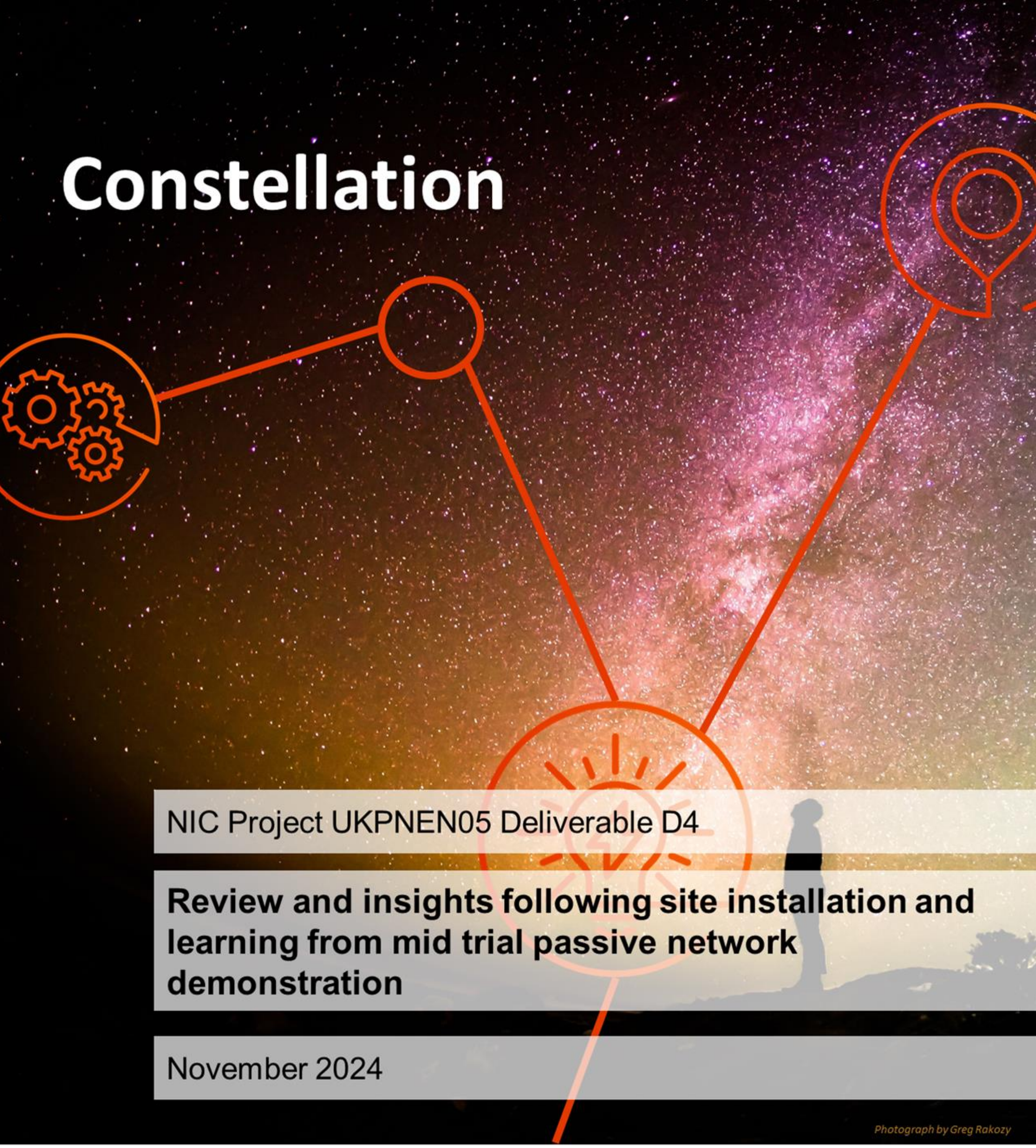

Constellation

NIC Project UKPNEN05 Deliverable D4

Review and insights following site installation and learning from mid trial passive network demonstration

November 2024

Photograph by Greg Rakozy

Constellation Partners

ABB GE VERNOVA UNIVERSITY of STRATHCLYDE PNDC SIEMENS UK Power Networks Delivering your electricity vodafone

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Table of acronyms and glossary

The acronyms and terms used throughout this document are clarified below.

Table 1: Table of Acronyms

Acronym	Full form
5G	5th Generation Mobile Network
ABB	Asea Brown Boveri
ADMS	Advanced Distribution Management System
ALoMCP	Accelerated Loss of Mains Change Programme
ANM	Active Network Management
AMQPS	Advanced Message Queuing Protocol Secure
API	Application Programming Interface
APS	Adaptive Protection System
ASB	As-Built (Drawings)
BaU	Business as Usual
BMCA	Best Master Clock Algorithm
BESS	Battery Energy Storage System
CAF	Cyber Assessment Framework
CAPE	Computer Aided Protection Engineering
CB	Circuit Breaker
CDM	Construction (Design and Management)
CGMES	Common Grid Model Exchange Specification
CIGRE	Conseil International des Grands Réseaux Electriques
CIRED	International Conference on Electricity Distribution
CIM	Common Information Model
CMC356	Universal Relay Test Set and Commissioning Tool (OMICRON)
CMS	Central Management System
COMTRADE	Common Format for Transient Data Exchange
CPC	Central Processor Complex
CPU	Central Processing Unit
CSV	Comma Separated Value
CT	Current Transformer
DANEO 400	Network Analyser (OMICRON)
DCGW	Date Core Gateway
DE WAMS	Digital Energy Wide Area Monitoring System
DER	Distributed Energy Resource
DERMS	Distributed Energy Resource Management System
DESNZ	Department of Energy Security and Net Zero
DG	Distributed Generation
DNO	Distribution Network Operator
DNP3	Distributed Network Protocol 3
DOC	Directional Over Current
DRX	Discontinuous Reception
EAM	Enterprise Asset management
EIS	Energy Innovation Summit
ENA	Energy Network Association
ER	Engineering Recommendation
ETS	Engineering Technical Specification

Acronym	Full form
FAT	Factory Acceptance Test
FEP	Front End Processor
FSP	Full Submission Pro-forma (in reference to the project proposal)
GA	General Arrangement
GE	General Electric
gNB	Next Generation Node B
GOOSE	Generic Object Oriented Substation Event
GPS	Global Positioning System
H&S	Health and Safety
HCIBench	Hyper-converged Infrastructure Benchmark
HMI	Human Machine Interface
HSR	High Availability Seamless Redundancy
HTTPS	Hypertext Transfer Protocol Secure
HV	High Voltage
ICMP	Internet Control Message Protocol
IDS	Intrusion Detection System
IEC 61850	International Electrotechnical Commission 61850 Communications Protocol Standard
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology
IP	Internet Protocol
IT	Information Technology
I/O	Input/Output
JRC	Joint Radio Committee
kV	Kilovolt
LAN	Local Area Network
LB	Load Blinding
LBRDOB	Load Blinder
LED	Light Emitting Diode
LoA	Limitation of Access
LoM	Loss of Mains
LV	Low Voltage
MAC	Media Access Control
MFA	Multi-factor Authentication
ML	Machine Learning
MMS	Manufacturing Message Specification
MQTT	Message Queuing Telemetry Transport
ms	Millisecond
MSSQL	Microsoft Structured Query language
MTU	Maximum Transmission Unit
MU	Measuring Unit
MW	Megawatt
NCSC	National Cyber Security Centre
NETCONF	Network Configuration Protocol
NIC	Network Innovation Competition
NIS	Network and Informational Security (directives)
NMAS	Network Model Analysis System
NMS	Network Management System

Acronym	Full form
NTP	Network Time Protocol
OCC	OMICRON Control Centre
ODMS	Open Data Management System
OIC	Open Innovation Competition
OS	Operating System(s)
OT	Operational Technology
P	Active Power
PAC	Protection and Control
PAM	Privileged Access Management
PCAP	Packet Capture
PDC	Phasor Data Concentrator
PESS	Protection Engineering and Simulation System
PhC	Phasor Controller
PLC	Programmable Logic Controller
PMU	Phasor Measurement Unit
PNDC	Power Networks Demonstration Centre
PPR	Project Progress Report
PRP	Parallel Redundancy Protocol
PSS	Power System Simulation and Modelling Software
PV	Photo-Voltaic
PTP	Precision Time Protocol
Q	Reactive Power
QA	Quality Assurance
GOOSE	Generic Object Oriented Substation Event
RNA	Radio Network Access
RoCoF	Rate of Change of Frequency
RT	Real Time
RTAC	Real-Time Automation Controller
RTDS	Real Time Digital Simulator
RTT	Round Trip Time
RTU	Remote Terminal Unit
SA	Standalone
SAT	Site Acceptance Test
SCADA	Supervisory Control and Data Acquisition
SCD	Substation Configuration Description
SCU	Switch Control Unit
SCL	Substation Configuration Language
SFTP	Secure File Transfer Protocol
SMV	Sampled Measured Value
SNMP	Simple Network Management Protocol
SSH	Secure Shell
STP	Spanning Tree Protocol
TCP	Transmission Control Protocol
TRL	Technology Readiness Level
TWh	Terra Watt Hours
TX	Transmission
UDP	User Datagram Protocol
UE	User Equipment
UK	United Kingdom

Acronym	Full form
UK Power Networks	UK Power Networks (Operations) Ltd consists of three electricity distribution networks: Eastern Power Networks plc (EPN) London Power Network plc (LPN) South Eastern Power Networks plc (SPN)
UPF	User Plane Function
URLLC	Ultra-Reliable Low Latency Communications
V2G	Vehicle to Grid (Electric Vehicles)
VLAN	Virtual Local Area Network
VM	Virtual Machine
vPhC	Virtualised Phasor Controller
VPN	Virtual Private Network
VSAN	Virtual Storage Area Network
VT	Voltage Transformer
WAM	Wide Area Monitoring
WAN	Wide Area Network
WAP	Wide Area Protection
WG	Working Group
WPA	Windows Performance Analyser
WS	Workstream

Table 2: Glossary of Terms

Term	Definition
5G Slice	A network slice is an independent end-to-end logical network that runs on shared physical infrastructure, capable of providing a negotiated service quality
Area	A geographical area that has a number of substation sites within close proximity. The areas considered in this document are given in the scope
Blackout and Brownout	A blackout is a complete loss of power, while a brownout is a temporary reduction in voltage
Equipment	Substation Server and all associated Hardware required at any Constellation site
Grid substation	A substation with an operating voltage of either 132kV or 66kV and may include transformation to 33kV, 11kV or 6.6kV
Hypervisor	A programme that separates a computer's physical resources from its virtual resources
IED	Intelligent Electronic Device that acquires hardwired inputs and/or current/voltage inputs and transmits data to a computer. The IED outputs may be configured for control and protection design requirements
Method 1 and Method 2	Methods 1 and 2 will be implemented, as described in Section 1.2, to achieve the primary aims of Constellation
Primary substation	A substation with an operating voltage of 33kV and may include transformation to 11kV or 6.6kV
User	Member of staff of UK Power Networks who will be involved with the supplied equipment and/or software on a technical or non-technical level
Solution	Individual solutions are developed by the Constellation partners and include hardware and software associated with Method 1 and Method 2
Substation Server	An industrial server suitable for substation operating environments. The server has hardware and software capability to process protection and control (PAC) function applications, utilising edge computing architectures (local processing of data). There are two types of Substation Servers for the Constellation project: • **Grid Substation Server:** it has advanced hardware and software capabilities. These are needed for sites with many PAC logical node demands. These include the UK Power Networks Grid, Primary and Secondary sites. • **DER Substation Server:** it has limited hardware and software capabilities. These are needed for sites with limited logical nodes and reduced PAC needs. These include DER sites.
Super Grid Transformer	A transformer providing 400/275kV to 132kV
Supplier(s)	A manufacturer or entity submitting an offer to UK Power Networks to manufacture, supply, install and/or commission equipment and/or software at a specified site
Virtual Machine	A virtual representation of a physical computer

Executive Summary

Constellation is a customer funded Network Innovation Competition (NIC) project led by UK Power Networks and delivered in partnership with ABB, GE Vernova, University of Strathclyde's Power Networks Demonstration Centre (PNDC), Siemens and Vodafone. The project aims to demonstrate, through a series of trials, how novel Protection and Control (PAC) solutions installed within Distribution Network Operator (DNO) substations can be used to:

- Facilitate the efficient connection of more Distributed Energy Resources (DER) on to power distribution networks; and
- Protect the use of flexibility services and de-risk the likelihood of sudden and widespread DER curtailment and/or disconnection thus reducing the risk of system wide frequency (instability) events.

The novel technology developed through Constellation is essential to facilitating Net Zero through enhancing the core of the distribution network – substations. In the future, DNOs will rely on services provided by DER assets to operate their networks optimally and reliably. The Constellation Solutions will enable a resilient and flexible approach to network PAC, to enable DER to support the network. Furthermore, the project will collect valuable quantitative evidence to assess how local network operation can improve network stability. Constellation will also protect the available network capacity from disruption caused by abnormal events, such as loss of communications, and reduce system balancing costs by allowing DER to ride through transient instability events.

To successfully develop and demonstrate the novel Solutions, Constellation is delivered by a consortium of partners who are at the cutting edge of technology. ABB, Siemens and GE Vernova bring global experience in technology development, while Vodafone is a world leader in telecommunications and 5G. Additionally, PNDC and UK Power Networks' expertise in network innovation is core to the testing and preparation for business as usual (BaU) phases of the project. Due to the multi-faceted nature of the project, this partnership is essential for the success of Constellation.

This report, which is the fourth Constellation deliverable, demonstrates that the activities required to be undertaken by all project partners during this phase of the project, as stipulated within the Full Submission Pro-forma (FSP)[1], have successfully been achieved and provides evidence that key learnings from the following activities have been captured and reported upon:

- The site installation process at DER sites and Primary/Grid substations; and
- Early learnings from Passive Network Trial demonstration.

In addition, this fourth Constellation deliverable reports upon how the following important key project aspects have successfully been progressed since submission of Deliverable D3[2]:

- Solution integration and functional testing at PNDC;
- Validation and testing of the Constellation virtualisation Platform at PNDC; and

[1] https://www.ofgem.gov.uk/sites/default/files/docs/2020/11/constellation_nic_2020_fsp_-_public_27.11.2020_0.pdf
[2] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-3-v1.0-Redacted.pdf

- Implementation of cyber security measures against the potential threats from malicious cyber security attacks at PNDC.

Deliverable D4 therefore comprises the following contents:

- Section 1 details the project background and purpose, as well as the scope of this report;
- Section 2 details the works undertaken to ensure the robustness of Constellation, plus the key lessons learnt;
- Section 3 details the activities required to prepare network sites for Constellation, plus the key lessons learnt;
- Section 4 details the network testing activities undertaken on site, plus the key lessons learnt;
- Section 5 focuses on ongoing activities and next steps;
- Section 6 provides the conclusions; and;
- Appendices present further lessons learnt, together with additional information from each project partner relating to the further development of the Constellation Solutions and network testing activities which can be used for reference.

Table 3: Deliverable D4 Requirements and Evidence Summary

Deliverable D4: Review and Insights (Site Installation and Passive Network Trials)	
Evidence item	**Relevant Section of the Report**
Details of the key lessons from site installation process at DER sites and Primary/Grid substations	Following the completion of the site installations in two Primary/Grid substations and four DER sites, project Constellation developed significant learnings that enabled the creation of a standardised framework for enabling Constellation on future sites. Utilising the iterative installations approach, lessons were captured and applied on subsequent installations resulting in successful end to end installations that significantly raised the business confidence in the project and facilitated its BaU transition. Some of the key lessons learnt include: - The complexity associated with retrofitting the Constellation Solutions in existing network substations resulting in Solutions and cubicles redesign; - The value of proactive planning and iterative testing in minimising the impact of unexpected challenges; and - The importance of effective stakeholder engagement when planning site activities to minimise disruptions; Additional details regarding the site preparation framework, the overall process, and key lessons learnt can be found in Section 3 and an extensive list of lessons learnt has been collated in Appendix A.1.2
Details of early learnings from the Passive Network demonstration	Project Constellation has successfully transitioned the theoretical design of the project Methods and Solutions from the lab environment at PNDC, to the UK Power Networks distribution network. The team used learnings from past project activities to efficiently set up all project components across all sites. An iterative installation approach was utilised to ensure learnings are proactively applied to subsequent

	sites which ensured that the final procedure is tested end to end and proven to be successful. As a result of that, the project team developed a standardised framework for conducting SAT and completing further tests during the Passive Network demonstrations. Some of the early lessons learnt include: - The importance of top-down business support of the project to ensure effective challenges resolutions and reinforce buy-in; - The value of in-house expertise and leveraging partnerships for upskilling the workforce and preparing a BaU transition; and - The necessity of having a varied representation of network substations during the passive trials to demonstrate broader applicability of the project. Additional details regarding the early learnings from the Passive Network demonstration, including the SATs, and key lessons learnt to date can be found in Section 4 and an extensive list of early learnings has been collated Appendix A.1.3

1 Project Background and Purpose

1.1 Purpose of this Report

This report, which forms the fourth Constellation Deliverable, provides evidence that the required key learnings have been captured and reported upon, in accordance with the FSP document[3]. This deliverable therefore outlines:

- Key lessons from site installation process at DER sites and Primary/Grid substations; and
- Early learnings from the Passive Network Trial demonstration.

Constellation is a highly innovative project, and as such, many technical issues associated with the Solution installations, Site Acceptance Tests (SAT) and Passive operation have been encountered, investigated, and appropriately addressed.

Furthermore, Constellation is delivered by a diverse partnership of organisations. This diversity in skills and expertise is core to delivering Solutions which are scalable and future-proof. This collaborative approach is evidenced in the Deliverable Reports as the content is reflective of the contribution and specific area of expertise of the partners.

Items which are outside the scope of this deliverable are summarised below:

- Description of the architecture, requirements and design for the Constellation Solutions are presented in Deliverable D1[4] (sections 4 and 5 respectively);
- Description of the process undertaken by the project partners to conclude the trial design and site selection process is detailed in Deliverable D2[5] (sections 2, 3, 4 and 5);
- Learnings associated with FATs of the Constellation Solutions. Summary details have been provided in Deliverable D3[6];
- Full learnings gained from PNDC off-network trials, which will be provided in Deliverable D7;
- Full learnings gained for the Passive and Active Network Trials, which will be provided in Deliverable D7;
- Justification and rationale for the Constellation Solutions is provided in the FSP, sections 2, 3 and 4;
- The initial benefit assessments of the Constellation Solutions are provided in the FSP, sections 3 and appendices 10.1, 10.2 and 10.3. These will be reassessed at the end of the project in Deliverable D7;
- Stakeholder engagement activities are summarised in the Project Progress Reports (PPR), hence only engagement directly relevant to this deliverable are presented; and
- Detailed project planning, which is provided in the PPR accessible through the project portal[7].

[3] https://www.ofgem.gov.uk/sites/default/files/docs/2020/11/constellation_nic_2020_fsp_-_public_27.11.2020_0.pdf
[4] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-1-Redacted.pdf
[5] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-2-Redacted.pdf
[6] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-3-v1.0-Redacted.pdf
[7] https://innovation.ukpowernetworks.co.uk/projects/constellation

1.2 Project Overview

Net Zero and Associated Challenges

The United Kingdom (UK) Government has set legally binding carbon budgets under the Climate Change Act 2008[8] which are intended to act as stepping-stones towards the UK bringing all greenhouse gas emissions to Net Zero by 2050. Given that, at the end of 2022, the UK's electricity production activities accounted for approximately 14%[9] of all UK greenhouse gas emissions, it is essential that the entire sector must be decarbonised. To help achieve this, the UK Government issued its Net Zero Strategy document in October 2021[10], subsequently updated in December 2021 and April 2022, plus a policy paper, entitled Powering Up Britain: Net Zero Growth Plan[11], which was published on 4th April 2023. The Net Zero Strategy document highlighted the importance of removing barriers associated with the anticipated large-scale introduction of low-carbon generation (e.g. wind farms, solar photo-voltaic (PV), battery energy storage systems (BESS), vehicle to grid (V2G) etc) so that up to 370TWh of low carbon renewable energy could be embedded into the power networks by 2030.

The amount of electrical power provided by such low-carbon embedded generation, universally known as a DER, has risen significantly in the last two decades and provided approximately 135TWh in 2020, up from circa 10TWh in 2000[12]. The introduction of this has created some significant challenges for the energy industry. In particular for the DNOs who have received the majority of these DER connection requests, as DER is typically associated with small-scale generating units located predominantly in rural and/or remote areas and hence require connection at the distribution level. More specifically, the DNOs are now having to manage a power network capable of importing and exporting power, which the existing PAC systems were not designed to accommodate. Additionally, new flexible methods of managing DER generation via flexibility services and/or flexibility connections have been introduced, which are intended to optimise the use of electricity network infrastructure. These type of solutions will govern the level of DER generation and/or connectivity under network constraint conditions to ensure the need for asset reinforcement is optimised.

UK Power Networks traditionally manage their distribution networks and DER connections via a standard Supervisory Control and Data Acquisition (SCADA) network, supported by Advanced Distribution Management System (ADMS) software applications. In order to manage the challenges associated with the large-scale integration of DERs into the distribution network, UK Power Networks have deployed a Distributed Energy Resource Management System (DERMS), with Active Network Management (ANM) capability, to provide a broad range of services addressing flexible connections, flexibility services, and network optimisation. However, for the DERMS to function, it requires access to real-time data associated with both the DER and the surrounding power network. If connectivity between the distribution network and DERMS is lost (e.g. due to telecommunications failure) then the DER in the impacted area is required to automatically curtail to a known safe level, or even to disconnect entirely to protect the integrity of the distribution network. Additionally, when local network fault conditions occur, the existing protection arrangements may cause DER to be disconnected even if not directly impacted by the fault. A method of preventing such disconnections is by enhancing the network protection required in order to prevent unnecessary loss of generation, allowing the DER to ride through transient instability events.

8 https://www.legislation.gov.uk/ukpga/2008/27/section/14
9 https://assets.publishing.service.gov.uk/media/65c0d15863a23d0013c821e9/2022-final-greenhouse-gas-emissions-statistical-release.pdf
10 https://www.gov.uk/government/publications/net-zero-strategy
11 https://www.gov.uk/government/publications/powering-up-britain/powering-up-britain-net-zero-growth-plan
12 https://www.gov.uk/government/statistics/uk-energy-in-brief-2021

With the continued exponential rise in connected DER over the coming years, the sudden loss of significant amounts of DER, following the above curtailment and disconnection events, may have severe consequences on the stability of the distribution network, and wider system, by potentially influencing grid frequency and electricity network loading leading to potential black or brown outs.

Constellation Aims

The primary aim of Constellation is to support achieving Net Zero by introducing new systems and architectures, which will permit an increase in the use of flexibility to better optimise future development of the electricity networks, in order to:

- Unlock network capacity (thus allowing additional DER to connect in the most cost-effective manner) whilst still maintaining system stability;
- Protect the use and operation of flexibility services by removing their reliance on telecommunication links back to a central control site, and by the application of sophisticated adaptable local PAC systems; and
- Enable a secure and flexible environment for scalable deployment of smart functionality across substations on the distribution network.

Constellation will demonstrate these primary aims by developing and trialling novel approaches to network PAC based on the introduction of local intelligence within DNO substations (known as "digitalisation"). In order to support the introduction of such local intelligence, secure and Ultra-Reliable Low Latency Communications (URLLC) between sites (based on 5G slicing) will be designed, implemented and trialled.

The novel approaches designed will be thoroughly tested at an "off-site" testing environment in PNDC before being implemented and tested at selected trial sites within UK Power Networks' distribution network.

Further Constellation aims are:

- To demonstrate that distribution substations can take advantage of modern digitisation techniques to rationalise the deployment of software applications across a minimal set of hardware ("virtualisation");
- To demonstrate that hardware and software from different vendors can be seamlessly integrated on a common platform ("interoperability");
- To provide an environment for quick and scalable deployment of smart network functionality as BaU software solutions;
- To demonstrate that, by introducing new technologies, the above can help enhance the cyber security of critical infrastructures; and
- Provide financial benefits through reduced over-procurement of flexibility services due to enhanced network visibility.

1.3 Summary Details on Individual Project Elements

Constellation will design, test and implement two distinctly different project Methods to demonstrate the benefits that can be achieved by providing local intelligence at the distribution substation level.

1.3.1 Method 1: Local ANM

This project Method will provide local network control and optimisation at the distribution substation level to provide resilience to DER operation against loss of communication with the central ANM system.

Whenever the central systems are unable to communicate with local network assets, the local intelligence at the area level will take over management for that specific provider, substation or area. If communications are lost between the substations within an area, then local intelligence at the generation sites will take over management for that site. This will enable the network to be operated more optimally, controlling the area locally, compared to curtailing the provider.

It will achieve this using high resolution measurements of network parameters at the Grid substation and DER sites, and identification processes of the network condition and its changes. This will result in improved DER asset operation during events when the central ANM system and/or DER communication links are unavailable. This concept is shown graphically in Figure 1.

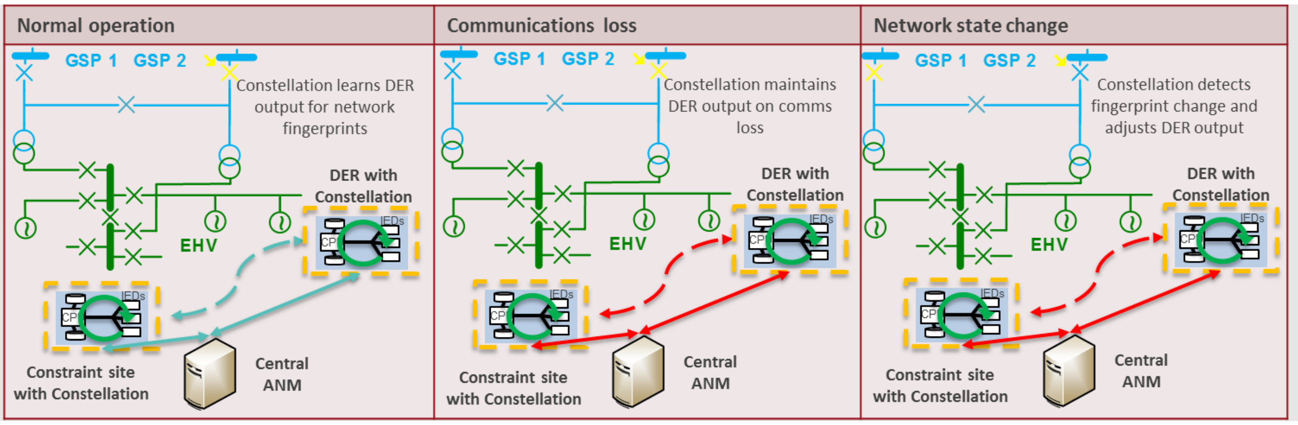

Figure 1: Local ANM (Method 1) Summary Diagram

1.3.2 Method 2: Wide Area and Adaptive Protection

This project Method will comprise of two distinct aspects, one designed to secure DER operations and the other to release additional network capacity. Each aspect is described individually below.

<u>Wide Area Protection</u>

Wide Area Protection (WAP) provides resilience to distributed generation (DG) operation against instability events triggering the conventional generator protection. Constellation will develop sophisticated protection algorithms to identify when the DER should disconnect if events have caused islanded operation. WAP algorithms will provide tripping and blocking facilities to DER sites in order to enable them to ride through an external network fault and support the distribution network by tripping out only under genuine Loss of Mains (LoM).

This will be achieved via the application of site-to-site communications utilising a low latency 5G telecommunications network to transmit Generic Object Oriented Substation Event (GOOSE) messages.

The above approach is in line with Engineering Recommendation (ER) G99[13] which provides the requirements for connecting generation equipment in parallel with public distribution networks, as well as complement with ER G59/3-7[14], which requires generating site owners to comply with the existing Accelerated Loss of Mains Change Programme (ALoMCP).

The wide area element of this Method provides protection capability across wider local areas through secure and scalable site-to-site communication. This represents a change in approach to generator protection, where the focus is to keep the generation connected, if at all possible, as opposed to disconnect it if there is any risk. This concept is shown graphically in Figure 2. If the DER is located outside the fault zone, a blocking signal will be used to ensure it stays connected. Similarly, the blocking signal will be used to prevent unwanted disconnections resulting from general system disturbances. Moreover, WAP will ensure disconnection if the DER is located within the fault zone. This is achieved through an intertrip signal.

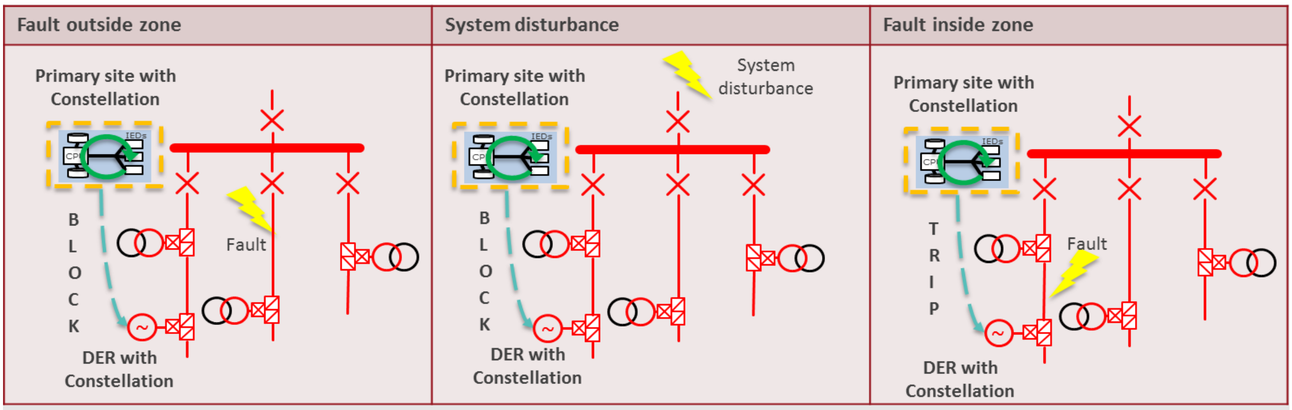

Figure 2: Wide Area Protection (Method 2) Summary Diagram

<u>Adaptive (load blinding) Protection</u>
In addition to WAP, dynamically adapted protection settings and enhanced wide area control will enable more flexibility for DER to connect. Constellation will develop the ability to supply dynamic protection settings from the substation to validate and modify load blinding protection settings[15] as required. This is a different approach to the traditional statically designed and rarely changed settings or to the approach of a small number of settings "groups" for a site.

Supplying dynamic protection settings will allow the load blinding protection function to adapt to the different topologies of the network, correctly discriminate between genuine faults and generation/load, and allow the release of capacity for more generation to connect to the distribution network. This concept is shown graphically in Figure 3.

[13] ENA EREC G99 Issue 1, Amendment 6
[14] ENA EREC G59, Issue 3, Amendment 7
[15] Load blinding protection settings are used to prevent distance relays from malfunctioning and tripping circuit breakers when there is a heavy load in the system or to mitigate the onset of cascading outages that can lead to widespread blackouts.

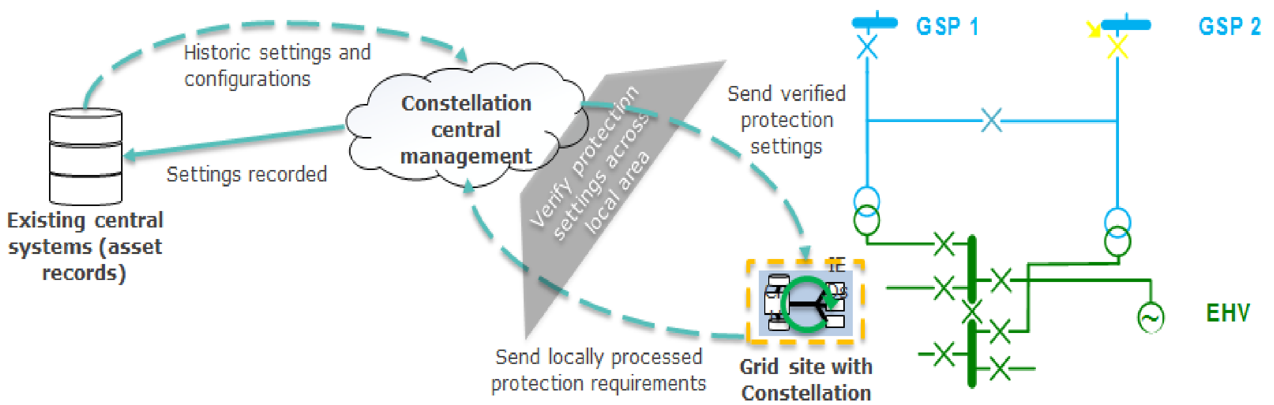

Figure 3: Adaptive Protection (Method 2) Summary

1.4 Project Methods and Constellation Solutions

The Methods designed and developed in Constellation, as described in Section 1.3, involve a number of interacting elements as well as integration of hardware, software and communications. In order to simplify the complex jargon used in Constellation, Table 4 below summarises the elements and Figure 4 visualises them.

Table 4: Summary of Constellation Elements

Constellation Elements
Platform: Refers to the hardware and software required for Constellation. This includes the Substation Server which hosts the physical resources for the Methods and the software which enables the virtualisation of the PAC functionality. This also includes devices which collect measurements from the network and the communication network within the substations and associated communication switches, routers and firewalls.
Solutions: Refer to the products developed by the project partners. This includes Method 1, Method 2 and the 5G slicing. The Solutions can consist of a number of systems and subsystems.
Methods: As defined in the NIC governance, Methods refer to the proposed way of investigating or solving the problems. In Constellation there are two Methods, consisting of three Solutions: • Local ANM (Method 1); • Wide Area Protection (Method 2); and • Adaptive Protection (Method 2).

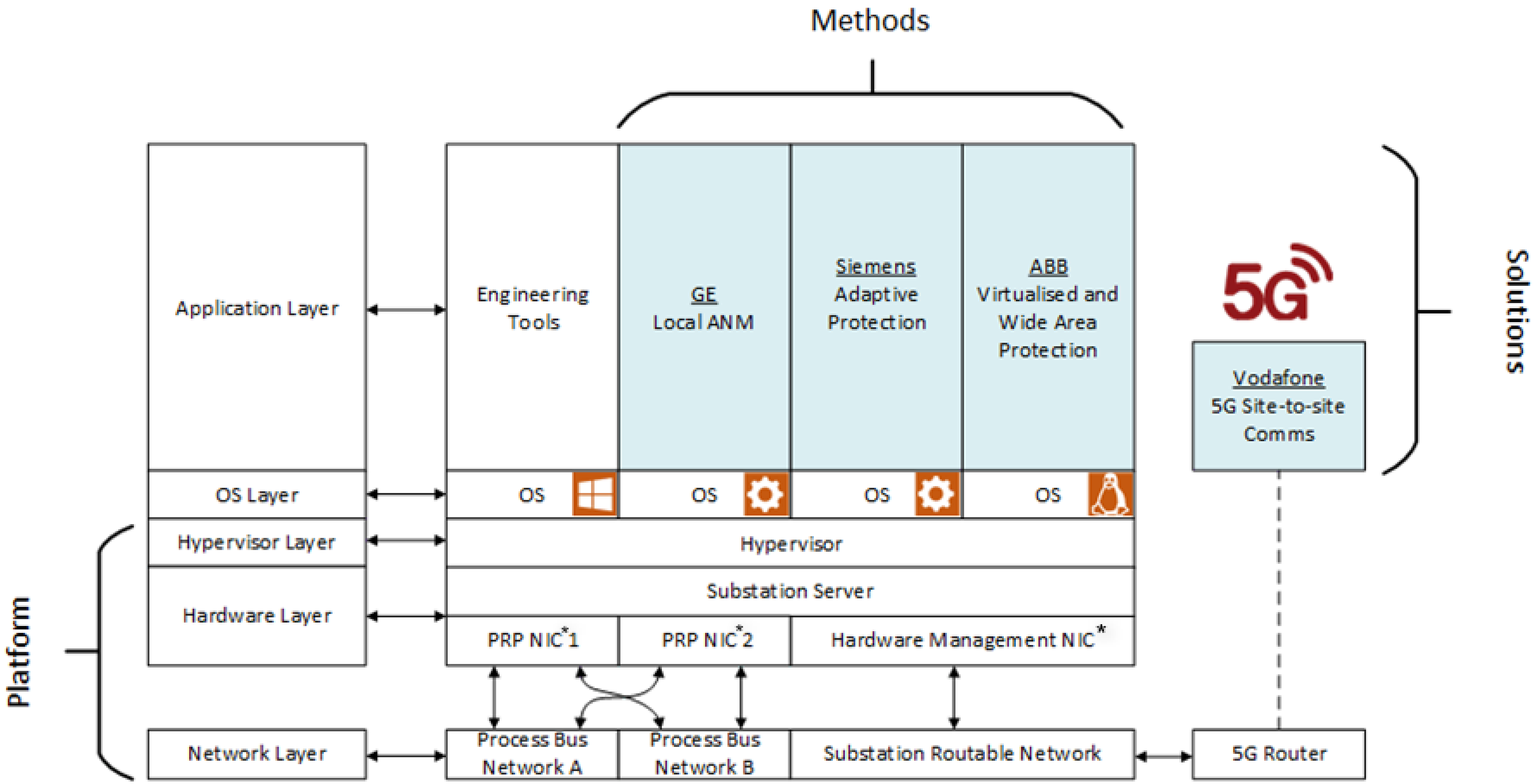

Figure 4: Constellation Elements

* NIC in the figure above, refers to the “Network Interface Card”.

1.5 Project Organisation

Due to the complexity of Constellation, combined with the fact that it is a multi-faceted technology project, Constellation will rely on a collaborative approach amongst a project team of global leaders in technology and innovation to deliver the project successfully.

A description of each partners' roles and responsibilities within Constellation is provided below and summarised within Figure 5.

The Design Authority, whose responsibility it is to review and approve all the key project design deliverables, will not only comprise technical leads from UK Power Networks, but also from PNDC Digital Substation Working Group (WG), which has key experts from Scottish Power Energy Networks and Scottish and Southern Electricity Networks. This will provide a much-valued multiple DNO input and design oversight to the project.

Furthermore, learning dissemination is essential to ensure the entire industry benefits from the learnings from Constellation. Therefore, throughout the project learning dissemination activities will be undertaken by all project partners, led by UK Power Networks.

Project partner roles in Constellation

UK Power Networks: Project lead and overall manager of the Constellation project. UK Power Networks will provide necessary governance to ensure that it delivers the required benefits, identify and prepare the trial sites, procure the required hardware and lead Workstreams (WS) 1, 2, 5 and 6. Additionally, UK Power Networks will provide distribution network expertise and services across all WS.

University of Strathclyde's Power Networks Demonstration Centre: In addition to the WG participation, PNDC will also provide the necessary "off-site" environment whereby all equipment and systems can be thoroughly tested prior to implementation and testing on a live power distribution network. PNDC is leading WS 3 and 4.

GE Vernova (previously referred to as GE): Providing specialist engineering expertise to design, develop and demonstrate the Local Active Network Management (Local ANM) Solution. GE Vernova is also supporting integration activities to the ADMS.

ABB: Providing specialist engineering expertise to design, develop and demonstrate the WAP Solution and virtualised protection.

Siemens: Providing specialist engineering expertise to design, develop and demonstrate the Adaptive Protection System (APS) and the Central Management System (CMS).

Vodafone: Providing specialist engineering expertise to design, develop and demonstrate the low-latency 5G slicing telecommunications capable of operating within a virtualised environment, which links the substation sites.

In addition to the above, in order to provide maximum confidence that the systems designed by the respective partners are able to be integrated seamlessly, UK Power Networks have engaged the services of the following three **specialist suppliers**:

- **OMICRON Electronics GmbH**, who will provide specialist support during the testing. OMICRON will also provide substation simulators capable of interacting with the various system messages being transmitted between vendors systems in order to detect potential conflicts. OMICRON will participate during both the off-site and the live network trials;

- **Siemens RUGGEDCOM**, who will support the provision of the communications equipment, 5G routers and switches, at the substation level;
- **JRC (Joint Radio Committee)**, who will provide technical support on the 5G Slice design and 5G site specific design.
- **UK Power Networks Services,** who will support the project team with onsite installations and various commissioning and testing activities; and
- **Technical Control Systems**, who will support with designing and assembling the Constellation cubicles in line with the site requirements.

To efficiently manage the project Methods given that there is some technical, testing and learning overlap between them, six WS have been implemented as detailed in Table 5 below. The responsibility for delivering and managing each individual workstream has been assigned to a specific partner on the project, as described in Figure 5.

The trial phase of the project, managed under Constellation WS 3, is responsible for de-risking the Solutions prior to BaU rollout. The trial phase encompasses offline trials at PNDC and network trials (both Passive and Active) within UK Power Networks' operational network.

Table 5: Definition of workstreams

Workstream	Description
WS1	Responsible for the specification, design and development of the software, architecture, integration and cyber security aspects across all Constellation elements.
WS2	Responsible for the specification, design and development of the functionality (performance) of all Constellation elements and the Equipment which will be trialled.
WS3	Responsible for the design and management of the Constellation trials, which incorporate off-network trials hosted at PNDC and network trials hosted on UK Power Networks' distribution network.
WS4	Responsible for running the Open Innovation Competition (OIC), which involves testing additional methods for deployment on the Constellation Platform.
WS5	Responsible for the academic insights and research into the future governance.
WS6	Responsible for the dissemination of the knowledge generated from the project.

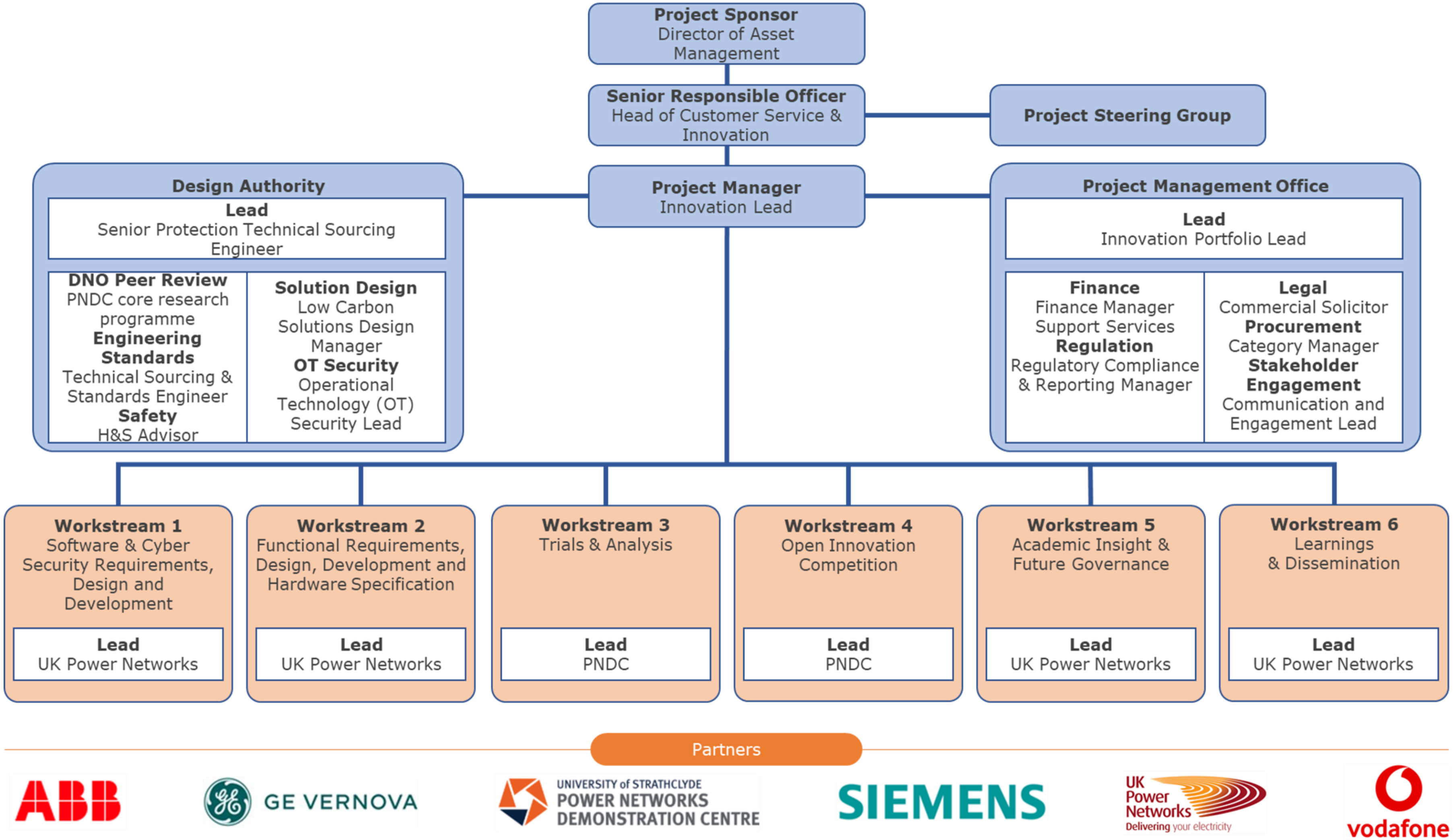

Figure 5: Project Organisation and Workstream Leads

2 Ensuring Readiness of the Constellation Solutions

2.1 Overview

Constellation is a multi-faceted and inherently complex technology project. Therefore, it necessitated the design of robust Solutions to deliver the project goals, the development for which has been reported upon within Deliverable D3[16].

To ensure readiness of the Constellation Solutions, extensive integration and off-network testing has taken place at PNDC to verify each Solutions robustness and compliance with the specified functional and performance design criteria. The Solutions were proven to perform as intended and when issues were identified, the iterative design approach ensured the coordinated resolution of such problems. Details of the lessons learnt from this iterative testing process are reported upon on the PPRs and key learnings to date are summarised in Appendix A.1.

Another important aspect of ensuring readiness is the robustness of the virtualisation Platform that hosts the various Constellation Solutions. Therefore, in parallel with integration and off-network testing at PNDC, the virtualised Platform was subjected to rigorous testing as summarised in Section 2.2 below. Key lessons learnt from testing the virtualised Platform are also provided at the end of this section, with key examples summarised in Appendix A.2.

In addition, since commencement of Constellation, the complex issues associated with ensuring UK Critical National Infrastructure is protected against the potentially harmful impacts caused by malicious cyber security attacks have escalated. This has required Constellation to continuously assess existing and emerging threats in detail and implement necessary measures to provide protection as summarised in Section 2.3 below. Lessons learnt from progressing the cyber security aspects are provided at the end of this section, with key examples detailed in Appendix A.3.

2.2 Virtualisation Platform

2.2.1 Introduction

One of the key aims of Constellation is to create a Platform that enables various innovative Solutions to work interoperably in a compact and robust environment within substations. Therefore, it is of utmost importance to ensure that such Platform is fit for purpose and is capable of performing as needed, both safely and reliably. The virtualisation Platform in Constellation has been subjected to rigorous tests, such as creating and running multiple virtual machines (VMs) on the physical servers to simulate different operating systems (OS), hardware configurations, and network conditions.

The tests were designed to verify the correct operation of the virtualisation Platform under the following conditions:

- Functional Testing of hypervisors and memory resources;
- Performance Testing of hypervisors and memory resources; and
- Security Testing of the network resources and access control.

[16] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-3-v1.0-Redacted.pdf

The primary objective of this testing is to verify the correct functionality and baseline performance of the various components of the Constellation virtualisation test environment at PNDC. The test results evidence the functionalities, performance and quality of the different virtualisation technologies developed including the key aspects tested and the test methods.

The tests undertaken are summarised within Section 2.2.2 with further details provided within Appendix A.2.

2.2.2 Summary of Testing

Prior to commencing test and evaluation, the test setup was prepared and the virtualisation hardware, software environment and network settings were configured as necessary.

The first step of the process was benchmarking. This required all aspects associated with the test environment memory, Central Processing Unit (CPU), disk space, network bandwidth, and management to be benchmarked using the Hyper-converged Infrastructure Benchmark (HCIBench)[17] tool. This tool facilitates testing automation across the IT infrastructure.

Following benchmarking, a smoke test[18] was then successfully undertaken. The results from the smoke test demonstrated that the test setup, configurations, software and hardware functioned correctly and operated as intended. The results obtained from this stage of the testing are detailed in Appendix A.2.1.

The next step of the process was to undertake the predefined test scenarios as detailed in this section's introduction and the findings are summarised as follows:

- Functional testing: These tests monitored the ability of creating VMs on the Platform in addition to the networking functionalities of all VMs.
  - VM creation and operation – Validated the ability to create a VM within Hypervisor hosts including the start and stop operation; and
  - VM Network Connectivity – Validated the VM network connectivity and integration with virtualisation systems and services.
- Performance Testing: These tests monitored the performance of developed PAC applications deployed in the virtualisation testbed to ensure efficient and accurate operation:
  - CPU, memory and storage resource usage measurement – Verified correct sizing and configuration was provided to ensure performance requirements are met;
  - CPU and memory adequacy – Validated that CPU and memory on each Hypervisor host are adequate and not causing congestion issues in terms of VM interaction with the underlying Hypervisor host's CPU;
  - High availability – Validated that in case of a single Hypervisor host failure, all affected VMs are powered back up onto other Hypervisor hosts in the cluster;
  - Network Input/Output (I/O) control shares and limits – Validated that network I/O control shares protected higher weighted traffic types in the event of contention and that the network I/O control limits are honoured for given traffic types;
  - Latency and response times – Verified that the networking configuration in the Hypervisor host was able to offer sufficient network performance for critical applications under load and no-load conditions;

[17] https://docs.vmware.com/en/VMware-Greenplum/7/greenplum-database/vsphere-validating-vxrail.html
[18] Smoke testing aims to discover simple but severe failures using test cases that cover the most important functionalities of the software solutions.

- Ability to update manager via the vSphere Client – Validated that the update manager was accessible and operational via the vSphere Client; and
- Failover – Hardware or network failures and VM failover have been simulated/tested in order to verify correct operation.

Appendix A.2.2 provides details of a selection of the above tests.

Some virtualisation Platform performance tests were limited due to the available setup in the PNDC test facility. These include some additional redundancy, performance, and load balancing tests. These tests, which are summarised below, will be further investigated on site to ensure accurate representation of the Constellation setup.

- Storage path availability – Validation that storage path failure and failback work as expected; and
- Network availability – Validation that in the event of a single upstream network failure (switch or switch port failure), the network connectivity to Hypervisor management and VMs remains active.

Through successfully progressing with the virtualisation Platform testing as highlighted in this section, Constellation was able to validate many key project uncertainties which are summarised in the following lessons learnt table.

Lessons Learnt (Virtualisation Platform Testing)	
1	VMs can be easily created on any host with failovers enabled on redundant hosts. The VMs can implement independent OS and deliver different solutions with their unique storage facility.
2	Optimal VM configuration was identified to enable VM traffic prioritisation. The trial results demonstrated that the virtualisation Platform is suitable for high-priority data in near real-time transmission.
3	Optimal minimum network bandwidth control share was experimentally proven to be best defined at 1Gbps. Since the minimum was defined, it allows the data transfer to exceed the minimum depending on available network resources and inherently ensures that sufficient bandwidth will always be maintained.
4	The functionalities require defined settings and configurations of the virtual Platform. Consequently, while certain settings are suitable for performance testing, they may conflict with other forms of testing, e.g. opening Secure Shell (SSH) ports for accessibility may compromise the system security. Therefore, it is recommended that the system usage should follow a strict management procedure considering hypervisor alerts and returning settings as required after use.
5	Dynamic allocation of resources: most of the system resources are statically defined. Consequently, resource-sharing capabilities would be limited under unbalanced load operations of the VMs. The scalability and utilisation of the virtualisation resources (CPU, memory) can be improved by exploring dynamic resource allocation schemes.

2.3 Cyber Security

2.3.1 Introduction

Due to the importance of maintaining security of the UK's Critical National Infrastructure, especially during the current period of heightened cyber security threats, Ofgem and the Department of Energy Security and Net Zero (DESNZ) continue to work with the DNOs to implement the legal measures detailed within the Network and Information Systems Regulations 2018[19] and the requirements outlined within the National Cyber Security Centre (NCSC) Cyber Assessment Framework (CAF)[20].

Constellation is increasing the level of digitalisation within the distribution networks' substations by introducing modern innovative Solutions which inherently increases the consequential risks associated with malicious cyber security attacks. Therefore, to ensure the security of the network, Constellation provides opportunities to increase our cyber resilience to level we could not achieve pre-Constellation.

As such, UK Power Networks, in collaboration with the project partners and suppliers, have developed a cyber security evaluation plan which outlines the physical and cyber security testing activities required to be undertaken at PNDC prior to delivery of the Solutions to site, in order to demonstrate the cyber security risks associated with integrating Constellation are defined, tested and mitigated.

The security testing of the Constellation Platform at PNDC on both the Local Area Network (LAN), Wide Area Network (WAN) and remote access layers is evaluated with a systematic approach encompassing reconnaissance, vulnerability assessment, exploitation and remediation stages to guide deployment at the UK Power Networks' Constellation trial sites. The LAN testing will help to identify potential weaknesses by simulating real-world scenarios, such as privilege escalation and lateral movement concepts. Similarly, WAN testing extends to cloud platforms and Virtual Private Networks (VPNs), with a focus on identifying misconfigurations and vulnerabilities in WAN, cloud services, VPNs or other network resources and segments.

A summary of the evaluation plan, together with how the required tests are successfully being undertaken and the results obtained are detailed in Section 2.3.2 below. Further details are contained within Appendix A.3.

2.3.2 Evaluation Plan

The cyber security evaluation plan for the Constellation Platform outlines the appropriate physical and cyber security testing activities necessary for the project. These include core security evaluation activities such as conducting vulnerability assessments of LAN, and WAN. Additionally, they include other specified resources based on the internal UK Power Networks' Engineering Technical Specifications like the security assessment of substation computer operating systems, third-party software applications, and intrusion detection systems.

The plan consists of a series of tests designed to exercise and analyse cyber risks to Constellation's WAP, APS and Local ANM Solutions. To ensure the security of the Constellation Methods cyber-attack tree methodologies were developed for each individual Solution, as provided in Appendix A.3.1.

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19 https://www.legislation.gov.uk/uksi/2018/506
20 https://www.ncsc.gov.uk/collection/cyber-assessment-framework

To complement the above, the tests were designed to adopt a secure by design approach in order to evaluate the layered security architecture of the test Platform. Aspects considered included the following:

- Access security control: the process of restricting access to virtualisation data and resources e.g. authentication/verification;
- Attack surface: all the vulnerability points of unauthorised entry used to attack the system data or resources;
- Least functionality: ensuring that all parts of the virtualisation platform use only the essential functions or capabilities at any time;
- Security hardening: actions or procedures that reduce the vulnerabilities of a system and prevent cyberattacks e.g. applying patches and updates;
- Data flow: data path from source to destination; and
- Logs collection: the process of keeping logs or events happening on the virtualisation platform.

The cyber security evaluation plan was jointly developed between UK Power Networks, PNDC and OMICRON, then reviewed and approved by cyber security and IT specialists within UK Power Networks.

The key activities of the cyber security testing at PNDC have now completed successfully. This ensured the readiness of the Solutions to be progressed into the Network Trial stage. Additionally, functionalities associated with verifying the vulnerability of the systems to external threats is continuously tested over the course of the project lifespan to ensure continued system security.

2.3.3 Test Methodology and Results

In order to ensure the tests were able to proceed robustly and accommodate the necessary auditable verifications, various software tools were used within the test Platform.

The main tool used was OMICRON's StationGuard solution as this had the capabilities to undertake testing for intrusion and threat detection, creating asset inventory/visibility, providing visibility of communication risks, along with vulnerability management and the functional monitoring for device, communication, synchronisation, interoperability and configuration issues.

A comprehensive suite of test cases was developed, aligned with best practices and regulations from the NCSC and Network and Informational Security (NIS) directives. The test cases developed for Constellation have all been developed on the basis of "zero trust" with all local and remote connectivity (e.g. it is assumed a threat always exists and no connection is completely safe), whilst exercising the LAN, WAN, access control, resource evaluation, security patching and Hypervisor security interactions.

The tests conducted validated the secure operation of network devices and protocols across both the LAN and WAN layers. For LAN, it confirmed the security of network devices, focusing on areas like port security, VLAN segmentation, and intrusion detection. WAN tests ensured the security of routers, IPSec tunnels, and intrusion prevention systems, identifying vulnerabilities and missing patches.

Access control was verified for correct operation of network permissions. Resource evaluation confirmed presence of the latest security software. It also validated the deactivation of unused ports. Security patching validated that all network components are up to date with firmware and patches. Hypervisor security tests confirmed that all settings, configurations, and hosts are completely protected from any unauthorized access or misuse.

Appendix A.3.3 provides further details on a selection of the specific test methodologies and results obtained from the testing undertaken to date.

Lessons Learnt (Cyber Security Testing)	
1	Access controls: Access to the Hypervisor host interfaces is granted through SSH, Hypertext Transfer Protocol Secure (HTTPS), with appropriate authentication via password verification. However, the management Hypervisor host implements a positive cybersecurity feature by disabling the SSH services. The Hypervisor will be centrally managed through the Hypervisor centralised management Platform to ensure that local access, if required, can be managed/ disabled centrally. Through the UK Power Networks Cyber Resilience Programme, access to the Hypervisor will be controlled via a specified Privileged Access Management (PAM) solution which will include Centralised Authentication and Multi-factor Authentication (MFA), with full session auditing. The host root account password will be rotated on a scheduled basis to avoid lengthy password ages.
2	Patches and updates: Software patches and updates are checked automatically which is essential to ensure that the most recent versions are installed on the systems. However, the system is not connected to the internet to get the patches. This applies to the Hypervisor hosts and VMs. Therefore, manual patches and updates must be undertaken manually on a regular basis. It is Important that patching systems, both Hypervisor and VMs are conducted under a controlled manner through the change management life cycle process, where testing has been completed to ensure compatibility and system stability. Through the UK Power Networks' Cyber Resilience Programme, vulnerability management of the Constellation Platform will be conducted in real time and reported on. From this, the criticality and exploitability of the vulnerability will inform the urgency of any patch implementation
3	Media Access Control (MAC) address: Changes of MAC address to network resources are rejected which is a positive security feature restricting unauthorised device access. This Hypervisor feature should not be changed as it can comprise the Platform.
4	Port management: Ports are opened on the Hypervisor hosts and other switches for testing and administrative purposes. However, these ports are not automatically closed which can pose a security risk. Procedures have therefore been introduced to ensure these ports are manually closed following completion of test activity. Through the UK Power Networks' Cyber Resilience Programme, base line configurations will be monitored, and verification of systems baselines and configurations will be monitored and alerted on where applicable.

5	Service status: Most services start and stop manually or when the host is switched on. To improve cyber security, the services settings were changed to start and stop depending on port usage. This will ensure that non-essential services are not running.

3 Preparing the Network for Constellation

3.1 Overview

In order to ensure the project readiness for network trials, it is essential that defined site preparation procedures are followed. This allows the site preparation activities to be standardised and optimised which shall facilitate future network trials and the BaU transition of Constellation once proven successful.

A prerequisite step to start this process is sites identification and selection. For project Constellation, a detailed five-stage site selection process was completed as outlined in Deliverable D2. It is important to highlight that the primary considerations when selecting any site for an innovation trial are:

- Identify areas of the network that align to the scope and requirements of the project;
- Select sites which are on sufficiently different parts of the power network to maximise learning; and
- Demonstrate different aspects of the project designs and their respective functionality.

For reference, the sites chosen for Constellation are detailed in Table 6 below.

Table 6: Constellation Sites

Maidstone Trial Area	
Grid	**DER**
Maidstone Grid	DER-1
Thanet Trial Area	
Grid	**DER**
Thanet Grid	DER-2
	DER-3
	DER-5
	DER-4

Another important subsequent activity that must be carried out prior to commencing any on site activity is the completion of all necessary FATs of the various equipment and Solutions to be used as part of Constellation. Such process has been outlined in Deliverable D3[21] of the project.

The Constellation site preparation procedure is illustrated in Figure 6 below. This procedure can be summarised as follows:

- Step 1: All trial sites must be assessed through surveys, drawings review, and design validation to develop a robust understanding of the site characteristics and plan ahead for Constellation deployment. This step is detailed in Section 3.2;
- Step 2: Site works must be carried out safely and in accordance with UK Power Networks standards and regulations. Outages must be booked where necessary, but

[21] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-3-v1.0-Redacted.pdf

efforts must be put in place to minimise the potential impact on DER customers. The process of completing the site upgrades is detailed in Section 3.3;

- Step 3: Another key site activity is upgrading the existing communication assets such as RTUs to enable the necessary functionalities required by the Constellation Solutions, as detailed in Section 3.4; and
- Step 4: The Constellation cubicle design is dependent on various site characteristics such as type, size, environment, and special constraints. The installation must be tailored to ensure optimal performance for the Constellation Solutions, as detailed in Section 3.5.

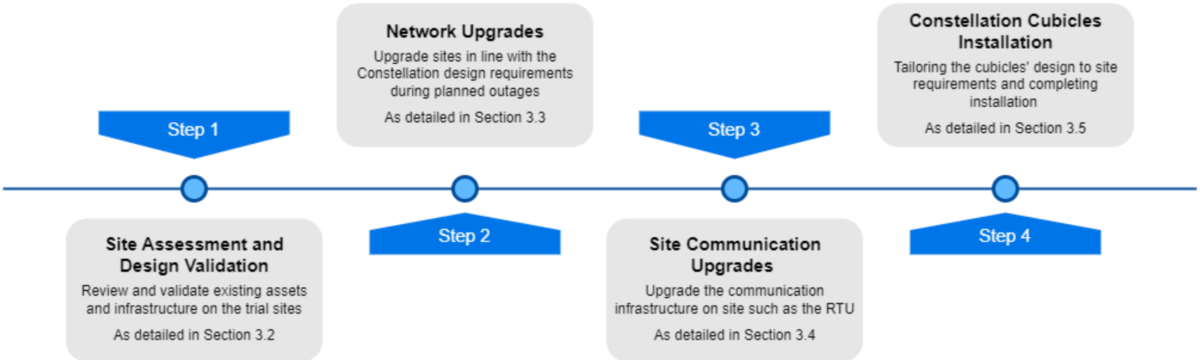


Figure 6: Constellation Site Preparation Procedure

In Constellation, the installation works initially commenced within the Maidstone trial area, with lessons learnt applied to the installations with the Thanet trial area which allowed further refinement and practical execution of the developed procedures.

The majority of all the above referenced activities have been undertaken by UK Power Networks' engineering teams, with support from the respective project partners when required. This ensures that the workforce is upskilled for these tasks which facilitates the BaU transition of the project once successful.

A summary of the key lessons learnt whilst preparing the network for Constellation is provided in Section 3.6. Furthermore, Appendix A.1.2 provides a full list of all lessons learnt during this stage of the project.

3.2 Site Assessment and Design Validation

Site surveys are essential to validate the site characteristics. The process of carrying out a site survey relied on existing standard practices and was tailored to Constellation. These practices include extracting the latest version of all existing site drawings which, for the Constellation project, are stored on UK Power Networks' SharePoint site under the relevant licenced network area.

The extracted drawings must undergo a detailed review against the site survey and existing equipment before modification to ensure they are up to date. This review will also determine which drawings may require revision (including, for example, the creation of red and green markups[22] to record the modifications required to the assets as the site works progress). Following this, a site drawing register must be compiled capturing all existing drawings that will require revision for site record and Quality Assurance (QA) purposes.

[22] Refers to the industrial-standard colour coding for marking up a drawing is: red for new, green for delete.

New drawings must reflect any phased installation works together with the ASB drawings for all new Constellation equipment. Such equipment is installed as "stand-alone" and not integrated within any existing asset.

The following types of drawings would typically be reviewed as part of this process:

- General arrangement drawings (cubicles, panels etc);
- Schematics and wiring diagrams;
- Cable schedules (power, communications etc);
- Cable installation and tray/duct drawings;
- Equipment Interface engineering drawings;
- Power supply requirements; and
- Civil works.

In addition to the above mentioned drawings, procedure documents covering the process of safe and appropriate progression of the works required by Constellation on site must be created, along with the necessary site commissioning files.

For reference, an example of a drawing that was produced as part of the Constellation site preparation activities can be found in Appendix A.4.7.

For Constellation, the design development of each Method and its application on site has been detailed within Deliverable D3[23]. Whilst progressing Constellation, certain aspects associated with the general design and network architecture have required adjustment to ensure optimal functionality and performance can be maintained. The changes made are summarised within the lessons learnt table within Appendix A.1.2.

Similarly, the network architecture had to undergo iterative changes based on the findings from the PNDC off-network testing and the progression on site. The finalised network architectures for each Constellation site are detailed within Appendix A.4.

3.3 Network Upgrades

A major part of the site installation works has been associated with the need to modify the existing switchgear located at each trial site location. This modification is required due to the following:

- Complete all wiring against the approved designs;
- The removal of existing redundant protection equipment; and
- Installation of the Constellation equipment within the required panels, which include:
  - Intelligent Electronic Devices (IEDs); and
  - Auxiliary components such as miniature circuit breakers, test blocks, terminal blocks and auxiliary relays.

[23] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-3-v1.0-Redacted.pdf

To facilitate the BaU transition of the project UK Power Networks developed standardised procedures to be used across all sites. These procedures cover the following activities:

- Electrical connectivity wiring between the IEDs, auxiliary and switchgear components;
- Installation and building of the Constellation cubicle which houses all communications equipment and fibre/category 5 links to the IEDs;
- Installation of fibre optic cables and/or patch cords to enable IEDs to connect with other devices via the Constellation network;
- Loading the latest configuration to the IEDs; and
- Validating that the installed devices and connections had been correctly deployed.

In order to ensure safety and to avoid interfering with the existing PAC systems in operation, all the above works have been undertaken under planned network outages, for which the considerations and processes undertaken are summarised below.

3.3.1 Outage Considerations and Processes

The secondary substations within project Constellation are dedicated to each DER site. Therefore, given the potential impact network outages may have on DER customers, UK Power Networks have carefully considered the optimal approach to plan and manage each site installation. This is crucial to avoid affecting the existing PAC systems in operation, whilst also considering how to mitigate network disruption to DER customers and owners. For clarification, no non-DER customers were impacted by these outage.

Early discussions with affected DER customers, notably the DER sites, were undertaken to ensure all parties had adequate notice periods for the forthcoming network connectivity disruption and understood the reasons for the outage. During such communications, any concerns raised were able to be discussed and resolved to both parties' satisfaction.

UK Power Networks prioritised the equipment installation works on circuits considered to be relatively simplistic, so that learnings could be gathered and used to verify the levels of complexity and task durations for site works associated with the more complicated installations.

This has proven to be extremely beneficial as learnings from the first installation resulted in a substantial Constellation cubicle redesign. Such redesign facilitated the progression of onsite installation, especially at the DER sites, and allowed the project team to overcome many environmental limitations. Additional information regarding this point can be found in Section 3.4.

Following that, the network outages for each site were proposed, agreed and entered into the UK Power Networks outage management portal, "Network Vision". This kept DER customers informed of start dates and times so that they could provide resources to operate their equipment at the start and end of the outages.

As an example, Figure 7 below provides a summary of how UK Power Networks scheduled the network upgrades for the Thanet area. If required, outages were booked for four days on average with the remainder time reserved for safely completing any outstanding activities before mobilising from site.

Additionally, and prior to any outage and equipment installation works commencing, UK Power Network's installation teams completed site safety inductions and put the legal requirements dictated by Construction (Design and Management) Regulations 2015 (CDM 2015) in place. This included assigning the duty holders and preparing the site CDM 2015 folder containing information relating to site inductions, hazards, fire escape plans and hours worked by staff on site.

At the time of writing, the Constellation installation associated with the final DER within the Thanet area has been postponed (highlighted in red). Additional details will be provided in the December 2024 PPR.

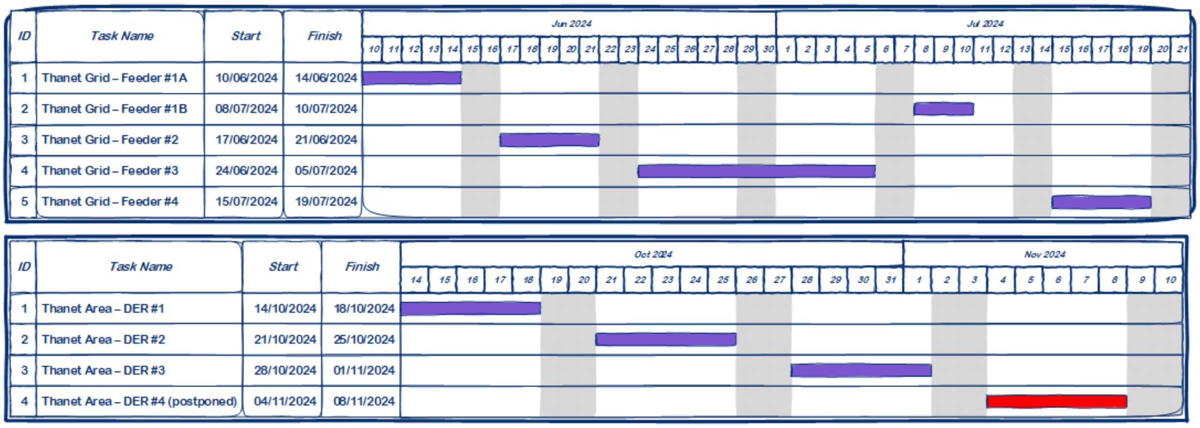


Figure 7: Thanet Area Network Upgrades Planning

For a Constellation site, the following site works activities have included:

<u>Pre-Outage</u>

- Creation/production of drawings and commissioning files to collect all relevant information during outages;
- Completion of staff training as required to cover aspects dictated relevant regulations for working within live electrical substations;
- Completion of CDM 2015 documentation and processes; and
- Scheduling outage with DER customer(s).

<u>During Outage</u>

- Isolating and switching out the 33kV feeders to make the equipment safe, followed by issuing Limitation of Access (LoA) safety documents for all 33kV outages;
- Removal of old (redundant) relay and switch equipment, as per the approved design. Where required, make new openings in the panels to house the new sub-rack;
- Installing new standard sub-racks to house the new IEDs;
- Carrying out wiring modifications as per the approved designs;
- Commissioning of new Constellation equipment including testing alarms back to UK Power Networks' control centre; and
- Completing switching procedures to re-energise DER customers affected by the planned outages.

Utilising learnings from multiple site activities and installation as part of Constellation, the network upgrade procedure regarding outage planning has been standardised. On any future site, the following sequence occurred during each outage period*:

- Day 1: Switching, isolating electric circuits, and issuing safety and operational documents. Followed by removal of all existing (redundant) equipment, preparing the panels to accommodate the new sub-rack and mounting all new equipment;
- Day 2: Carrying out wiring modifications as per the approved design drawings (Note: this took place over a three-day period for the DER sites due to the wiring complexities)[24]; and
- Day 3: Final wiring checks and commissioning of new equipment, including trip testing to ensure the circuit breaker operates when a fault occurs. Re-energising DER customers can then proceed following successful completion of all the above.

Post-Outage

- Monitoring equipment to ensure that faults have been accurately captured when interruptions to the network occur.

3.3.2 Constellation Network Upgrades

Figure 8, Figure 9, Figure 10 and Figure 11 below provide a selection of photographs detailing how these switchgear panel modification works have progressed across Constellation sites.

Appendix A.7 provides further photographic examples of the Constellation equipment as installed in the trial sites.

Figure 8: Examples of Maidstone Grid Switchgear Panels Containing Newly Installed Constellation Equipment

[24] Larger and/or more complex sites may require the outage plan to be tailored to the specific site characteristics.

Figure 9: Thanet Switchgear Room Following Constellation Equipment Installation

Figure 10: Examples of Thanet Grid Switchgear Panels Containing Newly Installed Constellation Equipment

Figure 11: Example of Wiring the New Constellation IED Equipment in the Switchgear Panel

3.4 Site Communication Upgrade

The Remote Terminal Unit (RTU) is an integral part of the UK Power Networks SCADA infrastructure, providing a bridge between network devices, IEDs and the central ADMS.

To achieve the scope of the Constellation project, RTUs are required to support:

- Distributed Network Protocol 3 (DNP3) communication protocol;
- International Electrotechnical Commission 61850 (IEC 61850) Edition 1 communication protocol; and
- Provision of dual communication channels.

In general, most DERMS RTUs are relatively new and are typically capable of achieving the above requirements following a relatively simple firmware and configuration upgrades. However, and to ensure the learnings from the Constellation project are maximised, the existing RTU installed at one of the DER sites required replacing. This was due to its inability to support the Local ANM logic and the required communication protocols. This allowed the project team to further document a standardised process that built on the existing RTU replacement program and tailored it to the Constellation use cases.

Both DNP3 and IEC 61850 communication protocols are designed to facilitate communications between the main process equipment, typically installed within a power utility environment. This includes communication between the substation computers, RTUs, IEDs and master stations, regardless of which vendor provides the equipment.

In this manner an open and interoperable system can be achieved which is not vendor constrained. This is of paramount importance within Constellation as the equipment utilised is sourced from a variety of suppliers, currently ABB, GE Vernova and Siemens, with equipment from additional suppliers due to be trialled during a later phase of Constellation.

Currently, when communications between the RTU and the centralised DERMS and ADMS systems have failed for a duration that exceeds a pre-determined timeframe, the RTU logic defaults to an Orphan mode in which fixed failsafe limits, set to the firm capacity of the DER (usually 0kW), are sent to the DER. Subsequently, the DER's ability to export to the network is curtailed, which corresponds to a revenue loss until communications are re-established.

Within Constellation, the Local ANM Solution "listens" to the RTU for the confirmation of communication loss with the central system. Upon receiving the confirmation, Local ANM will temporarily take over the constraint management of the DERs in a site, thus helping in a possible avoidance a full curtailment of the DER generation.

Under final configuration, the RTU will therefore be used to control flexibly connected DERs and act as a mediator between the centralised DERMS and ADMS systems, and the DER's controller. The RTUs have all been tested and proven to operate as intended. This was completed for BaU DERMS customers hosting the DERMS Logic and also for connectivity with the new Constellation equipment.

Figure 12 below details how the RTU interfaces with the wider UK Power Networks' systems. Additionally, Figure 26, which can be found in Section 4.2.8, further details how the RTUs are connected to the Constellation equipment.

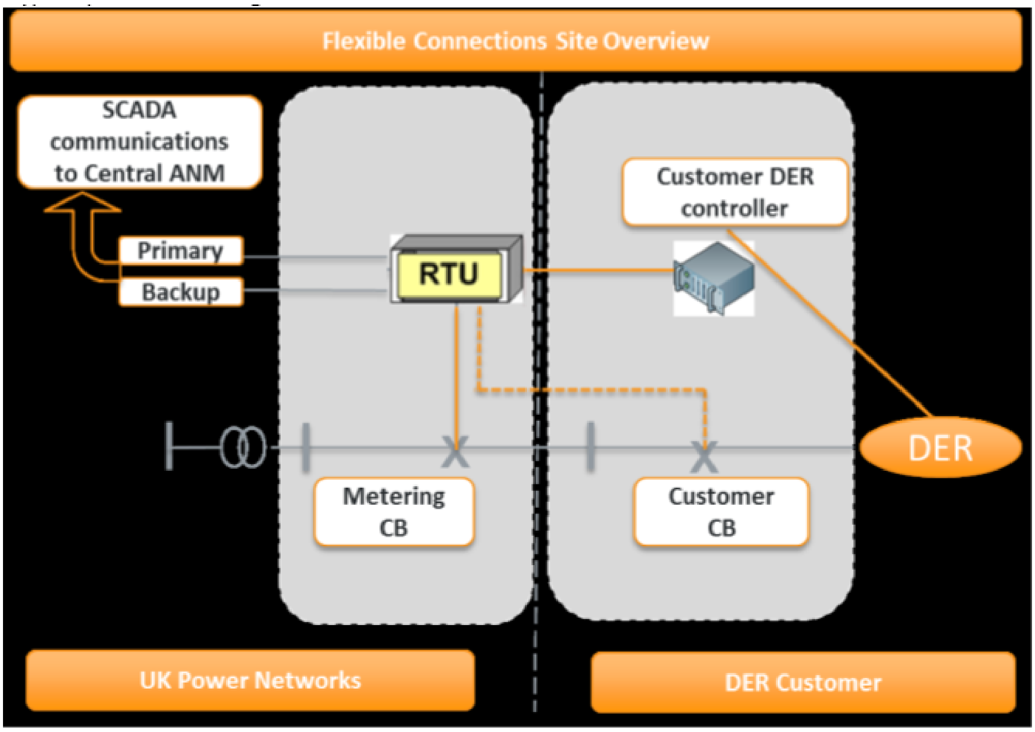


Figure 12: Typical RTU Connectivity for Constellation

Due to key learnings from the onsite activities, and whilst preparing the trial site for Constellation, a dedicated SCADA panel (DER constellation Cubicle) to house all the IEDs, server, switches and the RTU was designed as shown in Figure 13 below. This resulted in a more compact design that will facilitate BaU rollout of Constellation.

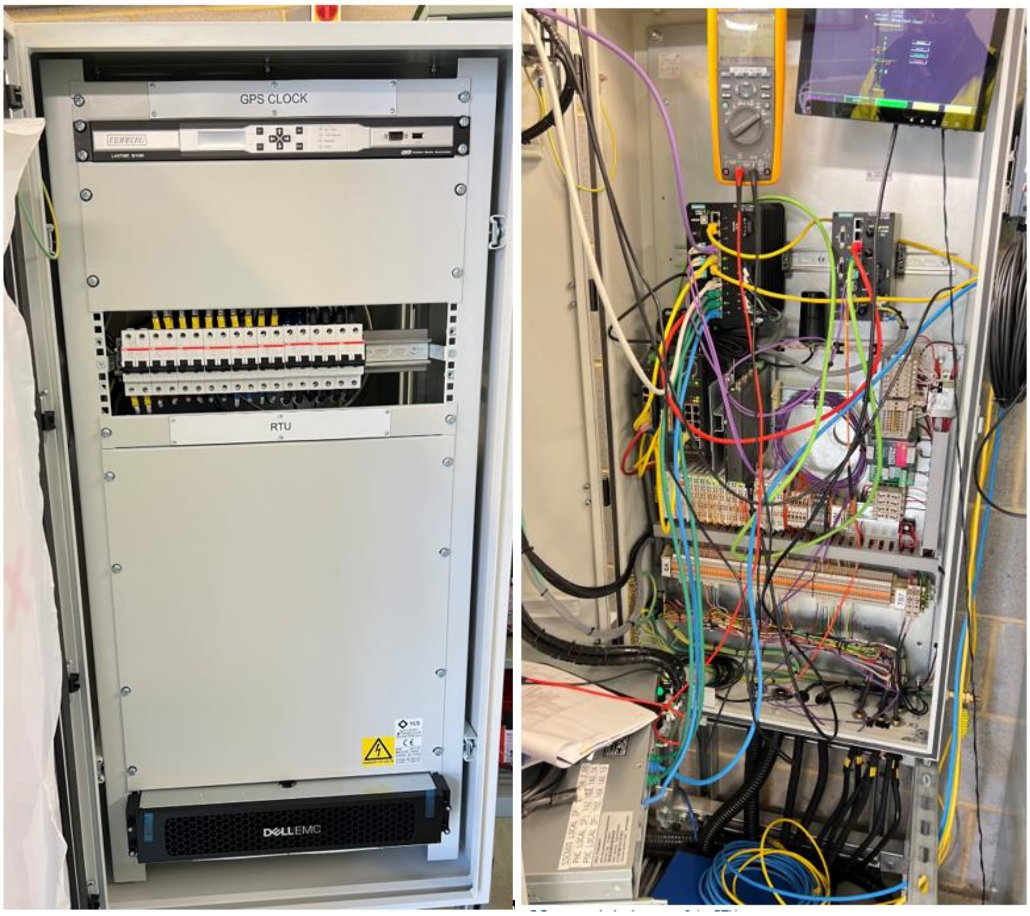


Figure 13: Combined Constellation Cubicle/RTU Installation and Pre-Commissioning Tests

3.5 Constellation Cubicles Installation

3.5.1 Overview

The purpose of the Constellation cubicles is to securely house key equipment required for the Constellation Solutions and, as such, considerations associated with its installation and commissioning processes must be appropriately completed to ensure successful operation.

For example, the Constellation cubicle houses the main Substation Servers and network switches, and therefore it must be securely installed within an environmentally controlled location with adequate access and availability of secure power supplies. Furthermore, when such conditions cannot be achieved, the design of the Constellation cubicle must be revised and tailored to the site conditions to overcome those challenges.

The following section details the specific equipment accommodated in each Constellation cubicle and, for completeness, Appendix A.4 provides the final architecture diagrams for each Constellation site, detailing all equipment installed at each site.

Additional details regarding the Constellation design and the developments of the cubicles can be found within Deliverable D1 of the project. Further developments have been reported upon within Deliverable D3[25].

3.5.2 Constellation Cubicle Design

Despite finalising the Constellation cubicle design at earlier stages of the project, the design continued to be reviewed and revised to match project development. One key reason behind such revisions is driven by the quantity and sizing of equipment required to be securely installed within it. Notably, the special limitations at the DER sites necessitating a complete overhaul of the DER cubicle design as highlighted in Section 3.4. Additionally, the number of the layer 2 switches used in the Grid Constellation cubicle must be revised to suit the size of the associated Grid site. The key changes to the design architecture can be found in Appendix A4.

Below is a list of the key components installed within each type of Constellation cubicle. Figure 14 and Figure 15 below detail a General Arrangement (GA) drawing of a Grid and a DER Constellation cubicle respectively. Furthermore, Section 3.5.3 provides a selection of photographs detailing the actual Constellation cubicles as installed within the Constellation project.

Grid Site Constellation Cubicle:

- Two Substation Servers (each containing VMs for each Solution);
- Layer 2 switches (quantity depends on site characteristics);
- One layer 3 switch;
- One Redbox (a device that connects devices to a network that provides redundancy);
- One GPS time server clock (Meinberg M1000);
- One OMICRON StationGuard – Cyber Security Intrusion Detection System (IDS);
- One 5G router;
- One Phasor Measurement Unit (PMU) device (subject to site characteristics); and
- Communication network cabling and devices.

DER Site Constellation Cubicle:

- 1 Substation Server;
- 1 layer 2 switch;
- 1 layer 3 switch;
- 1 GPS;
- 5G router; and
- Communication network cabling and devices.

[25] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-3-v1.0-Redacted.pdf

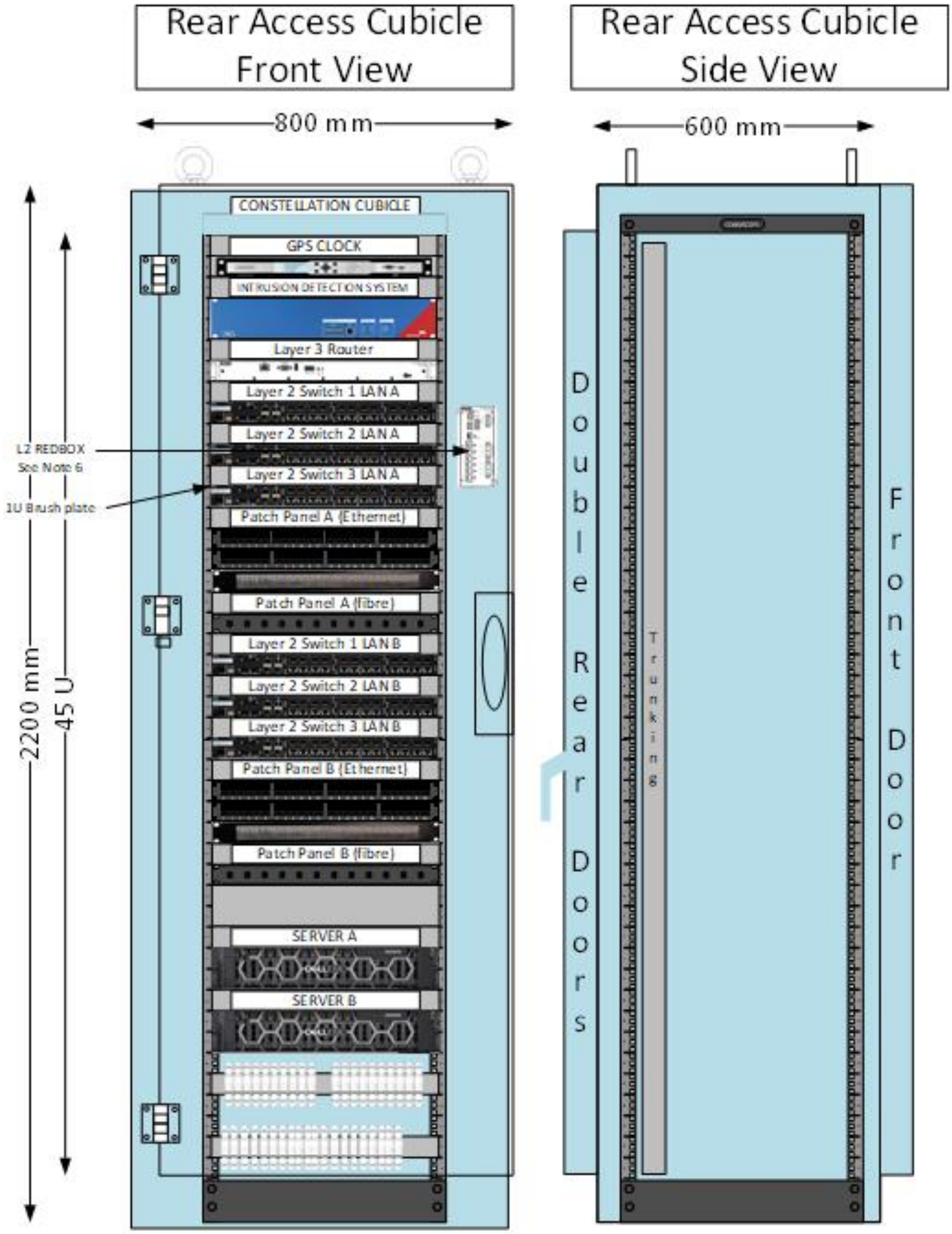


Figure 14: General Arrangement – Grid Site

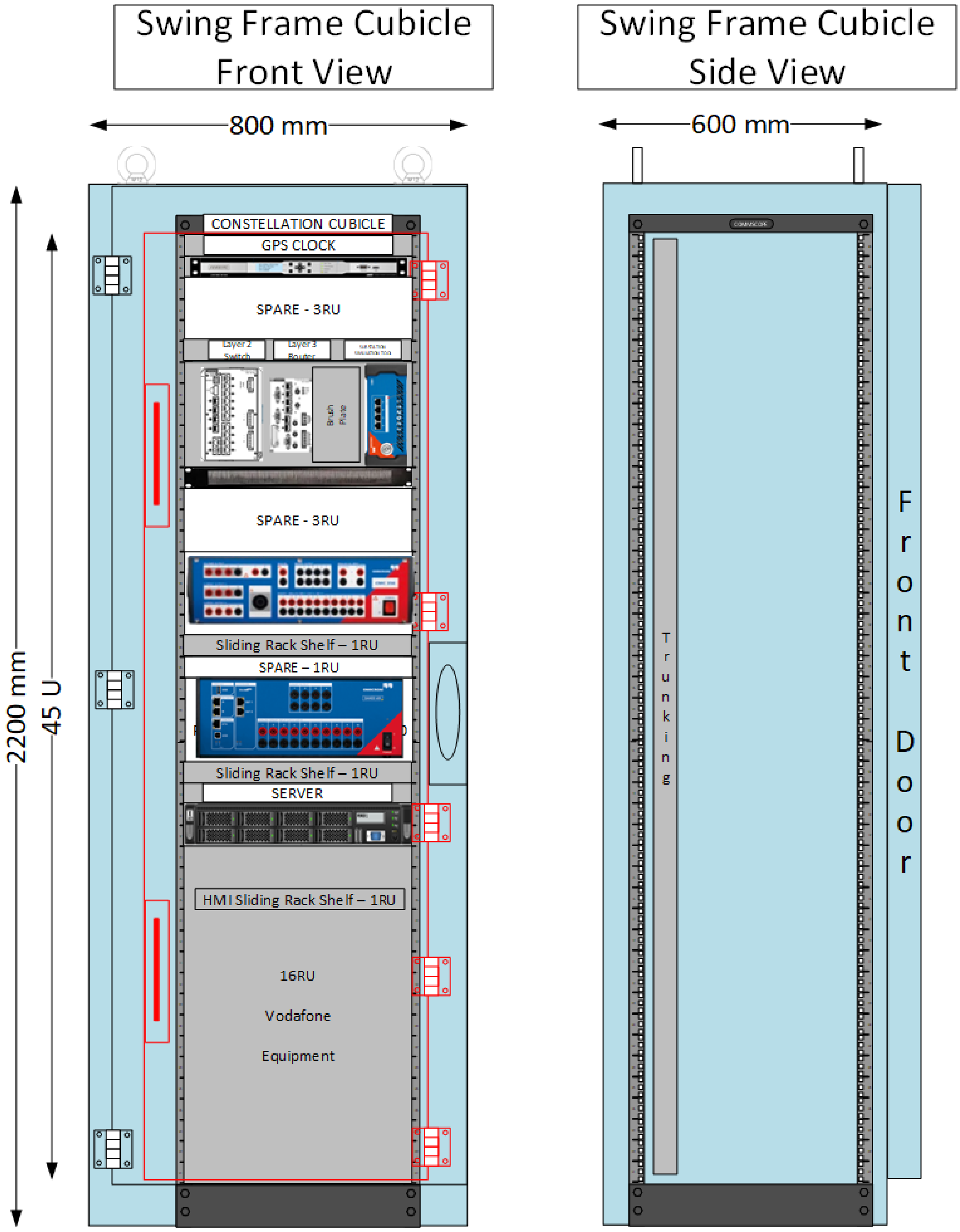


Figure 15: General Arrangement - DER Site

3.5.3 Constellation Cubicle on Site

Figure 16, Figure 17, Figure 18, Figure 19 and Figure 20 below provide a pictorial history of how Constellation cubicles have been installed at a typical Grid and DER site.

Appendix A.7 provides further photographs of how Constellation equipment can be installed in both a typical Grid and DER site.

Figure 16: Grid Constellation Cubicle Undergoing Installation

Figure 17: Close-Up Front View of a Grid Constellation Cubicle

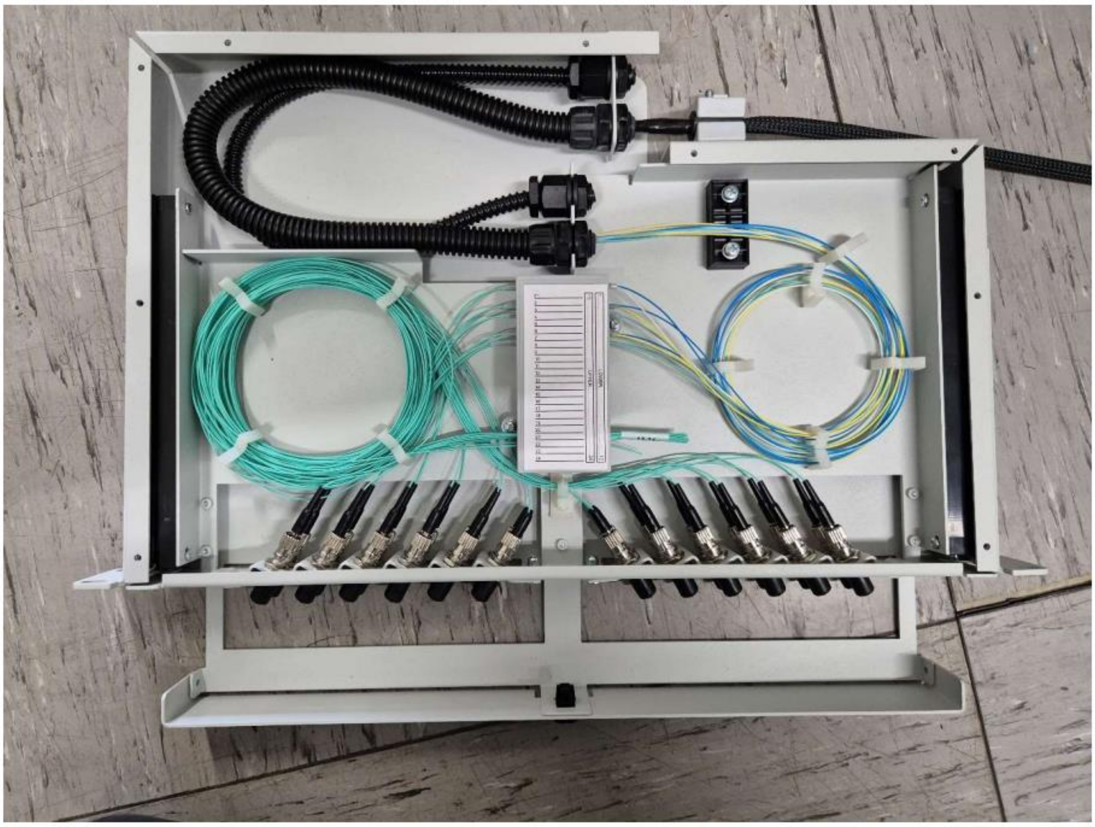


Figure 18: Cabling Inside a Fibre Optic Patch Panel

Figure 19: Example Wiring in Rear of a Grid Constellation Cubicle

Figure 20: Grid Constellation Cubicle Undergoing Test

3.6 Key Lessons Learnt

The key lessons learnt whilst progressing the Constellation site installation activities are detailed below.

Full details of all lessons learnt whilst progressing these activities are detailed in Appendix A.1.2.

Lessons Learnt (Network Preparations)	
1	All network preparation activities for Constellation were conducted at existing operational sites, requiring installations to be retrofitted into the existing infrastructure. This added significant complexity to the process. Vectorised versions of site drawings had to be obtained and thoroughly reviewed to understand pre-existing site conditions. These drawings were then substantiated through site visits to validate the ASB status and assess provisional locations for the Constellation equipment. Despite this detailed preparation, it was noted during site activities that unforeseen challenges often arose. For example, the harsh environmental conditions at DER sites required revisions to the cubicle design to ensure adequate ingress protection. However, addressing this issue led to another. The enclosed cubicle design caused some of the equipment to overheat. To resolve this, the cubicle doors were redesigned to provide sufficient ventilation while maintaining the necessary protection for the Constellation equipment. The project's iterative development approach ensured that these lessons were incorporated into the assembly of subsequent cubicles. This not only improved the efficiency of site works but also enabled issue-free, end-to-end Constellation site installations. As a result, the business gained significant confidence in its ability to scale Constellation to additional sites in the future should the project be successful.
2	To procure the correct specialist equipment for the trial areas, the Constellation team utilised insights gained from previous project deliverables. Following the appropriate procurement channels, the team collaborated with designated suppliers to finalise the equipment specifications ahead of delivery. Utilising learnings from past innovation projects, orders were placed five months in advance of the planned site activities to ensure timely availability. However, a global shortage of electronic components, which has significantly impacted the telecommunications industry, caused unforeseen delays in procuring the necessary equipment. To mitigate the impact of these delays, orders were split to allow partial deliveries as product batches became available. This approach enabled sequential completion of site works, aligning with the optimal site preparation procedure and minimising disruptions. This unexpected challenge also provided valuable additional learnings. The delays allowed the team to further refine the specifications of certain Constellation components, tailoring them to better meet existing site requirements, such as compatibility with the type of power outlets available on site for the Constellation equipment.

3	When planning works that may impact DER customers, it is crucial to ensure all necessary measures are in place to address any potential disruptions. This requires effective engagement to keep them fully informed of project progress and any forecasted changes. Additionally, accurate outage planning and seamless coordination across multiple departments within UK Power Networks and with specialist suppliers is critical. Given the nature of DER operations, there may be significant dependencies on specific seasons or times of the year for generating revenue. These factors must be carefully considered when developing the overall trial plan, particularly when scheduling outages. While outages are an essential part of the process, the project team found that continuous engagement and the provision of a robust and optimised outage plan helped gain DER customers' support. This proactive approach enabled works to be carried out with minimal complications and maintained strong relationships with stakeholders.

4 Undertaking the Network Trials

4.1 Overview

To ensure that the Constellation Solutions have been fully de-risked, an iterative sequential testing procedure has been put in place. Starting off with FATs to ensure each Solution operates as intended which was completed at each respective vendor premise and moving to implementing additional tests at the PNDC test environment. The initial two stages have been reported upon within previous deliverables and PPRs.

As shown in Figure 21, following the success of the FAT and PNDC testing stages, sufficient confidence has now been obtained which led to the commencement of the SATs and subsequently the launch of the Passive Network Trial.

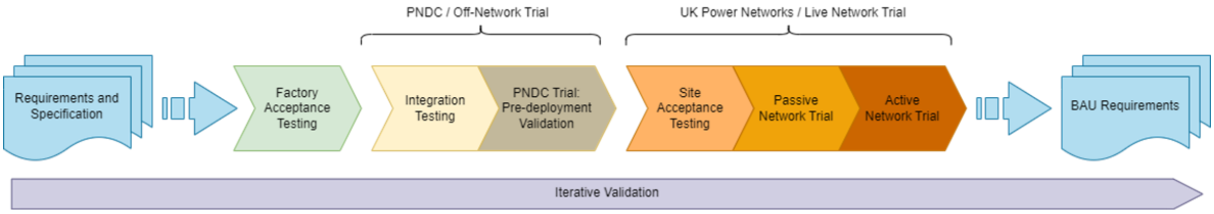


Figure 21: Constellation Testing Procedure Flowchart

The requirement to undertake a formal and comprehensive SAT of the Solutions within each trial area is a critical stage within the overall Constellation project as it represents the first instance the Solutions are interfaced with the physical site plant, in a real-world operational network environment.

When conducting the PNDC trial, and following the success of the FATs, tests were first carried out for the Maidstone area. This approach enabled the project team to utilise the learnings in the next area which further streamlined the testing procedures. This sequential approach was further extended to site as SATs in the Maidstone areas were able to commence as soon as the PNDC testing in that area was completed and results approved.

The latter was extremely beneficial as the core UK Power Networks team focused on defining standardised procedures for carrying out SATs, and subsequent activities in a smaller and relatively less complex site. These procedures were then utilised by wider UK Power Networks members and specialist suppliers to expedite the process in the larger Thanet area.

This approach was in valuable as not only did it enable the site activities to progress in an expedited pace, but it also upskilled the UK Power Networks workforce to manage such advanced technologies which will aid their roll out once the project is proven to be successful.

Furthermore, and as a result of the successful development of the project Solutions, their respective Technology Readiness Level (TRL) has been advanced. In particular, the TRL levels associated with each Solution have progressed as detailed in Table 7 below:

Table 7: TRL Levels

Partner's Solution	TRL at Project Commencement	TRL Upon Submission of Deliverable D4	TRL Upon Project Completion
ABB (WAP)	5	7	9
GE (Local ANM)	4	6	8
Siemens (APS and CMS)	5	6	8

Following the initial tasks required to prepare network sites for Constellation as detailed within Section 3.1, additional tasks are then required to progress the network sites through to the Active Network Trials, as illustrated in Figure 22 below.

Further details describing how to progress these works on site to implement the Constellation Solution are provided in the following sub-sections.

A summary of the key lessons learnt whilst undertaking the Network Trials is provided in Section 4.5. Furthermore, Appendix A.1.3 provides a full list of all lessons learnt during this stage of the project.

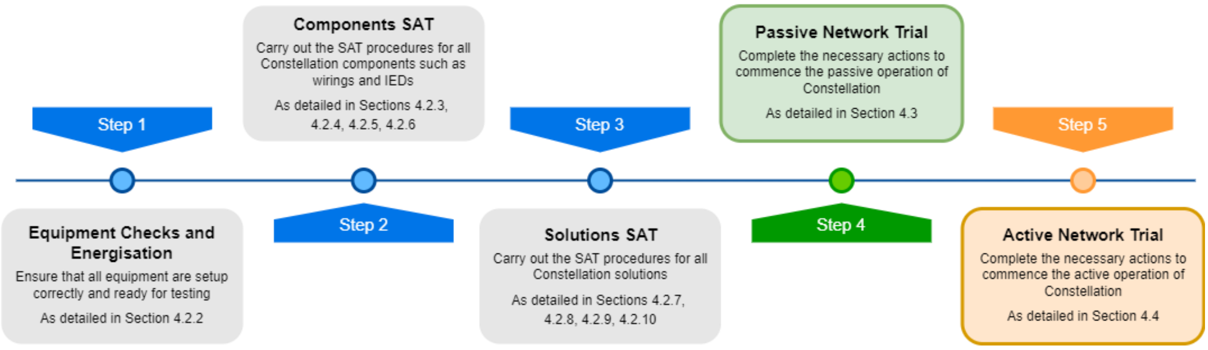


Figure 22: Network Trial Execution Process

In summary:

- Upon installation, the equipment is individually powered-up and tested to ensure no failure conditions exist and then configured, as detailed in Section 4.2.2 through Section 4.2.6 below;
- Individual Solution SATs within each trial area are then carried out in an optimised manner to ensure learnings from completed sites are taken into account. Details of how these SATs have been managed and successfully completed are provided within Section 4.2.7 through Section 4.2.10; and
- Once the SATs have been successfully completed and approved by the Technical Design Authority, the Passive Network Trial commences which includes additional testing and monitoring of the Solutions' performance to ensure their readiness ahead of transitioning to the Active Network Trial, Early learnings from the Passive Network Trial are detailed within Section 4.3 and Section 4.4 respectfully.

These activities have been undertaken by UK Power Networks' engineering teams, with support from the respective project partners and specialist suppliers when required. The focus of carrying most the activities in-house ensures that the workforce is upskilled for these tasks which facilitates the BaU transition of the project once proven to be successful.

A summary of the key lessons learnt whilst undertaking the network trials is provided at the end of this section. Appendix A.1.3 provides a list of early learnings obtained during this stage of the project.

4.2 Site Acceptance Test Activities

4.2.1 Introduction

In order to ensure the security of the Constellation Solutions and to mitigate any risks prior to the network trials, UK Power Networks enlisted OMICRON as a specialist supplier on the project.

OMICRON is an industry leader in testing, diagnostics, and monitoring of assets who leveraged their expertise to ensure the success of the testing. Prior to commencing the SATs. UK Power Networks and OMICRON met for an in-person workshop to jointly discuss, define and agree the overall SAT philosophy and contents for the respective Solution test procedures. The agreed sequence of activities is shown in Figure 23 below. For each phase, detailed test plans were prepared for test execution and documentation of the test results. The following sections provide summary details relating to each step in this process.

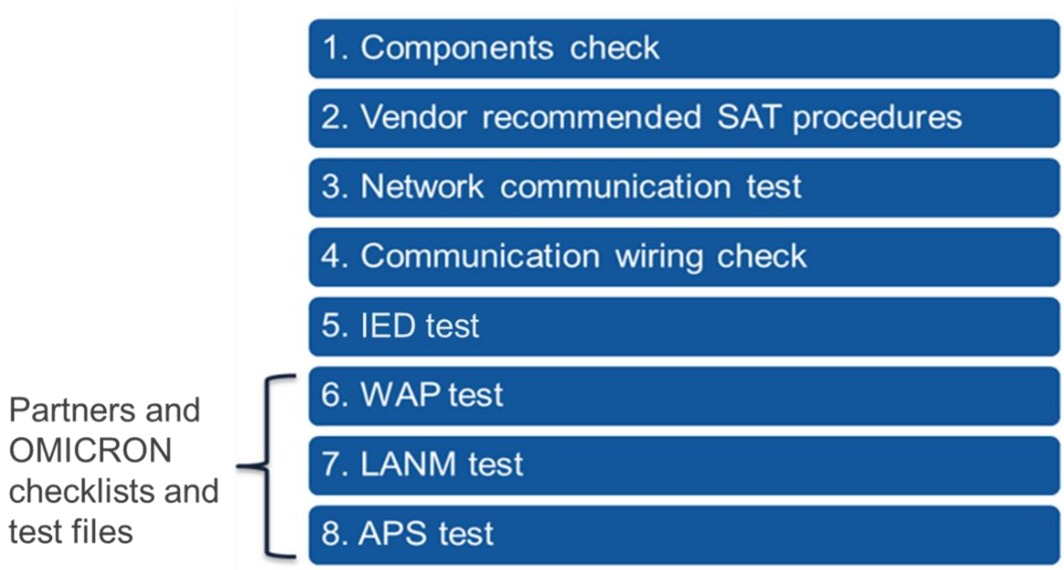


Figure 23: Breakdown and Sequencing of Agreed SAT Activities

4.2.2 Components Check

- Power-up and set up checks, to ensure that:
  - ➢ Items are appropriately energised;
  - ➢ No errors/alarm messages (or failure Light Emitting Diodes (LEDs)) present; and
  - ➢ Associated Human Machine Interfaces (HMI) were activated and functioning correctly (if any).

- Configuration, to ensure aspects such as:
  - ➢ Default protection settings have been correctly loaded on to the new IEDs;
  - ➢ Substation Servers are optimised for maximum performance
  - ➢ The VMs of each Solution are correctly deployed;
  - ➢ Communications are operable; and
  - ➢ All the necessary licenses are installed.

The above activities have been undertaken for all the Constellation equipment, located across the switchgear panels and Constellation cubicle. The equipment can be summarised as follows:

- Constellation cubicle components as detailed in Section 3.5.2;
- Configuration of VMs (ABB SSC600, Siemens SICAM GridEdge, GE Virtualised Phasor Controller (vPhC) and Phasor Data Concentrator (PDC), and the Windows 10 Engineering VM);
- GE Vernova's Reason MU320 MUs;VSiemens 6MU85 MU/PMU;
- ABB MUs (REF615 and RED615); and
- Maidstone PDC* (required to concentrate the PMU data from Maidstone and DER-1 and send to Azure Server/GE).

* This is only specific to the Maidstone Grid site and can be applicable to any future sites sharing similar characteristics.

Lastly, the equipment is also checked for physical damage throughout the process. Additionally, a record is taken of the equipment make, model and serial numbers plus versions of any software or firmware installed.

4.2.3 SAT Procedures

The SAT has been progressed using a suite of formal procedure documents which define a structured series of tests to be undertaken by the commissioning team. These tests are designed to exercise the Solution's functionality and performance to ensure safe operation of the Solution.

All SAT procedure documents for each solution have been prepared by the UK Power Networks' team in collaboration with the relevant project partners and specialist suppliers who possess the necessary technical expertise to define the required tests. Upon completion, all SAT procedure documents have then been reviewed and approved by the Technical Design Authority prior to any SAT commencing.

Examples of SAT procedures and result sheets are located within Appendix A.5.

4.2.4 Network Communication Testing

Communication is a key aspect of managing the electricity networks and its importance has only grown more as the systems evolved. Furthermore, the Constellation solutions rely on communication to ensure accurate and appropriate operation. Therefore, extensive network communication SAT tests must be undertaken across all trial areas to ensure the robustness of the communication system.

The following network communication and redundancy tests must be undertaken as part of SAT within any given trial site:

- Network Communication Verification - This test verified that the IEC 61850 signals of all IEDs are available and responding, and the substation network traffic is present on the communication network as defined. The test checks for overall integrity and identifies any mismatch in Substation Configuration Language (SCL) engineering file(s), IED configurations, and network configurations;

- Network Bandwidth and Filtering – This test verified that the network is not overloaded under normal conditions and there is enough reserve bandwidth by testing conditions with increased amount of traffic due to additional simulated data;
- Precision Time Protocol (PTP) Time Synchronisation – This test verified that the defined PTP Grandmaster (GM) clocks are available at all devices and configured correctly. It also validated that all devices are following Best Master Clock Algorithm (BMCA), in line with the PTP priority;
- Loss of Satellite Signal – This test verified that loss of the satellite signal had no negative impact on ability of all IEDs to remain PTP time synchronised up until the holdover time of the GM clock expired;
- PTP Clock Redundancy – This test verified that PTP clock redundancy in both Grid and DER sites functioned correctly. Additionally, it verified that all ABB REF615 devices are also able to function as PTP clocks and can become the GM if required;
- Validation of the correct operation of the Parallel Redundancy Protocol (PRP) network;
- Validation of all MAC address filters on layer 2 network;
- Sampled Values Synchronisation Flag – This test confirmed receipt of the correct synchronisation status of a Sampled Values stream; and
- Network Redundancy Verification – These tests verified appropriate operation of the communication network when one network failure occurred (e.g. broken links or network equipment).

A selection of the aforementioned tests has been detailed in Appendix A.5.4 as conducted in the Constellation trial areas.

4.2.5 Communication Wiring Check

The aim of this testing stage is to verify that the VMs are exchanging data correctly with other parts of the system such as: the RTU, PMU and IEDs.

This is achieved by progressing separate tests on each individual solution, in line with the solution specific testing procedure. For the Solutions used in Constellation, this is summarised as follows:

- Local ANM: Validation of all PMU data arriving in the PDCs and the RTU is receiving data from the vPhC;
- Adaptive Protection Settings: Check if the CMS Platform and Computer Aided Protection Engineering (CAPE) software are receiving the correct actual settings from the SSC600 and if the CMS Platform was accurately sending new settings back to the SSC600; and
- WAP: Validation if the GOOSE and Sampled Measured Values (SMVs) are being correctly received by the SSC600.

Figure 24 below details an example of the results obtained from undertaking such tests, the example provided relating to the APS solution.

Communication Test - Wiring Check
System under test: APS
Date:

Interface name			Source		Network Segments			Destination		Status
Test ¶	Data	Interface	Name	Port	Grid	-	-	Name	Port	
4.1	ettingGrou	GridEdge-Grid_SSC600	Server A/E	VM	NA			Server A/B	VM	☑

Signal Checks

	Signal	Description	Expected	Read	Write
1		Resistive reach Fw	11.9 Ohm	11.9 Ohm	11.9 Ohm
2		Resistive reach Rv	11.9 Ohm	11.9 Ohm	11.9 Ohm
3		Max impedance angle	42 deg	42 deg	42 deg
4		Min impedance angle	-42 deg	-42 deg	-42 deg
4		Directional Mode	Fwd	Fwd	Fwd
5		Start value	0.38 xln	0.38 xln	0.38 xln

Are the Settings groups service enabled on SSC600?

Description: Check the connection between GridEdge and Grid_SSC600 both running in the Grid_SCP to read and write settings described above.
Use IEDScout in parallel to read the current parameters in the IED and compare agaist the parameters shown in GridEdge

Notes: Default settings. Settings directly checked on SSC600 instead of IEDScout.

Interface name			Source		Network Segments			Destination		Status
Test ¶	Data	Interface	Name	Port	Grid	-	-	Name	Port	
2.18	MQTT	CMS-GridEdge	Cloud	-	L2 SwV2 LAN A/B			Server A/B	Relyum (PRP) LAN A/B	☑

Signal Checks

	Signal	Description	Expected	Read	Write
1		Resistive reach Fw	104.55 Ohm	104.55 Ohm	104.55 Ohm
2		Resistive reach Rv	104.55 Ohm	104.55 Ohm	104.55 Ohm
3		Max impedance angle	42 deg	42 deg	42 deg
4		Min impedance angle	-42 deg	-42 deg	-42 deg
4		Directional Mode	Fwd	Fwd	Fwd
5		Start value	0.07 xln	0.07 xln	0.07 xln

Description: Check the connection between GridEdge and CMS to read and write settings described above.
Use IEDScout in parallel to read the current parameters in the IED and compare agaist the parameters shown in CMS

Notes: Scenario 1 applied. Settings directly checked on SSC600 instead of IEDScout.

Certification					(✓)
All tests have been completed satisfactorily					
Contractor Commissioning Engineer (if applicable)					
Organisation		Name			
Date		Signature			
UK Power Networks Commissioning Engineer					
Name		Signature		Date	18/07/2024

Figure 24: Communication Wiring Check (Example for APS Solution)

4.2.6 IED Test

The aim of this test step is to verify that the configuration and behaviour of the installed IEDs is in line with the intended operation. In the Constellation project the IEDs used provide a number of functions, namely as a Merging Unit (MU), PMU, Switch Control Unit (SCU), and selected protection functionality etc. All these IEDs have been subjected to a two-stage check and test verification process:

- Initial tests are undertaken as the IEDs are being installed within the switchgear panels. These tests aim to verify that the current and voltage transformers (CT and VT) connections to each IED are wired using the correct ratio settings. Following this, additional checks are undertaken to ensure that the correct equipment alarms and status are reflected at the IEDs. The output signals from the IEDs to the switchgear are validated, with a final test undertaken to verify correct operation of the protection functions enabled in the IEDs; and

- As part of the SAT process, all signals sent by the protection software (SSC600) are tested to ensure they are arriving correctly at the respective IEDs. This includes checking that the fault recordings and logs were properly configured and validation of the PMU data/settings. Finally, as detailed in Section 4.2.4, the time synchronisation and PRP network performance is validated.

4.2.7 Wide Area Protection SAT

The solution provides resilience to DER operation against instability events that may unwantedly trigger conventional generator protection. Constellation has developed sophisticated protection algorithms to identify the appropriate scenarios when a DER should disconnect during actual islanding situations. WAP algorithms will provide tripping and blocking facilities to DER sites in order to enable them to ride through an external network fault and support the distribution network by tripping out only under genuine Loss of Mains (LoM).

The WAP SAT was carried out using OMICRON hardware CMC 356 and OMICRON software Test Universe via OMICRON Control Centre (OCC) files. All protection functions, Intertrip and Rate of Change of Frequency (RoCoF) functions were exercised by simulating the GOOSE and Sampled Values from the MUs via OMICRON's Universal Relay Test Set and Commissioning Tool, the CMC356.

In summary, the sequence of WAP SAT comprised the following procedure steps:

- Communication between MUs and SSC600 was successfully validated in order to confirm that GOOSE messages were correctly received from the SSC600 during a protection trip;
- Ability of the received signals to initiate the correct action (e.g. tripping the circuit breaker and triggering associated disturbance recordings, including the digital signals (GOOSE) and analogue signals (Sampled Measured Values (SMVs));
- Successful test of all protection functions of each feeder configured on the SSC600. Curve tests of each protection function were carried out to validate time and selectivity performance for several scenarios;
- Successful test of WAP functions – Intertrip logics and RoCoF block signals; and
- Validation of all alarms, LEDs and Disturbance recordings of the MUs and SSC600.

Each protection function was individually tested in order to validate correct operation.

Figure 25 below details the test configuration used (within the green border) for the WAP SAT.

Further details of the procedures developed for WAP SAT, and an example of the testing results obtained, are provided within Appendix A.5.2.

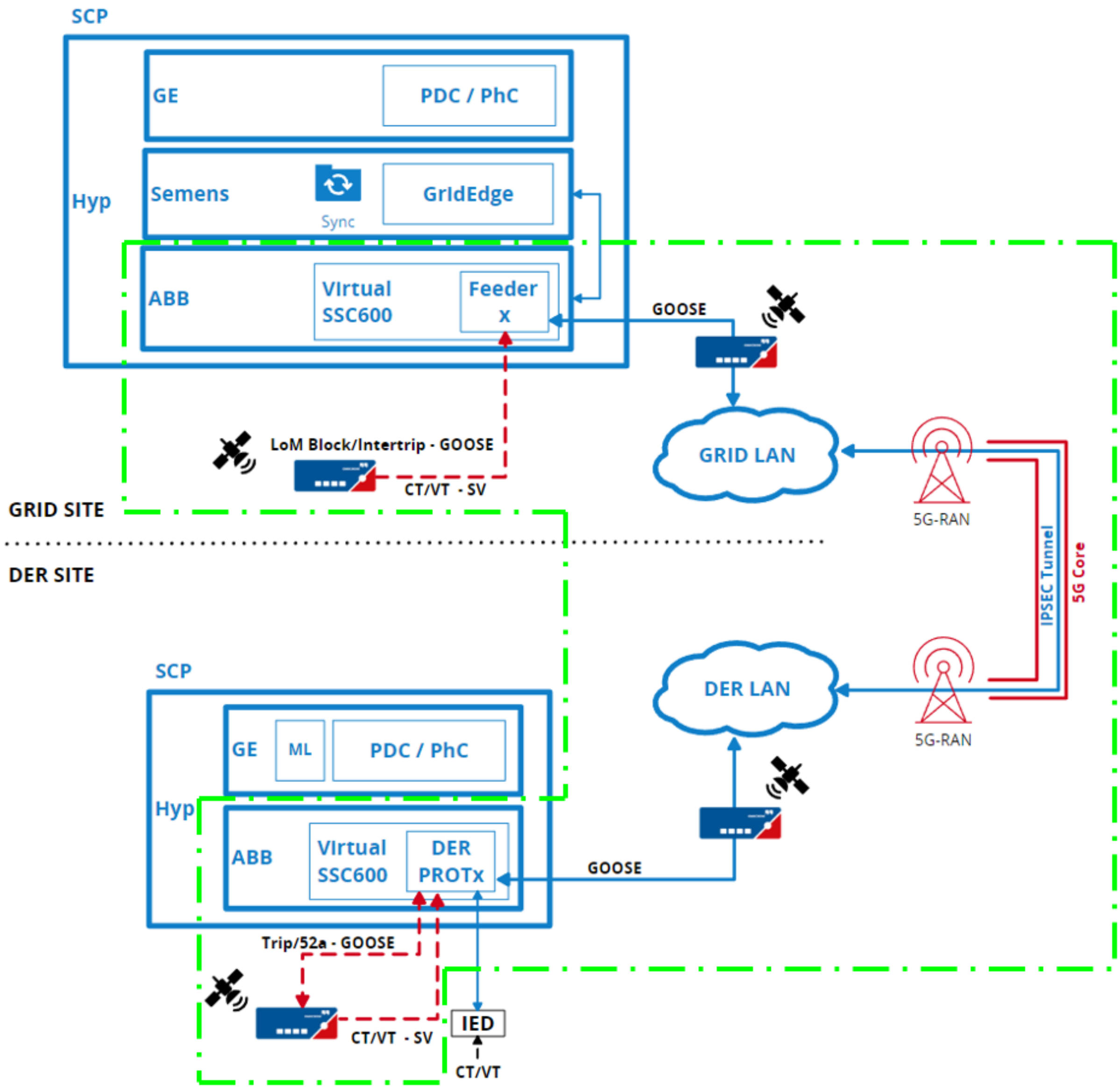


Figure 25: Test Configuration for the WAP SAT

4.2.8 Local ANM SAT

The solution allows local network control and optimisation at the distribution substation level to provide resilience to DER operation against loss of communication with the central ANM system. Whenever the central systems are unable to communicate with local network assets, the local intelligence at the area level will take over management for that specific provider, substation or area. If communications are lost between the substations within an area, then local intelligence at the generation sites will take over management for that site. This will enable more optimal operation of the network by enabling local control, compared to resolutions, such as curtailment.

The Local ANM SAT is carried out in accordance with the network trial plan, and it has verified that the signal routing and connectivity between the various equipment within each Local ANM deployment is in line with the solution design.

In summary, the SAT for Local ANM verified the following key items which are essential for its successful operation:

- Incoming and outgoing connections between equipment is appropriately setup;
- Any derived analogues or phasors defined in the PDC;
- Any signal renaming defined in the PDC;
- Programmable Logic Controller (PLC) I/O configuration;
- Field bus configuration;
- PMUs from Grid and DER are accurately transmitted to Grid PDC and then to Azure Server PDC successfully;
- Correct audit signal generation; and
- Correct user and default PLC log generation.

Figure 26 below provides an example of the Local ANM installation within the Maidstone trial area. Additional examples of the SAT results for Local ANM are presented in Appendix A.5.1.

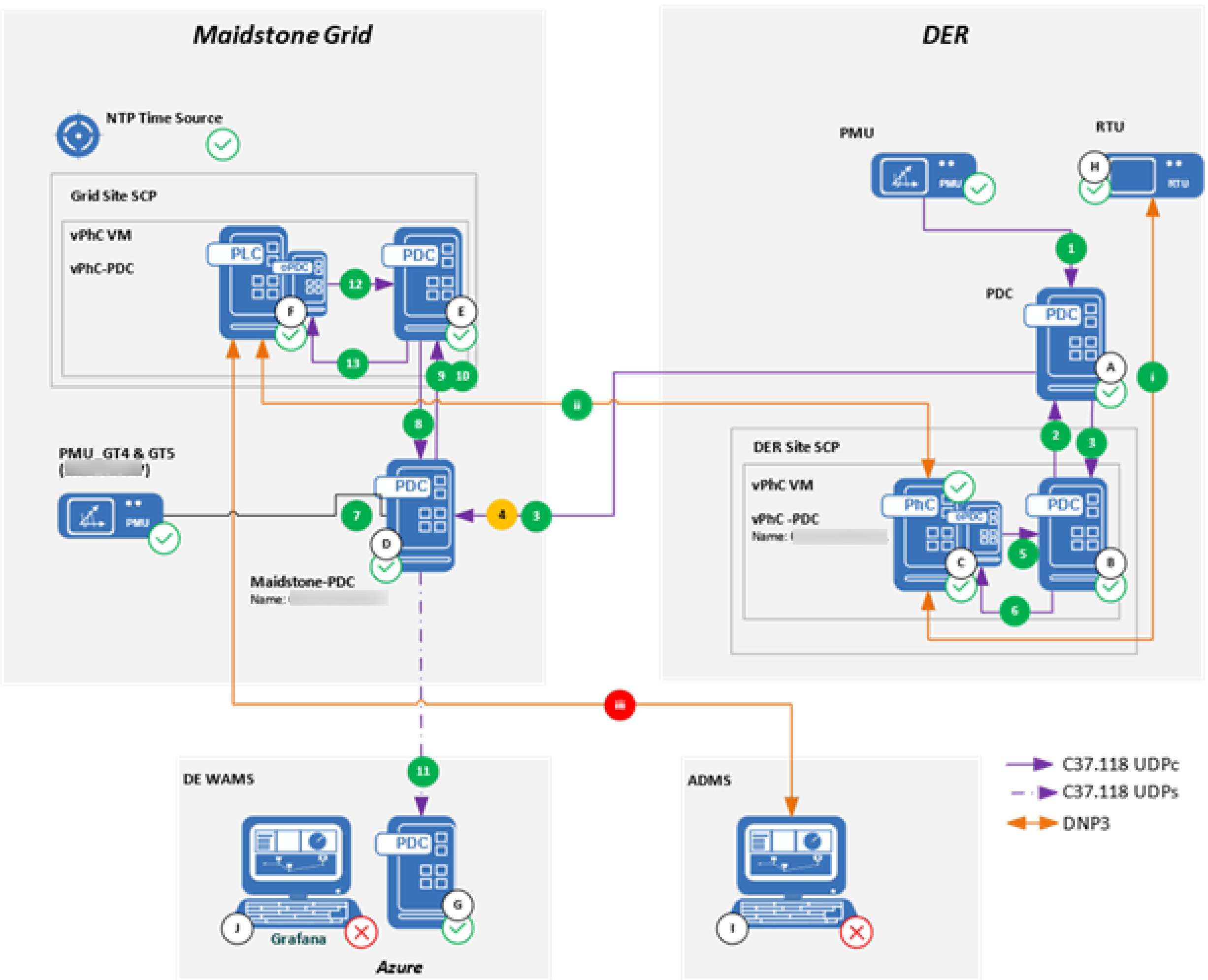


Figure 26: Local ANM SAT Configuration (Maidstone Trial Area)

4.2.9 APS and CMS SAT

The solution involves deploying the APS and CMS on virtual servers within the UK Power Networks' Azure cloud environment, while the SICAM GridEdge software is installed on a VM at the local substation. The CMS is responsible for collecting, managing, and modifying the settings of protection devices, as well as overseeing other secondary devices, including non-protection equipment whereas the APS adjusts load blinding protection settings at each Grid station according to the operational state of the trial grid. The new protection settings calculated by the APS are sent to the CMS, which processes this information and securely updates the new settings to the SICAM GridEdge. The SICAM GridEdge then applies these new settings to the SSC600 protection relays.

The following activities were undertaken to prepare the system for SAT to ensure successful operation of APS:

- SICAM GridEdge software deployment: The software is successfully installed on the substation's VM. All features and functions are thoroughly tested, in line with the test procedures, to activate the local gateway, facilitating communication and bidirectional data flow between the CMS and the SSC600 relay;
- Integration and data flow testing: Testing is performed to validate the workflow, ensure database access, and confirm network configurations;
- Troubleshooting: Issues with the software, network, and integration are resolved through effective troubleshooting activities involving the SSC600 relay, SICAM GridEdge, and the CMS Platform identified during the integration and data flow test; and
- Pre-SAT and scenario testing: Comprehensive end-to-end testing is conducted to verify data flow and ensure accurate simulation results prior to the commencement of the Passive Network Trial.

Figure 27 below details the system setup used for the APS and CMS SAT whilst Figure 28 below details the whole system with software component with definition of protocols and ports used for integration.

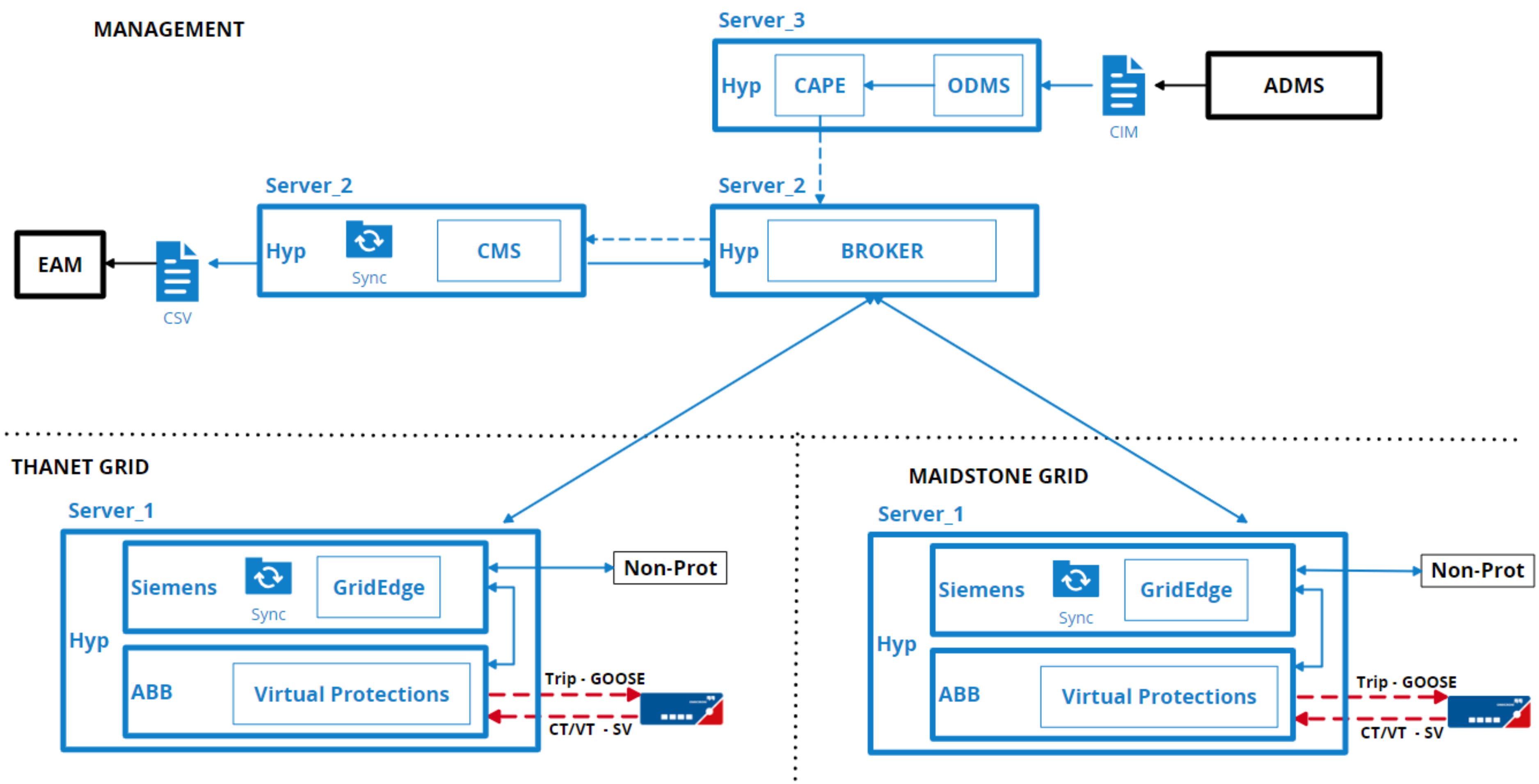


Figure 27: System under test and test setup

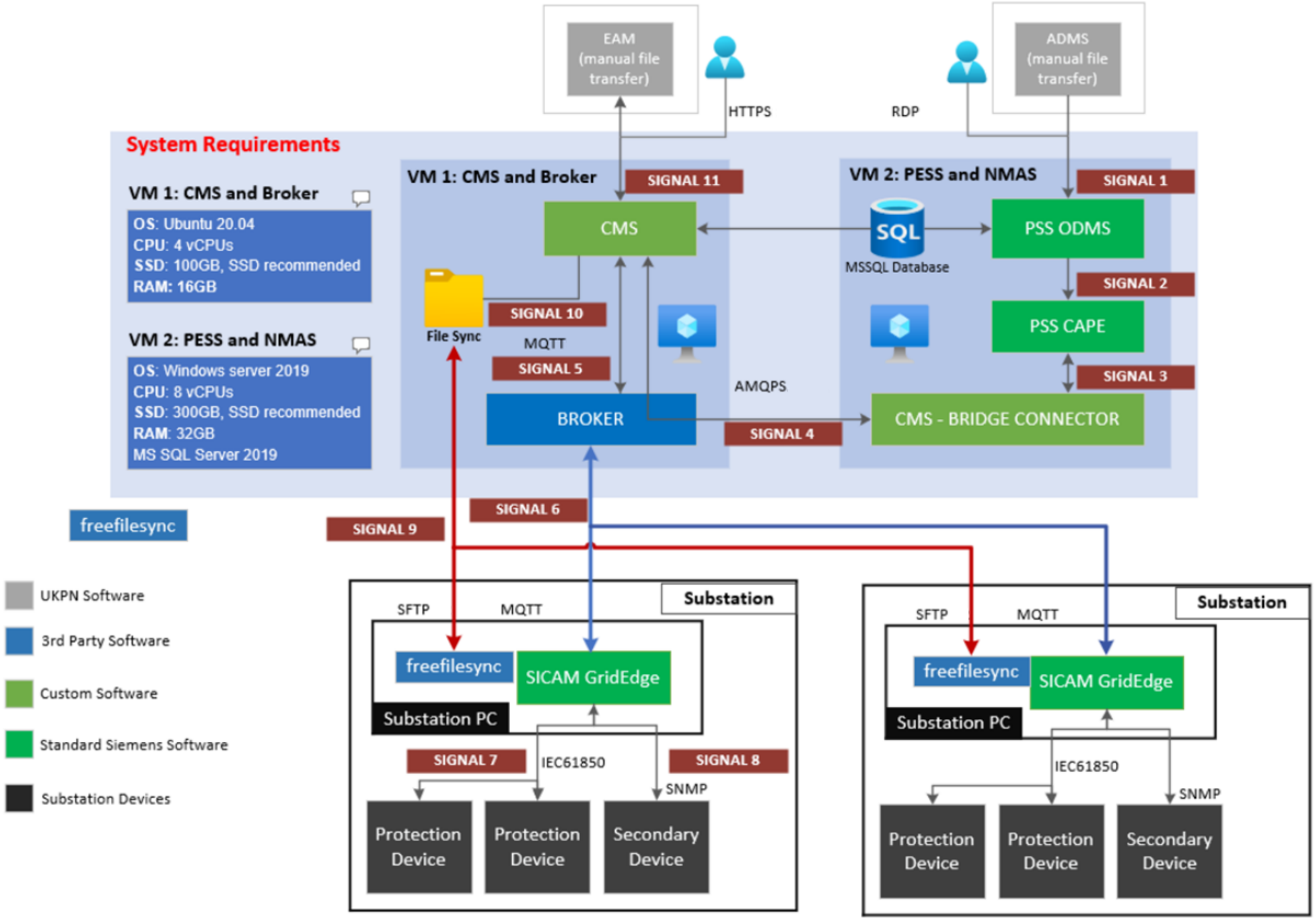


Figure 28: Whole system showing software components, protocols and ports used for integration

The functional tests that must be completed during APS SAT are summarised:

- Validation of the communication and bi-directional data flow between the protection and control units (SSC600) using SICAM GridEdge;
- Validation of the communication and bi-directional data flow between SICAM GridEdge and CMS Platform;
- Validation of the communication and bi-directional data flow between CMS Platform and PSS®CAPE; and
- Verification of the new protection settings applied to the SSC600 (following APS) using OMICRON CMC356.

To validate the operation of APS, four of the scenarios previously demonstrated during the FAT stage (as reported upon within Deliverable D3[26]) were repeated during the SAT. Whilst a slight discrepancy in the solution output (i.e. new protection settings) was noticed between the two, upon further investigation, this was found to be due to improvements made in the adaptation macro, network topology model and relay parameters. Such improvements resulted in more optimised APS outcomes enhancing the overall accuracy of the solution outputs.

Examples of the SAT results for the APS and CMS SAT are presented in Appendix A.5.3.

4.2.10 Communication Testing

To ensure the security of the network trial and that no uncontrolled actions occur during the SAT and moving into the Passive Network Trials, the piloting of the virtualised protection in the live network is divided into two phases in the Constellation project.

Overall, the centralised virtualised protection computers will be receiving measurements via IEC61850-9-2 SMV as well as switch statuses, trip signals and alarms via IEC61850-8-1 GOOSE from the MUs, and similarly sending trip commands and other messages to the MUs. However, a special “merging unit trip switch” logic is implemented in the MUs that determines whether the GOOSE-based trip commands from the centralised protection server are allowed to control the circuit breaker or not (i.e. Passive or Active modes of operation).

Although this trip switch can be manually enabled or disabled, even when the trip switch is enabled (active mode), the local protection functions at the MU will take over should the MU suddenly stop receiving frequently changing GOOSE “ping” supervision signals published by both grid site Central Processor Complex (CPC) servers (i.e., from the primary and the redundant CPC). This ensures secure operation of the protection at all times.

The following example presented in Figure 29, which is constituted from an MU disturbance recording gained during WAP SAT, illustrates the appropriate operation of this logic.

The signals detailed within Figure 29 can be explained as follows:

- The “MU TRIP SWITCH – SSC600 PROT ENABLED” is the signal that determines whether the MU allows the CPC servers to control the breaker or not;
- The “SSC1 General Trip” and “SSC2 General Trip” signals are the trip commands sent by the virtualised CPC devices to the MUs via GOOSE;

[26] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Deliverable-3-v1.0-Redacted.pdf

- The “MU General Trip” is the local master trip function output of the MU (which can also act as an IED);
- The “SSC1 PING” and “SSC2 PING” signals are the MU supervision signals that the MUs subscribe for knowing whether the virtualised centralised CPCs are operational or not; and
- The GOOSE-validity states of these “PING” signals are also displayed and named as “SSC1 PING VALID” and “SSC2 PING VALID”.

Should an MU stop receiving these PING signal for a defined period of time, the “SSC1_COMMDOWN” and/or “SSC2_COMMDOWN” signals are triggered and held active for a definable period (currently set to five seconds). If both of these signals are activated, the “SSC600_COMMDOWN” signal is also activated for a definable period during which the MU only has its local protection activated while any potential trip commands from the CPCs being rejected.

The “GOOSE_ALARM” is a local GOOSE supervision function. In contrast, the “COMM_ALARM” signal is activated if the “GOOSE_ALARM” is active, MU loses time-synchronisation, or if one of the two LAN cables (PRP) is disconnected.

The same level of testing must be completed over 5G to ensure redundant site-to-site connectivity.

The 5G communication channels within each trial site are used to transfer PMU (phasor measurements, analogues), GOOSE (intertrip, LoM block and breaker position), and DNP3 (Local ANM internal GE signals) data between the Grid and DER sites.

As such, it is important to subject the 5G Standalone (SA) Slice to robust testing throughout the process in order to verify channel availability (including validation of health status of each link and switchover procedure (in the layer 3 switch).

Initial on-site testing also verified that the correct data transfer occurred with acceptable latency and packet loss rates. An average of 33ms was achieved testing latency between UK Power Networks’ DER sites, which was within acceptable limits in line with the Solution design.

Figure 30 below details the 5G communication test setup and Appendix A.5.5 provides further details of the specific 5G SAT results obtained.

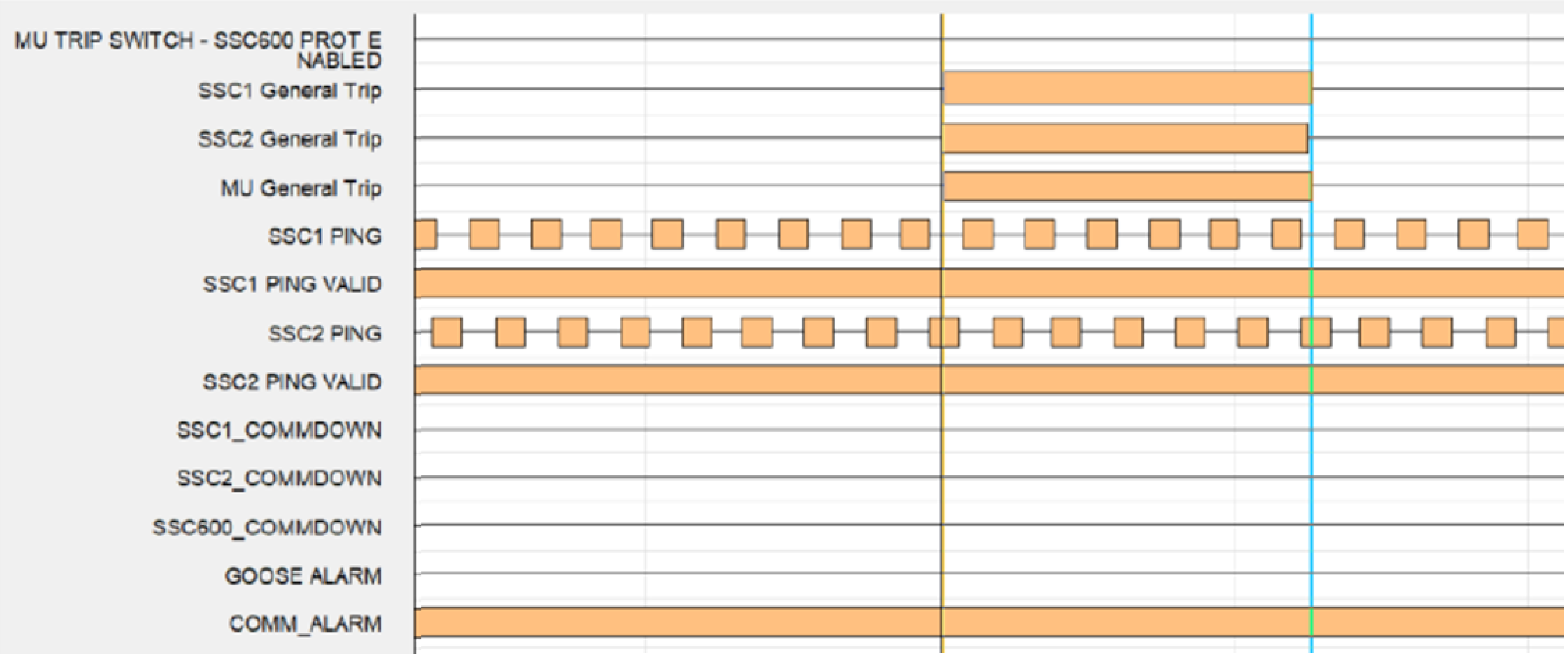


Figure 29: An example illustrating the functioning of the LAN supervision logic

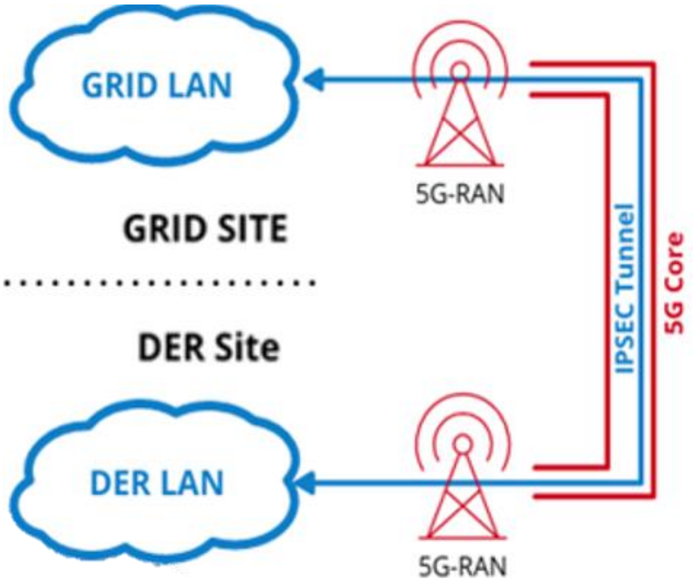


Figure 30: 5G Communication Test Setup

4.3 Passive Network Trials

4.3.1 Introduction

As showcased in Figure 21, upon successful completion of the SATs, the next step of the process is to commence the Passive Network Trial. The Passive Network Trials permit full functional testing of the solutions to carried out with no risk of taking any physical actions that may impact network operation. During this time, the existing feeder MUs will be responsible for protecting the electrical network, while the virtual protection operates Passively.

The Passive Network Trials are intended to verify that all solutions, when integrated together and interfaced with existing equipment within an actual electrical network, are stable and able to provide the functionality and performance as specified for each Method. Such setup allows the solutions to be further monitored to increase confidence is their secure operations and building the business case for transitioning to the Active Network Trial.

Appendix A.6 provides details of selected Passive Network Trial test results for the three solutions currently under Passive operation.

The key learnings gained from conducting the Passive Network Trials will be reported upon within Deliverable D7.

The Passive Network Trial testing procedure will include checks to ensure the following:

- Communications (including GOOSE and SMV), all hardware, and software are stable and operating as designed;
- Unexpected alarms (e.g. false positives) are not generated on any equipment or system;
- Time synchronisation across the integrated system is maintained without errors;
- Actual electrical network failure conditions are detected, and appropriate expected actions are recorded; and
- No perceived maloperations (e.g. inadvertent tripping) are recorded.

Each Passive Network Trial test is:

- Performed either manually, or automatically by virtue of the Solutions responding to the network conditions they are designed to respond to (e.g. loss of mains protection action or curtailment of generation);
  - The manual tests are carried out in line with the network testing procedures and also following any major changes introduced within the deployed Solution configuration/software;
- Undertaken with the tested Solutions' control outputs being physically or logically isolated or disabled from taking any physical action over primary plant; and
- Progressed via a combination of "wait and see" observations or deliberate stimulation of the tested Solutions by means of synthetic signals, sensitising settings or alteration of network conditions (e.g. network running arrangements).

Depending upon the nature of the observations and results obtained, further Passive Network Trial testing may be deemed necessary and/or further improvements to the Solution designs identified and implemented.

During this phase, considerations will also be elaborated upon regarding the preferred methods for Solution maintenance, documentation, training and progression to a full BaU solution.

Once all Passive tests in the trial areas have concluded, and the following criteria have been satisfied, the project will progress to the next testing stage, the Active Network Trials.

- All Passive Network Trials tests, as defined in Appendix A.6, Schedules A through C, have successfully completed;
- All major issues impacting value or progress have been identified, classified and either rectified by the project partners/Solution suppliers, or a resolution plan agreed for implementation at a later stage; and
- A risk assessment has been completed by UK Power Networks in collaboration with the project partners/Solution suppliers identifying the technical risks, impact on DER customers and control measures from maloperation during Active Network Trials as well as potential execution of specific test scenarios (e.g. resulting in deliberate breaker operation).

When successfully tested (and prior to commencement of the Active Network Trials), the protection functions will transition from the physical IEDs to the virtual SSC600 and the protection functions in the IEDs will be disabled and those devices will operate only as a MUs. At that time, the virtualised centralised protection unit will take over the responsibility for protecting the power network. Should communications fail, the protection functionality in the MUs will be automatically re-enabled.

The Solutions will then then be subjected to the Active Network Trials, which are defined in Section 4.4 and findings from that trial will be reported upon within Deliverable D7.

4.3.2 Roles and Responsibilities

In order to ensure robust progression through the Passive Network Trials, the roles and responsibilities of each project partner have been clearly defined and applied, as detailed in Table 8 below.

Table 8: Key Partner/Specialist Supplier Responsibilities During Passive Network Trials

Partner/supplier	Key responsibilities during trial stages (post SAT)
UK Power Networks	• Manage and perform Passive Network Trial tests; • Provide remote or on-site access to relevant partners to support testing; and • Review data generated during trials and consequently review fulfilment of trials objectives to enable the BaU rollout plan.
PNDC	• Coordination of all partners via bi-weekly calls; • Support the review of data generated during trials and provide recommendations for test modifications; and • Ad-hoc lab tests dictated by issues/anomalies experienced on the live network.
ABB	• Technical support for WAP trials; and • Identify, agree and implement changes required to the WAP Solution or its configuration based on regular review of trial outcomes.
GE Vernova	• Technical support for Local ANM trials; and • Identify, agree and implement changes required to the Local ANM Solution or its configuration based on regular review of trial outcomes.
Siemens	• Technical support for APS/CMS trials; and • Identify, agree and implement changes required to the APS/CMS Solution or its configuration based on regular review of trial outcomes.
OMICRON	• Support remote or on-site testing (with test procedures, tools, test plans); and • Lead the review of data generated during trials and provide recommendations for test modifications.

4.3.3 Monitoring Requirements

Throughout the Passive Network Trial testing undertaken up to time of submission of Deliverable D4, regular manual and continuous automated monitoring of the functionality and performance of the Constellation Solutions continues to progress in order to collect sufficient evidence to progress the trials as well as identify any issues that may require addressing prior to progressing with each stage.

Table 9 outlines the required data which is being monitored and evaluated for each of the Constellation Solutions being tested over the trials period. The supplier/owner of each of these is continuously advising the best approach to evaluating these considering the success criteria defined for each trial stage.

A time stamped log has been kept of any manually applied tests so that these can be considered in conjunction with monitored data. Moreover, any natural power network variations (e.g. loading) or network arrangement changes initiated by the control room (e.g. switchgear operation) are documented using the standard BaU procedures.

The data is regularly evaluated to allow for adjustment of tests and identification and resolution of issues where necessary. The ongoing biweekly partner meetings will continue to be utilised until the on-site system is fully stabilised. It is then envisioned to reduce the frequency of those meetings as necessary. Dedicated review sessions/meetings will be setup for each of the trialled Solutions and the associated data is assessed prior to the session. Each session will be attended by the respective owners from UK Power Networks and partners/suppliers.

Table 9: Monitored Data Acquired During the Passive Network Trials

Solution/subsystem	Monitored information
WAP	• Configured disturbance records and Manufacturing Message Specification (MMS) reports in all SSC600 SW (virtual) instances. Triggering conditions to be specified by UK Power Networks; and • Alarms configured in all SSC600 SW instance and mapped to substation RTU SCADA points for control room visibility (as required).
Local ANM	• Diagnostic logs configured in vPhC instances; and • Data streams and Local ANM status information archived in Digital Energy Wide Area Monitoring System (DE WAMS).
CMS and APS	• Diagnostic logs configured in CMS and accessible via CMS web HMI; • Diagnostic logs configured in PSS®CAPE, Bridge and PSS®ODMS and accessible via Azure CONSTLDTDB01 host; and • Diagnostic logs configured in SICAM GridEdge instances and accessible via web HMI.
LAN	• IEC 61850 communication supervision logs configured in OMICRON's Network Analyser (DANEO 400) e.g. GOOSE sequence issues, packet drops, PTP synchronisation issues; • StationGuard/GridOps alarms assuming device configured with final substation configuration description (SCD) file and known connected devices; • RUGGEDCOM RST switches syslog; and • RST switches diagnostics and configured alarms.
WAN	• Fortinet's Security information and event management (SIEM[27]) logs and alarms; • RUGGEDCOM RX routers syslog; • RX routers diagnostics and configured alarms; and • Scalance routers syslog.
Substation Server	• Host computer performance logs accessible via vCenter; • Host, hypervisor and configured alarms accessible via vCenter; and • PRP Network Interface Module Logs.

4.4 Active Network Trials

4.4.1 Introduction

Once the Passive Network Trial has been successfully completed in the Constellation trial areas, UK Power Networks will proceed with the Active Network Trials. As per the project

[27] SIEM solutions provide key threat-detection capabilities, real-time reporting, compliance tools, and long-term log analysis.

programme detailed in Section 5.2. Details of this project activity together with the lessons learnt will be reported upon within PPRs and Deliverable D7.

It is important to note that transition to the Active Network Trials will be subject to the readiness of each individual Solution. Therefore, it is possible that not all Solutions will transition to Active operation at the same time. The same applies to the transition from Passive to Active modes in each trial area depending on the area readiness and business confidence.

Upon completion of the Passive Network Trials, and prior to commencing the Active Network Trials, UK Power Network's will complete a risk assessment in collaboration with the project partners/Solution suppliers identifying the technical risks and potential impact on DER customers should, for example, an inadvertent maloperation of a circuit breaker be experienced at any time during any test. The risk management plan will also detail how to manage planned ("deliberate") operations which may impact DER customers, caused as a natural result of executing any controlled Active Network Trial. Suitable control measures mitigating risks and impact will be identified and agreed.

The following provides an overview of the works required before the Active Network Trials can commence and how such trials are currently planned to proceed.

4.4.2 Test Philosophy

The Active Network Trials are tests that are carried out on site with enabled test solutions' control outputs and hence able to perform physical control actions on primary plant.

One of the main activities that must be concluded before the Active Network Trials can commence is that all existing protection functionalities are removed from onsite protection systems and, the balance of MUs installed (where necessary) and the feeder protection functionality across all Constellations sites migrated to the virtualised protection Platform provided by the virtual SSC600 SW.

To achieve this, UK Power Networks' will undertake the following:

- At Maidstone Grid, the existing (old generation) numerical relays currently protecting the feeders will be decommissioned under a planned outage and the new MUs installed to provide the protection functions, followed by migration to the SSC600;
- At Thanet Grid, the pre-existing (mechanical) relays which remain in situ protecting the feeders will require decommissioning under outage. The new MUs, which have already been successfully installed, will be migrated to the SSC600 SW; and
- At the DER sites, the MUs are already successfully installed and protecting the feeders, so they will only need migration to the SSC600 SW.

Tests carried out are either performed manually or by virtue of the Solutions responding to the network conditions they are designed to respond to (e.g. loss of mains protection action or curtailment of generation). It is, however, expected that the emphasis will shift from manual testing to a more "wait and see" approach, as the IEDs will no longer be set in test mode.

The Active Network Trials will require regular monitoring and review of Solutions functionalities and performance over the scheduled Active Network Trial.

Similar to the Passive Network Trials, additional manual tests will be conducted as needed to ensure consistency of results. However, this is expected to hold a higher risk due to potential impact on DER customer supplies and the need to coordinate mitigation actions or planned network switching.

In advance of commencing the Active Network Trials, UK Power Networks has currently defined the testing success criteria as follows:

- All Active Network Trial tests have competed successfully against a set of approved testing procedures which exercise each Solution;
- All major issues encountered that impact value or progress are either rectified by the owner, or a resolution plan is agreed for implementation at a later stage (specifically for value concerns); and
- A BaU rollout plan is developed by UK Power Networks considering the outcomes of the trials and the achieved maturity of each of the Solutions subjected to the Active Network Trials stage.

Further refinements to the above may be made and, should this occur, will be reported upon within PPRs and Deliverable D7.

4.5 Key Lessons Learnt

The key lessons learnt whilst progressing the Network Trials are detailed below.

Full details of all lessons learnt whilst progressing these activities are detailed in Appendix A.1.3.

Lessons Learnt (Network Trials)	
1	A key lesson learnt from carrying out on-site activities is the value of top-down business support in ensuring the success of any innovative initiative. Challenges are inevitable, but strong support from leadership provides the necessary resources and guidance to overcome them effectively. Additionally, involving the end users of Constellation throughout the project's development ensures that they drive its progression and that the outcomes are tailored to their needs. Constellation's approach to securing strong business support began at its inception, with extensive stakeholder engagement. This process was built on clear problem statements and genuine business concerns, centred on the future of Net Zero. The outcomes of this engagement were translated into a robust business case that aligned with the organisation's strategic objectives, which, in turn, reflect the broader strategic direction of Great Britain's energy systems. To ensure this buy-in is sustained, stakeholders are kept informed of the project's progress through a tailored communication strategy designed for each stakeholder group. This effort is further supported by Constellation's active role in the industry, demonstrated through its strong presence at leading events and conferences.
2	Project Constellation emphasised the critical importance of having in-house expertise, particularly for site activities such as SATs. Such internal knowledge ensured efficiency, enabling swift decision-making when issues were identified, which contributed significantly to the success of these activities and trial progression.

<table>
<tr><td></td><td>The project team also relied on partners and specialist suppliers, such as OMICRON, to provide expert advice and support in addressing on-site challenges. Constellation leveraged these partnerships not only to overcome immediate obstacles but also to build lasting in-house expertise through tailored training and knowledge transfer. Workshops and hands-on sessions equipped staff with the skills necessary to independently manage similar tasks in the future.

Aligned with UK Power Networks' "Train the Trainer" initiative, Constellation provided training equipment and test racks that simulate the on-site Constellation cubicle. These resources enabled in-house experts to upskill the workforce effectively, creating a sustainable knowledge base.

By developing internal capabilities, the value derived from innovative initiatives like Constellation is maximised. This approach enhances adaptability and facilitates the seamless transition of Constellation into BaU once its success is demonstrated.</td></tr>
<tr><td>3</td><td>Another key lesson learnt when selecting sites for the network trials in Constellation was the importance of ensuring a true and varied representation of network substations. This approach was essential to demonstrate that the solutions developed would be compatible with additional sites beyond the project's scope, ensuring broader applicability and long-term success.

To achieve this, every step of the network trial process was thoroughly documented and assessed to establish robust procedures. Following the project's iterative approach, these procedures were continually revalidated and refined as on-site activities progressed.

Standardising the network trial procedures ensured consistency, efficiency, and repeatability throughout the project, while minimising the risk of errors. It provided a clear and reliable framework for teams to follow, which proved particularly valuable when working with novel and complex technologies.

Additionally, well-defined processes streamlined training for personnel, enabling new team members to quickly understand and adhere to established practices. This structure also facilitated effective knowledge transfer, helping to retain in-house expertise and support operational resilience.

If Constellation is successfully proven, these standardised procedures will be especially beneficial for transitioning the project into BaU operations, scaling activities, and transferring responsibilities between teams with minimal disruption.</td></tr>
</table>

5 Ongoing Activities and Next Steps

5.1 Ongoing Activities

In order to progress to the next project stage, several activities which remain ongoing at the time of Deliverable D4 report being prepared. Such activities are identified within Table 10 below and will be progressed and concluded in line with the project plan. Furthermore, several activities required to progress the next stage of the project will commence, as summarised in Section 5.2.

Each ongoing activity is being actively managed by the project team and each will be closed as appropriate within the next stages of Constellation.

Table 10: Summary of Ongoing Activities

Description of Ongoing Activity	Planned Actions
Completion of the Passive Network Trials	As scheduled based on the revised project plan (June 2024 PPR[28]), the Passive Network Trials remain ongoing at time of this deliverable submission. Key activities to be progressed are as summarised below and will be reported upon in Deliverable D7. • Testing Local ANM for the different scenarios onsite in using power system simulation with distributed injection of test signals (Sampled Values, voltages, currents) at defined Grid locations; • Provision of additional constraints, DER and Grid site logic parameters for Local ANM scheme development and testing to maximise the value of the test scenarios; • Final deployment and configuration of a permanent installed testing and monitoring solutions by OMICRON at trial areas; and • Repeating WAP and Local ANM tests using the OMICRON RelaySimTest equipment, which will permit a predefined test file to be prepared and used throughout all tests.
Preparations for BaU	Activities to be undertaken by UK Power Networks to prepare for BaU can be summarised as follows: • Continue progressing the development of necessary standards and documents required (e.g. equipment specifications, operation standards, commissioning procedures along with network architecture and cubicle design

[28] https://d1oyzg0jo3ox9g.cloudfront.net/app/uploads/2023/10/Constellation-Project-Progress-Report-June-2024-v1.0-External.pdf

	etc) to facilitate the BaU transition of Constellation; • Continue to analyse the Solutions commissioning test results in order to determine if any additional design improvements are required, especially those related to maintenance activities. For example, verify the need for additional I/O, alarms, alternative vendor equipment etc; and • Conclude the Constellation business case validation exercise including an equipment benchmarking activity, assessing the viability of using equipment (and variants of the same) from different vendors.

5.2 Next Steps

The following section details the next steps which the project partners will carry out to progress the delivery of Constellation. The high-level project plan for Constellation is as detailed within Figure 31, where each of D1 to D7 represents a Constellation Deliverable.

From this, it can be shown that after completion of Deliverable D4, the next stage of the project focuses on finalising the Passive Network Trials and commencing demonstration via the Active Network Trials, which will test the operation of all Solutions under live network operational conditions and monitor the live behaviour of the Constellation Solutions for the first time. During the Active Network Trials, the focus will be set on verifying the correct operation of all equipment and Solutions following both manually initiated triggers as well as unplanned network fault conditions. Upcoming PPRs and Deliverable D7 will provide details and learnings from this stage.

One key activity that will be a key focus of the project team is validating the stability of site-to-site communication over 5G. It is important to note that, to date, this testing was undertaken using Samsung and Oppo 5G SA mobile devices located at UK Power Networks' Thanet site and Vodafone Newbury site. A comprehensive test of the full suite has been conducted at PNDC and some key issues are being rectified prior to commissioning the Solutions on site. Additional details on 5G testing will be reported upon within the project PPRs and Deliverable D7.

ABB, Siemens, GE and Vodafone will continue to provide support to PNDC and OMICRON undertaking the Passive Network Trials as detailed in Section 4.3 to ensure successful completion and transition to the Active Network Trials.

The academic insight and future governance activities are currently being finalised and will be reported upon within Deliverable D6 and the Open Innovation Competition will be reported upon within Deliverable D5.

A summary of the main project activities remaining are therefore as detailed below:

<u>Project Quality Control</u>

- The live network trial procedures will undergo a final review prior to approval and closure by the Technical Design Authority;
- The project partners will continue working together to ensure successful development, integration and testing in the subsequent phases of Constellation.

<u>Project Activities</u>

- UK Power Networks will continue with:
  - ➢ Progressing the Passive Network Trial testing within both trial areas and capturing additional lessons learnt;
  - ➢ Preparing for, and undertaking, the Active Network Trials; and
  - ➢ Building test cubicles to be used for training and off-site testing throughout the remaining trials, procuring alternative Constellation equipment from different vendors (utilising the exiting equipment budget) and undertaking a benchmarking exercise to ascertain if other vendors/equipment variants (e.g. for servers, switches etc) would prove beneficial.
- PNDC will continue with:
  - ➢ Supporting the approval of the trial documentation;

   - Supporting with the finalisation of the Active Network Trial test specifications;
   - Completing the remaining (minor) off-network trials;
   - Supporting the Passive and Active Network Trials; and
   - Planning OIC incubation.

- ABB, GE, Siemens and Vodafone will continue with:
   - Supporting the approval of the trial documentation;
   - Supporting with the ongoing Passive Network Trial testing activities;
   - Supporting with the finalisation of the Active Network Trial test specifications; and
   - Supporting the Active Network Trials.

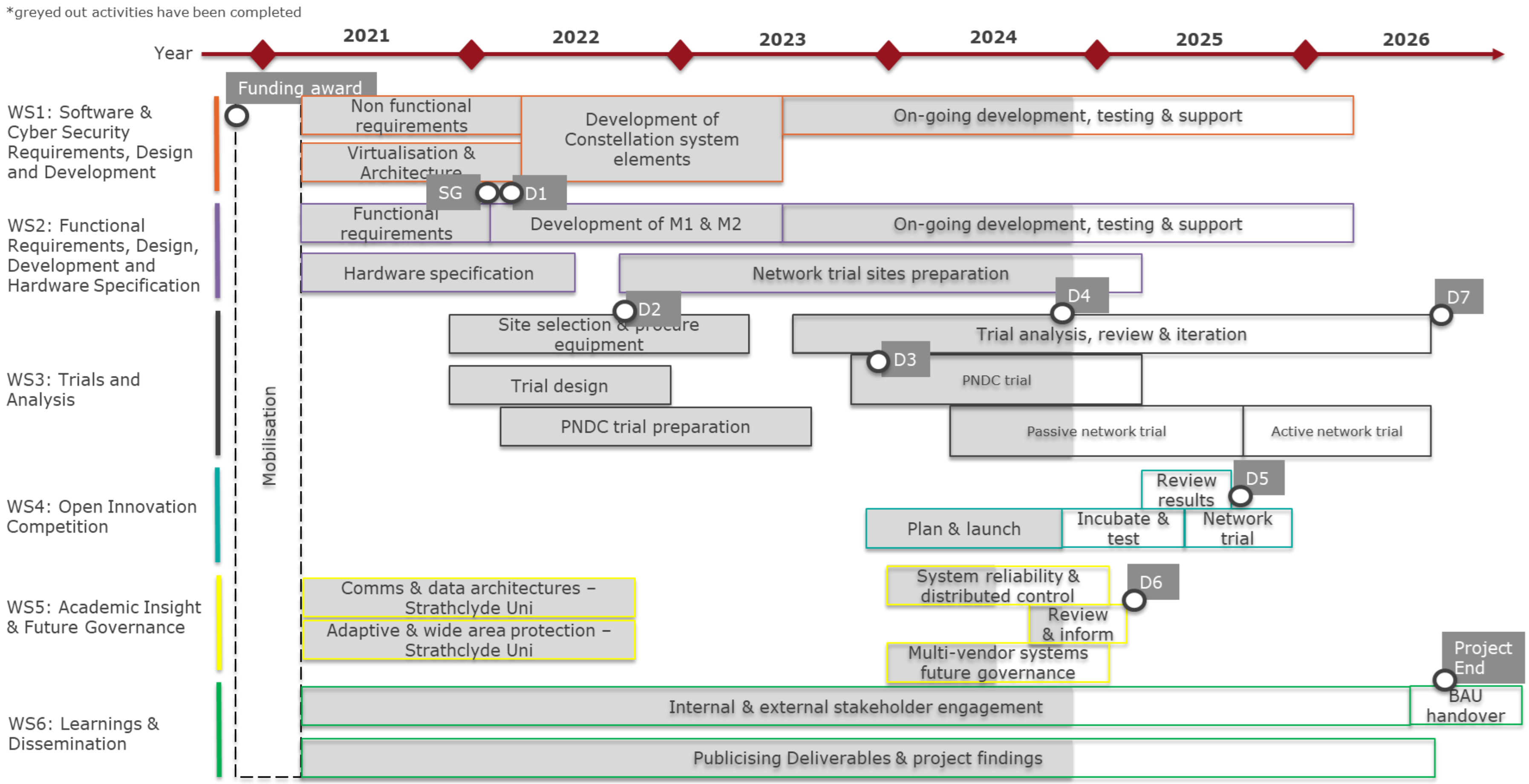


Figure 31: Constellation High-Level Project Plan (shaded elements are completed and partially shaded elements are in progress)

6 Conclusions

Project Constellation is a first of its kind project and will redefine the way distribution networks have traditionally functioned. By investigating state of the art Solutions such as WAP, Local ANM, and APS, Constellation aims to facilitate the net-zero transition of DNOs through reliably releasing more capacity to distributed energy resources and enabling them to optimise their operation. It also aims to provide a medium that will host future digitised innovative solutions, facilitating their implementation, and accelerating their transition to BaU.

In this project, the knowledge gained from extensive engineering activities and the lessons learnt through setbacks and hard work have all been put together to produce a blueprint for rolling out Constellation, or any similarly defined project, from the lab environment into the live electricity network. Most importantly, such transition was achieved safely, securely, and in a fully de-risked approach. Deliverable D4 complements, and builds upon, all previous Constellation deliverables which collectively demonstrate key project challenges as well as successes achieved to date.

Deliverable D4 therefore provides evidence of:

- The importance of building a solid virtualisation Platform, as highlighted in Section 2.2;
- The critical need to develop a robust and cyber secure solution, as highlighted in Section 2.3;
- The essential activities required to prepare a trial site for the roll out of innovative Solutions at the scale of project Constellation, including activities associated with site installation works at DER sites and Primary/Grid substations, as highlighted in Section 3;
- The importance of developing detailed and robust network trial procedures, as highlighted in Section 4, together with the activities associated with progressing the various SATs, as highlighted in Section 4.2;
- The early learnings gained whilst progressing the Passive Network Trials, as highlighted in Section 4.3.

Deliverable D4 closes with a forward look towards the Active Network Trial, as highlighted in Section 4.4, and, as innovation is a continuous process that is always identifying ways to improve, Section 5 summarises the key focus areas currently under consideration by the Constellation project team.

With due consideration to all the above, Deliverable D4 therefore provides detailed evidence that the key learnings defined in the FSP have been captured and demonstrated.

Constellation's progress so far has generated invaluable knowledge for the industry, which is being continuously disseminated. Further information on knowledge dissemination is available in each Constellation PPR, as well as a number of industry events and established conferences, such as Energy Innovation Summit (EIS), International Conference on Developments in Power System Protection by the Institution of Engineering and Technology (IET), DistribuTech, International Conference on Electricity Distribution (CIRED) and Conseil International des Grands Réseaux Electriques (CIGRE).

The approach to deliver all works detailed herein remains focused on effective collaboration between the project partners. This working ethos will remain consistent throughout the remaining phases of the project to ensure the learnings are maximised and clearly communicated.

Appendices

A.1 Lessons Learnt

A.1.1: PNDC Integration and Off-Network Tests

A.1.2: Learnings from the Site Installation process

A.1.3: Undertaking the SAT and Passive Network Demonstration

A.2 Virtualisation Platform Tests at PNDC

A.2.1: Smoke Test Results

A.2.2: Specific Test Case Results

A.3 Cyber Security Testing at PNDC

A.3.1: Introduction

A.3.2: Cyber Attack Trees

A.3.3: Security Evaluation Test Cases

A.4 Final Network Architecture Design

A.4.1: Maidstone Grid Site

A.4.2: Maidstone DER Site (DER-1)

A.4.3: Thanet Grid Site

A.4.4: Thanet DER Sites (DER-5 and DER-4 PV)

A.4.5: Thanet DER Site (DER-2 Generation)

A.4.6: Thanet DER Site (DER-3)

A.4.7: Engineering Design Drawing Example

A.4.8: RTU Cubicle Design

A.5 Network Trials (SAT)

A.5.1: Local ANM SAT Results

A.5.2: WAP SAT Results

A.5.3: APS and CMS SAT Results

A.5.4: Network Communication Test Results

A.5.5: 5G Communication Test Results

A.6 Network Trials (Passive Network Trial Testing)

A.6.1: Schedule A: Wide Area Protection Tests

A.6.2: Schedule B: Adaptive Protection and CMS Tests

A.6.3: Schedule C: Local ANM Tests

A.7 Site Installation Photographs

A.7.1: Maidstone Area – Maidstone Grid

A.7.2: Maidstone Area – DER-1 Generation (DER)

A.7.3: Thanet Area – Thanet Grid

A.7.4: Thanet Area – DER-5 (DER)

A.7.5: Thanet Area – DER-4 PV (DER)

A.7.6: Thanet Area – DER-2 Generation (DER)

A.1 Lessons Learnt

All lessons learnt whilst progressing project activities associated with the PNDC integration and off-network testing through to site installations, SAT and commencement of the Passive Network Trial testing, are detailed below.

A.1.1: PNDC Integration and Off-Network Testing

<table>
<tr><th colspan="2">Lessons Learnt from PNDC Integration and Off-Network Testing Activities</th></tr>
<tr><th colspan="2">Part 1: Main Lessons Learnt</th></tr>
<tr><td>1</td><td>The following are three overarching lessons learnt from the PNDC tests that should be considered when designing and testing virtual digital substation Solutions:

a) Data consistency and interoperability
Interoperability between different elements of the Constellation Solutions is achieved mainly through the use of communication standards and design considerations for the exchange of signals between those elements in real-time (e.g. exchange of IEC 61850 GOOSE messages between physical and virtual IEDs for achieving protection functionality) – this is to be expected in a digital substation setting. Moreover, close attention also needs to be placed towards exchange of data in a non-real-time setting between elements of the project as part of the implemented functionality or as part of testing procedures carried out during the trials.

One of the main forms of data and model exchange in the project is achieved through the Common Information Model (CIM), based on the Common Grid Model Exchange Specification (CGMES) maintained by the IEC TC57/WG16. In Constellation, a network model based on CIM is used by the APS Solution to maintain an up to date model for short circuit calculations and subsequent calculation of new Directional Over Current (DOC) and load blinding protection settings. Further, the network topology and load flow are also updated via CIM during off-network testing to initiate a fresh calculation reflecting a change in network running arrangements or possible change in fault contribution from connected DER. From the experience of using CIM and performing off-network testing, the following improvements and associated context are suggested:

• Not all elements in the test chain “speak” CIM directly. For instance, branch loading, circuit breaker status and tap changer position data obtained from Real Time Digital Simulator (RTDS) to drive a new DOC setting calculation are not readily available in a CIM compliant format. This necessitated the creation of additional scripts to transform the data and feed it into the APS Solution. Improving CIM interoperability is a particularly important consideration for elements involved in the APS Solution testing during network trials and BaU further down the line.
Furthermore, it is recommended that a common interface design for data exchange is developed at the early stages of a digitalisation project over and above real-time communication (or process) interfaces. Such design should encompass the lifecycle stages of the project including trials, operation and maintenance to ensure the desired data interoperability is achieved and that testing processes are more streamlined between stages; and</td></tr>
</table>

- Testing generates large quantities of data both from the test environment and Solutions (software) under test that is integrated within the test environment. Evaluation of the data to validate the Solutions under test. For the vast majority of testing related to protection Solutions, test data is stored in standard formats, such as Common Format for Transient Data Exchange (COMTRADE) for transient analogues and events and Packet Capture (PCAP) for LAN traffic (i.e. IEC 61850 GOOSE, SMV). This enables sharing and examination of the data readily by multiple partners. This is perfectly acceptable for transient and dynamic tests (most relevant for WAP testing). For tests involving steady-state conditions or longer term dynamics (e.g. violation of network constraints and subsequent DER control initiated by Local ANM), relevant test signals are archived in a database (DE WAMS) with the ability to export data into Comma Separated Value (CSV) format for instance. However, automation of test evaluation should be considered as part of the suite of test tools to improve the efficiency of the evaluation process and reduce human error. This is particularly important as the digital substation is a data rich environment and testing generates additional data requiring a context matching to the data generated in order to correctly interpret it. As such, it is suggested that improvements to testing tools to ingest additional signals or a combination of signals are implemented. For example, tools that ingest and compare C37.118[29] measurements in conjunction with DNP3 control actions as part of the Local ANM solution.

b) Traceability of configuration

The software-oriented nature of the virtualisation Platform and deployed Solution provides the network operator with greater flexibility in managing the deployed Solutions in terms of software updates, mapping of interfaces for data exchange and securing access to different users for remote configuration, testing and diagnostics. However, this necessitates a fit for purpose system for managing changes not only in software configurations, but also for the communication network configuration underpinning the secure exchange of process and management data. Making use of centralised management tools is recommended to ensure configurations are tracked and are traceable. As such, the following lessons and recommendations can be reported:

- The virtualisation Platform (consisting of Substation Servers, hypervisor and management tools) offers adequate functionality for the deployment and management of VMs and configuring virtual networks, shared storage and compute resources. As more experience is obtained by using these tools, improved tracking of configuration changes as well as a real-time monitoring of Platform performance can be achieved. Consequently, the virtualisation Platform can be managed by the network operator as an asset in a more effective manner.
  To realise such improvements, it is recommended that an alarm list is specified and configured in the virtualisation management tools (i.e. vCenter), which can be displayed on dashboards or fed into other network operator systems via Application Programming Interfaces (APIs). The alarms should, in the first instance, focus on server health and failures and compute resource utilisation. Furthermore, hypervisor tasks initiated automatically or by the user should be logged and defined reports are generated to review these tasks on a regular basis, especially during the trials stages to evaluate the level of information that the user requires to be

[29] C37 data streams are synchronized phasor measurement data exchanged between electronic power system devices in real-time

logged when transitioning the virtualisation Platform into BaU service. Equally, versioning of Solution software (deployed within VMs) should be tracked and logged in an asset database along with metadata to inform the user of the purpose of version updates; and

- The virtualised digital substation relies on robust and secure communication between various elements – namely IEDs, Substation Servers and VMs, monitoring and test tools, control centre interfaces, remote substations, etc. As the project progressed and testing outcomes were reviewed by partners, the communication network architecture was refined to ensure that it caters for the software Solutions and network operator requirements. To ensure alignment between testing sites (whether off-network or live) in terms of communication network architecture and configuration it is recommended that any configuration changes are tracked and shared between relevant parties. This can be in the form of change logs with reference to the original communication network design. Configuration files can also be shared as appropriate. To facilitate the management of these configurations and changes, central management tools supplied by the vendor should be utilised (where the equipment be supplied from a single vendor). Additionally, non-vendor specific management tools based on Simple Network Management Protocol (SNMP) on Network Configuration Protocol (NETCONF) can also be used as appropriate.

c) Translation to network trials

The trials stages and sites were designed and selected to ensure a progression of TRL and to initially address issues in a low cost and controllable test environment (off-network trials), ultimately leading to a live deployment where focus can be on the integration with physical substation switchgear and participating DER sites. In the effort to ensure this translation between trials stages is achieved effectively, the following lessons learnt can be reported:

- Complementarity and continuity of trials stages: each stage of the trials phase of the project fulfils a complementary role and leads to the following stage. Off-network testing focused on system level testing with all Solutions deployed within the virtualisation Platform and communication network installed at PNDC. As network operators gain more experience in the design, implementation, testing and operation of digital substation and virtualisation technology deployed in the substation, a critical mass of knowledge created, and upskilling of engineers is achieved. While experience is amassed, efforts should be focused on developing standard testing methods and environments to ensure a traceable and scalable approach to testing, which also encompasses improved tools and interoperability aforementioned; and

Partner engagement and forward planning: to ensure translation into network trials is achieved effectively and relevant stakeholders from each project partner have a common understanding of issues and a plan for resolution, regular (bi-weekly) trial review meetings were setup to report on trials progress, identify risks and dependencies, discuss technical issues and agree actions and resourcing to resolve these. Actions and decisions from these forums are logged in a project SharePoint for tracking. Ad-hoc meetings are also agreed during this forum to deep dive into technical issues. This approach proved successful in ensuring a collaborative spirit between partners to deliver robust Solutions ready for the network trials stage of the project.

Part 2: Lessons Learnt (PNDC Off-Network Testing)	
1	General It is important to ensure that all VMs and hosted OS are time synchronised (normally via Network Time Protocol (NTP)). Otherwise, connectivity issues may occur as well as aborting of control commands due to communicating hosts being out of time synchronisation; Documentation and communication between partners of differences between PNDC and live substation configurations to ensure smooth transition between trials phases and any gaps are addressed in the appropriate phase
2	Local ANM PNDC Testing and Further Development During the Local ANM SAT at PNDC, the use of the Phasor Controller (PhC) Designer (a GE Vernova software package used for configuring the Local ANM control scheme as well as monitoring scheme signals and parameters in real-time) proved very useful in identifying configuration and signal connectivity issues, thus enabling completion of the SAT without delay. Based upon this learning, use of this tool was incorporated as part of the UK Power Networks' substation SATs by licensing and appropriately configuring a remote jumpbox on the UK Power Networks' network. This change to the original plan greatly streamlined the delivery of the UK Power Networks' SATs. Packet filtering is configured on the Grid site layer 2 switches as well as on the DER site virtual switch (implemented on the local router). This is to avoid the transmission of SMV and some GOOSE signals between the two locations, thus avoiding overwhelming the wide area communications with unnecessary process bus traffic. Additional filtering configuration was necessary to whitelist some of the communication traffic between the sites to enable the Local ANM functionality. To achieve this, a fully specified Local ANM communication architecture was needed including MAC and IP addresses of communicating VMs. Careful attention should be taken when configuring the filters in case of changes of addressing schemes between locations or phases of the project trials. This is in contrast to filtering applied to GOOSE and SMV, where the destination MAC address can be solely relied on and is determined at the configuration stage independent of device MAC addresses.
3	WAP PNDC Testing and Further Development The core operational principle of the virtualised WAP Solution has remained aligned with the initial design. However, various changes to the bay level protection functions, protection settings, included MUs, GOOSE communication, measurements and appearance on the HMI have been made after the FAT and the LAN supervision functionality has been added. Several iterations during the engineering process are expected in innovation projects where new functionality is being defined and developed. Documenting the findings and creating clear guidelines is essential to have efficient engineering processes during BaU implementations.

4	APS and CMS PNDC Testing and Further Development • The range of settings configurable in the IED with DOC protection (SSC600 SW in this case) influences the maximum and minimum values of settings possible to apply in the field. • The calculation of new protection settings, that are a compromise between dependable and stable performance, ensure the new settings coordinate with the upstream and downstream network protection. This means that process of adaptation does not always yield new settings, which is particularly the case with high impedance fault scenarios (depending on the network configuration). The network operator should then carefully consider the impact of suboptimal DOC and Load Blinding (LB) settings during periods of high DER power export. This scenario may necessitate the use of manual setting mode for adjustment of settings prior to application to the field, based on engineering experience in light of calculation results from the APS. • It is recommended that for testing an APS Solution, that the network operator refer to their adopted DOC and LB setting guidelines to determine if the new settings are aligned with the operator's expectations and practices. The cause of any significant deviations should be understood and where applicable changes are made in the calculation algorithms. • Future improvements to the DOC setting calculation algorithm should take into account the use of different polarisation methods such as negative sequence voltage to accommodate the fault infeed characteristics of inverter based generation. Furthermore, accommodating the adaptation of duplicate/redundant protection IEDs to avoid discrepancy in performance is also important. • The current implementation of the APS involves writing to a new setting group (i.e. SG2 in the SSC600) and making this setting group the active one. It was agreed that a design change is necessary to only write settings to the already active group (normally SG1). This ensure that settings groups that have not been commissioned on site are not made active. This design change will be implemented and tested during the next reporting period. • Identifying the source of executable network model data for power flow and short circuit data was a challenge for the development phase of Constellation. While the PowerFactory Model had information on the zero sequence impedance and load status, the ADMS provided the information on the status of circuit breakers. Therefore, the information was identified to be stored in two different systems in different formats. This problem was solved through using the PI historian system, which combined data from the ADMS and the Power Factory model to produce an executable network model with all information. However, this Solution is suitable for the project testing but is less effective for use in BaU. UK Power Networks and Siemens will continue working on potential solutions and identify an effective Solution for BaU. • There are three potential methods to trigger the Adaptive Protection i.e. On-demand activation by operator, automation via SCADA scripting to reconfigure the network and reconfiguration based on load and generation forecasts. None

	of these methods could be implemented because technology on the ADMS side was not ready. To overcome this limitation, an alternative Solution was developed – creating an exchange directory where CIM data files could be manually copied, serving as the system trigger. This allowed the adaptation system to proceed despite the unavailability of ADMS technology. For BaU, UK Power Networks and Siemens will continue working on potential ways to adapt one of the three methods described above.
5	<u>5G Slice PNDC Testing and Further Development</u> • Testing and monitoring the network performance of the 5G link has been an important aspect, especially noting the special requirements for GOOSE data transmission in the WAN tunnel over 5G; • As GOOSE messages are not a standard data type in 5G Transport Communication, Vodafone was able to identify Internet Protocol (IP) redirects on the Data Core Gateway which was resulting in data losses when GOOSE messages were being transferred between sites. A policy change was then introduced to improve this communication; • OMICRON StationGuard was able to detect new devices or interfaces added to the network. It also keeps track of the communication between devices giving alarms as required; • The information about the detected devices is not automatically uploaded. This implies that the IEC61850 SCL file should be uploaded, or the device should be configured manually. Without this configuration, it is difficult for OMICRON StationGuard to correctly keep track of events; and • A security expert should be available to track and manage the alarms from OMICRON StationGuard as the device only detects security events.

A.1.2: Learnings from the Site Installation process

<table>
<tr><th colspan="2">Lessons Learnt from Preparing the Network for Constellation</th></tr>
<tr><td>1</td><td><u>Site Preparation</u>
When retrofitting the Solution on existing sites, additional works to vectorise existing drawings which were yet to be completed in line with the UK Power Networks' vectorisation programme were required. For future projects, an assessment should be done at an early stage of the project to identify any similar requirements ahead of time to ensure optimal coordination of work.</td></tr>
<tr><td>2</td><td><u>Network Architecture</u>
Whilst the network architecture designs at both Maidstone and Thanet Grid sites were initially identical, it was found necessary, following progression of the SATs, to make the following changes to the Maidstone Grid network architecture:
Provision of additional MUs connected to the layer 2 switches; and
Provision of a dedicated PMU device as the MUs installed at each Grid site were sourced from different vendors and those installed at Maidstone Grid were not able to send Institute of Electrical and Electronics Engineers (IEEE) C37.118 data.
Certain minor architecture changes associated with equipment connectivity across both Grid sites have also been required, in order to ensure that the networks across each site can be mounted in an identical manner whilst maintaining the same functionality.

For example, this has required cabling between ports between the layer 2 switches and the redundancy box (Redbox), plus certain Ethernet connections to ports on the layer 3 switch were required to be changed.</td></tr>
<tr><td>3</td><td><u>Design</u>
As the Constellation project progressed, and maturity of the Solutions increased, the original project design was iteratively revised to ensure its robustness. Some of the key design changes that occurred in light of these learnings are:
In order to resolve spatial limitations on congested site locations when installing the constellation cubicle, the project team reassessed the original cubicle design and identified means of reducing the overall spatial requirements of the unit. One key approach was the provision of a RTU device within the Constellation cubicle to provide a link between Constellation equipment and UK Power Networks' SCADA;
As site to site communication is one of the core benefits of Constellation, the project team assessed the original solutions designs to identify means for enabling communications across substations of different characteristics. One key learning to achieve this is that Radio Network Access (RNA) modules have been installed on PRP switches to enable the communication with different substation voltage levels via the High Availability Seamless Redundancy (HSR) network (Grid and DER sites);</td></tr>
</table>

	- Ensuring redundancy in the Constellation design is an integral part of raising business confidence in the project, especially in Grid/Primary substations. The original Constellation cubicle design had components which did not inherently allow for PRP. Therefore, the project team identified an alternative method of achieving that in order to enhance the project resilience. A Redundancy box (Redbox) has been added on the PRP network to enable non PRP devices to connect onto the PRP networks (Grid and DER sites); - By utilising the afore mentioned Redbox, OMICRON testing configuration box (Daneo 400) and secondary injection testing equipment (CMC356) are now connected through it, instead of directly connecting to the layer 2 switches (Grid and DER sites). Note: this OMICRON test equipment is only installed to aid the ongoing testing and will be removed from the Constellation cubicle before commencing with BaU implementation. The network design has been revised to provide dedicated ports on the RedBox for connection of this test equipment should it be required to re-introduce it for test and analysis purposes in the future; - A specific challenge that was faced on the DER sites is the ability to enable MMS communication between the server and layer 2 switch. To overcome this challenge, an additional Ethernet cable has been added between the two (DER sites only); and - Another important learning which was developed as the network preparations progressed is the importance of standardising the naming conventions, not only locally, but across the whole project team (internal and external). During the final configuration steps, the Virtual Local Area Network (VLAN) IDs have been updated according with the switches' configuration (Grid and DER sites) which moving forward will ensure cross component consistency.
4	<u>Network Outage Learnings</u> Constellation has required the planning and progression of a large number of network outages across both trial areas. Timely engagement with DER customers and/or owners also needed to be prioritised and concluded, along with managing the equipment orders and delivery of equipment to site in advance of the network outage commencing. Whilst all such activities were successfully managed by the UK Power Networks project team, it has been learnt that having a strong business case to ensure the availability of staff to progress all such activities is a vital pre-requisite to ensuring business buy-in.
5	<u>RTU Installations</u> An important learning from Local ANM testing was gained whilst attempting to configure the interface between the RTU and Local ANM components via 61850 MMS. As the RTU's are designed to work with a proprietary protocol known as Teleconnect 3 (TC3), additional works to develop the correct mapping between the 61850 logical nodes and the internal TC3 points was required, along with development works necessary to achieve a correct interface.

	To achieve this, a DNP3 interface was chosen for testing, with additional RTU firmware enhancements to further support its 61850 compatibility subsequently being developed, allowing its potential use as the interface during live site trials.
6	<u>Constellation Cubicle</u> The Constellation cubicles located at the Grid sites are identical apart from that the Maidstone Grid Constellation cubicle includes a PMU device, required to provide the interface with the MUs, collecting the PMU data via IEEE C37.118 from Maidstone and DER-1 DER sites for transmission to the Azure Server/GE. The Constellation cubicles located at each DER site are identical and inherently smaller than their Grid counterparts due to accommodating less equipment overall.
7	<u>Switchgear Panels</u> Within each trial site, the initial intent was to install all the new MU equipment within the switchgear panels (comprising 2 MU units per feeder) but retain the existing feeder protection relays in operation until such time as the Active Network Trials commenced, when the existing protection relays would be removed and the new MU equipment activated and placed into live operation. However, at the Maidstone sites, space restrictions within the switchgear panels has required installation of the MU equipment to be split into two distinct phases, as detailed below: • Phase one (Passive): Space limitations within the switchgear panels has meant that the new MU equipment could not be installed without first removing some of the existing protection relays. Therefore, for the Passive Network Trials, only one MU per feeder was installed, allowing tests to demonstrate the correct operation and performance of the Solution to be tested and verified. • Phase two (Active): Prior to commencing the Active Network Trials, all existing protection relays will be removed and the remaining new MU equipment installed. Such space restrictions were not encountered at the Thanet sites because there was sufficient space within the switchgear panels to retain the existing protection relays in operation whilst also installing the new MU equipment (comprising two MU per feeder). Prior to commencing the Active Network Trials, the existing protection relays will be disabled and left in situ. This learning adds additional value to the project team as it allowed the standardisation of the protection system upgrade under both possible scenarios. This aids in facilitating the BaU transition of the Solutions following project success. The Active Network Trials will allow the Constellation equipment to directly control the distribution network. This phase will only be carried out upon successful completion of the Passive Network Trial and all DERs and will be reported upon within Deliverable D7.

	Figure 8 through Figure 11 details examples of the existing switchgear located in Maidstone Grid and Thanet Grid respectively, which have been modified to accommodate the Constellation equipment.

A.1.3: Undertaking the SAT and Passive Network Demonstration

Lessons Learnt from Undertaking the Network Trials	
1	SAT Learnings (General) Constellation is a complex and multi-faceted innovation project, integrating several Solutions developed by the project partners. This presents numerous challenges not least due to the fact that intimate knowledge of the Solutions and how they interact to achieve the required Methods is required. The success of Constellation since inception has been largely due to the fact that all project partners continue to work together in a professional and co-ordinated manner, ensuring that technical issues are addressed and knowledge gained on the innovative Solutions documented and shared. Specifically, with regards the network trials phase, many general learnings have been gained whilst undertaking the complete suite of SAT testing activities for all Solutions across both trial sites. Key topics that any DNO should therefore be aware of before testing similar solutions are summarised as follows: • PRP network: understanding how to assemble the network, configure devices, and validate its reliability; • ABB MUs: learning about configuration, disturbance recording, and communication based on IEC61850; • Centralised virtualised digital protection systems (SSC600 SW): gaining knowledge about configuration, alarms, important supervision signals, disturbance recording, and communication based on IEC61850; • OMICRON tools: learning how to use the CMC356 to simulate MUs (GOOSEs and SMV protocols), check the performance of protection systems using the CMC356, and utilise DANEO 400 to verify network performance and troubleshoot errors; • PTP time synchronisation protocol: understanding how devices should be configured to implement BMCA; • Simulation/Test mode: learning how to utilise this mode on central protection systems, MUs, and CMC356, enabling the creation of test scenarios in a safe environment; and • Running the PDC VM on the Substation Server and the features and limitations of using different MUs to provide SMV to the PMU device.
2	SAT Learnings (Local ANM) • Engagement between all Parties involved in the SAT was demonstrated to be crucial to ensuring successful progress and completion of the testing activities; • Regular site progress calls were held with specific action trackers to ensure all parties were up to date on progress and all issues were captured. This was valuable in ensuring efficient work as site deployment inevitably leads to issues that are partially owned by multiple parties; • Efficient configuration of the PMU devices was achieved by using the flexible PDC and PLC devices and setting up the PhC designer license; and • During the course of the SAT preparation some temporary modifications were applied to the DER Site scheme. These entailed the inclusion of additional safeguards against

	the Local ANM logic issuing non-default active power limits to the UK Power Networks RTU while under test. The connection between the Grid Site vPhC and the ADMS remains part of the current Local ANM design, but verification of its correct operation has been deferred whilst better alternatives (e.g. dashboards within GE Vernova's Grid OS Platform) are considered which may provide enhanced operator level observability and control of the Local ANM. It is also considered that providing control via use of the existing ADMS connection to the UK Power Network's RTU may streamline BaU roll out.
3	<u>SAT Learnings (APS and CMS)</u> • The specifications for Debian OS[30] and Docker requirements necessitated multiple upgrades to ensure the successful installation and operation of the SICAM GridEdge software in the substation VM. Due to restricted internet access in the UK Power Networks' Operational Technology (OT) environment, these upgrades were only achievable with assistance from UK Power Networks' Information Technology (IT). For the next trial, more detailed specifications and prerequisites will be provided to avoid future upgrade needs; • Communication issues between SICAM GridEdge and the SSC600 relay were identified. Investigation of network traces revealed incomplete handshaking over the IEC61850 protocol. This issue arose from the use of a PRP network during the trial, which necessitated enabling jumbo packets in the VM. For the next phase of the trial, enabling jumbo packets in the VM will be established as a prerequisite to prevent this problem; • It was found necessary to assign and configure an additional Ethernet port on the Substation Server to the SSC600 device, to enable communication with SICAM GridEdge and RTU; and • SICAM GridEdge was not communicating with SSC600-2 due to PRP network packets being bigger than the packets in non-redundant networks. Maximum Transmission Unit (MTU) was increased on Linux (OS which SICAM GridEdge is running) to enable the correct operation of this VM.
4	<u>SAT Learnings (WAP)</u> • Simulation Mode and Test mode of IEC61850 were tested and validated on SSC600. By using those modes of operation, it is possible to test the protection functions of the feeder configured at SSC600 only by connecting CMC356 on the network and enabling the Simulation mode on SSC600 and CMC356. The test mode should also be enabled on the SSC600 in order to avoid the MUs receiving the signals from the SSC600. Removing the MUs of the feeder under the network is not required using Simulation Mode and Test Mode. • When the MU loses time synchronisation, a warning signal is activated on the SSC600 to indicate that the SMV received for this specific MU is not synchronised. This signal was not initially indicated, so the configuration was modified to activate an appropriate SSC600 alarm LED. In addition, an anomaly detection signal has also been added to identify when disturbance recording is activated during Passive operation and operation mode for disturbance recording has been changed from Saturation to Overwrite.
5	<u>SAT Learnings (5G Communications)</u>

[30] Free and open source Linux operating system (OS)

	• Following reports of continuous GOOSE packet drops in the 5G SA Network (in contrast to the Fibre Network), resulting in loss in transmission. This had a knock on effect on the link performance of the 5G SA Constellation Network. The IP redirects on the Date Core Gateway (DCGW) interface were removed which then prevented the DCGW from sending the GOOSE packets to the CPU processing. • After this configuration change, out of 78 million packets tested only 90 packets were dropped, providing only 0.0001% packet drop on the 5G SA Network.
6	SAT Learnings (Network Communications): • Ensuring the correct interoperability between devices using the communications protocol IEC61850 provided by different manufacturers has required significant effort to conclude. This has included, for example, the GOOSE and SMVs transmitted between ABB – Siemens equipment plus ABB and GE equipment. • Validation of the PMU data interoperability between SIEMENS – GE has required significant effort to conclude. This has included extensive testing of the GE and SIEMENS PMU devices to ensure correct data is being transmitted to GE's PDC. • In order to measure the traffic on each switch port, it is important to undertake tests under the worst case scenario – simulating SMVs and faults with an external set (OMICRON CMC356) and/or during downloading fault recordings.
7	Early Learnings from Passive Network Trial • A test pulse logic was added to Maidstone SSC600 SW instances to validate the communication with DER. This pulse signal can be easily issued to validate the GOOSE latency between Maidstone and DER without an external device (such as DANEO 400). • The complexity of the site deployments and the ongoing work and changes at each site has meant that certain issues were encountered during the early phases of the Passive Network Trials (e.g. lost data at the azure server due to local synchronisation issues, disconnection of data streams due to firewall changes and loss of settings due to server restarts). Prompt and clear communication between partners on these shared sites has proved essential in ensuring that the potential impacts of any changes/works have been able to be promptly reviewed and mitigated. • The initial design of Local ANM used a single, aggregate C37.118 stream to transfer all Local ANM data from the Grid site to the Azure server for archiving and visualisation. Then intent of this was to minimise connections and simplify deployment. During the course of the Passive Network Trials, it became apparent that this approach posed a higher than expected risk of data loss at the Azure server. This was primarily due to delayed data transmission from one or more sites causing this data to 'miss' the aggregate stream being sent from Grid site to the Azure. One solution is setting a long wait time for this stream, so all data is likely to arrive eventually. However, for Local ANM, this approach would severely slowdown the DE WAMS Grafana dashboards used as a tool for monitoring the behaviour of Local ANM, as all data would arrive with a long delay. As an alternative solution, the single stream from Grid site to Azure were separated into multiple streams with the data grouped according to importance (e.g. actual measurements are more important for long term archiving than the Local ANM audit streams) and estimated arrival time to minimise the severity of any data loss.

A.2 Virtualisation Platform Tests at PNDC

A.2.1 Smoke Test Results

Smoke Testing was undertaken to ensure that the Platform's test setup, configurations, software, hardware worked as expected, with the successful results obtained as detailed in Table 11 and Figure 32 below.

Table 11: Comparison of Expected and Actual Smoke Test Results

Test	Expected Results	Actual Results	Pass/Fail
1	Software build stable enough for more in-depth testing	Hypervisor 7.0.3 Build 19482537 Patch Release - Hypervisor70U3c-19193900 with Virtual Storage Area Network (vSAN) recommended patches Hypervisor70U3i-20842708*. vSAN Witness Host 192.168.1.53 (Hypervisor 7.0 U3). The VMs on Hypervisor 7.0 U2 and later (VM version 19) capability. * Not running latest firmware	Pass
2	Critical functionalities of the applications are working as expected.	All applications running as expected.	Pass
3	All the hardware running stable and the latest firmware	All the test Platform hardware has been checked for the latest and stable version of the software. However, where lower versions of the software are retained, they are secure without bug issues.	Pass
4	Access to enough CPU resources for protection application to complete tasks as expected	The existing configuration has an ABB protection solution on a passthrough via a dedicated Network Interface Card. However, the server's specifications are adequate for the installed VMs, see below:	Pass

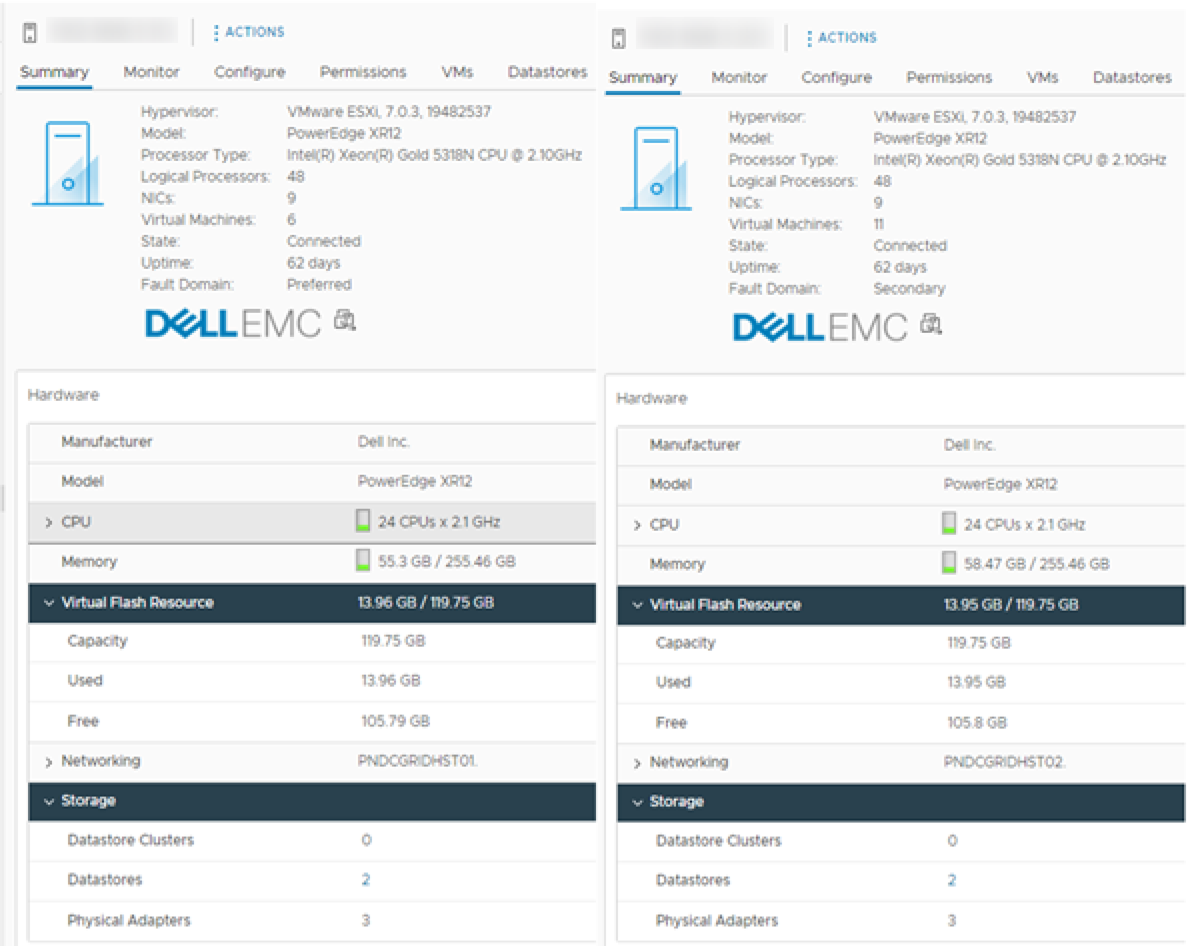


Figure 32: Example of Smoke Test Results Screen

A.2.2 Specific Test Case Results

a) VM Creation

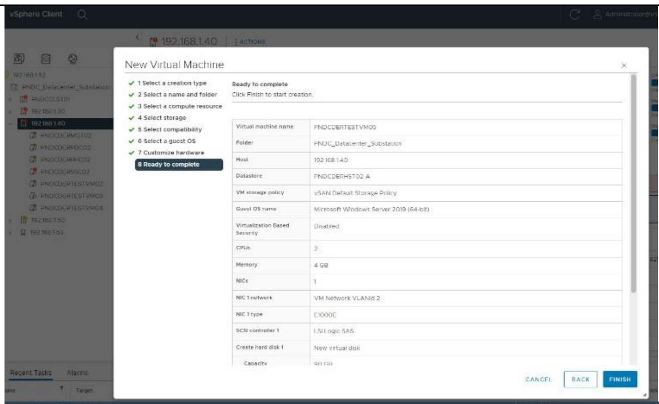
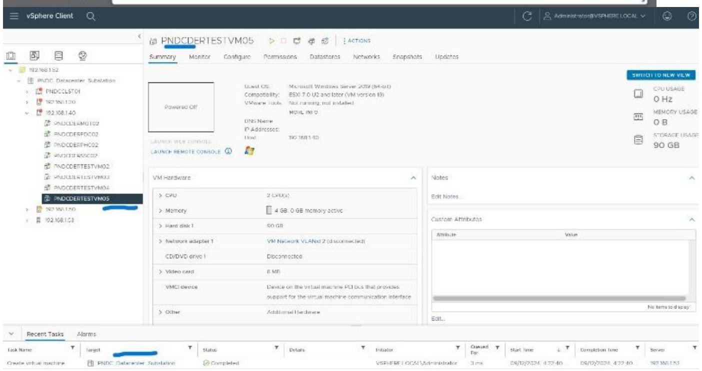
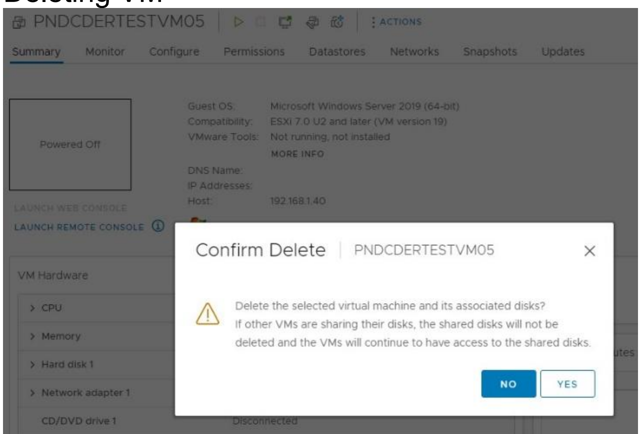
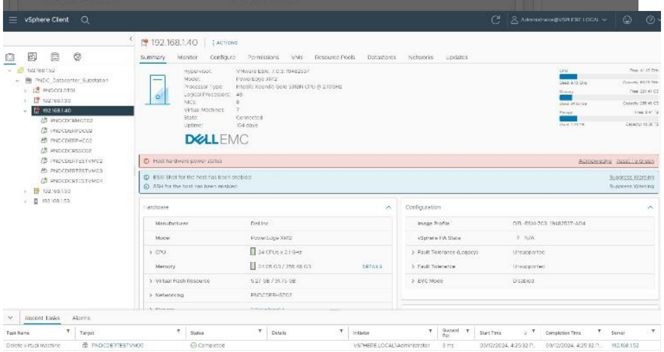
The ability to create a VM within Hypervisor hosts including the start and stop operation was successfully verified. The VM creation/deletion test per Hypervisor host creates a test VM on each host, which was able to be deleted, showing that vSAN networking plumbing, creation/deletion and I/O to object vSAN were correctly working.

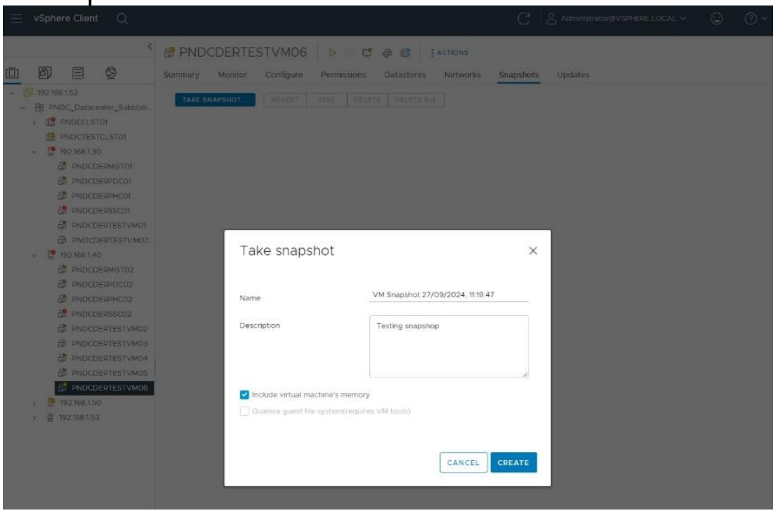
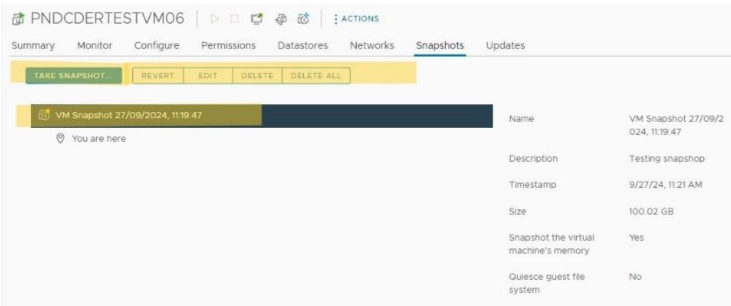
The tests also successfully verified that the management stack was operational on all Hypervisor hosts and that the vSAN network was working.

Test details achieved are detailed in Table 12 below.

Table 12: TVM Creation Test Results

Test	Expected Results	Actual Results	Pass/Fail
1	Test VM creation/deletion on Hypervisor hosts	VM can be created and deleted from the vSphere client and the Hypervisor host by completing the creation form with OS installed from desired datastores. Creating VM	Pass

		  Deleting VM  	
2	VMs start and stop operations working	All VMs can be started and stopped from vSphere client or the Hypervisor host	Pass

3	VMs snapshot creation and restoration working via vSphere	Snapshots are taken automatically when you suspend the VM and restore. Manual snapshots can also be taken from the vSphere client and restored.  	Pass

b) Latency and Response Times

These tests have successfully demonstrated that the networking configuration in the Hypervisor host is able to offer sufficient network performance for critical applications.

The existing VMs were configured to run a network testing tool (iperf3) between VMs in an attempt to saturate (heavily load) the hypervisor's networking stack.

The test tool monitored the critical networking performance and detected changes in latency or jitter across the critical links as network load was added or removed.

Ensuring that the network performance remains as expected throughout the period shows a **success scenario**, while a **failure scenario** means that stressing the internal virtualised network interface between VMs leads to service disruption.

To monitor the network and analyse the traffic between VMs and hosts, windows packet sniffer - pktmon application packetcapture utility (lightweight tcpdump) was used to diagnose networking issues, including slow connection, lost packets, and connectivity problems.

The tracer file was saved with the extension ".etl" which permitted viewing and analysis using the Windows Performance Analyser (WPA). Figure 33 below shows that the Transmission

Control Protocol (TCP) connect reported errors at the initialisation of the iperf3 TCP data, but that transmission then became reliable once the initialisation was completed, as shown in Figure 34.

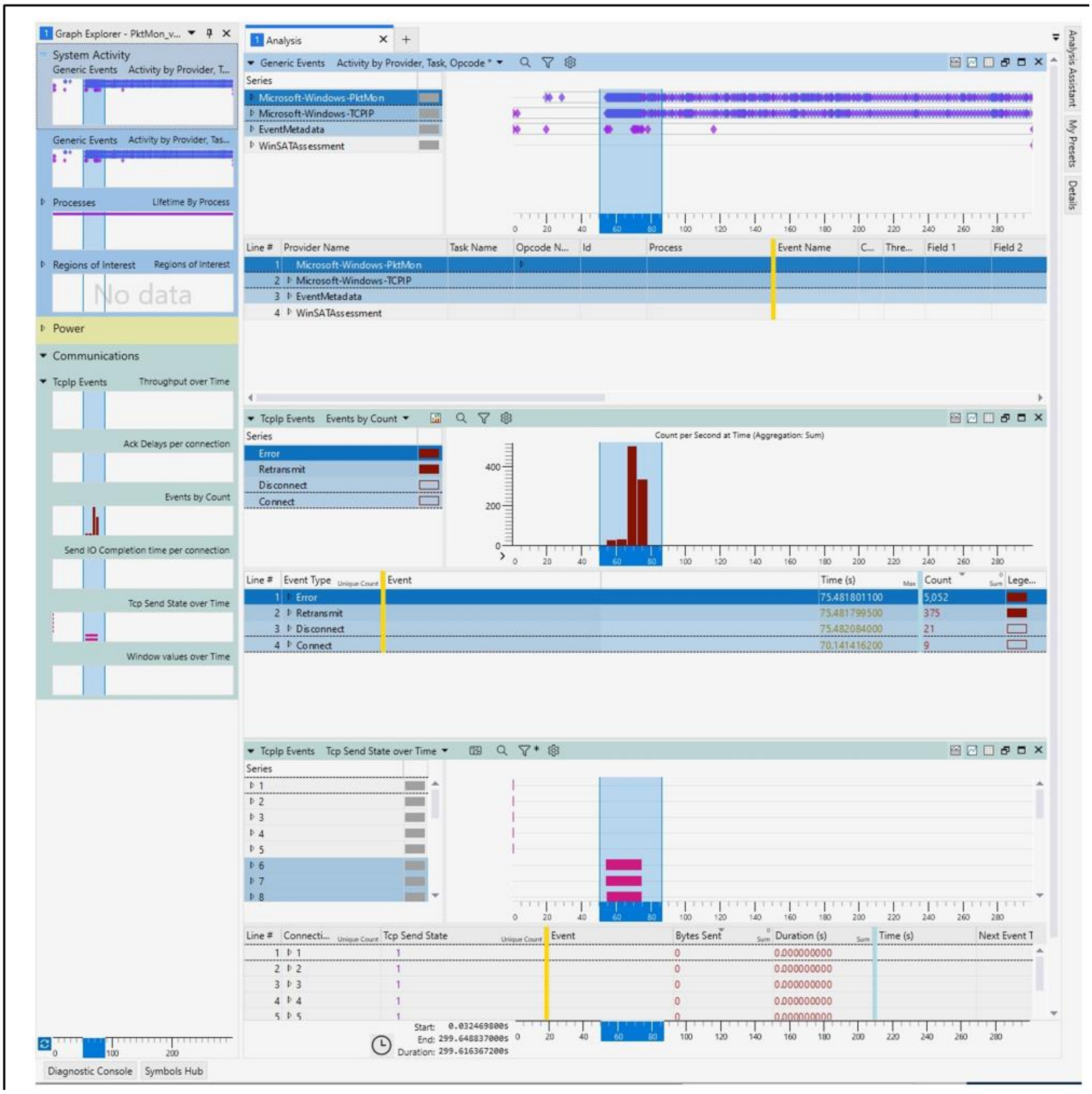


Figure 33: Windows TCP/IP Pktmon tracer using WPA (before initialisation)

Figure 34: Windows TCP/IP Pktmon tracer using WPA (after initialisation)

A.3 Cyber Security Testing at PNDC

A.3.1: Introduction
The cyber security testing and evaluation on the Constellation Platform at PNDC was carried out to outline the physical and cyber security limitations of the network. The testing involves core security evaluations such as vulnerability assessments of LAN, WAN, and other specified resources within the test Platform based on the UK Power Network ETS 05-1607 specifications and the cyber attack tree methodologies created as part of the Constellation architecture. The primary objective of the testing is to identify and propose mitigations to possible vulnerabilities within the system that could be due to the Platform's implementations, hardware/software-related misconfigurations, external/internal threats, or physical/logical access.

A.3.2: Cyber Attack Trees
In order to analyse cyber risks to the Constellation project's protection (Wide Area LoM and Adaptive Load Blinding)" and Local ANM applications, two cyber attack tree methodologies were created as detailed respectively in Figure 35 and Figure 36 below.

The process involved identifying the high-level unacceptable business impacts and linking them to the lower-level methods or exploitation routes that could contribute to such events occurring.

[Figure Redacted]

Figure 35: Cyber Attack Tree (Protection) – Wide Area Protection System (ABB) and the Adaptive Protection System (Siemens)

[Figure Redacted]

Figure 36: Cyber Attack Tree (Local ANM) – PMU-based Local ANM System (GE)

A.3.3: Security Evaluation Test Cases

[Section Redacted]

A.4 Final Network Architecture Design

A.4.1 Maidstone Grid Site

[Figure Redacted]

A.4.2 Maidstone DER Site (DER-1)

[Figure Redacted]

A.4.3 Thanet Grid Site

[Figure Redacted]

A.4.4 Thanet DER Sites

[Figure Redacted]

A.4.5 Thanet DER Site

[Figure Redacted]

A.4.6 Thanet DER Site (DER-3)

[Figure Redacted]

A.4.7 Engineering Design Drawing Example

[Figure Redacted]

A.4.8 RTU Cubicle Design

[Figure Redacted]

A.5 Network Trials (SAT)

A.5.1 Local ANM SAT Results

The following sections provide details of the specific SAT test results for:

- DER site PDC (Equipment "A" as referenced within Figure 26); and
- Grid site PhC (Equipment "F" as referenced within Figure 26)

DER Site PDC (Equipment "A")

The outcomes of the acceptance process can be summarised as follows:

- The PDC is accessible, synchronized and has the appropriate firewall configuration;
- The PDC has the appropriate incoming connections configured and the observed latency was acceptable (non-blocking); and
- The PDC has the appropriate outgoing streams configured and latency appears appropriate. Additional streams have been configured to partially overcome an observed network issue.

The following figures provide screenshots of the configuration and confirmation of the above.

Defect 001: The DER Archive Stream on the DER Site PDC has been split into three TCP streams to provide a partial work around to the packet loss issues observed between DER-1 and Maidstone Grid.

Note 001: The 1002 stream on the DER Site PDC provides a route from DER-1 to the azure using spontaneous User Datagram Protocol (UDP.) This is not required but is retained and inactive to allow convenient restoration of this option.

[Redacted]

Grid Site PhC (Equipment "F")

The outcomes of the acceptance process can be summarised as follows:

- The PhC is accessible, synchronized and has the appropriate firewall configuration;
- The PhC has the proper packages, firmware and scheme installed; and
- The I/O config has the appropriate incoming and outgoing connections configured.

The following sections provide screenshots of the configuration and confirmation of the above.

***Non-Impacting Defect 001* – PLC I/O will not retrieve all phasor values**: The PLC I/O config appears unable to access all of the provided phasor values simultaneously. Proper selection of the values in the configuration and adjustment of the PLC scheme bypasses this issue (so is non-impacting) but is unexpected and undesirable.

[Redacted]:

[Figure Redacted]

Figure 37: PhC system information

[Figure Redacted]

Figure 38: Installed packages

The synchronisation result is shown in Figure 45 below.

[Figure Redacted]

Figure 39: Synchronisation

Test results associated with the PLC I/O Inputs are detailed in Figure 46, Figure 47 and Figure 48 below, with those associated with the PLC outputs detailed in Figure 49 and Figure 50.

[Figure Redacted]

Figure 40: Input configuration

[Figure Redacted]

Figure 41: PMU configuration within PLC

[Figure Redacted]

Figure 42: PLC I/O Output configuration

[Figure Redacted]

Figure 43: PLC I/O Wait time configuration

[Figure Redacted]

Figure 44: DNP3 interface to DER

A.5.2 WAP SAT Results

Table 15 below provides details of the specific SAT set-up configuration and results for Maidstone Grid.

Table 13: WAP SAT Test Configuration and Procedures

[Table Redacted]

Comments

The WAP was tested in two different stages:

1. Maidstone Grid servers tested isolated (without connection DER-1), and DER-1 also tested isolated. OMICRON CMC356 simulated several scenarios of RoCoF and Intertrip, validating the performance of these servers.
2. All servers connected via fibre link. OMICRON CMC356 simulated 2 cases of RoCoF (one on GT4 and another on GT5) and one case of Intertrip validating the communication link between main grid and DER.

The tests mentioned on item 2 must be repeated when 5G communication is fully established.

Test Equipment		
Purpose	**Make/Type**	**Serial Number**
Simulating SMVs packets	OMICRON CMC356	QG517A
Validation of communication network traffic	OMICRON Daneo 400	GD248H

Certification					**(✓)**
All tests have been completed satisfactorily					
Contractor Commissioning Engineer (if applicable)					
Organisation		Name			
Date		Signature			
UK Power Networks Commissioning Engineer					
Name	[redacted]	Signature	[redacted]	Date	18/07/2024

Figure 51 below details the test results obtained from the successful completion of the intertrip and RoCoF tests, using a fibre optic network. These tests will be repeated using the 5G network once it is available.

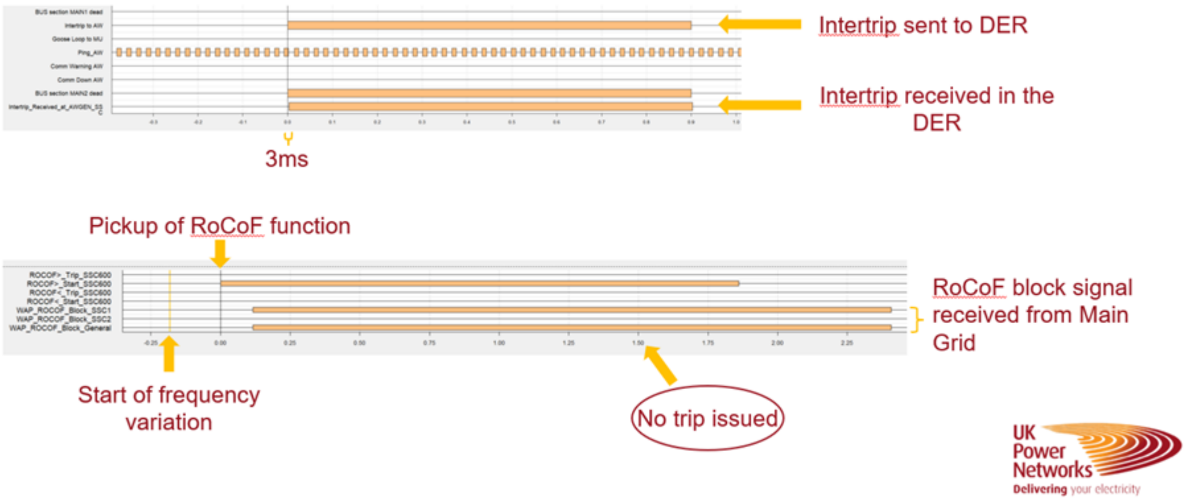


Figure 45: WAP Test Results – With Fibre Connection Between Main Grid and DER Site

Figure 52, Figure 53 and Figure 54 show results obtained when executing the single test and curve tests.

The single tests are executed to validate that the disturbance recordings, LEDs, logs and GOOSE datasets are set up properly within the SCC600 and to validate if the MUs are receiving the GOOSE data from the SSC600 and taking the correct actions.

During the curve tests, the performance of the SSC600 for each protection function was verified under several different conditions, in order to validate that the operation of the protection functions only occurs when required and within the correct time window.

Both of the above two tests are performed using OMICRON CMC356 test equipment.

51 phase C trial 1:

Test Settings

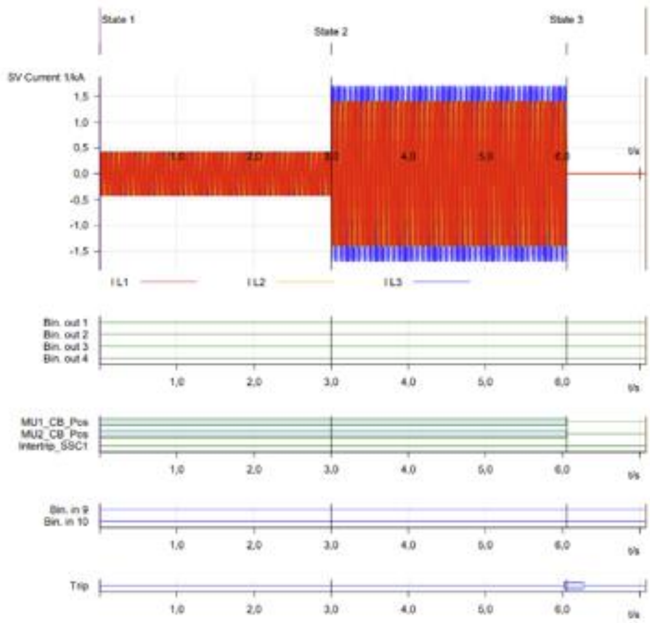
State	State 1	State 2	State 3
I L1	300,0 A -45,00 ° 50,000 Hz	1,000 kA -45,00 ° 50,000 Hz	0,00 A -45,00 ° 50,000 Hz
I L2	300,0 A -165,00 ° 50,000 Hz	1,000 kA -165,00 ° 50,000 Hz	0,00 A -165,00 ° 50,000 Hz
I L3	300,0 A 75,00 ° 50,000 Hz	1,200 kA 75,00 ° 50,000 Hz	0,00 A 75,00 ° 50,000 Hz
Bin. out 1	0	0	0
Bin. out 2	0	0	0
Bin. out 3	0	0	0
Bin. out 4	0	0	0
MU1_CB_Pos	1	1	0
MU2_CB_Pos	1	1	0
Intertrip_SSC1	0	0	0
Max. State Time	3,000 s		1,000 s
Trigger Logic		OR	
Trip		1	
User interaction	no	no	no
CMGPS trigger	no	no	no
IRIG-B/PTP trigger	no	no	no
Pulses / seconds	1	1	1
Delay after Tr.	0,00 s	30,00 ms	30,00 ms
On trigger jump to test end	no	no	no
Diagrams			

Test Results

Time Assessment

Name	Ignore before	Start	Stop	Tnom	Tdev-	Tdev+	Tact	Tdev	Assess
Trip	State 1	State 2	Trip 0>1	3.009 s	100.0 ms	100.0 ms	3.021 s	12.20 ms	+

Assess: + .. Passed x .. Failed o .. Not assessed



Cursor Data

	Time	Signal	Value
Cursor 1	0,00 s	<none>	n/a
Cursor 2	7,08 s	<none>	n/a
C2 - C1	7,08 s		n/a

Event recorder

Time	Type	Signal name	Slope
6.021 s	Input	Trip	0>1
6.051 s	Output	MU1_CB_Pos	1>0
6.051 s	Output	MU2_CB_Pos	1>0
6.271 s	Input	Trip	1>0

All values are primary

Test State:
Test passed

Figure 46: Example of Timed Overcurrent on Phase C Single Test

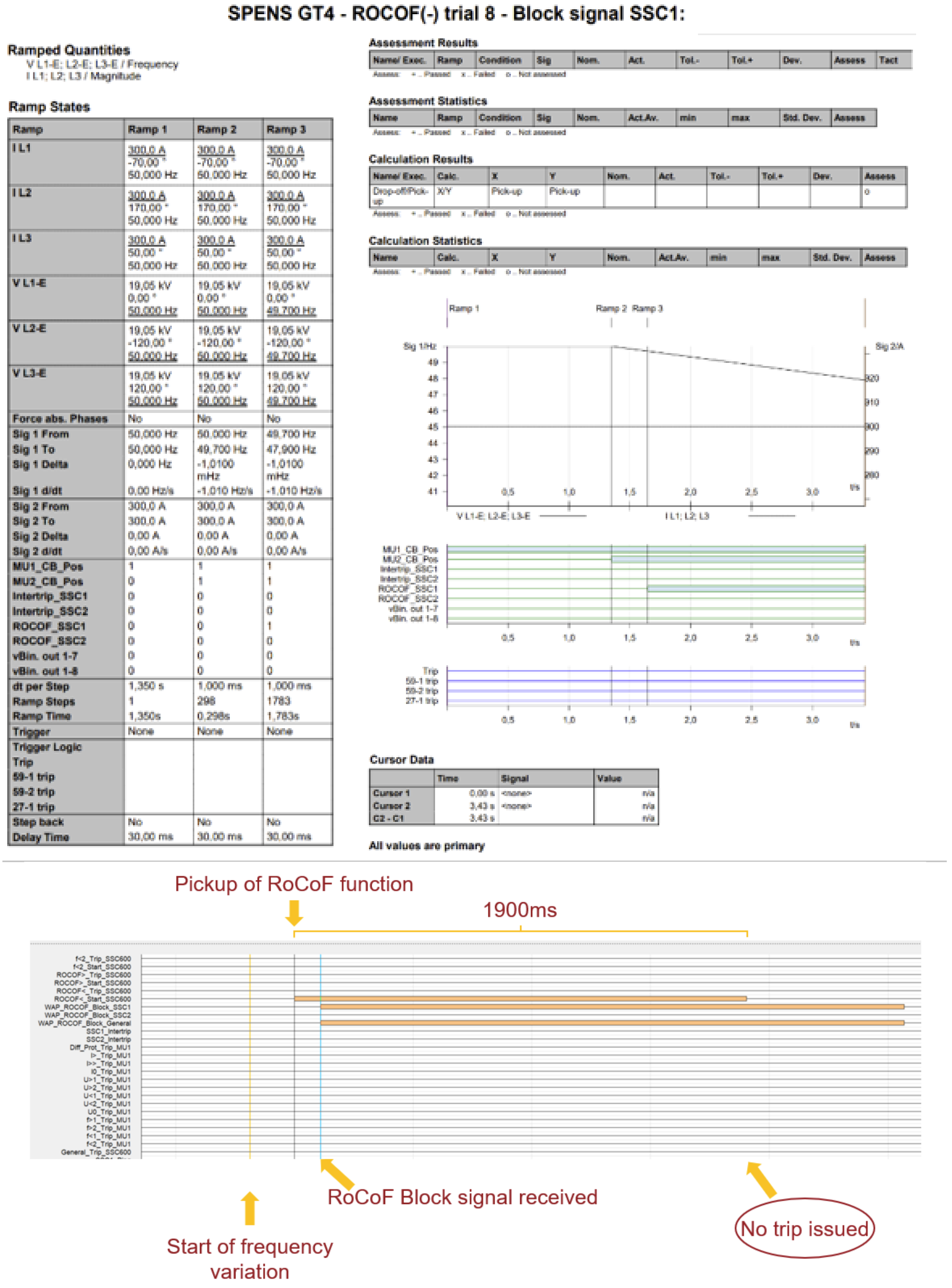


Figure 47: Example of Rate of Change of Frequency test in the DER Receiving the Block Signal from the Grid. No Trip Issued

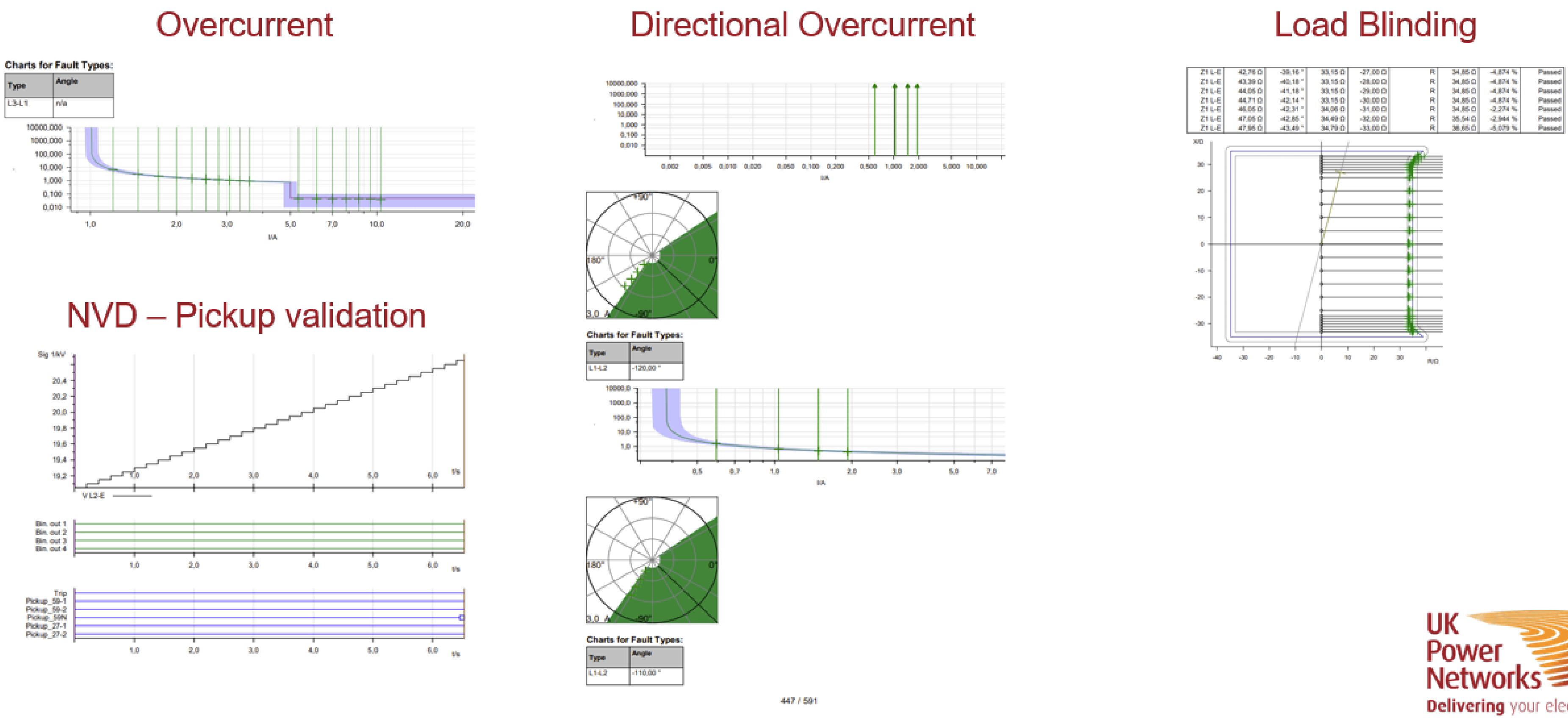


Figure 48: Example Curve Tests Validated on the SSC600

A.5.3 APS and CMS SAT Results

Table 16 below provides details of the specific SAT procedures (for Maidstone Grid) and Table 17 details the signals checklist used throughout the test.

Figure 55 details the communication and data flows used during APS and CMS SAT and Figure 56 details examples of the successful test results obtained.

Table 14: APS and CMS SAT Test Procedures

[Table Redacted]

Comments
The script was run a few times to validate that the APS Solution is sending new settings to the relay, and we have used OMICRON CMC356 to validate the new load blinding settings on the SSC600-1. During testing, some script-related issues were identified, and Siemens is actively working to resolve them. These will be addressed with the release of the updated version of the CMS.

Test Equipment		
Purpose	**Make/Type**	**Serial Number**
Simulating SMVs packets	OMICRON CMC356	[Redacted]

Certification					(✓)
All tests have been completed satisfactorily					✓
Contractor Commissioning Engineer (if applicable)					
Organisation		Name			
Date		Signature			
UK Power Networks Commissioning Engineer					
Name	[redacted]	Signature	[redacted]	Date	18/07/2024

Table 15: Signal Checklist with Description of Information from Source to Destination

Signal Flow Check		Source	Destination	Protocol/ Format	Verify	Description	Comments
A	SIGNAL 1	ADMS	PSS®ODMS	CSV	☐	CSV file with up-to-date network status	Network status of the CIM file will be updated by CSV.
B	SIGNAL 1	PSS®ODMS	PSS®ODMS	Text	☐	Importing CIM file status	Multiple information showing successful import and Errors during import
C	SIGNAL 1	PSS®ODMS	PSS®ODMS	Text	☐	Run Power Flow	Multiple information showing successful and failed power flow conversions.
D	SIGNAL 2	PSS®ODMS	PSS®CAPE	CIM/XML based	☐	Import CIM file to update CAPE network model	Network status of the PSS®CAPE network model will be updated by CIM file.
E	-	PSS®CAPE	Local PSS®CAPE Program folder: UKPN PRC results	Text	☐	Protection settings calculation/validation	Calculated new setting group and validation report
F	SIGNAL 3	PSS®CAPE	Bridge	AMQPS:5671	☐	New Protection settings sent	Bridge or CMS logs can be viewed for the results. Calculated new setting group is the content.
G	SIGNAL 4	Bridge	CMS	AMQPS:5671	☐	New Protection settings sent	Calculated new setting group is the content. CMS logs can be viewed for the results.
H	-	CMS	CMS	N/A	☐	New settings - Waiting for user validation	Settings wait to be confirmed for sending to the field. That stage happens only on CMS.
I	SIGNAL 5,6	CMS	SICAM GridEdge	MQTT:8883	☐	New settings Validated	Settings are sent to the field by user command. New setting group is the content.
J	SIGNAL 5,6	CMS	SICAM GridEdge	MQTT:8883	☐	New settings transferred to GridEdge.	This action's log can be seen on CMS.
K	SIGNAL 7	SICAM GridEdge	Protection Device	IEC 61850	☐	New Settings transferred to SSC600_1	This action's log can be seen on SICAM GridEdge.
L	SIGNAL 7	SICAM GridEdge	CMS	MQTT:8883	☐	New settings are applied in SSC600_1	This action's log can be seen on CMS.
M	SIGNAL 4	CMS	Bridge	AMQPS:5671	☐	Result of the application on the field are sent to Bridge	Setting group ID that is successfully applied or previous setting group ID because of rollback in case of an error.
N	SIGNAL 3	Bridge	PSS®CAPE	AMQPS:5671	☐	Result of the application on the field are sent to CAPE	Setting group ID that is successfully applied or previous setting group ID because of rollback in case of an error.

O	SIGNAL 11	EAM	CMS	CSV/Entry	☐	Import of EAM ID for each relay, using serial number as identifier	EAM IDs and serial numbers of each relay
P	SIGNAL 11	CMS	EAM	CSV	☐	Export of asset data into CSV	45 information field that are specified in design document are exported to CSV file.
Q	SIGNAL 5,6	SICAM GridEdge (Maidstone, Thanet)	CMS	JSON via MQTT:8883	☐	New data collected from	Asset Data in Substation: Data from SICAM GridEdge, part of 45 information field that are specified in design document.
R	SIGNAL 7	Protection Device	SICAM GridEdge	IEC 61850	☐	New data collected from	Asset Data in Substation: Data from GridEdge, part of 45 information field that are specified in design document.
S	SIGNAL 8	Non-Protection Device	SICAM GridEdge	SNMP V3	☐	New data collected from	Asset Data in Substation: Data from GridEdge, part of 45 information field that are specified in design document.
T	SIGNAL 9	Substation Sync Folder	CMS Sync Folder	SFTP: 22	☐	Add File in CMS Sync Folder	Relay configuration file
U	SIGNAL 9	CMS Sync Folder	Substation Sync Folder	SFTP: 22	☐	Add File in Substation Sync folder	Relay configuration file

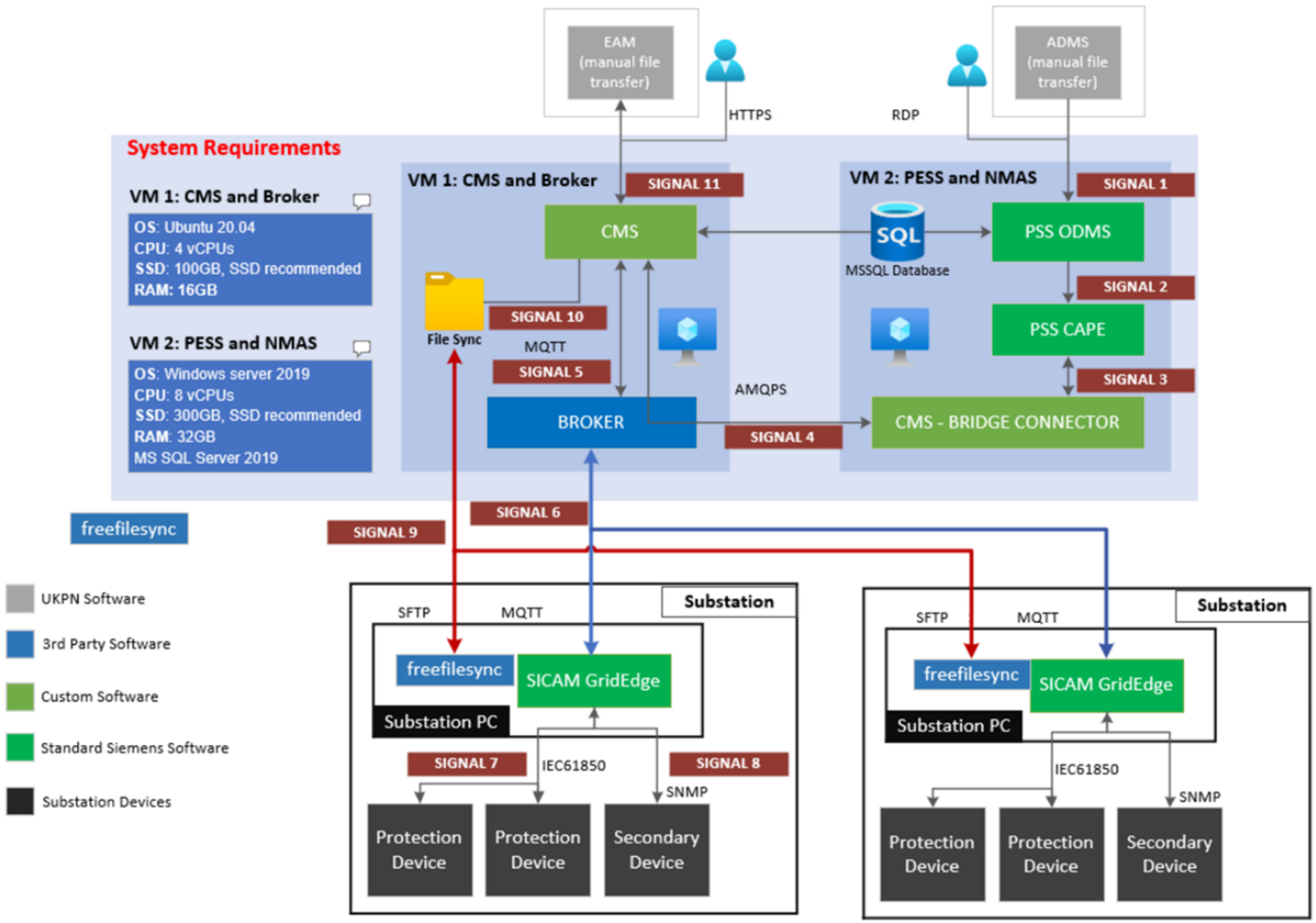
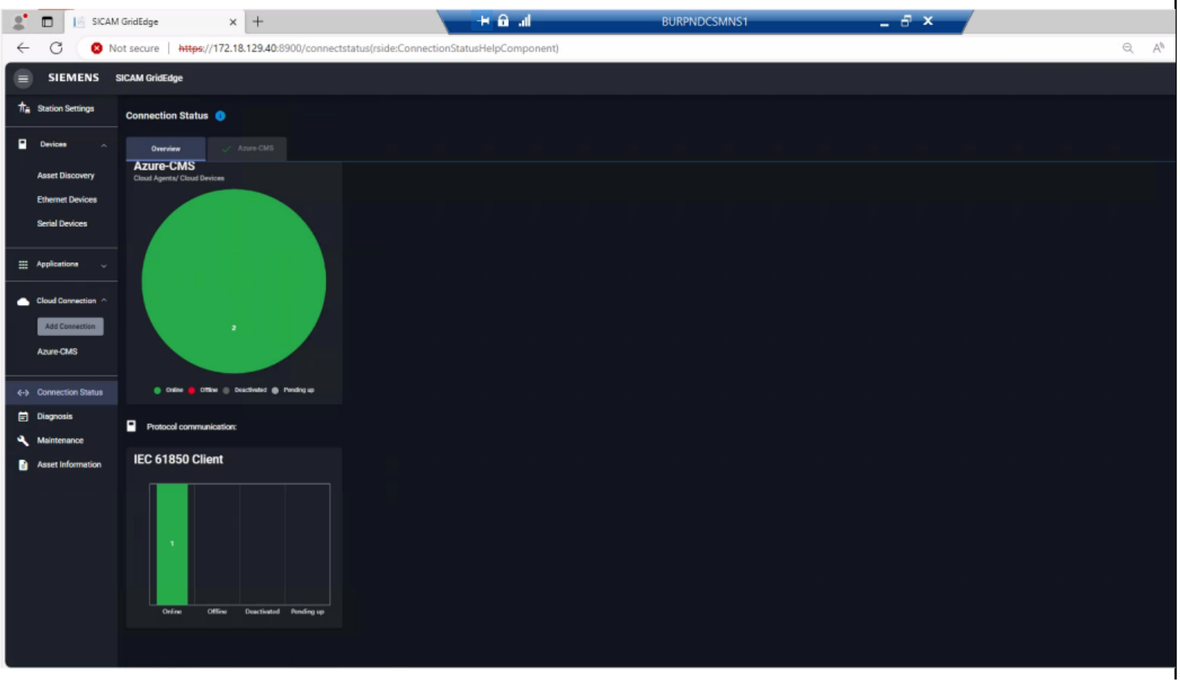


Figure 49: Communication and Data Flows Used During APS and CMS SAT

Test#4

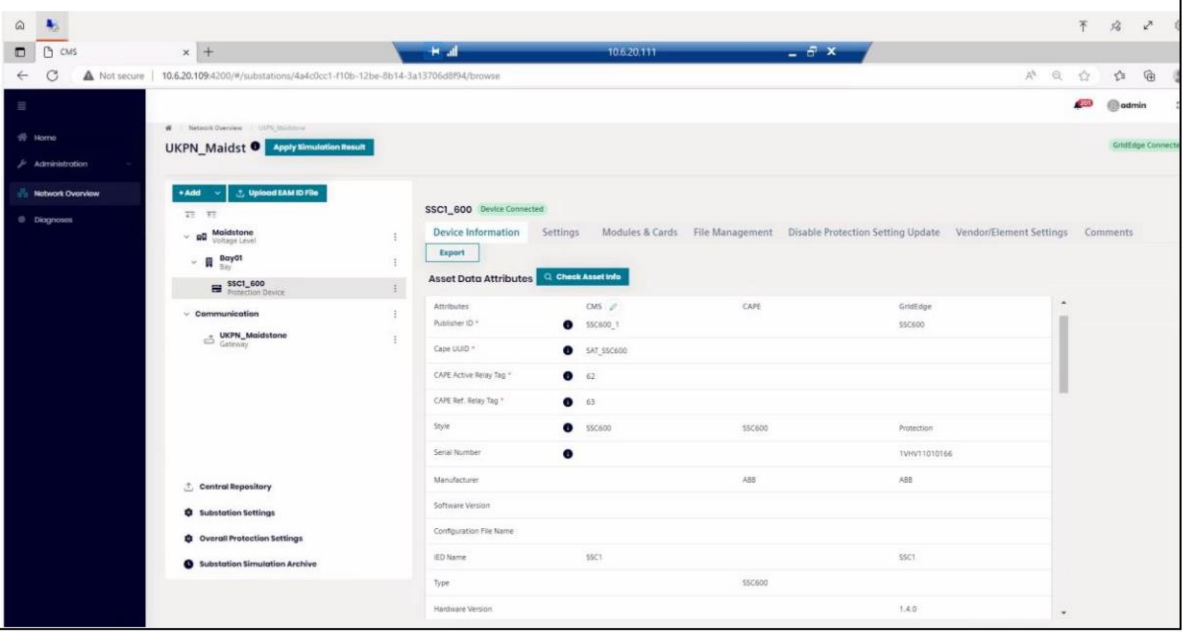
Test Description	Result	Remark
Check the communication heath in the Connection status section of SICAM GridEdge.	Pass	See two screenshot Cloud connection online Device connection online.

Screenshot-1



Test#9

Test Description	Result	Remark
Check the communication status and asset information from CAPE and GridEdge from the Network Overview=> UKPN_Maidstone tab=> SSC1_600=> Device Information tab.	Pass	See screenshot. SSC1_600 : Device connected Asset information in the columns CAPE and GridEdge.



Test#15

Test Description	Result	Remark
Check the field information from Maidstone from the Network Overview=> UKPN_Maidstone tab=> SSC1_600=> Setting tab=>Target value column to see the new target value from the adaptive protection system.	Pass	See screenshot New values in the Target value column with status Ready To Apply.

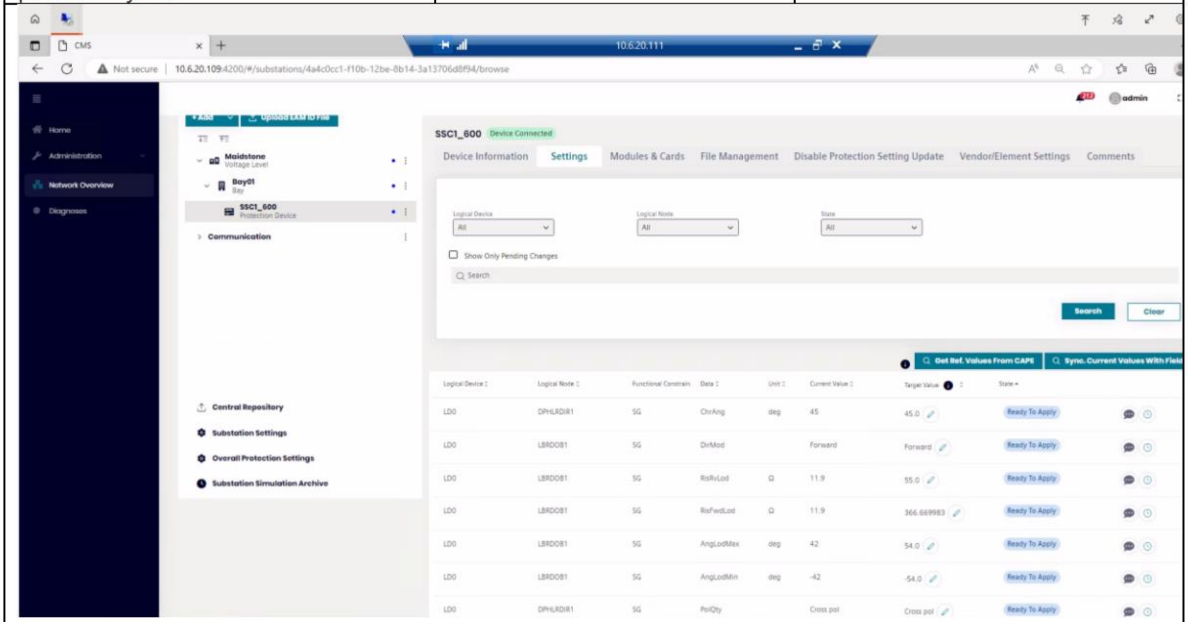


Figure 50: Examples of APS and CMS SAT Results

[Redacted]

Maidstone Power Flow Result: -

Oct_2_2024_11_07_05_adaptation_power_flow_result.txt - Notepad

File Edit Format View Help

```
   13 2-wdg N-circuit transformers
    2 3-wdg N-circuit transformers
Warning: invalid characters in 1 transformer name temporarily replaced by underscores; use SAVE_LINE_NAMES_TO_DB to
update database
All bus voltage angles are computed from wye-delta transformer angles in database: BREF 2
   154 total +seq angles;    154 +seq buses;    4 neutral nodes;    158 buses in network
Bus voltage angles are set to match transformers; loops are consistent
91 bus reference angles are different from database values
To update bus angles in database (for data export), select File/Save/Save Bus Reference Angles to DB
 ** Building and verifying data tables
Process ties
Reading Power-Flow Network: completed
 Number of electrical islands is     5
 Buses in isolated islands will be set offline if no reference bus is available
      45 slack term 1 is the reference bus for island    1 containing    150 buses.

  ****************** Starting Point ******************
  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
   File exists
  ****************** Go to SC ******************
  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
  Ibackfeed (pu) =  0.15882 p.u. @  61.7628 degrees
  Base amps (A) =  1749.55
  Ibackfeed (A) =  277.860

  Power Flow Ia =  0.15882 p.u. @  61.7628 degrees Primary current:  277.860 A
  Power Flow Ib =  0.15882 p.u. @  -58.237 degrees Primary current:  277.860 A
  Power Flow Ic =  0.15882 @  -178.24 degrees Primary current:  277.860 A
  Power Flow In =      0.0 @      0.0 degrees Primary current:      0.0 A
  Power Flow Va =  1.15375 @  16.3043 degrees Primary voltage:  38.0739 V
  Power Flow Vb =  1.15375 @  -103.70 degrees Primary voltage:  38.0739 V
  Power Flow Vc =  1.15375 @  136.304 degrees Primary voltage:  38.0739 V
  Power Flow Vn =      0.0 @      0.0 degrees Primary voltage:      0.0 V

  Apperaent Power (S)MVA: 18.3238
  P,Q values (MVA); (positive values mean toward downstream)  :  12.853,-13.06
  power flow angle control (cosfi) :  0.70143

  IDOC * 0.8 for the comparison 1:  187.872

  Ibackfeed greater than Calculated DOC pickup value

  RLBmax,n-1 :  118.627
  ILBmax,n-1 :  160.609
  I_LB current from the relay :  1601.06
  min_adapt_LB_step value is :  80.0528
  There is no change on the I_LB current
   New ILBmax,n setting calculated : 1601.06
  ****************** Go to SC 2 ******************
  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
  P,Q values; positive values mean toward downstream :  12.853,-13.06
  Power flow angle is : -45.459
  Operation in the Quadrant3 and the alpha is: 45.4585

  alpha_in_the_relay - security_margin_anle - power_flow_angle greater than min_adapt_angle_step
  alpha_base-security_margin_angle lower than power_flow_angle
  Adapted alpha value :  50.4585
```

Jul_12_2023_16_05_11_adaptation_power_flow_result.txt - Notepad

File Edit Format View Help

```
   13 2-wdg N-circuit transformers
    2 3-wdg N-circuit transformers
Warning: invalid characters in 1 transformer name temporarily replaced by underscores; use SAVE_LINE_NAMES_TO_DB
to update database
All bus voltage angles are computed from wye-delta transformer angles in database: BREF 2
   154 total +seq angles;    154 +seq buses;    4 neutral nodes;    158 buses in network
Bus voltage angles are set to match transformers; loops are consistent
91 bus reference angles are different from database values
To update bus angles in database (for data export), select File/Save/Save Bus Reference Angles to DB
 ** Building and verifying data tables
Process ties
Reading Power-Flow Network: completed
 Number of electrical islands is     5
 Buses in isolated islands will be set offline if no reference bus is available
      45 slack term 1 is the reference bus for island    1 containing    150 buses.

  ****************** Starting Point ******************
  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
   File exists
  ****************** Go to SC ******************
  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
  Ibackfeed (pu) =  0.15892 p.u. @  61.8504 degrees
  Base amps (A) =  1749.55
  Ibackfeed (A) =  278.035

  Power Flow Ia =  0.15892 p.u. @  61.8504 degrees Primary current:  278.035 A
  Power Flow Ib =  0.15892 p.u. @  -58.150 degrees Primary current:  278.035 A
  Power Flow Ic =  0.15892 @  -178.15 degrees Primary current:  278.035 A
  Power Flow In =      0.0 @      0.0 degrees Primary current:      0.0 A
  Power Flow Va =  1.15437 @  16.3223 degrees Primary current:  38.0943 V
  Power Flow Vb =  1.15437 @  -103.68 degrees Primary current:  38.0943 V
  Power Flow Vc =  1.15437 @  136.322 degrees Primary current:  38.0943 V
  Power Flow Vn =      0.0 @      0.0 degrees Primary current:      0.0 V

  Apperaent Power (S)MVA: 18.3451
  P,Q values (MVA); (positive values mean toward downstream)  :  12.852,-13.09
  power flow angle control (cosfi) :  0.70056

  IDOC * 0.8 for the comparison 1:  108.208

  Ibackfeed greater than Calculated DOC pickup value

  RLBmax,n-1 :  104.554
  ILBmax,n-1 :  182.226
  I_LB current from the relay :  1601.06
  min_adapt_LB_step value is :  80.0528
  There is no change on the I_LB current
   New ILBmax,n setting calculated : 1601.06
  ****************** Go to SC 2 ******************
  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
  P,Q values; positive values mean toward downstream :  12.852,-13.09
  Power flow angle is : -45.528
  Operation in the Quadrant3 and the alpha is: 45.5281

  alpha_in_the_relay - security_margin_anle - power_flow_angle greater than min_adapt_angle_step
  alpha_base-security_margin_angle lower than power_flow_angle
  Adapted alpha value :  50.5281
```

Figure 51: SAT Test Result Data Comparisons

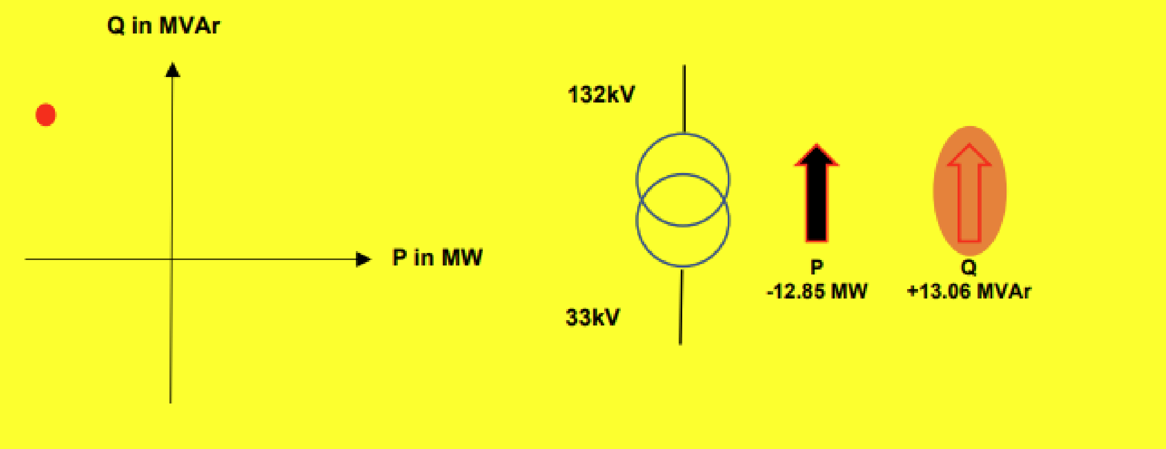
Final Scenario: Normal Power Flow to 33kV i.e. Reverse Power Flow to 132kV

Power flow at LB relay:	-12.85 MW, +13.06 MVAr
Network Model:	same as the base model, 40 MVAr generation at Allington Waste 33kV
Fault Types and Locations:	Close infeed for I_SC_min

Maidstone Tie:Open Fault Locations of type SLG(20ohm), TPH(20ohm)
Worms Hill 132 kV (88): Bus Fault
Canterbury 132 kV (72): Bus Fault
Sittingbourne 132 kV (25): Bus Fault
Maidstone Tie:Closed Fault Locations of type SLG(20ohm), TPH(20ohm)
Worms Hill 132 kV (38): Bus Fault
Canterbury 132 kV (139): Bus Fault
Sittingbourne 132 kV (23): Bus Fault

Expected Adaptation Result:

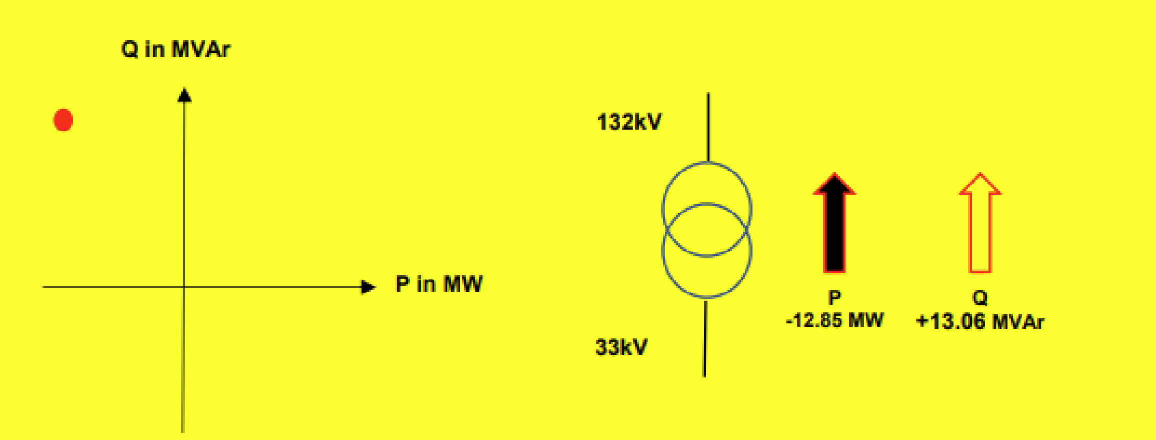
Final Scenario : Normal Power Flow to 33kV i.e. Reverse Power Flow to 132kV



LB power angle= at the initial value of 42° or at the last adapted value.	Alpha= 50°
LB maximum load current = the initial value of 0.8* I_3pR20 By back feed max (120% x I_Backfeed, I_LB,max); valid for this case	I_LB,max = 1601 A
LB resistive reach = 33kV / (1.73 x I_LB,max)	R_LB_min = 11.9 Ohm
Directional Overcurrent Pickup= 80% x I_SC_min	I_DOC> = 187 A

Observed Final Results: Expected vs. Actual

Final Scenario: Normal Power Flow to 33kV i.e. Reverse Rective Flow to 132kV



1- with no settings adapted (standard settings)

Alpha= 42°, I_LB,max = 1601 A, R_LB_min = 11.9 Ω, I_DOC> = 600 A, U< = 28050 V, I2>= 228A

Number #	Location	Fault type	Expected result	Actual result	comments	PASS/FAIL
1.1	Load Blinder Relay, Power Flow Only	-	No Trip	No Trip		PASS
1.2	Worms hill	3ph	Trip	No Trip	Trip with DOC but inside of LB, no trip I2 and U/V	FAIL
1.3	Worms hill	1ph	Trip	Trip	Trip with DOC and out of LB, no trip I2 and U/V	PASS
1.4	Canterburry	3ph	Trip	No Trip	no trip as there is not 2 out of 2 criteria.	FAIL
1.5	Canterburry	1ph	Trip	No Trip	no trip as there is not 2 out of 2 criteria.	FAIL
1.6	Sittingbourne	3ph	Trip	No Trip	no trip as there is not 2 out of 2 criteria.	FAIL
1.7	Sittingbourne	1ph	Trip	No Trip	no trip as there is not 2 out of 2 criteria.	FAIL

2- with adapted settings

Alpha= 50°, I_LB,max = 1601 A, R_LB_min = 11.9 Ω, I_DOC> = 187A, U< = 28050 V, I2>= 228 A

Number #	Location	Fault type	Expected result	Actual result	comments	PASS/FAIL
2.1	Load Blinder Relay, Power Flow Only	-	No Trip	No Trip		PASS
2.2	Worms hill	3ph	Trip	No Trip	Trip with DOC but inside of LB, no trip I2 and U/V	FAIL

2.3	Worms hill	1ph	Trip	Trip	Trip with DOC and out of LB, no trip I2 and U/V	PASS
2.4	Canterburry	3ph	Trip	No Trip	no trip as there is not 2 out of 2 criteria.	FAIL
2.5	Canterburry	1ph	Trip	Trip	Trip with DOC and out of LB, no trip I2 and U/V	PASS
2.6	Sittingbourne	3ph	Trip	Trip	Trip with DOC, U/V and out of LB, no trip I2	PASS
2.7	Sittingbourne	1ph	Trip	Trip	Trip with DOC and out of LB, no trip I2 and U/V	PASS

Note: arc fault resistance of 20 Ohm considered.

Figure 52: Further APS and CMS SAT Test Results

The above figure demonstrates that through the use of adaptive settings the performance is substantially improved.

A.5.4 Network Communication Test Results

Table 18 through to Table 22 and Figure 59 and Figure 60 provide details of the specific SAT test results for a selection of network communication SAT's undertaken within each trial area.

Table 16: Network Communication Verification

Test step	Expected result	(Ok or n/a)
IP connectivity to the IEC 61850 servers	Green check for all IEDs of the system	OK[1]
GOOSE messages present on the network and parameters match SCL configuration	Green check for all IEDs	OK
SMV streams present on the network and parameters match SCL configuration	Green check for all IEDs	OK
Additional GOOSE messages present on the network	No GOOSEs found in the orphans sniffing for the maximum GOOSE repetition interval (wait at least 60s)	OK[2]
Additional SMV streams present on the network	No SMVs streams found in orphans sniffing	OK[3]
Print DANEO "System Verification" and "System under Test" report sheet and attach it to this test plan.	Report printed and attached	OK

1) Green check for all devices except the SSC600 VMs. Daneo could not connect to the Logical devices SSC1LD0, SSC1CTRL, SSC1DR, SSC2LD0, SSC2CTRL, SSC2DR via SSC600 service port. However, using another tool such as IEC-Browser it was possible to connect to all these logical devices.
2) A GOOSE Dataset found as Orphan. These Goose Dataset was created on GT5 MU2 during the SAT and the SCD haven't been updated. This Goose Dataset is used only for tests as the GE MU320 has significant limitations to visualise the results of the tests. No further actions required.

3) A SMV Dataset found as Orphan. This SMV is from the SPENS12 MU2 and it has been used to provide the measurements to the PMU device. Temporary signal until we deploy the system in DER-1. No further actions required.

Table 17: Network Bandwidth and Filtering

[Table Redacted]

Table 18: PTP Grandmaster Clock Status (Maidstone Grid)

[Table Redacted]

Table 19: Time Synchronisation Verification (Maidstone Grid)

[Table Redacted]

Table 20: PTP Grandmaster Clock Status (DER Site)

[Table Redacted]

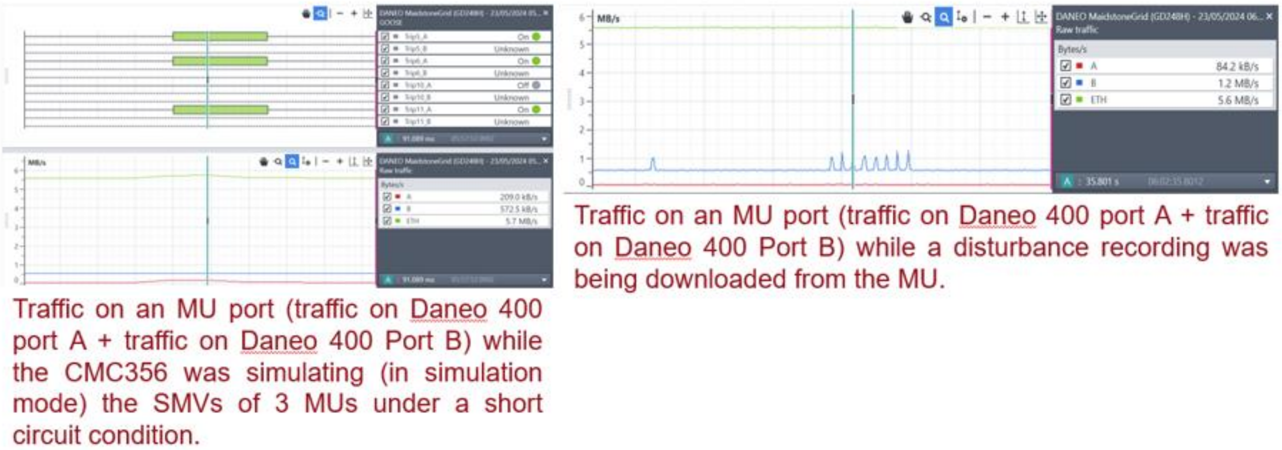


Figure 53: Network Communication Tests - Traffic Measurement Examples

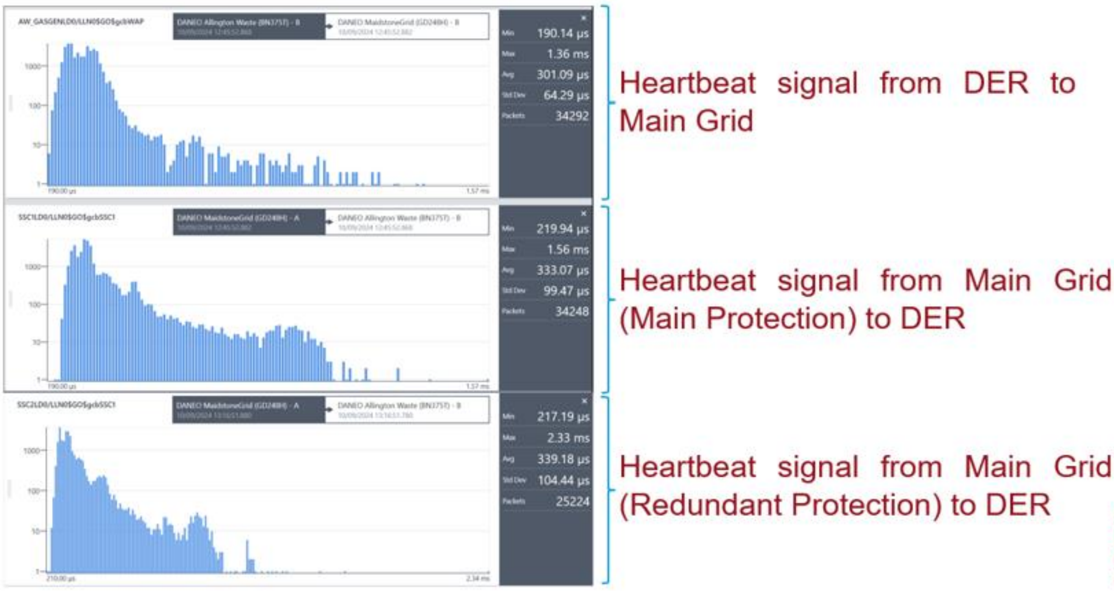


Figure 54: Network Communication Tests - Communication Between Grid – DER Sites Via Fibre Optic Cable

A.5.5 5G Communication Test Results

The 5G SAT comprised a series of three ping tests, each used to test the reachability of a host on a network.

The tests are undertaken by sending Internet Control Message Protocol (ICMP) echo request messages to the target host and waiting for a response, thus allowing the diagnosis of network issues and measuring the round-trip time for the messages sent to the destination.

Test 1: Ping test from User Equipment (UE1) in Thanet to google

With reference to Constellation Test 1, the Ping test was used to determine the response time of a request from Thanet Grid site to google, as detailed in Figure 61 below.

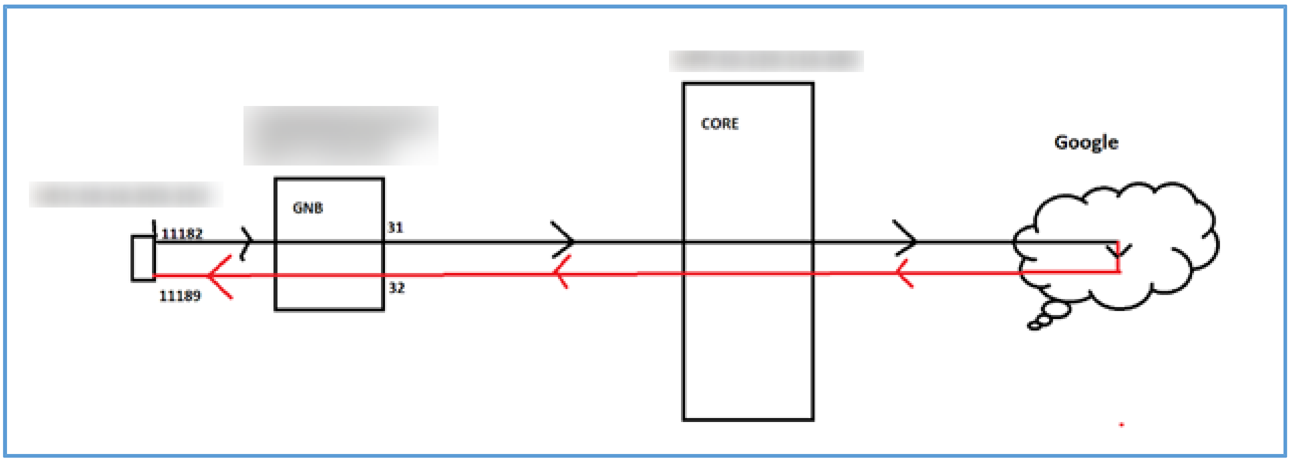


Figure 55: Ping Flow Diagram

Test 1: UE to Google Latency Analysis

The results from ping test 1 are detailed in Table 23. As can be seen, an average latency of 28.8ms was achieved.

- Latency introduced by Core and Transmission (TX) Round Trip Time (RTT): (32 and 31) = 16.1ms;
- Ping Latency on the UE1 (RTT): (11189 and 11182) = 28.8ms;
- Next Generation Node B (gNB) to User Plane Function (UPF) (RTT) = 9.3ms;
- UPF to GOOGLE latency (RTT) = (16.1 – 9.3) = 6.8ms; and
- UE1 to gNB (RTT) = 28.8 – 16.1 = 12.7ms.

Table 21: Test 1 Results

Test 1 UE to google, Latency breakdown per element					
28.8ms	UE to Node	Transmission	Slice	Transmission	Google
Out	6.35ms	4.65ms		3.4ms	
Return	6.35ms	4.65ms		3.4ms	

Test 2: Ping from UE1 in Thanet to UE2 in Newbury

With reference to Constellation Test 2, the Ping test was used to determine the response time of a request from UE1 in Thanet Grid site to UE2 in Newbury, as detailed in Figure 62 below.

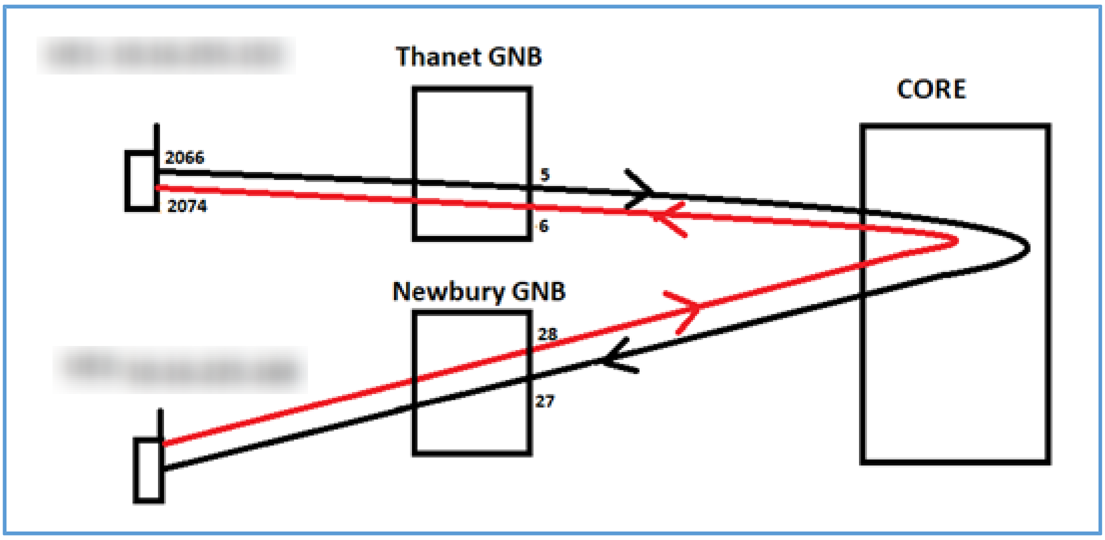


Figure 56: Ping Flow Diagram

Test 2: Latency Analysis

The results from ping test 2 are detailed in Table 24. As can be seen, an average latency of 33.7ms was achieved.

- Latency introduced by Core and TX (RTT): (27 – 5) + (6 – 28) = 8.1ms + 7.8ms = 15.9ms;
- Ping Latency on the UE1 (RTT): (2074 - 2066) = 33.7ms;
- Thanet gNB to Newbury Latency gNB via Core (RTT) as per ping test in gNB: (6ms + 9.3ms)= 15.3ms;
- UE1 to Thanet gNB (RTT): (2074 - 2066) – (6-5) = 33.7ms – 27.3ms = 6.36ms; and
- UE2 to Newbury gNB Latency (RTT): (28 – 27) = 11.6ms.

Table 22: Test 2 Results

Test 2 Thanet UE to Newbury UE, Latency breakdown per element			
33.7ms	UE to T-gNB	T-gNB to N-gNB	N-gNB to UE
Out	3.18ms	8.1ms	5.6ms
Return	3.18ms	7.8ms	5.6ms

Test 3: Ping from UE1 and UE2 in Thanet

With reference to Constellation Test 3, the Ping test was used to determine the response time of a request from UE1 in Thanet Grid site to UE2 in Thanet, as detailed in Figure 63 below.

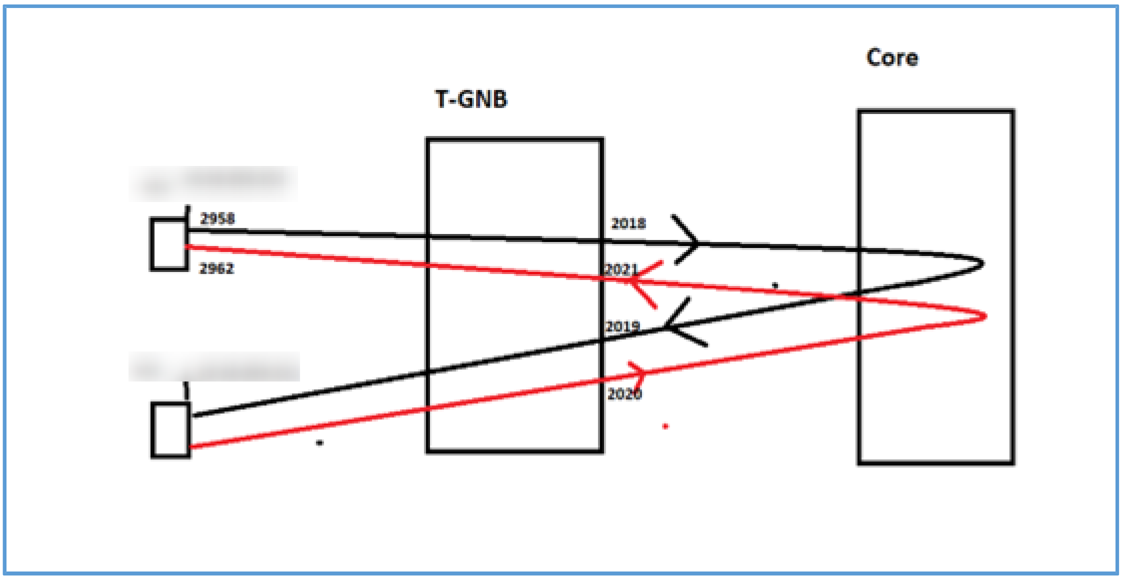


Figure 57: Ping Flow Diagram

Test 3: Latency Analysis

The results from ping test 3 are detailed in Table 25. As can be seen, an average latency of 50.5ms was achieved.

- Latency introduced by Core and TX (RTT): (2019 – 2018) + (2021 – 2020) = 9.5ms + 9.5ms = 19ms;
- Ping Latency on the UE1 (RTT): 2962 – 2958 = 40.5ms;
- UE1 to Thanet gNB (RTT): 40.5ms – 19ms = 21.5ms; and
- UE2 to Thanet gNB (RTT): (2020 – 2019) = 10ms.

Table 23: Test 2 Results

Test 3 Thanet UE to Newbury UE, Latency breakdown per element			
50.5ms	UE1 to T-gNB	T-gNB to T-gNB	T-gNB to UE2
Out	10.75ms	9.5ms	5ms
Return	10.75ms	9.5ms	5ms

Testing Limitations:

a) UEs and gNBs are NOT time synched since they have difference time reference source. Therefore, we can't calculate latency by subtracting the time between UE and gNB;
b) We have only analysed one PING RTT cycle in each test case;

c) Both gNBs are running on 22q2C1 software and prescheduling/discontinuous Reception (DRX) parameters are aligned;
d) For Test 1: unable to work out Latencies introduced by SLICE and GOOGLE. From the gNB ICMP timings we could only workout total latency towards GOOGLE from gNB (i.e. TX + Slice + Google); and
e) UEs physical location is same for all three Tests so radio condition expected to be the same.

A.6 Network Trials (Passive Tests)

A.6.1 Schedule A: Wide Area Protection Tests

Following the successful completion of the WAP SAT on the Maidstone Grid and DER sites, the Passive Network Trial testing has commenced.

The tests detailed in this section are applicable for all manually applied tests.

Responses of the WAP Solution to events occurring in the network are evaluated based the data that is reviewed regularly as detailed in Section 4.3.2.

Passive Network Trials

Tests during the Passive Network Trials stage include the following:

- WAP dependability tests;
- WAP stability tests; and
- WAP timing tests for wide area GOOSE messages over fibre and 5G.

Pre-conditions

Prior to commencement of the Passive Network Trials, the following checks have first been carried out:

- Place each SSC600 SW IED involved in the scheme in "IED test" mode, as shown in Figure 64;
- Verify test mode status of IED using an MMS client software, as shown in Figure 65;
- Verify test flag in published GOOSE messages using packet sniffer or DANEO 400, as shown in Figure 66;
- Verify absence of wide area communication alarms in the SSC600 SW dashboard (for both Grid and DER IEDs);
- Set and verify bay IEDs (Bay Control Units) for DER sites are in Test/Blocked mode;
- Grid site IEDs modes are to be set in accordance with UK Power Networks policy in line with Passive Network Trial test objectives. It is recommended that a test mode checklist is created for all physical and virtual IEDs in the trial networks; and
- Disconnect Siemens GridEdge from Grid site SSC600 SW [for manual tests only] and verify that setting group 1 is active.

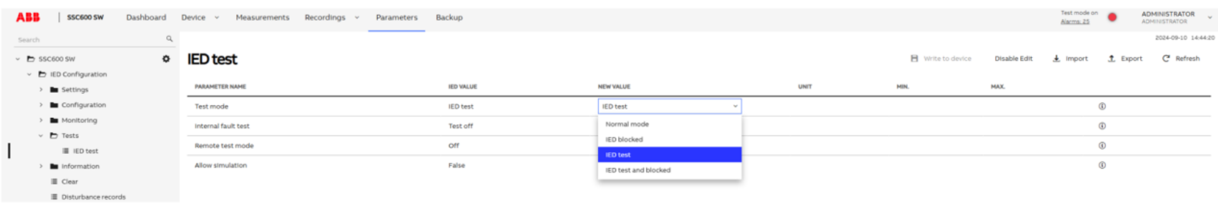


Figure 58: Placement of SSC600 SW IED in Test Mode

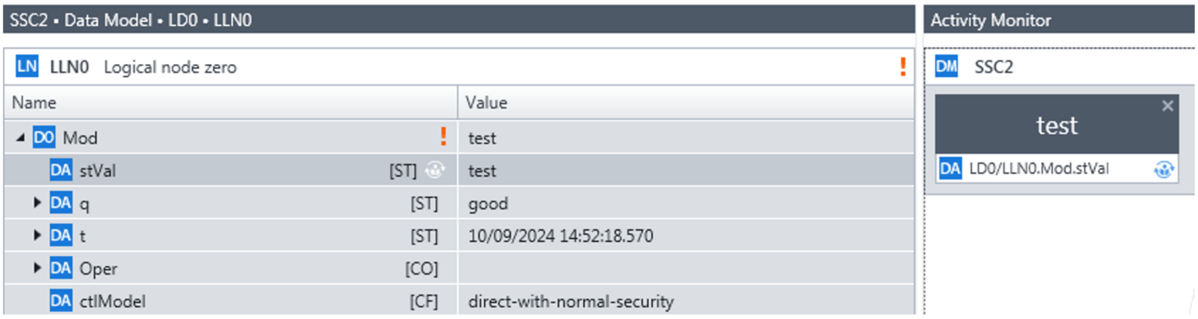


Figure 59: IED verified in test mode using MMS client software

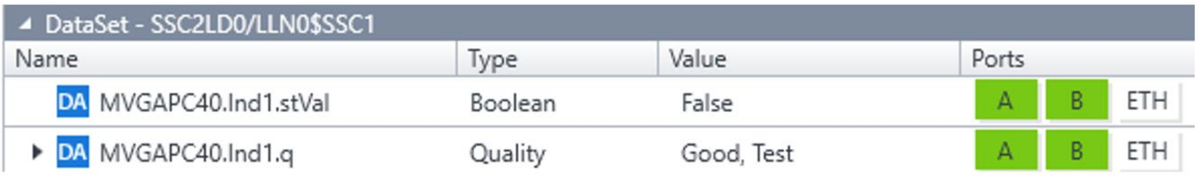


Figure 60: GOOSE message published by SSC600 with test flag = true

<u>System test configuration</u>

Figure 67 below illustrates the WAP test configuration which has been adopted to enable the application and monitoring of system tests.

RelaySimTest based test cases running on RBX hardware distributed between the Grid and DER locations are used to manually initiate tests.

This configuration is scalable to multiple DER sites, dependent on the amount of hardware available to publish simulated GOOSE messages and SMV streams.

[Figure Redacted]

Figure 61: WAP system test configuration

System tests

WAP dependability tests are summarised in Table 26, which verify the protection action when called upon due to genuine islanding (intertrip) or remote frequency disturbances (blocking). WAP stability tests are summarised in Table 27, which verify the protection inaction during negative tests (i.e. no intertrip or blocking expected).

For each of these tests the wide area GOOSE messages issued to trip or block the relevant DER IED are monitored (using DANEO 400) to determine the latency over WAN. This constitutes the timing tests.

Table 24: WAP dependability tests

WAN configuration	Network running arrangement	Intertrip tests	Blocking tests
Tests to be repeated over fibre and 5G for Maidstone and over 5G only for Thanet (due to unavailability of a fibre network throughout the area). **Single WAN tunnel active in Maidstone, while four tunnels are active for Thanet. In both cases, the WAN tunnels are carrying all configured traffic (i.e. GOOSE, C37.118, specific Local ANM DNP3).**	Tests to be repeated for all network running arrangements. Relevant Grid substation Circuit Breaker (CB) status is published through simulated GOOSE messages. RelaySimTest model to reflect running arrangement. For manual tests, DER power export is simulated via simulated SMV publishing. Simulated power export is set to maximum and 50% of DER rating to vary generator response to simulated disturbances.	**T1.1** Simulate islanding by opening CB combinations resulting in isolation of grid supply to DER (e.g. simulate GT5 and SPENS61 CB open in Maidstone). **Expected outcome:** Grid site SSC600 SW issues intertrip GOOSE and received by islanded DER site SSC600 SW. Bay IED tripping is blocked in Passive Network Trial test stage.	**T1.3** Simulate remote disturbance/frequency event resulting in measured RoCoF at both Grid and DER sites greater than 1 Hz/s for more than 500ms. **Expected outcome**: Grid site SSC600 SW issues blocking GOOSE and received by islanded DER site SSC600 SW.
		T1.2 Simulate fault on feeder to DER followed by simulated feeder CB open (e.g. fault on SPEN12 feeder followed by SPENS12 CB open in Maidstone). **Expected outcome:** Grid site SSC600 SW issues intertrip GOOSE and received by DER site SSC600 SW. Bay IED tripping is blocked in Passive Network Trial test stage.	**T1.4** Simulate fault on feeder to DER (followed by simulated opening of feeder CB) simultaneously with remote disturbance/frequency event resulting in measured RoCoF at both Grid and DER sites greater than 1 Hz/s for more than 500ms. **Expected outcome**: Grid site SSC600 SW issues blocking GOOSE and received by islanded DER site SSC600 SW.

Table 25: WAP stability tests

WAN configuration	Network running arrangement	Intertrip tests	Blocking tests
Tests to be repeated over fibre and 5G for Maidstone and over 5G only for Thanet. **Single WAN tunnel active in Maidstone, while four tunnels are active for Thanet. In both cases, the WAN tunnels are carrying all configured traffic (i.e. GOOSE, C37.118, specific Local ANM DNP3)**	Tests to be repeated for all network running arrangements. Relevant Grid substation CB status is published through simulated GOOSE messages. RelaySimTest model to reflect running arrangement. For manual tests, DER power export is simulated via simulated SMV publishing. Simulated power export is set to maximum and 50% of DER rating to vary generator response to simulated disturbances.	**T1.5** Simulate CB opening combinations at Grid site, but without resulting in isolation of grid supply to DER (e.g. simulate GT4 and SPENS05 CB open in Maidstone). **Expected outcome:** No intertrip GOOSE published and DER IED remains unaffected	**T1.7** Simulate remote disturbance/frequency event resulting in measured RoCoF at both Grid and DER sites less than 1 Hz/s for more than 500ms (or greater than 1 Hz/s for less than 500ms). **Expected outcome**: No blocking GOOSE published and DER IED remains unaffected
		T1.6 Simulate high impedance transient fault on feeder to DER not resulting in feeder CB trip (e.g. high impedance transient fault on SPEN12 feeder resulting in protection start but no trip of SPENS12 CB in Maidstone). **Expected outcome:** No intertrip GOOSE published and DER IED remains unaffected	**T1.8** Simulate high impedance transient fault on feeder to DER (resulting in feeder CB protection starting, but not tripping) simultaneously with remote disturbance/frequency event resulting in measured RoCoF at both Grid and DER sites less than 1 Hz/s for more than 500ms. **Expected outcome**: No blocking GOOSE published and DER IED remains unaffected

A.6.2: Schedule B: Adaptive Protection and CMS Tests

Following the successful completion of the APS and CMS SAT on the Maidstone Grid site the Passive Network Trial testing has commenced.

The tests detailed in this section are applicable for all manually applied tests.

Responses of the APS and CMS Solution to events occurring in the network are evaluated based the data that is reviewed regularly as detailed in Section 4.3.2.

Passive Network Trials

Tests during the Passive Network Trials stage include the following:

- DOC stability tests for active and reactive power export from 33kV to 132kV via the grid transformers;
- DOC dependability tests for remote infeed faults; and
- Complete setting adaptation workflow including manual and automatic setting changes.

Pre-conditions

Prior to commencement of the Passive Network Trials, the following checks have first been carried out:

- Place Grid site instances of SSC600 SW in “test mode” and verify as described in Appendix A.6.1. Alternatively, we have also been able to place directional overcurrent protection function of grid transformer bays in test mode and verify accordingly if this feature is implemented, which has been the preferred approach;
- Compatible CIM files have been obtained from PowerFactory model and prepared to reflect test scenarios defined in “System Tests” below;
- Verify absence of connectivity alarms in GridEdge and CMS. This has included connectivity between CMS and GridEdge, GridEdge and SSC600 IEDs, CMS and PSS®CAPE bridge (see Figure 68 and Figure 69 respectively); and
- Ensure that “setting group 1” is active in grid site instances of SSC600 SW.

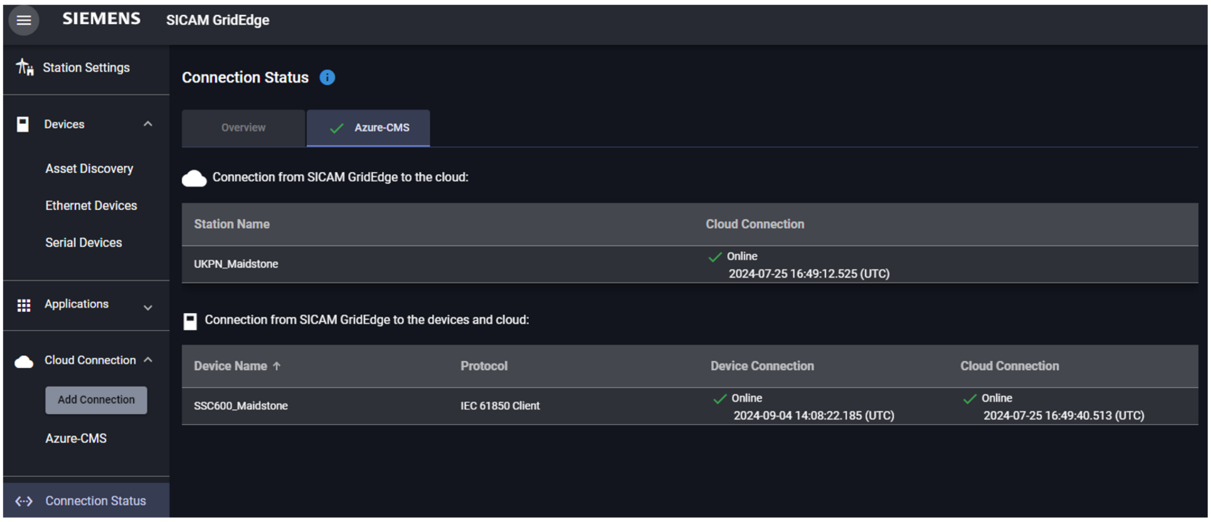


Figure 62: GridEdge healthy connection status with CMS and SSC600 relay

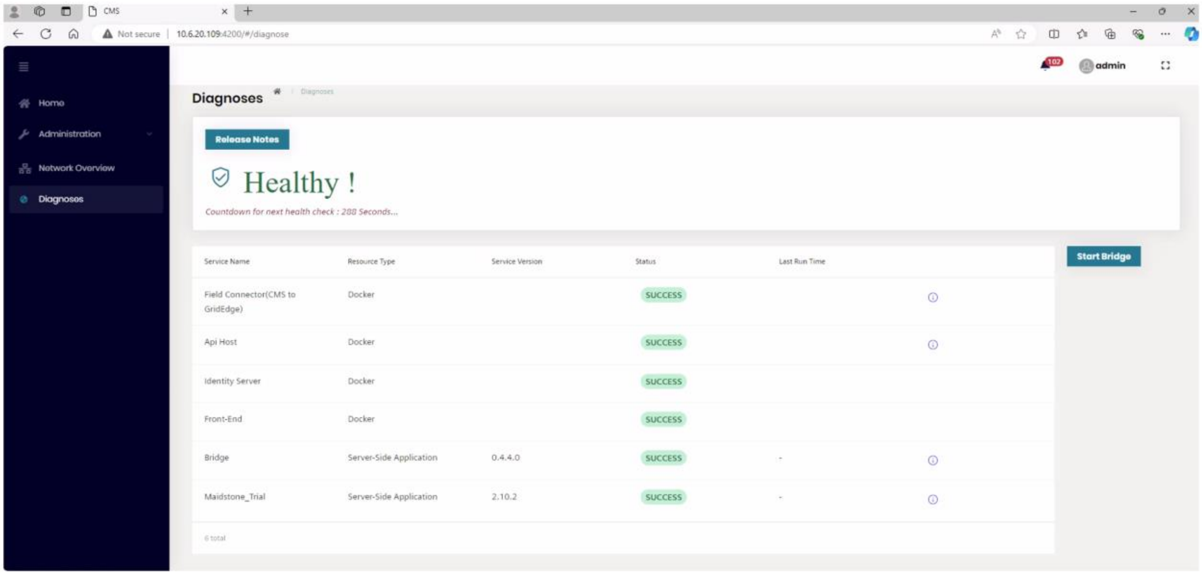


Figure 63: CMS component health and connectivity status

<u>System test configuration</u>

[Figure 70](#) below illustrates the APS/CMS test configuration to be adopted to enable the application and monitoring of system tests.

RelaySimTest based test cases running on RBX hardware placed at the Grid site is used to manually initiate tests.

Rather than using ADMS, the CIM file information source has been derived from PowerFactory models of the trial networks for each test scenario, the CIM file has been prepared to contain required switchgear status information, branch active and reactive power flow information (load and generation) and grid transformer tap positions.

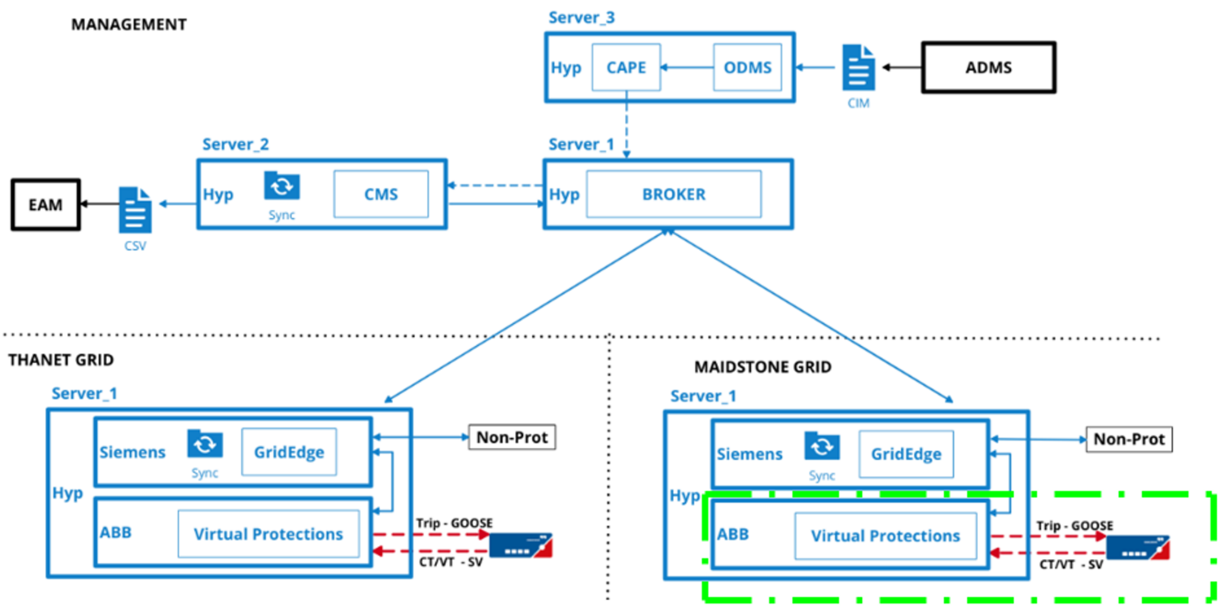


Figure 64: AP and CMS system test configuration

System tests

The workflow tests that are being undertaken to check the end to end process of adapting settings, whether manually or automatically triggered are described in Table 28.

Table 29 describes the tests involving reverse power flow through the grid transformers to evaluate the adapted DOC setting stability against load current.

Table 30 describes the DOC setting dependability tests for faults applied at the remote end infeeds to the grid transformers.

Note that for each of the stability and dependability tests defined, one workflow iteration test needs to be performed. In other words, test T2.1 or T2.2 in Table 28 is always carried out with each test in Table 29 and Table 30, provided that the underlying network topology and load flow is different between test iterations. The adaptation of the setting depends on the range of the initial value. If the initial setting falls within the defined range, the calculated minimum short-circuit current and back-feed current will preserve the initial setting.

However, if the initial setting is outside the defined range, the relay setting will adjust accordingly. Furthermore, dependability tests are applied for each of the tests (i.e. for each revere power flow scenario, a remote fault is applied assuming the DOC is stable for the amount of reverse power flow set).

Table 26: Adaptive Protection setting workflow tests

Adaptive Protection mode (see Section A.3.2.4)	Workflow implementation	Expected outcomes
T2.1 Manual	1. PowerFactory model configured to reflect network running arrangements for test scenario of interest (see Table 6) 2. CIM file generated from PowerFactory and placed in the CMS shared directory 3. New setting calculation script executed 4. New settings are available in CMS HMI and can be reviewed before application to grid IED (manual mode only)	New settings calculated by CMS and awaiting manual approval and application by operator. New settings are in line with DOC load blinder settings policy specified by UK Power Networks
T2.2 Automatic		New settings calculated by CMS and are applied to the grid IED automatically. New settings are in line with DOC load blinder settings policy specified by UK Power Networks

Table 27: DOC stability tests

Network running arrangement	Reverse power flow through grid transformers	Expected outcome
Tests to be repeated for all network running arrangements. **RelaySimTest model to reflect running arrangement and publish SMV streams for the grid transformer bays.** **Tests are repeated for grid transformer tap positions at centre tap as well as staggered up to +/- two tap positions relative to centre tap.**	**T2.3** Active power export equal to the difference between maximum DER active output and minimum active load Reactive power import equal to the maximum reactive load	Grid transformer DOC protection remains stable
	T2.4 Active power export equal to the difference between maximum DER output and minimum active load Reactive power export equal to the difference between maximum DER reactive output and minimum reactive load	Grid transformer DOC protection remains stable

	T2.5 Additional scenarios of active and reactive power export are possible but require additional simulated DER that is not currently connected to the trial network. Voltage limits at 33kV nodes must be maintained within grid code limits.	For scenarios with current export exceeding 50% of transformer nominal rating, load blinder blocks the operation of grid transformer DOC protection

Table 28: DOC dependability tests

Reverse power flow scenario	**Remote infeed faults**	**Expected outcome**
As per T2.3	**T2.6** Apply individual faults (through simulated SMV injection) at remote 132kV infeed to grid transformers (e.g. faults at, Canterbury, Northfleet East and Sittingbourne for Maidstone). All faults are repeated for phase-earth, phase-phase, phase-phase-earth and three-phase. All faults are repeated for 0 Ω and 20 Ω impedance.	Outcome is evaluated on a case-by-case basis. In general, a grid transformer DOC protection trips for all fault scenarios upstream of the concerned transformer. An exception to this is if the protection setting is not sensitive enough to high impedance faults.
As per T2.4		
As per T2.5		

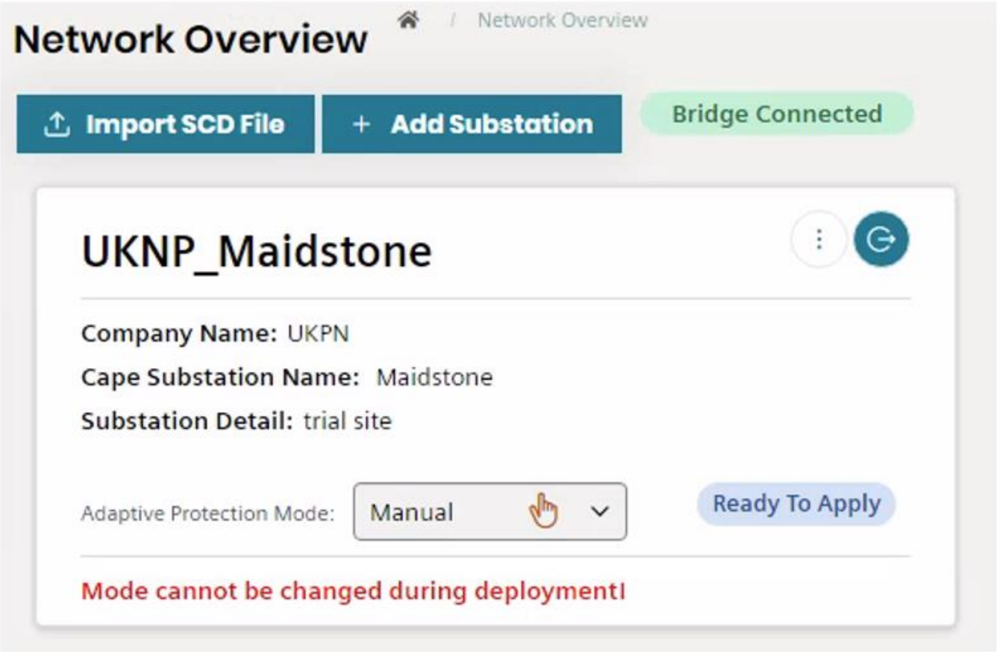


Figure 65: CMS HMI with option to change Adaptive Protection mode (manual/automatic)

Figure 71 above showcases the HMI of CMS and the ability to change modes of operation. Note the following settings are the only ones adapted (Automatic). Manual setting changes are also possible through CMS when the calculation process is completed.

- Start current value of direction overcurrent protection element;
- Forward resistive reach of load blinder (impedance element);
- Reverse resistive reach of load blinder (impedance element);
- Maximum impedance angle of load blinder (impedance element); and
- Minimum impedance angle of load blinder (impedance element).

New settings applied can be verified in SSC600 SW web HMI or via an MMS client (e.g. IED scout, see Figure 72 and Figure 73).

Logical Device	Logical Node	Functional Con:	Data	Unit	Current Value	Target Value	State
LD0	DPHLPTOC1	SG	TypRsCrv		Immediate		Up To Date
LD0	DPHLRDIR1	SG	MinRvA...	d.	80	80.0	Ready To Apply
LD0	DPHLRDIR1	SG	MinFw...	d.	90	90.0	Ready To Apply
LD0	DPHLPTOC1	SG	DirMod		Forward	Forward	Ready To Apply
LD0	DPHLRDIR1	SG	VMemT...		0	0.0	Ready To Apply
LD0	LBRDOB1	SG	AngLod...	d.	-50	-50.0	Ready To Apply
LD0	LBRDOB1	SG	RisFwd...	Ω	11.9	11.9	Ready To Apply
LD0	LBRDOB1	SG	DirMod		Forward	Forward	Ready To Apply
LD0	LBRDOB1	SG	RisRvLod	Ω	11.9	11.9	Ready To Apply

Figure 66: IED settings ready to be applied by CMS

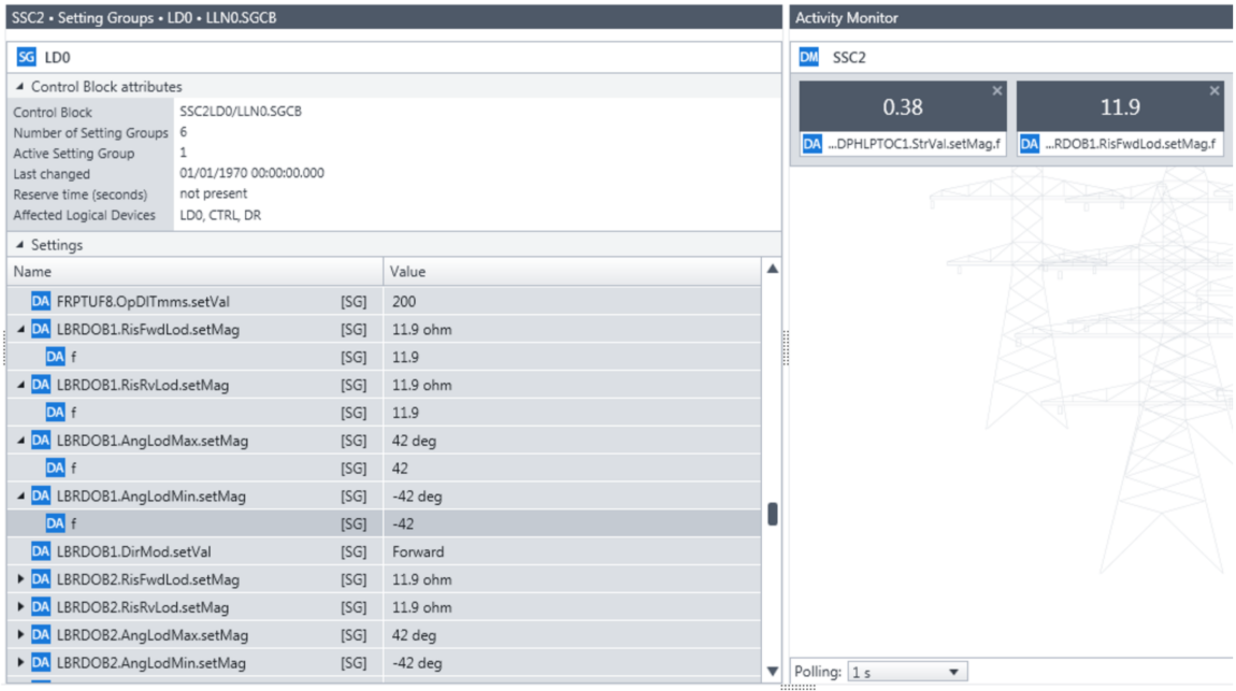


Figure 67: Verification of applied settings using an MMS client

A.6.3 Schedule C: Local ANM Tests

Following the successful completion of the Local ANM SAT on the Maidstone Grid and DER sites the Passive Network Trial testing has commenced.

The tests detailed in this section are applicable for all manually applied tests.

Responses of the Local ANM Solution to events occurring in the network are evaluated based the data that is reviewed regularly as detailed in Section 4.3.2.

Passive Network Trials

Tests during the Passive Network Trials stage include the following:

- Direct Distributed Local ANM mode tests;
- Local ANM mode override tests;
- Local ANM response timing tests; and
- Isolated (Learned Limit and Holdover) Local ANM mode tests. These will be defined once the Machine Learning (ML) model part of the Isolated Local ANM mode functionality is fully implemented.

Pre-conditions

Prior to commencement of the Passive Network Trials, the following checks have first been carried out:

- All configured C37.118 streams are connected and transmitting data. These have been checked in vPDC HMI (see Figure 74);
- DER site RTU is in the correct mode for each test, which has generally been in Network Management System (NMS) mode at the start of each test; and
- Verify expected correct reporting of Local ANM and RTU mode as well as correct reception of PMU data in DE WAMS Grafana dashboards (see Figure 75).

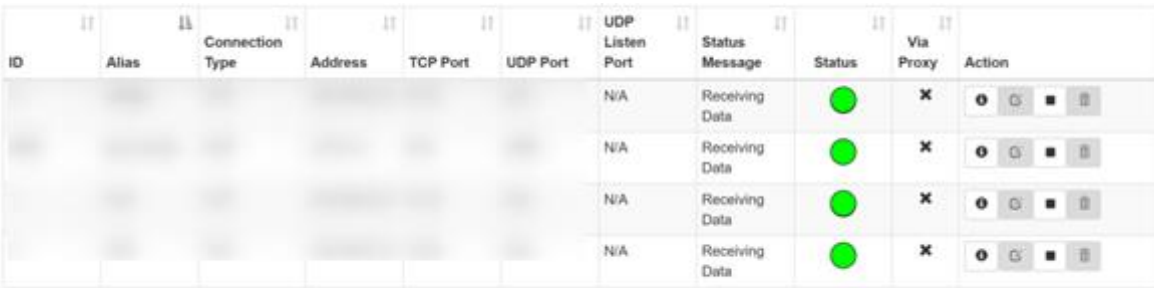


Figure 68: Grid vPDC receiving configure input PMU streams

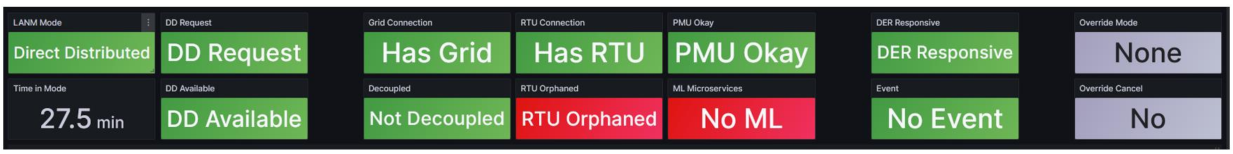


Figure 69: DE WAMS Grafana dashboard reporting relevant Local ANM scheme status information

System test configuration

Figure 76 below illustrates the Local ANM test configuration to be adopted to enable the application and monitoring of system tests.

RelaySimTest based test cases running on RBX hardware placed at the Grid and DER sites is used to manually initiate tests.

This configuration is scalable to multiple DER sites. The analogue injection into the dedicated MUs with PMU functionality (Siemens 6MU85) produces the desired PMU (C37.118) streams for Local ANM functionality.

DE WAMS is deployed in UK Power Networks Azure cloud to visualise the state and measurements being made by the Solution as well as archive all received data. Configured DNP3 points in ADMS are used for Local ANM override commands by the control engineers.

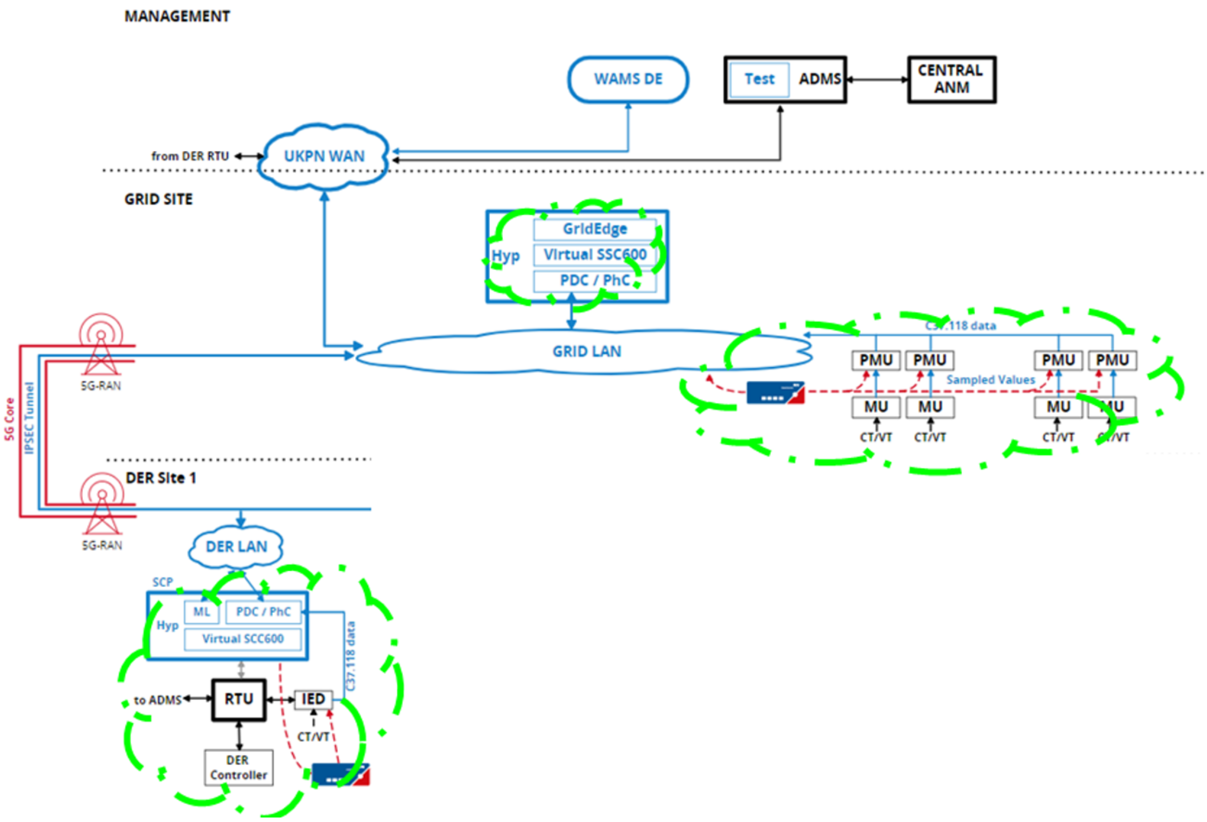


Figure 70: Local ANM system test configuration

The response of the DER is critical to the assessment of the Local ANM response. During Passive or Active Network Trials where DER curtailment/release is not possible due to technical or commercial reasons, the real response from DER may not be available. Therefore, an alternative using a Real-Time Automation Controller (RTAC) with DNP3 and C37.118 interfaces could be used. An example of which is the SEL-3350 (computing platform) with RTAC functionality, support for the aforementioned communications standards a logic processor (e.g. using IEC 61131-3) and analogue input card.

The RTAC analogue inputs have been used to translate the DER bus voltages and currents from secondary injection (determined by RelaySimTest) into C37.118 streams. The DNP3 interfaces is used to hand the connection to the DER RTU and Local ANM.

System tests

Table 31 describes the tests that are being carried out while the Local ANM Solution is in Direct Distributed mode (that is when Central ANM connectivity is lost to the managed DER RTU). Table 32 describes the override command tests initiated from ADMS to force Local ANM mode transitions. The network running arrangement has no bearing on the Local ANM functionality, so it has not been considered in the tests, rather the focus is on simulating constraints at the constraint points, which the Local ANM scheme responds to.

The time response of each of the tests is defined in Table 31 and Table 32, in particular the time it takes for Local ANM mode transitions, the timing of curtailment or release commands and the response of the controlled DER. These timing are being verified against configured settings in the Local ANM scheme. These constitute the Local ANM response timing tests.

Table 29: Direct Distributed mode tests (DER RTU orphaned)

Power flow through constraint point	Test variables	Expected outcome
T3.1 Simulated power flow through constraint point results in configured headroom violation	Test repeated with headroom power flow step to trigger an “extreme violation” as configured in the Local ANM scheme. Tests repeated with non-responsive DER	Local ANM issues curtailment order of DER participating in the Local ANM scheme to so that power flow through the constraint point is returns within configured headroom. Curtailment steps to be verified against configuration. Verify curtailment steps if extreme violation occurs. Non-responsive DER result in fall back mode.
T3.2 (following T3.1) Simulated power flow through constraint point results in removal of configured headroom violation	Tests repeated with non-responsive DER	Local ANM issues release order of DER participating in the Local ANM up to allowed headroom at the constraint point Non-responsive DER results in fall back mode

Table 30: Local ANM mode override tests

Initial conditions	Test	Expected outcome
Local ANM in Central ANM mode (DER RTU in NMS mode)	**T3.3** Issue ADMS override command instructing transition into Direct Distributed mode	Local ANM transitions into Direct Distributed mode

Local ANM in Central ANM mode then DER RTU is disconnected from DER (decoupled mode)	**T3.4** Issue ADMS override command instructing transition into Direct Distributed mode	Local ANM rejects command to transition into Direct Distributed mode

A.7 Site Installation Photographs

A.7.1: Maidstone Area – Maidstone Grid
In this section, a collection of photos highlighting the site activities carried when preparing the Maidstone Grid site for the Constellation network trial.

Figure 71: Maidstone Grid – Entrance

Figure 72: Maidstone Grid – Constellation Cubicle

Figure 73: Maidstone Grid – Open Vodafone Cubicle

Figure 74: Maidstone Grid – Existing Switchgear

Figure 75: Maidstone Grid – Protection Panel Example


Figure 76: Maidstone Grid – GPS Antenna

A.7.2: Maidstone Area – DER-1 Generation (DER)
In this section, a collection of photos highlighting the site activities carried when preparing the DER-1 Generation DER site for the Constellation network trial.

Figure 77: DER-1 Generation – Entrance

Figure 78: DER-1 Generation – Substation Exterior

Figure 79: DER-1 Generation – Existing Assets Example

Figure 80: DER-1 Generation – Protection Panel

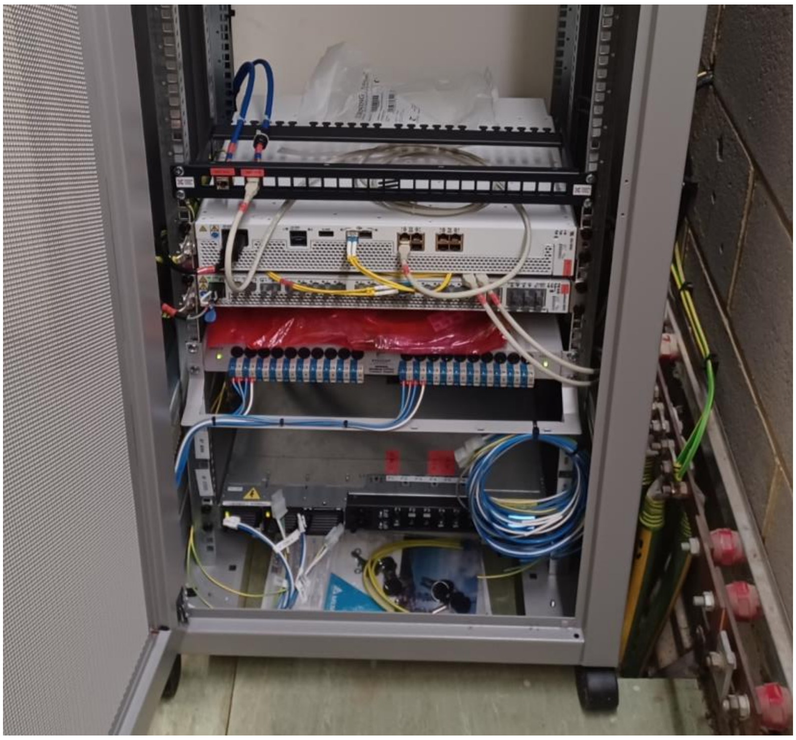


Figure 81: DER-1 Generation – Open Vodafone Cubicle

Figure 82: DER-1 Generation – Constellation / RTU Cubicle

A.7.3: Thanet Area – Thanet Grid
In this section, a collection of photos highlighting the site activities carried when preparing the Thanet Grid site for the Constellation network trial.

Figure 83: Thanet Grid – Entrance

Figure 84: Thanet Grid – Switchgear

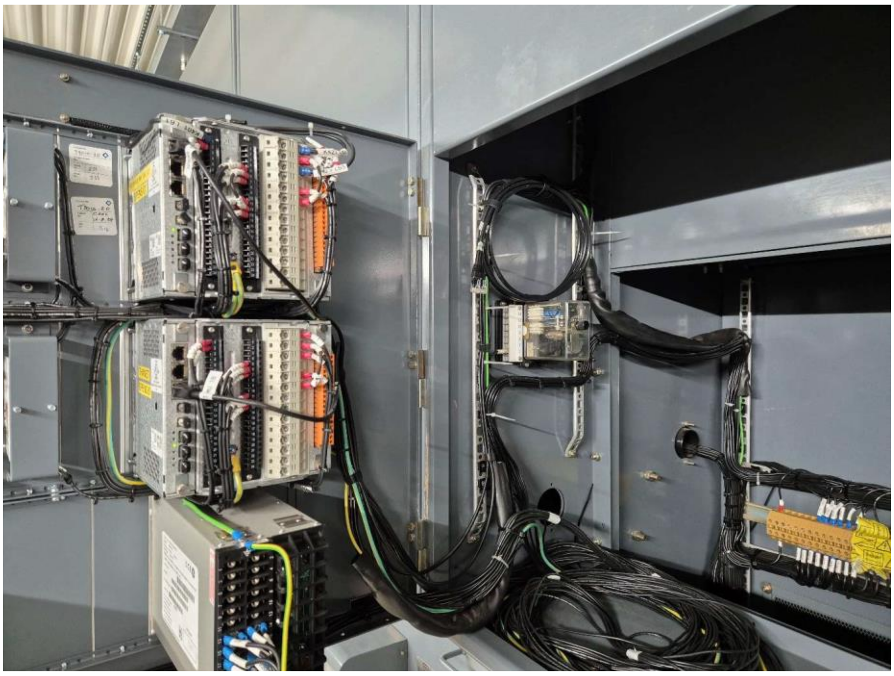


Figure 85: Thanet Grid – Protection Panel (Interior)

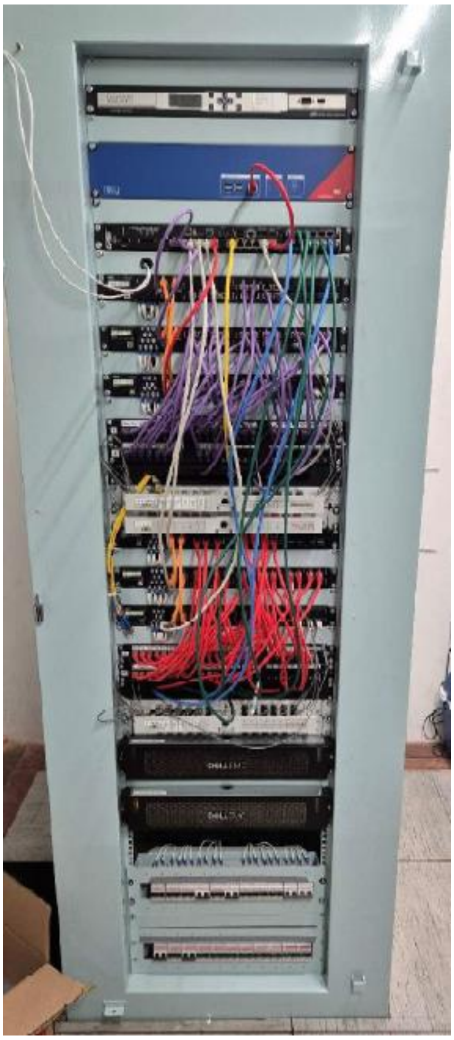


Figure 86: Thanet Grid – Constellation Cubicle

Figure 87: Thanet Grid – Fibre Box Example

Figure 88: Thanet Grid – Fibre Cabinet

A.7.6: Thanet Area – DER-2 Generation (DER)

In this section, a collection of photos highlighting the site activities carried when preparing the DER-2 Generation DER site for the Constellation network trial.

Figure 89: DER-2 Generation – Entrance

[Figure Redacted]

Figure 90: DER-2 – Switchgear

Figure 91: DER-2 – Typical Protection Panels (With Redundant Protection)

Figure 92: DER-2 – Typical Protection Panel

Figure 93: DER-2 – Constellation / RTU Cubicle

Figure 94: DER-2 – GPS Antenna

A.7.4: Thanet Area – DER-5 (DER)

In this section, a collection of photos highlighting the site activities carried when preparing the DER-5 DER site for the Constellation network trial.

Figure 95: DER-5 – Entrance

Figure 96: DER-5 – GPS Antenna

Figure 97: DER-5 – Protection Panel

[Figure Redacted]

Figure 98: DER-5 – Switchgear

Figure 99: DER-5 – Constellation / RTU Cubicle

[Figure Redacted]

Figure 100: DER-5 – Constellation / RTU Cubicle (Interior)

A.7.5: Thanet Area – DER-4 PV (DER)

In this section, a collection of photos highlighting the site activities carried when preparing the DER-4 PV DER site for the Constellation network trial.

Figure 101: DER-4 PV – Entrance

Figure 102: DER-4 PV – GPS Antenna

Figure 103: DER-4 PV – Protection Panel

Figure 104: DER-4 PV – Constellation / RTU Cubicle

Figure 105: DER-4 PV – Constellation / RTU Cubicle (Interior)

Figure 106: DER-4 PV – Vodafone Cubicle