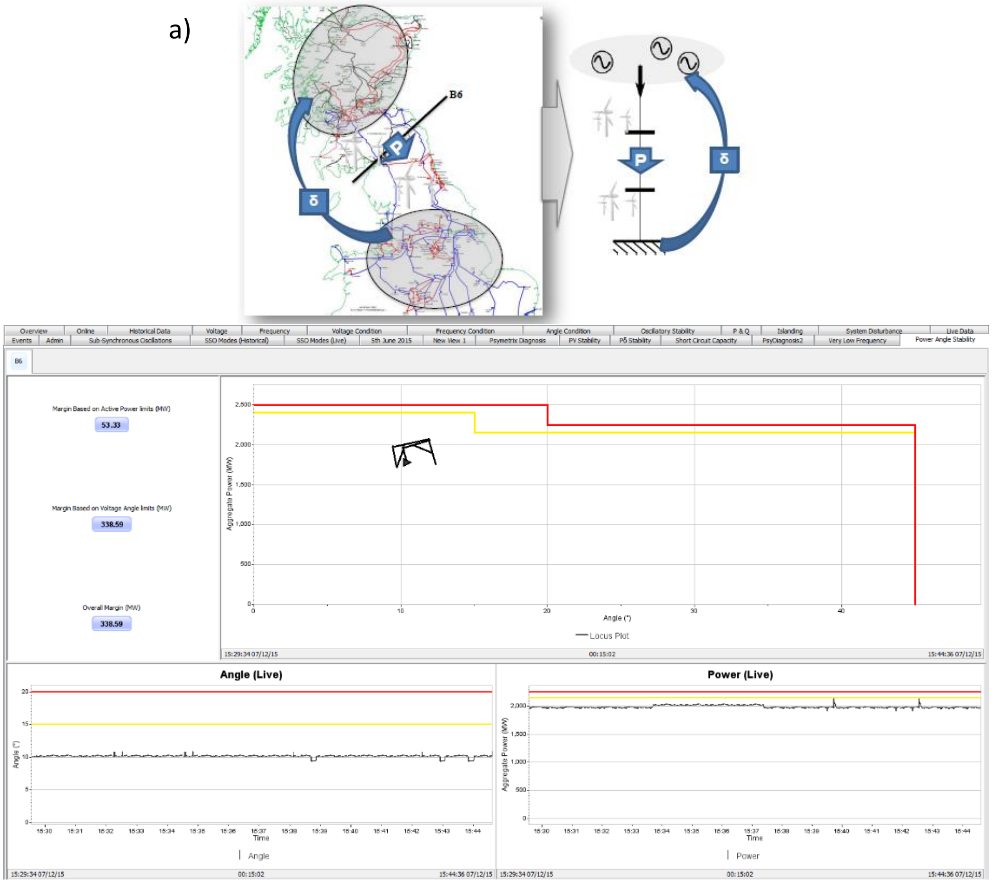

Figure 16. B6 power and angle boundary representation a) concept and b) actual

Angle-based transfer limit monitoring was specifically designed to demonstrate a new approach to provide a measure of stability and transfer limit monitoring which is more closely related to the physical stability limit than the conventional constraint on MW power flow. This measure was based on aggregated angle calculation across a boundary, and was designed to complement the existing MW constraint. With minor development and refinement, this approach could be expanded to cover all GB power boundaries to provide real-time visibility of the stability of critical circuits.

4.3.3 Application Benefit Areas

The project has demonstrated the important role WAMS applications can play in supporting network owners and operators by enhancing three main aspects of daily operations and long-term management of the system: post-event analysis, system planning, and real-time operation, as outlined below.

1) Post-Event Analysis Benefits

Following a disturbance or event in the power system, several analysis processes examine network behaviour and performance to determine root cause analysis, verify the performance of protection equipment, and/or view control and damping response.

Typically, DFRs capture events in high resolution, however, the process of assembling the captured event data from multiple DFR records can be very time-consuming. Automated processes can be established that retrieve and assemble the data from multiple devices scattered across the network, thereby reducing the time taken to perform the necessary post-event analysis. However, visibility will only be available at locations where a DFR has triggered, unless wide-area cross-triggering is implemented, which has its own implementation challenges.

As part of a WAMS, high-resolution synchronised measurements are continuously collected across a wide area, and stored. This makes the investigation of disturbances, and the producing of incident reports following a disturbance event, much easier, thus saving analyst time and potentially gaining greater insight into system behaviour, proactively identifying behaviour that requires correction such as a non-compliant generator response to a fault.

As the measurement data provides greater insight and accuracy of the state of the system at a given instant in time, WAMS data can be used to monitor the performance of series compensation devices to validate anticipated response and enhance models. In the same way, the SO could utilise WAMS to verify that generator frequency/voltage support response remains compliant with contracted levels.

An example is shown in Figure 17, showing response of multiple generators to a frequency disturbance. With WAMS, this can be generated in a few mouse clicks, whereas using DFR data would require devices to have triggered, and then manual/automatic retrieval and combination of multiple data files. In addition, the automated disturbance impact characterisation capability demonstrated under VISOR can immediately highlight locations that suffered the most impact from an event, a non-compliant response is likely to be highlighted in this way.

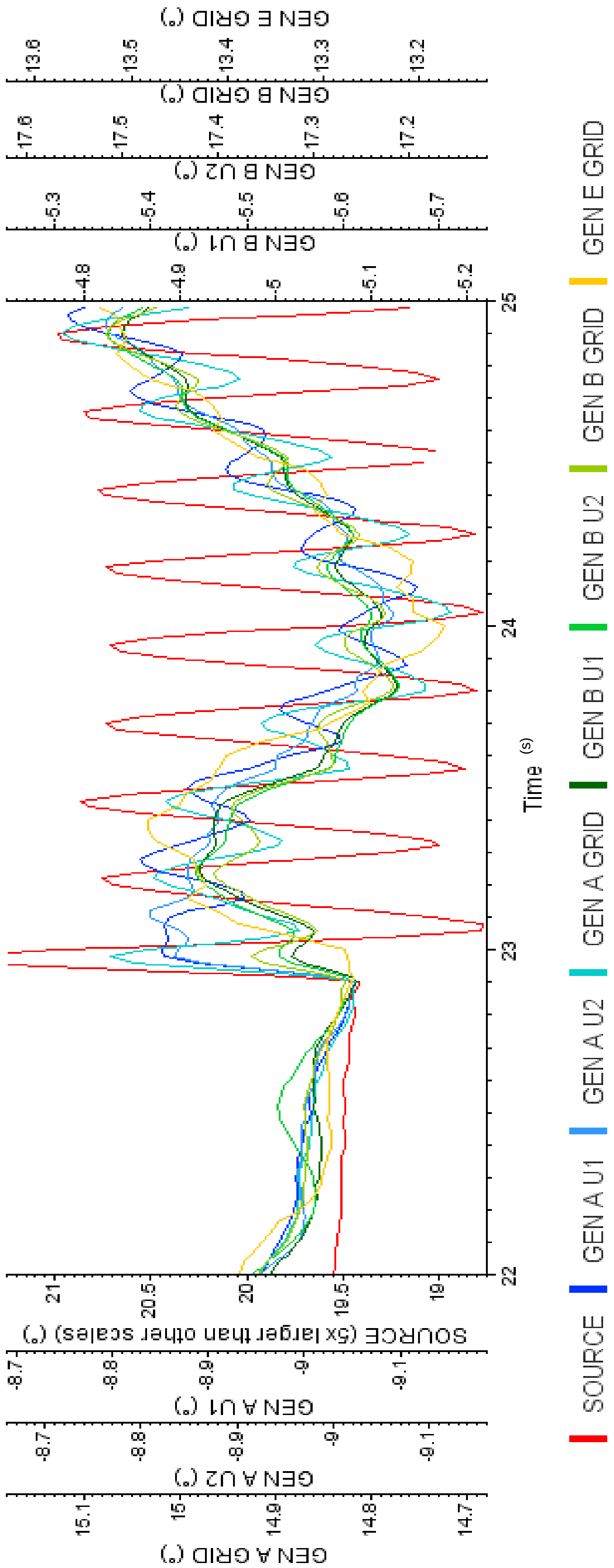

Figure 17. Example WAMS capture of generator response to a disturbance (anonymised)

The provision of accurately time-synchronised high-resolution measurements by the GB WAMS can offer process and/or accuracy improvements of several post-event actions, namely:

- Faster information about a disturbance, and Post-Event Analysis process improvement (data is already gathered and aggregated on the WAMS server)
- Transient stability studies (based on improved model configuration)
- Review of control and damping optimisation
- Plant performance and compliance (generator, HVDC link, FACTS devices etc.)
- Dynamic model validation and calibration
- Operator training simulator

2) System Planning Benefits

The use of synchronised measurements through WAMS delivers similar benefits to system planning through improved analysis accuracy and capability and enhanced process efficiency as it does for Post-Event activities.

The time-synchronised and high-resolution measurement data enhances analysis capability in system planning, supporting activities such as transient studies, oscillation analysis, and model validation. As processes develop, these processes could become automated to increase speed and potentially provide some form of computer-aided model validation.

The continuous observation of oscillatory stability can be used to validate the accuracy of dynamic models of the system by identifying differences in modelled and observed performance that highlight areas to prioritise for more detailed investigations. Where there is uncertainty in the model-based evaluation of the stability of the system, the detailed information that can be extracted from time-synchronised measurements offer a greater understanding of system dynamics, improving the model tuning and validation process.

The process of model validation could be further supported by automated processes that automatically detected differences and propose fine-tuning certain coefficients. However, this process would require substantial development effort to make this sufficiently robust before computer-aided model validation can be achieved, but some elements of WAMS integration with model validation could be pursued as an initial development which would deliver benefits to increase the speed of the process.

Furthermore, the enhanced understanding and management of system dynamics and improved modelling may also support planning and modelling black start scenarios, and form the starting position for potential future applications to assist with control room implementation of islanding and recovery actions.

WAMS facilitates or supports the following applications which provide benefit to system planning activities:

- Offline Model Validation, leading to automated dynamic model validation and calibration
- Backup to the existing SCADA
- Achieve marginal boundary increases, deferring major reinforcements until the need case is firm

- Asset Performance indication
- Line Parameter Estimation
- Data analytics (Complex Event Processing)
- Black-Start planning
- Condition control measures and optimise settings

3) Real-Time System Operation (i.e. Control Room)

Whilst there are certain benefits achievable within the post-event and planning business areas, a large portion of the financial benefits will arise from real-time operation in the control room by the WAMS-based applications discussed below that were demonstrated by VISOR, as well as other potential future applications.

The new wide-area monitoring capabilities and analysis tools have proven benefit by increasing visibility and enhance understanding and situational awareness specifically in relation to system dynamics and providing early warning of system risks. This real-time visibility has been invaluable during the commissioning of new plant, and to support unusual operating conditions.

Angle-based transfer limit monitoring was specifically designed to demonstrate a new approach to provide a measure of stability and transfer limit monitoring which is more closely related to the physical stability limit than the conventional constraint on MW power flow. This measure was based on aggregated angle calculation across a boundary, and was designed to complement the existing MW constraint. With minor development and refinement, this approach could be expanded to cover all GB power boundaries to provide real-time visibility of the stability of critical circuits.

HSE occupies the middle ground between classical state estimation (SE) and linear state estimation (LSE) and forms a logical step in realising the benefits of synchronised measurements for state estimation with only partial observability of the system from PMUs. The integration of WAMS data into HSE will enhance system planning activities, such as power-flow studies and contingency analysis, to more accurately determine circuit parameters, load-flow, and voltage and transient stability limits. The anticipated improvements in the accuracy of the HSE solution due to WAMS data and faster execution are in the order of 2-3%. If these improvements were realised in GB it would save millions of pounds in system balancing costs.

All of the proposed control room applications working together to ultimately give control room operators an enhanced and more accurate picture of the real-time stability of the system to facilitate more precise and dynamic management of the whole system and reduce total constraint.

In terms of the applications which have been investigated to date, the following are considered to provide benefit to real-time operation of the system:

- Monitoring and alarming: V, f, df/dt, P, Q, angle difference
- Oscillation Monitoring
- Oscillation Source Location
- Improve State Estimation using Hybrid State Estimation (HSE)

4.4 Learning and Recommendations on Coverage and Technical Architecture

The transition beyond a pilot innovation project into the business requires strong evidence and benefit cases for the deployment of the technology.

Establishing and operating the WAMS-EMS training and demonstration with live data streams and alarming functions has helped provide the necessary experience and understanding to specify the optimum infrastructure, application, cybersecurity and procedural requirements to support roll-out. The main learning outcomes, which must be addressed or considered to achieve successful roll-out and future expansion of the GB WAMS are detailed below.

4.4.1 Infrastructure Learning Outcomes

Learning 1: Restrictions of Using OPTEL

The setup of the GB WAMS infrastructure certainly can benefit from using National Grid's Operational Telecom Network (OPTEL) services, which has certain performance advantages. The OPTEL network is used to support control traffic within National Grid SO and TO, so it is a fast private network that has exceptional reliability, and the connection has already been established between National Grid and SPT. The main issue is that the OPTEL is a Critical National Infrastructure (CNI) but the GB WAMS setup for VISOR is a non-CNI system, and connecting non-CNI systems to CNI facilities would create security issues that will need to be addressed and managed properly. Although a work-around solution could be employed to use CNI to carry VISOR data it would have introduced an element of risk that could have potentially hindered the overall progress of the project, so this option was not used.

Use of OPTEL could be looked at as an option for deploying a productionised GB WAMS system. However, while the OPTEL network has a handoff to the SPT control WAN, there is currently no path to SHET. Significant work would be required from SHET to get their network connected to the OPTEL network, either directly or via SPT's network. This will need to be resolved before OPTEL can be used for GB WAMS.

Key Learning:

- **To utilise WAMS applications in the control room, the underlying data acquisition and communication infrastructure would need to be designed as CNI.**

Learning 2: Communication Services Supply Chain Issues

A significant learning point of the VISOR project was the uncontrollable delays incurred by supply chain issues in establishing the communication link between SPT and SO. The order for a MPLS link was placed through a service provider, who in turn contracted the telecommunication network provider to deliver the physical fibre optics.

This chain of supply resulted in an inability to query or expedite the process directly with the company installing the fibre, which was not foreseen. Without any method for the project team to exact leverage over the MPLS installation, plus the absence of any planning, or clear reporting from it, the project was in a constant 30-day cycle of awaiting progress updates.

The MPLS link was the preferred choice for SPT among the various options for the communication link to the WAMS Data Hub and given the contractual agreements in place with the service provider, the risk of delay was considered minimal. However, after the delays exceeded the notional maximum 6-month delivery period, the IPSec Tunnel was used as the contingency plan.

Key Learning:

- **Careful consideration of third-parties for infrastructure, in particular communications.**
- **Enacting IPSec Tunnel as an interim solution rather than a contingency plan.**

Learning 3: Necessity of Pre-production Facility to Demonstrate New Technology

A vital aspect of transitioning new technology from an innovation project into the daily operations is the thorough demonstration of the complete system operation to applications, visualisation and analysis screens that operators will use and the associated data connections and cybersecurity protocols required to do so.

VISOR introduced new monitoring system practices to examine new capabilities and benefits, and in doing so, has also emphasised the necessity of a pre-production facility in order to demonstrate this new technology in an operational environment with an interface with the EMS and other Business as Usual (BaU) functions. A new **e-terra***phasorpoint* WAMS server was subsequently established within SPT CNI for the first time.

Key Learning:

- **Pre-production demonstration facility critical to replicate live control room environment and demonstrate end-to-end applications and interface with EMS to enable operators to be trained appropriately and understand capabilities of the new system, view alarms from WAMS on existing screens, and instil necessary operator confidence to deploy applications in daily operations of the live system.**
- **Expert resource in cybersecurity and IT-solution architects required to design suitable environment with cybersecure architecture and configurations for secure data stream and data transfer connections entering and exiting.**

Learning 4: Data Security - UDP packets

The introduction of a 200 fps WMU has highlighted a security versus performance issue. The data stream coming from a normal PMU sampling at 50 fps is approximately 45 Kb/s using TCP packets. However, a WMU sampling at 200 Hz, and providing both 200 Hz and 50 Hz data streams requires nearer 130 Kb/s using UDP packets. The WMU has been designed with the performance of the network as a consideration, and therefore uses UDP and not TCP.

UDP has performance advantages over TCP as it is a connectionless method of communication. Through UDP, data is simply sent to a defined IP address, and there is no error checking or verification that data has been successfully transmitted. This means that the UDP protocol has very little overhead, which reduces bandwidth and latency, but it also means that if a packet does not arrive the data is lost.

Conversely TCP is a connection-oriented transport method. It will open a socket or a connection between the two IP addresses and will provide error checking and packet receipts to ensure all the packets have arrived. If packets fail to arrive, they will be resent. This means that there is a lot of overhead and extra information in a TCP datagram, but it does provide greater reliability in the data transmission.

The use of UDP causes an issue with the configuration of the firewall, as the connectionless transport protocol means that the UDP ports need to be opened up on the firewall so that it allows data inbound to the data centre from the substation. As TCP is connection oriented, the TCP socket can be initiated from the WAMS server out to the WMU at the substation, and therefore means that the firewall rules at the data centre are opened to allow connection out from the data centre and not into the data centre from the outside.

Key learning:

- **Experience to date suggests that for the roll-out of WAMS as an operational tool in GB, data must be received at the control centre via TCP. However, in situations where solutions are not available using TCP, a potential solution would be for UDP to form the first stage of the PMU data route and aggregation for monitoring purposes and bandwidth reduction can then be carried out at a regional or central level, followed by conversion to TCP for reliable and security-compliant delivery into the WAMS Data Centres. Proxy solutions are also possible (no aggregation, but stream forwarding and conversion to TCP) and have been deployed in Production WAMS.**

Learning 5: Transition of Communication Connection between TO and SO into CNI

The communication infrastructure established through VISOR has a direct connection from the Corporate LAN in SPT to the Corporate LAN in SO. The Corporate LAN and CNI LAN employ different degrees of security and as such, direct connections are heavily restricted and avoided, where possible. However, in order to transition the system into the daily operation, the WAMS infrastructure and communication links must move into the CNI networks, therefore, a coordinated approach must be taken to ensure appropriate network security protocols are upheld and agreed between each involved party; in particular, that each end of the communication link between TOs and SO are secured to the same degree.

Key Learning:

- **Continued data transfer between TOs and SO can only be retained if servers at each end of the connection reside within an equivalent security layer, or an alternative solution would have to be established, such as a proxy server.**

- **Coordination between TO and SO is essential so that each party is made aware of changes that may impact the other, in particular with respect to dedicated data transfer channels.**

- **During initial stages of widespread uptake, there is an argument for data separation between EMS and WAMS to safely manage the WAMS expansion.**

Learning 6: Measurement & Functional Performance of PMUs/WMUs

During the project, various measurement and functional issues were observed with the PMUs and WMUs used. Examples include PMU algorithm errors leading to data jumps or noise, filtering delays, and loss of synchronisation. These were not entirely unexpected, given that the bulk of pre-existing PMUs were legacy DFR platforms that had been upgraded, and were not certified to the IEEE C37.118 standard, and that the WMUs were running newly-developed firmware prototyping a new function. Most issues were rectified with firmware updates. However this highlights the importance of stringent testing of PMU performance, incorporating comprehensive measurement performance tests as well as functional acceptance test. Continuous soak tests are also strongly recommended, and comparison with a test control device such as a different PMU model, this will serve to detect issues that only present on occasion.

Key Learning:

- **Identification of PMU performance requirements (IEEE C37.118.1-2014 strongly recommended).**
- **Comprehensive test and monitoring strategy to cover measurement performance and soak testing.**

4.4.2 Application Learning Outcomes

Learning 7: Detected Oscillations

One of the fundamental objectives of the GB WAMS is to increase network resilience and provide enhanced visibility of system disturbances and oscillations that pose a risk to the security of the system. PMUs are typically used to monitor oscillations in the frequency range of 0.1Hz to 10Hz. VISOR has trialled new Waveform Measurement Unit devices that extend oscillation detection up to 46Hz.

The continuous GB-wide visibility delivered through VISOR, coupled with the new oscillation analysis and source location tools demonstrated, has allowed GB oscillatory behaviour to be closely monitored and characterised through long-term direct observation, to a level not achieved before. System modes, including GB-wide inter-area oscillations, have been characterised in terms of the key contributors and participants; a number of small localised behaviours have been identified which are of interest to system analysts, and the VISOR data and tools have provided valuable contributions to investigation and cause identification of some significant events.

VISOR has detected several oscillations in both the electromechanical and SSO frequency ranges which have been fairly localised and of low magnitude, these would not have been detected using conventional SCADA monitoring devices. Such behaviour includes local electromechanical modes, power electronic or voltage control modes, and the torsional modes of generators. The new visibility of the 4-46Hz range has revealed many previously unseen frequencies in the system, most of which are believed to originate from power electronic converters and controls. The vast majority of the oscillations that have been detected are not severe in magnitude and pose little risk to system security in their current form, however, by tracking these oscillations, it is possible to baseline normal and abnormal system behaviour to identify changes in severity, oscillation frequency, and incidence over time.

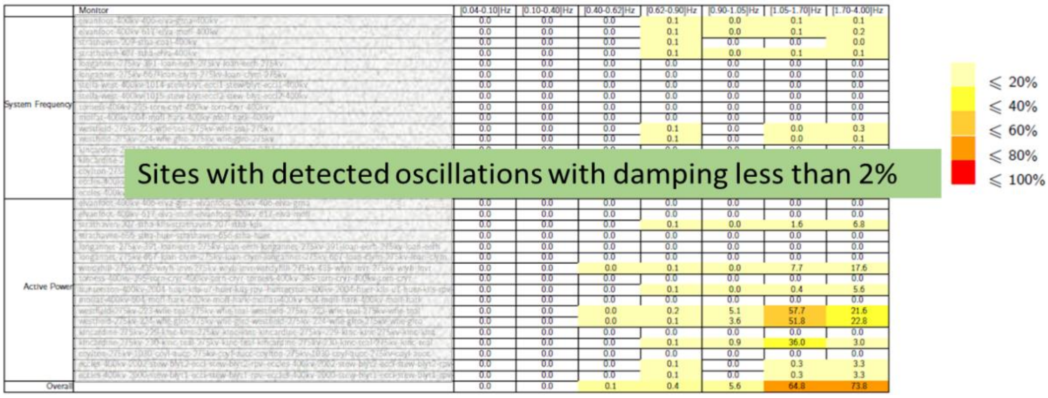

Figure 18. Example of oscillation tracking

In addition to the valuable learning gained by tracking the changes in small-scale system events and deviations from normal baseline activities, the detection of power-electronic related oscillations also presents new and significant learning opportunities to network owners and operators to highlight events that may otherwise go undetected and instigate studies that can result in better modelling accuracy and improved network resilience. Two noteworthy examples of new oscillation modes that have been detected by the VISOR WAMS are discussed in Section 4.3.1.

Whilst most of the modes observed by the GB WAMS in the 4-46Hz SSO range are low in amplitude and visible over a limited area, some present a risk of interaction, being relatively less well behaved, close in frequency to known plant modes, and present in the wider network. A number of very low-level but nonetheless distinct interactions have been observed. An example is shown in Figure 15, which illustrates a variable-frequency mode moving close to a known plant mode, and a corresponding degradation in mode damping and amplitude at the plant in question.

Key Learning:

- **The continuous GB-wide visibility delivered through VISOR, coupled with the new oscillation analysis and source location tools demonstrated, has allowed GB oscillatory behaviour to be closely monitored and characterised through long-term direct observation, to a level not achieved before. An active WAMS provides insight into normal and abnormal oscillations, which guides investigations to determine the cause and potential remedial actions. Over time, the archive of oscillation behaviour will highlight trends and potentially plant that requires additional tuning.**

- **Detecting oscillations between new and old network components, the full breadth of which are unlikely to be representable through existing modelling studies. This problem will be exacerbated over time with increasing complexity and diversity if network modelling does not progress correspondingly.**

Learning 8: Data Volumes and Linkage with Poor Data Quality

Allocating appropriate bandwidth is critical for a WAMS to perform adequately and ensure business practices are improved upon. Initial estimates of traffic volumes of the pilot GB WAMS were based on the original small number of PMU devices connecting to the WAMS. However, the decision by SPT to upgrade multifunctional devices to provide PMU measurement meant original data assumptions were invalid, and the SPT to SO bandwidth would not be sufficient for the duration of the project.

For a system with 55 PMUs and 5 WMUs, for example, the data storage requirement is approximately 4.2 TB/year with an outbound communication bandwidth of 1.9 MB/s. In this case, a server capable of holding 5 years' worth of data would be required but the latency and redundancy communication requirements will depend on the desired applications, and will have significant bearing on the cost. For real-time operation, these costs will be significant.

A number of PMUs with poor data quality have been proven to cause significant stress on servers tasked with collating and archiving high volumes of data files in order of magnitude greater than designed. However, a key learning from the pilot project is the need to carefully plan WAMS data stream configuration to avoid the case (to use an extreme example) where all PMU data is sent in a single stream, and one stuttering PMU causes the entire stream to stutter, impacting server and communications infrastructure performance. The solution is a mix of splitting data streams, and waiting less time for late data packets to arrive.

Key Learning:

- **Ensure sufficient IT and communication infrastructure headroom as contingency to account for uncertainties surrounding innovative aspects and integrating new technology.**
- **Data quality and availability dependent on reliable GPS signals, communication network and right server configuration can greatly affect the quality and reliability of results from WAMS applications.**
- **Need for self-supervision within the WAMS to limit the extent that invalid or rogue data can disrupt or unnecessarily occupy data storage.**

Learning 9: Potential for WAMS to Inform Model Validation

Analysis applications are used to inform a plethora of network management operations such as state estimation, generator dispatch, and contingency analysis. With electricity generation from intermittent source reaching unprecedented levels in GB, system dynamics will become increasingly less predictable, and analysis applications will, therefore, become ever more important, as will the underlying system models. WAMS not only enhances sophisticated analysis applications, but can also be used to better define and validate network models.

For GB to realise the full benefits of applications such as Hybrid State Estimation and dynamic stability limits, it may be necessary to establish new processes so that WAMS data be used to support model validation.

Key Learning:

- **New practices are required to ensure the additional information provided by WAMS is used to improve model accuracy.**
- **Research shows that the GB power system is fast evolving to a scenario where deploying Hybrid-State Estimation and using WAMS data for model validation will provide substantial operational and financial benefits, however significant development effort is required.**

Learning 10: Regular Reporting Detailing the Performance of both the Power System and WAMS Independently

The information gathered from the GB WAMS is collated and concisely reported across the relevant business functions using a number of regular reports. These reports are designed to bring value from the continuous monitoring and detection of oscillations and disturbances including how system dynamics vary throughout the day and under different operating conditions and in the longer term, track how these dynamics evolve. These reports were trialled both annually and monthly at different stages throughout the project:

- **Power System Performance reports** - monitor and report the oscillatory stability of the GB system, providing baseline trending of overall system stability dynamics and behaviour across the different oscillatory frequency modes.
- **Power System Disturbance reports** - present power system behaviour during significant disturbances, e.g. generator loss or transmission line faults.

In addition to the Power System reports listed above, regular WAMS system health reports detailing operational health of the VISOR WAMS system were produced to ensure areas of unsatisfactory performance could be identified and investigated. These reports were trialled both annually and monthly at different stages throughout the project, on a monthly basis during the initial stages of WAMS operation:

- **Data Quality summaries** - provide concise and interactive high-level statistics to easily identify problematic devices.
- **Data Stream Connection summaries** - in a similar form to the above, high-level statistics provide a quick overview to identify devices with poor communications.
- **PMU Connection Analysis reports** - identify and investigate poorly performing devices and recommend actions to resolve.

Key Learning:

- **VISOR System reports and additional monthly reports provide a strong business case for the additional insight and analysis capability offered by WAMS applications.**

- **Creating these system reports is labour intensive, and TOs should engage with suppliers to develop and target a process by which these reports are produced and circulated automatically.**

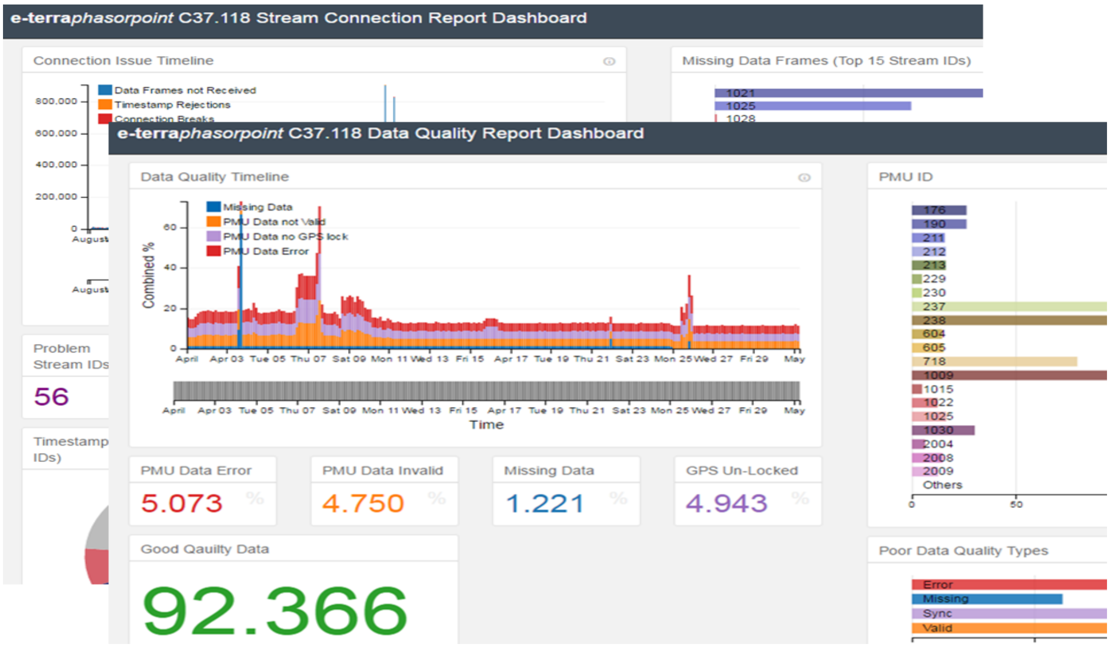

Figure 19. Monthly reports illustrating WAMS performance of connection streams and data quality

4.4.3 Process Learning Outcomes

Learning 11: WAMS: Critical Function

Introducing new additional processes into a process which is already considered to be functioning, VISOR has made a strong effort to engage with key stakeholders from both TO and SO to ensure their opinions drive the development of the WAMS, and in particular the applications, and yet, whilst many demonstrations have been given through knowledge dissemination events, many of the end users are yet to use the applications for themselves and will need some time in doing so before they have sufficient confidence to call upon the system in live operation.

Through the duration of the pilot project, certain WAMS applications have already gained sufficient recognition within the business and used as a valuable addition to post-event and planning operations. The stakeholder engagement to date has shown a strong desire to deploy this technology in one capacity or another. However, it is recognised that it make take several years of live operation before infrastructure and applications are sufficiently secure and reliable in order to deploy in the control room. The testing facility will enable WAMS applications to be demonstrated and tested within a replicate control centre environment.

Key Learning:

- **As WAMS applications transition into daily operations, WAMS must be recognised as a ‘mission-critical’ function and monitoring requirements defined to provide a clear directive.**
- **GB TO should maintain their individual WAMS for applications related to protection of TO assets with an increase in system dynamics.**
- **Identify the resilience and safety-critical process levels to build into the service provision.**

Learning 12: Unlocking Full WAMS Benefit Requires New Data-sharing Agreements

To improve the accuracy and robustness of certain applications that rely on accurate network modelling, TO modelling will need to gain visibility beyond the license area boundaries. For applications such as oscillation source location and disturbance management to deliver the most benefit to TOs, a high-level GB-wide view is required to allow detected oscillations and disturbances to be placed in their proper context. Much of these benefits can be obtained through sharing of sparse measurements that could be considered to have low confidentiality or commercial sensitivity (voltage and frequency measurements). However, such data-sharing arrangements are not currently in place.

Key Learning:

- **Sharing of relevant WAMS data between TOs is required from certain critical points of the network such as system boundaries for realising full value of WAMS applications for TOs.**

Learning 13: Need for Specialist Resource

Recruiting and retaining the specialist resources necessary to implement and use WAMS in BAU is vital to establish the technology in daily operations.

Key Learning:

- **Recruiting and retaining the specialist personnel are vital to implement and establish WAMS technology into daily operations.**
- **An implementation group comprising of representatives and technology specialists from each key stakeholder is recommended to further support the successful technology roll-out.**

5 Performance Compared to the Original Project Aims, Objectives and SDRC/Project Deliverables

The key issue originally identified in the VISOR proposal stemmed from the increased penetration of wind generation and power electronic-based devices affecting maximum transfer capacity between Scotland and England and also the increased uncertainty regarding true system dynamics and the increased potential for sub-synchronous oscillations and interactions of which conventional monitoring systems offer little or no observability. The solution to this, as described in the full submission, aimed to:

> ***Provide the experience, knowledge base as well as appropriate equipment/infrastructure to enable the appropriate and cost-effective deployment of the next generation control and monitoring systems for the GB transmission network owners and operator.***
>
> ***Through the demonstration and the associated studies of VISOR, the TO/TSO will be able to judge the tools and practices that would be of value for operation and analysis of the system. This will lead to the development of the necessary robust business cases for efficient and coordinate network investment using this new knowledge in the subsequent roll-out as a normal business function.***

And through demonstration in VISOR, sought to provide:

- ***transmission network owners with a risk-mitigating measure in a period of uncertainty to help safeguard the network against low probability high-impact events that may result in partial or widespread system failure.***
- ***The system operator with the ability and confidence to utilise the full capacity of the network through greater understanding the dynamic behaviour of the system where a large volume of wind generation is present.***

The aim, therefore, was to establish a system capable of detecting potentially hazardous SSO events and improving situational awareness to enhance understanding of true real-time system dynamics to the benefit of network owners and operators. This overall objective has been successfully achieved, the underlying WAMS infrastructure has been commissioned and a suite of WAMS applications have been deployed on all WAMS servers and are fully operational and accessible for members of staff.

The project extension has enabled SPT to design and develop a WAMS-EMS training and testing facility to replicate the live control room environment to train operators and engineers in utilising these new capabilities and in doing so support the transition from demonstration to the control room.

Multiple delays in the commissioning of the Western HVDC link has subsequently delayed the analysis and publication of the report assessing the impact and observations before and after commissioning. The VISOR extension has allowed monopole commissioning to be captured and analysed. The full bipole commissioning will also be captured, analysed and reported as part of the VISOR project however this report will not be finished until later in 2018.

5.1 Performance Versus Project Objectives

5.1.1 Successful Delivery Reward Criteria

Criterion	Required Evidence	Resultant evidence
SDRC 9.1 ***Successful delivery of Sub-Synchronous Oscillation (SSO) monitoring prior to start of Series Compensation commissioning.***	• SSO Device qualification report (WP 4C, Dec 2014)	WMU FAT Test witnessed and approved by project partners on 28 Nov 14, evidence reported in Project Progress Report Dec 2014. Two supporting reports (confidential): SSO specification report, Nov 2014 WMU Technical Justification report, Apr 2016
	• Visualisation of multiple SSO information sources at data centre (WP 1A, prior to the commissioning of series compensation reinforcement)	Successful detection of SSO events using Oscillation Stability Management application. SSO analysis prior to commissioning of series compensation documented in first Baseline and comparator report, Mar 15 (see below).
	• Baseline and comparator report for SSO behaviour (WP 1, March 2015, March 2016, March 2017, Dec 2017)	Multiple SSO analysis reports produced by GE. All reports are confidential. Evidence of first and most recent reports provided in Appendix 4: 1) Mar 2015: PSY-VISOR-Datareview2014-V02 2) Nov 2015 3) 6x Monthly reports produced between April 2016 and Sep 2016 9) Dec 2017: PSY-VISOR-Datareview2017.
SDRC 9.2 ***Enhanced stability tools delivered, including Oscillation Source Location and Disturbance Impact***	• 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	WAMS Data Centre Server and Applications Site Acceptance Test sign-off, including WAMS oscillation management applications, May 15. Extract of WAMS SAT provided in Appendix 4.
	• Report on PMU roll-out requirements for the applications (WP 4B, March 2017)	Technical Specification draft: SPT Technical Specification for WAM Equipment submitted for review on 6 Mar 17. See Appendix 4.
	• Simulation cases for presentation & training (WP 5.2, March 2017)	A number of event case studies have been identified through VISOR data reviews in SDRC 9.1
SDRC 9.3 ***Successful model validation activity completion***	• Report on PMU based line parameter estimation and variability (WP 2.1, March 2015)	Report produced: Psy-VISOR-R150216-Line Parameter Estimation-V02.Docx, Mar 15. Extract provided in Appendix 4.
	• Report on accuracy of simulation models for small-signal and large-signal against naturally occurring events (WP 2.2-2.3, Dec 2016)	Report produced: Monitoring and Management of Torsional Oscillations (Sub-synchronous Resonance), Dec 16. Extract provided in Appendix 4.
SDRC 9.4 ***Successful improvement options for management of transient stability constraints***	• Report on quantification of uncertainty in stability calculations (WP 3.1, Dec 2016)	Report produced VISOR Project: Impact of Uncertainty on Stability and Security Margins, Dec 16. Extract provided in Appendix 4.
	• Display incorporating power, angle and associated thresholds (WP 3.3, Dec 2015)	Application specification report: VISOR-WAMS-B6-001 B6 Boundary Display Application Specification-v2, Feb 15 Applications commissioned at SAT, May 15

	• Report on findings from benefits of hybrid state estimator (WP 3.2, Dec 2016)	Report produced: VISOR Project Comparison of Hybrid State Estimators, Dec 16. Extract provided in Appendix 4.
	• Report on long-term monitoring of area angle measurements (WP 3.4, Dec 2016)	Report produced: GE-VISOR-161130-Report on Area Angle Measurements-v1, Dec 16. Extract provided in Appendix 4.
***<u>SDRC 9.5</u>* Successful deployment of the supporting infrastructure of the VISOR project.**	• System specification and PMU supplier contracts awarded (April 2014)	Contract awarded to GE Grid Solutions, Jul 14. Reported in Project Progress Report December 2014
	• System commissioning report (WP 4A, Dec 2015)	Report produced: VISOR System Commissioning Report, Dec 15. Extract provided in Appendix 4.
	• Visualisation of data in SPT, NGET, SHET Transmission including real-time and historic (WP 4A, Dec 2015)	WAMS Data Centre Server Site Acceptance Test sign-off, including visualisation of data from multiple sources in real-time and historical playback, May 15 Reported in Project Progress Report June 2015
	• Roll-out report (WP 4A, Dec 2016 - March 2017)	Report produced: VISOR Roadmap - Issue 2, Dec 16. Download link provided in Section 13.
***<u>SDRC 9.6</u>* Successful dissemination of knowledge generated from VISOR project.**	• Establish on-line portal and keep up to date throughout project (WP 5.2, Sep 2014)	Website activated in Sep 14, as reported in Project Progress Report Dec 14, and updated throughout the project.
	• Timely delivery of project progress reports (WP 5.4, Sep 2014, Mar 2015, Sep 2015; Mar 2016, Sep 2016, Mar 2017, Sep 2017)	All reports submitted to Ofgem at 6-month intervals. Public-facing reports available on VISOR website Links provided in Section 13.
	• Academic partner delivery of knowledge capture and publications (WP 5.2, Dec 2016 - Mar 2017)	Agenda of events: Evidence in Appendix 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)	Agenda of events: Evidence in Appendix 1
	• Delivery of Independent Phasor Data Visualisation and Interaction Tool (Mar 2017)	Application deployed, Mar 17. Reported in Project Progress Report June 2017. Screenshot of tool in Figure 13 (p.28)
	• Commissioning of WAMS-EMS interface and training facility (Jun 2017)	Facility Design approved Apr 17 and configuration complete Jun 17. Evidence provided in Appendix 4.
	• Undertaking of WAMS-EMS training within dedicated training facility (Sep 2017)	Training conducted in Oct'17, Dec'17, Jan'18 Evidence in Appendix 2

6 Required Modifications to the Planned Approach during the Course of the Project

All project objectives and SDRC have been met and the project has followed the planned approach in accordance with the original project proposal. However, the project was extended to capture the delayed Western HVDC commissioning and consequently the milestone dates of the project conclusion and associated final reports were modified accordingly. The total spend of the project, including the extension matches that of the original budget. Details of the project extension are provided below.

6.1 Project Extension

One of the main objectives of VISOR was to capture the 'fingerprint' of system behaviour before and during the multi-stage commissioning of the Western HVDC link utilising the newly commissioned SSO monitoring devices installed at Hunterston (SPT) and Connah's Quay (NGET).

The Western HVDC project experienced delays to the start of the commissioning process, and subsequently no longer fell within the original timeframe of the VISOR project. Whilst the VISOR monitoring devices could still have captured the commissioning (providing the monitoring infrastructure and processes were retained), the dissolution of the VISOR project and associated analysis resource would therefore not guarantee the experience of the VISOR project partners would be utilised in conducting detailed system behaviour and SSO analysis, and the onward dissemination of learning and conclusions.

Another key objective of the extension was to complete the commissioning and integration of the newly established WAMS-EMS testing and training facility and to begin operation of this facility by conducting training workshops and dissemination activities. The facility brings WAMS closer to engineers and operators by providing a live representative environment (mirror of the live EMS) in which operators can learn how to utilise tools and applications enabled by VISOR, and to trial future ones.

A project extension of 9 months from April 2017 to December 2017 was undertaken to extend the SSO monitoring and analysis window to cover for the delayed commissioning of the Western HVDC link, but also enables additional efforts to be made that enhance the business case for development and further support the transition of WAMS into BaU. The table below illustrates the focus areas of the project extension.

Table 6. Focus areas of project extension

	Understanding dynamics & SSO	Enhancing Business Case	Transition to BaU
Western HVDC capture and analysis	X	X	
WAMS-EMS integration & interfacing		X	X
WAMS-EMS demonstration & training		X	X
Architecture design and network requirements			X
Phasor Data Visualisation and Interaction Tool			X

The extension enriched business case development and bolstered the effort to establish a feasible and effective continuation plan for all GB Network Licensees by:

- Bringing WAMS technology & applications physically and operationally closer to the control rooms in SPT (new facility at the control room and within the secure network),
- Bringing WAMS technology & applications operationally closer to the control rooms through demonstration and training workshops,
- Demonstrating the operational benefits of WAMS based on a live environment,
- Establishing business cases for each aspect and application of the WAMS data,
- Documenting the optimum communication and cybersecurity requirements of the underlying infrastructure and data sharing processes requirement, and,
- Setting out a Roadmap by which these benefits can be realised, from both TOs and SO.

6.1.1 Modifications to Project Deliverables

With the additional duration and scope of the project a number of modifications and additional deliverables were made to the SDRC requirements, listed in the tables below:

Table 7. Additional SDRC Milestones to account for additional work streams

SDRC	Evidence	Completion Date
9.1.1	Baseline and comparator report for SSO behaviour (WP 1, March 2015, March 2016, March 2017, December 2017)	Dec 2017
9.6.1	Timely delivery of project progress reports (WP 5.4, Sep 2014, Mar 2015, Sep 2015; Mar 2016, Sep 2016, Mar 2017, Sep 2017)	Sep 2017
9.6.2	Delivery of Independent Phasor Data Visualisation and Interaction Tool	Mar 2017
9.6.2	Commissioning of WAMS-EMS interface and training facility	Jun 2017
9.6.2	Undertaking of WAMS-EMS training within dedicated training facility	Sep 2017

Table 8. Alterations to completion dates of SDRC

SDRC	Evidence	Current Completion Date	Revised Completion Date
9.5.1	Roll-out report (WP 4A, Dec 2016 - March 2017)	Mar 2017	Dec 2017
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)	June 2017	Dec 2017

7 Significant Variance in Expected Costs

The project including the extension has been delivered within the original project budget, with noteworthy savings in contractor cost following tendering negotiations.

NIC Funding Cost Category	Forecast Budget (£k)	Actual Spend (£k)	Spend v. Forecast (%)	Justification of Variance (in excess of 10%)
Labour				
WP1 - Enhanced System Oscillation Monitoring	£180.25	£180.58	100.2%	
WP2 - System Model Validation	£110.73	£115.45	104.3%	
WP3 - Improvements for Management of Stability Constraints	£260.08	£249.39	95.9%	
WP4 - Supporting Infrastructure	£293.55	£295.12	100.5%	
WP5 - Knowledge Dissemination	£368.23	£399.57	108.5%	
Dedicated Resources	£1,845.40	£2,983.22	161.7%	Increased SPT, National Grid, SSE and UoM resources utilised for project extension and additional work streams. Long term external consultancy and project support has also been classed as Labour. Strong focus on developing skills and retaining resources longer term as opposed to short term assignments.
Equipment	£437.50	£411.05	94.0%	
Contractors				
WP1 - Enhanced System Oscillation Monitoring	£315.68	£309.86	98.2%	
WP2 - System Model Validation	£368.69	£281.31	76.3%	Contractor input into system modelling activities reduced during tendering stage. Contractor input into System Model Validation was restricted due to sensitivity of GB system models.
WP3 - Improvements for Management of Stability Constraints	£667.97	£657.57	98.4%	
WP4 - Supporting Infrastructure	£451.50	£460.63	102.0%	
WP5 - Knowledge Dissemination	£173.88	£46.09	26.5%	Strong support from in-house Communications & Stakeholder Engagement department, resulted in less than anticipated contractor input.
Dedicated Resources	£271.00	£112.79	41.6%	Dedicated resources reallocated in Labour Dedicated Resources in order to retain skills longer term.
IT	£979.60	£419.77	42.9%	Achieved by using existing system and infrastructure where possible.
IPR Costs	£0.00	£0.00		
Travel & Expenses	£313.33	£77.66	24.8%	Regular Project Delivery Team meetings held via teleconference where possible to reduce time and travel costs.
Payments to users	£0.00	£0.00		
Contingency	£332.44	£0.00	0.0%	
Decommissioning	£0.00	£0.00		
Other	£0.00	£0.00		
Total	£7,369.82	£7,000.06	95.0%	
Interest shortfall	-£108.25			
Actual Total Budget	£7,261.57	£7,000.06	96.4%	

8 Updated Business Case and Lessons Learnt for the Method

The original project submission identified WAMS as a vital tool to assist transmission owners and operators in managing the volatility of the GB transmission system associated with the move toward a low carbon future. VISOR sought to establish the necessary monitoring and communication infrastructure in order to demonstrate a suite of new applications to enhance understanding and visibility to address the following key challenges:

- Drastically changed power flow pattern and daily curves, leading to many boundaries of the GB transmission system becoming more frequently congested and either operated with higher stability margins or dynamically managed, at potentially increased constraint cost unless new network options or services are implemented.
- Potential introduction of new types of sub-synchronous oscillations associated with power electronics converters and controllers that pose a potential risk to plant and may hinder transfers across power boundaries, resulting in higher constraint cost if oscillations cannot be properly detected and mitigated.
- A more dynamic system with reduced system inertia and short circuit level, increasing reliability risks if no enhanced tools are provided as this change leaves operators with much less time to make the right decisions after an unscheduled outage or disturbance.

Furthermore, the complexity and extent of these challenges is likely to increase in the future as the level of HVDC interconnection capacity is forecast to increase from 4GW to 7.3GW by 2022, and further still, National Grid *Network Options Assessment 2016/17* suggests the optimal total capacity between GB and European markets would be 14.8GW-17.3GW by 2030. This substantial increase in HVDC interconnectors and any supplementary active control devices heightens the risk of interactions and oscillations which WAMS has proven detection capabilities.

Prior to the VISOR project, the most significant business cases for WAMS stemmed from two different aspects of real-time operation, notably:

- Maximising the use existing assets by using WAMS to set system security limits closer to true real-time limits based on current operating conditions, thereby delivering benefits to the GB customer by:
  - avoiding network reinforcement costs, and
  - reducing constraint cost
- Reducing the risk of system outages by increasing visibility and modelling accuracy of sub-synchronous oscillations that may arise due to increased levels of power-electronics, thereby delivering benefits to the GB customer by:
  - reducing likelihood and impact of outage

Whilst the project submission highlighted these headline benefit cases for real-time system operation, the VISOR project has also explored and demonstrated a range of benefits that can be achieved from implementation across all three main business areas: post-event analysis, system planning, and real-time system operation. Examples of benefits to post-event and system planning include the following and are discussed further below: informing investigations and analysis to validate the dynamic performance of active control devices (SVCs, STATCOMS and series compensation, etc.); validate operational tripping schemes; verify generator compliance; and validate system models of frequency and voltage response.

The underlying business case has not altered from the original project submission, however, lessons from VISOR and international experience, has shown that it can take several years before WAMS applications are suitably mature and robust for use in real-time system operation in order to realise these real-time system operation benefits. As such, WAMS deployment should initially target post-event and system planning implementation, and focus on creating a suitable resilient and secure infrastructure that underpins the system.

8.1 Benefit Areas

The overall capability of the GB WAMS, and therefore the overall benefit to the GB customer, will increase with time as applications, models, processes and coordination between TOs and the SO improve, however, even at this early stage of deployment, the existing GB WAMS infrastructure can deliver noteworthy benefit to TOs and SO across three main business functions: post-event analysis, system planning and real-time system operation. The business case for each is discussed below.

8.1.1 Post-Event

It took more than six months for a team consisting of tens of industry experts to get a full understanding of what had happened to cause the 2003 blackout in the northeast United States and Canada. North American Electric Reliability Corporation (NERC) has been on the forefront in promoting the adoption of the PMU technology through reliability standard development and leading and participating in North American Synchrophasor Initiative (NASPI) activities. The wide adoption of the technology resulted in a much quicker turnaround of the 2011 blackout post-event analysis, and further improvement is expected as more and more transmission substations will be equipped with PMUs. WAMS is ideal for identifying the sequence of events and the related system dynamics across an interconnected power system in a post-event analysis. Many utilities are using WAMS to support post-event analysis and have realised similar benefits as NERC, these include India, China, South America, Australia and Europe (examples are provided in Appendix 3).

Before WAMS in SPT, a combination of fault recorder data along with historic SCADA data held in a historian was used for post-event analysis. Going between two sources was unnecessarily cumbersome and there were significant difficulties aligning events due to the lack of synchronisation between different SCADA sources and fault recorders. WAMS has allowed one single source to be used for post-event analysis and because all WAMS measurements are synchronized to an absolute time reference, recreating events for post-event analysis is much easier and quicker. Once fully trained, engineers should be able to conduct post-event analysis much quicker than using the old approach, resulting in a considerable efficiency improvement.

The provision of accurately time-synchronised high-resolution measurements by the GB WAMS can offer process and/or accuracy improvements of several offline analysis activities and post-event actions, namely:

- Post-Event Analysis process improvement (easy data alignment and improved reporting capability)
- Transient stability studies
- Model Validation
- Control and damping optimisation
- Operator Training Simulator
- Faster analytics based on improved state estimation
- Generator compliance
- Automated dynamic model validation and calibration

Process and/or financial benefits:

- Faster post-mortem analysis: Detailed and time-synchronised coherent data recorded allows faster analysis with less uncertainty in the sequence and timing of events.
- New capabilities in oscillation monitoring and transient studies: Oscillation alarms and baselining reviews will identify oscillation modes of each generation plant and identify hazardous operating conditions. Prior knowledge of such modes could reduce future constraint requirements and in the worst-case scenario, avoid outages of large generators, particularly interconnectors.
- Managing network risk, this should enable a small percentage (5-10%) of the annual balancing budget for balancing services to be reduced

8.1.2 System Planning

The use of time-synchronised measurements through WAMS delivers similar benefits to system planning through improved analysis accuracy and capability and enhanced process efficiency as it does for Post-Event activities. WAMS facilitates or supports the following applications provide benefit to system planning activities:

- Dynamic model validation and calibration
- Backup to the existing SCADA monitoring
- Achieve marginal boundary increases, deferring major reinforcements
- Asset performance indication
- Line Parameter Estimation
- Data analytics (Complex Event Processing)
- Black-Start planning
- Condition control measures and optimise settings

Process and/or financial benefits:

- Faster system planning analysis: detailed and time-synchronised coherent data recorded allows faster analysis and more accurate analysis with enhanced applications such as line parameter estimation.
- Improved model accuracy: indirect benefits through more accurate models. Prerequisite for future dynamic model validation

- New and enhanced data analytic tools: use of WAMS data to support functions such as black start would initially focus on offline analysis and planning and with greater confidence lead to potential control room applications.
- Potential to reduce uncertainty on scheme costs by 5-10% through more optimised design

8.1.3 Real-time System Operation

Whilst there are certain benefits achievable within the post-event and planning business areas, a large portion of the financial benefits will arise from real-time operation in the control room by the below WAMS-based applications as demonstrated by VISOR, and other potential future applications

In terms of the applications which have been investigated to date, the following are considered to provide benefit to real-time operation of the system:

- Monitoring and alarming: V, f, df/dt, P, Q, angle difference
- Oscillation Monitoring
- Oscillation Source Location
- Improve State Estimation using Hybrid State Estimation (HSE)

Process and/or financial benefits

- Reduced constraint costs: through improvements in state estimation and contingency analysis model parameters could result in 3%-5% improvement in constraint precision.
- Based on £126.83m constraint in FY16/17 (see Table 9), this equates to £3.8m - £6.3m, per annum.
- **Quantifying potential financial benefits is highly speculative at this stage, however, based on current and future levels of constraint, with even a small improvement of less than 5% reduced constraint the potential saving would be in the order of millions per year.**

Table 9. Breakdown of Constraint Cost by fuel type in previous financial year (Apr16-Mar17)

FY2016-2017	All Values £m		
Fuel Type	Payments to Manage Constraint	Payments to Rebalance System	Net
COAL	10.10	66.84	76.94
GAS	14.42	135.43	149.85
INTERCONNECTOR	-4.89	-8.99	-13.88
WIND	77.92	0.39	78.31
OTHER	29.27	6.41	35.68
Total	126.82	200.08	326.90

9 Lessons Learnt for Future Innovation Projects

A list of the lessons learnt which may prove valuable for similar future projects are listed below:

Table 10. Lessons learnt for consideration of future projects

Lessons Learnt (+/-)	Lesson Learnt	Mitigating Actions
Positive	The presence of a contingency plan and coordination successfully enabled the project delivery team to overcome challenges and unforeseeable delays, in particular, those experienced with cross-TO communication links and data transfer.	Close monitoring and management of the process, with the team assigned to focus on problems and identify solutions or contingency plans which ensured project milestones and other dependant work streams were not significantly impacted.
Positive	Project milestones and work packages should be capable of changing in order to achieve the overall objective of the project in response to project findings or changes in the landscape.	VISOR adapted and identified aspects that required further development that were unforeseenat at the outset. By undertaking additional initiatives, the project is in a stronger position to deliver successful outcome.
Positive	Ensuring IT cybersecurity personnel are engaged with changes/developments in architecture design, particularly in pilot projects which can follow 'unconventional' routes into the business.	Ensure the successes of the new technology are controlled in such a way that 'new users' do not breach IT practices.
Positive	Importance of internal and external stakeholder engagement. The stakeholder events enabled the project team to engage with external expertise with similar experience, as VISOR has done with experience Pacific Gas and Electric Company (PG&E) and Quanta Technology in particular.	VISOR has highlighted the value of strong external stakeholder engagement which has added great value to the project especially in terms of highlighting steps to transition from pilot project to BaU. Similarly, the project has also shown the importance of internal stakeholder engagement to ensure the Business' needs are understood and satisfied.
Negative	Early, direct engagement with business IT experts is essential for assuring technical requirements are understood on both sides so that deployment schedules are realistic. This should be done at the tendering stage.	Business IT experts should be engaged and directly involved early in project delivery and specification stage to avoid potential risks and delays.
Negative	Need for greater emphasis on IT infrastructure on system monitoring projects.	Early engagement and direct involvement from all IT partners from all involved parties to arrive at realistic estimates for the project.

10 Project Replication

WAMS comprises of a multitude of monitoring, communication, and data processing electronic devices connected through communication channels, IT networks, and security protocols with an indeterminate number of possible configurations and dependant on a variety of factors pertinent to each WAMS operator. To assist other potential WAMS operators in replicating a similar monitoring system, rather than provide a list of all physical components forming the VISOR WAMS, which would be neither practical nor useful, it is more appropriate to consider each of the necessary components of WAMS so that potential operators can design and implement a solution most suitable to their needs.

When designing a WAMS, there are three main components to consider:

1. Infrastructure:
   - Physical infrastructure: monitoring and data processing equipment
   - Communication infrastructure: from monitoring device to local or regional PDCs to system level PDC.
2. Applications:
   - Data processing and analysis software running on PDCs (e.g. **e-terra***phasorpoint* and associated analysis modules).
3. Process:
   - Data reporting mechanisms, data security and access, overall system maintenance.

Physical infrastructure

Section 3.1 of this report outlines the major infrastructure components used in this project and the communication channels employed to transmit data between each TO PDC (regional PDC) and the SO PDC (system level PDC).

To be able to determine the required underlying infrastructure, however, the overall purpose or desired application(s) of the WAMS deployment must first be established. The two primary objectives of VISOR (monitoring of SSO and B6 boundary constraint) were met by installing monitoring devices at substations connecting HVDC links, large generation plant and along the B6 corridor. VISOR subsequently established a high density of WAMS monitoring coverage across the central belt of GB with less monitoring at the peripheries of the system such as the South and South-East coast of England, as illustrated in Figure 3.

If the primary objective of VISOR had been to provide full system observability, the location of monitoring devices installed would have been quite different. Recognising the importance of appropriate placement of monitoring devices for a WAMS to achieve the desired outcome, the UoM led a study into the optimal placement of monitoring devices for observability of every system bus to support state estimation. To accomplish this, UoM developed a PMU placement tool capable of determining the minimum cost solution to achieve full observability (through measurement or calculation) of a system, based on variable inputs of network topology and existing monitoring status of each bus. The findings of this study can be found in the paper entitled, *VISOR Project: PMU Placement for GB Transmission System,* (Jin, Wall, & Terzija, Dec 2016).

Another key consideration in terms of infrastructure is the chosen system architecture of the WAMS. The key decisions relate to the use of “local PDCs” for data aggregation and the degree of redundancy required. Local PDCs can offer greater control and management of data traffic and additional data archiving options however they come at a cost of increased servicing and maintenance. VISOR has not employed the use of local PDCs, although this option could still be utilised in the long-term, as shown below.

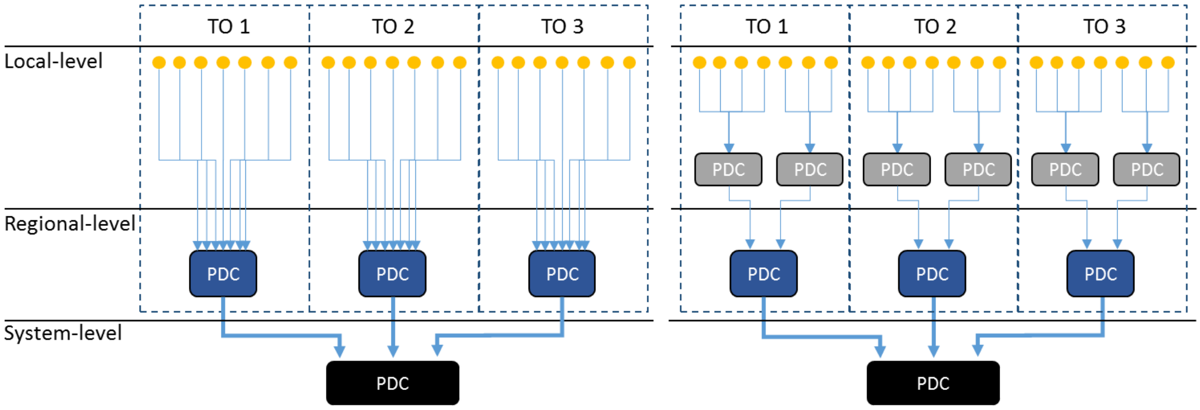

Figure 20. Monitoring infrastructure (a) without Local PDCs (b) with Local PDCs

Long established 50Hz PMU devices are typically used to provide measurement data in WAMS. However, VISOR has successfully demonstrated the use of 200Hz devices which provide the same functionality as conventional 50Hz PMU devices but also offers greater SSO monitoring capabilities, extending the upper-frequency range to 46Hz (typical PMU range limited to <10Hz). Currently, the only 200Hz device available is supplied by GE, the *RVP311*. It should be noted however that the basic WMU function is fairly straightforward to implement, from a signal processing point of view, and it is hoped that this type of measurement function will become more widely adopted. The WMU function is fully compliant with the existing IEEE C37.118 standard used in WAMS, the data rate of 200 fps is atypical, but still compliant.

The additional capabilities offered by the 200Hz device mean the communication requirements are greater than conventional PMU devices, as illustrated in Table 11. It should also be noted that the WMU device (Reason RVP311) does not currently support TCP. UDP has been used for the purposes of the VISOR project but the use of UDP in the future productionised system may require further consideration as a potential compromise between security and bandwidth.

Table 11. Data transfer rate comparison between typical PMU and the RPV311 WMU

Device		Bandwidth	
		Device -> PDC	PDC -> PDC (based on 20 devices)
PMU (50fps, +ve seq)		34 kbps UDP	200 kbps TCP
WMU RPV311	PMU stream (50fps, 3-phase)	50 kbps UDP	460 kbps TCP
	WMU stream (200fps, +ve seq)	125 kbps UDP	470 kbps TCP

Communication Infrastructure

The chosen system communication channels will vary between the operator, based on their individual IT security practices. Adequate communications and GPS coverage is one of the most significant costs affecting installation and operational costs and in most cases, has greater transmission and data quality requirements than traditional monitoring systems.

WAMS measurement data must adhere to the IEEE C37.118 standard for data acquisition and transmission. For the purposes of this project, existing infrastructure formed the communication link between monitoring device and regional PDC but was assigned with low priority. For any roll-out, a bandwidth assessment is necessary to ensure sufficient communication capacity is in place.

Both IPSec and MPLS techniques were successfully used to transmit data between PDCs. For other potential deployments, the use of a high-speed and high-reliability link (such as MPLS) may be most appropriate, or even necessary, depending on its application.

Applications:

The applications demonstrated by VISOR are described in Section 3.2 and listed in Table 3. These applications have been selected in accordance with the primary objectives of the project and would therefore likely differ from the requirements of other deployments. More information regarding the applications demonstrated can be found in previous project progress reports and presentations from knowledge dissemination events.

The applications trialled by the project have been restricted to those available through GE, who retain the IPR for the application modules trialled through VISOR; however alternative applications are offered by other technology providers.

Process:

Appropriate data analysis and reporting mechanisms must be established to create valuable and actionable information from WAMS, both in terms of the new insight offered by WAMS and also the performance of the WAMS system itself.

When first establishing a WAMS, it is important to closely monitor the performance of the overall monitoring system to identify issues affecting performance. Regular reports proved that documenting performance statistics such as connection drops per PMU and data quality (as reported by PMU/WMU) is highly valuable during the initial stages of live monitoring. Once satisfactory performance was achieved, the frequency of reporting could be reduced although system health is constantly monitored.

Finally, power system engineers and operators must also be trained to use the applications and tools made available by the WAMS. Section 3.3 of this report explains the efforts made to establish suitable training facility and accompanying programme to support this project. More information on training workshops can be provided upon request.

Cost:

The cost of implementing a WAMS will depend on the application and the scale along with a variety of additional factors all of which impact the number of monitoring devices, the data storage and data processing requirements, the communication infrastructure and bandwidth, data and cybersecurity, as well as redundancy. It would be impractical to provide a factual estimate of the cost of implementing a WAMS. VISOR has deployed a bottom-up approach to WAMS which is not the conventional industry standard, for example following blackouts in the USA, the Recovery Act Smart Grid Investments supported the installation of 1,000 PMUs across North America, supplemented with high speed communications networks and advanced analytical applications. Twelve Smart Grid Investment Grant (SGIG) projects and two Smart Grid Demonstration Projects have installed PMUs at a total project cost of over $328 million (combined federal and private funding).

11 Planned Implementation

Following the successful trial, efforts are being made to continue WAMS operation and analysis in the immediate future. To support these efforts, VISOR has developed a Roadmap to evaluate the deployment options applicable to all project partners over the near-, mid-, and long-term as shown in Figure 21.

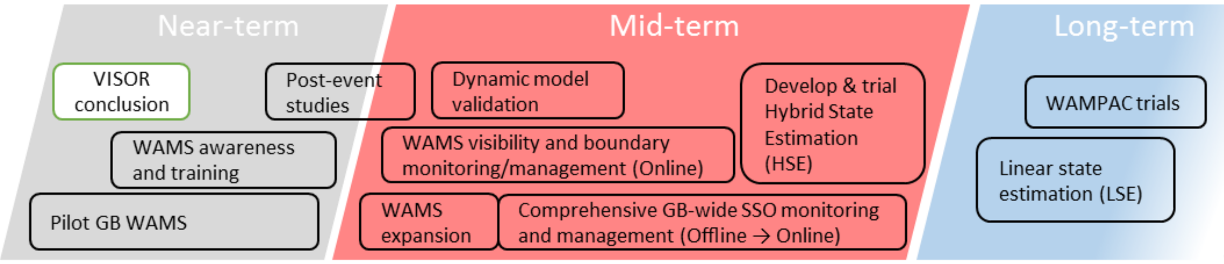

Figure 21. Proposed WAMS implementation

The Roadmap assessed roll-out strategies considering implementation requirements for TOs and SO following the conclusion of the project. The main focus is the interim period up to RIIO-T2, wherein the foremost objective is to retain the existing infrastructure in order to preserve oscillation monitoring and analysis capabilities, to continue gaining valuable learning to help safeguard system security and to inform investment decisions and innovation strategies in relation to the next price control.

The Roadmap set the following near-term objectives to guide investment and roll-out strategy for the GB WAMS:

- Secure funding for the continued operation of the GB WAMS, in particular:
    - Renew contract of MPLS between SPT and NGET
    - Procure software licenses (server and analysis applications)
    - Consider the need for a WAMS 'task force' to oversee deployment and develop STC requirements
    - Identify resource and processes for maintaining network infrastructure
- Establish WAMS infrastructure in operational network across TOs and SO;
- Decide upon future operating framework and TO-to-SO coordination;
- Prepare future WAMS expansion plans in next Price Control Period;
- Develop a set of implementation objectives for RIIO-T1,-T2, and beyond

A WAMS delivery team or task force, with representatives from TOs and SO, is recommended to be established to oversee the support for the transition from demonstration to production system. The delivery team will be necessary to manage deployment actions internally but also to address challenges that affect the whole system such as common communication channels, monitoring requirements and device specifications. An important challenge in the near-term is the need to establish a collaborative future strategy for WAMS deployment, particularly the level of coordination between TOs and SO.

Implementation plans are separated across three categories: Process, Infrastructure, and Application. Each category comprises of various non-trivial deliverables requiring different internal and external resource skillsets and dependencies, and each having a bearing on the eventual successful outcome. Through this exercise, the following implementation timeline has been proposed:

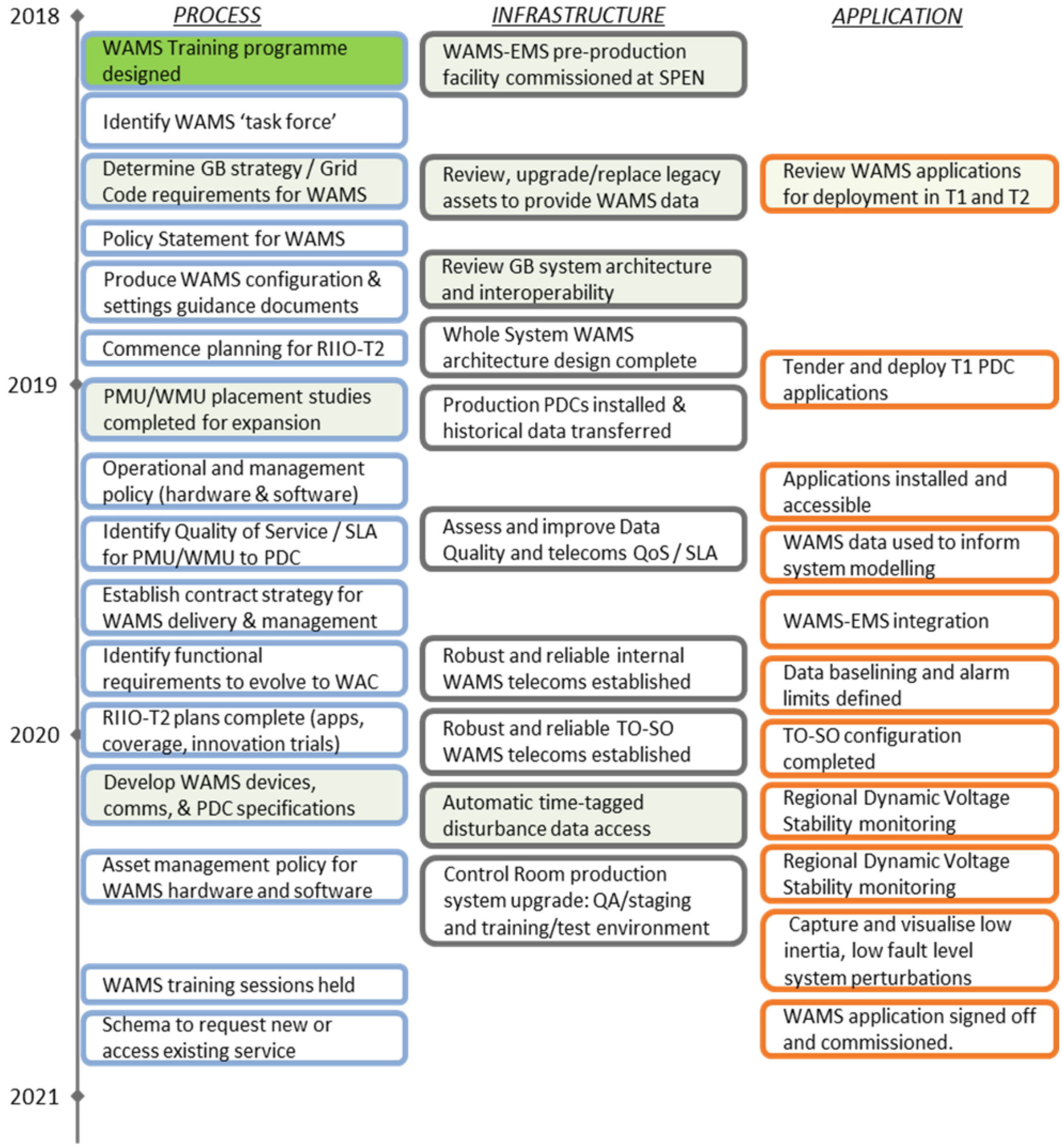

Figure 22. Proposed Near-term timeline

12 Learning Dissemination

12.1 Stakeholder Engagement

VISOR has continually shown a strong commitment to stakeholder engagement to discuss and develop objectives with key internal and external stakeholders and obtain learning from international experience to guide the VISOR project and keep sight of key challenges, and ensure that findings and recommendations satisfy the needs of each Network Licensee and deliver maximum benefit.

Stakeholder engagement has been approached on an annual basis in line with the annual cycle of many industry conferences and events. Stakeholder engagement has been planned at the beginning of each year in order to identify suitable activities and determine the content and representation at each. A full calendar of the knowledge dissemination events attended or hosted is provided in Appendix 1, with the high-profile events summarised below.

12.1.1 Dedicated VISOR Stakeholder Engagement Events

The main focal point of knowledge-sharing and stakeholder engagement activities has been dedicated VISOR engagement events hosted by the project delivery team. These events aimed to:

- raise awareness of the project's aims and objectives across the GB industry,
- disseminate project learning gathered to date,
- showcase the new tools and capabilities introduced by WAMS,
- provide a forum to hold Q&A and round table discussions with technical experts, end-users, solution providers and policy shapers.

The decision was taken to wait until the second calendar year of VISOR (2015) to host the first dedicated stakeholder event to ensure the event could present noteworthy learning following the installation and configuration of the WAMS which was the primary project focus following completion of contractual arrangements and project kick-off in June 2014. Three dedicated stakeholder events were then planned as follows:

- **First stakeholder event**, mid 2015
- **Half-way point stakeholder event**, mid 2016
- **Final stakeholder event following project close down**, originally planned for June 2017 and rescheduled to March 2018 to account for project extension

The first major dedicated dissemination event was hosted in the second year of the project, on the 18th August 2015, at Park Plaza Westminster Bridge Hotel, London. The second public event was held on the 6th July 2016, at IET London: Savoy Place, London. The final close down event was also held at the IET London on 12th March 2018. Presentation slide packs are available for download on the VISOR website.

In addition to the above, the project has sought to engage with key internal stakeholders from each project partner by conducting numerous internal stakeholder activities. These activities have mostly taken the form of demonstration events and workshops whereby overall WAMS operations and applications have been showcased with some more hands-on workshops on specific WAMS applications. In 2016, innovation days were held at both SPT and NGET operational control centres to engage and gather feedback directly from control room engineers.

In order to ensure stakeholder events deliver maximum value to the audience and project team alike, feedback was gathered throughout the course of the day through live audience participation. In these events, questions are put to the audience through presentation slides to which the audience could respond using keypads; enabling presenters to dynamically focus on areas that are perhaps less understood or revisit some aspects. This method of stakeholder engagement has proven valuable in both educating the audience in the project, WAMS technology and enabling quick and direct feedback and discussion.

12.1.2 Representation at Key Industry Events

External stakeholder engagement activities have included attending and presenting at numerous recurring conferences including LCNI, Cigre, CIRED, NASPI, IEEE General Meetings, and PAC World. Presentation material from these events has also been made available to the wider audience through the VISOR website. A full list of the main knowledge dissemination events is provided in Appendix 1.

12.1.3 Knowledge Dissemination Outcomes

Overall, the activities listed above have enriched the project's ability to deliver solutions that satisfy the needs of the GB industry.

Noteworthy direct outputs of stakeholder engagement activities include:

- Obtaining vital support and technical input from parties with prior experience of the design and operation of WAMS deployments undertaken elsewhere in the world to help guide and inform the future roll-out strategy for the GB WAMS:
    - Quanta Technology, technical expertise and experience in supporting numerous utilities design and deploy WAMS solutions across the Americas;
    - Vahid Madani, project lead for deployment of the large-scale interconnected advanced warning systems, integration of WAMS technology into PG&E's EMS.
- Undertaking two additional workstreams to improve integration into business functions:
    - WAMS-EMS training and testing facility, providing a live representative environment in which control room operators can learn, configure and build screens to meet their needs' whilst also providing a safe environment for trialling and testing new applications.
    - Phasor Data Visualisation tool, an independent web-based high-level visualisation and educational tool aimed at a wider audience, to complement the operational situational awareness and analysis provided by the primary WAMS software.

12.2 Feedback Following Peer Review of Close Down Report

UK Power Networks
Delivering your electricity

Registered Office:
Newington House
237 Southwark Bridge Road
London SE1 6NP

Registered in England and Wales No: 3870728

Company:
UK Power Networks
(Operations) Limited

Christopher Halliday
Senior Project Engineer – SP Energy Networks
Ochil House
10 Technology Avenue
Hamilton International Technology Park
Blantyre
G72 0HT

Tel: 0141 614 7847 | 07702 511627

29th March 2018

Dear Christopher,

Visualisation of Real Time System Dynamics using Enhanced Monitoring (VISOR) – Close-Down Report – DNO Peer Review

Further to your request for UK Power Networks to review and comment on the Close-Down Report produced in respect to SP Energy Networks Real Time System Dynamics using Enhanced Monitoring (VISOR), NIC funded project, I can confirm that we have undertaken this review and consider that the objectives and deliverables as agreed in the Project Direction have been satisfied by SP Energy Networks.

In addition, subject to the requirements of the NIC funding governance arrangements, we can confirm that we consider that the Close-Down Report as reviewed by UK Power Networks is clear and understandable and contains sufficient detail and information to enable a DNO, not closely involved with the project, to make use of the learning generated to implement their own network solution. Moreover, increased network visibility and real-time monitoring would help facilitate other DNO projects such as Active Network Management.

Should you wish to discuss anything further or have any additional requirements that you need to address in respect to the VISOR project, please do not hesitate to contact me.

Yours sincerely

Tatiana Ustinova
Technical Coordination – Power Potential
UK Power Networks

THE SUNDAY TIMES 30 BEST BIG COMPANIES TO WORK FOR 2017

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INVESTORS IN PEOPLE | Gold

13 Key Project Learning Documents

13.1 Project Progress Reports and Key Learning Documents

Project progress reports and key learning documents are listed below. Public versions of these documents can be downloaded from the project website:

https://www.spenergynetworks.co.uk/pages/visor.aspx

Document Title
VISOR Project Progress Report June 2014
VISOR Project Progress Report December 2014
VISOR Project Progress Report June 2015
VISOR Project Progress Report December 2015
VISOR Project Progress Report June 2016
VISOR Project Progress Report December 2016
VISOR Project Progress Report June 2017
Roadmap for the GB Wide Area Monitoring System
Stakeholder Engagement Presentations 2015
Stakeholder Engagement Presentations 2016
Close Down Event Presentations 2018
Technical Papers presented at industry leading conferences. List of key technical documents and their authors provided in Section 13.2.
System Performance Summary Reports (Not Available for public distribution. Please enquire)

13.2 Technical Papers

Title	Authors
Application of Advances in Wide Area Monitoring to Address the Challenges from an Evolving Power System	S. Clark, D. H. Wilson, O. Bagleybter, K. Hay, P. Mohapatra, F. Macleod, C. Halliday, M. Osborne, P. Ashton, P. Wall, V. Terzija.
Learning from GB Wide Area Monitoring and Progress Towards Operations Integration	S. Clark, D. Wilson, K. Hay, O. Bagleybter, P. Mohapatra, F. Macleod, C. Halliday, P. Ashton, M. Osborne, N. Hird, P. Wall, P. Dattaray, V. Terzija, Z. Jin
VISOR Project: Opportunities for Enhanced Real Time Monitoring and Visualisation of System Dynamics in GB	P. Wall, P. Dattaray, P. Mohapatra, J. Yu, D. Wilson, S. Clark, M. Osborne, P. Ashton and V. Terzija
Addressing Emerging Network Management Needs with Enhanced WAMS in the GB VISOR Project	S. Clark, D. Wilson, N. Al-Ashwal, F. Macleod, P. Mohapatra, J. Yu, P. Wall, P. Dattaray, V. Terzija, P. Ashton, M. Osborne
VISOR Project: Initial learning from Enhanced Real Time Monitoring and Visualisation of System Dynamics in Great Britain	S. Clark, D. Wilson, K. Hay, O. Bagleybter, P. Mohapatra, F. Macleod, J. Yu, P. Ashton, M. Osborne, P. Wall, P. Dattaray, V. Terzija
Advances in Wide Area Monitoring and Control to address Emerging Requirements related to Inertia, Stability and Power Transfer in the GB Power System	D. H. Wilson, S. Clark, S. Norris, J. Yu, P. Mohapatra, C. Grant, P. Ashton, P. Wall, V. Terzija.
Novel Sub-Synchronous Oscillation Early Warning System for the GB Grid	S. L. Zimath, D. Wilson, M.Agostini, R. Giovanini, S. Clark
Justification of 200fps Waveforms for Visibility of SSO	N. Al-Ashwal, D. Wilson, S. Clark
Monitoring Sub-synchronous Oscillations in Power Systems using Synchronised Measurement Technology	P. Wall, P. Dattaray, A. Nechifor, and V. Terzija
Impact of Load Dynamics on Torsional Interactions	P. Wall, P. Dattaray, D. Chakravorty, P. Mohapatra, J. Yu, and V. Terzija
Inertia Estimation using PMUs in a Laboratory	P. Wall, P. Regulski, Z. Rusidovic and V. Terzija
Identifying Sources of Oscillations Using Wide Area Measurements	D. Wilson, N. Al-Ashwal, M. Parashar
Development of a WAMS laboratory for assessing PDC compliance with the IEEE C37.244 Standard	A. Nechifor, M. Albu, R. Hair, P. Dattaray, P. Wall, and V. Terzija
Defining constraint thresholds by angles in a stability constrained corridor with high wind	D. Wang, D. H. Wilson, S. Clark

A selection of the technical papers have been collated into a single document which is available for download on the VISOR website.

14 Data Access Details

To access and download material generated through the project, please visit the VISOR website using the link below:

https://www.spenergynetworks.co.uk/pages/visor.aspx

For more information regarding the VISOR project, please contact Chris Halliday or James Yu, Future Networks Manager, SP Energy Networks.

15 Contact Details

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16 References

Clark, S., Wilson, D. H., Hay, K., Bagleybter, O., MacLeod, F., Mohapatra, P., . . . Wall, P. (2017). Learning from GB Wide Area Monitoring and Progress Towards Operations Integration. *PAC World.* Wroclaw, Poland.

Dattaray, P., Wall, P., & Terzija, P. (2016). *VISOR Project: Monitoring and Management of Torsional Oscillations (Subsycnchronous Resonance).*

Jin, M. Z., Wall, D. P., & Terzija, P. V. (Dec 2016). *VISOR Project: PMU Placement for GB Transmission System.*

Wall, P., Dattaray, P., Chakravorty, D., Mohapatra, P., Yu, J., & Terzija, V. (2016). *Impact of Load Dynamics on Torsional Interactions.*

17 Appendices

17.1 Appendix 1 - Full List of Knowledge Dissemination Activities

Year	Events
2014	• Cigre Biannual Meeting, Paris, 24^{th}-29^{th} August 2014 • Engagement with OFTO and Offshore Renewable Developers, Glasgow, 11^{th} September 2014 • Hub Net meeting, Manchester, 14^{th} October 2014 • Low Carbon Network Innovation Conference, Aberdeen, 20^{th}-22^{nd} October 2014 • Engagement with EPRI, Cumbernauld, 4^{th} November 2014 • Top Tail Engagement, Southampton, 17^{th}-18^{th} November 2015
2015	• **Key Knowledge Dissemination and Stakeholder Engagement in Park Plaza Hotel London, 18^{th} August 2015.** • IET Preparing for the Grid of the Future Event, Birmingham, 21^{st} April 2015 • All Energy Conference, Glasgow, 7^{th} May 2015 • Presentation at IET Synthetic Inertia Breakfast Event, Birmingham, 14^{th} May 2015 • Presentation at 1st International Symposium on Smart Grid Methods, Tools and Technologies, Jinan, 18^{th}-20^{th} May 2015 • PAC World Glasgow, 29^{th} June-2^{nd} July 2015 • IEEE General Meeting, Denver, 26^{th}-30^{th} July 2015 • Internal stakeholder event at the National Grid Control Centre Wokingham, 24^{th} September 2015. • APAP Conference, Nanjing, 20^{th}-26^{th} September 2015 • Cigre Study Colloquium B5, Nanjing, 20^{th}-26^{th} September 2015 • Journal Paper describing VISOR in Special Issue of Modern Power Systems and Clean Energy (MPCE) • SGTech Europe Smart Grid conference, Amsterdam, 22^{nd}–24^{th} September 2015 • EPRI International User Group conference, Dublin, 23^{rd} September 2015 • EPSRC-NSFC Project Meeting, Chengdu, China 12^{th}-15^{th} October 2015 • LCNI conference, 24^{th}-26^{th} November 2015. • Alstom User Group meeting, Cannes, 28^{th} October 2015.
2016	• **Key Knowledge Dissemination and Stakeholder Engagement Event, hosted by SPT at the IET London, 6^{th} July 2016** • WAMS Roadmap and Investment strategizing with different function areas of the TO and SO businesses, taking place in July, August and November 2016. • PAC World Conference 2016, 13-17^{th} June, Ljubljana, Slovenia • PSCC Conference, Genoa, 20^{th}-24^{th} June 2016 – two papers presented • IEEE General Meeting, Boston 17^{th}-21^{st} July 2016 • CIGRE Conferences, Paris, 21^{st}-26^{th} August 2016 • CEPSI 2016, Bangkok, Thailand, 23^{rd}-27^{th} October 2016 • IEEE Innovative Smart Grid Technologies Europe, Ljubljana, 9^{th}-12^{th} October • Low Carbon Networks and Innovation conference, Manchester, 11^{th}-13^{th} October • Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MedPower), Belgrade, 6^{th}-9^{th} November 2016
2017	• VISOR Steering board meeting, Glasgow, 17^{th} March 2017 • 2017 IEEE PowerTech Conference, Manchester 18^{th}-22^{nd} June 2017 • PAC World Conference 2017, Wroclaw, Poland, 26-30^{th} June 2017

	• **Research Findings Knowledge Dissemination and Stakeholder Engagement Event, hosted by SPT and UoM, at the Technology and Innovation Centre, Glasgow, 26th September 2017** • Low Carbon Networks and Innovation Conference, Telford, 6th-7th December 2017
2018	• **VISOR Close Down Event, hosted by SPT at the IET London, 12th March 2018** • CIGRE 2018 Session, Paris, 26-31st August 2018

17.2 Appendix 2 - Training Workshop Agenda 10/01/18

Date: 10 January 2018   Training: VISOR WAMS: Introduction to **e-terra***phasorpoint* Applications

START TIME	TOPIC	ITEM	Description
9:00	WELCOME, COFFEE & INTRODUCTION		Introductions, review agenda and report structure
9:15	WAMS & PHASORPOINT INTRODUCTION	WAMS concepts & benefits	Introduction to WAMS concepts and benefits
9:35		Case studies	Brief review of some example WAMS case studies
9:45		e-terraphasorpoint overview	Overview of e-terraphasorpoint solution - functions, capabilities and use cases
9:55	WAMS INFRASTRUCTURE	IEEE C37.118, PMUs and PDCs	Introduction covering measurement, communications, protocol and architecture aspects
10:25		e-terraphasorpoint software architecture	Overview of e-terraphasorpoint software architecture (PDC, client interfaces, databases and archives)
10:40		SPEN WAMS infrastructure	Overview of SPT WAMS architecture including PMUs and WAMS server architecture
10:50	BREAK		
11:50	PHASORPOINT BASICS (inc. hands-on)	Workbench overview and standard components	Introduction to the e-terraphasorpoint workbench client covering:
			- Access, navigation and basic displays
			- Live & Historical data review
11:50		Alarms	Alarm configuration and implementation in e-terraphasorpoint
12:50		Custom calculations, events and displays	Creation of custom calculations, composite events and flexible displays
12:50		Data interfaces and export	External interfaces and ways to export data from e-terraphasorpoint
13:00	LUNCH		
13:30	OSCILLATORY STABILITY (inc. hands-on)	Introduction to power system oscillations	Overview of oscillation types
13:40		Very Low Frequency oscillation module (VLF)	Introduction to the VLF module (inc. 10 mins hands-on, inc. review of report examples)
14:50		Low Frequency oscillation module (OSM)	Introduction to the LF module (inc. 30 mins hands-on, inc. review of report examples)
14:50		Sub-Synchronous Oscillation module (SSO)	Introduction to the SSO monitoring solution (inc. 30 mins hands-on, inc. review of report examples)
15:35	BREAK		
15:50	SYSTEM DISTURBANCES (inc. hands-on)	System Disturbance Management module	Introduction to the SDM module, including event Impact Measures (inc. 20 mins hands-on, inc. review of report examples)
16:20	ISLANDING, RESYNCH & BLACKSTART	IRB module	Introduction to the IRB module
16:30	SHORT-CIRCUIT CAPACITY	Short-Circuit Capacity module	Introduction to the SCC module
16:40	SUM-UP	Sum-up of the day's discussions	Discussion of any further topics of interest or further actions

17.3 Appendix 3 – Examples of Global Deployment of WAMS

In the United States, the utilisation of the technology has been greatly accelerated in the last few years through American Recovery and Reinvestment Act[1] of 2009, which expanded measurement coverage in the US transmission grid substantially, from 199 PMU installations in 2009 to over 1,700 in 2015[2] as well as 226 PDCs (Figure 23). As a consequence of the US Department of Energy *Smart Grid Investment Grant* projects, operators now have near 100% visibility of the behaviour of the entire US high voltage transmission network. This technology provides operators with visibility into the transmission systems that serve approximately 88% of the total US load and covers approximately two-thirds of the continental US.

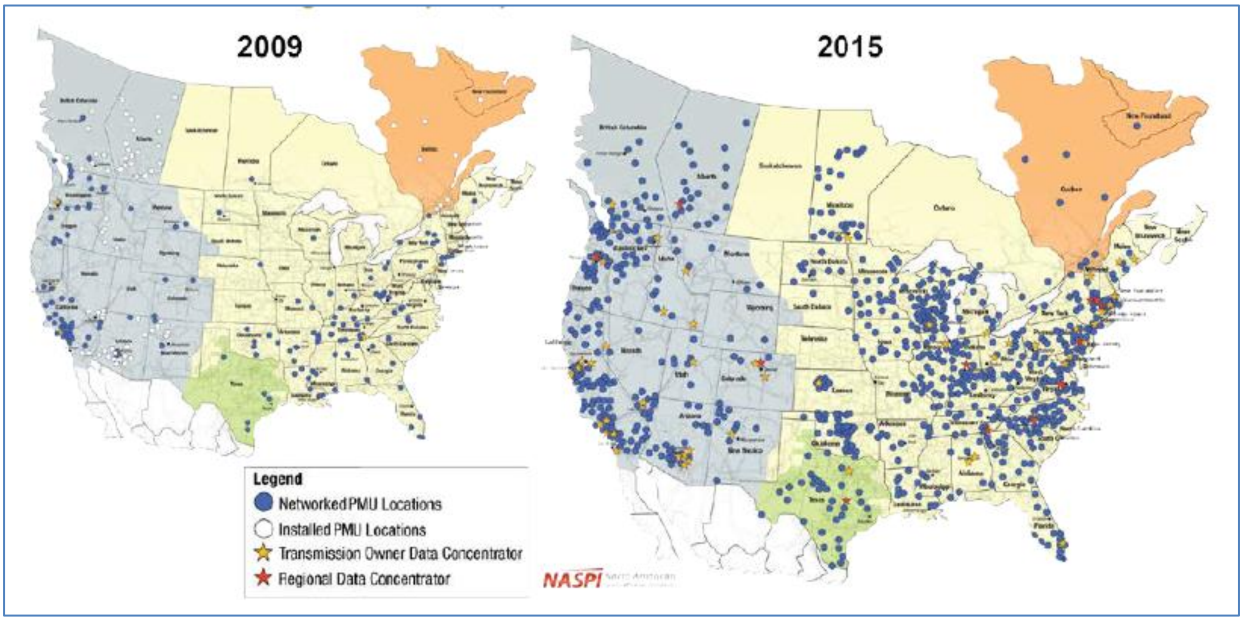

Figure 23. Left – concentration of PMUs in 2009; right – networked PMU concentration as of 2015

In China, the PMU-based measurement systems have been installed in thousands of locations. For instance, China Southern Grid has PMUs installed at more than 340 substations and generation stations (all 500 kV and some 220 kV stations). It has been reported[3] that all PMU signals are sent to the control centre at rates of 100 fps. The data has been used in offline post-event analysis, real-time monitoring, system stability protection, and various power system controls (e.g. oscillation damping control). It is reported[4] that low-frequency oscillation management at China Southern Grid has been addressed by WAMS technology employing a combination of PMU-based alarms, HVDC modulation control and generator disconnection or control mode switching based on oscillation source location.

In India, after the initial pilot installations, a major deployment project is underway by Power Grid India, the central transmission utility of India that operates ~90% of inter-state/inter-regional

[1] http://www2.ed.gov/policy/gen/leg/recovery/implementation.html

[2] Source: DOE Report, "Advancement of Synchrophasor Technology in Projects Funded by American Recovery and Reinvestment Act of 2009, March 2016

[3] Kun Men, "Application of Wide Area Monitoring and Control in CSG", NASPI Meeting, Feb. 2013

[4] Bonian Shi, Integrated Measures for Low Frequency Oscillation and Control, Beijing Sifang Automation Co., NASPI, Mar 2014

networks. The *Unified Real-Time Dynamic State Measurement* project aims to provide a full visibility of system dynamics across the entire interconnected India national power grid by installing PMUs at:

i. all transmission substations at 400 kV and above (total of 354 substations);
ii. all generating stations at 220 kV and above;
iii. HVDC terminals and inter-regional and inter-national tie lines, and;
iv. both ends of all the transmission lines at 400 kV and above.

By the end of the project, 1,186 PMUs will be deployed. One of the success stories of its implementation is a number of Special Protection Schemes across the country.

There are other WAMS projects across continental Europe[5], Eastern Europe and Iceland[6]. In addition, there is an ongoing WAMS deployment project in the Norwegian Transmission grid led by the Norwegian SO, Statnet[7]. Continental European Transmission System Operators cooperate through the WAMS hosted by SwissGrid[8] with applications such as fault analysis support, load monitoring, dynamic line thermal monitoring, power system restoration support tool, and online dynamic system stability monitoring, as well as some offline applications based on historical data analysis.

In South America, WAMS technology has gained wide acceptance with a number of major deployments effort underway in many countries (e.g. Brazil, Colombia, Mexico, etc.) and some successful deployment experience (e.g. System Integrity Protection Scheme for Ecuador's System Operator CENACE)[9].

The following are a few examples that show how the technology has been successfully deployed to address specific business needs and realise true benefits.

- NERC[10] post-event analysis – It took more than six months for a team consisting of tens of industry experts to get a full understanding of what had happened to cause the 2003 blackout in the northeast United States and Canada. NERC has been on the forefront in promoting the adoption of the PMU technology through reliability standard development and leading and participating in North American Synchrophasor Initiative (NASPI) activities. The wide adoption of the technology has resulted in a much quicker turnaround of the 2011 blackout post-event analysis, and further improvement is expected as more and more transmission substations will be equipped with PMUs. WAMS are ideal for identifying the sequence of events and the related system dynamics across an interconnected power grid in a post-event analysis. Many utilities are using WAMS to support post-event analysis and have realised similar benefits as NERC.

- Generator model validation and calibration in Peak RC[11] control area (western US) – In 1996, a blackout event captured by WAMS had shown that the system generator dynamic model for the region was not accurate, which caused the simulated results to deviate substantially from the actual event. As a result, the affected power transfer corridor had to be de-rated to

[5] W. Sattinger, "Continental European WAMs System Analysis, Protection and Dynamics Applications", IFAC-PapersOnLine, 49-27 (2016) 382-385 (www.sciencedirect.com)
[6] Ragnar Guðmannsson, Landsnet: Five Years of synchrophasor use in the control center", NASPI, Feb 2013.
[7] http://www.nordicenergy.org/wp-content/uploads/2015/11/STRONgrid.pdf
[8] Sattinger W. and Giannuzzi G., Monitoring Continental Europe, IEEE Power & Energy, Vol. 13, Nr. 5, Sept/Oct. 2015
[9] Diego Echeverria, "Successful Deployment Experience of a Synchrophasor-Based System Integrity Protection Scheme (SIPS)", NASPI, 2015
[10] North American Electric Reliability Corporation
11 Peak Reliability Coordination (Peak RC) branched out of Western Electricity Coordination Council (WECC) in 2014

avoid the potential re-occurrence of the non-converging inter-area oscillations, leading to higher generation costs to consumers. Since then, a concerted effort has been made by the network operators in the region to validate and calibrate their generator models including the use of PMU measurements, which has a much lower cost for such model validation and calibration compared to taking generator outages. As a result of this effort, the simulation results for a 2011 blackout matched the captured event quite closely. It should be pointed out that for an interconnected power system, the full benefits can only be achieved when all generators are validated and calibrated.

- System Integrity Protection Scheme (SIPS) for Ecuadorean transmission grid – Rapid expansion of generation capacity and load growth has led to stressed grid operations of the Ecuadorean transmission grid, i.e. for certain transmission circuits, a double contingency could lead to a complete system collapse. If the transfer limits are set to avoid the system collapse, it would severely reduce the useable circuit capacity and increase the electricity cost to consumers as a result. Taking a systematic approach from performing system studies to clearly identifying the problem areas, developing the mitigation methods (i.e. using SIPS to take quick actions upon the occurrence of a double contingency), developing a SIPS system design and requirement specifications, to going through a formal open competition procurement process and a well-managed installation and commissioning process, CENACE was able to start the use of the SIPS system at the beginning of 2015. The entire process took less than three years from when the investigation started. There have been immediate benefits from the higher transfer capacity of those circuits enabled by the SIPS, and the SIPS had already operated correctly several times as designed, which alone has realised multi-million US dollars of benefit. The deployed system is currently in the Phase 2 expansion to cover more areas.

- Power System Stabiliser (PSS) commissioning support for Landsnet Iceland - GE installed a 5-PMU WAMS in Iceland in 2006 and provided support for the commissioning of PSS at existing power stations as well as a new 700MW hydroelectric power station and aluminium smelter. The WAMS has been extended since then to a larger number of PMUs, with plans for further extension. It is used extensively in the control room for operational monitoring of stability during operational procedures, particularly related to the 132kV ring around the country. It is also used in detecting islanding and resynchronisation. In addition to real-time uses, it is also the main resource for disturbance analysis, oscillatory stability review and controller tuning. The main benefits provided are:

    - Real-time and offline monitoring of the dynamics of the power system
    - Fast and accurate detection of islanding and resynchronisation support
    - Regular reports on the dynamic behaviour of the power system
    - Successful PSS tuning and commissioning
    - Dynamic modelling and control tuning of a large smelter load for increasing utilisation and reducing risk of shutdown of the plant
    - On-going collaboration for expanding the use of WAMS in control

  A pilot Wide-Area Defence Scheme is also currently being deployed in Iceland to avoid separation of the two main generation centres, based on frequency and angle difference.

- Short-Circuit Capacity (SCC) estimation for Energinet Denmark - to determine the likelihood of HVDC commutation failure. Energinet, the SO of Denmark, sought an application where the short circuit capacity of the system could be estimated with high accuracy using PMU measurements. The main drive for this was that this knowledge was important for the start-up of HVDC terminals, although knowledge of short-circuit capacity could also assist in protection design and could point out limitations in the connection of renewable generation on the distribution network. Identification of short circuit impedance is possible using naturally occurring disturbances, by determining the Thevenin impedance from the source. However, research carried out by Energinet.dk and its academic partners imply that although this approach is possible it may not be accurate enough. Therefore, for this approach, there will be a PMU and a switchable reactor or filter required at each location where it is desired to measure the SCC. In addition to the voltage which is measured directly at the bus, one current channel of the PMU should normally be applied to the current through the reactor (filter). It must be possible to carry out the measurement for both switching operations, i.e. switching the reactor or filter on or off.

- Damping Constraint Implementation for AEMO Australia - AEMO operates the Australian National Electricity Market (NEM) as well as the gas transmission market. It provides security coordination of the electricity system covering five Australian states serving a peak demand around 35GW. The system has an end-to-end distance of about 4000km, and the transmission distances mean that the system is susceptible to oscillatory instability. The system depends on active damping controls of power system stabilisers and SVC power oscillation dampers to maintain stable and secure operation. Real-time dynamics monitoring and alarming have been used in the control room since 2001, in conjunction with the National Electricity Rules related to damping. Comprehensive benchmarking of the dynamics monitoring was carried out to validate the approach. The original monitoring platform using active power monitoring has been upgraded to a phasor-based monitoring system, to use industry-standard measurement equipment, and also to enable the use of damping monitoring using angle differences that provide an improvement in observability of the modes of interest over the original active power signals. Oscillation monitoring and conditional constraints are now applied to three modes of interest in the NEM.

17.4 Appendix 4 - SDRC Evidences

17.4.1 Extract of Baseline and Comparator Reports for SSO Behaviour, Mar 15

PSYMETRIX AN ALSTOM COMPANY

Document Type	Technical Report
Title	**GB Wide Area Monitoring System: Power System & Infrastructure Performance Review - March 2015**
Synopsis	This report, produced for SP Energy Networks, National Grid UK and Scottish Hydro Electric under the VISOR Project, outlines the findings from an infrastructure & data review of continuous wide-area synchrophasor and waveform monitoring in the Great British electricity transmission network. This incorporates data gathered from the ScottishPower and National Grid transmission areas in 2014 and early 2015. The review covers: • The performance and data quality of the Wide-Area Monitoring System infrastructure. A number of measurement performance issues have been identified and some recommendations for managing these issues are included in this document. • Baselining of small- and large-signal dynamic behaviour, as well as the observed voltage angle pattern across the system. Oscillation and disturbance events have also been identified. However, it has been highlighted that measurement infrastructure improvements are necessary in order to accurately monitor oscillatory stability behaviour and detect large disturbances. • Initial Oscillatory Stability alarm attributes and System Disturbance detection thresholds, proposed based on the data available. A more detailed review of these attributes is recommended when data quality is improved. • Results of Sub-Synchronous Oscillation analysis performed on some initial periods of data acquired in February and March 2015, from new Waveform Measurement Units installed under the VISOR Project at Hutton and Eccles substations on the Anglo-Scottish B6 interconnection.
Document Status	CONFIDENTIAL TO VISOR PROJECT
Document ID	PSY-VISOR-Datareview2014-V02.Docx
Date	25/03/2015

PSYMETRIX AN ALSTOM COMPANY	**Alstom Grid - Psymetrix** 1 Tanfield Edinburgh EH3 5DA Scotland, UK	**General** Telephone Fax **Support** Telephone Email	 +44 (0)131 510 0700 +44 (0)131 555 5185 +44 (0)131 510 0709 wams-support@alstom.com

17.4.2 Evidence of Baseline and Comparator Reports for SSO Behaviour, Dec 17

GE
Grid Solutions

VISOR Project

GB Wide Area Monitoring System: Power System Performance Review 2017

20/12/2017

GE-VISOR-DataReview2017-v01.docx

Authors: Karine Hay, Stuart Clark

imagination at work

17.4.3 Evidence of Data Centre (and Advanced Applications) SAT, May 15 [CONFIDENTIAL]

VISOR Data Centre Server SAT Procedure

Test Procedures for the Site Acceptance Testing of a Data Centre Server of the UK VISOR Project Wide Area Monitoring System.

The VISOR Project (Visualisation of Real-Time System Dynamics Using Enhanced Monitoring) is a UK Network Innovation Competition (NIC) project funded by the Ofgem, the UK regulator, led by Scottish Power in collaboration with National Grid UK, Scottish Hydro Electric and the University of Manchester.

Document Date:	**5th May 2015**
Author:	**Richard Davey**
Reference:	**VISOR-WAMS-TST-002**
Version:	**3**
Classification:	**Confidential**

Contents

6.3 Section Signoff

	Name	Signature	Date
Tester	P. ASHTON	[redacted]	11/5/15.
Observer 1	STUART W A CLARK	[redacted]	11/5/15
Observer 2			

6.3 Section Signoff

	Name	Signature	Date
Tester	S CLARK	[redacted]	14/5/15.
Observer 1	F. MACLEOD	[redacted]	14/5/15.
Observer 2			

17.4.4 Evidence of PMU requirements Technical Document under review, issued 6 Mar 2017

SP ENERGY NETWORKS

TECHNICAL SPECIFICATION WIDE-AREA MONITORING SYSTEM EQUIPMENT

XXX-XX-XXX
Issue No.

1 SCOPE

This document details the technical requirements for Wide-Area Monitoring equipment employed to provide synchronised measurement of voltage and current on the GB Transmission or Distribution System. It contains functional, performance and interface requirements for these devices and also covers the functionality, where it is provided as part of an integrated function in another device or substation process.
The Substation Phasor Data Concentrator (PDC) and associated remote data collection for Wide Area Monitoring Systems (WAMS) will be addressed in a separate Technical Specification.

17.4.5 Evidence of Line Parameter Estimation & Variability Report, Mar 15

Document Type	Technical Report
Title	**Line Parameter Estimation & Variability**
Synopsis	This report, produced for SP Energy Networks, National Grid UK and Scottish Hydro Electric under the VISOR Project, describes and evaluates the results of the Line Parameters Estimation (LPE) algorithm for lines where Phasor Measurement Units (PMUs) are available at both ends. Moreover, the present document reports the variation and confidence of the calculated parameters over time. For the performance evaluation of the Line Parameters Estimation algorithm both simulated and real data were used.
Document Status	CONFIDENTIAL
Document ID	Psy-VISOR-R150216-Line Parameter Estimation-V02.Docx
Date	13/03/2015

	Alstom Grid - Psymetrix 1 Tanfield Edinburgh EH3 5DA Scotland, UK	**General** Telephone Fax **Support** Telephone Email	 +44 (0)131 510 0700 +44 (0)131 555 5185 +44 (0)131 510 0709 wams-support@alstom.com

17.4.6 Evidence of SSR Report for SDRC 9.3, Dec 16

MANCHESTER 1824

The University of Manchester

Title: **VISOR Project: Monitoring and Management of Torsional Oscillations (Subsynchronous Resonance)**

Synopsis: This report presents the findings of research into the torsional oscillations that occur as a result of subsynchronous resonance in series compensated transmission systems. Topics covered include: a review of international practice for managing subsynchronous oscillations, the impact of load dynamics on the damping of torsional oscillations; the first identification of subsynchronous load interactions, an interaction between induction motors and torsional oscillations; a method for identifying generators that are vulnerable to SSR and critical lines, the removal of which will expose these generators to greater risk of SSR; and a new method for torsional oscillation mitigation using variable frequency drives.

Document ID: VISOR Project: Subsynchronous Resonance

Date: 27th December 2016

Prepared For: Internal Use
The University of Manchester
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17.4.7 Evidence of Report on Uncertainty on Stability Calculations for SDRC 9.4, Dec 16

MANCHESTER 1824

The University of Manchester

VISOR Project: Impact of Uncertainty on Stability and Security Margins
30th December 2016

Title: **VISOR Project: Impact of Uncertainty on Stability and Security Margins**

Synopsis: This report presents the conclusions of the UoM's work on the impact of uncertainty on stability and security margins. A summary of existing research is presented alongside some examples of the impact of uncertainty and the potential for probabilistic, risk based approaches for managing security limits in the more uncertain and variable power systems of the future.

Document ID: VISOR Project: Impact of Uncertainty on Stability and Security Margins

Date: 30th December 2016

Prepared For: Internal Use
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17.4.8 Evidence of Power-Angle Application Specification for SDRC 9.4, Feb 15.

PSYMETRIX AN ALSTOM COMPANY

ALSTOM

VISOR: GB Stability Management with Power and Angle limits in PhasorPoint

The document describes the functions that will be presented in the PhasorPoint application for monitoring the stability of the GB transmission system. The stability of the GB system is characterised by the power flow in the B6 Boundary and a derived angle difference between Scotland and England.

This document is provided for discussion with the VISOR partners and as a basis for implementing the power-angle application.

Document Date:	**16th February 2015**
Author:	**David Wang, Stuart Clark, Douglas Wilson**
Reference:	**VISOR-WAMS-B6-001**
Version:	**2**

17.4.9 Evidence of Hybrid State Estimator Report for SDRC 9.4, Dec 16

MANCHESTER 1824

The University of Manchester

VISOR Project: Comparison of Hybrid State Estimators
20th December 2016

Title: **VISOR Project: Comparison of Hybrid State Estimators**

Synopsis: This report presents the results of a comparison of five hybrid state estimators using simulations and mathematical derivations. The relative performance of the HSEs is discussed in terms of accuracy, convergence time and resilience to gross measurement and model errors. Recommendations are made for future work.

Document ID: VISOR Project: Comparison of Hybrid State Estimators

Date: 20th December 2016

Prepared For: Internal Use
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17.4.10 Evidence of Report on Area Angle Measurements for SDRC 9.4, Dec 16

GE
Grid Solutions

VISOR Project

Report on Area Angle Measurements

01/12/2016

GE-VISOR-161130-Report on Area Angle Measurements-v1.docx

Authors: Christos Takoudis, Stuart Clark

imagination at work

17.4.11 Extract of System Commissioning Report, Dec 15

1 Executive Summary

The VISOR project showcases the role of an enhanced Wide Area Monitoring System (WAMS) in addressing some of the challenges faced by network Transmission Network Owners and the System Operator, as the transmission network evolves to include a greater degree of generation intermittency and increased levels of power electronics.

The state-of-the-art synchronised monitoring system deployed in VISOR is the first GB WAMS and also marks the first deployment of new Waveform Measurement Units (WMUs), supplied by GE Grid Solutions, that generate 200 frames per second data in order to extend the range of the detection of Sub-Synchronous Oscillations (SSO) up to 46Hz.

The monitoring of voltage and current phasors at dozens of locations across England, Scotland and Wales revolutionises the real-time monitoring of the GB system to provide GB-wide real-time visibility of the dynamic system behaviour of the network.

This report details the overall system deployed by VISOR and the key learning gained through planning, installing, commissioning and operating the first combined WAMS between the three GB Transmission Owners (TOs) and the System Operator (SO). The following stakeholders have contributed to this report:

- SP Transmission (SPT),
- Scottish Hydro Electric Transmission Limited (SHE TL),
- National Grid Electricity Transmission (NGET), and,
- National Grid Electricity Transmission System Operator (NGETSO).

The findings of this report place an emphasis on the significance of the underlying communication infrastructure, the associated security risks and the feasibility of various data transfer methods; giving consideration for progression into the business, and highlighting the significance of coordination between project partners and third-party communication service providers.

1.1 Key findings

The system commissioning of WMUs, WAMS server and communication links has generated significant learning regarding processes, risks and challenges involved in large scale installations like that in project VISOR.

The most significant learning has stemmed from the delays incurred by the service provider, which suffered repeated and uncontrollable delays in establishing the communication link between SPT and NGET. The order of a Multiprotocol Label Switching (MPLS) link was placed through NGET who placed the order with their supplier, Verizon, who in turn required BT Openreach to deliver the physical fibre

17.4.12 Evidence of WAMS-EMS Facility Design and Commissioning [CONFIDENTIAL]

Grid Solutions
A GE and Alstom joint venture

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Project Milestone Acceptance Certificate

Project Name:	SPEN WEDS
Client:	SP Energy Networks (SPEN)
Project Description:	Provision of a demonstration transmission SCADA EMS and Wide Area Monitoring System and related services
Milestone Date:	13th December 2016

Project Milestone/Deliverable Description:

- Completion of Design

By signing this document I acknowledge that I have delivered the stated deliverable(s) at the agreed level of quality.	By signing this document I acknowledge that I have received the stated deliverable(s) at the agreed level of quality.
GE Project Manager:	SPEN Authorised Client Representative: [redacted]
Date:	Date: 3/4/2017

SPEN WEDS (Sandbox) – 2017-06-19 GE Progress Report

2017-06-19 WEDS GE Progress Report

Date

19 Jun 2017

Updates

Item	Notes
WAMS Installation	PhasorPoint initial configuration complete: - database cloned from SPEN VISOR and upgraded to version 6.20-1 - Poor performing PMUs removed to avoid potential impact on performance Dataflow from SPEN Production WAMS to WEDS WAMS configured, activated and validated: - Live data available in WEDS WAMS!