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

In collaboration with

Roadmap for the GB Wide-Area Monitoring System

December 2017

Issue 2

Table of Contents

GLOSSARY OF TERMS

CNI	Critical National Infrastructure
DFR	Digital Fault Recorder
EBS	Electricity Balancing System (the Balancing Mechanism replacement)
ENIS	Electricity Network Innovation Strategy
fps	Frames per second
IRM	Innovation Rollout Mechanism
LAN	Local Area Network
NASPI	North American Synchrophasor Initiative
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
NETS	National Electricity Transmission System
NGET	National Grid Electricity Transmission
OPTEL	National Grid's Operational Telecoms Network (operational network supporting CNI)
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
ARRA	American Recovery and Reinvestment Act 2009
RTS	SPEN's Real-Time System (operational network supporting CNI)
SCADA	Supervisory Control and Data Acquisition
SHET	Scottish Hydro Electric Transmission
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 Executive Summary

Wide Area Monitoring Systems (WAMS) are revolutionising how power systems are operated around the world by utilising time-synchronised, high-resolution measurements of the electricity 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.

This document presents a roadmap for the continuation of the GB WAMS following the conclusion of the innovative demonstration project, *Visualisation of Real-Time System Dynamics Using Enhanced Monitoring (VISOR)*, funded through Ofgem's Network Innovation Competition (NIC), to support the transition into day-to-day business practices and to guide and inform investment plans for the lead participants of VISOR, namely, the GB National Electricity Transmission System Operator (SO) and the three mainland Transmission Owners (TOs): SP Transmission, National Grid Electricity Transmission and Scottish Hydro Electric Transmission.

The business case for GB rollout has been assessed based on the experience of the GB WAMS to date with the support of Quanta Technology and their experience in supporting numerous utilities design and deploy WAMS solutions. From this, key challenges that lay ahead have been highlighted and options for the future roll-out and operation of the GB WAMS evaluated.

WAMS is an enbling technology which provides the underpinning support required to address the complexities of system planning and operation in the years ahead. In itself it will not directly address the problem, but it will enable the TO& SO to see the problem and understand how to address it.

The roadmap concludes that there is sufficient justification to warrant the continued operation of the WAMS established through VISOR for the duration of RIIO-T1 to provide enhanced monitoring of sub-synchronous oscillations that would otherwise go unnoticed, to better understanding true system behaviour, to improve modelling capabilities and accuracy, and to support the development of future planning and rollout in subsequent regulatory periods. The current GB WAMS demonstrates valuable benefits to offline analysis and system planning functions, however, with time and further infrastructure and process development, additional benefits can be unlocked through real-time system operation and control room functions.

WAMS and associated Smartgrid applications can provide very responsive solutions, however unlike the new circuits and plant items they are replacing, these require regular supervision and optimisation to ensure they are functioning correctly. Furthermore the complexity of what they are monitoring is difficult to predict, so certainly for the next few years these system will require dedicated resource to ensure they are working reliably before they can become trusted and reliable applications.

Roadmap implementation

The establishment of the working group under the System Operator - Transmission Owner Code (STC) to establish baseline Policy for various aspects of System Performance Monitoring which includes WAMS will be the implementation strategy. All parties concerned will agree on the requirements and mechanism to meet the policy requirement, which once ratified will become coded requirements for each party to meet.

The basic principle of engagement is that the TOs will manage their own networks in terms of technology deployment for monitoring and analytics and provision the SO with a data service for real time (using PMU) and post event analysis.

Recommendations for rollout

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:

Application recommendations:

- Following the conclusion of VISOR in 2017, it is recommended to focus immediate efforts on the continued operation of the existing applications by renewing the licenses of the applications that have been demonstrated through VISOR, detailed in Table 2 (p.26), and maintaining the necessary infrastructure and processes to support them;
- 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 development of existing or trial new applicaitons.

Infrastructure recommendations:

- Each project partner to assess and upgrade accordingly:
    - To ensure the communication infrastructure achieves a suitable 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 are 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.
- System architects from each TO/SO must work together to design a resilientarchitecture to serve the needs of the GB WAMS as a whole, for inclusion in RIIO-T2 planning.
    - The system architecture should allow for potential WAMS expansion to one WAMS monitoring device per transmission substation in RIIO-T2.

The following procedural changes are recommended:

- 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 rollout: 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 by RIIO-T2;
- 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 IS architecture.

The purpose of this roadmap is to document the status of the WAMS deployment in GB and the key learning gathered in getting to this point, the business case for WAMS rollout in GB to form recommendations for the next steps. Each section of this report covers a different topic:

Section 2	Provides an overview of VISOR and global WAMS deployments
Section 3	Describes the current status of the GB WAMS
Section 4	Explores the business case and benefit areas for GB WAMS justifying immediate rollout and outlining future opportunities offered by WAMS
Section 5	Discusses implementation plans, focusing on the immediate future, highlighting key challenges and possible solutions for secure, robust and effective rollout
Section 6	Articulates four different deployment options and coordination strategies for consideration in GB
Section 7	Draws conclusions and recommendations on the next steps for the GB WAMS

2 Introduction

Wide-Area Monitoring Systems (WAMS) are being increasingly deployed to provide system monitoring utilising monitoring devices (typically Phasor Measurement Units) which provide time-synchronised measurements to an accuracy of less than 1 microsecond. This section provides an overview of the first large-scale WAMS deployment in GB, and examples of deployments elsewhere in the world.

2.1 Summary of VISOR

The **Visualisation of Real-Time System Dynamics Using Enhanced Monitoring** (VISOR) project was formed through Ofgem's Network Innovation Competition (NIC) framework with the objective of establishing and demonstrating a next-generation monitoring system across GB.

The VISOR project is led by SP Energy Networks (SPEN), through their transmission network business, SP Transmission (SPT), and is a collaboration between:

- the three GB mainland Transmission Network Owners (TOs): SP Transmission, National Grid Electricity Transmission (NGET), and Scottish Hydro Electric Transmission (SHET);
- the National Grid Electricity Transmission System Operator (SO);
- the University of Manchester (UoM); and
- GE Grid Solutions (formerly Psymetrix at the time of project inception) as the WAMS technology provider.

Establishing this new WAMS aimed to assist electricity network owners and operators in maintaining safe and reliable operation by providing an accurate instantaneous view of the network by using time-synchronised measurements and a suite of analysis applications, potentially unlocking a number of benefits, including:

- enhanced understanding of true system dynamics;
- reducing uncertainty to improve situational awareness;
- increasing the accuracy of system modelling and safety limit calculation that govern power system capacity margins and overall operation as a whole;
- increasing power system resilience by extending the ability to detect and help mitigate against high-impact, low-probability events that can cause plant damage and blackouts;
- ultimately reduce both operational and capital expenditure.

Through the project, each TO has commissioned WAMS data centres, Phasor Measurement Units (PMUs) and new Waveform Measurement Units (WMUs), which feed monitoring and analysis applications developed by GE Grid Solutions, who are a market leader in the research and development of WAMS solutions for utilities. Each TO shares measurement data with the SO data centre to enable analysis applications and visualisations based on a GB-wide view of the system.

The GB WAMS collates, analyses and visualises time-synchronised measurements from over 100 sites to provide unparalleled monitoring and understanding of the dynamic behaviour of the GB system and provides a level of insight beyond the un-synchronised measurements offered by SCADA.

VISOR focused on the following key application areas to enhance understanding, accelerate uptake and bring significant benefits to network operators and in-turn GB customers:

- **Real-time monitoring, alarming and source location of Very Low Frequency (VLF), Low Frequency (LF) and Sub-Synchronous Oscillations (SSO) across the range 0.002Hz to 46Hz,**
- **Dynamic model validation using post-mortem analysis of WAMS data,**
- **Hybrid state estimation using PMU and SCADA data, and,**
- **The potential use of angle based security limits to increase power flow on the B6 boundary between Scotland and England.**

2.1.1 Project Partner Objectives

SPT Role & Objectives in VISOR:

- To install WMUs to cover both double circuits across the "B6" boundary for the purpose of monitoring/managing any potential risk of SSO introduced following the installation of series compensation,
- To conduct SSO monitoring at critical infrastructure - in particular, large generation/import sites at Torness and Western HVDC link at Hunterston.
- To ensure system reliability is retained with increasing penetration of power electronic based devices, i.e. series compensation equipment and HVDC links.
- Lead the project on behalf of the project partners.

NGET Role & Objectives in VISOR:

- To install WMUs to cover both double circuits across the "B6" boundary for the purpose of monitoring and managing any potential risk of SSO introduced following the installation of series compensation, at Hutton and Stella West.
- To install WMUs to monitor any potential SSO risk at the following sites:
  - Connah's Quay, introduced by the combination of multiple windfarms, the HVDC interconnector to Ireland (EWIC), and the intra-network Western HVDC link,
  - Grain, introduced by the BritNed interconnector and the local generation.

SHET Role & Objectives in VISOR:

- To install two WMUs, an associated server, and a communication link with the SO to share phasor and waveform measurement data from the SHET network,
- Install WMUs on boundary circuits with SPT to enhance understanding of dynamic behaviour and, in doing so, enable improved utilisation of assets,
- To explore the potential benefits phasor data and WAMS can offer to the business.

National Grid SO Role & Objectives in VISOR:

- To install a central server, termed the Data Hub, to collate WAMS data from each TO and explore benefits of the new GB-wide visualisation and analysis capabilities,
- SO play an important role in VISOR and the future of WAMS, as a substantial portion of the potential benefits facilitated by WAMS accrue to the SO through the real-time operation of the power system.

2.1.2 VISOR Background

The initial concept of VISOR originated from the desire to improve understanding of the true system dynamics across key points of the network. The growing level of intermittent generation, largely owing to substantial increases in wind generation, drastically changes the amount and consistency of power transfer between regions and consequently how this is monitored and managed. Of particular importance for SPT is the "B6" boundary between Scotland and England where two 400kV double-circuits conventionally transferred large bulk power from the North of the island to the South.

In 2013, SPT, supported by the other transmission licensees and the academic partner, made a full proposal submission for the VISOR project, under the 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 WAMS-EMS 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 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 undertaking can be categorised into three stages - Installation, Operational, and Transitional - as illustrated below, whereby the final stage includes the production of this roadmap.

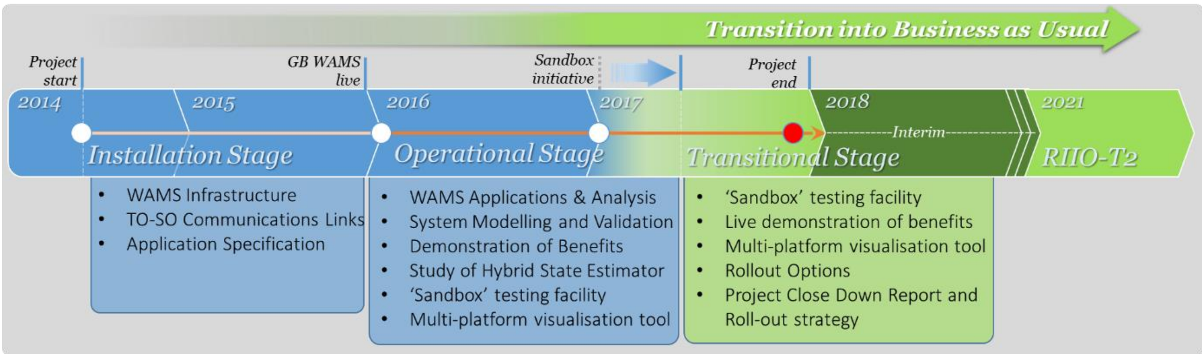


Figure 1. The three stages of the VISOR project

2.1.3 VISOR Technology: Infrastructure, Communications, and Applications

2.1.3.1 Measurement Infrastructure

Following contract signing, the work commenced in mid-2014 with the detailed design, procurement, and installation of the data acquisition and data centres/servers, including ten globally innovative point-on-wave *Waveform Measurement Unit (WMU)* monitoring devices. WAMS data centres were established by each TO to collate and analyse information offered by the synchronised view of their network. In addition to the WMU devices, SPT and NGET utilise PMU devices to report phasor measurements to data centres.

The VISOR WAMS incorporates two forms of wide-area synchronised measurements produced at a rate of 50 (phasors) and 200 (waveforms) frames per second (fps), taken from over 100 sites across Scotland, England and Wales which provides unparalleled monitoring and understanding of the real-time dynamic behaviour of the GB system when compared to unsynchronised SCADA data that is typically sampled at one frame per second.

The measurement information taken from the three different regions is communicated to the System Operator to offer a synchronised view of the whole system. The GB-wide visibility of the dynamic behaviour brings new capabilities through new applications such as system stability analysis and oscillation monitoring, which are discussed further in Section 3.2.

The figure below shows the infrastructure established by VISOR (left) and how this is translated to the new visualisation software (right). The depicted application provides oscillation source location across the whole system, and although the oscillation shown is a known system mode of low amplitude, such instances do help to characterise the behaviour observed and validate models.

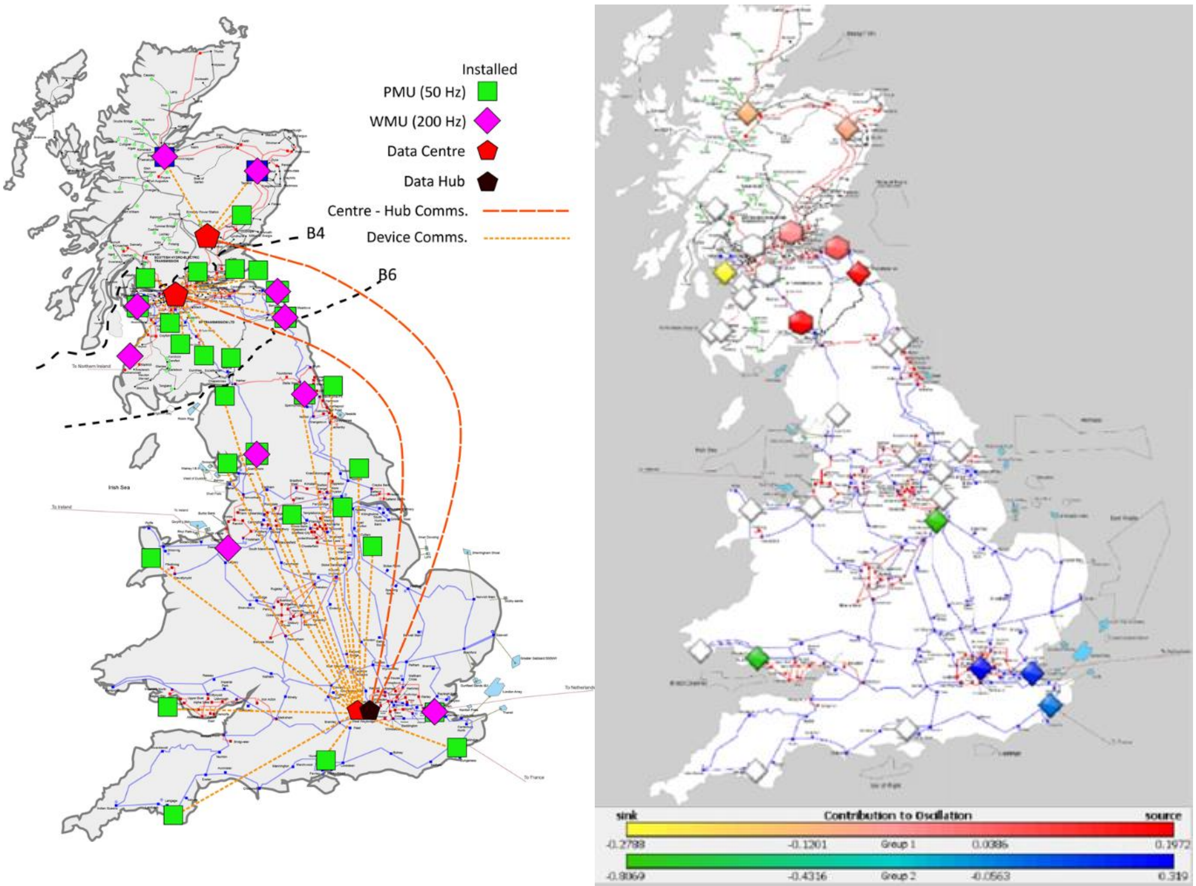


Figure 2. New GB-Wide infrastructure and analysis capability established by VISOR

2.1.3.2 WAMS Integration, Testing and Training Facility at SPT

A dedicated WAMS integration, testing and training facility has been commissioned by SPT to directly address the concerns surrounding future integration of new WAMS data into the operational control room environment, in particular, its integration with the existing Energy Management System (EMS) platform. The facility is located within the SPT Operational Control Centre and resides on the SPT operational network with the sole purpose to bring live WAMS and EMS together into one testing, development and training environment. More information can be found in Section 3.2.5 (p.31).

2.1.3.3 Communications 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 3:

SHET → SO: IPSec[1]

SPT → SO: IPSec + MPLS[2]

NGET → SO: Direct LAN

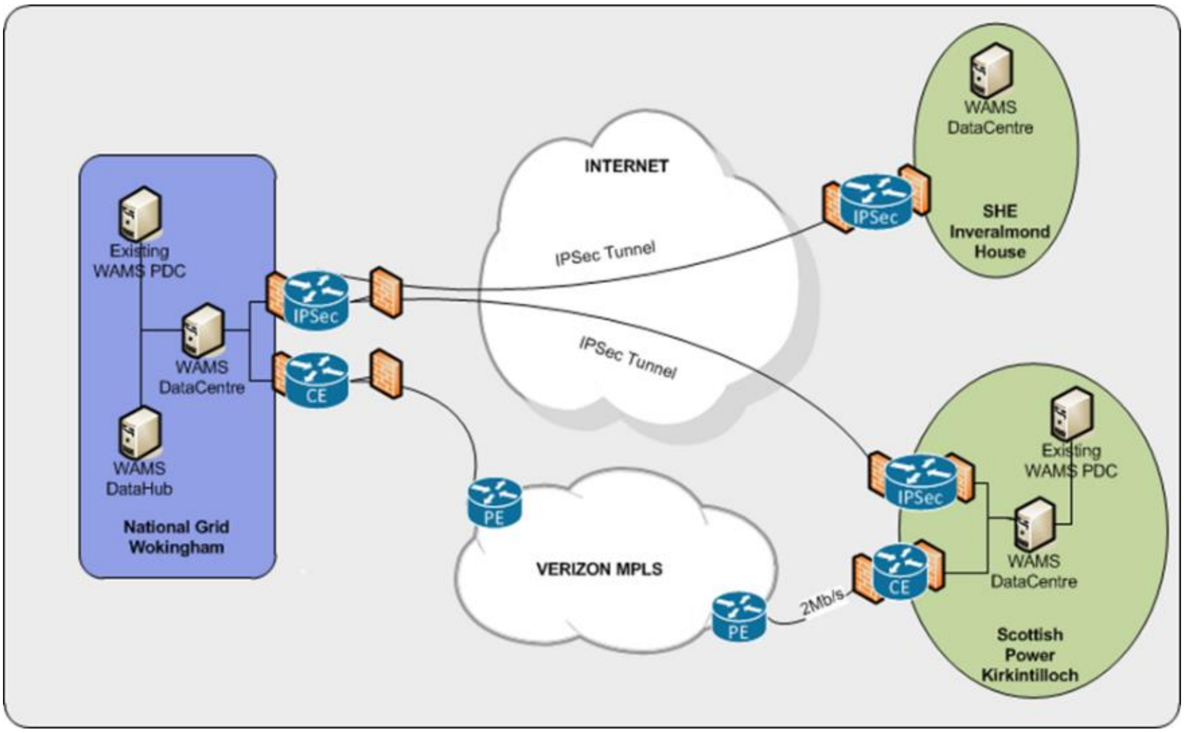


Figure 3. VISOR Communication Links between SHET, SPT, NGET and the SO

A Multiprotocol Label Switching (MPLS) optical fibre network was established between SPT and SO, which is managed by Vodafone. At the time of writing, the bandwidth utilised is 4Mb/s (upgraded from 2Mb/s depicted above) 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

[1] Internet Protocol Security (IPSec) Tunnel is a protocol suite for secure Internet Protocol (IP) communications by authenticating and encrypting each IP packet. Hosted in the internet gateways of the participating TSOs. This method is acceptable for use on the corporate LAN but not acceptable for use as CNI for security reasons.

[2] Multiprotocol Label Switching (MPLS) is a mechanism in high-performance telecommunications networks that directs data from one network node to the next based on short path labels rather than long network addresses, avoiding complex lookups in a routing table. Separate network hosted by the service provider. This method is used to host CNI.

between SO and TOs to function accurately. The extent of data sharing required will be discussed later as a key learning outcome from this project.

2.1.3.4 Deployed WAMS Applications

The application layer of the GB WAMS employs PhasorPoint software supplied by GE Grid Solutions, which receives conventional PMU data via IEEE C37.118 at 50 fps and also accommodates the new 200 fps WMU devices through the following functionality:

- Receiving the data via IEEE C37.118-2005
- Forwarding the data to other PDCs via IEEE C37.118-2005
- Storing and processing the 200Hz data
- Retrieving the 200Hz data for historical review
- Debugging – e.g. connection, data quality, or data availability issues

The WAMS applications deployed through VISOR targeted three key areas of system management as shown below in Figure 4.

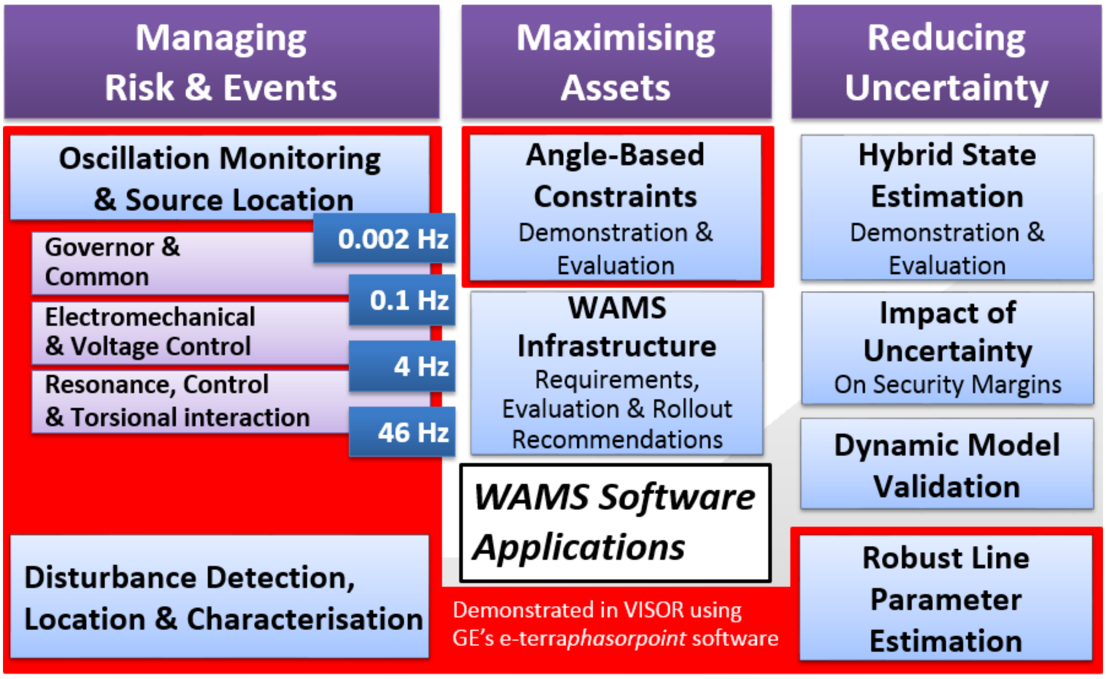


Figure 4. VISOR target areas and WAMS application available on PhasorPoint

A key aspect of power system performance assessed by VISOR is oscillatory behaviour, which is made possible through dedicated PhasorPoint applications capable of detecting oscillation across the following different frequency ranges (or "modes"):

- **"Very Low Frequency" (0.002-0.1Hz) behaviour** 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 control systems opening or closing the "tap" of water/steam feeding a generator to maintain a certain speed (mains frequency).
- **"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.
A number of 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 Oscillations" (4-46Hz)** introduced by control systems in power electronic converters such as those found in wind farms and HVDC links, by mechanical resonant torsional frequencies in generator shafts, and by series capacitors installed on the transmission network.

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 not 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 WAMS applications are designed with the following common principles in-mind to provide clear and actionable information to operators, and valuable and usable data for long-term study:

- **Analyses are performed in real-time**, with results stored for later study e.g. model validation, baselining or operational review. Live and historical values can be accessed within the application and can be exported for further analysis in third-party tools as comma separated value files or via a database driver.
- Results are grouped into **configurable frequency bands** for independent alarming and visualisation, enabling focus on modes of interest such as generator torsional frequencies. The analysis and results stored are unaffected, so as not to influence the historical review.
- **Mode selector tabs** allow users to switch between bands in charts and map views and display the present dominant frequency and alarm state of each band.
- **Alarm and source location information is shown in map views** through simple "traffic light" or colour gradients respectively. Charts below display mode frequency, damping and amplitude for the user-selected location, alongside the worst-case system-wide value.

2.1.3.5 Regular Power System and WAMS health reports

A series of monitoring reports have been produced by GE to demonstrate the enhanced visibility provided by the WAMS document the performance of the power system based on VISOR observations, enabling system baselining, disturbance investigation and analysis to be carried out. In addition, separate reports have monitored the health of the WAMS itself; examining PMU and WMU performance to identify repeated packet-losses or connection drops, that signal erroneous PMUs or connectivity issues, and take remedial action to deliver adequate data acquisition and data quality.

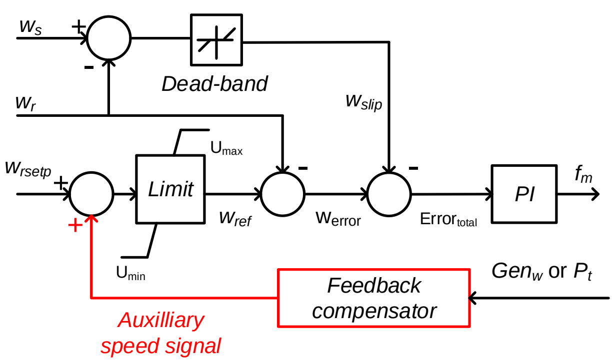
These reports highlight the new capability offered through the GB WAMS and illustrate, in detail, the enhanced, and in some cases completely new, level of monitoring and analysis applications available.

The production of these reports has however been funded through the demonstration project and a long-term enduring solution must, therefore, be developed as part of the rollout strategy.

2.1.3.6 Research Applications

The University of Manchester led research into three key and potentially highly valuable applications to support the development of applications for by network operators: Hybrid State Estimation; PMU placement; and, Sub-Synchronous Resonance mitigation, summarised below. The findings from these studies can be used to inform future application development and trials.

- **Hybrid State Estimation (HSE)**: HSE use both SCADA and WAMS measurements, and the system model, to calculate the state estimation and represents a step toward Linear State Estimation, where the state is derived from a fully-observable set of synchronised measurements using linear equations. The performance of different HSE approaches was evaluated and concluded that the "Integrated" HSE approach provides optimum accuracy, resilience to gross errors, and reliability (relative to measurement placement).
- **PMU Placement:** UoM led an investigation into optimal monitoring device placement to ascertain the optimum level of penetration and device type (e.g. many PMUs that monitor only 1 or 2 channels vs a smaller number of PMUs that monitor many channels) to provide the desired level of network coverage. A MATLAB application has been produced which uses an approximation of the GB topology to solve the optimal placement problem.
- **Sub-synchronous Resonance (SSR) mitigation:** UoM have proposed a new damping controller that enables power plant auxiliary loads to provide SSR mitigation through the inclusion of an Auxiliary Damping Controller, which adds an auxiliary speed signal to the existing speed reference, as shown in the figure below.



Feedback compensator incorporated into the frequency control loop of the VFD closed loop control to derive the auxiliary speed signal.

Figure 5. Modelling Sub-Synchronous Resonance mitigation

2.2 Global Deployment of WAMS

WAMS deployment globally has been shown to provide a multitude of tangible benefits to various areas of power system operation including real-time decision-making, offline analysis, asset protection, and control. The technology provides precise time-synchronised (< 1 microsecond) phasor, analogue value, digital status, frequency and df/dt (Rate of Change of Frequency) measurements at a high resolution, which has enabled electricity utility providers worldwide to implement a wide range of applications to support their operations.

In the United States, the utilisation of the technology has been greatly accelerated in the last few years through American Recovery and Reinvestment Act[3] of 2009, which expanded measurement coverage in the US transmission grid substantially, from 199 PMU installations in 2009 to over 1,700 in 2015[4] as well as 226 PDCs (Figure 6). 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.

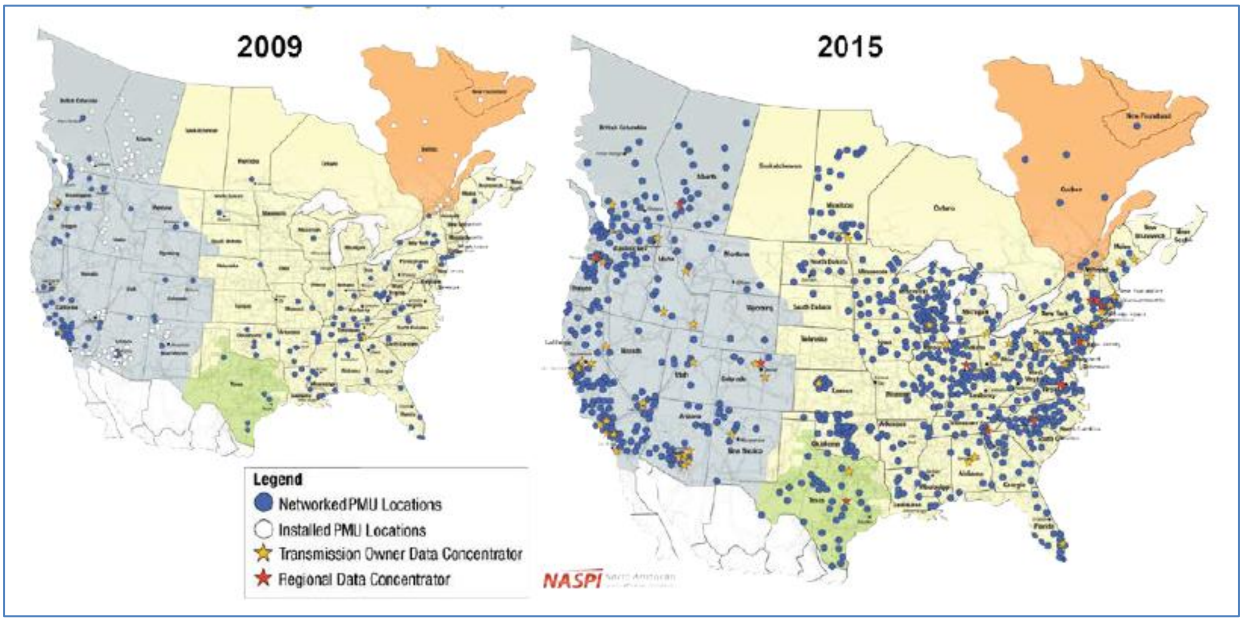


Figure 6. Left – concentration of PMUs in 2009; right – networked PMU concentration as of 2015

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[5] 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

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

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

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

damping control). It is reported[6] 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 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[7], Eastern Europe and Iceland[8]. In addition, there is an ongoing WAMS deployment project in the Norwegian Transmission grid led by the Norwegian SO, Statnet[9]. Continental European Transmission System Operators cooperate through the WAMS hosted by SwissGrid[10] 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)[11].

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[12] 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

---

[6] Bonian Shi, Integrated Measures for Low Frequency Oscillation and Control, Beijing Sifang Automation Co., NASPI, Mar 2014
[7] W. Sattinger, "Continental European WAMs System Analysis, Protection and Dynamics Applications", IFAC-PapersOnLine, 49-27 (2016) 382-385 (www.sciencedirect.com)
[8] Ragnar Guðmannsson, Landsnet: Five Years of synchrophasor use in the control center", NASPI, Feb 2013.
[9] http://www.nordicenergy.org/wp-content/uploads/2015/11/STRONgrid.pdf
[10] Sattinger W. and Giannuzzi G., Monitoring Continental Europe, IEEE Power & Energy, Vol. 13, Nr. 5, Sept/Oct. 2015
[11] Diego Echeverria, "Successful Deployment Experience of a Synchrophasor-Based System Integrity Protection Scheme (SIPS)", NASPI, 2015
[12] North American Electric Reliability Corporation

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[13] 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 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
    - Monthly reports on the dynamic behaviour of the power system

13 Peak Reliability Coordination (Peak RC) branched out of Western Electricity Coordination Council (WECC) in 2014

- 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.

2.3 Lessons from VISOR and Global WAMS deployment

In summary, some major trends have emerged from various deployment efforts:

1. **Significant process development and effort is required for WAM systems and applications to get deployed into control room use:** Many WAMS have been deployed globally intended for control room real-time operational use. However, many deployed systems have not been fully integrated into the control room for operational use as yet, despite the fact that the systems and the applications have been in place for a few years. The main reasons for this are that the following areas must be properly addressed before a deployed WAMS, and its applications, can be used in a control room real-time operational environment:

   - **Meeting production-grade system requirements**: For control room use WAMS must meet the same stringent production-grade system requirements as other control room IT systems (e.g. EMS), which include high availability through redundant system design, sound change management processes facilitated by separate QA and development subsystems, and operator hands-on closed-loop training with WAMS application operator training systems.

   - **Assured high data quality** to ensure the trustworthiness of the WAMS data used for operational decision making: In addition to making sure the data arrives at control centres on-time with minimal disruptions, state estimators such as linear state estimators must be applied to detect the bad data from the received raw data.

   - **Implementing system model based WAMS applications**: Although measurement-based (or model-less) WAMS applications play an important role in control room real-time operations, model-based applications are another important group of applications that could provide more advanced data analytics such as establishing the links among the measurement data and events, determining cause-effect relationships of various events and projecting the direction that the system is heading through simulations.

   - **Development of operational processes and procedures**: The objective of wide-area situational awareness is to get the operators' attention to an occurred or evolving situation that may require the operators' actions. Proper operation processes and procedures need to be developed so that operators can follow them to take appropriate actions that alerted such situations.

   - **Operator training and acceptance**: Many system events could have a major impact on the system but do not occur very often. It is important that operators are properly trained to use the applications and have confidence in using the system.

2. **New and dedicated engineering resource and analysis skills:** are required at the early stages of WAMS deployment to design, build, implement and develop the systems and establish the necessary training and operational procedures to utilise the systems. Additional resource will be required to perform the initial dynamic modelling and validation of the solutions.

3. **The need for an overall WAMS asset management strategy:** to cover ongoing maintenance and servicing to keep the end to end systems operational. Annual operational costs are required to ensure the WAMS services are available, and additional resource and costs required to productionise solutions for use in the control room are not insignificant.

4. **The need for asset owners, system operators and regulators to work together:** WAMS technology is ideal for implementation of wide-area applications that have clear benefits at

the system level rather than to individual asset owners directly. For example, installing PMUs at large generators for generator monitoring and model validation may not provide major direct benefits to generator owners. However, full visibility of all large generators and an accurate system model, including accurate generator models could bring major benefits to overall system reliability and the efficient operation of the power system.

Whilst wide-area applications introduce improvements across many business functions for both asset owners and system operators, it will be difficult to establish clear business cases for such a deployment by asset owners on an individual basis in GB. It may be more appropriate for parties (e.g. system operators) who are in the position to realise such system-level benefits from the deployment to initiate and structure the deployment.

The following considerations should be made regarding rollout in GB:

- The System Operator must define the functional services (including levels of resilience) they require such that the TO or generator can establish the most effective way to provide the service.
- There may also be a need for regulatory policy support to enable asset owners to be able to initiate and carry out such deployment.
- Jointly determine and define the short-term mandatory requirements and the long-term strategic direction so that 'least regret' investment decisions can be made on the network.

5. **Successful PMU-based System Integrity Protection Scheme (SIPS) systems deployment and operational use have been achieved elsewhere in the world:** A number of PMU-based SIPS systems have been successfully deployed and in operational use today to address specific system operational issues where they are deployed. There are clear business cases with good cost-benefit ratios for such deployments, which generally are very similar to that of deploying SIPS systems using traditional measurements. Using PMU data for SIPS systems provides the following added benefits and advantages:
   - PMU data is time synchronised and provides more information (e.g. phase angle information) than the traditional SIPS measurement data.
   - Such a system makes post-event analysis of system disturbance events and the assessment of the SIPS own performance during such events much easier to perform with the archived PMU data
   - The PMUs and communication infrastructure deployed for SIPS could also be used to implement other WAMS applications that can bring in more benefits

3 Status of GB WAMS and Challenges

This section provides an update of the status of the GB WAMS infrastructure and applications presently installed and available to the network owners and operators; lists relevant learning outcomes obtained so far and concludes with the key challenges facing the rollout of WAMS in GB.

3.1 Current WAMS Infrastructure in GB

The backbone of the WAMS comprises of the network infrastructure and analysis applications developed and demonstrated through the VISOR project (see Section 2). There are two other WAMS-based projects in flight which utilise aspects of the GB WAMS infrastructure but focus on a specific area of WAMS implementation. The needs of these projects will be considered in the Conclusion and Recommendation (Section 7).

- SPT's Series Compensation project[14], a RIIO-T1 project which has augmented SSO visibility by specifically monitoring series compensation devices installed on the SPT network.
- National Grid's Enhanced Frequency Control Capability (EFCC) project[15], is an innovation-funded project which has trialled a WAMS-based monitoring and control system for fast frequency response from renewable energy technologies.

The GB WAMS is underpinned by a foundation infrastructure comprising of measurement devices, communication channels and data centres atop of which the WAMS analysis layer is built. The three types of data centres, also called Phasor Data Concentrators (PDC), referred to in this text are:

- WAMS Data Centre – PDC operating at regional level in each of the three TO networks
- WAMS Data Hub – PDC operating at a system level in the System Operator control centre
- Existing WAMS Servers – legacy PMU recording servers which redirect certain PMU streams

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 have access to its own WAMS data (from PMUs and WMU), while SO has access to data from all TOs.
- Each TO has its own WAMS applications that only use its own data – there is no data exchange between TOs.
- SO and TOs are all using GE's PhasorPoint platform for the PDC and analysis applications. Currently, there is no data exchange between the VISOR system and the Production EMS.
- There is currently no redundancy in the implemented system infrastructure.

[14] https://www.spenergynetworks.co.uk/pages/mscdn_series_compensation.aspx
[15] http://www2.nationalgrid.com/UK/Our-company/Innovation/NIC/EFCC/

- Waveform Measurement Units are implemented on GE's Reason RPV311 product that produces both phasor measurements at 50 fps and analogue waveform samples at 200 fps, sent in two separate data streams via UDP protocol (not TCP).

LAN and WAN Networks:

- SO and TOs initially deployed WAMS servers on Corporate LAN Networks
- Communication channels between TOs and SO were chosen relative to security and bandwidth (see below).

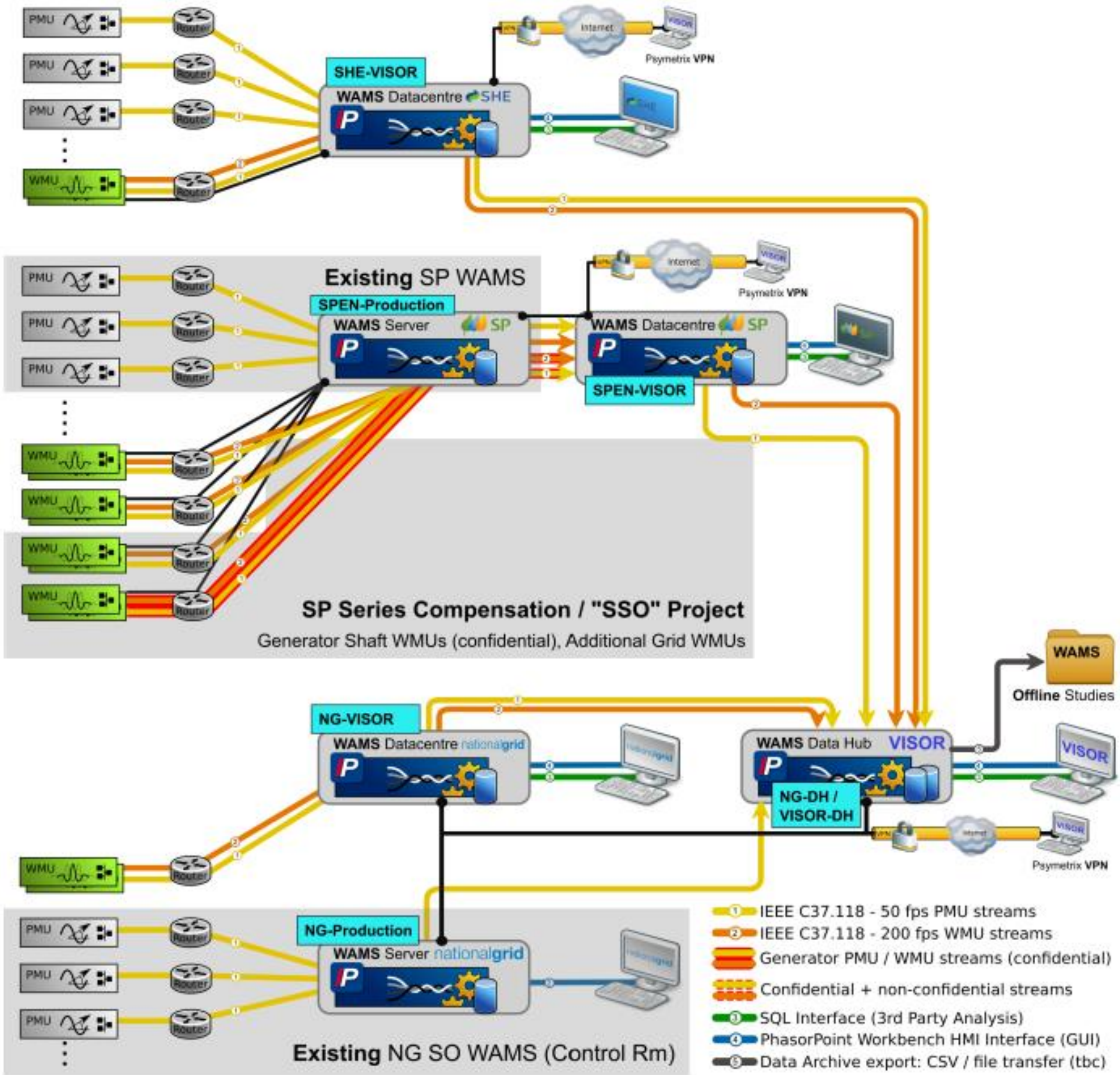


Figure 7. The present GB WAMS infrastructure

3.1.1 Communication Channels

Communication channels between the TOs and SO established by VISOR and currently in use are shown below, along with a comparison of the merits of Internet Protocol Security (IPSec) Tunnel and Multiprotocol Label Switching (MPLS) shown below in Table 1:

SHET → SO: IPSec
SPT → SO: IPSec + MPLS
NGET → SO: Direct LAN

Table 1. 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 network 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, Fibre connections into the building and the 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 -it 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 increases 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 (termed RTS at SPT, and OPTEL at National Grid) offer a fast private network with exceptional reliability and there are no technical or security issues preventing WAMS in this environment but migrating the existing system across will require coordination regarding the data transfer and the existing communication links to external parties.

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 were not connected to OPTEL and VISOR/WAMS is not yet considered CNI.

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 currently 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.

3.2 Current WAMS Applications in GB

This section outlines the capabilities of the applications demonstrated through VISOR and subsequently available for rollout in GB. Researched applications for potential future development and deployment are also discussed.

The installation of series compensation, and the increasing penetration of power electronic converters and controllers associated with renewable generation, HVDC and active control devices, add vital flexibility and capacity to the power system and help in the move to a low-carbon grid. However, this plant also introduces new challenges, not only in protection when considering fault scenarios, but also in steady-state and post-fault operation as they heighten the risk of oscillations.

The analysis applications are fundamental to extracting value from the WAMS by interpreting measurement data into actionable information. The WAMS platform presently used in the GB WAMS is called PhasorPoint through which VISOR has introduced and developed a set of PhasorPoint applications to analyse PMU (50 fps) and WMU (200 fps) to improve visibility of interactions and oscillations and enhance understanding of real-time system dynamics. The table below lists the suite of applications, and their respective measurement and device requirements, introduced to the GB WAMS through VISOR.

Table 2. Current suite of PhasorPoint applications available to GB WAMS

Application		Data Rate (Minimum)	Measurement Type	Device Type
Oscillation Detection and Location	0.002Hz - 0.1Hz Very Low Frequency (VLF) Oscillation Detection & Location	10Hz	Phasors	PMU
	0.1Hz - 4Hz Low Frequency (LF) Oscillation Detection & Location	10Hz	Phasors	PMU
	4Hz - 46Hz Sub-Synchronous Oscillation Detection	200Hz	Analogs (point-on-wave)	WMU
System Disturbance Management Detection & Location		10Hz	Phasors	PMU
Power-Angle Boundary Constraint		1Hz (any)	Phasors	PMU
Line Parameter Estimation		10Hz	Phasors	PMU

The applications listed above are licensed by GE Grid Solutions for the duration of the VISOR project and are a subset of the applications available on the PhasorPoint platform.

3.2.1 Oscillation Detection and Location Applications (VLF, LF and SSO)

Several inter-area modes are already known in GB, with power system stabilisers and oscillatory stability monitoring having been in place since the 1980s. Whilst these modes have been relatively stable in the past, some are less well understood and this behaviour is likely to change as the power system continues to evolve. In addition to the existing oscillation modes, the increasing number of power-electronic devices on the system introduces the possibility of new oscillation modes for which the system operators currently have very limited visibility.

Currently, operational response to an oscillation will either require prior study of the mode or else apply general guidelines such as reducing power flow between participating regions; both will usually impact the economic and efficient operation of the grid. The capability to identify oscillation sources is of significant benefit in targeting both real-time response and offline investigation to a contributing region or plant. Once the source(s) and cause have been identified, procedures can be developed, models validated and controller tuning instigated.

With sufficient monitoring devices and coverage, VISOR has demonstrated new tools that are capable of detecting and locating the source of sub-synchronous oscillations, monitoring angle-separation between regions, generating alarms upon detection and signalling likely sources and sinks.

A number of oscillations have been observed in both the electromechanical and SSO ranges, which have so far been fairly localised and low-level. Such behaviour includes local electromechanical modes, power electronic or voltage control modes, and the torsional modes of generators. **The enhanced visibility of the 4-46Hz range obtained through VISOR has revealed many previously unseen oscillation frequencies in the grid; most are believed to originate from power electronic converters and controllers.**

Two key examples of observed events are shown below (these have been anonymised)

i. The first example (Figure 8) involved a brief and relatively low amplitude, but significant oscillation observed in active power, in a segment of the GB system. This oscillation was detected in real-time along with the region from which the source originated and later confirmed to be consistent with the manual investigation using Digital Fault Recorder (DFR) data.
ii. The second example (Figure 9) detected 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. This event was sufficiently small in amplitude that it did not cause protection to operate or DFR to trigger but highlights an area for examination to reduce risk against future occurrences.

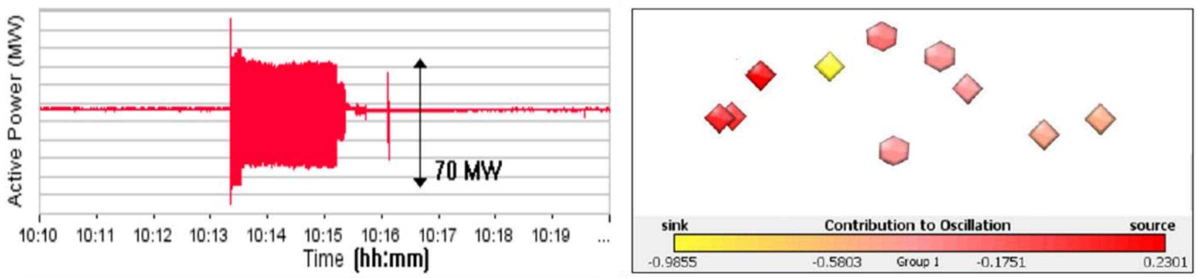


Figure 8. Example (anonymised) of a significant oscillation event observed in active power (left) and real-time source location display (right) for the relevant segment of the GB network.

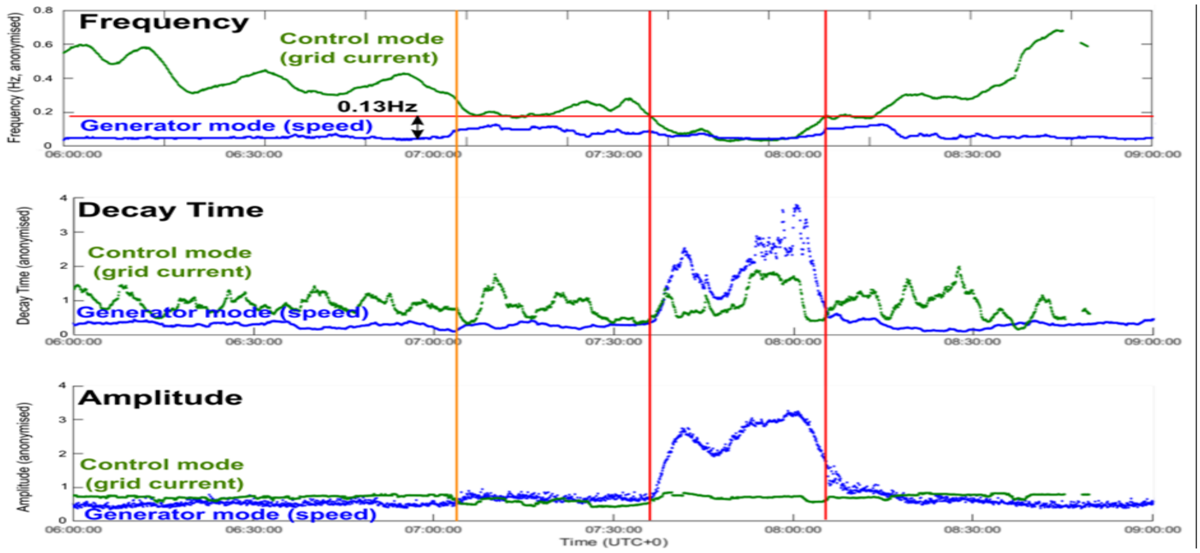


Figure 9. Example of very low-level sub-synchronous interaction observed (anonymised)

These observations are valuable to system design and analysis teams as they flag up behaviour that might represent grid code non-compliance, or be relevant to future system studies. The information is also valuable to asset owners, as it can highlight plant faults as well as validating mechanical or controller models. This can be used in planning to identify areas to avoid or which require specific mitigation in respect of SSO as more active control systems connect to the network.

All SSO events observed to date have been very low-level, well below values which would trigger any generator stress protection. In capturing these minor interactions however they can be investigated, their risk assessed and any necessary action taken to avoid potential problems that may escalate under different grid conditions.

3.2.2 System Disturbance Monitoring (SDM) Application

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

The SDM tool utilises the phasor data to calculate the likely source of a disturbance informing control engineers to take remedial action, such as a ramping down/up specific generation from specific plant. By establishing an understanding of commonality of the different SSO modes, and the possible remedial actions, a severity matrix will be formulated over time, allowing observed modes to be classified as in terms of severity. The increased understanding can subsequently be used to inform a set of mitigation actions or guidelines that do not currently exist.

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

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

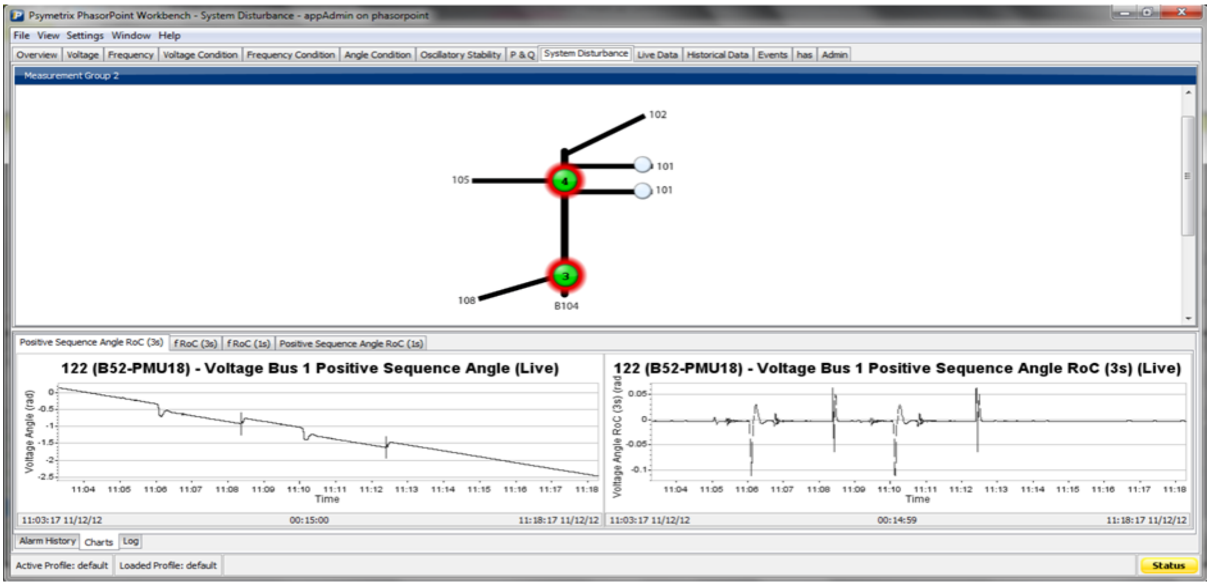


Figure 10. SDM application in PhasorPoint

3.2.3 Power-Angle Boundary Constraint: B6 Display Application

In the current practice, the B6 boundary transfer and limits are defined in terms of the MW transfer in the cut-set of lines crossing the Scotland-England border. At day-ahead timescales, the maximum capacity of the transmission boundary is required to be planned such that the system does not experience any instability, unacceptable voltage condition, or overloading of any network assets for any credible system fault.

The Power-Angle Boundary Constraint application demonstrates this new approach to provide a measure of stability across the B6 boundary that is complementary to the existing MW constraint, which may increase power-transfer limit across the boundary and introduce the potential for dynamic stability limits. This application has been initially developed for the B6 boundary but can be applied across a different region providing sufficient monitoring data is available.

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

The theory is that the direct measurement of system angle separation provided by the WAMS offers a more direct reliable measure of transient instability risk than MW flow at an arbitrary boundary alone. The key advantages of angle-based constraint management include:

- Dynamic limits are more closely related to the area angle movement than to the power through a cut-set. Both first-swing (transient) and damping limits are physically related to the following phenomena:

- Effective impedance between the areas: *Angle increases with weakening of corridor between areas*
- Loading of the interconnection lines: *Angles increase with power interchange between areas*
- Distribution of power within the connecting areas: *Angles increase as greater proportion of power far from the boundary*

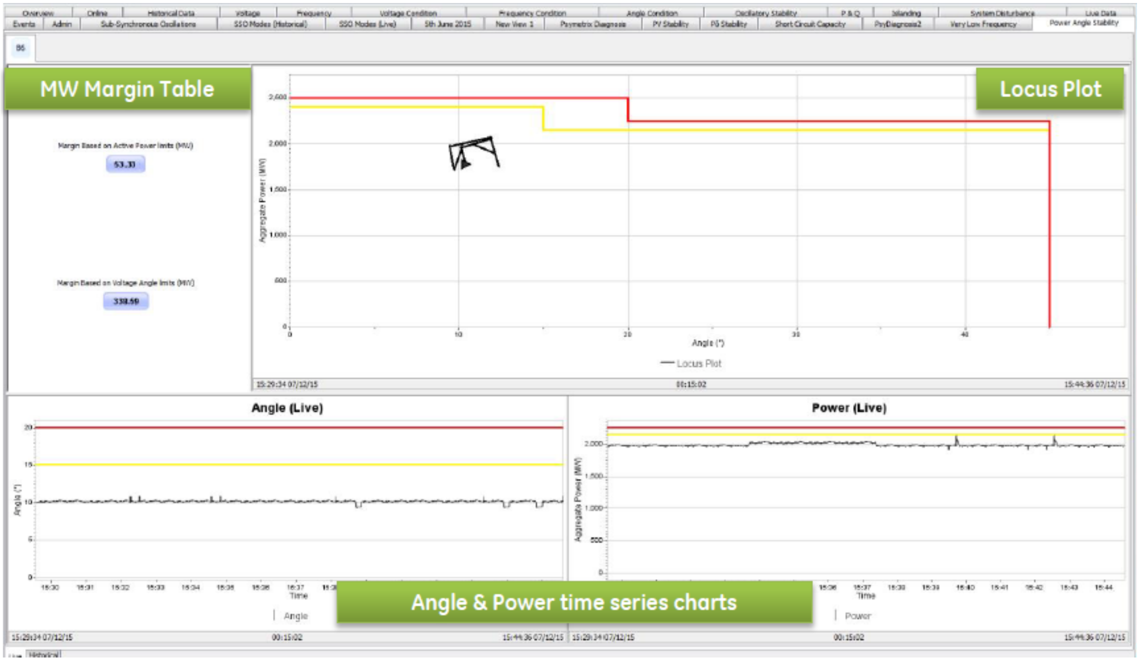


Figure 11. Boundary constraint application in PhasorPoint

3.2.4 Line Parameter Estimation

Line Parameter Estimation (LPE) is significantly improved through the use of time-synchronised phasor measurements at both ends of a transmission line, with additional onward benefits to several areas including State Estimation, fault level calculation, and voltage stability assessment.

The LPE application was successfully developed and demonstrated through VISOR and found that the key challenge to robust LPE lies in addressing measurement noise and systematic error so as to calculate consistent and reliable results.

The figures below show the significance of signal processing and successful application of the LPE algorithm to "good" quality PMU data. The data reports better performance with ~5% and 0.5% standard deviation in R and X respectively, which are comparable to the daily variations that are evident. It should be noted that factors such as line voltage, length and load variation will also have influenced the algorithm performance.

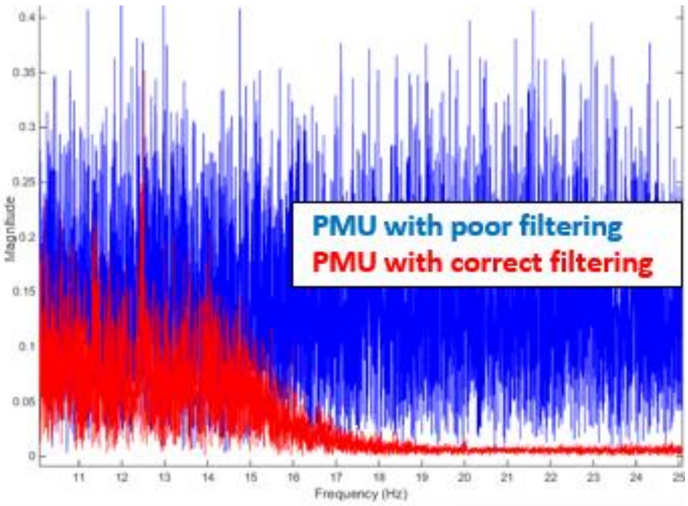


Figure 12. Example of PMU data with "poor" and "good" filtering

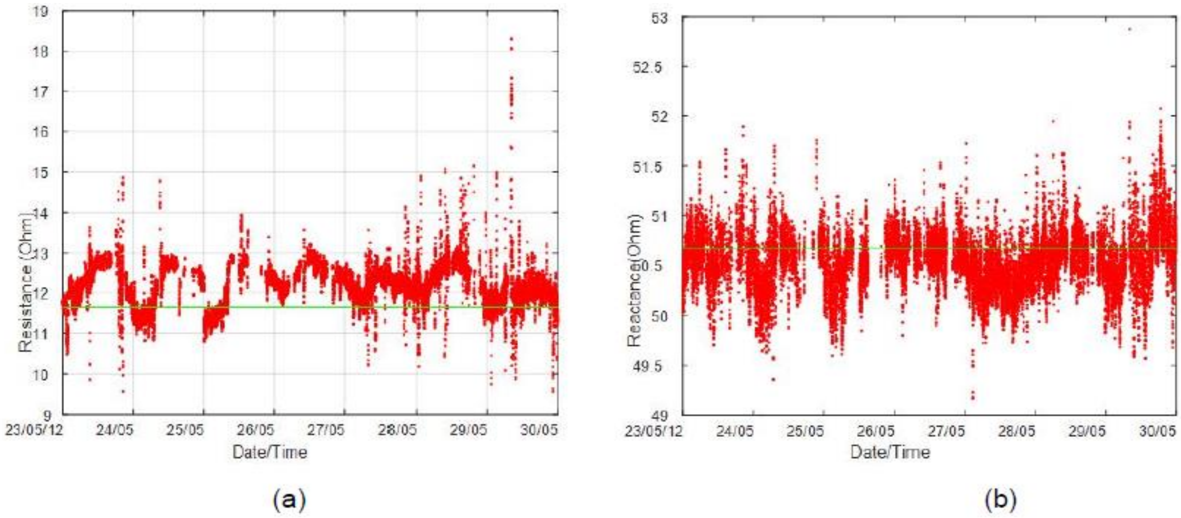


Figure 13. (a) Resistance and (b) reactance of a particular circuit estimated by robust LPE

3.2.5 WAMS-EMS Interfacing Demonstration and Testing environment

VISOR put a unified GB WAMS in front of system operators for the first time, with many entirely new application modules seeing their world-first demonstration under VISOR. These new applications and capabilities have been presented and demonstrated to potential end-users and key personnel to pro-actively introduce and integrate PhasorPoint as effectively as possible, however, the VISOR system is not an operational-grade system as it currently resides within the corporate network and does not interact with or replicate the true control room environment.

There could be benefit in not trying to integrate this into the SO EMS, but develop awareness and uptake in the planning area to get sign on and wider acceptance.

A new WAMS-EMS Interfacing Demonstration and Testing facility, shown below, has been commissioned within the SPT Operational Network to bring WAMS closer to the control room engineers 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
- **trialling WAMS applications,** the next generations and phases of WAMS-EMS integration and visualisation capabilities
- **facilitating WAMS training sessions and application workshops** to be held to educate, demonstrate and train operators from all TOs/SO to utilise and interrogate these new capabilities in order to visualise, and potentially quantity, the true benefits facilitated by WAMS. Engaging with key users and stakeholders may also identify the supplementary benefits and determine areas for future investigation or development.

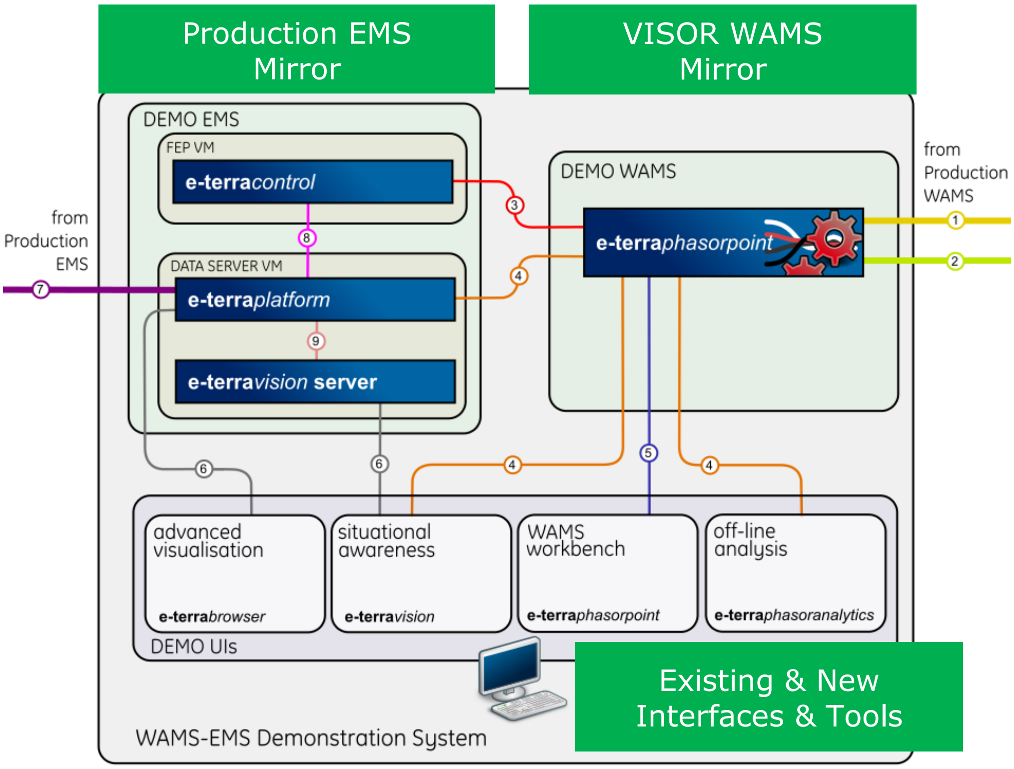


Figure 14. WAMS-EMS Interfacing Demonstration and Testing facility system architecture

The facility provides the opportunity to directly address the concerns of interfacing between new WAMS data and the SPT EMS, and to bring greater appreciation of the benefits of this interaction, including:

- **Improved situational awareness capabilities**
  e-terra*vision* will be able to show WAMS events and key data within the geospatial visualisation environment
- **Improved data integration**
  e-terra*browser* will allow WAMS data and oscillatory stability results and alarms to be viewed and integrated with other Grid Stability Assessment tools
- **New historical analytics tooling**
  The addition of e-terra*phasoranalytics* can be used in both the new environment and the current VISOR systems to provide easy off-line analysis tools and reporting capabilities

As mentioned above, one of the primary objectives of the testing demonstration facility is make the GB WAMS more accessible for all project partners by enabling demonstration and training workshops, 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 new WAMS-EMS integration and visualisation capabilities and applications. A set of training sessions has been designed for a variety of participants from relevant business functions.

The PhasorPoint platform was originally developed by Psymetrix with further application development funded through the VISOR project. Psymetrix has since been acquired and is now GE Grid Solutions, with PhasorPoint now integrated as part of the wider GE e-terra product suite.

3.3 Key Learning Outcomes from GB WAMS Deployment to date

This section provides an overview of the learning outcomes gained through the deployment of the GB WAMS through the VISOR project. The table below summarises the main learning points, and difficulties encountered (many of which stem from infrastructure and data security requirements) to inform the future rollout strategy in relation to the planning, deployment, and future expansion of the GB WAMS.

	Learning	Outcome
Infrastructure	**Learning 1: Data Security - User Datagram Protocol (UDP) packets** The data stream coming from a normal PMU uses Transmission Control Protocol (TCP) packets at 50fps, however, a WMU uses UDP packets at 200fps and 50fps. 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; UDP protocol has very little overhead but if a packet does not arrive the data is lost, whereas the TCP datagram provides greater reliability at a cost of increased overhead. The use of UDP subsequently introduces a security issue with the configuration of firewalls as the connectionless transport protocol 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, 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.	Security protocols dictate that data fed into the CNI must be received at the control centre via TCP. However, WMUs use UDP and do not currently support TCP. An alternative solution may be for UDP to form the first stage of the 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 Data Centres. The WMU is a single vendor at this time. Utilise PMU where possible and encourage developmentof the supply base. The solution needs to be non propriety for wider roll-out
Infrastructure	**Learning 2: Transition of communication connection between TO and SO into CNI** The communication infrastructure established through the VISOR project has a direct connection from the Corporate LAN in SPT to the Corporate LAN in SO. The Corporate LAN and Operational 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 Operational 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.	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 of 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 increases in scale. Utilities will need to pay for these additional secure services, unless they can adapt their own systems. The SO does not necessarily require the full bandwidth provision.
I	**Learning 3: Necessity of pre-production facility to**	Pre-production demonstration facility critical to

	demonstrate new technology 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 BaU functions. To do this within SPT, a new PhasorPoint WAMS server was established in the CNI LAN for the first time. This facility will be used to demonstrate WAMS-EMS integration to all TOs/SO.	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 cyber security and IT-solution architects required
Infrastructure	**Learning 4: Communication Services Supply Chain Issues** The order for a Multiprotocol Label Switching (MPLS) link was placed through the SO who placed the order with their supplier, Verizon, who in turn contracted BT Openreach to deliver the physical fibre optics. This chain of supply resulted in an inability to query or expedite the process directly with BT Openreach, which was not foreseen. Without any method for the project team to exact leverage over BT Openreach, plus the absence of any planning, or clear reporting from it, the project was in a constant 30-day cycle of awaiting updates from BT Openreach. Such supply chain caused issue must be considered in the production GB WAMS deployment.	Careful consideration of third-parties for infrastructure, in particular communications. Enacting IPSec Tunnel as an interim solution rather than a contingency plan (Note: If connected to the CNI, IPSec Tunnel over internet is not an option)
Application	**Learning 5: Detected Oscillations** VISOR has trialled new WMU devices, which extends SSO detection up to 46Hz. Multiple oscillations have successfully been detected by the GB WAMS, which would not have been detectable using the existing SCADA monitoring devices. The vast majority of the oscillations that have been detected are not severe in magnitude and do not pose a risk to system security in their current form, however, by tracking these oscillations we are able to baseline normal and abnormal system behaviour to detect changes in severity, oscillation frequency, and, incidence over time. Whilst most of the many 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 distinct interactions have been observed.	An active WAMS provides insight into normal and abnormal oscillations, which occur on a regular basis, and those that do not, which guides investigations to determine the cause and potential remedial actions. Over time, the archive of oscillation behaviour will highlight trends and potentially generation 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. Need to differentiate the sensitivity and capability between the resolution required for SCADA equivalent, PMU derived and WMU waveform capture
Application	**Learning 6: Data quality and data volumes:** A number of PMUs with poor data quality have been proven to cause significant stress on servers tasked with collating and archiving high volumes data files in order of magnitude greater than designed. However, a key learning from the pilot project was the discovery	Ensure sufficient contingency to account for uncertainties surrounding innovative aspects and/ integrating new technology data/PMU quality and availability dependent on reliable GPS signals, communication network and right server configuration can greatly affect the

	that even one individual monitoring device with poor data quality can result in the creation of multiple data files, rather than one, placing undue stress on PDC processing	quality and reliability of results from WAMS applications. Robust WAMS applications are required to ensure operational performance is not hindered by problematic monitoring devices. Need for self-supervision within the WAMS to limit the extent that invalid or rogue data can disrupt or unnecessarily occupy data storage. Need supervisory resource to manage and understand the data issues
Application	**Learning 7: Potential for WAMS to inform model validation** As analysis applications are used to inform network management operations, improvements to model accuracy will provide knock-on benefits to operators and the GB customer. To unlock the full benefits of applications such as Hybrid State Estimation and dynamic stability limits, validating model accuracy is crucial.	New practices are required to ensure the additional information provided by WAMS is used to improve model accuracy. This is the main business benefits WAMS delivers n that it enables the system planners understand the performance of the networks and more accurately model the system optimising investments
Application	**Learning 8: Regular reporting detailing the performance of both the Power System and WAMS health** 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. Regular Power System Reports cover: Monthly Power System Performance reports; Monthly Power System Disturbance reports; Monthly Data Quality summaries; Monthly Data Stream Connection summaries; PMU Connection Analysis reports	VISOR System reports created in 2015 and 2016 and additional monthly reports produced in 2016 provide a strong business case for WAMS applications. Creating these system reports is labour intensive and TOs should engage with suppliers to develop processes by which these reports are produced and circulated automatically.
Process	**Learning 9: Need for specialist resource** Recruiting and retaining the specialist resources necessary to implement and use WAMS in BAU is vital to ensure establish the technology in daily operations	Recruiting and retaining the specialist personnel are vital to implement and establish WAMS technology into daily operations A WAMS implementation group comprising of representatives and technology specialists from each key stakeholder is recommended to further support the successful technology roll-out.

Process	**Learning 10: WAMS to be considered as a Critical Function** Introducing new additional processes into a process which is already considered to be functioning perfectly will be met with resistance. To enact business change, a demonstrable case of the benefits and business need of the additional process(es) is a necessary. VISOR has made a strong effort to engage with key stakeholders from both TO and SO to input into the development of the WAMS, and in particular the applications. Yet, whilst many demonstrations have been given through knowledge dissemination events, operators will require hands-on training, live testing, and trial periods in order instil sufficient confidence to be called upon in live operation. Specific WAMS applications have already gained sufficient recognition within the business and have subsequently been used as a valuable addition to post-event and planning daily operations. However, the testing facility will be critical in delivering applications to the control room in the long-term.	As WAMS applications begin to transition into the real-time operations the WAMS function should be considered a critical function and a set requirements defined to establish a clear operating framework with appropriate cyber security measures. 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. • Wider resilient deployment of PMUs across the regions • Regional PDCs to manage data volume and bandwidth • Resilience in the Central PDC • In house maintenance resource • Secure web based access • Visualisation to see WAMS working and improve uptake
Process	**Learning 11: 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. However, such data-sharing arrangements are not currently in place.	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. Start with SO to formalise the basic level of service they require from the TOs
Process	**Learning 12: Investment and Payback** WAMS do not neatly fit into current regulatory mechanisms. Unlike traditional reinforcement measures, which are usually capital intensive in terms of costs, however once constructed the bulk of the investment is returned as asset value. WAMS are more OPEX intensive and only return a profit if they continue to provide a reliable service. This needs to be factored into the business planning scenarios when comparing different reinforcement options. Initial business case estimations for the live deployment of the GB WAMS, based on a combined total capital plus the operational investment of £22m would present a Net Present Value of £49m over 15 years with a payback period of 5 years.	WAMS is an enabler and as such is not the direct solution to the problem. It helps to understand it through better modelling and visibility. The decision support tools and wide area control are the more direct benefits Initial "rough" estimates show TOTEX investment of £5-6m per GB TO/SO (£22m (TOTEX) for whole GB system) in next 4 years should generate an NPV of £49m over next 15 years with a payback period of 5 years. This excludes the on-going maintenance costs.

3.4 Key Challenges for Rollout

The key challenges and issues that must next be addressed are summarised below, with solutions discussed in Section 5.

3.4.1 Challenge 1: IT System Architecture

Network infrastructure is a critical element in power system protection, control and management, much the same as it has become an essential service in our domestic and business lives. Data and cyber-security of paramount important to WAMS resilience.

The current architecture is orientated towards all substations feeding into the control centres, therefore substation to substation links remain via the hub. For most applications, especially in respect of monitoring functions, this is adequate, however, traffic prioritisation may result in slower updates where a minimum transmission time is required between substations.

Achieving accurate timestamping of measurements, will initially be more important than realtime receipt of the data. The data can be retrieved later when the network is less busy

3.4.2 Challenge 2: Inclusion in RIIO-T2 planning

The provision of WAMS schemes and infrastructure in RIIO-T2 will have to compete against other business priorities. If elements of the Requirement for Generators, HVDC code and Demand Connection Code directives can be translated into WAMS services, this could become standard requirements for new connections. The retrofitting is more of a challenge and will probably need to be justified on a regional level e.g. South East WAMS, Anglo Scottish, North Wales etc.

The TOs and SO need to agree on an enduring mechanism or driver for T2 to fund the provision of WAMS and the ongoing support necessary for this type of system.

3.4.3 Challenge 3: WAMS consideration in future design & planning

Applying a “WAMS-ready” approach and inclusion in engineering standards for wider substation new build or substation replacement works will provide network readiness once the technology is fully established as part of BaU. This is being considered in the STC System Performance monitoring working group between the TOs and SO. Something similar may be required for the SO/DSO interface

3.4.4 Challenge 4: Specialist resources

Retaining and recruiting WAMS specialists is vital to achieving the benefits of WAMS implementation in daily operations, including analytical skills to understand the information emerging from WAMS; Information systems (IS) skills to support the ‘end to end’ process. Specific skills: Power system Dynamic stability, IT critical infrastructure, data management, visualisation development. 'End to End' project management. Interface engineering between WAMS and EMS.

Initially this may need to be dedicated resource to integrate WAMS into the Business as Usual workstreams, as some of the specialist resources are not currently in place.

3.4.5 Challenge 5: Collaborative implementation strategy

A lack of collaboration and coordination between TOs and SO regarding deployment and future development of WAMS applications and infrastructure may lead to increased integration complexity or incompatibilities.

The establishment of the STC System Performance Monitoring working group between the TOs and SO should provide the forum to address these issues.

3.4.6 Challenge 6: Standardisation

Establishing a common approach or standardisation of monitoring devices governing performance and communication required for future investments to ensure measurement data can be collated and analysed as part of a unified system.

The STC Policy for System Performance Monitoring should help to deliver this, through defining minimum requirements and expectations.

3.4.7 Challenge 7: Data-sharing to maximise application effectiveness

TOs require cross-boundary measurements for accurate analysis which will require new data-sharing arrangements to be agreed.

The STC Policy for System Performance Monitoring should help to deliver this, through defining minimum requirements and expectations.

4 Business Case

This section explores the overall justification for the deployment of WAMS in GB and the various benefits available to three key business functions: post-event, planning, and the control room.

4.1 General

WAMS technology has been around for decades however its implementation across the globe has largely been reactive whereby severe power oscillations and lack of wide-area situational awareness has led to major disturbances, thus establishing a clear business case for preventative measures to be taken. To date, this phenomenon has mostly affected large countries more so than smaller ones, where transmission networks span thousands of miles and are managed by a consortium of network operators. Nowhere is this more apparent than in the United States (US), where wide-area measurement was reportedly first introduced following the blackout in 1965, which led to a body of research and the ultimate development of the first PMU prototype in 1988[16]. However, it was not until the major 2003 North East blackout, where 50 million people lost power for up to two days costing at least 11 lives and an estimated 6 billion US dollars, that led the US Department of Energy to establish NASPI in 2007 to advance the understanding and use of WAMS and later the American Recovery and Reinvestment Act in 2009, which has been the major driving force behind the coordinated uptake of WAMS in the US.

Similar cases of large-scale WAMS deployments following outages are becoming commonplace across the world, as large-scale blackouts in the north-eastern region of India lead to recommendations of unified WAMS between regions, and China, which has a very large implementation of WAMS incorporating oscillation management. For more details on examples of WAMS deployment, see Section 2.2 (p.17).

The management and growth of the GB system is well-regulated through 8-year price controls which focus on delivering maximum reliability and energy security at best value for money for the GB customer; large-scale regional blackouts are subsequently very rare. The RIIO license conditions also recognise the important role of innovation in developing solutions to meet challenges that either presently exist or are on the horizon. VISOR is a product the RIIO innovation stimulus, designed to demonstrate tools that bolster TO and SO abilities to manage the increasingly diverse network.

PMU devices (many of which are multi-functional devices with PMU functionality enabled) have been installed sporadically across GB in recent decades however VISOR established the first GB WAMS, which brought together the three mainland Transmission Owners and the System Operator, to provide a system-wide view to enhance and extend visibility and understanding of system dynamics and improve the monitoring capability to protect against new potential risks of oscillation and interactions, with the added potential to lead to improved and increased utilisation of network assets enabled by new WAMS applications.

For more information on WAMS applications demonstrated by VISOR, see Section 3.

[16] A. G. Phadke. Synchronized phasor measurements a historical overview. In *Proceedings of the IEEE Transmission and Distribution Conference and Exhibition*, volume 1, pages 476-479, 2002.

4.2 Business Case for Continued Operation of the GB WAMS

4.2.1 Why WAMS in GB?

The key business needs and drivers of GB TOs and SO stem from the major generation and load landscape shifts in the GB transmission system. The changes introduce a range of operational challenges to which WAMS can help manage, including:

- 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.
- 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.
- There is very little visibility of the transmission system response to wide area disturbances such as vector shift and ROCOF operation. Only WAMS can provide the bigger picture instantly.
- Increasingly network capacity is being dictated in non peak windows and is limited by voltage and transisent stability limits.

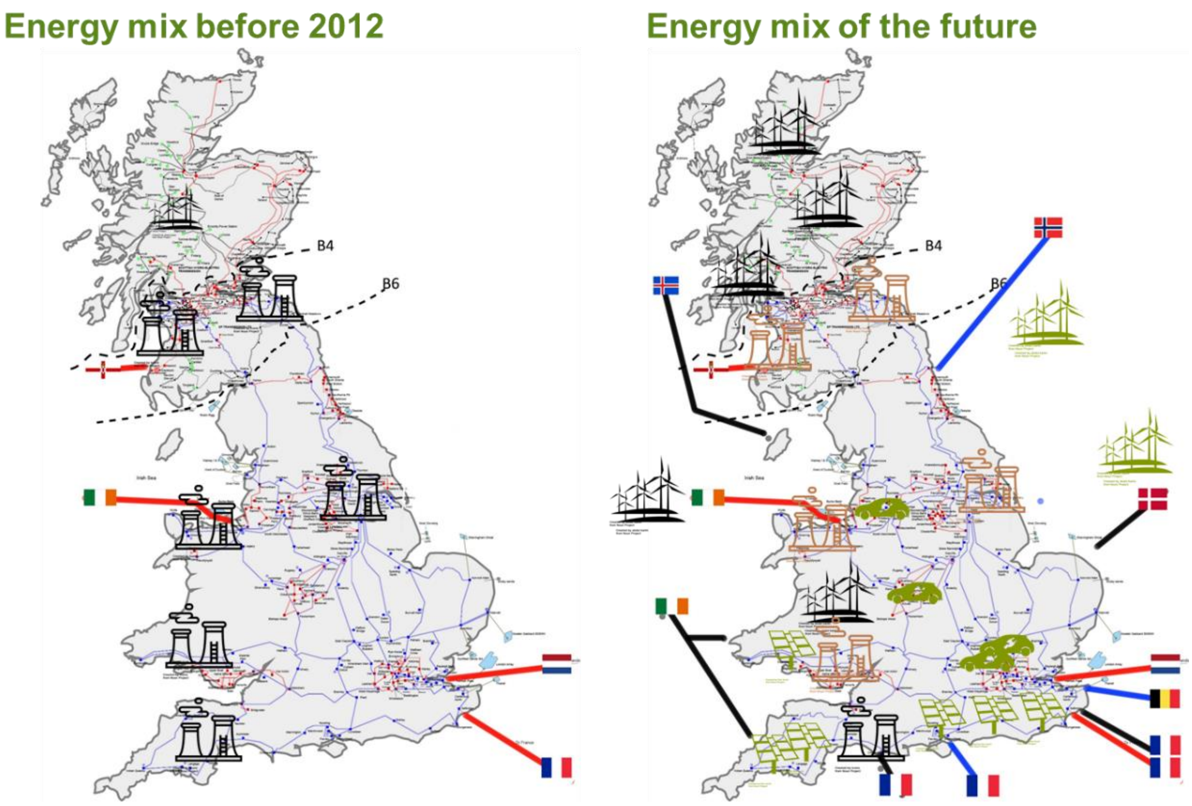


Figure 15. Significant changes in sources of electricity generation planned by 2030 (based on 2016 ETYS)

The overall capability of the GB WAMS, and therefore the overall benefit, will increase with time as applications, models, processes and coordination between TOs and the SO develop, however, even at this early stage of deployment, the existing GB WAMS infrastructure can deliver noteworthy benefit to TOs and SO.

Furthermore, as WAMS provide additional monitoring capability to assist the TO/SO introducing new technologies, in particular, the increasing levels of power electronic devices, there are synergies to be utilised in coming years between the GB WAMS and the MIGRATE project[17].

WAMS will help to deliver additional thermal capacity, however the real value is reducing the operating costs during lighter load and network contingency conditions.

4.2.2 GB WAMS in T1

The current installed interconnection capacity is 4GW and a further 7.3GW is expected to be connected to the GB system by 2022. The latest Network Options Assessment 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 other active control devices heightens the risk of interactions and oscillations, for which experience of the GB WAMS has proven benefit in detecting capturing such oscillation events, which may otherwise go unnoticed.

The new level insight offered by WAMS not only brings benefit to real-time functions but to many other applications that benefit post-event and system planning business functions, for example: to inform 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.

International experience has, however, shown that it can take several years before WAMS applications are suitably mature and robust for use by control room operators. 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.

In view of the current status of GB WAMS deployment, a relatively small investment is required to continue operating the system covering the interim period leading up to the next price control period. By retaining the existing system, monitoring and analysis functions can be maintained, allowing engineers to further build knowledge of system behaviour and embed applications into business, and better inform future decision-making regarding deployment and future development.

[17] MIGRATE (Massive Integration of power Electronic devices) is a EU Horizon 2020 project investigating various approaches to solving key technical issues relating to grid stability, supply quality, and control and security of supply that arise owing to the challenge posed by the ever-increasing use of renewable energy feed-in sources.

https://ec.europa.eu/inea/en/horizon-2020/projects/H2020-Energy/Grids/MIGRATE

The following points describe the strong business case for the rollout of WAMS applications successfully trialled in VISOR project with immediate effect, as well as other applications that are sufficiently mature and can be supported by the same infrastructure for operational use in SO and TOs control rooms and by other users.

- Mitigate operational constraints caused by oscillations: Certain oscillations could cause major issues for transmission network operations and reliability, such as equipment damage, reduced boundary transfer limits, and so on. Operators need to have the visibility across a broad range of frequencies to be able to manage and mitigate those oscillations that could cause problems to the equipment and network operation. Otherwise, the network will have to be operated at a more conservative level resulting in congestion and generation constraint if there is any suspicion that some type of dangerous oscillations is present.
    - If this was to be rolled out across the GB transmission system, the aggregated benefits would be much higher when all boundaries that might be impacted by oscillations will be able to maintain the full capacity after the VISOR rollout.
- Maintain system reliability: The areas described below will be part of the VISOR rollout, which can help to reduce the risk of a GB-wide blackout.
    - Enhanced situational awareness of the GB-wide transmission system and visibility of power system dynamics: WAMS provide high resolution trending charts and monitoring of voltage magnitude, system frequency and the rate of change of frequency, and active and reactive power, plus phase angle difference based stability margin monitoring.
    - Early indication of emerging problems before they become faults and major network disturbances: Control engineers can no longer heavily rely on historical performance as a marker for network behaviour, the rate of change of generation technology and consumer behaviour is unprecedented.
    - Model validation: WAMS will allow the TOs to manage marginal boundary constraints through more accurate models and better understanding of factors which could lead to wide scale disruption. The TO must authorise the SO to increase boundary ratings as it may affect the integrity of their assets. Therefore, the use of WAMS and PMUs will be central to providing the confidence through asset monitoring and improved model validation to permit enhanced ratings.
    - Support the deployment of control applications: Enable SO and TOs to benefit from other WAMS applications, the same PMU/WMU measurements and the infrastructure can be used to condition control schemes , such as phase angle assisted breaker closing; dynamic line rating; hybrid state estimator; post-event analysis, model validation; and so on. These applications will provide additional benefits at minimal incremental costs.

A recent GB Royal Academy of Engineering report includes an assessment of the "Value of Lost Load" or VoLL (Table 3, below) and concludes by stating that the cost of a blackout in the GB would be in the billions of pounds[18].

[18] Royal Academy of Engineering. "Counting the cost: the economic and social costs of electricity shortfalls in the GB." Council for Science and Technology, November 2014.

- Leverage investment already made and experience gained through the VISOR project: Immediate VISOR rollout can benefit from the PMUs/WMUs that have been installed and the experience gained in setting up the communication infrastructure.

Table 3. Average VoLL for the GB, for interruptions of one-hour and 12-hour duration (£/MWh) ***(Source: Royal Academy of Engineering)***

	Winter			Summer		
	Peak	Off-peak	Weekend	Peak	Off-peak	Weekend
1 hour	£6,495.69	£6,525.70	£5,634.43	£6,268.91	£5,727.02	£5,178.49
12 hours	£4,381.59	£4,960.35	£4,079.17	£3,920.55	£4,433.08	£3,749.33

4.2.3 Benefit Areas of the GB WAMS

WAMS analysis applications provide the basis for new and improved insight and alarming capabilities to individual network owners and operators. Time-synchronised measurements offer benefits to both real-time operations in the control room and activities undertaken away from the control room, i.e. applications used for offline post-event analysis (including model validation) and system planning, whereas control room applications involve real-time actions directly affecting the network. The relationship between cost and benefits area is illustrated in the figure below.

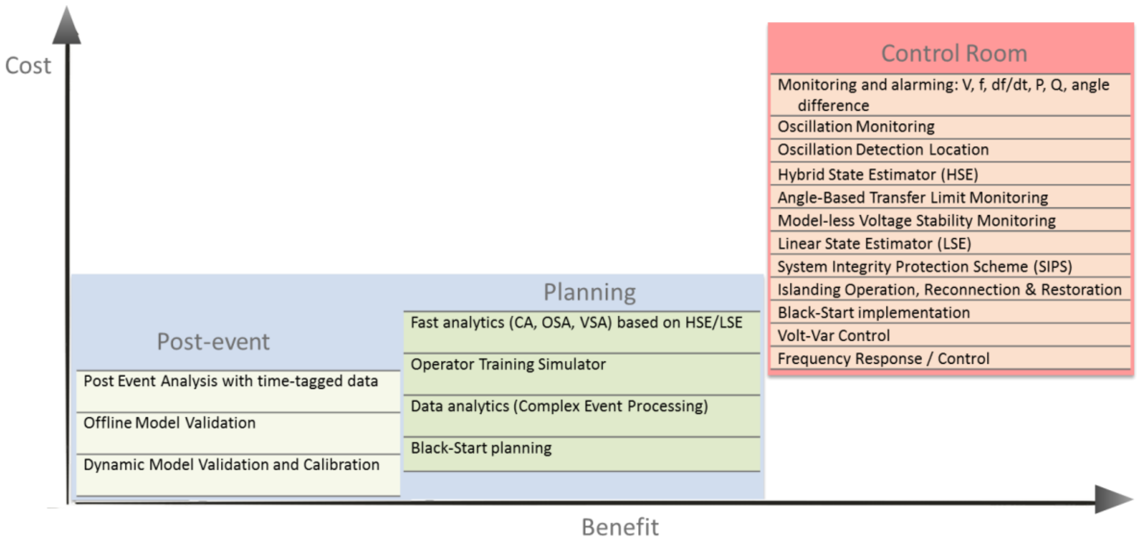


Figure 16. Illustrative Cost Vs Benefit of the three benefit areas of the GB WAMS – significant savings are realised through real-time actions but these require the greatest cost (and time) to achieve

Some applications have an element of both offline analysis and real-time control room use (such as model validation, phasor-based analytics, and black-start / system recovery) but it must be noted that there are strict data security, reliability and redundancy requirements imposed on control room processes but also vitally important is the need for sufficient certainty that the overall process will improve on existing practices to warrant the increased investment. Control room implementation, therefore, necessitates robust and accurate WAMS applications which may take several years of deployment and development before they can be used in real-time or automated processes.

Where appropriate and feasible, certain WAMS applications such as boundary constraint analysis may also benefit from increased measurement data-sharing above what is presently practised, between TO-SO and potentially TO-TO. Additional data-sharing and new applications, as part of an overall collaborative TO-SO GB WAMS, will ultimately deliver maximum benefit to the GB customer by exploiting technical and commercial synergies of the rollout, maximising the real-time operations of managing and balancing the system, and efficiently investing in future network reinforcement planning.

4.2.4 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. 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:

- Faster analytics - Post Event Analysis process improvement (easy data alignment & improved reporting capability)
- Transient stability studies (based on improved model configuration)
- Review of control and damping optimisation
- Generator performance and compliance
- Dynamic model validation and calibration
- Operator Training Simulator

Typically, Digital Fault Recorders (DFR) 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, as the DFR data is not time-synchronised, this process must allow for slight variances between the internal clocks of the DFRs and is further complicated by widespread or cascading events.

As part of a WAMS, high-resolution time-synchronised measurements are collected and stored within the PDC from which data from multiple nodes can be easily extracted, analysed, plotted, compared and exported with ease. At a fundamental level, depending on the practices already in place this simplified data extraction offered by WAMS may be beneficial to post-event actions by improving efficiency and simplicity in assembling time-aligned data following an event. This will prove beneficial in quickly developing incident reports following a disturbance event.

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 grid support/compensation devices to validate anticipated response and enhance models. In the same way, the SO could utilise WAMS to verify the performance of grid support response services provided by third parties or that generator frequency/voltage support response remains compliant with contracted levels.

In summary, the benefits that can be realised using the existing GB WAMS infrastructure, without substantial effort or investment, include:

- Faster post-mortem analysis: Detailed and time-synchronised coherent recorded data 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 trends will identify oscillation modes of each generation plant and identify hazardous operating conditions. Prior knowledge of such modes is likely to 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 budget for balancing services to be reduced

4.2.5 System Planning Benefits

In addition to the features already mentioned in the previous section, the use of time-synchronised measurements through WAMS delivers similar benefits to system planning through improved analysis accuracy and capabilities. WAMS facilitates or supports the following applications provide benefit to system planning activities:

- 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

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.

Black Start planning – enhanced understanding and management of system dynamics and improved modelling to better abilities in planning and modelling black start. Starting position for potential future application to assist with control room implementation of islanding and recovery actions.

Process and/or financial benefits:

- Faster system planning analysis: detailed and time-synchronised coherent recorded data allows faster analysis and more accurate analysis.
- Improved model accuracy including line parameter estimation: indirect benefits through knock-on use of more accurate models.
- New and enhanced data analytic tools: use of WAMS data to support offline analysis and planning and with greater confidence lead to potential control room applications (described in Section **Error! Reference source not found.**).
- Potential to reduce uncertainty on scheme costs by 5-10% through more optimised design

4.2.6 Control Room (Real-Time System Operation) Benefits

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 discussed later in Future Opportunities section (p. **Error! Bookmark not defined.**).

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)

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. Details on the capabilities and oscillation monitoring applications can be found in Section 3.2 (p.26)

An angle-based transfer limit monitoring application was specifically developed and demonstrated by VISOR to demonstrate a new approach providing a measure of stability and transfer limit monitoring, based on angle difference across the B6 boundary, designed complement 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.

Angle-based transfer limits is an example of measurement-only WAMS analysis application. Voltage-stability monitoring is another such application that has been discussed to provide notable benefit to the control room. This application has not been demonstrated and is expected to require offline development and trial before benefits can be realised in the control room.

HSE is a 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 HSE solution due to WAMS data and faster execution are in the order of 2-3%. There is no analysis available for how this will translate to reduced system balancing costs but even a 1% improvement could result in savings of millions of pounds per annum.

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.

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 the £126.83m constraint in FY16/17 (see Table 4), 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 4.Breakdown of Constraint Cost by fuel type in previous financial year (Apr16-Mar17) [19]

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

4.3 GB WAMS Cost Benefit Analysis

Following completion of the VISOR project, there remains no doubt that WAMS applications offer new network management capabilities and situational awareness of otherwise undetectable oscillation and angular behaviour that, in the long term, are certain to bring both operational and financial benefits to the owners and operators alike, especially once WAMS applications are implemented within real-time system operations. Determining the financial benefits is a highly complex process, dependent on a array of factors such as coverage, application deployment, coordinated operaton At this stage, however, with applications trialled within a demonstration project, it is not possible to conduct an accurate cost benefit analysis, in order to derive likely finance returns.

[19] National Grid Service Report "MBSS_March_2017", http://www2.nationalgrid.com/UK/Industry-information/Electricity-transmission-operational-data/Report-explorer/Services-Reports/

Based on the experience of VISOR and feedback from potential users of the WAMS, there is a strong business case to retain the existing monitoring capability and analytical processes that will form a foundation from which all further integration and development efforts can be made.

5 GB WAMS to Business

This section of the report outlines a set of WAMS application objectives and their estimated benefits across the near-, mid-, and long-term, and the necessary infrastructure and process requirements to facilitate them.

This roadmap sets particular focus on the objectives and requirements through the remainder of RIIO-T1 for the continued operation of the GB WAMS in order to preserve existing applications and to carry learning forward to inform the decision-making for future investment and development in the next price control period, RIIO-T2.

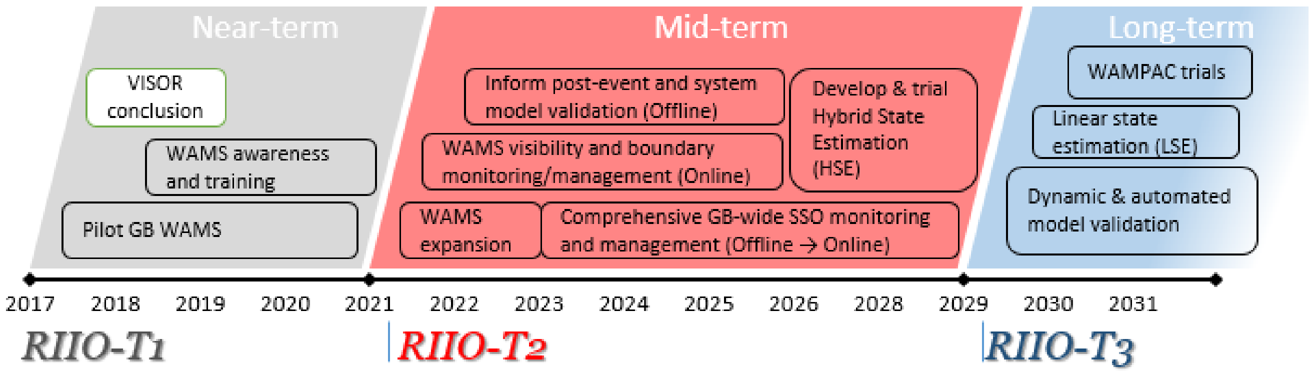


Figure 17. Timing of investment windows and proposed WAMS implementation

The deployment of identified WAMS applications for overall GB business case can be divided into the following groups of investment type:

1. Immediate rollout applications: These have been proven through implementation elsewhere and/or trialled in the GB with evidence of viable benefit that easily augments existing practices without posing risk to system security and management functions. Investment and infrastructure requirements are well established.
2. Applications which require further trials: These applications have been developed to a prototype stage but not demonstrated in the operational environment and therefore lack supporting evidence to quantify benefits. Investment and infrastructure requirements remain largely hypothetical.
3. Applications that require development and/or technological advances: These are applications that currently do not belong to the above two groups. These applications maybe mature and beneficial but may require substantial investment and/or may not qualify as innovative. These applications could be rolled out as part of the VISOR rollout deployment or bundled together with trialled new applications in the second group, or to deploy through RIIO-T2 and RIIO-T3 funding.
4. Network services: As the role of the SO becomes more independent across the transmission and distribution networks the provision of services utilising WAMS features which can benefit the consumer by helping to reduce the overall costs of securing the network will become essential as the system becomes more complex and commercial services increasingly commonplace.

5.1 Electricity Network Innovation Strategy

From 2017, Network Licensees are now obligated to develop and maintain an Electricity Network Innovation Strategy (ENIS) in cooperation with other Network Licensees that will be reviewed every two years and updated where deemed necessary.

The aim of the ENIS is to outline all foreseeable challenges that face the electricity network which could be addressed by innovation projects and identifying challenges are being addressed by innovation projects and those which are not, in order to ensure challenges are met with minimum duplication of effort and learning is shared effectively. To accomplish this, each Network License must describe all planned innovation projects to address each particular challenge, and if no projects are planned to address a particular challenge a reason must be provided. The first ENIS report is due to be published by 31 March 2018.

5.2 Investment Mechanisms for GB WAMS

Under the current RIIO framework, the deployment and development of the GB WAMS infrastructure and applications could be funded through either the Business Plan or through one of the three mechanisms of the RIIO innovation stimulus - the Network Innovation Allowance (NIA), the Network Innovation Competition (NIC), or the Innovation Rollout Mechanism (IRM). Further information on these mechanisms is provided in Appendix A.

In determining the investment mechanism and timing to continue and expand the GB WAMS, the WAMS system can be categorised into three different components and considered separately from a funding perspective, as shown in the table below.

Table 5. Investment type and most suitable funding mechanism(s)

Investment Type	Investment mechanism(s)
Infrastructure: • the measurement devices (PMU/WMUs), which must be installed at points of interest • the communication infrastructure, capable of delivering measurement data within appropriate timescales and reliability • the processing hardware, i.e. the physical data server/hardware (PDCs) •	**The most suitable investment mechanism for physical infrastructure is through the BP however alternative innovative funding through IRM.**
Applications: • the processing infrastructure software, i.e. the server platform running WAMS applications, and the analysis applications	**Mature or well-established applications would require funding through BP (or potentially IRM) but concept or novel applications may be trialled or developed through NIA or NIC, if available.**
Processes: • policies and procedures to utilise information • ownership and responsibility for managing infrastructure and applications	**Establishing operating principles best suited to BP, however, any additional policies and/or procedures for applications deployed through NIA or NIC should be adjoined to the project.**

5.3 Objectives (RIIO-T1, 2018 – 2021)

Applications ultimately drive the continued operation and expansion of the GB WAMS as these deliver benefits to network operators, whereby maximum benefits can be obtained through real-time operations within the control room. However, as experience global deployments have shown, integrating WAMS into control room functions can take several years' worth of infrastructure and process development effort to satisfy the requirements of the control room.

Therefore, in developing a long-term strategy for integrating WAMS into the control room to achieve maximum benefits, objectives must be set to develop the required infrastructure and post-event and system planning implementation, before WAMS applications can be fully utilised in the control room environment. The largest investment relates infrastructure which can be recovered through the Business Plan, or potentially through the IRM mechanism, although additional innovation mechanisms may be utilised for further application research and development.

At the time of writing, there are no specific requirements in place for the provision of WAMS measurements from TO to the SO, however, it is envisaged, and encouraged, that such requirements may be introduced through changes to licence condition requirements. Initial discussions through VISOR have postulated that requirements may look to expand WAMS coverage to one WAMS monitoring device per Grid Supply Point.

In the interim period following the conclusion of VISOR up to RIIO-T2, the foremost objective should be to retain the existing GB WAMS infrastructure in order to preserve oscillation monitoring and analysis capabilities that will continue to safeguard system security and generate valuable learning in operating delivering a resilient system to support, and inform, future rollout strategy.

The recommended overall objectives for the GB WAMS over the period 2018-2021 are to:

- **Secure funding for the continued operation of the GB WAMS, in particular:**
  - **Renew contract of MPLS between SPT and NGET**
  - **Extend PhasorPoint software licenses (server & analysis applications)**
  - **Establish WAMS steering committee and management group**
  - **Identify resource and processes for maintaining network infrastructure**
- **Establish WAMS infrastructure in operational (RTS/CNI) 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 the GB WAMS infrastructure and applications in line STC monitoring policy developments and, where appropriate, synergised with the Electricity Network Innovation Strategy.**

To date, the GB WAMS has been, for the most part, a demonstration deployment largely funded through the VISOR project, which created new WAMS data centres in SPT, SHET, NGET and SO, and dedicated resources to uncover new learning for dissemination. Both SPT and NGET had PDC servers running prior to the VISOR project, collecting data from the small fleet of PMUs scattered across the network that were installed sporadically over the previous decades, however, there was no coordination or data exchange between the two systems. The VISOR project installed new PDC servers at each company including a data centre at SO (known as the Data Hub), which consolidated the synchronised measurements taken by PMUs and WMUs across the three network regions, presenting a system-wide view of synchronised measurements for the first time and offered numerous new analysis capabilities.

The VISOR project laid foundations from which other WAMS projects now depend on, for example, SPT's Series Compensation project uses the Phasorpoint platform, applications, and WMUs to monitor and mitigate oscillations; and NGET's Enhanced Frequency Control Capability project which utilises PhasorPoint applications. All data processing and archiving functions have been achieved using licensed WAMS software solution, PhasorPoint.

With the conclusion of the VISOR project in 2017, several areas which rely on VISOR for funding will cease unless enduring funding is provided:

Infrastructure:

- MPLS Communication link between SPT and NGET, currently managed by Vodafone [redacted]

Applications:

- PhasorPoint server & analysis applications licences at SPT, SHET, NGET, SO
- PhasorPoint application support [redacted]

Process:

- Dedicated WAMS resource within TOs and SO to oversee the management and development during the interim period
    - establish GB WAMS group to succeed VISOR project delivery team and continue to coordinate with other in-flight WAMS projects
- Resource for PMU/WMU hardware maintenance
- Resource for network hardware and communications maintenance
- WAMS-based System Performance reports, provided by GE Grid Solutions
- WAMS System Health reports, provided by GE Grid Solutions

  (Total cost: Resources requirement only, assuming reports are undertaken in-house)

5.3.1 RIIO-T1 Application Benefits & Technical Requirements

The applications proposed as part of near-term objectives are listed below, with associated benefits and requirements shown in Table 6 and Table 7, respectively:

1. Post Event Analysis tools with accurately time-tagged data **
2. Oscillation Monitoring, Detection & Location tool (continue offline deployment) **
3. Offline Planning Model Validation tool
4. Wide Area Visibility and Situational Awareness in the control room *
5. Monitoring of V, f, df/dt, P, Q, and angle difference at boundaries *
6. Enhanced System Oscillation Monitoring, Detection & Location (control room) *
7. Asset commissioning and compliance monitoring

Deployed in VISOR

****Deployed and used by the business in VISOR***

Table 6. Near-term application benefits, applicable TO and SO

APPLICATION	BENEFIT	POST-EVENT	PLANNING	CONTROL ROOM
1. Post Event Analysis tools with accurately time-tagged data	• Enhancing existing practices by easier and quicker data extraction and time-alignment of multiple sources following an event, which may improve system restoration times and reduce engineer time. • Synchronised measurements facilitate quicker and better accuracy of other applications such as line parameter estimation, to the benefit of system planning. • Future development could include automated actions and analysis following alarms or on a routine basis.	✔	✔	
2. Oscillation Monitoring, Detection & Location tool (non-control room initially)	• Improving the monitoring capability of the network by detecting oscillations that would otherwise go undetected and that perhaps may eventually lead to outage or plant damage. Post-Event activities could investigate to determine the cause and potential mitigation actions. This benefit has been realised during VISOR. • Incorporating oscillation visibility will provide additional unique insight into system behaviour following an event, and the ability to validate system studies and to confirm compliance of grid support services and controlled response. • Ability to baseline observed behaviour and trends to determine severity, where SSO re-occur	✔	✔	
3. Offline Planning Model Validation tool	• Synchronised measurements can greatly improve model validation via improved line parameter calculations and dynamic system response, improving accuracy and confidence in model-based applications and analysis. • Near-term, this benefits system planners to analyse network capacity more accurately. • More accurate network models will unlock additional benefits with regards to state estimation and system limits determination. • Future development would look to introduce dynamic model validation capability.		✔	
4. Wide Area Visibility and Situational Awareness in the control room	• Integrating WAMS into the control room offers improved visibility & situation awareness of real-time system dynamics. • Validate true dynamic system behaviour with expectations. Allows for baselining normal/abnormal operating conditions.			✔
5. Monitoring of V, f, df/dt, P, Q, and angle difference at boundaries	• Ability to better understand dynamic behaviour across power transfer boundaries, including the ability to determine frequency and transient response. • Better overall understanding enhances system stability management.	✔	✔	✔

APPLICATION	BENEFIT	POST-EVENT	PLANNING	CONTROL ROOM
6. Enhanced System Oscillation Monitoring, Detection & Location (Online)	• Provides the enhanced oscillation awareness capability to detect and locate SSO in real-time which may otherwise go undetected and, if necessary, perform mitigation actions. • In the event of an outage, operators can verify whether an oscillation/interaction may have been the cause, improving situational awareness and recovery times. • Continuous monitoring for SSO allows baselining normal and abnormal operating conditions over time to build understanding so that future oscillations are effectively mitigated or prevented.	✔	✔	✔
7. Asset commissioning and compliance monitoring	• Utilise WAMS data for commissioning and compliance testing • May enable 'remote' commissioning/compliance testing • Processes can be developed for real-time or automated operation	✔	✔	✔

Table 7. Near-term infrastructure and process requirements

	REQUIREMENTS	Status (R/A/G)
INFRASTRUCTURE	Production-Grade PMUs/WMUs Installation Completed	A
	Historical Database system installation completed	G
	TO Internal WAN Setup	R
	TO-SO WAN Setup	A
	Control Room Production Grade system upgrade: QA/Staging and Training/Test environment	A
	Data Quality Issues Resolved (latency, dropped data frames, stalled data, etc.)	A
	Equipment Interoperability from Various Vendors Resolved	A
	Automatic time-tagged disturbance data access available	G
	Data retention and access procedures in place (historical data base, size and data retrieval)	G
PROCESS	Training Plan and Training Materials for VISOR applications developed	G
	Training on VISOR Applications delivered to relevant users	A
	Post-event analysis manuals and procedures developed and in use by relevant users	R
	Data baselining and alarm limits procedures developed	A
	PMU & WMU Placement studies for all applications completed	A

5.3.2 RIIO-T1: Challenges and Changes Required to Infrastructure, Applications, and Process

Any future implementation or expansion of the GB WAMS will benefit from a degree of coordination between all parties to establish coherent long-lasting solutions and ensure an operational solution is in place by the end of RIIO-T1. The following pages list the changes required and challenges to address in delivering the near-term objectives.

Table 8. Division of responsibility matrix

Action	SPT	SHET	NGET	SO
Define company rollout strategy for inclusion in RIIO-T2 planning Articulate strategy in Electricity Network Innovation Strategy	✔	✔	✔	✔
SO to define requirements upon TOs (measurement requirements and placement)				✔
Devise PMU/WMU placement strategy	✔	✔	✔	
Identify WAMS 'task force'	✔	✔	✔	✔
Facilitate WAMS-EMS training at OCC facility	✔			
Coordinate and update communication architecture (internal and external links) with sufficient QoS in preparation for RIIO-T2.	✔	✔	✔	✔
Develop functional specifications for WAMS – monitoring devices, processing servers and communication	✔	✔	✔	✔
Engagement with market suppliers regarding future WAMS solutions	✔	✔	✔	✔
Update or upgrade existing monitoring infrastructure (PMU/WMUs) in preparation for RIIO-T2 where required	✔	✔	✔	

5.3.3 Enabling Infrastructure: Challenges and Changes

Challenge 1: IT System Architecture

Network infrastructure is a critical element in power system protection, control and management, much the same as it has become an essential service in our domestic and business lives. Data and cyber-security of paramount importance to WAMS resilience.

The current architecture is orientated towards all substations feeding into the control centres, therefore substation to substation links remain via the hub. For most applications, especially in respect of monitoring functions, this is adequate, however, traffic prioritisation may result in slower updates where a minimum transmission time is required between substations.

Possible Solution: Potential use of regional/local PDCs

A full appreciation of the significance of a robust, reliable and future-proof communications architecture is vital to facilitate the increased WAMS data transfer and analysis requirements whilst retaining or improving cyber security. The solution must be secure to penetration testing, key risk to availability is the provision of an end to end asset management service and high availability assigned to the services.

Need to upgrade the business systems used for current monitoring services to a more secure and resilient service, rather than move WAMs into the operational telecoms networks and compromise the protection and control functions. Data storage is an active issue as the volumes of WAMS data grows and how this data is accessed and archived. One possible solution is to consider the use of substation or regional PDCs reducing the burden on centralised PDCs.

Challenge 2: Inclusion in RIIO-T2 planning

The provision of WAMS schemes and infrastructure in RIIO-T2 will have to compete against other business priorities. If elements of the Requirement for Generators, HVDC code and Demand Connection Code directives can be translated into WAMS services, this could become standard requirements for new connections. The retrofitting is more of a challenge and will probably need to be justified on a regional level e.g. South East WAMS, Anglo Scottish, North Wales etc.

Possible Solution: Rollout strategy & provision of WAMS services to the SO

It is important that each TO and the SO establish some baseline policies against which any WAMS will be mandated, and included in future business plans. Part of this needs to be the provision of operational costs to support an ongoing service with reasonable expectations for resilience and availability. This should justify the asset management budget for ongoing maintenance, replacement and procurement of third-party services such as communications and data management.

Coordinated and/or collaborative development of new applications, such as Linear State Estimation, should be undertaken to preserve national system security and integrity, which may be best served with provision of sufficient monitoring and communication infrastructure as part business plan of each Network Licensee, along with the development of the LSE applications via dedicated innovation projects NIA/NIC.

Challenge 3: WAMS consideration in future design & planning

Applying a "WAMS-ready" approach and inclusion in engineering standards for wider substation new build or substation replacement works will provide network readiness once the technology is fully established as part of BaU.

Possible Solution: Better visibility of load at Grid Supply Points

Acknowledgement that WAMS is anticipated to play a key role in validating and then understanding the changing nature of the transmission and, in time, the distribution networks, will change the mindset within the industry to prepare to adopt the technology by consideration in future planning.

In the Planning phase, the improved visibility and measurements will allow the quality of modelling to be improved, arguably enabling more capacity to be extracted from the existing network, potentially deferring major capital reinforcement. WAMS coupled with weather profiling could support the wider rollout of dynamic ratings, this, however, needs a greater element of probabilistic planning to be adopted.

5.3.4 Enabling Process: Challenges and Changes

Challenge 4: Specialist resources

Retaining and recruiting WAMS specialists is vital to achieving the benefits of WAMS implementation in daily operations, including

- Analytical skills to understand the information emerging from WAMS
- Information systems (IS) skills to support the 'end to end' process
- Specific skills: Power system Dynamic stability, IT critical infrastructure, data management, visualisation development. 'End to End' project management. Interface engineering between WAMS and EMS

Possible Solution: Provisions and commitment of resource to support WAMS rollout

This will require close working with the academic community to develop the skills which both utilities and solution providers require to design and manage these types of applications. Utilities need to make WAMS data more accessible for analysis to be carried out and tools developed.

Challenge 5: Collaborative implementation strategy

A lack of collaboration and coordination between TOs and SO regarding deployment and future development of WAMS applications and infrastructure may lead to increased integration complexity or incompatibilities.

Possible Solution: Coordinated strategy for WAMS rollout

Basic principles around WAMS needs to be established, so all affected utilities play their role in the provision of a basic level of synchronised measurements. Ideally, there should be a GB working group (possibly as part of the Grid Code review panel) to coordinate these activities.

This can be further supplemented with joint innovation strategies and deployment through NIA and NIC type activities.

Challenge 6: Standardisation

Establishing a common approach or standardisation of monitoring devices governing performance and communication required for future investments to ensure measurement data can be collated and analysed as part of a unified system

Possible Solution: Policy across the GB, Provision of a service to the SO

The provision of WAMS data and delivery to a defined PDC should be part of any load related scheme. The WAMS data format is standard so any PMU-ready device should be capable of streaming the data. At this time the implication of CT and VT accuracy and location is not sufficiently established to force any recommendation. Many devices currently derive their data from assets required for protection purposes. Monitoring devices for use in WAMS in GB should adhere to the Standard, and service provided to the SO as defined.

5.3.5 Enabling Applications: Challenges and Changes

Challenge 7: Data-sharing to maximise application effectiveness

TOs require cross-boundary measurements for accurate analysis which will require new data-sharing arrangements to be agreed.

Possible Solution: Establish TO/SO data-sharing arrangements

This will be determined by the responsibilities allocated to SO and TO entities. Visibility of adjacent TOs is a dilemma especially if competition is encouraged. Arguably it should enable both TOs (across a boundary) to identify operational measures which can be implemented to get improvements in boundary capacity or better resolution around stability risks, which need to be managed via new control methods.

The SO should consider how a set of cardinal points and system metrics are provisioned such that each TO has GB network visibility. Presently this is referenced through frequency, however, angle associated with key load groups could be helpful. Boundary flow and indication around available capacity could be helpful, particularly where dynamic ratings may come into play.

5.3.6 RIIO-T1 Implementation Timeline

An important challenge in the near-term is the need to establish the future strategy WAMS deployment, particularly the level of coordination between TOs and SO in terms of defining monitoring coverage requirements and technical specifications. Each TO should also endeavour to develop a set of implementation objectives for RIIO-T1,-T2, and beyond, and provide an outline in The Electricity Network Innovation Strategy, and thereby outline the overall direction of GB WAMS.

To meet the target objectives in the near-term and address the changes and challenges listed in Section 5.3, the following implementation timeline is proposed:

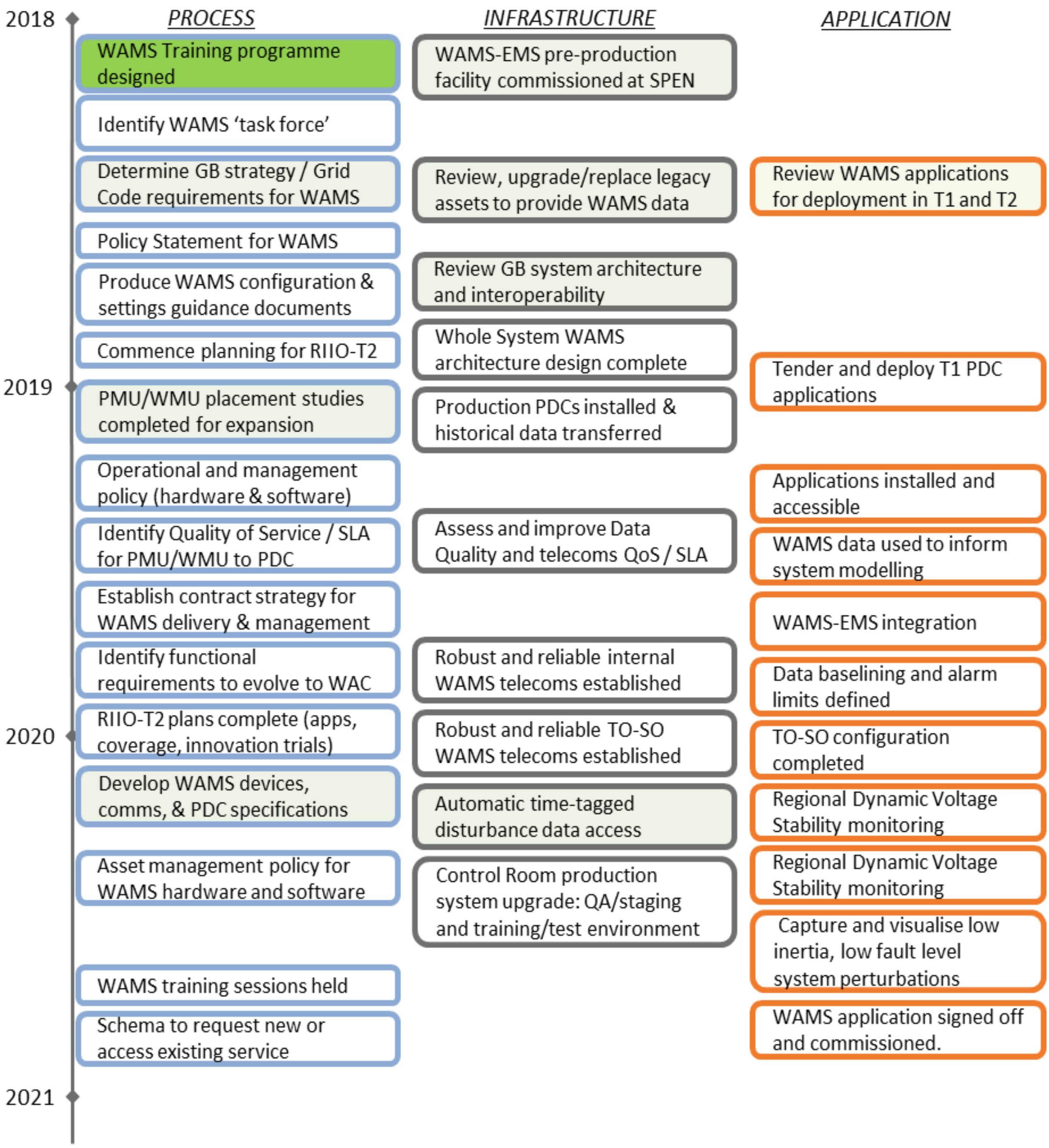


Figure 18. Proposed Near-term timeline

5.4 RIIO-T2 period, 2021-2029

The mid-term objectives focus on the next price control period, RIIO-T2, whereby the TOs should seek to:

- Deliver WAMS infrastructure deployment projects as per the RIIO-T2 Business Plan
- Deliver WAMS services to the SO as per policy or regulatory requirements.
- Update policy on monitoring requirements for PMUs to be installed at all generation sites, including interconnectors, and GSP substations
- Continue to implement WAMS applications from RIIO-T1
- Trial and development of new WAMS tools and analysis applications with support from academia and third-parties; examples of likely high-value applications are listed below.
- Seek to progress deployment of control room applications

The overall objectives for the RIIO-T2 should centre on refining existing WAMS applications into daily business functions, deploying and trialling new applications and transitioning applications into the control room across TOs and SO. With the WAMS systems fully deployed and operation, studies should examine the benefits of:

a) upgrading the accuracy of substation measurement transducers
b) increasing the WAMS monitoring to full coverage
c) introduction WAMS visibility at strategic points within the distribution networks,
d) procuring WAMS services through a commercial framework

The applications and associated benefits proposed as part of mid-term objectives are listed below in Table 9, and requirements are shown and Table 10.

5.4.1 Mid-Term Application Benefits and Requirements

Table 9. Mid-term application and their benefits

APPLICATION	BENEFIT	PLANNING	CONTROL ROOM
Dynamic Model Validation and Calibration tool	• Integrate WAMS measurements into model validation to improve accuracy • Develop real-time and/or automated processes capable of validating models against actual measurement data, highlighting areas to tune, and progressing toward the potential of dynamic calibration	✔	✔
Angle-Based Transfer Limit Monitoring in the control room	• Online determination of instantaneous transfer limits at boundaries to enhance system security calculation • Develop and trial of measurement-based dynamic stability limits to maximising system capacity in real-time		✔

APPLICATION	BENEFIT	PLANNING	CONTROL ROOM
Hybrid State Estimation (HSE) application	• Develop and trial HSE - combining WAMS and SCADA measurement data - in the control room • HSE benefits by improving accuracy of SE, reducing uncertainty, and providing faster and better assessment of security margins		✔
Model-less Voltage Instability Monitoring in the control room	• Measurement-based modelling requires sufficient measurement coverage but yields improved modelling accuracy and avoids time extensive model development and validation • Factual-based stability management		✔

Table 10. Mid-term infrastructure and process requirements

REQUIREMENTS	
INFRASTRUCTURE	Data Bandwidth needs to be met (communication infrastructure)
	Cyber Security Implementation in place
	System Redundancy in place (system architecture)
	High Availability in place (system architecture)
	WAMS Integration with EMS operational
	Data Sharing: SO-TO and TO-TO processes and applications operational
PROCESS	Operating Procedures and training for use of PMU technology in control room in place
	Cyber security procedures and training in place
	Institutional awareness and maintenance of current industry standards in place
	Procedures for data sharing between TOs and SO developed and deployed
	Model validation procedures for system planning and engineering developed and deployed
	Procedures developed for adding and removal of equipment
	Maintenance procedures developed and deployed

5.4.2 Future Opportunities for WAMS T2 applications

As we look further ahead, identifying the opportunities and challenges naturally becomes more speculative. However, this section briefly discusses some of the potential applications that the future GB WAMS may look to deliver in order to give thought to the long-term strategy.

Given the substantial benefits that these innovative applications could bring to network operations and the consumers, there is a strong case to trial and develop applications during RIIO-T2 to evaluate benefits that may justify further development of rollout.

The initial goal of the GB WAMS was to improve system awareness and provide oscillation monitoring system for the control room, however, it is important to consider potential future applications the additional requirements to facilitate these applications. For instance, if the long-term strategy incorporates system protection and control functions, the requirements of the underlying infrastructure will extend beyond that of a monitoring-only system; where applications inform real-time system operations the infrastructure would be expected to require protection-class transducers, communication latency, and full redundancy.

The list below provides an indication of some potential and innovative future applications of WAMS; these are at various levels of maturity and many are far beyond the capability of the current GB WAMS, however, all could bring substantial benefits to the reliable and economic operation of the GB transmission system:

- **Frequency Response / Control:** The concept of very-fast frequency control being investigated through EFCC project.
- **On-line generator compliance monitoring:** Real-time monitoring may allow compliance testing to be witnessed remotely by NG, improving speed and reducing cost.
- **Linear State Estimator (LSE):** A LSE directly calculates the power system state without an iterative estimation procedure, as with sufficient PMU measurements estimating the system state becomes a linear problem. This requires full observability of the power system (PMUs at approximately 1/3 of all buses), which is not a realistic expectation in GB at this time. Improvement in state estimator precision would result in improved energy balancing precision accordingly.
- **Volt-Var Control:** Improved state estimation passed onto volt/var scheduling for loss optimisation, may reduce system losses by a small percentage each year equating to savings in the order of millions of pounds per year.
- **System Integrity Protection Scheme (SIPS).** SIPS can be applied as an alternative to network reinforcement to help reduce the constraint cost rather than installing new lines or FACTS devices, and also offers increased flexibility during scheduled outages that may further reduce constraint. In addition, SIPS offer an additional line of system protection for major disturbances.
- **Improved Black-Start coordination** - Islanding Operation, Reconnection & Restoration
- **Black out avoidance:** SIPS significantly reduce the risk of black out; avoiding or reducing an outage that may otherwise occur would represent significant financial and societal savings in the order of tens-to-hundreds of millions of pounds.

6 Roadmap implementation

The establishment of the working group under the System Operator - Transmission Owner Code (STC) to establish baseline Policy for various aspects of System Performance Monitoring which includes WAMS will be the implementation strategy. All parties concerned will agree on the requirements and mechanism to meet the policy requirement, which once ratified will become coded requirements for each party to meet.

The basic principle of engagement is that the TOs will manage their own networks in terms of technology deployment for monitoring and analytics and provision the SO with a data service for real time (using PMU) and post event analysis.

The main deployment targets and challenges for near, mid and long-term timeframes have been described in detail in Section 5 as foreseen by the VISOR project delivery team. In this section, four different deployment frameworks are discussed to undertake the deployment activities, with varying degrees of coordination and responsibilities between parties under each scenario. The discussions will be focused on identifying the key challenges and changes required for these options.

Four potential options will be discussed and the recommended solution is covered in Section 7:

1. Option 1 – SO to lead the overall GB WAMS deployment with TOs supplying the data – US ISO and RC model, Brazil ONS model
2. Option 2 – SO and TOs deploy their respective WAMS independently with TOs also sending all available data to SO – Large US TOs model
3. Option 3 – Deploy a GB WAMS for post-event analysis only – under either Option 1 or Option 2 model
4. **Option 4 – SO and TOs jointly deploy a GB WAMS as a shared decision-making tool for all entities – A joint TO/SO model**

6.1 Option 1 - WAMS led by SO, data acquisition by TO

For this option, SO would lead the overall deployment effort with TOs supplying the PMU/WMU data to SO. SO will work with TOs jointly with distinct responsibilities for SO and each TO:

- SO's responsibilities
  - Overall planning for carrying out the deployment activities
  - Overall system design
  - Determine PMU/WMU placement
  - Secure CapEx and OpEx funding from Ofgem for SO
  - Oversee and coordinate deployment activities
  - Monitor and ensure the data quality
  - Supervise and coordinate post-deployment on-going support and maintenance of the deployed GB WAMS
- TO's responsibilities
  - Install PMUs/WMUs at locations as determined by SO
  - Setup required of the communication network for sending data to SO
  - Coordinate deployment activities with SO

- Provide and coordinate post-deployment support and maintenance for installed PMUs/WMUs and communication links

This option assumes that TOs will not deploy their own WAMS as part of the GB WAMS. TOs control room will be able to view the same displays as seen in the SO control room for operation coordination but may not have the ability to change and/or navigate to such displays shared by SO. Only the SO will have control of the GB WAMS during the real-time operations.

This is an option that has been adopted by some of the large system operators and their TOs around the world, such as those who are members of the GO15 initiative[20]. This is especially the case where TOs and SO are still part of one corporation (e.g. India, China).

Although this option has its advantages, in particular for the SO, adopting this option will need to address a number of key challenges, which may require certain changes (outlined below) to be made to make it a viable option.

6.1.1 Key Challenges

The key challenges in adopting this option for GB TOs and SO include the followings considering market structure, the regulatory framework and SO's & TOs' own business needs/drivers:

1. Need SO to take extra duties beyond the current SO license requirements: In this option, SO will need to take extra duties and responsibilities to plan, oversee, supervise, and coordinate the deployment activities as well as post-deployment operation support and system maintenance, which will be a major challenge since SO was not set up and organised to do so.
2. Provide proper motivations to TOs: In this option, TOs will be providing required data and support to SO. Since each TO is operated as an independent entity financially, unless there is certain financial incentives and benefits associated with doing so, it will be unreasonable to expect TOs to provide the required support.
3. Ways to address TOs own business needs and drivers: This option will be good for addressing business needs at the GB wide level. However, there could be unique business needs that a TO may have and can benefit from specific WAMS applications. The TO generally is responsible to address such TO unique business needs, but not the SO.

6.1.2 Changes Required

To address the key challenges in adopting the Option 1 for GB WAMS deployment, the following changes will be required:

1. Revise SO licence requirements in "Transmission Licence Standard Conditions" (TLSC) to include those extra duties and responsibilities as part of the SO licence requirements.

[20] GO15 (formerly Very Large Power Grid Operators Association – VLPGO) is a voluntary initiative of the world's 18 largest Power Grid Operators representing more than 70% of the world's electricity demand and providing electricity to 3.4 billion consumers on the 6 continents.

2. TOs and SO work with Ofgem to devise a financial framework under the current regulatory framework to clearly define the financial incentives and benefits to TOs and SO under this option.
3. Devise a way for TOs to address their business needs and drivers when the GB WAMS is deployed using this option.

6.2 Option 2 - WAMS equally applied by TO and SO

For this option, SO and TOs would each take the lead to deploy their own WAMS, and all deployed TO WAMS will be obligated to send all the data to SO WAMS. The responsibilities for SO and TOs include:

- SO's responsibilities
  - Overall planning for carrying out the SO WAMS deployment activities
  - Overall SO WAMS system design and implementation
  - Determine desired PMU/WMU placement based on SO's WAMS applications
  - Secure CapEx and OpEx funding from Ofgem for SO WAMS deployment and post-deployment operation and support
  - Coordinate SO WAMS deployment activities with TOs
  - Setup required of the communication network for receiving data from TOs
  - Monitor the data quality for data from TOs and alarm TOs for data quality issues
  - Coordinate post-deployment on-going support and maintenance of the deployed GB WAMS with TOs
- TO's responsibilities
  - Overall planning for carrying out the TO WAMS deployment activities
  - Overall TO WAMS system design and implementation
  - Determine desired PMU/WMU placement based on TO's WAMS and SO's WAMS applications
  - Install PMUs/WMUs at locations as determined by SO
  - Secure CapEx and OpEx funding from Ofgem for TO WAMS deployment and post-deployment operation and support
  - Setup required of the communication network for sending data to SO
  - Coordinate TO WAMS deployment activities with SO WAMS deployment activities
  - Provide and coordinate post-deployment support and maintenance for installed PMUs/WMUs and communication links

This option allows each TO to have a full control over the deployment and use of their own WAMS, which will become part of the GB WAMS. TOs control room operators will have the full control of the TO WAMS during the real-time operations, while SO operators will only have the full control of the SO WAMS during the real-time operations. TOs and SO may share their WAMS display screens for operation coordination purpose, but the receiving entity's control room operators may not have the ability to change and/or navigate to shared displays.

This option has been adopted by some large TOs and their system operators around the world, such as the large TOs in the US.

Since TOs WAMS deployment in this option now is driven by TOs own business needs and drivers, a deployed TO WAMS and the associated supporting infrastructure will have to meet the requirements of its own WAMS applications for operational use. This will be the main advantages of this option. However, adopting this option will need to address a different set of challenges, which may require certain changes to be made to make it a viable option.

6.2.1 Key Challenges

The key challenges in adopting this option for GB TOs and SO include the followings considering market structure, the regulatory framework and SO's & TOs' own business needs/drivers:

- Establish TO's business cases: Each TO will need to establish their own business case in order to obtain Ofgem approval for their deployment funding application. Given the differences among three TOs, the challenge will be whether every TO will be able to establish a solid business case for itself, and even if they could, will they will have been able to justify the same level of deployment among all three TOs.
- Align TOs' business needs and drivers with SO's: As each TO's business needs could be very different from that of SO's, and also among TOs, it will be a major challenge for SO to have all TOs fully align their deployment efforts to support SO's business needs.
- Deployment and operation coordination between TOs and SO: Since TOs' WAMS deployment under this option will be relatively independent to SO's, SO will have little direct control over how each TO will plan and execute their deployment activities, and operate the deployed system. It will be a challenge for TOs and SO to coordinate their independent efforts in order to maximise the benefits to consumers.

6.2.2 Changes Required

To address the key challenges in adopting the Option 2 for GB WAMS deployment, the following changes will be required:

- Allow TOs to use SO WAMS benefits: In a TO's business case, the TO should be allowed to use benefits of SO WAMS that could be realised by the TO's WAMS deployment. This will help to address the above three challenges from the very beginning of a TO's deployment effort.
- Make changes to SO's licence requirement: The SO's licence requirement should be revised to make it an SO's obligation to identify and provide TOs with realisable benefits by SO WAMS that can be attributed to specific TO's WAMS deployment, as well as adding other SO's deployment and operation coordination duties.
- Make changes to or clarify TO's licence requirements: According to current requirement D2(d) of TLSC, a TO licensee is required to provide "*a means of enabling the system operator to obtain information in relation to the licensee's transmission system which is needed by the system operator to enable it to coordinate and direct the flow of electricity onto and over the national electricity transmission system and, consistent with such means, providing such information to the system operator.*" The System Operator Transmission Owner Code (STC)

further defined the provision of Transmission Services by TOs to SO, and the obligations of SO. The PMU/WMU measurements and the necessary communication and networking facilities to transport the data could be clarified in STC as part of the "information in relation to the licensee's transmission system" that it is a licence obligation by TO to SO. Alternatively, specific language may be added in STC to make this inclusion apparent. This change or clarification will make several major cost components in a TO's WAMS deployment effort as a part of its licence obligation, which will make it easier for TO to establish its business case for any additional deployment efforts to address its own business needs/ drivers.

6.3 Option 3 - WAMS post-event only

For this option, the GB WAMS would be deployed for post-event analysis only, which will remove the stringent performance requirements for real-time control room use and lowers the security requirements since it will not be used for real-time decision making.

Such deployment could be led by SO as in Option 1 but responsibilities would be separated as in Option 2. The extent of the responsibilities placed on the TOs will depend on the requirements of the SO, outside of which the responsibility of each party will depend on their own implementation strategy.

- SO's responsibilities
  - Overall planning for carrying out the SO WAMS deployment activities
  - Overall SO WAMS system design and implementation
  - Determine desired PMU/WMU placement based on SO's WAMS applications
  - Secure CapEx and OpEx funding from Ofgem for SO WAMS deployment and post-deployment operation and support
  - Coordinate SO WAMS deployment activities with TOs
  - Setup required of the communication network for receiving data from TOs
  - Monitor the data quality for data from TOs and alarm TOs for data quality issues
  - Coordinate post-deployment on-going support and maintenance of the deployed GB WAMS with TOs
- TO's responsibilities
  - Overall planning for carrying out the TO WAMS deployment activities
  - Overall TO WAMS system design and implementation
  - Determine desired PMU/WMU placement based on TO's WAMS and SO's WAMS applications
  - Install PMUs/WMUs at locations as determined by SO
  - Secure CapEx and OpEx funding from Ofgem for TO WAMS deployment and post-deployment operation and support
  - Setup required of the communication network for sending data to SO
  - Coordinate TO WAMS deployment activities with SO WAMS deployment activities
  - Provide and coordinate post-deployment support and maintenance for installed PMUs/WMUs and communication links

6.3.1 Key Challenges

Depending on whether the deployment is led by SO as in Option 1 or be carried out by TOs and SO separately as in Option 2, it will have similar challenges as in Option 1 or Option 2 respectively.

- In addition, as a major portion of benefits in GB WAMS deployment is attributed to real-time operation use, as well as the real-time protection and control application, of the WAMS technology, it will be a challenge for a GB WAMS deployed for post-event analysis only to justify the cost of such deployment with the realisable benefits.

6.3.2 Changes Required

Depending on whether the deployment is done as in Option 1 or be carried out as in Option 2, similar changes as either in Option 1 or Option 2 should be made to make this option a viable one.

- The changes to STC may also need to make it clear that installing PMUs/WMUs and provisioning communication and networking facilities for transmitting the data is part of the TO licence condition.

6.4 Option 4 - WAMS as a decision-making tool shared between TOs and SO

Option 4 is that the GB WAMS be deployed as one system and its use is shared by all TOs and SO. Each entity will deploy the same set of WAMS applications and the software package. The selection of the applications will take both TOs' and SO's business needs into consideration. SO may still be taking a leading role as in Option 1, while all TOs become equal partners in this option.

The main differences may be in the amount of data each entity will be allowed to access. The SO will have access to all TOs data, while each TO will have full access to its own data but may only have access to a subset of other TOs' shared data.

This will be a joint-effort option that has not been adopted by others under the similar market structure and regulatory framework to our knowledge.

There are some apparent advantages of this option that include:

- The benefits of deploying a GB-wide WAMS to TOs and to SO at the transmission level can be aggregated to justify the total cost of the deployment, and only one business case needs to be established for GB WAMS
- TOs and SO will be able to use the same WAMS software in their control rooms, which make coordinate their operations and other activities much more easily
- Lower the overall procurement cost through single procurement process and volume discount
- Reduce the overall on-going cost such as annual maintenance and support fees
- Lower the system integration, overall support and training related costs

However, adopting this option will have its own special challenges that will require some major changes, which will be discussed below.

6.4.1 Key Challenges

The key challenges in adopting this option for GB TOs and SO include the followings considering market structure, the regulatory framework and SO's & TOs' own business needs/drivers:

- Organisational support: It will be a major challenge to get all entities agree to adopt this option as this likely will be the first time that things will be done this way. Deploying one system to be shared by all TOs and SO will need to resolve many practical issues, such as business and financial arrangements, technical solution choices and arrangements, and so on. An agreement among all entities can only be reached once these practical issues have been discussed and resolved. Reaching the agreement will be critical to have the full support of all entities for this option.
- Regulatory support: As this option will be a departure from what the current regulatory framework supports, it will be a challenge for Ofgem to fully support the adoption of this option under the current regulatory framework.
- Licence condition and grid code support: Similar challenges exist for this option as for other options in this aspect. It will be a challenge to define SO's and TOs' responsibilities and obligations under this option.
- Technical challenges: These challenges may arise from the differences in each entity's current control room setup, preferences in IT and network technologies and solutions, security policies and management, and so on. Among them, the security aspect could be the most challenging one to resolve.

6.4.2 Changes Required

To address the key challenges in adopting the Option 4 for GB WAMS deployment, the following changes will be required:

- Make necessary organisational changes at each entity: Certain organisational changes will need to be made at each TO and SO based on the agreed business and financial arrangements, technical solution choices and arrangements, and so on. Proper processes and procedures may also need to be developed as part of these changes to support the adoption of this option.
- Update current regulatory framework: Should TOs and SO had agreed that this option is the best option for GB WAMS deployment, they would also need to obtain the full support of Ofgem and work with Ofgem to update the current regulatory framework so that the application for GB WAMS deployment funding under this option can be approved under the updated regulatory framework.
- Revise licence conditions and grid code: The STC and TLSC should also be revised to clearly define the responsibilities and obligations of TOs and SO under this option.
- Develop technical solutions for making required changes: Technical solutions will need to be developed and implemented to address the challenges arising from the differences in each entity's current control room setup, preferences in IT and network technologies and solutions, security policies and management, and so on.

6.5 Options Responsibility Matrix

	Option 1 WAMS led by SO, data acquisition by TO	Option 2 WAMS equally applied by TO and SO	Option 3 WAMS post-event only	Option 4 WAMS as a decision-making tool shared between TO and SO
• **Overall planning of PMU/WMU placement and specifications**	SO	SO/TO, collaboration recommended for SO to notify of their requirements	SO/TO independent, with SO to notify of their requirements	SO/TO, collaboration necessary for SO to notify of their requirements
• **Overall WAMS system design – cyber security and data communications**	SO	SO/TO, collaboration recommended for interoperability	SO/TO, collaboration recommended for interoperability	SO/TO, collaboration necessary for interoperability
• **Funding – CAPEX (deployment) and OPEX (post-deployment operation and support)**	TO, through dedicated WAMS allowance	TO, partly through business plan and partly through dedicated allowance	SO/TO independent, with SO to notify of their requirements	SO/TO, collaboration necessary for interoperability
• **Provide and coordinate post-deployment support and maintenance for installed PMUs/WMUs and communication links**	TO, through dedicated WAMS allowance	TO, partly through business plan and partly through dedicated allowance	TO, with SO to notify of their requirements	TO, with SO to notify of their requirements

7 Roadmap Conclusion and Recommendations

This roadmap documents the status of the WAMS deployment in GB following the completion of the innovation project VISOR in order to ascertain the true and potential benefits offered by WAMS in order to justify its continued operation for a range of applications in the immediate future, and pave the way for further development and trials to bring the technology to the control room in the future.

To further support the recommendations of this roadmap, a survey of other examples of WAMS deployments has examined the level of deployment in other parts of the world to identify similarities and to draw experience from. This survey has made the following noteworthy discoveries and common trends between deployments:

- WAMS deployments have seen a widespread uptake in many countries across the world over the past 15 years, with substantial deployments (greater than 1000 PMUs) in the US, China, and India, with smaller deployments also in Brazil, Columbia, Mexico, Denmark, Iceland, and Australia.
- Many of these deployments have been in response to severe system outages and/or system stability issues. For example, the US Department of Energy established the North American Synchrophasor Initiative (NASPI) and two Smart Grid funding mechanisms worth 4.5 billion USD, which have been the main driving force behind WAMS deployments.
- WAMS have been implemented for a range of applications, including post-event analysis, generator model validation and calibration, power station commissioning support, short-circuit capacity estimation to assess the likelihood of HVDC commutation failure, oscillation monitoring and damping constraint support. It was also found that WAMS has been implemented to support an operational protection scheme in Ecuador, since 2015.

Some common trends pertinent to GB are:

- Significant process development and effort is required for WAM systems and applications to be successfully deployed into the control room.
- Reliable, robust and secure infrastructure is a crucial enabler and a significant challenge to WAMS.
- New and dedicated engineering resource and analysis skills are required at the early stages of WAMS deployment to develop and implement the systems.

7.1 Benefits based on Experience

VISOR established and demonstrated the use of a system-wide WAMS with a suite of applications to enhance system awareness and provide new visibility into the oscillatory behaviour of the system, in order to evaluate the benefits. Based on experience, the key benefits are summarised below.

- One of the most significant benefits is the ability to provide detection, localisation and characterisation of system disturbances and oscillations in real-time that provides valuable insight into behaviour which would otherwise go unnoticed. The improved monitoring capabilities have identified a significant amount of previously unseen oscillatory behaviour:

  - Some observations have prompted investigation and assessment, and the monitoring and analysis capabilities demonstrated under VISOR have been instrumental in this. These investigations have led to the identification of the relevant unknowing offenders on the GB network, allowing corrective action to be taken before the relatively low-level behaviour has a chance to become dangerous. The capture and study of these are also valuable for developing understanding and experience of oscillatory behaviour, and knowledge of modes and interactions that are present in the system, thereby informing future investigation and management of oscillatory behaviour to the benefit of all customers.
  - Certain oscillations could cause major issues for transmission network operations and reliability, such as equipment damage and reduced boundary transfer limits. By giving operators visibility across a broad range of frequencies to be able to manage and mitigate those oscillations that could cause problems to the equipment and network operation.
- Provide enhanced situational awareness of the transmission system and visibility of power system dynamics, WAMS provide high-resolution trending, charts and monitoring of voltage magnitude, system frequency and the rate of change of frequency, active and reactive power, and phase angle difference based stability margin monitoring.
  - WAMS information has already been used by SPT to inform SO actions
- WAMS will help to provide an early indication of emerging problems before they become faults and major network disturbances. Control engineers can no longer heavily rely on historical performance as a marker for network behaviour as the rate of change of generation technology, active control devices, and consumer behaviour is unprecedented.

Moreover, time-synchronised measurements also bring benefit to support the following applications for both TO and SO outside of the control room:

- Benefits are applicable to many business functions (detailed in Section 4), including Post-event analysis process improvement, through faster, easy data alignment & improved reporting capability; transient stability studies; model validation; control and damping optimisation; operator training simulator; and, generator compliance.
- Validate the dynamic performance and compliance of active control devices SVCs, STATCOMS and series compensation, quad-boosters, mechanically switched capacitors and shunt reactors. Observability during various operating scenarios is required to establish suitable performance and compliance, and could also be used to optimally set the devices. This information would be combined with power quality monitoring to manage compliance levels regarding harmonics and national policy.
  - In time, this can be incorporated into wide-area coordinated control to optimise the response and increase boundary and reduce constraints.
- Post-event analysis can validate the performance of Operational Tripping Schemes (OTS) and optimise the OTS settings and Automatic Route Setting performance. In time, this could be automated to establish a Regional Voltage control scheme.

7.2 Roadmap Conclusion

In view of the benefits offered by the WAMS applications, both currently and potentially available, as highlighted in this roadmap, it is the recommendation of this report that the operation of the GB WAMS is retained through the remainder of RIIO-T1 for following reasons:

1. A proactive WAMS deployment represents a prudent and cost-effective method to manage the future needs of the system with increasing penetration of renewable energy and active demand networks.
2. To continue monitoring of oscillation behaviour, as a minimum, to:
    a. provide system operators with the ability to detect oscillations and interactions should they occur;
    b. over time, provides behaviour baselining to ascertain normal and abnormal oscillations, and the location and frequency of their occurrence;
    c. instruct post-event investigations to further understanding of dynamic behaviour, and begin to identify potential mitigation actions to thereby reduce the future risk posed to asset health and system reliability.
3. To continue system integration efforts to embed WAMS into each business, using the experience of operation to:
    a. inform the overall GB system architecture, to be established either before at the outset of RIIO-T2;
    b. identify existing infrastructure for improvement, such as extending monitoring coverage for key parts of the network with limited WAMS visibility (i.e. South-East England) or replacing legacy or problematic PMUs with dedicated PMU/WMU;
    c. ensure sufficient Quality of Service agreements between monitoring devices and data centres are established either before or at the outset of RIIO-T2.
4. To educate and train engineers in the use, and potential use, of WAMS applications and integration with EMS to build operator confidence and advance the development of application and infrastructure functional specifications.
5. To ensure the specialist knowledge and skilled resources are retained and utilised to continue the momentum initiated by VISOR.

7.3 Roadmap Recommendations

The experience gained through VISOR and international experience of WAMS deployment, allows this roadmap to make the following recommendations in relation to the rollout of WAMS in GB.

7.3.1 WAMS Deployment and Application

Applications ultimately drive the continued operation and expansion of the GB WAMS as these deliver benefits to network operators and in-turn the GB customer. WAMS applications offer new and enhanced capabilities to operations both within and outside (e.g. post-event, planning) the control room. Maximum benefits will be realised through both real-time operational actions and offline improvements to analysis and modelling activities.

- The recommendation of this roadmap is to focus immediate efforts on the continued operation of the existing applications by renewing the licenses of the applications that have been demonstrated through VISOR, detailed in Table 2 (p.26), and maintaining the necessary infrastructure to support them (see below).

- Learning from VISOR and deployments elsewhere suggests a substantial development and deployment effort is required to unlock the full potential of WAMS achieved by informing both real-time system operation decision-making and offline system analysis applications. To enable this, however, the underlying infrastructure and processes must first satisfy the security, reliability and performance requirements of the real-time operation. A long-term strategy will guide both application and infrastructure deployment.
- SPT and NGET both have WAMS projects currently underway which have benefitted from the GB WAMS deployment. There is a strong argument to continue the operation of the GB WAMS as a fundamental building block to facilitate and encourage other WAMS projects to come forward and advance existing or trial new applications. For example, innovation projects may utilise WAMS data to trial and develop tools such as Hybrid State Estimation.

7.3.2 WAMS Infrastructure

VISOR demonstrated GB WAMS deployment to explore the potential benefits offered, however, the system was built upon a demonstration architecture created outside of the operational network. This approach was deemed most suitable and feasible within the scope and time constraints of the innovation project. To support the move from demonstration to a production system, this roadmap makes the following infrastructure recommendations:

- Each project partner to assess and upgrade to the underlying infrastructure accordingly:
    - To ensure the communication infrastructure achieves a suitable Quality of Service between PMU/WMU and data centre;
    - Review of communication infrastructure and data routing between TO and SO;
    - Legacy and problematic monitoring devices are 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.
- System architects from each TO/SO must work together to design fully system architecture to serve the needs of the GB WAMS as a whole, for inclusion in RIIO-T2 planning.
    - The minimum system architecture should allow for potential WAMS expansion to one PMU/WMU per transmission substation.

7.3.3 WAMS Process

In order to meet the above recommendations, the following procedural changes are recommended:

- Identify WAMS delivery team(s) or task force responsible for overseeing deployments in the immediate future: this team should comprise of representatives from each TO and the SO,
- New data sharing arrangements between SO-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 by RIIO-T2.

- 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, monthly. Currently, these reports are compiled by a skilled resource, but future effort should be made to automate this process, where possible.

7.3.4 Regulatory Recommendations

- Network Licensees will likely be guided by Ofgem in relation to which operating framework will be followed. Potential options of operating frameworks have been examined and determined that the most efficient and economic strategy will be achieved through a coordinated roll-out between TO and SO, whereby requirements are placed upon TOs based on SO requirements.
- For future investment into the GB WAMS to be made efficiently and remain effective over the long term, there is now a need for discussion between the TO and the SO to discuss long-term strategies and requirements.

8 Appendices

8.1 Appendix A: RIIO Investment Mechanisms for GB WAMS

Under the current RIIO framework, several options exist to facilitate the deployment and development of the GB WAMS infrastructure and applications. The RIIO framework provides strong incentives for Network Licensees to innovate as part of normal business, however, through the RIIO innovation stimulus package, three time-limited mechanisms exist to enable and encourage speculative and innovative projects that yield uncertain commercial returns.

- Business Plan (BP): through which Network Licensees apply for funding through the eight-year price control period by describing network development, reinforcement, and the innovation strategy of the period and how this will be implemented to ascertain and justify total expenditure required,
- Three mechanisms of the time-limited RIIO innovation stimulus package (see note below):
    1. Network Innovation Allowance (NIA): an allowance through the BP funding smaller innovation Projects that will deliver benefits to Customers as part of a RIIO-Network Licensee's price control settlement.
    2. Network Innovation Competition (NIC): an annual competition to fund selected flagship innovative Projects that would deliver low carbon and environmental benefits to Customers. The VISOR project was awarded funding through the 2012 Network Innovation Competition.
    3. Innovation Rollout Mechanism (IRM): two application windows to fund the roll-out of proven innovations which will contribute to the development in GB of a low carbon energy sector or broader environmental benefits. Applications for funding under IRM can be made by TOs, DNOs and SO at different intervals during the price control period, however, the only remaining TO IRM application window the current price control period is 1st May 2018 – 31st May 2018.

**Note, Ofgem are yet to publish the framework for RIIO-T2 (due early 2018) so whether the existing Innovation Stimulus Package will be reused, modified or removed remains to be seen. Based on an assessment of the Low Carbon Network Fund, the predecessor to the RIIO stimulus package, RIIO should deliver significant financial benefits as a consequence of the roll-out of innovative solutions, so although this roadmap does not rely upon reinstating the stimulus package, some mechanism to encourage and support innovation projects, which lack commercial certainty, can be expected.*