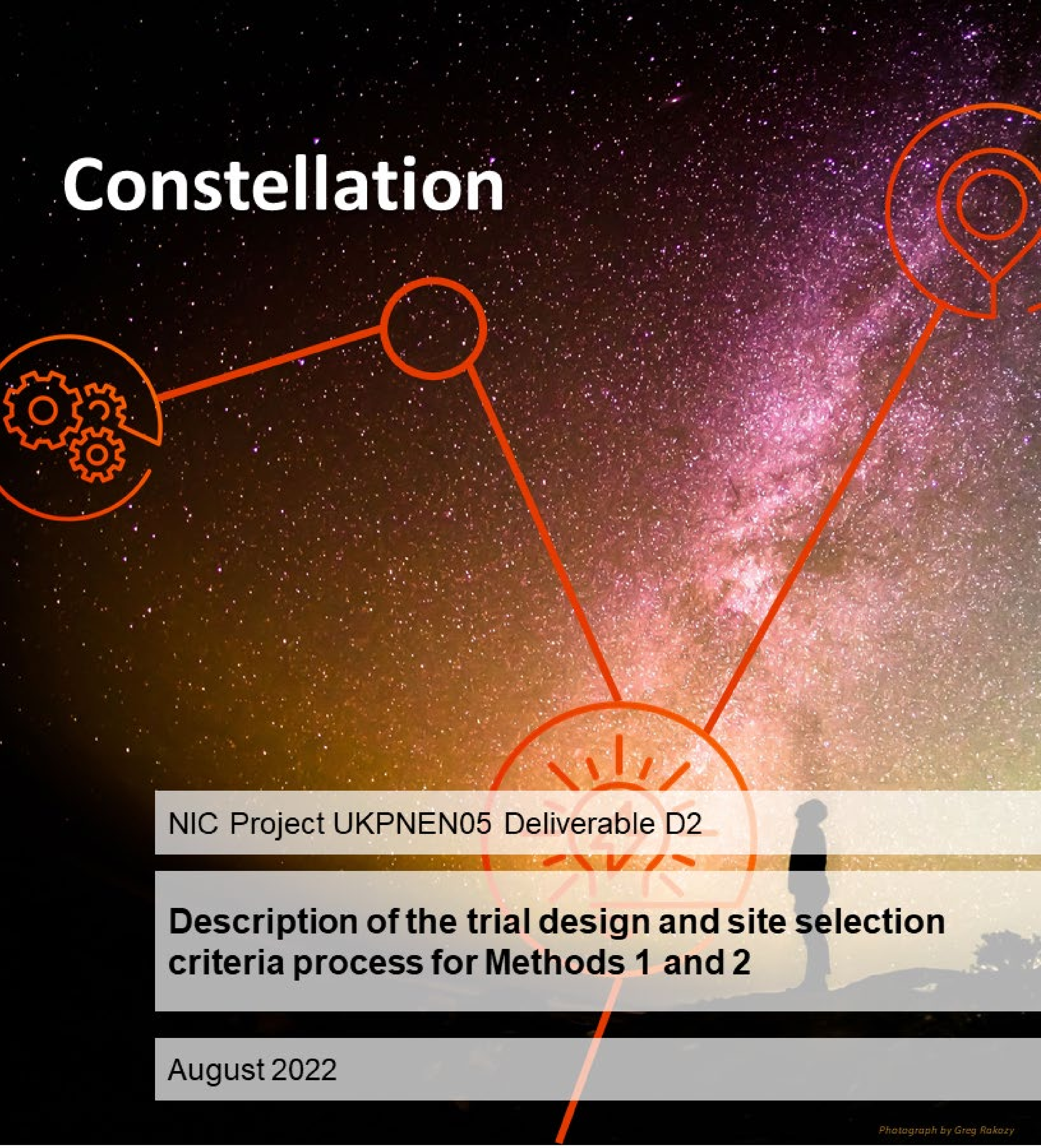

Constellation

NIC Project UKPNEN05 Deliverable D2

Description of the trial design and site selection criteria process for Methods 1 and 2

August 2022

Photograph by Greg Rakozy

Constellation Partners

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

ukpowernetworks.co.uk/innovation

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Table of acronyms & glossary

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

Table 1: Table of acronyms

Acronym	Full form
3GPP	Standards organisation who develop protocols for mobile telecommunications
4G	4th Generation Mobile Network
5G	5th Generation Mobile Network
5G SA	5G Stand Alone Architecture
ABB	Asea Brown Boveri
ADMS	Advanced Distribution Management System
ALoMCP	Accelerated Loss of Mains Change Programme
AMF	Access and Mobility Management Function
ANM	Active Network Management
ANSI/ IEEE	American National Standards Institute/ Institute of Electrical and Electronics Engineers
API	Application Programming Interface
APS	Adaptive Protection System
AUSF	Authentication Server Function
BaU	Business as Usual
BESS	Battery Energy Storage System
CAPE	Computer Aided Protection Engineering
CB	Circuit Breaker
CCSM	Cloud Core Session Management
CEE	Cloud Execution Environment
CIM	Common Information Model
CMC	Universal Relay Test Set & Commissioning Tool
CMS	Central Management System
CoRoCoF	Comparison of Rate of Change of Frequency
CP	Constraint Point
CPU	Central Processing Unit
CSV	Comma Separated Values
CT	Current Transformer
D1	Deliverable 1
D2	Deliverable 2
DANEO 400	Hybrid Measurement System (Omicron)
DBE	Database Editor
DC	Data Centre
DC-GW	Data Centre Gateway
DER	Distributed Energy Resource
DERMS	Distributed Energy Resource Management System
DG	Distributed Generation
DMP	Data Management & Analysis Plan
DNO	Distribution Network Operator
DNP3	Distributed Network Protocol 3
DOC	Directional Over Current
DUT	Device Under Test
EAM	Enterprise Asset Management

Acronym	Full form
EDA	Ericsson Dynamic Activation
eMBB	Enhanced Mobile Broadband
ENA	Energy Network Association
ER	Engineering Recommendation
ETS	Engineering Technical Specification
FAIR	Findable Accessible Interoperable, and Re-usable
FAT	Factory Acceptance Test
FSP	Full Submission Pro-forma (in reference to the project proposal)
FW	Firmware
GB	Great Britain
GE	General Electric
GOOSE	Generic Object Oriented Substation Event
GPS	Global Positioning System
GSP	Grid Supply Point
HMI	Human Machine Interface
HV	High Voltage
IE	Integrity Protection Indication
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IM	Instant Messaging
I/O	Input/Output
IoT	Internet of Things
IP-SEC	Internet Protocol Security
IT	Information Technology
JRC	Joint Radio Committee
kV	Kilovolt
L2TP	Layer-2 Tunnelling Protocol
LAN	Local Area Network
LoM	Loss of Mains
LTE	Long Term Evolution
LV	Low Voltage
MBX	Mobile Branch Exchange
MMS	Manufacturing Message Specification
MQTT	Message Queuing Telemetry Transport
ms	millisecond
MU	Master Unit
MW	Megawatt
NIC	Network Innovation Competition
NR	New Radio
ODMS	Open Data Management System
OIC	Open Innovation Competition
OS	Operating System
P	Active Power
PAC	Protection and Control
PC	Personal Computer
PCC	Packet Core Controller
PCG	Packet Core Gateway
PDC	Phasor Data Concentrator
PDU	Protocol Data Unit
PESS	Protection Engineering and Simulation System
PF	Power Factor
PhC	Phasor Controller

Acronym	Full form
PMU	Phasor Measurement Unit
PNDC	Power Network Demonstration Centre
PPR	Project Progress Report
PRP	Parallel Redundancy Protocol
PSA	Protection Security Analysis
PSS	Power System Simulation and Modelling Software
pu	Per Unit
PV	Photo-Voltaic
PTP	Precision Time Protocol
Q	Reactive Power
R-GOOSE	Routable Generic Object Oriented Substation Event
RAG	Red/Amber/Green
RAN	Radio Access Network
RAT	Radio Access Type
RBX	Radio Branch Exchange
RFA	Ready For Acceptance
RoCoF	Rate of Change of Frequency
RT	Real Time
RTDS	Real Time Digital Simulator
RTU	Remote Terminal Unit
SA	Stand Alone
SAT	Site Acceptance Test
SCADA	Supervisory Control and Data Acquisition
SDI	Software Defined Infrastructure
SDN	Software Defined Network
SFTP	Secure File Transfer Protocol
SIM	Subscriber Identity Module
SLD	Single Line Diagram
SMF	Session Management Function
SMS	Short Message Service
SMV	Sampled Measured Value
SNMP	Simple Network Management Protocol
SQL	Structured Query Language
SUCI	Subscription Concealed Identifier
TCxx	Test Case xx
TRL	Technology Readiness Level
TWh	Terra Watt Hours
UDM	Unified Data Management
UDR	Unified Data Repository
UE	User Equipment
UK	United Kingdom
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
UPIP	User Plane Integrity Protection
URLCC	Ultra-Reliable Low Latency Communications
V2G	Vehicle to Grid (Electric Vehicles)

Acronym	Full form
VF	Virtual Function
VLAN	Virtual Local Area Network
WAM	Wide Area Management
WAMS DE	Wide Area Management System Digital Edge
WAN	Wide Area Network
WAP	Wide Area Protection
WG	Working Group
WMG	WiFi Mobile Gateway
WMI	Windows Management Instrumentation
WS	Workstream
XML	Extensible Markup Language

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
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
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
Substation Server	An industrial server suitable for substation operating environments. The server has hardware and software capability to process protection and control function applications, utilising edge computing architectures. 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 protection and control (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, University of Strathclyde's Power Network Demonstration Centre (PNDC), Siemens and Vodafone. The project aims to demonstrate, through a series of live site trials, how novel protection and control solutions located locally within Distribution Network Operator (DNO) substations can be used to:

- Facilitate the reliable connection of increased Distributed Energy Resources (DER) on to power distribution networks; and
- Protect the use of smart services to reduce the risk of system wide frequency (instability) events by de-risking the likelihood of sudden and widespread DER curtailment and/or disconnection.

Constellation is a world first innovation initiative which 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 protection and control, to enable DER to support the network. Furthermore, we will obtain valuable quantitative evidence to assess how local network operation can improve network stability. Constellation will also save the capacity unlocked by our smart systems from abnormal events, such as loss of communications, and reduce system balancing costs by allowing DER to ride through transient instability events.

This report is the second Constellation deliverable, D2, covers the activities undertaken since Deliverable 1 until mid-July 2022 by all project partners. The trial phase of the project, managed under Constellation workstream 3, is responsible for de-risking the solution prior to BaU rollout. The trial phase encompasses offline trials at each partner`s premises, offline trials at the PNDC facilities and live trials in UK Power Networks` network. This report provides evidence that the trial design and site selection criteria for Methods 1 and 2 have been finalised, in accordance with the Full Submission Proforma (FSP) document requirements[1].

Constellation is a multi-faceted project requiring specialist contributions from each project partner. The solutions designed and developed in the Constellation project involve a number of interacting subsystems[2] as well as an integration of hardware, software and communications. As such, the D2 activities of Constellation involved:

- Continued collaboration and knowledge sharing through a series of workshops and technical meetings. This provided a suitable environment within which the project partners developed and agreed site selection and trial design details;
- Designing a suitable site selection process to assess the distribution network and identify the most suitable trial sites. Learning from the Active Response NIC project was used to facilitate the site selection;
- Identifying appropriate site selection criteria and evaluating the trial sites to select the most suitable ones for the trials; and
- Extensive work to develop the design for each stage of the Constellation trials. This included defining the scope of testing and the performance requirements and aligning them to the Constellation requirements.

[1] Full Submission Proforma, Section 9, Table 11.
[2] Subsystems refer to the individual solutions developed by the Constellation partners which includes hardware and software associated with Method 1, Method 2.

Therefore, this report confirms that:

- The site selection process and site selection criteria for the UK Power Networks trials of Methods 1 and 2 are completed, with two suitable areas (Maidstone and Thanet) selected;
- The trial requirements and design for demonstration of each element of Constellation is completed. Furthermore, this report summarises the trial objectives and focus for each phase of the trials.
- Significant learning has already been generated whilst undertaking site selection and trial design and these are detailed within this report.

Deliverable 2 contents:

- **Section 1** of this report details the project background and purpose, as well as the scope of this report;
- **Section 2** details the site selection process, including the approach and details of changes from the Constellation bid;
- **Section 3** provides concise results from the site selection;
- **Section 4** provides the details of the trial overview for each phase of the Constellation trials;
- **Section 5** provides the details of the trial designs for Methods 1 and 2;
- **Section 6** details how the trial data analysis and management is progressed;
- **Section 7** focuses on ongoing activities and next steps;
- **Section 8** provides the conclusions;
- **Appendices** presents additional information from each project partner which can be used for reference.

Table 3: Deliverable 2 Requirements

Deliverable D2: Description of the trial design and site selection criteria	
Evidence item	Relevant section of the report
Report containing:	
A description of the trial site selection criteria process for each phase of the network trials	Details can be found in sections 2 and 3.
Details of the trial requirements for the demonstration of each element of Constellation	Details can be found in sections 4, 5 and 6.

1 Project Background and Purpose

1.1 Purpose of this Report

This report, which forms the second Constellation Deliverable (D2), covers the activities carried out by the project partners to select sites and agree the trial design. It provides evidence that the site selection and trial design activities for Methods 1 and 2 have been finalised, in accordance with the Full Submission Proforma (FSP) document[3]. This deliverable outlines:

- The approach the project team employed to carry out site selection for the Constellation trials;
- The site selection criteria which was designed to identify suitable trial sites;
- The high-level trial objectives, encompassing the requirements for factory testing, off-site testing at the PNDC and live network trials within the two UK Power Network areas; and
- The trials methodology used to guide the development of detailed trial specifications. However, the fully detailed testing specifications and test plans are not presented in this report. Instead, key trial details are summarised. It should also be noted that the testing acceptance criteria will be reported upon within future Deliverables which focus on the testing results.

Constellation is a highly innovative initiative, and as such, the trial requirements and designs described in this report will be different to the ones at the end of the project. This is resulting from the iterative approach to trailing and demonstrating innovative solutions.

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.

Other items which are outside the scope of this Deliverable are summarised below:

- Justification and rationale for the Constellation solutions is provided in sections 2, 3 and 4 in the FSP;
- Description of the Methods architecture, solution requirements and design are presented in Deliverable 1 (sections 4 and 5 respectively);
- The initial benefit assessments of the Constellation solutions are provided in sections 3, 10.1, 10.2 and 10.3 of the FSP and will be reassessed at the end of the project in Deliverable 7;
- 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 PPRs.

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[4] which are intended to act as stepping-stones towards the UK bringing all greenhouse gas emissions to net zero by 2050. Given that the UK's electricity

[3] Full Submission Proforma, Section 9, Table 11.
[4] https://www.legislation.gov.uk/ukpga/2008/27/section/14

production activities currently account for approximately 24%[5] 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[6]. This 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 350TWh could be embedded into the power networks by 2030.

Between 1990 and 2020, the amount of electrical power provided by such low-carbon embedded generation, universally known as a Distributed Energy Resource (DER), has risen from approximately 70TWh to 180TWh[7]. The introduction of this has created some significant challenges for the energy industry. In particular the distribution network operators (DNOs) who have received the majority of 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 protection and control systems were not designed to accommodate.

Additionally, new flexible methods of managing DER generation via smart services are being introduced, which are intended to optimise the use of electricity network infrastructure. For example, smart services will govern the level of DER generation and/or connectivity under network constraint conditions to ensure the need for asset reinforcement is minimised.

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 commissioned a new Distributed Energy Resource Management System (DERMS), with Active Network Management (ANM) capability, to provide a broad range of services addressing flexible connections, flexible 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 are 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 by assessing the power network status over a wider area is required in order to prevent unnecessary loss of generation, allowing the DER to ride through transient instability events.

With the continued exponential rise in connected DER over the coming years, the sudden loss of significant amounts of such DER following the above may have severe consequences on the stability of the distribution network, and wider system by potentially influencing grid frequency and electricity network loading.

Constellation Aims

[5] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/972583/2020_Provisional_emissions_statistics_report.pdf
[6] https://www.gov.uk/government/publications/net-zero-strategy
[7] https://www.gov.uk/government/statistics/uk-energy-in-brief-2021

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 smart (flexible) energy services in preference to reinforcing or upgrading the electricity network, 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 these smart services by removing their reliance on telecommunication links back to a central control site, and by the application of sophisticated local protection and control 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 protection and control based upon 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 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 in order 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 (“inter-operability”);
- 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 smart services (e.g. flexibility).

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. The design philosophy associated with the two Methods can be further elaborated upon as follows:

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 our local network assets, the local intelligence at the area level will take over optimisation 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 optimisation 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.

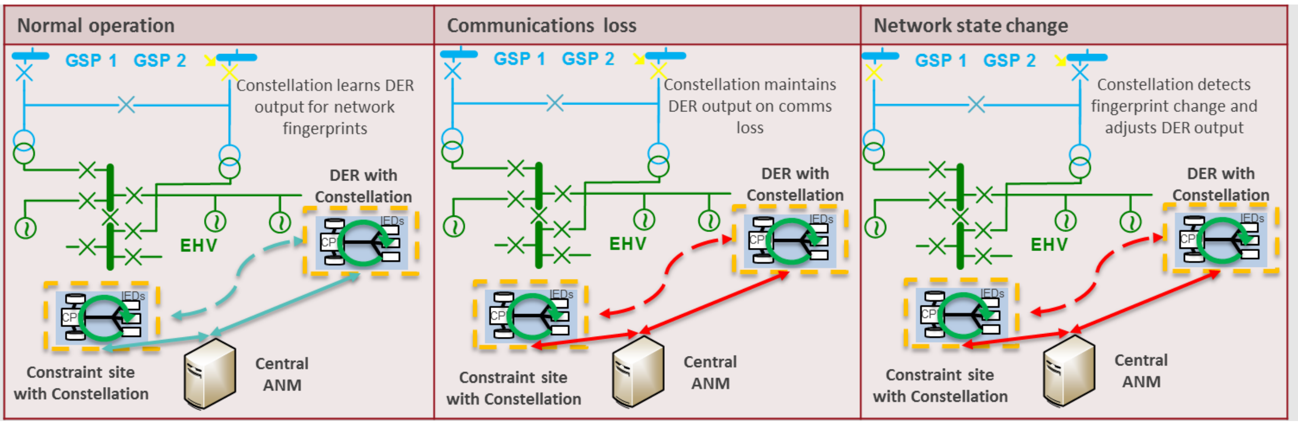


Figure 1: Local ANM (Method 1) Summary Diagram

1.3.2 Method 2: Wide Area and Adaptive Protection

This project Method will comprise 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. Wide Area Protection algorithms will provide tripping and blocking facilities to DER sites in order to enable them to ride through an external 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 Routable Generic Object-Oriented Substation Event (R-GOOSE) messages.

The above approach is in line with Engineering Recommendation (ER) G99[8] which provides the requirements for connecting generation equipment in parallel with public distribution networks, as well as complement ER G59/3-7[9], 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.

[8] ENA EREC G99 Issue 1, Amendment 6
[9] ENA EREC G59, Issue 3, Amendment 7

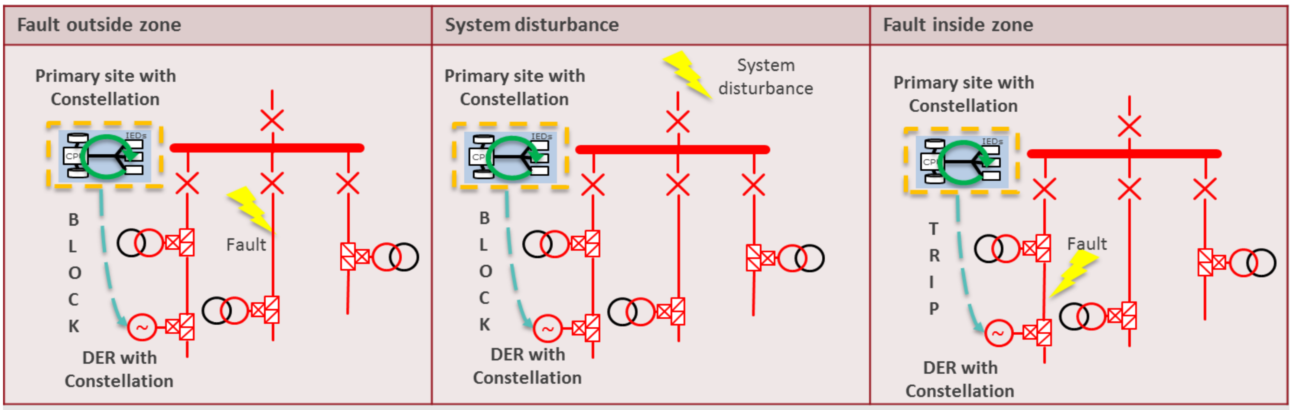


Figure 2. Wide Area Protection (Method 2) Summary Diagram

<u>Adaptive (load blinding) Protection</u>
In addition to Wide Area Protection, 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 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.

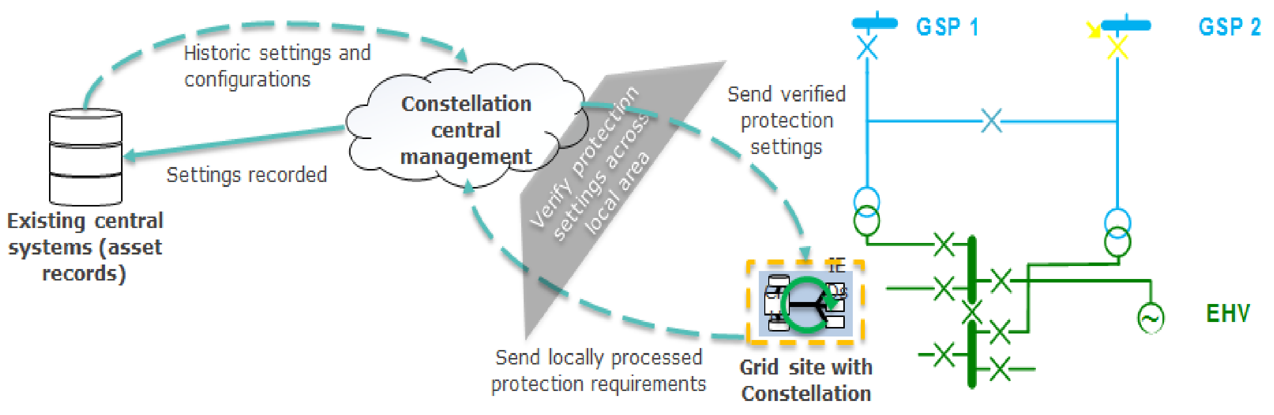


Figure 3. Adaptive Protection Settings (Method 2) Summary Diagram

1.4 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 selected via a competitive tendering process, to deliver the project successfully.

A description of each partners roles and responsibilities under Constellation is provided below and summarised within Figure 4.

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 comprises 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 entire project learning dissemination activities will be undertaken by all project partners, led by UK Power Networks.

Description of the role for each project partner in Constellation

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

University of Strathclyde's Power Networks Demonstration Centre (PNDC): 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 test on a live power distribution network. The PNDC is leading workstreams 3 and 4.

GE: Providing specialist engineering expertise to design, develop and demonstrate the local Active Network Management (ANM) solution. GE is also supporting integration activities to the ADMS.

ABB: Providing specialist engineering expertise to design, develop and demonstrate the Wide Area Protection solution and virtualised protection.

Siemens: Providing specialist engineering expertise to design, develop and demonstrate the Adaptive Protection solution and the central management system.

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 two 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; and
- JRC (Joint Radio Committee) will provide technical support on the 5G Slice design and 5G site specific design.

In order to efficiently manage the project Methods given that there is some technical, testing and learning overlap between them, six workstreams have been implemented as detailed in Table 4 below. The responsibility for delivering and managing each individual workstream has been assigned to a specific partner on the project, as described in Figure 4.

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

Table 4: 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 live trials hosted on the 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

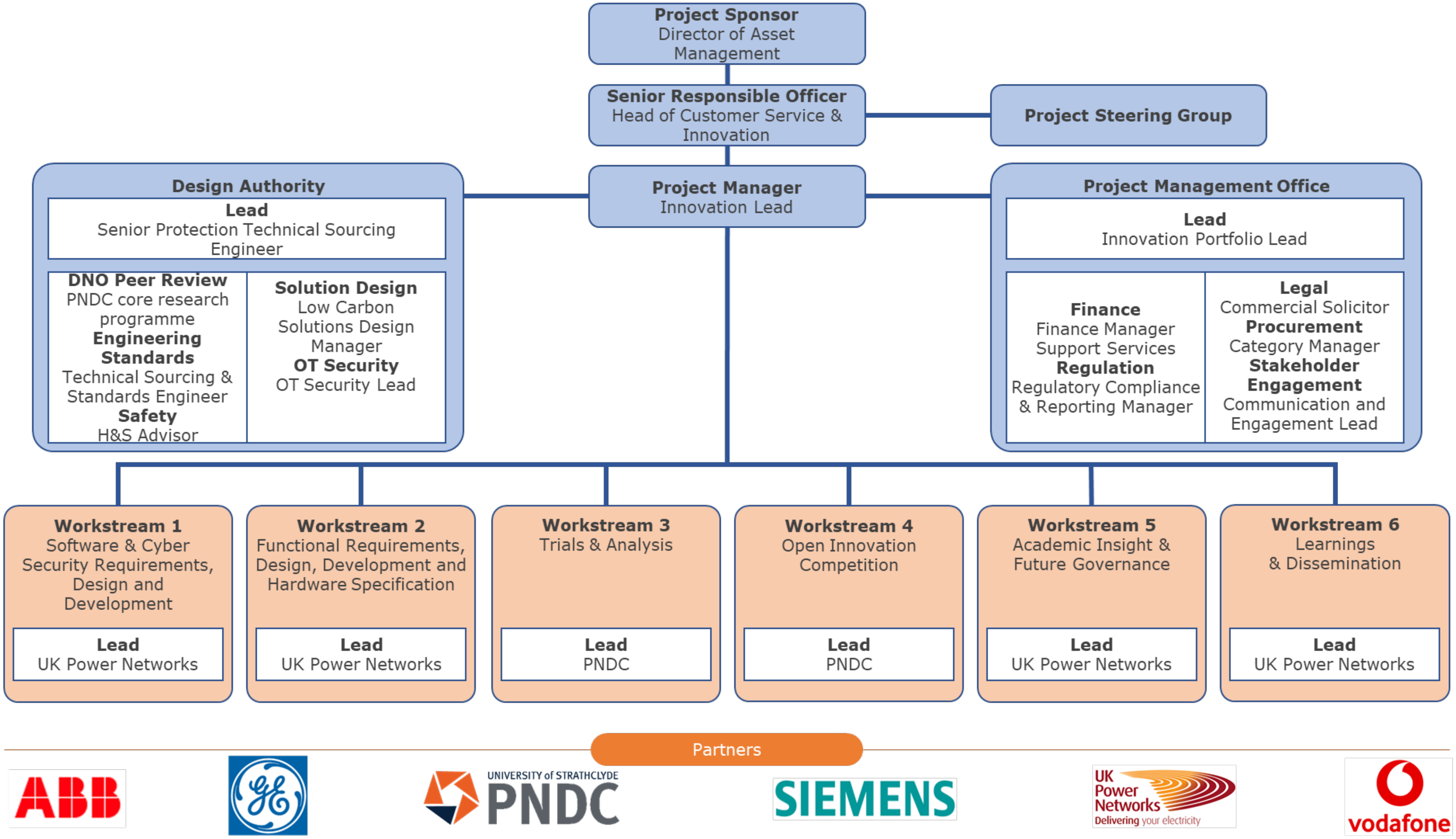


Figure 4. Project Organisation and Workstream Leads

2 Site Selection Process

2.1 Introduction

The core aim of Constellation is to trial the solutions on the live electricity network in order to demonstrate that the benefits described within the FSP can be realised. This aim includes documenting all learnings for assessment and action in order to further improve the solutions for BaU rollout.

At the FSP stage, it was agreed that it is most cost effective to trial Constellation across two UK Power Networks' areas[10]. This is as a result from an assessment to understand the optimal number of areas required for the trials. The selected number of areas needs to ensure the functionality afforded by each Method can be sufficiently tested in a cost-efficient manner, whilst also ensuring sufficient learning from the project can be obtained. After analysis of the various possible network areas and the resulting need to install equipment to test, it was determined that three areas would increase the trial cost significantly and not generate a likewise increase in project learning. It has also been considered that by implementing and testing the project Methods on significantly different portions of the power network, we will be able to demonstrate different aspects of the project designs and their respective functionality. This allows testing in a number of realistic network configurations and testing in areas with different generation technology types.

This section therefore describes the process undertaken by UK Power Networks to select the most suitable two areas, and sites to be used within those areas. The key selection criteria used to formulate this are also described herein.

2.2 Site Selection Approach

Throughout the entire bid development and initial delivery stages of Constellation, significant work has been undertaken by UK Power Networks and the project partners to analyse and determine the most suitable areas for the trials. The main activities undertaken are summarised as below.

Engagement with key stakeholders

The site selection process was underpinned by extensive engagement with key stakeholders across UK Power Networks, as well as experts from the Constellation partners. The purpose of this engagement was to understand the solution requirements (presented in Deliverable 1), as well as the practical considerations for the sites. The engagement for site selection began during the bid stage before the project started. This was limited to a high-level exercise as described in Section 2.3 to determine suitable areas on the network, which would be later verified during the project.

Once the project had started, we set out engaging with experts from UK Power Networks' internal teams who have relevant knowledge to the site selection process (such as Network Planning, Outage Planning, Cyber Security, Operational Telecommunications, Network Control and Network Operations teams). This engagement was in the form of:

- Requirements and design workshops (presented in Deliverable 1);

[10] A trial area consists of a number of individual trial sites, consisting of: one hub site (typically grid site) and at least one DER site.

- Site selection discussions with internal stakeholders as part of regular Constellation internal engagement; and
- Site visits with operational engineers.

The engagement continued throughout the site selection process to ensure feedback was appropriately carried through. As a result of the engagement, and based on further network assessments, we identified four network areas suitable for Constellation trials, as described in Section 2.4.

Learning from previous projects

UK Power Networks has significant experience in delivering large scale innovation projects, such as Low Carbon London, Active Response and Optimise Prime. To ensure we learn from previous experience, we reviewed relevant projects for their methodology applied for site selection in order to utilise learnings and best practice for Constellation.

We identified that whilst being a significantly different project, Active Response[11] had similar overarching trial objectives in validating a novel system on the distribution network. Therefore, we customised the staged site selection process developed for Active Response with updated selection metrics which are suited to Constellation.

Staged site selection process

In order to determine areas within UK Power Networks South Eastern license area (SPN) that may be most suited to Constellation and ensure the two Methods can be adequately demonstrated via a series of live network trials, a detailed four-stage site selection evaluation process was undertaken. The feedback shared from stakeholders on suitable trial areas was used as a starting point to initiate the four stage evaluation process. Once the most suitable areas were determined, a fifth stage in the evaluation process commenced in order to confirm the suitability of each individual site within each area.

The net result of this detailed site selection evaluation process provided agreement on which sites in all areas would be selected for installation of the Constellation equipment and demonstration of the two Methods.

Throughout the entire site selection process, the primary considerations have been to:

- Identify two areas, both of which have a main area substation and a number of dedicated substations which are connected to DER;
- Select sites which are on sufficiently different parts of the power network; and
- Demonstrate different aspects of the project designs and their respective functionality.

Figure 5 below graphically illustrates the site selection evaluation process undertaken.

[11] Active Response Deliverable #2 (https://innovation.ukpowernetworks.co.uk/projects/active-response/)

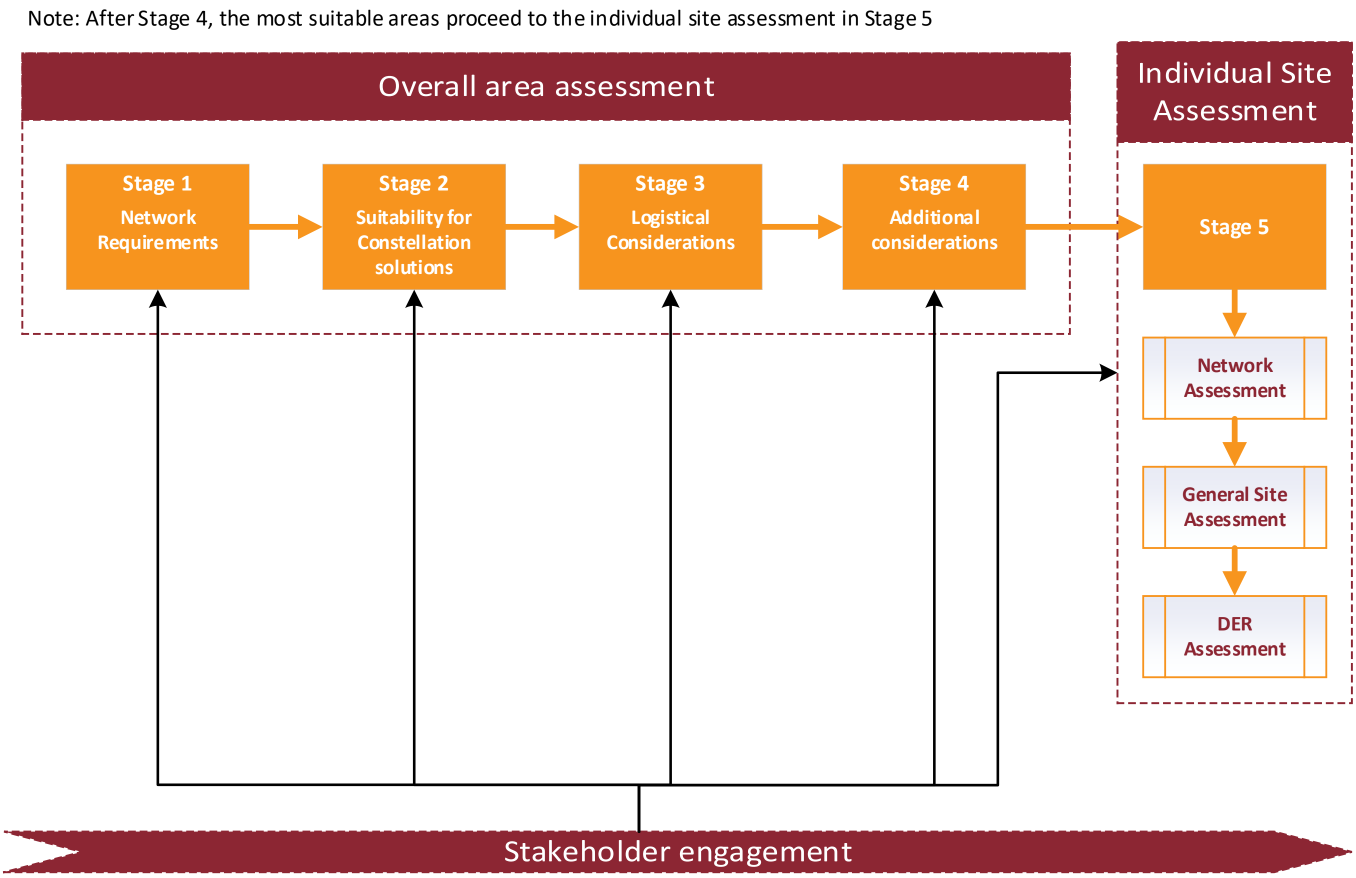


Figure 5: Site Selection Process Diagram

2.3 Initial Site Selection During the Bid for Constellation

In order to prepare the FSP, UK Power Networks undertook initial analysis of the entire SPN network in order to identify two areas, in different geographical locations, which provide suitable network configurations to allow testing of the project Methods.

To identify the preferred areas, the Constellation team consulted with key business experts and specialists from all appropriate technical and operational departments. As a result of the internal consultations and a high-level desktop analysis of the network, two areas containing twelve individual sites were identified, all within SPN's Maidstone and Lewes areas. Essentially these two areas were selected during the FSP submission stage for the following main reasons:

<u>Maidstone Grid Area</u>

- Maidstone Grid provides a relatively simple environment for testing the Local ANM design (project Method 1), with only a single DER connected directly at 33kV [redacted].

  This area is considered to provide a suitable platform on which to implement and test the various protection functionality (project Method 2), in particular the Adaptive Protection setting functionality as the entire area is currently constrained due to Directional Over Current (DOC) protection.

Lewes Grid Area

- Lewes Grid represents a 33kV ring network topology. This area provides a suitable hub connecting four medium-scale DER [redacted]. Lewes Grid is typically supplied from Ninfield GSP and connected to Bolney GSP as a "loose couple".

  Due to the many running arrangements possible on the 33kV ring, it was also considered to be ideal to demonstrate Method 2 (wide area protection and control).

Whilst both Maidstone and Lewes areas provided limited scope for demonstrating Method 1 (Local ANM), it was considered that selecting these two areas would permit Methods 1 and 2 to be demonstrated in complex running arrangements on locations with a high penetration of DER.

These initial considerations, presented within the FSP, were later assessed as the project started in line with the five stage site assessment.

2.4 Site Selection – Stages 1 to 4 Evaluation

Upon project commencement, further workshops and stakeholder engagement were held as described in Section 2.2 in order to re-assess the initial considerations identified in Section 2.3 and identify any further areas for consideration.

The SPN area was re-assessed in order to determine if any other areas within SPN could provide a suitable environment to demonstrate the two Methods, noting that each required differing network configurations and blend of connected DER and central ANM connectivity. All potential areas were identified and, after further internal consultations, four areas were selected for the detailed site selection evaluation process.

These four areas were as follows:

- Maidstone Grid area;
- Thanet Grid area;
- Lewes Grid area 1; and
- Lewes Grid area 2.

Appendix A.1 provides the basic Single Line Diagrams (SLD) for each of these four areas. It should be noted that there were two suitable areas in Lewes, which are referred to as Lewes Grid area 1 and Lewes Grid area 2. Lewes Grid area 2 was the one which was used during the bid stage.

All four areas were therefore evaluated as per the site selection process detailed within Figure 5. In summary, these four stages considered the following:

1) Network requirements: An overarching assessment of the area to identify a suitable "hub" site with DER sites connected to it. Stage 1 also examined the possible running arrangements for each area, as well as the availability of 5G coverage.

2) Constellation solution suitability: This stage focused on the following details:
   - An assessment of the types and volumes of DER in the area; and

- An assessment of the suitability for demonstrating Local ANM, Wide Area Protection and Adaptive load blinding Protection.

3) Area logistic consideration: An assessment of the practicalities of each area, focusing on:
    - Cost of preparing for trial;
    - Space for equipment; and
    - Identification of other planned work in the area during the Constellation trial phase.
4) Other considerations: This stage focused on identifying synergies with previous or ongoing relevant projects and suitability for trial data collection over a long period.

2.5 Site Selection – Stage 5 Evaluation

On conclusion of the initial four-stage site selection evaluation process, the two areas which were most suitable were then further assessed through the fifth evaluation stage. Stage 5 assessed the individual sites within each area in order to confirm that they are entirely suitable for Constellation.

The assessment within this site evaluation stage considered both individual site network details and wider aspects such as physical space, interfacing, availability of necessary IT and DER suitability. In summary, this fifth stage therefore considered the following:

a. Network assessment: Evaluation of the network capacity, fault history and network constraints.
b. General site assessment: An assessment of the physical space, availability of power supply and IT infrastructure in each site for all Constellation equipment. This part of stage 5 also focused on a detailed 5G survey.
c. DER assessment: A detailed review of each connected DER to understand the technology type, DER capacity and export limits in place.

The detailed results of all the above site selection evaluations are provided in Section 3.

D2 Section 2 : Lessons Learnt	
1	Constellation is a complex and highly innovative project spanning multiple different industry domains. As such, it requires significant specialist input from several diverse stakeholders. The close collaboration between all stakeholders has been key in the Constellation success so far. While the frequency and format of engagement can be adjusted, we recommend other large innovation projects use a similar focus on collaboration as learning from Constellation.
2	Assessing all previous large innovation initiatives was vital in developing a robust site selection approach for Constellation. Using Active Response's approach and adapting it to Constellation ensured we maximise the learning from previous work, while also reducing the duplication of work.

3 The Results From Site Selection

3.1 Introduction

As discussed in Section 2, following on from the workshops and stakeholder engagement, four areas were identified as being suitable for Constellation and, in order to determine the two most suitable areas, each was assessed as per stages 1 to 4 as detailed within Figure 5.

For each area, all criteria were assessed with the results being recorded in Table A.3.1. The assessment was qualified and, where relevant, quantified. Certain criteria[12] were also colour coded Red/Amber/Green (RAG) to provide a quick and easy-to-view identification of which areas provided the best locations to demonstrate the two Methods.

Following on from this initial four-stage evaluation, the two preferred trial areas were subjected to a fifth evaluation stage, which is recorded in Table A.3.2 and Table A.3.3.

3.2 Site Selection Evaluation Results – Stages 1 to 4

With the commencement of Constellation and as the site selection evaluation stages progressed, it was determined that the network around Thanet provides a more suitable test platform than both Lewes areas for trialling the Constellation Methods. Therefore, the Constellation project has migrated from the initially proposed sites within the Maidstone and Lewes areas to those within the Maidstone and Thanet areas.

The deciding factor for selecting Thanet area over Lewes areas was suitability for demonstrating Method 1 (Local ANM). This is because only sites within the Thanet area interface with central ANM, which is a desirable pre-requisite for trialling Method 1 (Local ANM).

In summary, the following conclusions were determined:

- While Maidstone does not include any DER managed through central ANM, it includes a low number of sites, which provides a relatively simple environment for testing the Local ANM design (project Method 1), with only a single DER connected directly at 33kV;
- Maidstone provides a suitable platform to implement and test the various protection functionality (project Method 2), in particular, the Adaptive Protection setting functionality as the entire area is constrained due to Directional Over Current (DOC) protection;
- Maidstone was used as a test bed for the Unified Protection project which has direct synergies to Constellation;
- Thanet provides a suitable environment for testing the Local ANM design as this substation can be connected to multiple DER, depending on the running arrangements. Some of the DER are connected to the central ANM [redacted]; and
- The mix of generation in Thanet provides both inverter and synchronous generation. This allows testing of the different responses to frequency changes for Local ANM and Wide Area Protection. The Thanet area is also constrained due to DOC protection on

[12] Some criteria are unsuitable for RAG comparison.

the Grid transformers, which makes it suitable for demonstration of the Adaptive Load Blinding Protection (project Method 2).

In addition, the quantities of installed equipment and the costs for site implementation required at Maidstone/Thanet are similar to those that would have been required should Maidstone/Lewes areas ultimately chosen, hence the overall costs for Constellation remained comparable.

3.3 Site Selection Evaluation Results – Stage 5

In order to ensure that the individual locations within Maidstone and Thanet would prove suitable for demonstrating the two Methods, each area was then evaluated in stage 5 as detailed within Table 5. For each area, all criteria were assessed with the results recorded in Table A.3.2 and Table A.3.3.

A key aspect of the stage 5 evaluation included assessing the physical space at each site to ensure that the new Constellation equipment could be accommodated as well as verifying logistical considerations such as access.

To support stage 5, both UK Power Networks and Vodafone visited each site within both Maidstone and Thanet areas and a summary of their respective findings is located in Appendix A.2 and summarised below.

Purpose of UK Power Network Site Surveys
The surveys focused on the following aspects:

- Survey building, space restrictions and availability of existing measurement equipment;
- Data collection to plan installation works, including space and location for IEDs, cables, 5G communication and Constellation equipment;
- Confirmation of location and volumes for IEDs on the switchgear panels; and
- Data collection to assist with electrical design including general arrangement of sub-racks. These include photographic evidence, on-site drawings, existing power supplies, and existing fibre optic cables.

Appendix A.2.1 details the results of these site surveys.

Purpose of Vodafone 5G Site Surveys
The surveys focused on assessing each site to ensure the civil, infrastructure and hardware requirements for the Vodafone 5G equipment could be accommodated. Additionally propagation modelling was carried out to determine the potential indoor signal strength for the 5G internet of things (IoT) equipment and the equipment required to implement the solution.

Site selection conclusion
As a result of the site selection evaluation process stage 5, it is confirmed that each individual site within both Maidstone and Thanet areas is suitable for accommodating the equipment required for demonstrating the two Methods. As part of the site surveys, we also determined the specific on-site work for each site.

Constellation will also be trialling solutions from alternative suppliers as part of workstream 4 (the "Open Innovation Competition (OIC) project stage) and these solutions will also be trialled within the chosen two areas. The progress of this will be reported upon within Deliverable No. 5.

3.4 BaU Considerations for Site Selection

In order to implement successful Constellation deployments in the future, it is important that sufficient sites within an area are available with a suitable "hub" and associated "satellites". Apart from assessing the distribution network connectivity, attention should be given to understanding the DER connected (or scheduled to be connected in the short-to-medium term) and whether they will benefit from Methods 1 and 2.

Furthermore, it is essential that site surveys are carried out to predetermine physical space, interfacing and IT connectivity.

Based on network assessments for Constellation, we estimate that other areas are suitable for a BaU implementation within all three UK Power Networks license areas. However, these estimates depend on the success of the Constellation trial to demonstrate the benefits of the Methods. Nevertheless, the site selection approach used in Constellation is suitable for BaU and will be employed, with appropriate enhancements, if Constellation is rolled out to the distribution network at scale.

D2 Section 3 : Lessons Learnt	
1	In Constellation, the concept of distributed intelligence will be demonstrated. This relies on local sites working together to increase the network resilience and unlock network capacity. Therefore, site selection was split in two parts: identifying suitable areas and then verifying each site in the areas is individually suitable for the trials. This approach of identifying suitable areas first is recommended to selecting sites for digitalised substations, as it reduces the effort of researching each individual site before the area is confirmed to be suitable for smart solutions similar to Constellation.
2	Suitable areas may change over time due to the introduction of further embedded DER and connectivity to other external systems. Therefore, a robust site selection evaluation is vital to ensure all current network considerations are captured and assessed. Apart from power network considerations, other aspects such as the 5G coverage needed to be re-assessed, given that such infrastructure was continually being developed and commissioned regardless of Constellation.

4 Trial Design (Overview)

4.1 Project Methods

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 5 below summarises the elements and Figure 6 visualises them.

Table 5: Summary of Constellation elements

Constellation Elements
Platform: In this report 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 protection and control 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: 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) • Adaptive protection (Method 2)

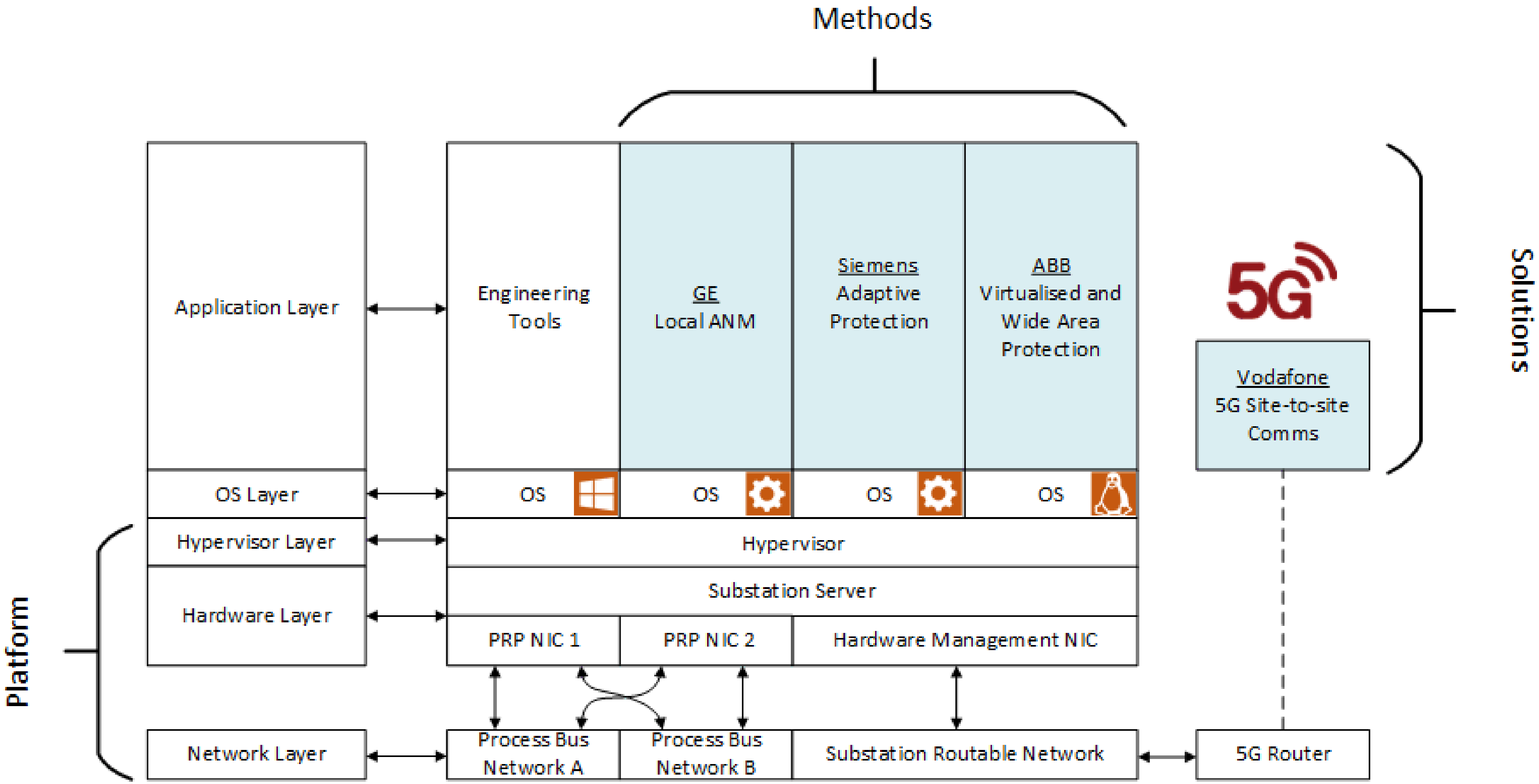


Figure 6: Constellation elements

4.2 *Trial Aims and Stages*

The trial phase of the project, managed by Constellation workstream 3, is responsible for de-risking the solutions prior to BaU rollout. The trials aim to demonstrate the correct operation of the Methods when integrated together on the Constellation platform to provide benefits for our customers. As such, this phase is essential to the successful delivery of Constellation.

The main aim of the trials is to confirm that the solutions have been designed and implemented correctly as per the approved design and requirements specifications and that the operation of the two project Methods is demonstrated on the live electricity network with learning captured and documented. To achieve this, the Constellation solutions will be demonstrated through structured testing across the partner`s test facilities, the PNDC test environment and the UK Power Networks live network, within the two trial areas chosen during the site selection stage of the project, as described in Section 3 of this Deliverable. The different stages of the trials are visualised in Figure 7.

The testing commences with the Factory Acceptance Test (FAT) at each of the respective project partners facilities, where the respective solutions will be individually subjected to rigorous testing.

The main distinction between the FATs and the following trials is that each solution will be tested in isolation during the FATs. This means that there will be no interaction with any other Constellation solution or system. For example, Local ANM will be tested in isolation in GE`s facilities to verify the functional and non-functional requirements have been successfully fulfilled. Similarly, Adaptive Protection and Wide Area Protection will be tested in isolation in Siemens and ABB`s facilities respectively. Conversely, during the testing in the PNDC facilities and UK Power Networks trial areas, the solutions will be tested utilising system level testing. This means that all the solutions will be running together in parallel on the Constellation platform during this stage of testing.

After the FATs are successfully completed, the solutions will be integrated on the Constellation platform in the PNDC test environment. There, the solutions will be extensively tested. The off-site PNDC trials will begin with integration testing, the “Site Acceptance Testing” (SAT), of all the solutions running on the same platform. After the PNDC SAT, the trials will continue rigorous testing of the software functionality in a realistic operational environment. The PNDC testing environment will also allow for more accelerated testing and exposing the Constellation platform to conditions that are not easily or practically replicable in a live network trial.

The PNDC trials will be delivered using a combination of real-time simulation and HV/LV testing facilities. The detailed test results from this part of the trials will be analysed in order to determine the level of functional compliance of the two Methods against the approved designs. The results will then be used to re-validate the solution and remediate any flaws to improve the solution and ensure correct operation as per the design specifications.

Finally, the solutions will be deployed on the distribution network at the selected sites for the final phase of the trials. This will begin with a SAT to ensure all the solutions are correctly installed on site. After that the solutions will be tested passively, without the ability to make changes on the live distribution network. Once sufficient evidence is collected to assess the correct functional and non-functional operation, the solutions will be tested “actively” and will be relied on to protect and control the distribution network.

Figure 7 shows the Constellation trial stages and Table 6 summarises the focus and approach to each respective trial phase.

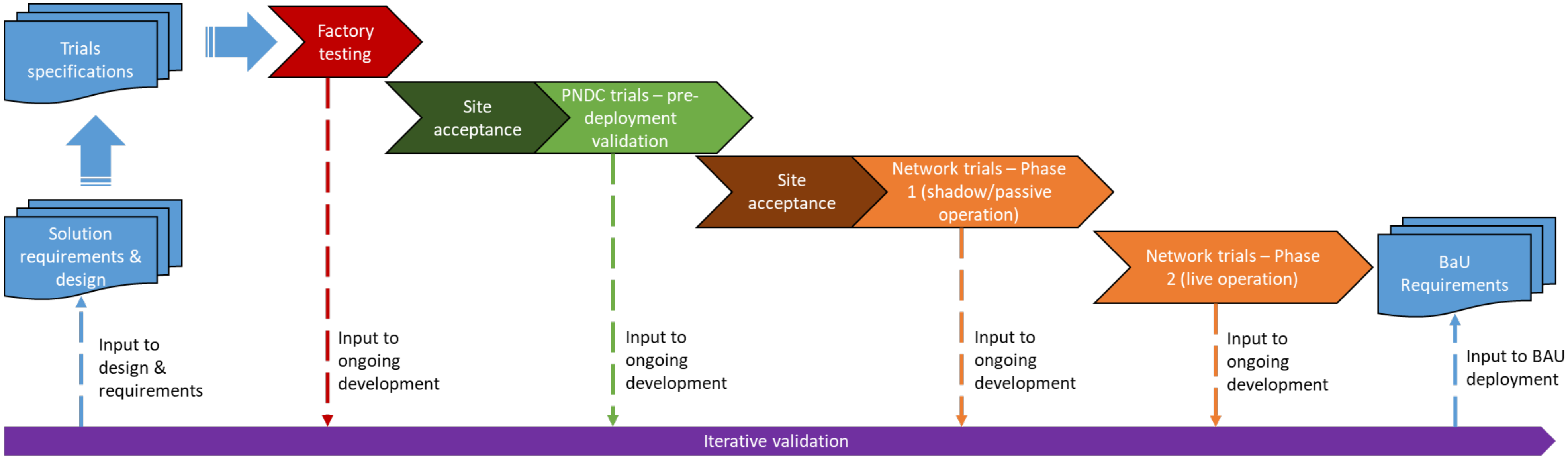


Figure 7: Constellation Trial Stages

Table 6: Aims and Approach to Trial Activities

Aims	Approach
Factory Acceptance Testing (for the solutions)	
Aims	**Approach**
• Demonstrate that the individual designs are compliant with the relevant UK Power Network engineering technical specification (ETS) and test specification documents; • Demonstrate that the solutions are robust and performance is acceptable; and • Demonstrate that the solutions operate correctly in isolation. • Demonstrate that the solutions are ready for SAT in the subsequent trial phase.	• Implementing a test environment to demonstrate the solution operation; • Carry out testing as per the approved testing specifications; • Perform and validate testing with key experts; and • Iterate and update solutions to resolve any major issues before proceeding with the PNDC trial.
Off-site trials at the PNDC	
Aims	**Approach**
• Functional and non-functional verification of the Constellation Methods requirements in a realistic test environment; • Evaluation of the hardware and software of the Constellation local intelligence and virtualisation platform; • Interoperability testing between solutions; • Assessment of the 5G site-to-site communication; and • Assessment of the cyber security resilience of the Constellation solution. Initial penetration testing on the Constellation system will be undertaken to ensure the security of the full solution meets the secure by the design requirements.	• Implementing and test a replica of trial site equipment and configurations using PNDC hardware in the loop test setup; • Simulation of operation scenarios with the Real Time Digital Simulator (RTDS); • Retrofit of PNDC 11kV substation; and • Regular engagement with the project partners and UK Power Networks will occur to review issues as they arise and perform regression tests of resolutions where applicable.
Network Trials – Phase 1 (Shadow/passive operation) **Involves monitoring, control and protection actions in an open loop configuration and will span approximately 1 year or until sufficient evidence of performance is observed**	
Aims	**Approach**

• Integration with UK Power Networks' systems such as Azure servers, central ANM and ADMS • Identification of issues related to site installation, configuration, interoperability and operation of the Constellation solutions including a larger quantity of interacting systems (compared to offline trials); • Passive functional and non-functional verification of the Constellation solutions requirements in a real operational environment; • Assessment of the 5G site-to-site communication; • Assessment of the cyber security resilience of the Constellation system to ensure the security of the full solution meets the secure by design requirements; • Informing the relevant policy, standards and guidelines to enable BaU adoption of the Constellation solutions; and • Facilitating the engagement with UK Power Networks internal stakeholders and owners of the BaU rollout.	• Implementation of test scenarios for each Constellation element; • Commissioning the Constellation system on the trial locations; • Integration with central systems plus Interfacing with Grid/DER site level intelligent electronic devices (IEDs)/phasor measurement units (PMUs)/DER controllers/remote terminal units (RTUs); • Passive testing of all Constellation elements during network events which normally occur, such as topology reconfiguration, faults, loss of comms, demand changes, voltage fluctuations; and • Regular engagement with the project partners to review issues as they arise and perform regression tests of resolutions where applicable.
Network Trials – Phase 2 (Live Operation) **Involves actuating live assets with control and protection signals and will span approximately 1 year or until sufficient evidence of performance is observed**	
Aims	**Approach**
• All of the aims from Phase one; and • Long-term evaluation of the Constellation platform (virtualisation hardware and software) in an operational environment; • Validation of the Constellation business case assumptions; and • Full functional performance and assessment of the Constellation system including Methods 1 and 2, communications, central management and, when completed via workstream 4, verification of the OIC use cases.	• Live testing the Constellation elements during network events which normally occur, such as topology reconfiguration, faults, loss of comms, demand changes, voltage fluctuations; • The live trials for each solution will depend on sufficient confidence in the solution performance. It is expected that the live trials for each solution begin at different time; and • Regular engagement with the project partners to review issues as they arise and perform regression tests of resolutions where applicable.

Collectively, the PNDC and UK Power Networks trials are designed such that their outcomes are complementary and provide logical technology readiness level (TRL) advancement of the solutions. The expected TRL advancement is visualised in Figure 8 below, however, this will be further verified as part of the trials. The PNDC off-site testing will remain active in parallel with the UK Power Network live trials in order to ensure continuous support and validation of any changes that may be required when trialled upon the operational power network.

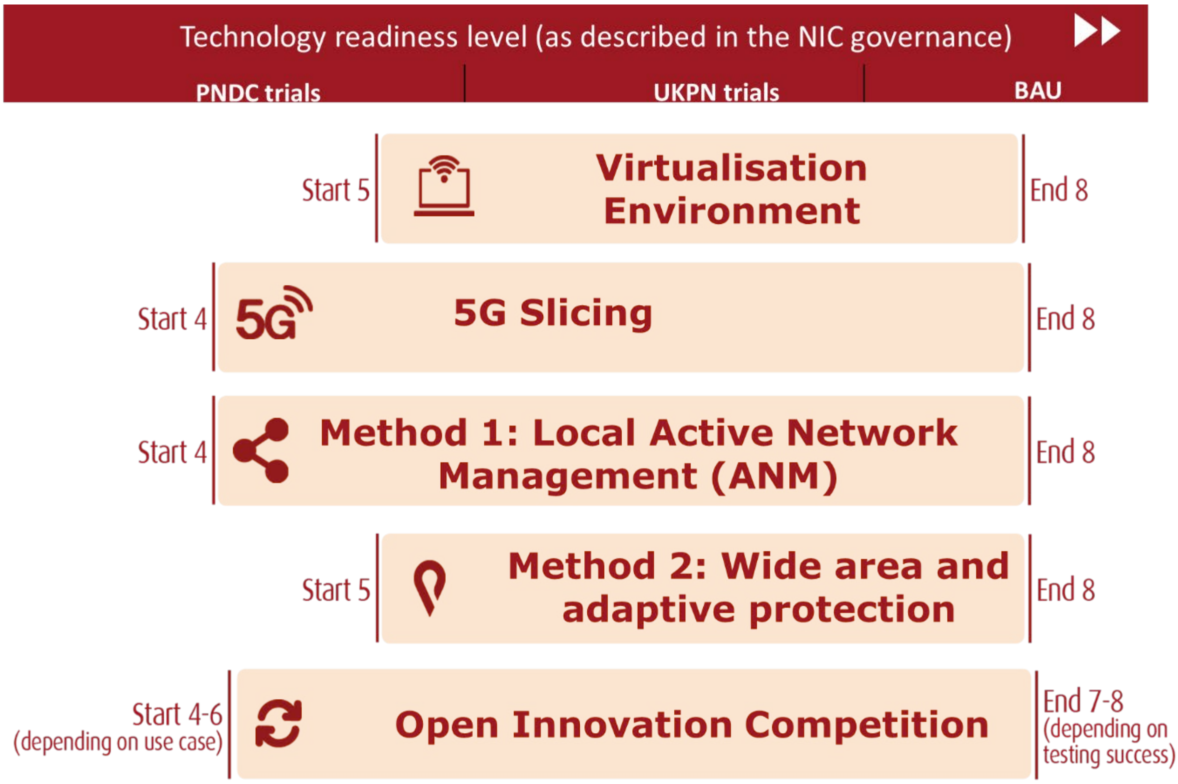


Figure 8 : TRL Advancement

4.3 Trial Roles

During the trial phase of the project, each partner has a key role in ensuring the success of the testing. Figure 9 below details each project partners' role and the documentation to be developed during progression of the project trials.

- UK Power Networks are responsible for verifying all solutions and will manage and witness the individual FATs. They will also provide, and carry out testing upon, the UK Power Networks' test environment, and provide expert input across all trial activities;
- The project partners providing the solutions (ABB, GE, Siemens and Vodafone) are all responsible for preparing for and carrying out the respective FATs and for providing support and updates to their designs as necessary as the trials progress through the off-site (PNDC) and live network (UK Power Networks) stages;
- Omicron will provide an independent evaluation across all FAT and SAT activities, expert input across all trial activities and provide training in how to use the specialist Omicron tools provided to assist testing; and
- PNDC are responsible for leading the trials and subsequent analysis of data. PNDC will provide a suitable test environment within their premises for the off-network trials, carry out the off-site testing and provide expert input across all trial activities. PNDC will also be responsible, under the third workstream, for gathering data and insights

from the trials. Ultimately, the PNDC responsibilities will oversee the de-risking of the solution prior to BaU rollout.

In order to ensure the success of the trials throughout each testing stage, a whole suite of documents will be produced throughout the trial period, as summarised below:

- Factory testing and site testing specification: this will describe the tests which will be carried out to ensure each solution complies with the functional and non-functional requirements.
- PNDC trial design: this implements a test environment and regime to advance the Constellation Methods TRL;
- UK Power Networks' trial design: this will describe the environment at the trial areas and the test scenarios which will be carried out during the UK Power Networks' trials; and
- Data analysis plan: this defines the data volume, fidelity and means of collection for the data generated during trials as well as the type of analysis required to provide an evidence base of the performance of the constellation Methods necessary to support a BaU transition case.

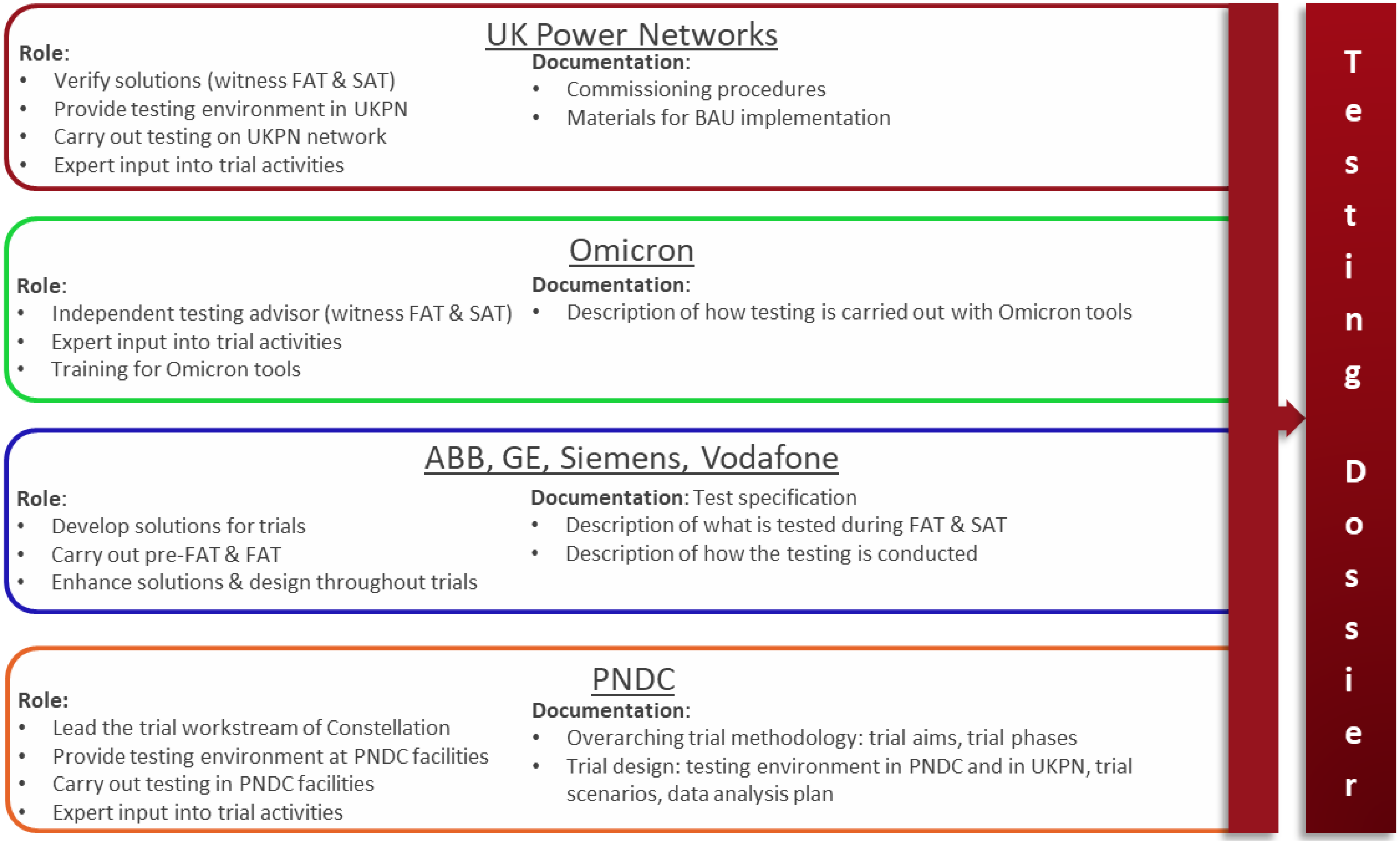


Figure 9: Project partners Roles & Trial Documentation

4.4 Methodology (PNDC & UK Power Networks)

4.4.1 Introduction

The Constellation solution presents a number of challenges unique to its software-oriented architecture. As such, the testing methodology developed to de-risk the solution will need to address these challenges compared to common testing approaches for substation protection, automation and control functions. These challenges include:

- Software version control and trust;
- Proving the scalability of the solution from the point of view connected functions as well as virtualisation platform scalability;
- Multi-vendor and application level interoperability; and
- Engineering process involved in the configuration, operation and maintenance of the solution.

This section focuses on describing the methodology for designing the trials for Constellation.

4.4.2 Trial Design Approach for PNDC and UK Power Networks Testing

Comprehensive test cases have been developed to fully exercise both Methods and demonstrate compliance against UK Power Networks' ETS documents. The intent is to also utilise these test cases, suitably modified to take into account any deficiencies recorded during the PNDC off-site trials and/or any variations required due to application of the test, on the live power network. These test cases can be summarised as follows:

- Test Cases TC01 - to demonstrate compliance against the Local ANM requirements (ETS 05-1603:Constellation Requirements – Method 1: Local ANM/DERMS);
- Test Case TC02.1 - to demonstrate compliance against the Wide Area Protection requirements (ETS 05-1605: Constellation requirements – Method 2: Wide Area Protection and Virtual PAC Functions);
- Test Case TC02.2 – to demonstrate compliance against the Adaptive Protection requirements (ETS 05-1604: Constellation Requirements – Method 2: Adaptive Protection Settings); and
- Test Case TC02.2a – to demonstrate the correct exchange of data from the IEDs on site and the central management system database.

The test cases structure the focal points of investigation for Constellation Methods 1 & 2 i.e. the test categories - integration, function and performance tests for each methodology. Each test case links the methodology with testing principle, measurands and qualifying attributes and provides details addressing the integration, functionality and performance required, along with the test design, test system, test metrics and expected outcome.

An outline of the test description is given in Figure 10.

Appendix A.5 provides an example of one PNDC test case, together with summary descriptions of the remainder.

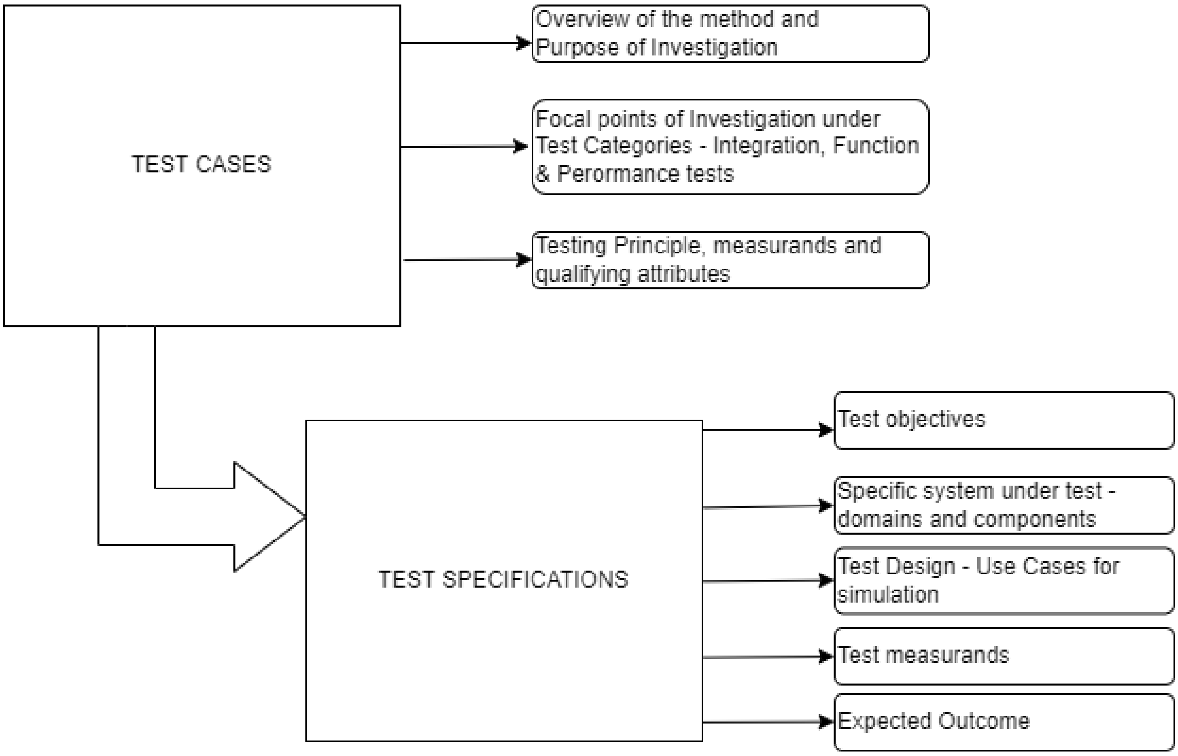


Figure 10 : Outline of the test description

4.4.3 PNDC Trials

The PNDC trials are composed of four main activities as shown in Figure 11, and are described as below.

Figure 11: Focus of PNDC Trials

Functional Verification

The objective of this activity is to verify the protection and control functional requirements of both project Methods as specified in the Constellation requirements documents[13] (ETS 05-1601, ETS 05-1603, ETS 05-1604 and ETS 05-1605).

The functional verification will be achieved by initiating system test scenarios that will stimulate these functions. For instance, loss of mains events and remote faults will be simulated to determine the sensitivity (trip) and stability (blocking) of the wide area LoM protection as part of Method 2.

Performance Verification

The objective of this activity is to verify the performance requirements of both project Methods. Similar to functional verification, system tests are applied to elicit a response from the Methods under test. For example, a wide area disturbance is simulated while the latency of the R-GOOSE blocking signal is recorded to verify the end-to-end latency requirement.

Platform Evaluation

The objective of this activity is to evaluate the virtualisation architecture (hardware and software) used to host both project Methods. The evaluation will focus on:

- Central processing unit (CPU) and memory loading over time with different processing demands;
- Local area network (LAN) performance;
- Separation and compute resource management between different applications;
- Application level redundancy and fault tolerance;
- Device and application level interoperability;
- User access control; and
- Software installation and upgrade process.

Cyber Security Assessment

The objective of this activity is to assess the cyber resilience and identify vulnerabilities of the Constellation solution.

This assessment will focus on:

- Identification of physical and logical perimeter access points;
- Assessment of configurations, policies and procedures impacting security;
- Network, operating system (OS) and application penetration tests; and
- Data integrity assessment.

4.4.4 UK Power Network Trials

The focus of the UK Power Networks trials is shown in Figure 12 and comprise four main activities as described below.

[13] As part of Deliverable 1, UK Power Networks produced a series of Engineering Technical Specifications (ETS) to capture the key requirements for each solution.

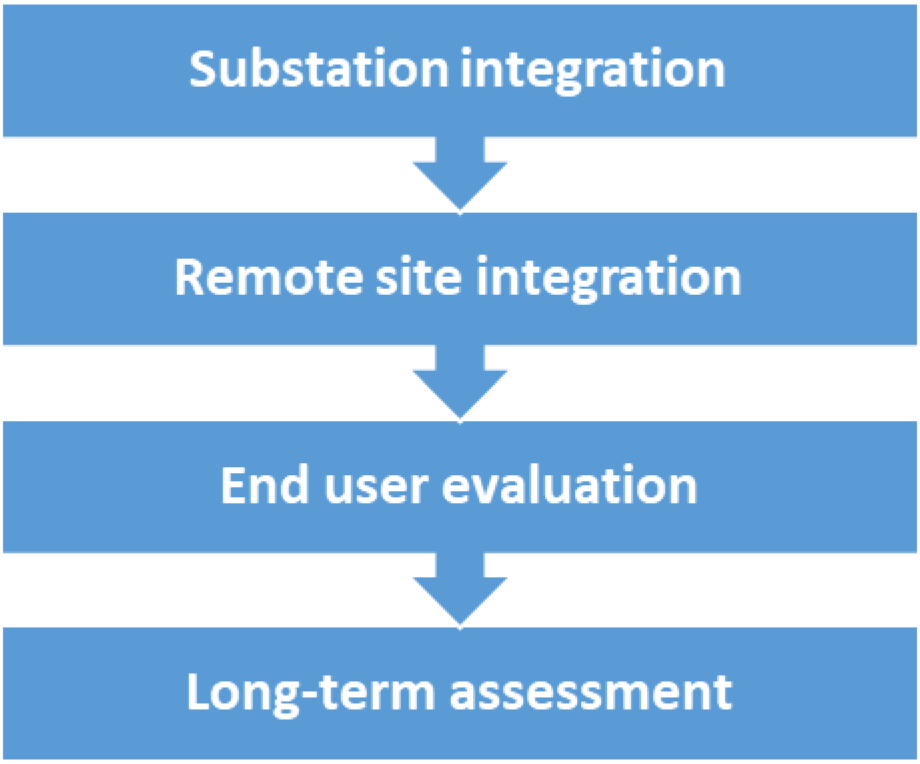


Figure 12: Focus of UK Power Networks Trials

<u>Substation Integration</u>
The objective of this activity is to verify the integration requirements of the Constellation solution within a Grid substation and DER site(s). This involves verifying:

- Integration with own and third party RTUs;
- Interoperability with existing substation equipment (e.g. IED's, LAN equipment, gateways); and
- Methods 1 and 2 integration within substation platform.

<u>Remote Site Integration</u>
The objective of this activity is to verify the integration requirements between different sites hosting the Constellation solution (i.e. Grid and DER sites as well as ADMS and cloud integrations). This involves verifying:

- End to end integration with ADMS, central ANM and cloud hosted Methods (e.g. SIEMENS CMS);
- Integration with existing WAN;
- Integration with new 5G infrastructure; and
- End to end security.

<u>End User Evaluation</u>
The objective of this activity is to validate the overarching project use cases and benefits. This involves the evaluation of the following in a real substation environment:

- Functional and non-functional aspects of Methods 1 and 2;

- Functionality and performance of OIC Methods;
- User experience of operation and maintenance personnel; and
- Interactions with the partners during SATs and operation of the solution (including addressing technical issues and integration with third party cloud services).

In order to verify some of the functionality in the live network it may be necessary to reconfigure the network to elicit changes in protection settings or elicit Local ANM actions.

Long-Term Assessment
The objective of this activity is to assess the longevity of the solution over a long trial period (the trial period outcomes will be included in future Deliverables) in a live network and following the analysis of the long-term data collected during this period. Assessment of longevity considers:

- Future proofing versus obsolescence of the Constellation solution over its lifecycle in meeting specified requirements. This includes specification of the Substation Server hardware and software to accommodate future functions; and
- Maturity of the engineering process for configuration, testing and operation of the Constellation solution (including software upgrades for implementing new functionality and security fixes).

4.5 Trial Outputs

The trials will provide the learning and confidence necessary to accelerate the development of the Constellation platform and Methods and increase the success of adoption into BaU.

There are four main outputs of the trials:

- Documentation and dissemination of learning and data associated with the Constellation platform to ensure scalability across networks in GB and potentially globally;
- Development of a collaborative environment that focuses end users and multiple suppliers' efforts on producing a 'working' demonstration of Constellation;
- Kick-starting an eco-system for suppliers to innovate in the substation environment by reducing barriers to entry through opening up substation computation platforms; and
- Learnings from the trials will identify the requirements for compliance and certification to ensure an equivalent level of traceability to that of existing protection and control systems.

D2 Section 4 : Lessons Learnt	
1	The trial phase in Constellation consists of three distinct phases: • Demonstration of individual solutions in partner facilities; • Demonstration of all solutions operating in parallel in a safe environment (PNDC facilities); and • Demonstration of all solutions operating in parallel on the distribution network. While it is high in management effort, the three phases of the trials enable a robust testing process for the duration of the project. This approach allows the Constellation team to carry learnings from each phase of the trial through to the next. In doing so, the project will collect a high volume of trial results which are complementary and enable the full evaluation of the solutions. We recommend other innovation projects to take a similar approach and progress TRL in several different stages.
2	As part of preparing for the Constellation trials, the partners prioritised clarifying the role of each organisation during the trial period. This exercise is essential in ensuring readiness for the trial commencement.
3	Due to the novelty of 5G technology, preliminary testing will be carried out in Vodafone`s research laboratory to ensure their design is suitable for the Constellation trials later in the project. Similarly, preliminary testing of the software virtualisation environment has been completed successfully. It should be noted that this early testing will not replace any of the PNDC or UK Power Network trials.
4	Due to the large number of internal and external stakeholders involved in the project it was apparent that it is necessary to communicate the Constellation trials objectives and phasing clearly with different sets of stakeholders. It was decided that dedicated material will be developed to achieve this. It may be necessary to tailor this material to different audiences such as network operators and solution suppliers
5	In order to better capture and understand the response of the real power system, in a reasonable manner, in a laboratory environment it is essential to understand and use the right system data and system boundaries for modelling the components involved. The complex models available in simulation software may not necessarily give the required practical response unless the right input data is provided when no specific plant information is available. Also, the accuracy of the model being used can be proportional to its importance in the use case being simulated or the power system study that is being done.

5 Trial Design (Overarching Requirements)

5.1 Introduction

The testing phase of Constellation begins with each solution`s FAT in order to verify that they fulfil the functional requirements. After the FATs are completed, the respective systems will be brought together at the PNDC test facility and later at the UK Power Networks trial sites. As part of the installation and commissioning of the Methods in PNDC and UK Power Networks trial sites, we will carry out testing similar to the FAT. This will form the site acceptance testing (SAT). After the SATs are completed, we will commence the specific testing scenarios for the respective PNDC and UK Power Networks trial phases.

While the FATs are the first phase of testing, the bulk of the Constellation trials will be split between PNDC and UK Power Networks (refer to Section 4). All the testing will be carried out as per the trial specifications and designs described in Section 4. The methodology for designing the trial specifications for the PNDC and UK Power Networks trial phases is described in Section 4.4. The purpose of this section is to summarise the specific trial requirements and design for each phase of the Constellation trials, in order to successfully demonstrate that the solutions are suitable for BaU roll out.

5.2 Factory Acceptance Testing

5.2.1 Method 1 (Local ANM, GE)

Overview and requirements

The objective of this FAT is to demonstrate the correct behaviour of Method 1 when it is deployed as a virtualised application on the Substation Server.

The FAT for Local ANM includes demonstration of three Local ANM modes, and power system event detection (the summary details of the design of Local ANM are available in Deliverable 1).

For the purposes of the FAT open loop testing will be applied to the DER site and Grid sites in isolation. The steps required to carry out the FAT testing are:

- Identify subset of requirements under test;
- Prepare a suitable scenario and state change to isolate the target behaviour;
- Define the configuration of the Local ANM for this test;
- Write a description of the expected output of each component under test;
- Prepare input data:
  - If necessary, simulate power system model to create basis for PMU data;
  - Create PMU data streams; and
  - Create non phasor data inputs (e.g. IEC 61850 MMS or DNP 3.0).
- Document and store the configuration, inputs and outputs according to template.

Note, certain tests will not be achieved via changes in the input signals but rather through changes to the configuration or test setup. In such a test the inputs will be non-varying signals and the output signals will be compared to the expected output as in other tests.

In order to generate the necessary C37.118 phasor data, simulated networks will be developed for the FAT as summarised below:

1) Thanet ANM boundary;
2) Maidstone ANM boundary;
3) Simple one constraint system; and
4) Simple two constraint system.

Each simulated network will be developed in DigSILENT Powerfactory and the modelling practices applied will be aligned, where possible, with the PNDC to ensure that similar practices are applied in both sets of testing.

Appendix A.4 provides examples of the tests that will be performed, where these examples focus upon the mode changes of the Local ANM (e.g. operator instructed transition into direct distributed.

FAT Setup and Testing Boundary

In order to make best use of the available Substation Server hardware and allow the efficient execution of the FAT, the Grid site Substation Server functionality and the DER site substations server functionality will be tested in isolation, allowing a convenient isolation of the Local ANM functionality under a broader range of conditions. To enable this, two virtual machines will be created on the Substation Server (one for the Grid site and another for the DER site) and only activate the one under test.

The test setups will therefore comprise the following equipment:

1) Grid site Substation Server instance or DER Substation Server instance depending on the functionality under test;
2) Communication protocol simulators to enable playback and capture of signals (e.g. C37.118, IEC 104 and IEC 61850 MMS);
3) Equipment for the visualization and archiving of test outputs; and
4) WAMS DE2.0 Server.

An example of the Method 1 FAT configuration is as detailed in Figure 13 below and Appendix A.4 provides further details on selected test configuration set-ups and the data exchange requirements.

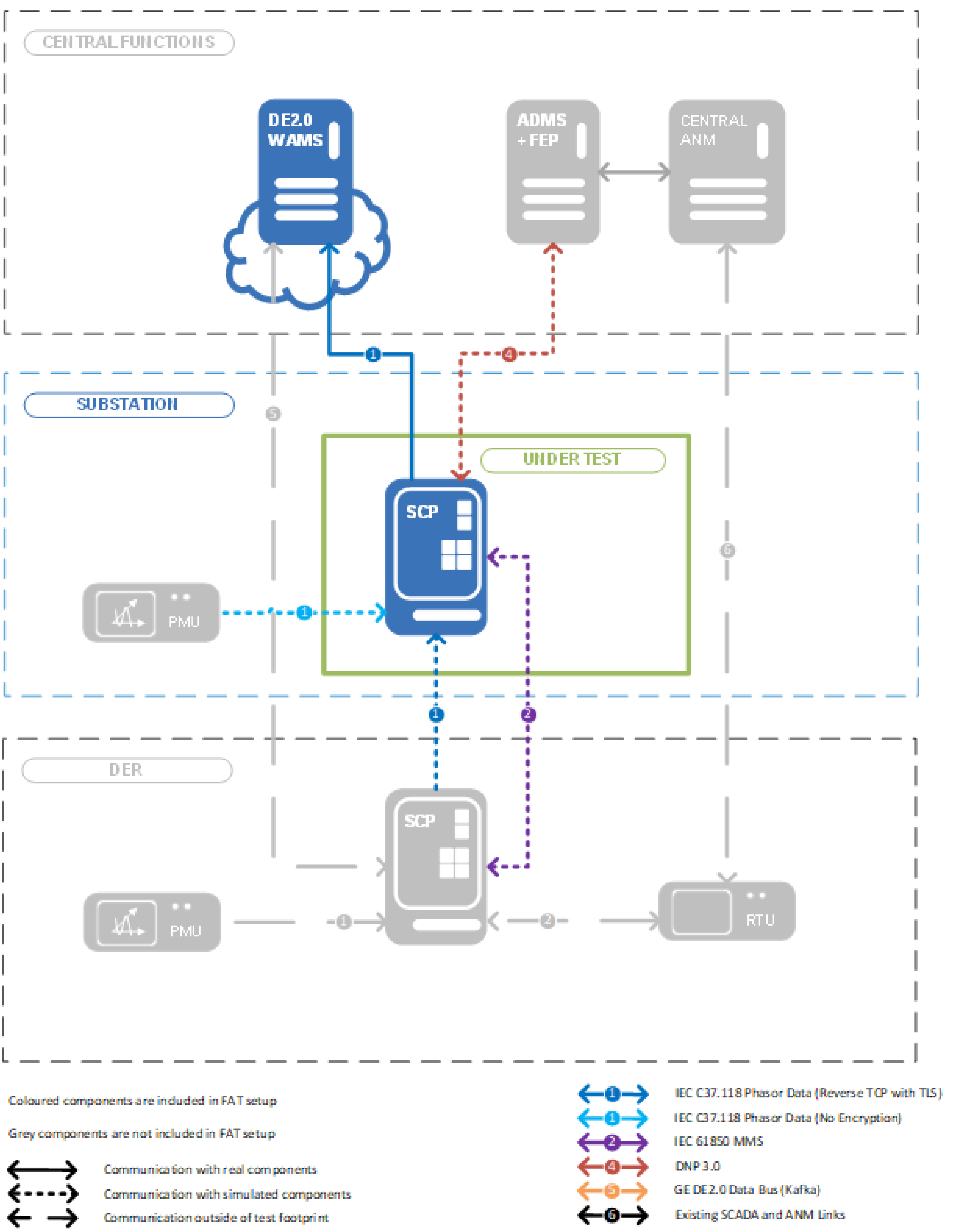


Figure 13: Overview of Local ANM Equipment that will be Included in the Grid site Functionality FAT and the Actual/Simulated Data Connections

5.2.2 Method 2 (Adaptive Protection, Siemens)

Overview and requirements

The objective of this FAT is to demonstrate the correct behaviour of the adaptive (load blinding) functionality by executing a series of approved tests on the FAT test platform. The proposed suite of factory testing that will be undertaken is as detailed within Figure 14.

The testing of the Siemens solution requires:

- Allowing a central management system to act as the hub between data capture from across the distribution network; and
- Allocating the data to software models that read and assess network parameters and protection settings before modification. Then relaying that information via central management to a management software package that securely issues commands and settings to substation protection devices.

FAT Environment

A cloud based configured test environment will be utilised to demonstrate the solution design, test its functional operation, prove communication interfaces and facilitate assessment fallback scenarios to be demonstrated throughout the FAT. Network events, data simulation and switch status modification will be recreated to simulate load and generation changes, along with network connectivity changes.

Figure 14 below details the test environment configuration and Appendix A.4 provides some additional information on the proposed factory test configuration.

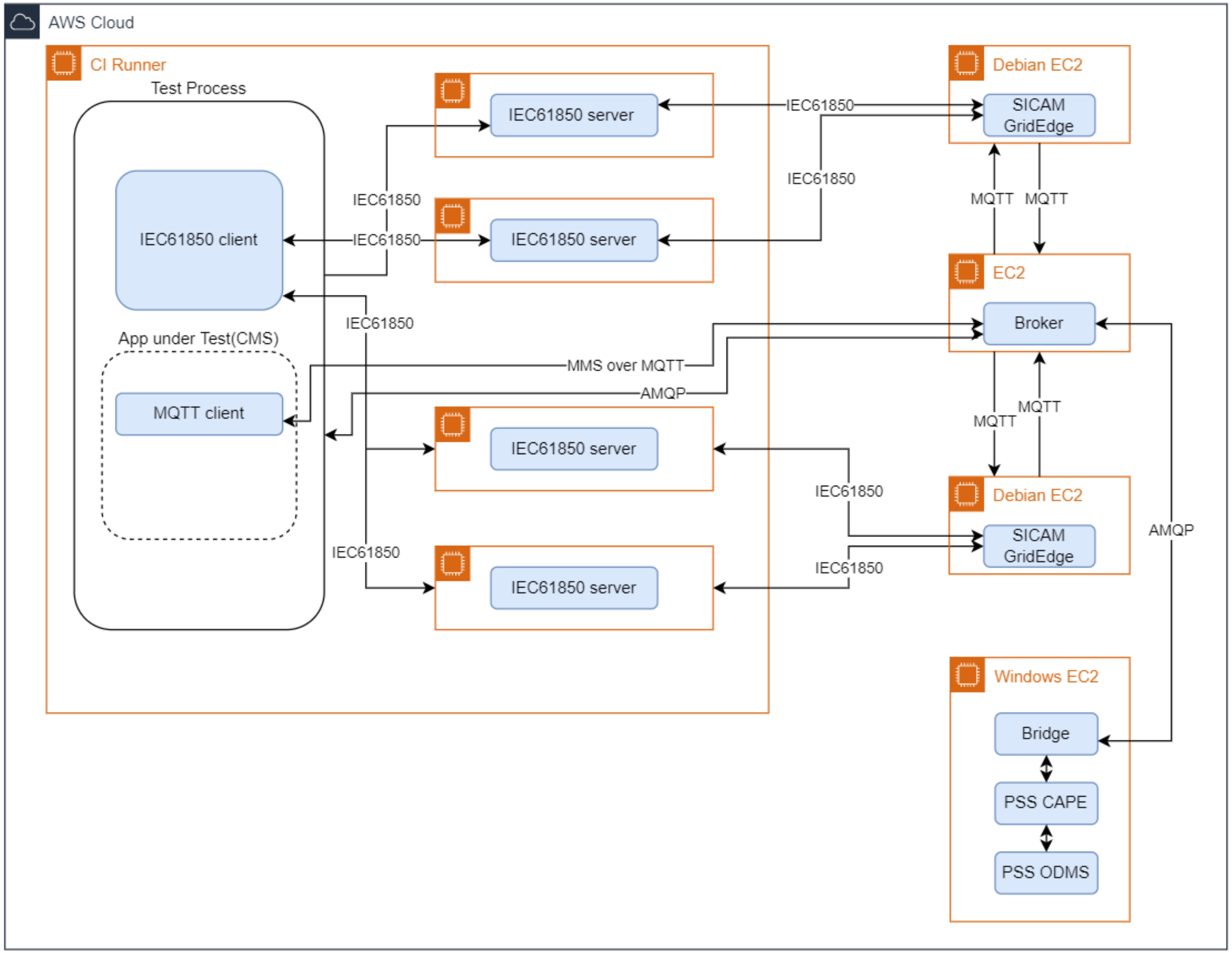


Figure 14: Test Environment Configuration

Scope of Specific Tests

The following provides summary details of the specific tests that will be undertaken within the factory to simulate, monitor and check the quality of operation, identify and report errors, and allow the user to interact via the user interface.

1) ODMS Network Model Analysis. This will consume network model data updates from Power Factory in CIM16 XML format, run State Estimator/Power Flow analysis in PSS®ODMS and Short Circuit analysis in PSS®CAPE.
2) Central Management System. Testing will be undertaken to verify correct operation for the following:
    - Manage asset information in two Grid substations by linking IDs of the connected assets in CMS with UK Power Networks' Enterprise Asset Management (EAM);
    - Manage protection settings adaptively based on network model with up-to-date operation status and PSS®CAPE simulation regarding protection settings in the relays; and
    - Enable user to upload, display and synchronize files between Substation Server and the Central Server on which Central Management System runs.
3) ODMS and CAPE Management Systems. The protection engineering and simulation system (PESS) will perform the following specific tasks, all of which will be tested:
    - Receive an up-to-date primary network model from PSS®ODMS inclusive of the operational data (circuit breaker and switch status, load and generation status);
    - Retrieve the latest protective relay settings from the relay asset database into the PSS®CAPE database;
    - Perform the Adaptive Protection settings calculations for load blinding protection based on this network model and protection settings; and
    - Save the adapted settings back to the PSS®CAPE database for subsequent communication to the Central Management System.

As part of the above tests, the following features will be tested for correct operation:

- A Siemens SIPROTEC five device 7SA86 will be modelled with load blinder characteristic and functionality and 132 kV relays are to be modelled as generic with real settings;
- A macro shall be created in PSS®CAPE to calculate Adaptive Protection settings for the load blinding protection based on the network model including the operational data; and
- The PSS®CAPE Simulation Engine will offer a procedure to automatically validate the previously calculated protection settings, e.g. by means of the PSA matrix. The user shall be able to conveniently adapt the validation procedure by changing and saving of validation options as a file in the PSS®CAPE program. Where the validation is not successful, a recalculation of the respective settings shall be automatically triggered, followed by a new validation. This process shall be repeated until a successful validation. Once validated, these settings shall be provided as the new recommended settings to the relay asset database through the API.

4) SICAM GridEDGE Substation Gateway. Tests will be undertaken to verify the correct operation of the following functions:

- Substation secondary device hardware version, device firmware version, and software versions of substation automation products and of Windows-based PCs will be read through the protocols SNMP, IEC 61850 and WMI;
- Substation IED Protection settings will be read through the protocol IEC 61850;
- The SICAM GridEdge software change/adapt individual reference protection settings received from the CMS over substation LAN through IEC 61850 to the protection relays in the substation;
- During fallback condition in presence of substation bus communication, SICAM GridEdge activates the setting fallback group in IED. SICAM GridEdge software will use the IEC61850-7-2 Setting Group Control Block function to change the protection setting; and
- One SICAM GridEdge software handles one trial Grid substation. There are two trial Grid substations at Maidstone and Thanet.

5.2.3 Method 2 (Wide Area Protection, ABB)

<u>Overview and requirements</u>

The purpose of the Wide Area Protection (and virtual protection) FAT is to demonstrate that the protection and control functionality provided by the virtual protection relay and associated functions are in line with the Constellation requirements.

The protection and control functionality testing will be divided into two different types of testing which corresponds to virtualised protection testing and Wide Area Protection testing. The full scope of the FAT covers the protection of the substation bays in the two trial sites, Maidstone Grid and Thanet Grid, and the respective DG units at the DER sites which are connected to these substations.

Each substation bay in the Grid sites has two protection IEDs (Main & Backup) and two Substation Servers, each running a virtualised SSC600. Similarly, at the DER site there is a single Substation Server running the virtualised SSC600.

To test and validate the functionality of the configuration implemented in the virtualised SSC600 a simplified system with a reduced number of IEDs will be used, which will be sufficient to test the main protection and control functions found in the IEDs according to the type of bays found in the trial areas.

The main components of the test system (Main-Tie-Main) are therefore described in Table 7.

Table 7: Main-Tie-Main Test System

Location	Bay Type	Busbar
Grid substation	Incomer	1
	Outgoing feeder	1
	Bus tie	1
	Incomer	2
DER substation	DG unit	1

Scope of testing of the virtualised protection
This testing includes the following:

- Validation of precision time protocol (PTP) time-synchronization in Device Under Test (DUT);
- Validation of GOOSE signals exchange between the protection IED and the Virtualised SSC600;
- Validation of the measurements sent as SMV streams from the protection IED towards Virtualised SSC600 when injecting secondary measurements in the protection IED;
- Validation of the correct measurements displayed in DUT and SCADA system;
- Validation of local/remote interlocks in DUT and SCADA system;
- Validation of protection functions and schemes performance in DUT; and
- Validation of protection functions and schemes pickup and tripping signals being reported over MMS to the SCADA system from the DUT.

FAT environment for the virtualised protection testing
This testing will be carried out in the Digital Systems Laboratory of ABB Finland, located in Vaasa. The general test setup diagram as well as the rack designated to perform the protection testing functionality for the typical bay testing is shown in Figure 15.

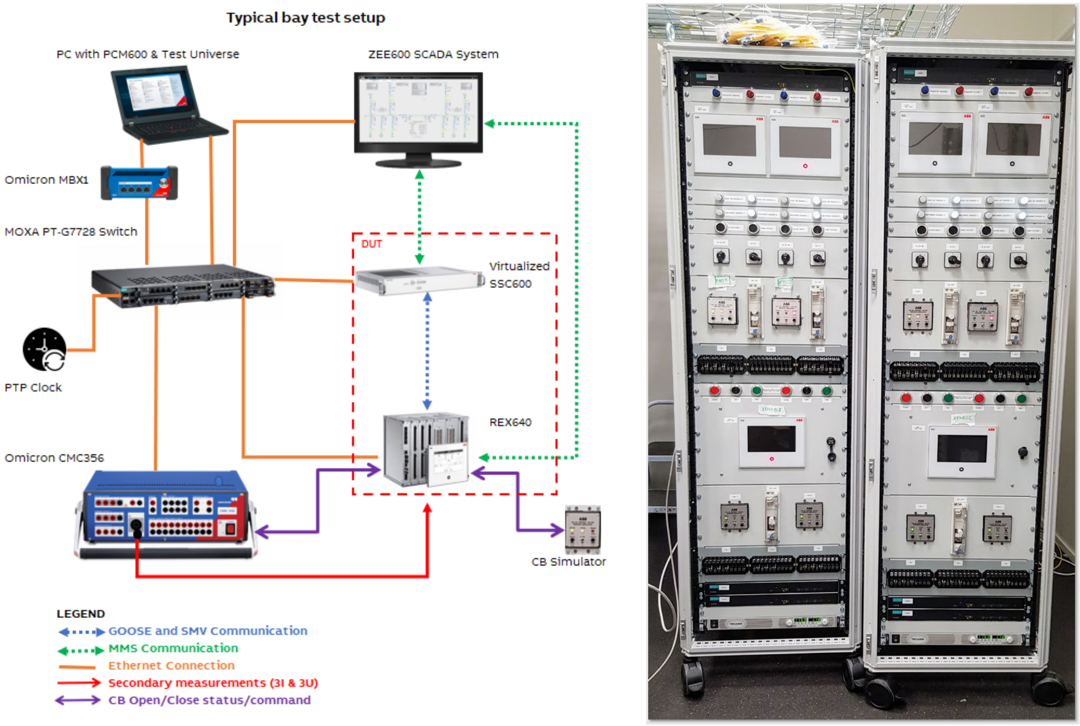


Figure 15: Typical Bay Test Setup

<u>Scope of testing for the Wide Area Protection</u>:
The second type of testing corresponds to the Wide Area Protection scheme which will be carried out using a real time (RT) simulation using a RTDS system to simulate voltage and frequency disturbances in the power system in a controlled manner. This will validate the correct operation of the Wide Area Protection functionality developed and implemented in the virtualised SSC600s at the Grid substations and at the DER sites. This testing includes the following:

- Validation of R-GOOSE signals exchange and supervision logic between Virtualised SSC600s located in the Grid substation and at the DER site;
- Validation of the Enable/Disable functionality of the Wide Area Protection scheme;
- Validation of the transfer trip scheme over WAN;
- Validation of the RoCoF blocking scheme over WAN; and
- Validation of DER CB status exchange towards PCC.

<u>FAT environment for the Wide Area Protection testing</u>
This testing will be carried out in the RTDS Laboratory of ABB Finland, located in Tampere. The general setup for the wide-area protection scheme is shown in Figure 16.

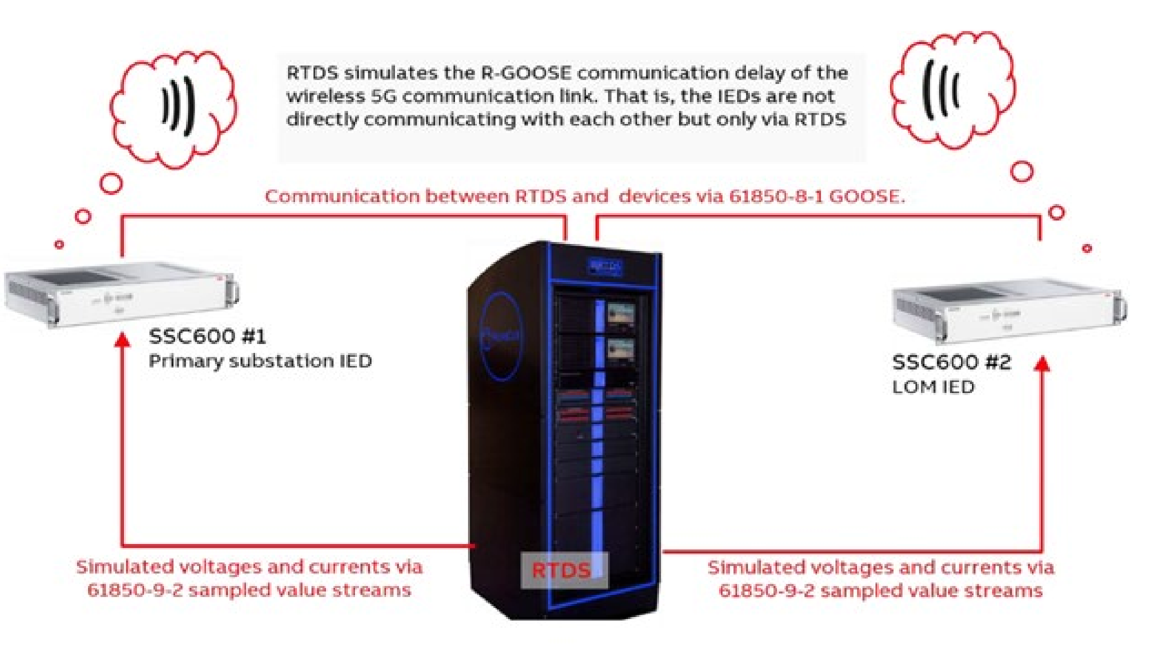


Figure 16: Wide-Area Protection Test Setup

To complement the above, various test procedures have been developed to vigorously test the functions as summarised below. Appendix A.4 provides examples of a selection of these test procedures:

- Power cycle validation;
- Communications validation;
- Measurements validation;
- Interlocks validation;
- Protection functions validation; and
- LoM protection validation.

5.2.4 5G Site-to-Site Communications (Vodafone)

Overview and requirements

The purpose of the 5G FAT is to demonstrate how the Constellation 5G Slice will function in its final operating environment.

Vodafone will be deploying a 5G Network slice to enable secure substation-to-substation communications between Grid and DER sites. A 5G network slice is built around 5G Radio Access Network (RAN) and 5G Core. The 5G network slice to be used for the FAT is built to accommodate continuous, fast data traffic over low latency (10ms), high reliability, self-healing, secure communication between sites.

To carry out the testing, a dedicated environment with specific hardware is required. The hardware and software required for this testing is defined in Table 8 below and is visualised in Figure 17.

Table 8: Environment for 5G FAT

Name	Count
Physical Hardware Servers: • HPE DL360 Standard CLX DC • HPE DL380 Perf Bandwidth CLX-R DC	 2 1
Physical Cabling	As required
(Ericsson) Cloud Execution Environment (CEE)	6
Software Defined Networking (SDN)	6
Software Defined Infrastructure (SDI)	3
(Ericsson) Cloud Container Distribution	264

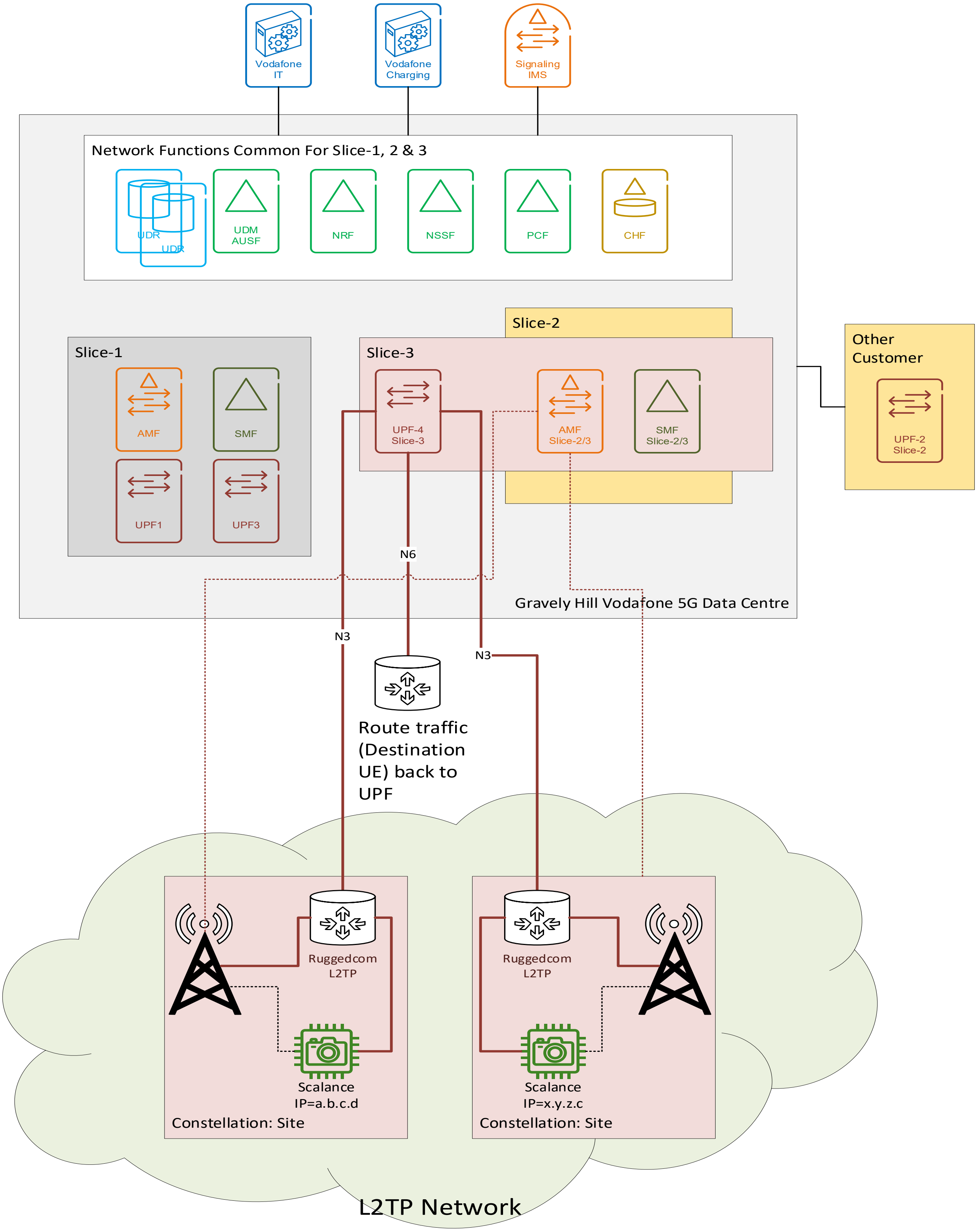


Figure 17*: Visualisation of FAT Set-Up*

<u>Scope of testing</u>
The objective of the FAT is to carry out verification of the deployed solution prior to deployment to the PNDC and UK Power Networks trial locations. The system will be declared Ready For Acceptance (RFA) at the end of this stage. Functions to be tested are listed below:

- Node testing of new Packet Core Gateway (Health of PCG);
- Registration of 5G stand alone (SA) Device in new slice using SUCI SIM cards;
- Protocol Data Unit (PDU) Session Establishment of 5G SA device over new slice and selection of new User Plane Function (UPF); and
- Communication of simulated traffic between the 5G devices.

The Constellation Setup is designed to be provided with a dedicated network slice in the Gravelly Hill Vodafone site within the 5GC workloads.

The existing 5G Core in Vodafone UK datacenter has 2 slices (Slice 1 and Slice 2):

- Slice-1: This is the 5G SA core slice for enhanced Mobile Broadband (eMBB). This is to be used for all 5G eMBB use cases like data, mobility (5G/4G, WiFi etc.), charging, Voice and SMS. However, eMBB is out of scope for Constellation, hence this slice is not directly in use for the setup; and
- Slice-2: This slice is the Low Latency slice. This slice will be used as the Control Plane (Signalling) – For low latency will provide low latency data path between Device <> RAN <> 5G Core.

A dedicated network slice (Slice-3) involving both RAN and 5G Core workload is to be deployed for the proposed Constellation workload:

- Slice-3: This is the User Plane slice for Constellation and will transport data between substation-to-substation. It should be noted that while the 5G network does not identify the different data categories, the 5G slice is designed and configured to accommodate the data requirements for Constellation.

The specific test objectives for this stage of 5G testing are summarised in Appendix A.4.

5.3 PNDC Trials

5.3.1 Introduction

PNDC will develop the test environment for the Constellation solutions (an overview of which is provided in Section 1.3). The environment will be used to advance the Methods overall TRL from 4/5. Figure 20 depicts the high-level PNDC test setup incorporating the different solutions from the project partners.

5.3.2 Configuration of the PNDC trial environment

The key element of the test bed at PNDC is the Real-Time Digital Simulator (RTDS) and it comprises of a combination of custom hardware and simulation software. The hardware and software are together utilised to achieve real-time simulation of the power system for the selected trial sites. This will enable the hardware-in-the-loop testing of the novel protection and control applications within Constellation. The multiprotocol communication interface capabilities of the RTDS are used to integrate the modelled UK Power Networks trial sites with the constituents of the Constellation solutions, using analogue and digital I/O mapping.

One Grid site and two DER sites will be also implemented in the test environment in addition to the RTDS modelled trial sites. The volumes of the physical installations may change subject to the quantity of available hardware (e.g. Substation Servers), which is being determined as part of the PNDC trial preparation[14]. It is intended to integrate one of the physical DER sites to part of the PNDC 11 kV live test network, to demonstrate the integration of the Constellation solutions with physical switchgear as well as the functionality of 5G between two physically remote locations. Secure remote access to some elements of the test environment (e.g. GE WAMS, ADMS) will also be provided to enable remote support and software/configuration updates.

The RTDS facilitates the realisation of relevant system conditions, for instance thermal/reverse power flow constraints, and will also allow testing to demonstrate the level of compliance of the Constellation solution against approved design and functional requirements.

Further, the UK Power Networks' ADMS capabilities as relevant to the test set up of the Constellation project, are duplicated at PNDC, utilising the GE PowerOn solution installed in the PNDC ADMS sever. The UK Power Network trial sites modelled in RTDS exchange analogue and digital I/O signals with the ADMS using DNP3 communication protocol via the RTDS interfacing capabilities.

The key test elements which form part of the PNDC testbed along with the proposed principle of use are summarised below in Table 9.

An example of a test case which shall be developed and simulated within the RTDS is summarised in Appendix A.5, along with a summary of objectives for remaining test cases.

Table 9: Key Elements of the PNDC Test Environment

No.	Item description	Solution	Purpose
1	Real-time digital simulator	RTDS Technologies real-time simulator with RSCAD® simulation software	RSCAD is used to model the trial sites and to configure simulation use cases, which are then run on the RTDS. This facilitates testing multiple test elements in a closed loop along with the simulated network during varying contingency scenarios/network parameters/settings.
2	Cybersecurity platform	Omicron RBX1 (StationGuard)	Serve as the security monitoring system, detect cybersecurity threats like malformed packets/disallowed control communication failures, time synchronization problems
3	Mobile substation test platform	Omicron MBX1 (StationScout)	Test interlock logics, trace digitised data flow, simulation features
4	Protection test set	Omicron CMC 356	Universal relay testing tool

[14] It should be noted that PNDC trial preparation is part of Deliverable 3.

5	Integrated GPS antenna and PTP grandmaster	Omicron OTMC-100p	Time Synchronisation Solution
	PTP grandmaster clock	Meinberg M1000	
6	IEC 61850 network analyser	Omicron DANEO 400	Digital signal recorder and analyser (IEC 61850, IEEE 1588). SCL based communication verification/supervision.
7	IEC 61850 and SCADA simulation and test suite	To be confirmed	Substation Configuration Language (SCL) based automated testing of RTUs/ IEDs, Network load testing, Substation communication and cybersecurity testing
8	LAN traffic generator	To be confirmed	Performance evaluation of communication networks and devices with standard performance measurements, Capture/ reproduce/amplify network traffic in a controlled lab environment, validate firewall performance and resiliency
9	Grid site server	Dell PowerEdge XR12	Hardware for virtualisation of Grid substation applications
10	DER site server	Dell PowerEdge XR12	Hardware for virtualisation of DER substation applications
11	ADMS server	HPE DL360 Gen 10	Server hosting GE PoA ADMS solution
12	Layer 2 switch	Ruggedcom RST2228P	Communication network switches/routers for high port density applications with support for IEEE 1588
13	Layer 3 router	Ruggedcom RX1536	
14	Edge router	Ruggedcom RX1400	
15	5G router	Ruggedcom Scalance MUM including outdoor antennas	SCALANCE M 5G routers for wireless secure access over industrial 5G networks

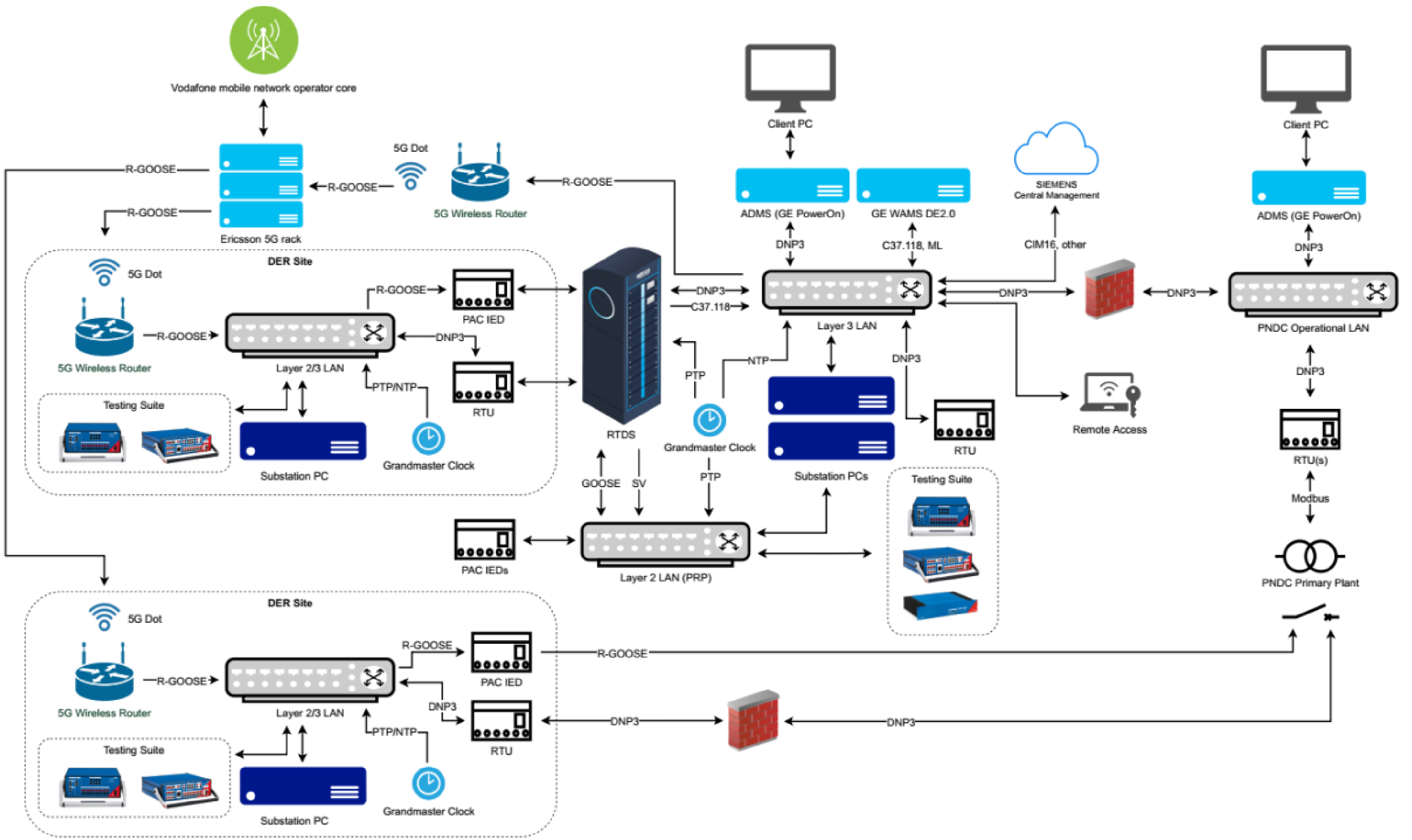


Figure 18: PNDC Trial Environment

Once all individual FAT's are successfully completed by the respective project partners, the integrated off-site testing can commence at the PNDC test facility. The precursor to the PNDC trials will be the SATs, which will confirm that each solution is deployed successfully and is ready for the PNDC trials.

5.3.3 PNDC trial details

The use cases developed for the PNDC trials are simulated in RTDS (section 5.3.2), which facilitates the realisation of relevant system conditions, for instance voltage/thermal/reverse power flow constraints or grid frequency events and to demonstrate the capabilities of the Constellation solution, against approved design and functional requirements.

The test cases in the PNDC trials developed focal points of investigation for the Constellation Methods 1 & 2. These form the test categories, which are integration, function and performance tests:

- The integration tests will establish and test the interfacing, integration and communication of different parts of each Method as per approved design, including the operational settings, parameters, access credentials, relevant networking and security elements, as a whole system;
- The functional tests will verify the protection and control operation associated with each Method, which will be achieved by initiating system test scenarios that will stimulate the relevant functions in RTDS; and
- The performance verification includes system tests that are applied to elicit a response from the Methods and asses its responsiveness, stability and speed when examined under varying workload conditions, e.g. end to end latency requirement.

The key functional and non-functional tests covered for each Method during the PNDC trials are summarised below.

5.3.3.1 Method 1: Local ANM

The main objective is to test the decentralised, virtualised Local Active Network Management (LANM) application based on machine learning, which has visibility over network constraints and the state of the network, using local, time synchronised measurements, in the event of communication loss between Central ANM and Grid and/or DER sites. The functional and non-functional tests in PNDC trials will focus on testing:

- Measurement, aggregation and visualisation of C37.118 WAMS data at the virtualised applications in the Grid Substation Server (including via 5G), at the local WAMS DE in DER Substation Server and central WAMS DE2.0 server;
- Seamless switch over between three Local ANM modes during communication failure of Central ANM or manual enable/disable from ADMS;
- Ability of the Local ANM application to measure network constraints, estimate available headroom to maintain the optimal DER asset operation and maximise the DER output, in the event of communication loss to Central ANM;
- Fail safe response on unwarranted response to a regulation action aggravated by ANM;
- Multiple DER sites to be associated with multiple power network constraints, arbitrations to avoid conflicts among instructions;

- Establish the limits of the machine learning model during events of loss of communications to the managed DER units;
- Audit Trail/event log at the Substation Server; and
- Network parameters such as throughput, latency, effect of loss of time synchronisation on reliability of the Local ANM function, effect of quality of measurement, fail safe response on failure of network nodes.

5.3.3.2 Method 2a: Wide Area Protection

The main objective is to test and validate the wide area enhanced loss of mains protection based on R-GOOSE through 5G communication and anomaly detection function running on the virtualised environment. The functional and non-functional tests in PNDC trials will focus on testing:

- Measurement and aggregation of sampled values for the virtualised protection functions;
- Enabling/disabling the Wide Area Protection function;
- Identification of island formation and provide enhanced loss of mains protection, receiving the status of chosen CBs and sending R-GOOSE transfer trip signals via 5G communication network to DER CB;
- Differentiating the oscillations in ROCOF due to upstream wide area disturbances and enhance the reliability of ROCOF by providing a blocking signal to DER ROCOF protection and preventing unintended operation, if the main area substation measurements indicate an external disturbance;
- Mitigating the rare event of external ROCOF oscillation occurring simultaneously with a real LoM event;
- Identify atypical events which could potentially be indicative of future performance degradation or fault occurrence; and
- Effect of: communication switching events (e.g. switching from main to a redundant path) on the reliability of R-GOOSE transmission and Wide Area Protection scheme reliability, effect of loss of synchronism on reliability of the Wide Area Protection function, effect of network traffic on the reliability of data transmission, fail safe response on failure of network nodes.

5.3.3.3 Method 2b: Adaptive Protection System (and Central Management System)

The main objective is to test and validate the capability of Adaptive Protection System (APS) application to adapt, dynamically validate and set the virtual load blinding function, installed in the Substation Server (by ABB), according to the network state. The test objective also covers testing and validation of Central Management System (CMS) application to enable data exchange from the IEDs on site and the central management system database. The functional and non-functional tests in PNDC trials will focus on testing:

- Enabling/disabling of the Adaptive Protection functionality by an authorised user;
- Automatic triggering of Adaptive Protection setting calculation based on pre-defined conditions or time-based interval (e.g., 30 min) trigger or manual operator-based trigger (button on ADMS/PowerOn);

- The capability of the adaptive setting calculation algorithm to derive the precise settings dynamically, according to the present state of the power system network;
- Validation of the new protection settings changes;
- The ability of the application to adapt the calculated load blinder setting in the virtualised relay at the Grid Substation Server by a different OEM;
- Functionality of: CMS to send/receive/store protection settings with time stamp, storage/management/visualisation of firmware versions, serial numbers, installed protocols, installed modules, and protection settings of secondary devices, bidirectional synchronisation with via SFTP link; and
- Effect of loss of time synchronisation on reliability of the Adaptive Protection function.

5.3.3.4 5G Communication

The 5G connectivity will be used to provide a communication link for R-GOOSE signals as part of the Wide Area Protection functionality as well as for the synchrophasor data transmission (in accordance with IEEE C37.118) between DER and Grid sites for the Local ANM functionality. Testing of the 5G communication is essential to verify its ability to reliably transmit R-GOOSE messages within acceptable latency limits and having sufficient bandwidth to carry the continuous synchrophasor data streams. In order to verify the 5G functionality and performance, the trials will focus on the following:

- Measuring the latency of R-GOOSE over 5G transmission between end points whilst ensuring Wide Area Protection stability is not affected by transmission latency. The same will be repeated to assess the impact of latency on Local ANM functionality including the confidence of synchrophasor data quality being received;
- Evaluating the consistency of the 5G transmission latency over a prolonged testing period; and
- Measuring the bandwidth utilisation of the 5G slices carrying the R-GOOSE and synchrophasor traffic.

5.3.4 Cyber Security Testing

A core part of the PNDC trials is to carry out dedicated penetration testing in order to confirm the overall integrity of the Constellation solutions. There are different paths in a digital substation which, if not correctly mitigated or managed, may facilitate cyber attacks from external users, as detailed below:

- Path 1: [redacted];
- Path 2: [redacted];
- Path 3: [redacted];
- Path 4: [redacted]; and
- Path 5: [redacted].

In the off-site PNDC test configuration, described in Figure 11, it can be seen that there are several wired and wireless connections to switches, routers, client PCs, cloud, remote connectivity, Substation Server, IEDs and testing suites etc, any of which could present a possible avenue for cyber attack. In addition, the use of a 5G network may present unique cyber-security challenges which will also be addressed during these tests.

To counter these threats, the following phases of penetration testing will be undertaken as shown in Figure 19, using the following methods:

- Internal testing – tested from behind the firewall;
- External testing – targeting resources visible via the internet;
- Blind testing – testing by only knowing the name of the enterprise being targeted; and
- Double-blind testing – testing without any form of advance notification or detection.

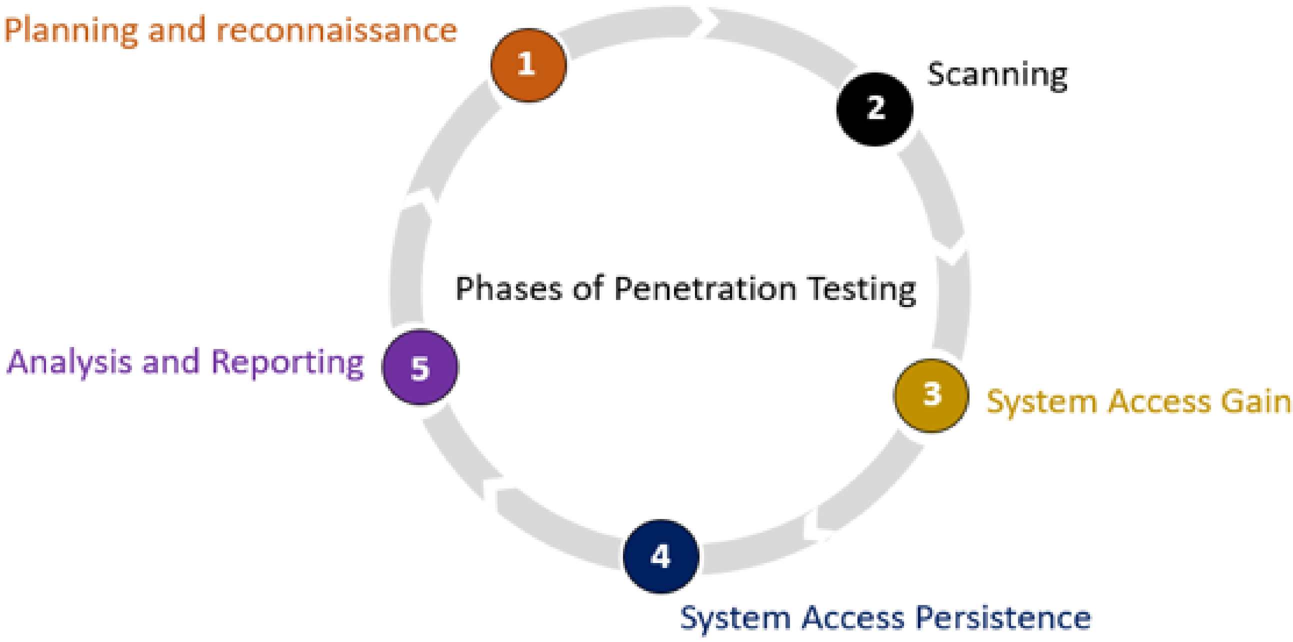


Figure 19: Phases Involved in Penetration Testing

<u>Phase 1: Planning and Reconnaissance</u>
This step requires planning to simulate a malicious attack – the attack is devised in a way that facilitates gathering as much information on the system as possible. This is one of the most time-consuming stages as it requires a thorough diagnosis of the system, taking note of the vulnerabilities, and how the organization's tech stack responds to system breaches. The information investigated ranges from names and email addresses of the company's employees to network topology, IP addresses, domain names, mail server, among others.

<u>Phase 2: Scanning</u>
Depending on the result of the planning phase, PNDC will use scanning tools (Kali Linux/Wireshark and Metasploit) to investigate the system and network weaknesses. This phase identifies system's weaknesses that are potentially used for targeted attacks. It is vital to obtain all this information accurately, as it will specify the success of the following phases.

<u>Phase 3: System Access Gain</u>
After understanding the system's vulnerabilities, PNDC will infiltrate the infrastructure by exploiting security weaknesses (such as cross-site scripting, structured query language (SQL) injection and backdoors). The system will further be exploited by escalating privileges to understand the threat penetration depth of the target environments.

Phase 4: System Access Persistence

This step identifies the potential effect of a vulnerability developed by leveraging access privileges. After having a foothold in the system, the tester will access and hold the simulated attack long enough to achieve and imitate malicious hackers' goals. The tester will try to obtain the maximum level of privileges, network information, and access to as many systems as possible by identifying which data and/or services are accessible. This phase will explain what this security breach could mean for the Constellation design.

Phase 5: Analysis and Reporting

This is the result of a penetration test. As part of the last stage, PNDC will prepare a detailed report explaining the entire penetration testing process. Some of the information that will appear are:

- The severity of the risks arising from the vulnerabilities revealed;
- The tools that can effectively penetrate the system;
- Underlining those points where security had been employed correctly; and
- Vulnerabilities that need to be fixed and the methods to prevent future attacks (remediation recommendations).

Phase 5 is the most important phase. This report is likely to be read by both technical and non-technical staff/employees, therefore, the report will include both general explanation and technical aspects. Suitable evidence will be provided with the final report, that include documentation of the used tools. The tester will also provide evidence of actual use of the tool for testing the network product (e.g., by providing a trace, screenshot etc.). The output document presented by PNDC for its evaluation task, will include test techniques, the test outcomes and other associated information.

5.4 UK Power Networks Trials

5.4.1 Introduction

After the PNDC trials are completed, the Constellation solutions will be installed in the Maidstone and Thanet trial areas. A series of approved functional tests similar to the FATs and the PNDC SAT will be undertaken on the integrated systems to demonstrate compliance with the Constellation requirements (which are discussed in Deliverable 1).

5.4.2 Configuration of the UK Power Networks trial environment

The key components of the environment are summarised below and visualised in Figure 20. It should be noted that the diagram is for visualisation purposes only as it is simplified and omits some elements. It should also be noted that specific details about the UK Power Networks site preparation and device details will be presented as part of Deliverable 4.

The Constellation platform

The platform consists of the Substation Server, the hypervisor, the switches and routers required for communication and the measurement devices within the substation. This includes the redundant PRP network for communication between IEDs and the server, as well as the interfaces with the 5G network and the SCADA network with integrated firewalls. The purpose of the platform is to enable the deployment and operation of the Constellation Methods, as well as other software which can be used to support the testing (e.g. hardware monitoring software). The platform will be deployed at each substation. The hardware capabilities of the platform, as well as the level of redundancy, are different for Grid sites and DER sites due to space constraints in smaller DER substations.

Testing equipment and tools
The Omicron testing equipment consists of the protection test platform, substation test platform and cyber security test platform. The same equipment is also used in the PNDC testing, as described in Section 5.3.

The 5G network
Most of the trial sites will not have access to public standalone 5G within the timescales of the project. As such, Vodafone are deploying dedicated 5G infrastructure to facilitate the 5G requirements. This consists of a number of 5G capable antennas, devices and associated power supply and accessories. This equipment is separate from the switches and routers in the Constellation platform.

Existing UK Power Networks central systems
Access to existing central systems, such as ADMS, is established using existing secure interfaces of the existing SCADA network. The integration requirements with existing central systems for each Method are described in Deliverable 1.

New UK Power Networks central systems
The Local ANM and Adaptive Protection solutions, described in detail in Deliverable 1, require access to dedicated central environments to support their operation. These central systems are hosted in the UK Power Networks' Azure environment. They consist of systems which are deployed by:

- Siemens to support the verification and management of protection settings; and
- GE to support the Machine Learning capability of Local ANM and act as a repository for the syncrophasor data.

The UK Power Networks test environment is aligned with PNDC's test environment to ensure results from the PNDC testing are scalable and verifiable to the UK Power Networks trial. The core difference with the PNDC environment is the RTDS, as UK Power Networks will utilise the physical network, rather than the simulated model one used in the PNDC trial.

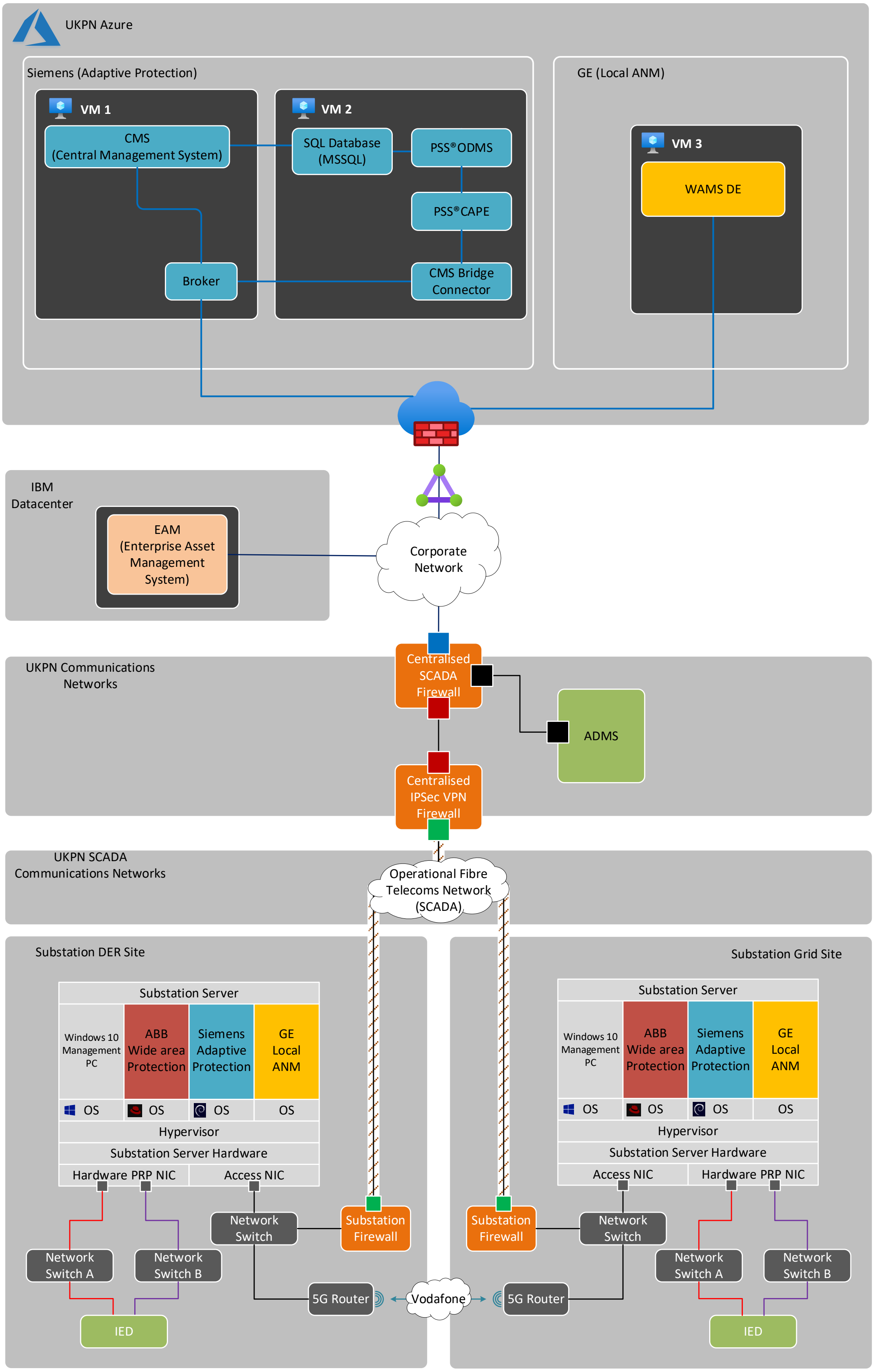


Figure 20: UK Power Networks Trial Environment

5.4.3 UK Power Networks trial details

Lessons learned from the FATs and PNDC trials will feed into the configuration of the Constellation solutions which are deployed during the UK Power Networks trials. The state-of-the-art features in OMICRON test equipment, e.g. transplay of live events or sample events from PNDC trials, will be utilised in this phase. This will demonstrate the core Methods interoperating with existing systems, interacting and arbitrating with each other and executing the individual underlying logics, on the virtualised platform, at the trial sites. The key functional and non-functional tests covered for each Method during the UK Power Networks' trials are summarised below.

5.4.3.1 Method 1 (Local ANM)

During the live network trials, the main goal is to test Method 1 using real data from the power system trial area. Additionally, it is required to be able to simulate system events, using test sets, in order to verify the novel control functionality, as the case for Holdover and Learned Limit modes.

From the Local ANM scope, the general and mode-specific test goals are described in Tables A.4.6.1 and A.4.6.2 respectively, and are also summarised below:

- Verification of the necessary PMU measurements for Local ANM: this requires testing the accuracy and phase sequence for the measurements;
- Validation of the trigger for Local ANM: this requires simulated failure of communications between central ANM and the RTU in the trial substations;
- Validate event detection and classification: this requires the simulation of various topologies and faults to test Local ANM correctly detects and classifies them;
- Headroom verification: this requires a comparison between the Local ANM calculated headroom values against the measured ones. This will be carried out for each Local ANM mode;
- Constraint management validation: this requires testing the changes in DER output Local ANM recommends as a response to real or simulated events on the network; and
- Validation of initiation of appropriate Local ANM mode: this requires testing the transition to the appropriate Local ANM modes based on real or simulated events on the network (e.g. transition from inactive to direct distributed on a communication failure and then a return to inactive when communication is restored).

<u>Test approach using data from the real system</u>

During the first stage of trials on the live power network, the Local ANM will play a passive role, running all its functions without managing the network constraints. This will enable it to verify its measurements, calculations, estimations, and logic sequences without interfering with the normal system operation. To run such tests, the setup is as showed for the Thanet area in Figure 21. The black elements represent existing components in the system, and the blue ones are the new virtualised components installed on type-1 hypervisors (Hyp) as part of Local ANM solution. In most cases, even the existing components as IEDs and RTUs will need configuration changes with aim to adopt the new control modes and communication requirements. The Maidstone area follows a similar setup. The core difference is that Maidstone has seven measurement points and one DER associated.

During the UK Power Networks' trials, it is required to verify the correct interaction with the real components, RTU and ADMS. Additionally, the ability to calculate and estimate the headroom values at the constraint points, as well as execute the logic to curtail or release generation based on the headroom conditions is essential.

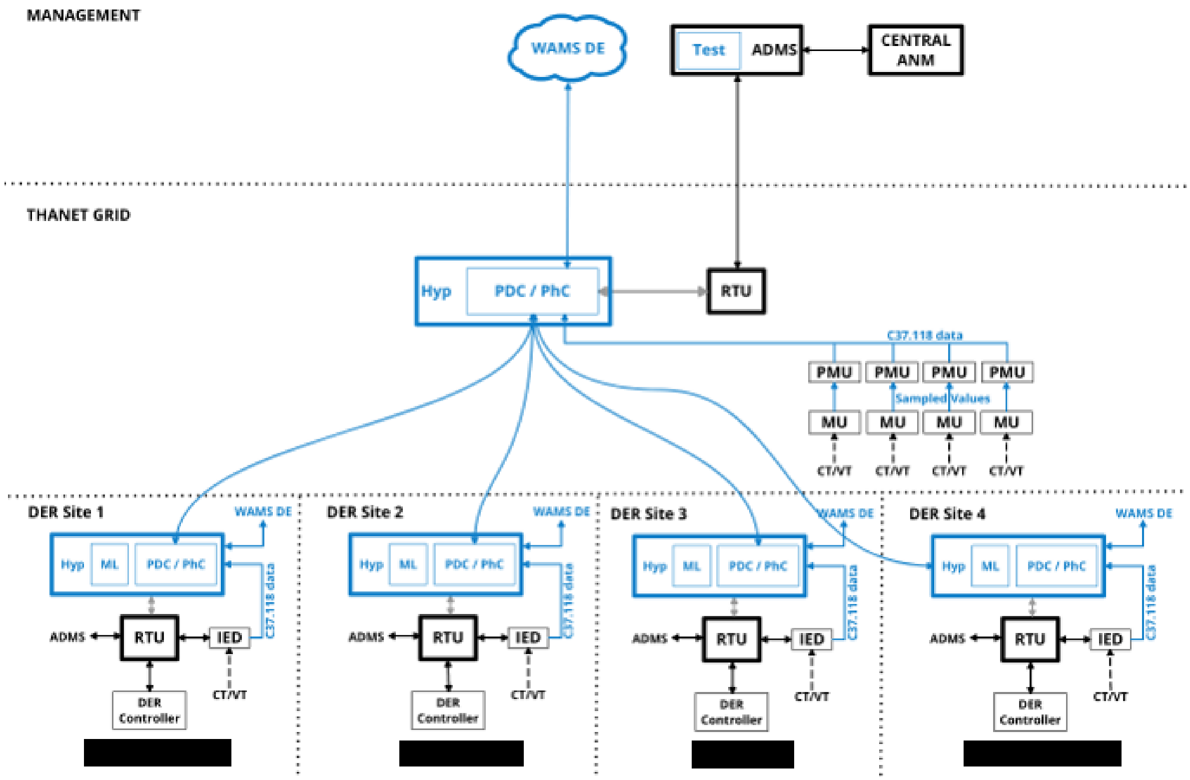


Figure 21: Test setup for Local ANM in Thanet using real system data

An additional requirement for the Local ANM testing, during this stage, is to check the correct detection and classification of local or remote events, as an input condition to curtail generation until minimum values or switch to failsafe. However, some of the testing requirements above will need to be carried out with simulated data sources. The testing approach of using test sets as a source of data is summarised in Appendix A.5.

Test approach using test sets as source of data

Through the different trial stages of the UK Power Networks testing, and later when the system is running as BaU, it is required to run different topologies and event scenarios, based on simulations, instead of real data, in order to verify the system behaviour under specific system conditions. These tests should be carried out using a combination of modern IEC61850 test capabilities and conventional methods, based on the technology installed in each site.

Figure 22 shows the setup using test sets to simulate different topologies, power flow and event conditions to the Local ANM system in the Thanet area. The Maidstone area follows a similar setup.

In the Grid site, the test set injects analogue measurements using IEC61850 Sampled Values to feed PMUs and also simulate topology conditions to the Phasor Controller (PhC) using IEC61850 GOOSE messages. At DER sites, the test sets inject hardwired analogue signals to IEDs. Topology conditions to the PhC and control setpoints, from the PhC are also received as GOOSE messages.

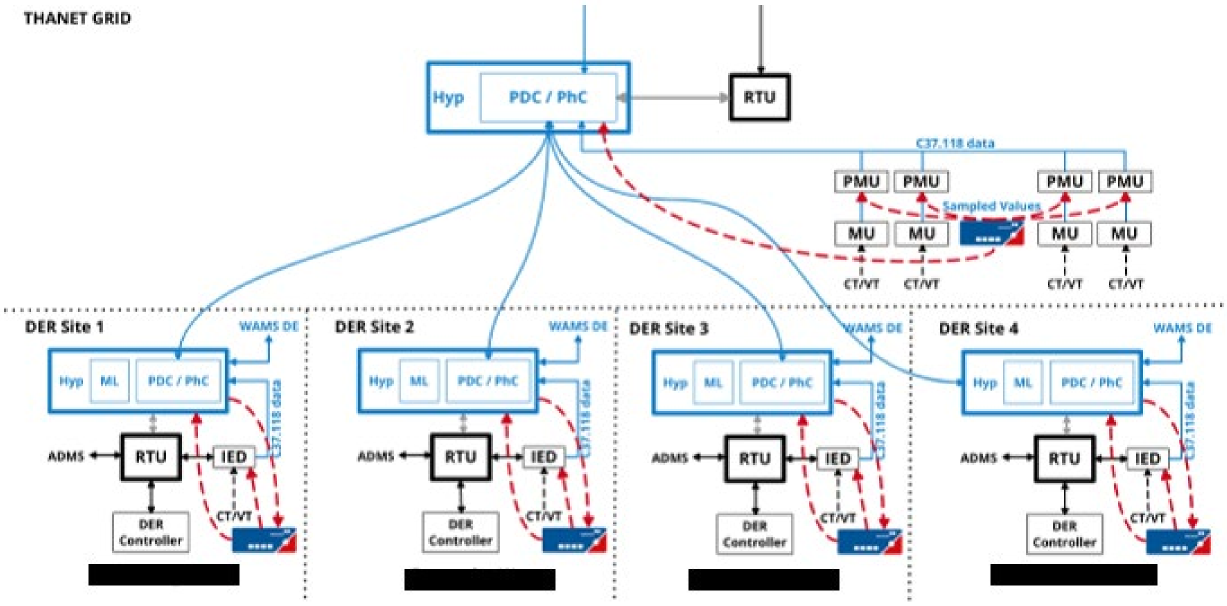


Figure 22: Test Setup for Local ANM in Thanet using test sets

To perform this test scenario, it is necessary to run a novel power system modeling software - OMICRON RelaySimTest, capable to inject synchronized analog and IEC61850 signals using distributed test sets, following test sequences defined under the system topology and implementing a tailored generator inverter model, as part of Constellation project.

5.4.3.2 Method 2 (Adaptive Protection Settings and Central Management System)

Multiple modules for Adaptative Protection Setting and Central Management System are tested during the FAT and the PNDC trials, including the communication between the internal Siemens systems (ODMS, CAPE, CMS, GridEdge) and even the interfaces to receive changes in the system model via CIM data files and to export information to the existing UK Power Networks systems via Comma Separated Value (CSV) files.

During the UK Power Networks trials the main objectives are to test:

- The interfaces with external components, specifically the virtual ABB protection;
- Implementing the standardised method for updating:
  - Protection settings using IEC 61850; and
  - Non-protection devices such as switches, routers, etc using SNMP
- The final interfaces with the ADMS and other existing UK Power Networks systems and their file structures.

Furthermore, it is required to demonstrate how the whole Adaptative Protection Settings system is successfully completing the cycle: reading the updated new topology, calculating the new protection settings, uploading them to the virtualised protection, and finally checking the operational protection zones under specific power flow using IEC61850 sampled values injection.

For Method 2 (Adaptive Protection settings), the general and mode-specific test goals are described in Table A.4.6.3 and are also summarised below:

- Verification of End-to-End Encryption: confirm that communications between the Central Management System and the outstations is correctly managed;
- Confirmation that CIM files can be imported and validated; and
- Review the accuracy of Load Blinder settings calculation and that the application of new settings is managed correctly.

Test approach

The test scenarios include the interaction with the system model inputs and validation of the new protection settings in the virtual protection relay, as shown in Figure 23.

The test requires the application of different system model scenarios, where the standardised DOC settings are not optimal to maximize the DER generation and simultaneously protect the line correctly.

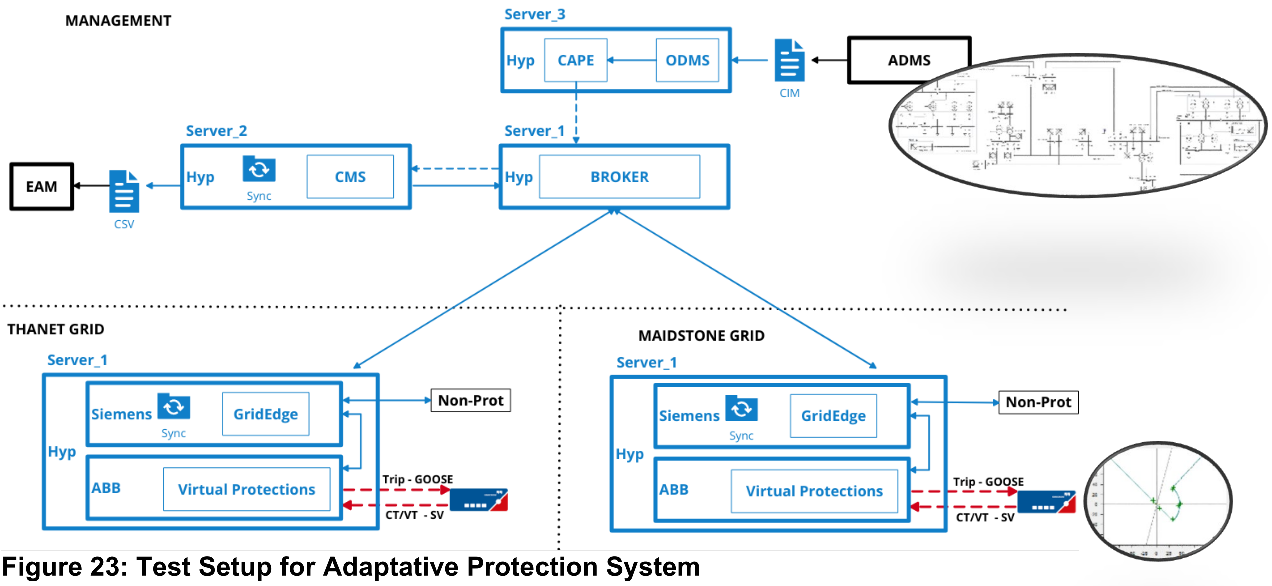


Figure 23: Test Setup for Adaptative Protection System

In the Figure 26, the test set is used to validate the protection zones for DOC individually at each protection feeder (virtual component), updated with new protection settings. This allows the validation of the new load blinder areas. The total time to import the required data files, generate the new settings, update the CMS and protection IEDs will be also measured. However, it is not a time-critical application, and expected results are around tens of minutes, which is sufficient for adapting the load blinding protection.

5.4.3.3 Method 2 (Wide Area (LoM) Protection and Virtualized Protection)

This part of the UK Power Networks trials is focused on all virtualised protection functions part of the Constellation project. All protection functions are executed on the virtualised SSC600 protection system. A specific focus is on testing the Load Blinding, which will be adapted by the Adaptive Protection solution, and testing the wide area LoM, which is based on remote communication between DER sites and Grid sites.

Virtualised feeder protection test objectives

Most protection functions running in the virtualised protection systems work as stand-alone components. This means operation without communicating with the other IEDs. During the

UK Power Networks' trial these tests will focus on performing stand-alone injection using IEC61850 Sampled Values and GOOSE messages as communication interfaces to evaluate the accuracy and speed of the virtual protection system. This testing will be performed when all other virtual machines are running in parallel (GE Local ANM, Siemens Adaptive Protection). The results from this testing will be compared to the results from the FAT and PNDC trial. The main objectives to be met are as shown in Table 10.

Table 10: Feeder Protection Test Goals

Feeder protection test goals	Assessment conditions
Protection test: Accuracy and operation times	Test the accuracy and speed of protection function as per the standard protection performance requirements.
Offline test methodology	Check the test sequence to run remote protection test using IEC61850 test capabilities, without interference with other system components.

Wide area protection test objectives

During the UK Power Networks' trials the testing of the wide area LoM will be carried out using the novel communication link (via 5G slicing). The purpose of the tests is to understand if the operation time varies because of communication delays, or because the Substation Server shares resources with the other Constellation solutions. The main objectives of these tests are as shown in Table 11.

Table 11: Wide Area Protection Test Goals

Wide area protection test goals	Assessment conditions
Intertrip signal test	Check the logic and measure the total operation time for End-to-End intertrip signal.
Power Swing block signal test	Measure the total transmission time of Power Swing block signal.
Breaker position signal verification	Check that Breaker position is transmitted correctly from DER to substation Grid site and measure the update time.
Wide Area Protection LoM test	Using system model test, locating faults in or out of the DER area, check the proper operation and block of LoM function.

Test approach for Wide Area Protection schemes

The DER sites and the Grid sites are physically isolated from each other. Therefore, it is necessary to carry out end-to-end test using synchronised test sets at Thanet Grid, and at the DER sites (e.g. Strasbourg Street), as visualised in Figure 24.

The requirement for the tests is for them to be performed in pairs, between the virtual feeder in the Grid site and the corresponding protection in the DER site. There is no interaction between DER sites for Wide Area Protection, and no need for more than two simultaneous test points.

Even though all the protection functions tests are focused in the virtual SSC600, as a final test, it is required to measure the complete operation time between the physical IEDs at the Grid site and DER site.

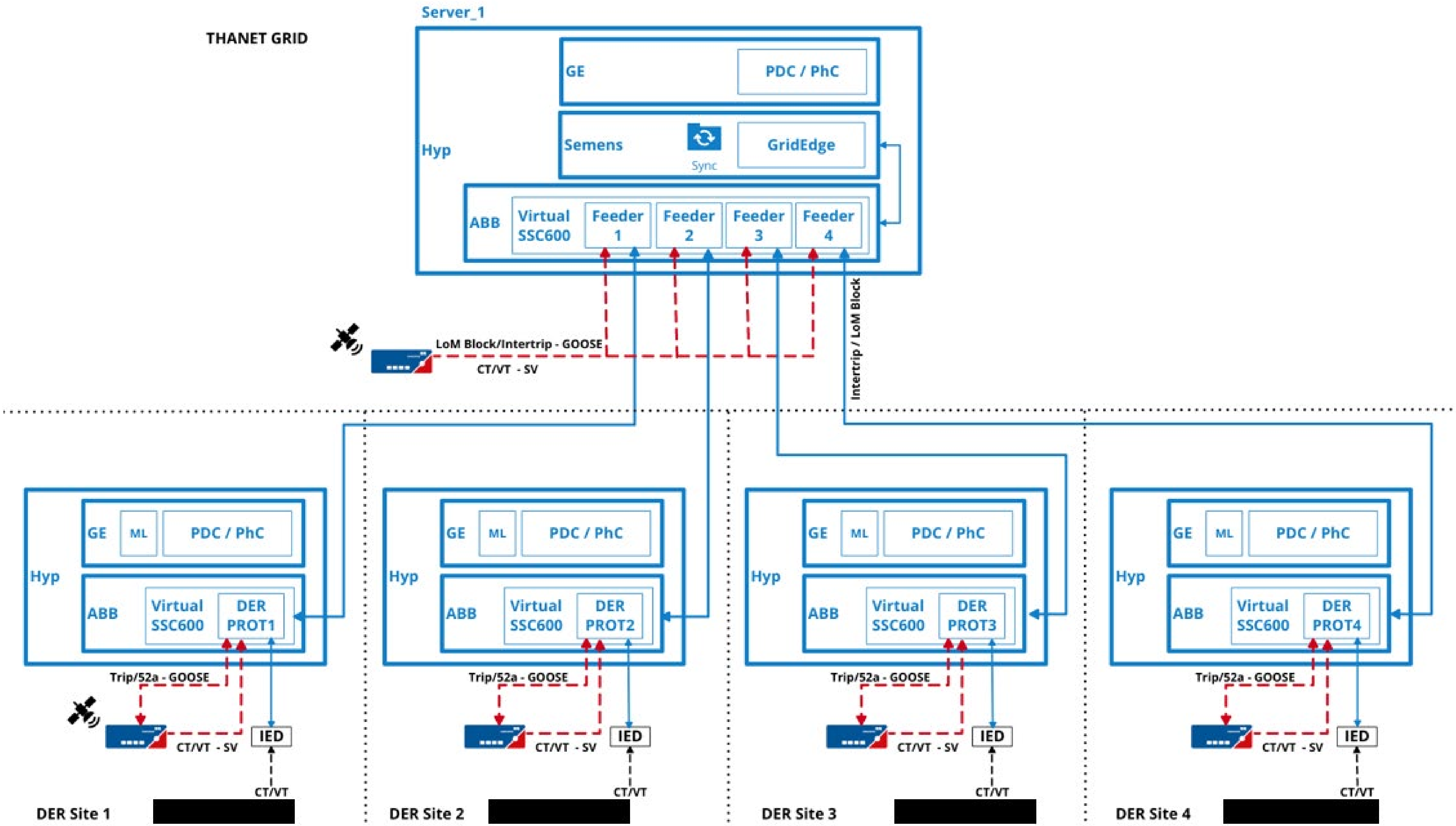


Figure 24: Test Setup for Wide Area Protection

5.4.4.4 5G site-to-site communications

During the live network trials, it is required to re-run similar tests as undertaken during the FAT and PNDC off-site trials. This is because the final traffic and radio access network will be in place. It is therefore required to measure the final latency and availability of the 5G slice.

Additionally, it is required to verify the security of the 5G slice because the 5G-RAN might be different to the previous trial phases.

For the 5G communications the main test objectives are as detailed in Table 12 below:

Table 12: Main 5G Test Goals

5G communications test goals	Assessment conditions
Channel availability test	Analyse PMU and R-GOOSE data at Grid and DER sites and detect possible communication failures.
Latency test	By detecting identical packages in Grid and DER sites, measure the latency for intertrip, LoM block and breaker position messages using R-GOOSE.
Verify that only sessions using user plane security are used	By checking the configuration in the 5G user plane modules (AMF/SMF) verify if the Integrity Protection Indication (IE) is set to preferred for the session establishment.
Check the user identity encryption 5G-AKA as defined 3GPP-SUCI	By checking the configuration in the 5G control plane module (UDM) check if SUCI is enabled.
Verify the IP-SEC tunnelling	By checking the configuration in the substation radio routers verify if the IP-SEC tunnelling is activated. Also, it is required it is verified by traffic sniffing.

Test approach

To facilitate the testing, end-to-end packet analysis and accurate time synchronization will be utilised. This will enable the measurement of the latency of the communications channel, including the local area on both sides (Grid site and DER site). The proposed test configuration is shown in Figure 25.

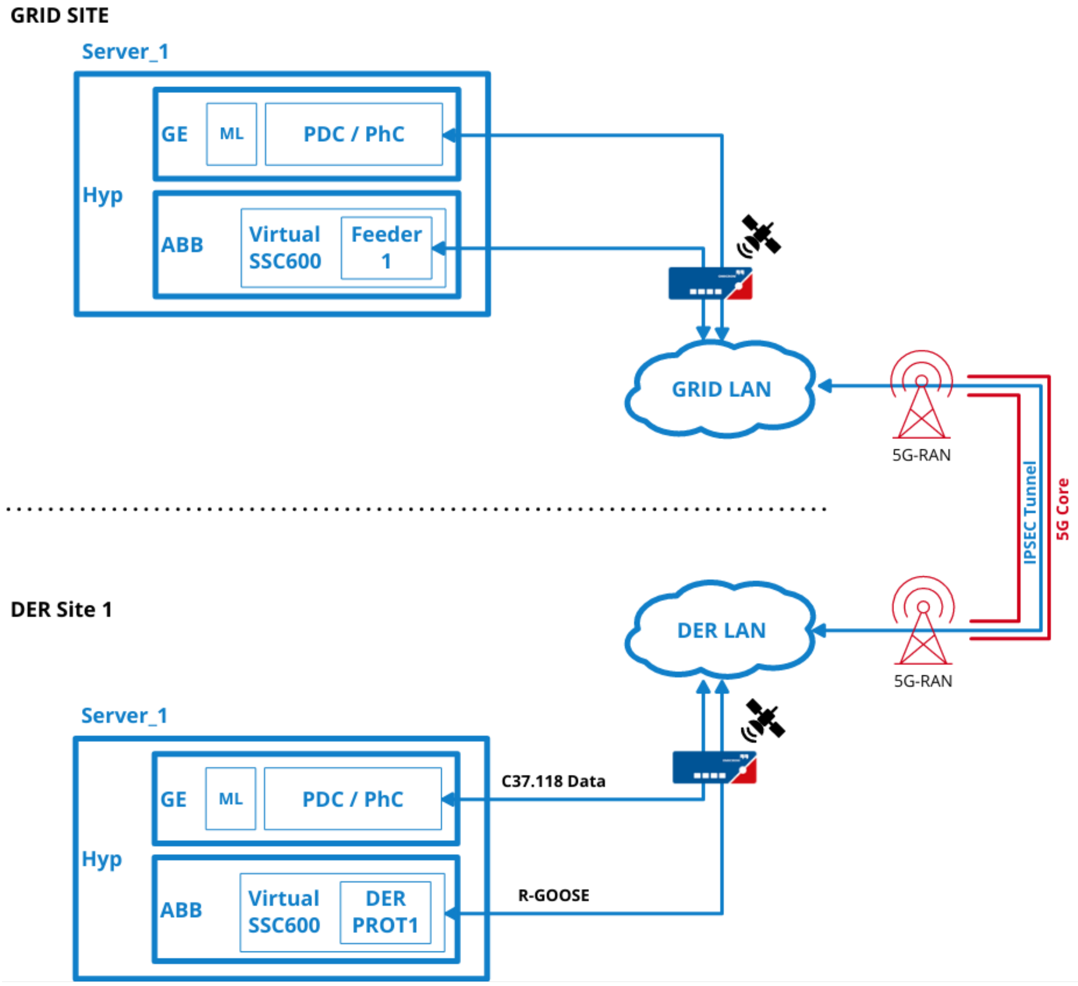


Figure 25: 5G Communication Test Set-Up

In order to evaluate the communication latency, an analysis of network packets is required at both distributed test sets. The statistical results will show maximum, minimum, and standard deviation of the total transmission time between each remote location (site).

Additionally, to carry out further cyber security tests, traffic analysis of different configuration revisions with the same test setup is required. This will enable IP SEC tunnelling and user plane security testing.

D2 Section 5 : Lessons Learnt	
1	A key requirement for the demonstration of Methods 1 and 2 is establishing a suitable trial environment. As such, it was essential PNDC work closely with all partners and ensure their facilities can provide a representative test environment which is fit for purpose. Additionally, UK Power Networks and PNDC coordinated in identifying the necessary equipment to ensure that testing results from the PNDC trials are transferrable to the UK Power Networks trials.
2	During live trials it is also essential to understand the level of operational flexibility for testing available at DER site. Say for example in terms of operation possible during live trials at DER site, is it possible to run use cases involving varying output i.e. ramp up/down generation output, on live network and analyse DER response.
3	Developing tests for some functions in a laboratory environment can be challenging. For example, tests for machine learning algorithm of the Local ANM Method require a level of background network "noise" which cannot be readily simulated. This "noise" includes normal network load variations, switching events and small system oscillations. This limitation can be circumvented by the complementary nature of the offline and live network trials. The machine learning algorithm is expected to be exposed to this "noise" in the live network trials phase of the project.

6 Trial Data Analysis and Management

6.1 Introduction

As a large volume of data will be generated during the Constellation trials a common data analysis and management plan, which is currently under discussion by all project partners, will be agreed and concluded before the PNDC off-network trials commence. This will ensure efficient exchange and interpretation of trial results.

To facilitate this, prior to the commencement of the trials, PNDC will create an integrated portal for developing and establishing a knowledge repository. It will facilitate:

- Structured data collection;
- Data management and storage;
- Collaborative knowledge management and analysis; and
- Visualisation.

The objective of this is to enable cohesive data management throughout the trials phase and, in future, to enable secure data sharing within the project partners as well as to discuss dissemination of data produced and published. This will support accelerating the adoption of Constellation solutions and future scalability, by leveraging on the knowledge and experience gained throughout the project, from requirements specification to design and finally trials.

All project partners acknowledge that a straightforward access to valuable information will help reduce duplication of effort and empowers the research and industrial community to build upon the lessons learned and accomplishments of the project undertaken, to advance and scale the solutions developed. Furthermore, the generated data will underpin the evidence required to support the initial business case assumptions and benefits set out by the project.

6.2 Framework Design

The primary phase is to create useful data based on a data management plan which will guide in creating, storing, backing up, sharing and preserving the data. It also specifies any associated legal compliance/ethical issues need to be taken care of, who will be responsible for the data management and usage of standard/interoperable data format.

The next step entails selecting a consistent approach to organise the data by using a logical and uniform naming convention. Structuring the data and saving it in hierarchical folders, allows easiness in locating, identifying and controlling the versions of files. The hierarchical framework also simplifies collaborative working on the data for instance test results.

Once the useful data is built and organised properly, it can be uploaded into a digital data repository e.g. a centrally managed storage or university cloud storage. Rules also need to be put in place for managing remote access securely. Deciding on the proper approach to store and back up the data, ensure secure storage & access while simplifying version control and effective collaboration. Keeping the data Findable Accessible Interoperable, and Re-usable (FAIR), is key.

Figure 26 below graphically details the data management framework to handle and manage the data produced thus agreed upon by the project partners.

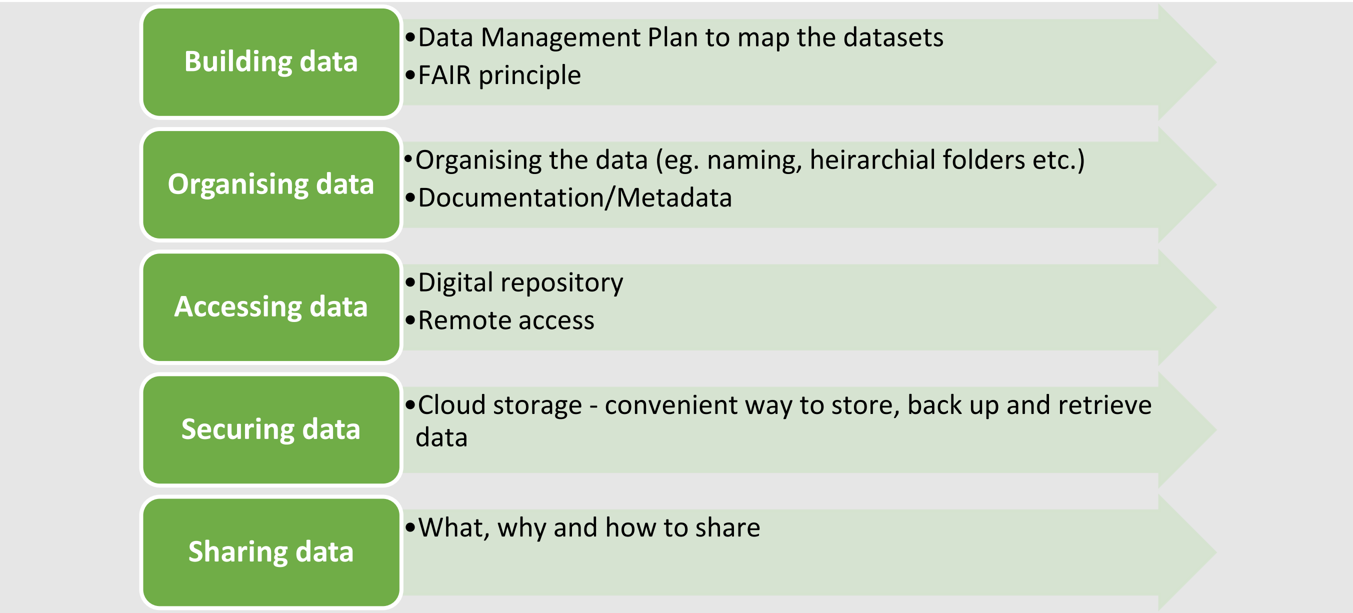


Figure 26: Data Management Framework

6.3 Data Management & Analysis Plan

The Data Management & Analysis Plan (DMP) is essential to draw a framework that ensures the data is useful, traceable, accessible, interoperable and reusable throughout and beyond the project lifecycle.

The DMP will address the following aspects:

6.3.1 Data Collection

Data will be recorded from different sources by all project partners. It is expected that each Method will have its own logging functionality in addition to substation equipment (e.g. PMUs used in the Local ANM solution). Data generated from PNDC trials will be hosted on a cloud server. PNDC trials data stored in a cloud server will be available for sharing with the project partners throughout the lifetime of the project.

Table 13 details the data expected to be collected and from which project partner.

Table 13: Data Collected From project partners

No.	Partner Responsible	Data Collected
1	PNDC	1) Trial Design Documents for the Constellation project – Objective, Methodology, Specification for PNDC/UKPN trials which includes details on the PNDC test bed 2) PNDC trials data – measurements, results (to be read along with the test metrics as part of each test specification above), analysis 3) PNDC trials report 4) Open Innovation Competition – Design document, OIC method specifications, Trials design, Trials data and analysis report

		5) Network trials data analysis report evaluating Method 1, Method 2 and open innovation algorithms deployed in network trials
2	OEMs of solutions	1) User guide/Installation & Commissioning/Operation manual which could include/separate documents on: • Flowchart of the process • Decision map/matrix • Setting Calculation • Networking parameters • Configuration parameters • List of software with version • Virtualisation hardware requirements • User access data 2) Draft FAT/SAT procedure 3) Draft FAT/SAT test results 4) Alarm/Event logs from specific applications during PNDC/UKPN live trials
3	Omicron	Test data/reports/event logs from Omicron test equipment during UKPN live trials
4	UK Power Networks	5) Approved Design Documents 6) Approved Requirements Specifications 7) Approved FAT and SAT procedures 8) Details of trial sites including connected DERs – Single Line Diagram, Technical Parameters, Operational Data 9) Approved FAT results 10) Approved SAT results 11) Approved Deliverable Reports

6.3.2 Data File Naming, Versioning and Structure Convention

The file names shall be chosen logically and in a consistent manner. For example <Project Name>_<Method Name/No>_<Specific File Name>_<Date of Upload>_<Initials of person responsible>_<version>. Naming convention can be discussed and agreed upon across the partners. Deciding on a naming convention will offer uniformity, thus making it easy to locate and identify as well as prevent version control issues when working on files collaboratively. A similar approach shall be adopted, for hierarchal and coherent grouping of files in separate folders, sorting out work under progress and completed work for periodic review.

6.3.3 Storage, Backup and Sharing

The appropriate location, for example University data repository, shall be chosen for storing the data where files on the network are automatically backed up. Remote and secure access shall be provided by enabling controlled user access to files and folders in shared drives. Length of data retention can be mutually agreed upon between project partners.

6.3.4 Ethics and Legal Compliance/Intellectual property (IPR) issues

Matters regarding ethical/legal/copyright shall be followed as per initial collaboration agreement signed between all partners.

6.3.5 Documentation/Metadata

A content tracker document filled in by the owner of the data/person uploading the data in the shared repository shall be updated and information shall be added as the project progresses. This shall help in tracing the revision numbering and the individual who made an amendment.

6.3.6 Data Analysis

Detailed analysis of the trials data collected will be carried out in line with the testing principle, test cases, test metrics and the expected outcome detailed in the test specifications of each Method as in Section 4 above. The procedure for analysis and the qualifying attributes will be specific to each test case above and will be comprehensively covered in the test report.

The purpose of the analysis carried out on the collected data is to ensure specified requirements and design objectives are met by the supplied solution and that sufficient evidence is provided to support or revise the project business case. Furthermore, the analysis will provide valuable learning and scalability of project outcomes including:

- Supporting decision making in relation to requirements, designs and adoption of the solution;
- Best practices for commissioning, operation and maintenance of the Constellation solution. Development and adoption of FAT and SAT policy; and
- Limitations and requirement for further improvement of the platform or Methods.

The analysis will use diverse input data from the trials to provide insight on sufficient and traceable evidence to ascertain that the design objectives & requirements specified are achieved by the supplied solutions. The data analysis strategy based on the test specifications is summarised in Figure 27.

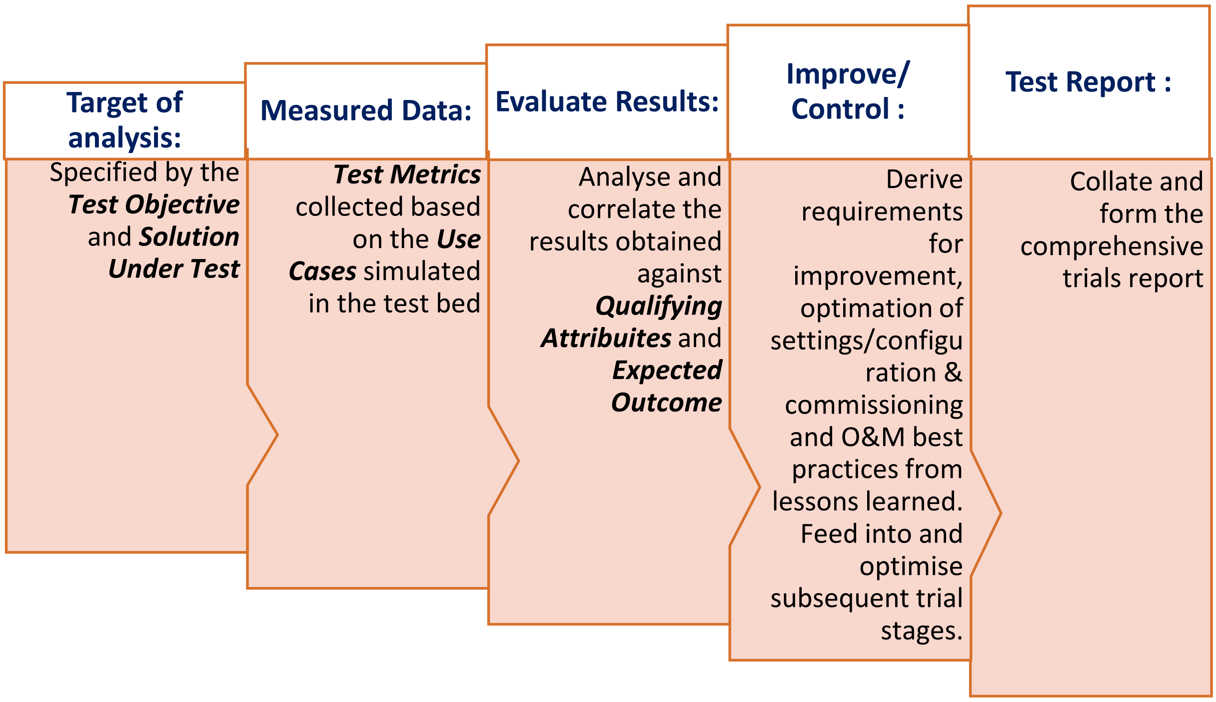


Figure 27: Data Analysis Strategy

6.4 *Trial Plan/Timeline*

A high-level plan of workstream 3 is depicted in Figure 28 along with the relevant Ofgem deliverables. The PNDC trials are split into two phases. The first phase focuses on the priority test necessary to enable the launching of the UK Power Networks passive trials on time. The second phase of testing follows on to complete the PNDC testing scope while also supporting the UK Power Networks trials should any issues arise. The timelines associated with the trials are indicative and subject to the completion of partners' development and successful FATs, which is the focus of Deliverable 3.

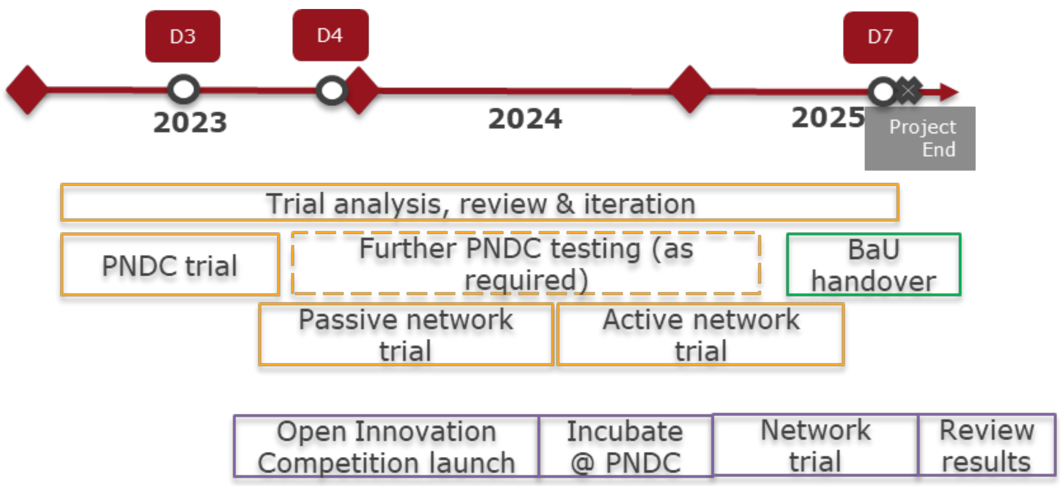


Figure 28: Trials Timeline (Including Ofgem Deliverables). Deliverables 5 and 6 excluded as they are not directly related to the trials

D2 Section 6 : Lessons Learnt	
1	The Constellation trials will produce a large volume of data which needs to be accessed by multiple stakeholders from different organisations. Therefore, the trial data framework developed by PNDC is key to Constellation`s success. It is important that this framework is deployed such that data and trial results can be fully analysed.

7 Ongoing Activities & Next Stage

7.1 Ongoing Activities

In order to progress the next project stage, several activities which remain ongoing at the time of this deliverable report being prepared, identified within Table 14 below, will be progressed and concluded and several activities required to progress the next stage of the project will commence, as summarised in Section 7.2.

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

Table 14: Summary of Ongoing Activities

Description of Ongoing Activity	Planned Actions
The Local ANM solution requires syncrophasor data (currents and voltages) from strategic nodes on the network.	UK Power Networks will continue with installation of PMUs as planned. To minimise the impact of this, the testing will begin with the non-data dependent Local ANM modes first. After sufficient data is available “holdover ANM” and “Learned Limit ANM” will be tested.
Trial site preparations for Maidstone, Thanet, associated DER sites and PNDC	The trial preparations are currently ongoing. The PNDC facilities will be prepared first in time to commence the PNDC trials.
Equipment procurement for the trials is ongoing.	The equipment required for the PNDC and UK Power Networks trials is identified. We are currently working with suitable vendors to procure the equipment in time for the trials.
Trial data management details are in progress	The data management details presented in section 6 are due final approval between all partners. This will be completed prior to the start of the trials.
To ensure a successful implementation of the 5G slice, UK Power Networks and Vodafone have agreed to carry out preliminary testing, prior to the FATs.	Separate testing is scheduled and will be conducted with Vodafone to verify compatibility with the 5G devices, which will be used as the end-user equipment in Constellation.

7.2 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 29 where each of D1 to D7 represents a Constellation Deliverable.

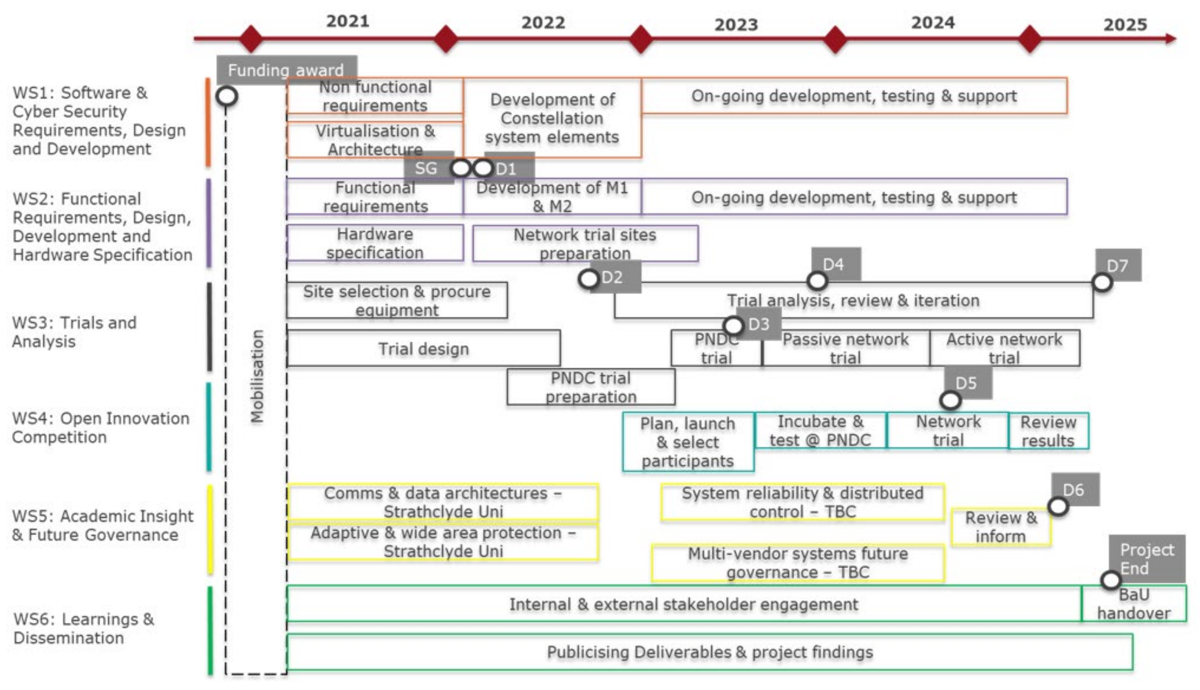


Figure 29: Constellation High-Level Project Plan

From this, it can be shown that after completion of Deliverable 2, the next stage of the project focuses on:

- Preparation for trials in PNDC and UK Power Networks;
- Finalisation of the development of the Constellation solutions; and
- Commencement of the PNDC trial.

<u>Project Quality Control</u>

- All the trial specifications and design documents will undergo a final review prior to approval and closure by the Technical Design Authority. To facilitate this:
    - The Constellation requirements and design documents will be used as a baseline against which to complete;
    - A formal design review by the Technical Design Authority will be carried out; and
    - Feedback from the design review will be implemented before each trial document is approved.
- The aim is for all ongoing actions (summarised in Table 14) to be addressed, actioned and closed as appropriate;
- 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 proceed with:
  - Attending the upcoming FATs and verifying the solutions performance; and
  - Supporting the trial preparations for each partner.
- PNDC will proceed with:
  - Hosting the PNDC trials; and
  - Supporting the approval of the trial documentation.
- Vodafone will proceed with:
  - Setting up the 5G coverage in the PNDC and UK Power Networks sites; and
  - Finalising the 5G slice development prior to the trial start.
- ABB, GE, Siemens will proceed with:
  - Finalising the development of the Constellation solutions; and
  - Organising and carrying out the FATs.

8 Conclusions

This deliverable report, D2, provides the detailed evidence that the trial site selection criteria and the site selection process for each phase of the network trials has been successfully delivered. Furthermore, the trial requirements and design for the demonstration of each element of Constellation have been successfully developed.

The site selection and trial design activities carried out and described in this report demonstrated that the Constellation team has successfully fulfilled the Deliverable 2 requirements. 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 Project Progress Report.

The approach to deliver the work so far is focused on effective collaboration between the 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 Single Line Diagrams for Areas Evaluated

Figure A.1.1: Maidstone Grid Trial Area Single Line Diagram

Figure A.1.2: Thanet Grid Trial Area Single Line Diagram

Figure A.1.3: Lewes Grid Area 1 Trial Area Single Line Diagram

Figure A.1.4: Lewes Grid Area 2 Trial Area Single Line Diagram

A.2 Site Survey Data

A.2.1 UK Power Networks Site Survey Data Capture

A.2.2 Vodafone 5G Signal Strength

A.2.3 Vodafone Site Survey Data Capture

A.3 Site Survey Evaluation Tables

A.4 Factory Acceptance Test Procedures (Examples)

A.5 PNDC Test Cases

A.6 UK Power Networks General and Mode Specific Test Goals

A.1 Single Line Diagrams for the Shortlisted Areas

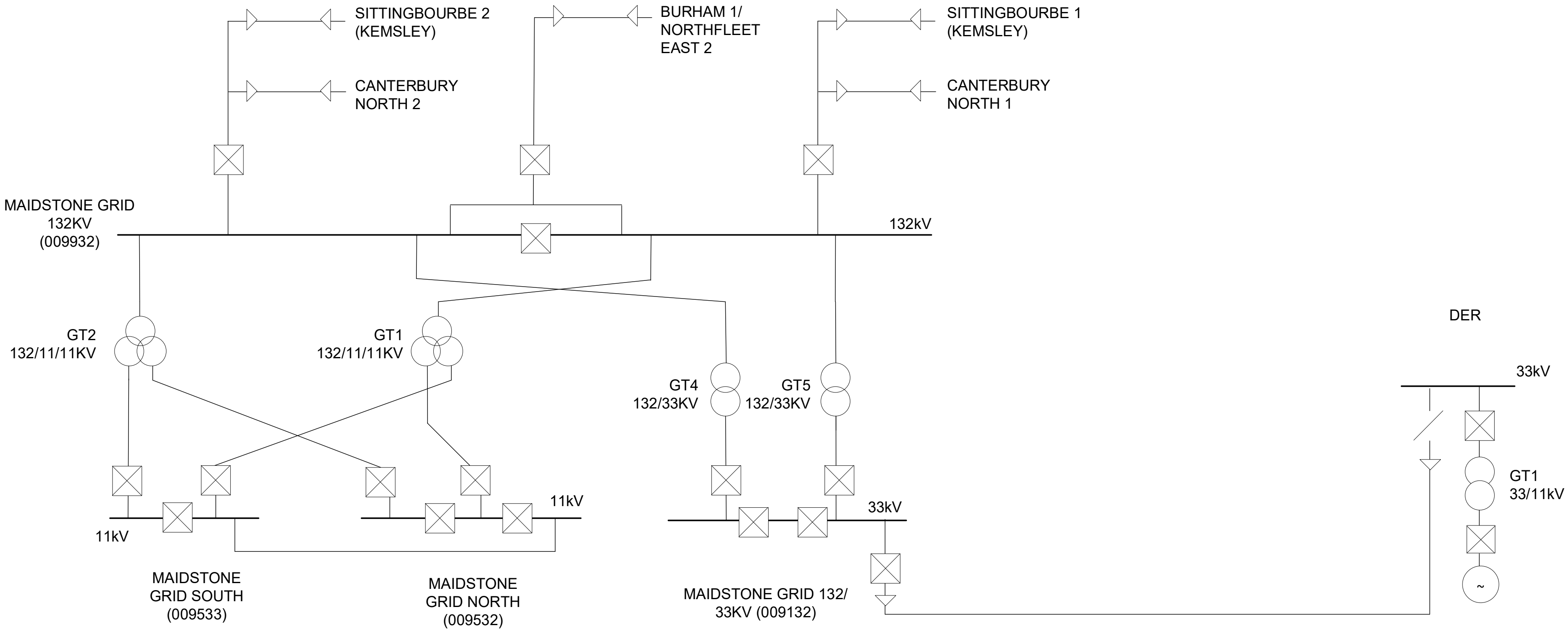


Figure 30: Maidstone Grid Trial Area Single Line Diagram

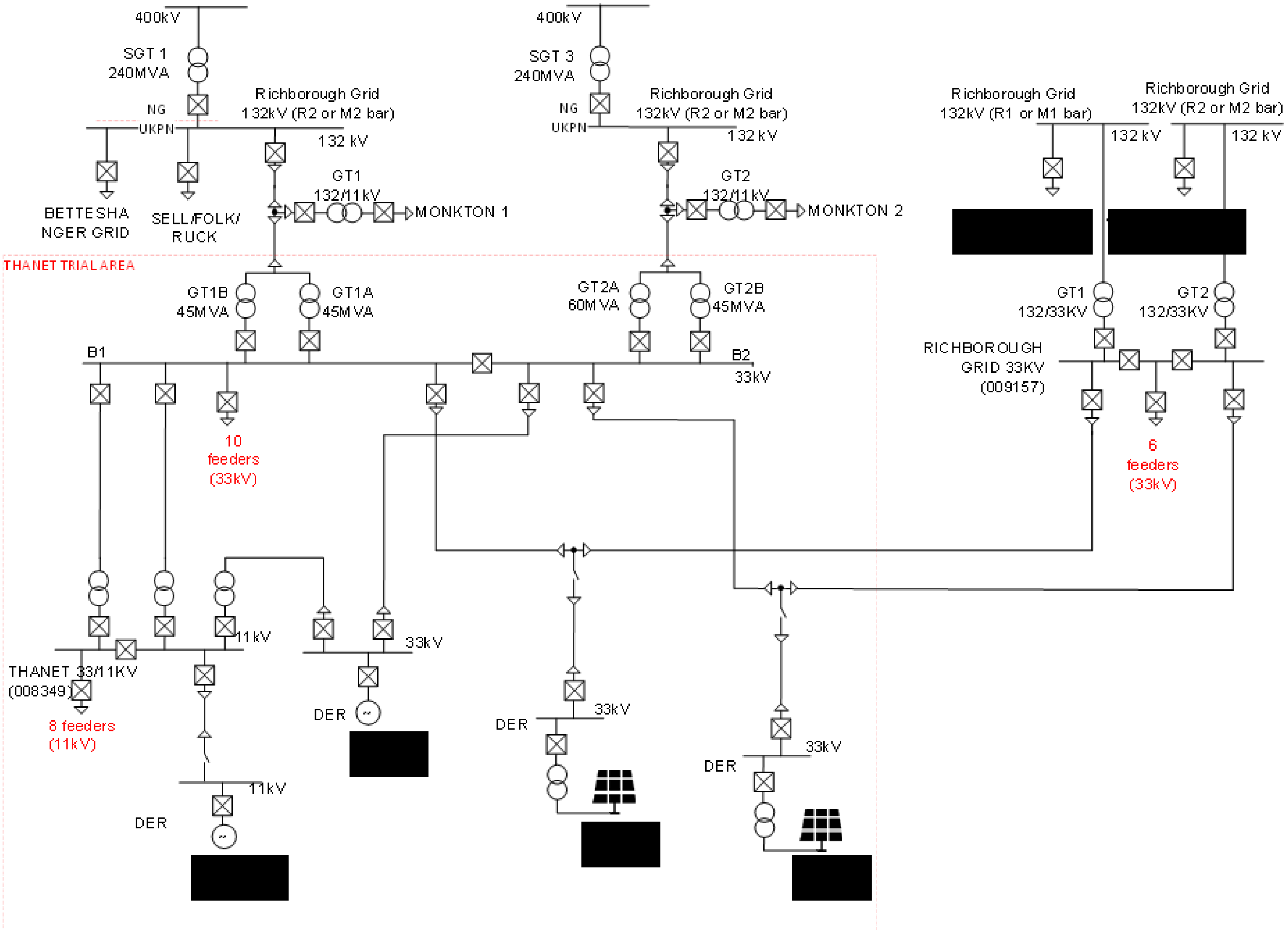


Figure 31: Thanet Grid Trial Area Single Line Diagram

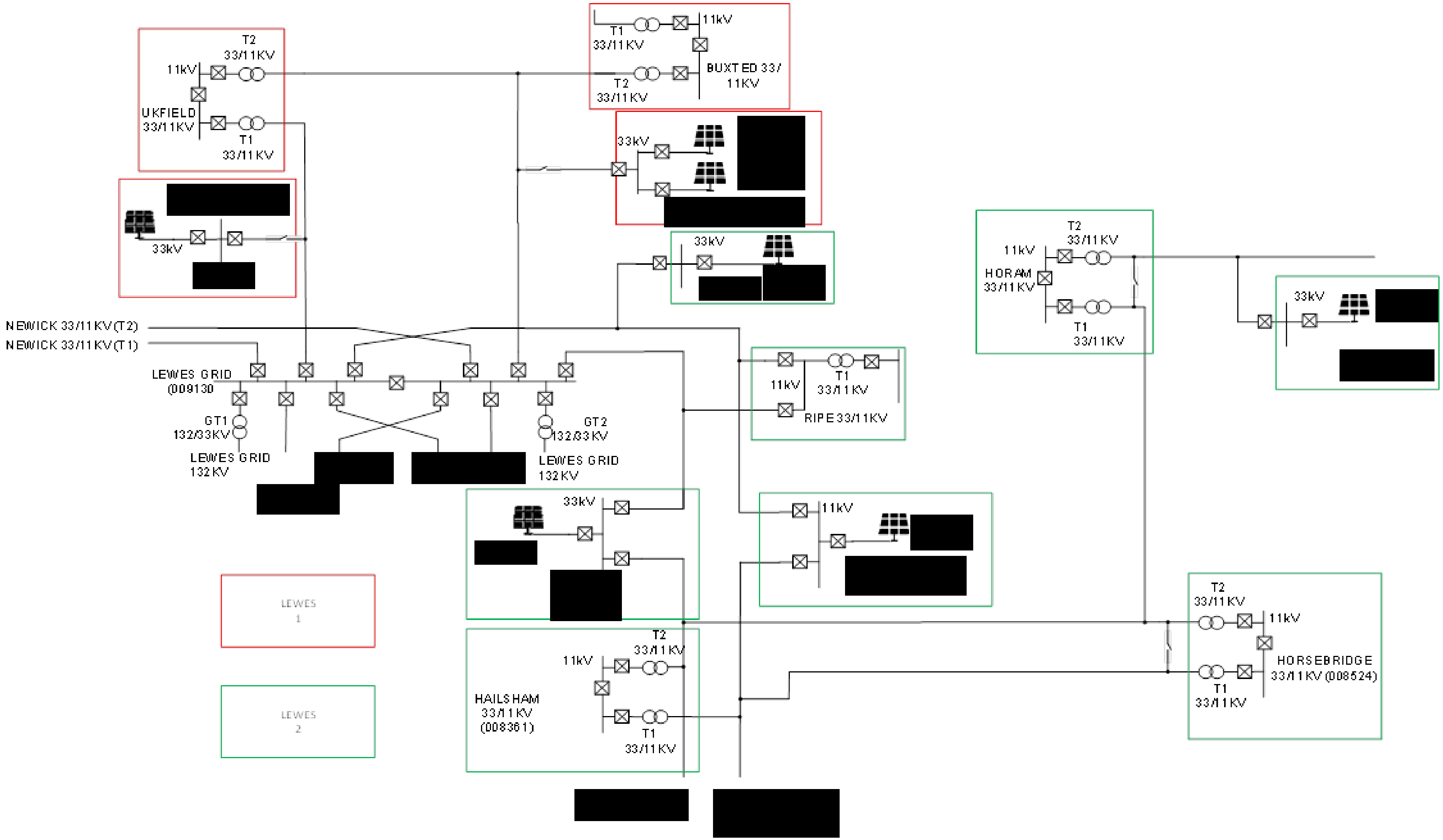


Figure 32: Lewes Grid Area 1 & 2 Trial Area Single Line Diagram

A.2 Site Survey Data

A.2.1 UK Power Networks

Maidstone Grid 33kV Telecoms Room

The room provides ample space for the installation of an 800x600mm Constellation equipment cubicle and a 600x600mm 5G communications cubicle. The room has a cable temperature monitoring panel that will be decommissioned. The telecoms room is adjacent to the switchgear room, where IEDs will be installed. See Figure 33 below for the proposed location of IEDs and new cubicles at the Maidstone 33kV building.

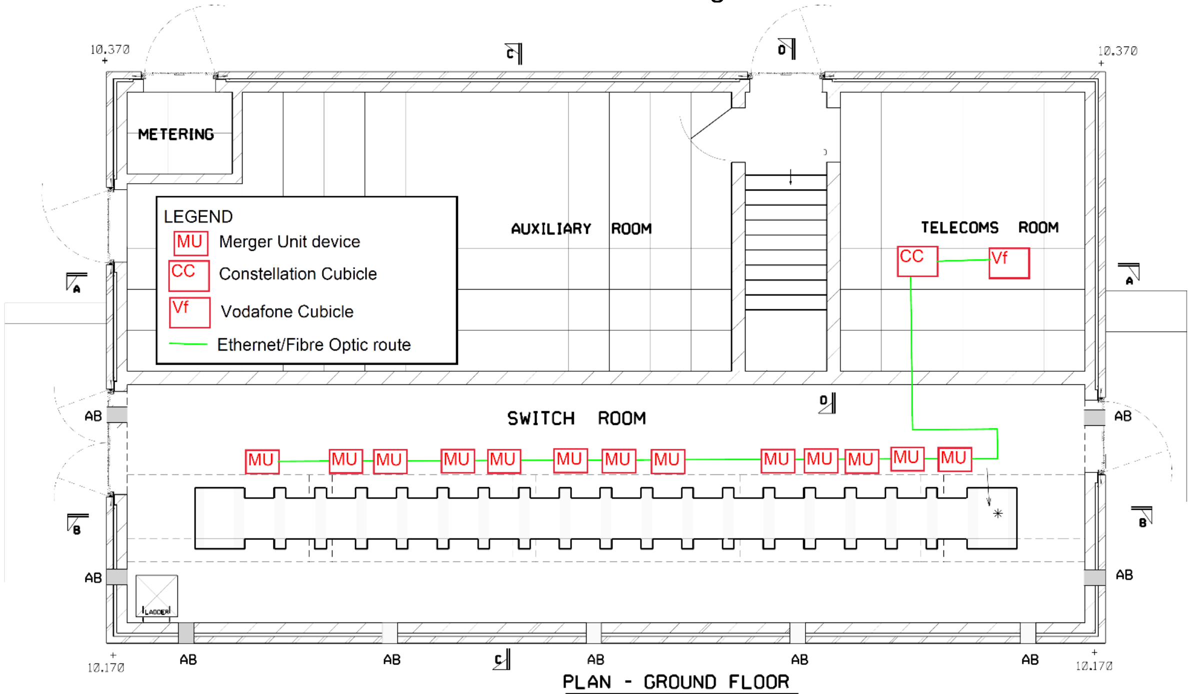


Figure 33: Maidstone Grid 33kV building layout.

AC power supply is available on each room. There is DC supply on site, which is provided by a set of batteries on the 33kV relay room (auxiliary room). These include provision of 48Vdc and 110Vdc.

Maidstone Grid 33kV Switchgear room

The room includes 16 switchgear panels. These include panels for GT4 and GT5 switchgear, bus section 61 and bus section 62 switchgear, and 12 feeder panels.

During the site visit, asset data was collected including photos, measurements of racks and relay data. This data was passed to an electrical engineer which worked on electrical drawings to add or replace devices. The objective is to have two merger units per panel. The straightforward installation and commissioning method of these includes adding devices on the panel when space is available. If space is not available, then existing relays may need to be moved or replaced to make space for more advanced devices with protection and merger unit capabilities, including compliance with IEC 61850 communication protocol.

The feeder panels have protection devices mounted on the front of the cubicle while GT4 and GT5 protection is on an adjacent room. The panels of the GT4, GT5 bus section 61 and bus section 62 have considerable space. The feeder panels have space constraints due to existing devices and will require an extensive replacement programme.

There are three panels that have unit protection schemes, and four panels that have non-unit protection schemes. In addition, there are two panels that are shared with network rail. On these, main protection belongs to Network rail, while the DNO own the back-up protection.

For this reason, and in order to minimise disruption, the railway panels will have one merger unit device instead of two. In summary, devices will be added to 13 panels at the 33kV switchroom at Maidstone Grid. These will bring indications, control, and measurement data from the panels to the constellation cubicle that is located in the adjacent 33kV telecoms room.

<u>DER site</u>
The site is contained in a single building with a 5.2x4.2m footprint. This site will have merger units for one feeder, Constellation equipment, and 5G communication equipment.

The site has two panels, being one for the 33kV feeder that goes to Maidstone Grid 33kV, and the other being for the DER transformer located at the customer premisses. [redacted].

The merger units will be located on the feeder panel, where replacement of one relay is required.

Following site survey, it was decided to use one cubicle with the footprint of 800x600mm. This means that Constellation equipment and 5G communication equipment can be mounted on the same cubicle. This saves space, which is very limited on DER sites. In addition, the cubicle will be of the type swing frame opening – these have a front door and a frame (where devices are mounted) that opens to the front. There is no rear door access as the cubicle will be located against a wall.

<u>Thanet Grid 33kV telecoms room</u>
The telecoms room will host the 5G Communication cubicle and the Constellation Equipment cubicle. The Thanet 33kV telecoms room, and the 132kV room at an adjacent building, are undergoing an upgrade that will go until Q1/Q2 2023. Fibre cables will be extended from the 132kV telecoms room, via trenches available on site, to the 33kV telecoms room.

The room offers ample space for the installation of the 5G communications and Constellation equipment. The room floor is made of moveable tiles, with a gap of approximately 50cm to the concrete floor for cables to run in. This space will be used to run ethernet of fibre optic cables to the IEDs located at the 33kV switchgear room.

<u>Thanet Grid 33kV Switchgear room</u>
This room has 20 cubicles with 33kV switchgear, protection, and control relays. 15 of these cubicles are destined to 33kV feeders, four cubicles are for the four Transformer incomers (G1A, G1B, G2A and G2B) and one cubicle is for the bus section breaker (SPENS 61).
Each cubicle is relatively large and contains three panels. The top panel includes most of the relays. The mid panel, which has a door, has selector switches and indications. The bottom panel is dedicated to interface with the switchgear.

The mid panel offers most space for the addition of new IEDs. This panel is 650mm high and 950mm wide which is sufficiently large. All the 20 cubicles have the same dimensions. For this reason, electrical design will progress with addition of IEDs on the mid panels at the 33kv Switchgear room.

<u>Thanet Grid Telecoms 33kV Relay Room</u>
At the relay room, there are panels for protection of the four Grid transformer incomers. These have available current and voltage measurements, which will also be available at the cubicles at the adjacent switchgear room. It was decided to not install IEDs on the relay room cubicles and place them at the panels at the switch room. This approach keeps consistency with the location of IEDs.

<u>DER site</u>
This is a single brick building with dimension of 4.2x5.4m. [redacted]. One cubicle is reserved for the breaker, protection, and power quality monitoring devices for the customer. The remining circuits are reserved for breaker and protection for circuits to Thanet Grid 33kV and to Thanet Local 33/11kV.

The panel 02, connected to the customer, will accommodate two new redundant IEDs. This will be placed at the bottom of the cubicle, while the power quality device will be moved. The structure to house the Constellation equipment will be a wallbox type structure, instead of an 800x600x2200mm cubicle. There is sufficient space to install a wallbox on site.

<u>DER site</u>
This is a very small pre-fabricated compost building with dimensions of 3x3m. It contains a transformer, AC supplies, 24Vdc batteries, [redacted], protection wallbox and RTU boxes.

The footprint of this site is the most limited one, while the number of existing equipment is quite extensive. On this site, one IED will be installed. Due to space constraints, the existing protection wallbox will be replaced by a new walbox with a device capable to replace the protection and in addition, to bring PMU measurements and IEC618510 signals.

In terms of space for the Constellation equipment, a cabinet with the dimensions 600x600x800mm (DxWxH) will be used. [redacted].

Figure is redacted

Figure 34: DER site: internal view of the site with proposed location of the Constellation equipment.

<u>DER site</u>
This is a single brick building with dimension of 4.6x5.1m. There are two switchgear cubicles on site. One cubicle includes power quality monitoring and protection devices. In this cubicle, two new IEDs will be mounted and replace part of the existing protection.

The site has sufficient space to have a new cubicle mounted against a wall to house Constellation and 5G communications equipment.

<u>DER site</u>
This is a single brick building with dimension of 5x5.mm. [redacted].

There are two switchgear cubicles at the DER site. One cubicle includes power quality monitoring and protection devices. In this cubicle, two new IEDs will be mounted and replace part of the existing protection.

The site has ample space to have a new cubicle mounted against a wall to house Constellation and 5G communications equipment.

A.2.2 Vodafone 5G – Signal Strength

The figures below present the signal strength as recorded during the individual site surveys recorded by Vodafone at each site within both Maidstone Grid and Thanet Grid areas.

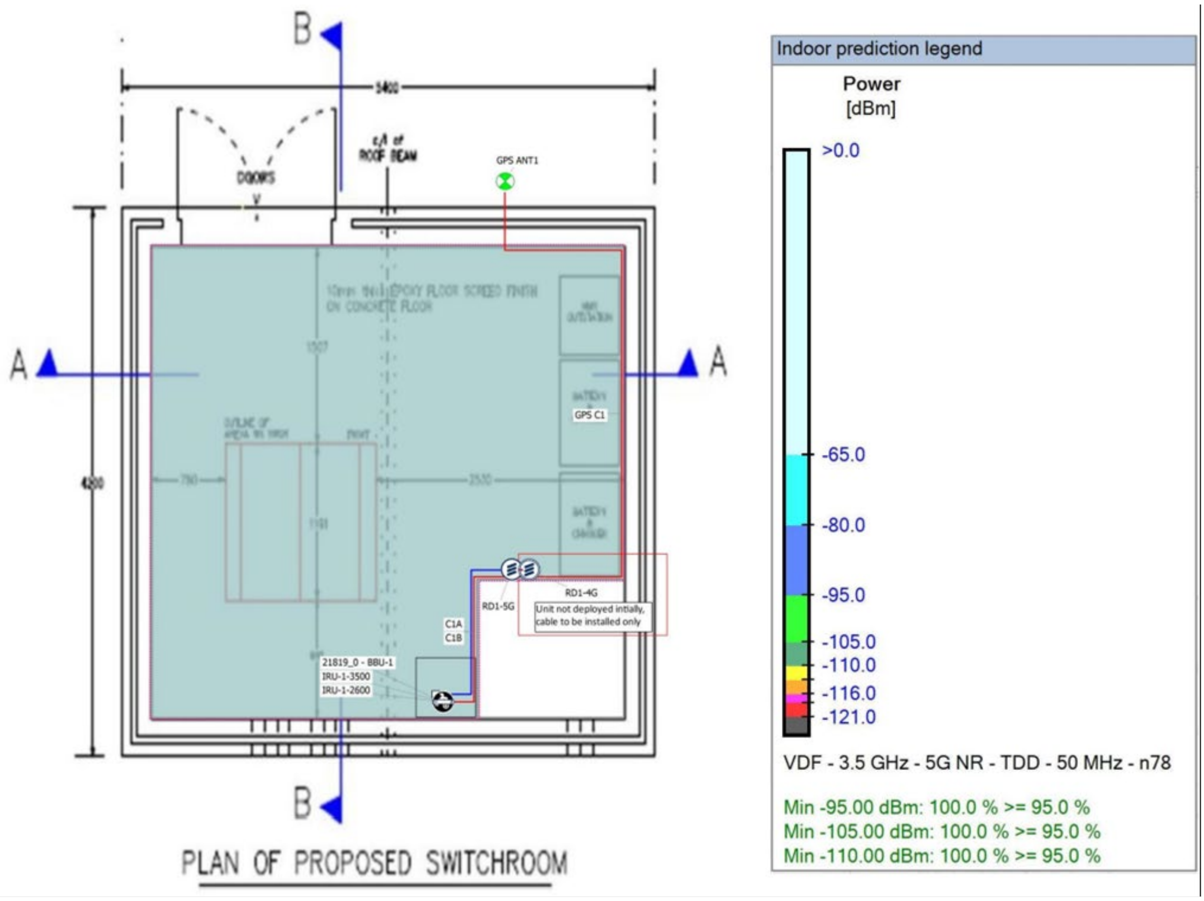


Figure 35: DER site

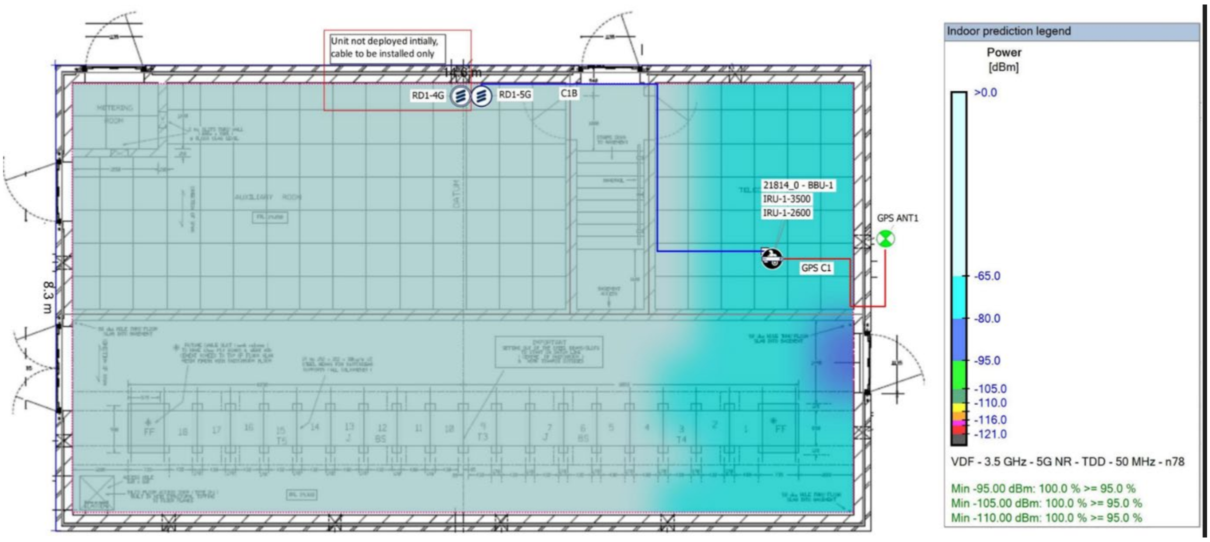


Figure 36: Maidstone

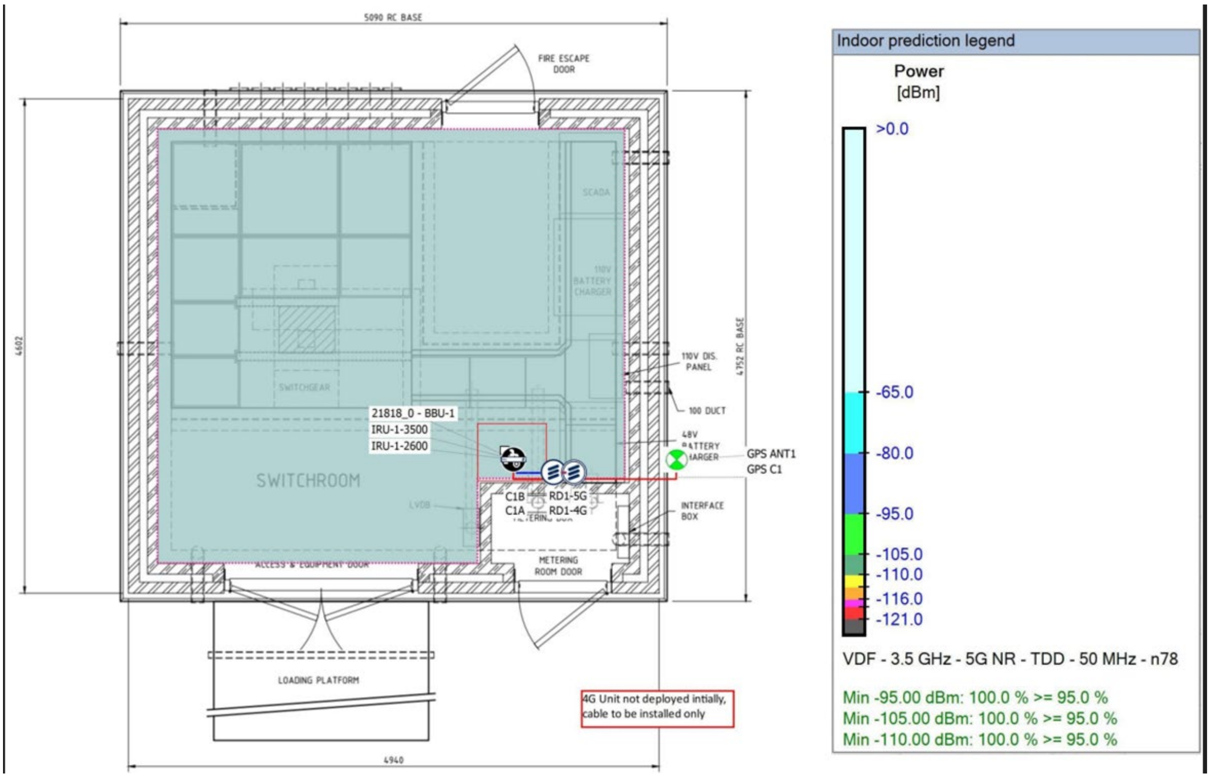


Figure 37: DER site

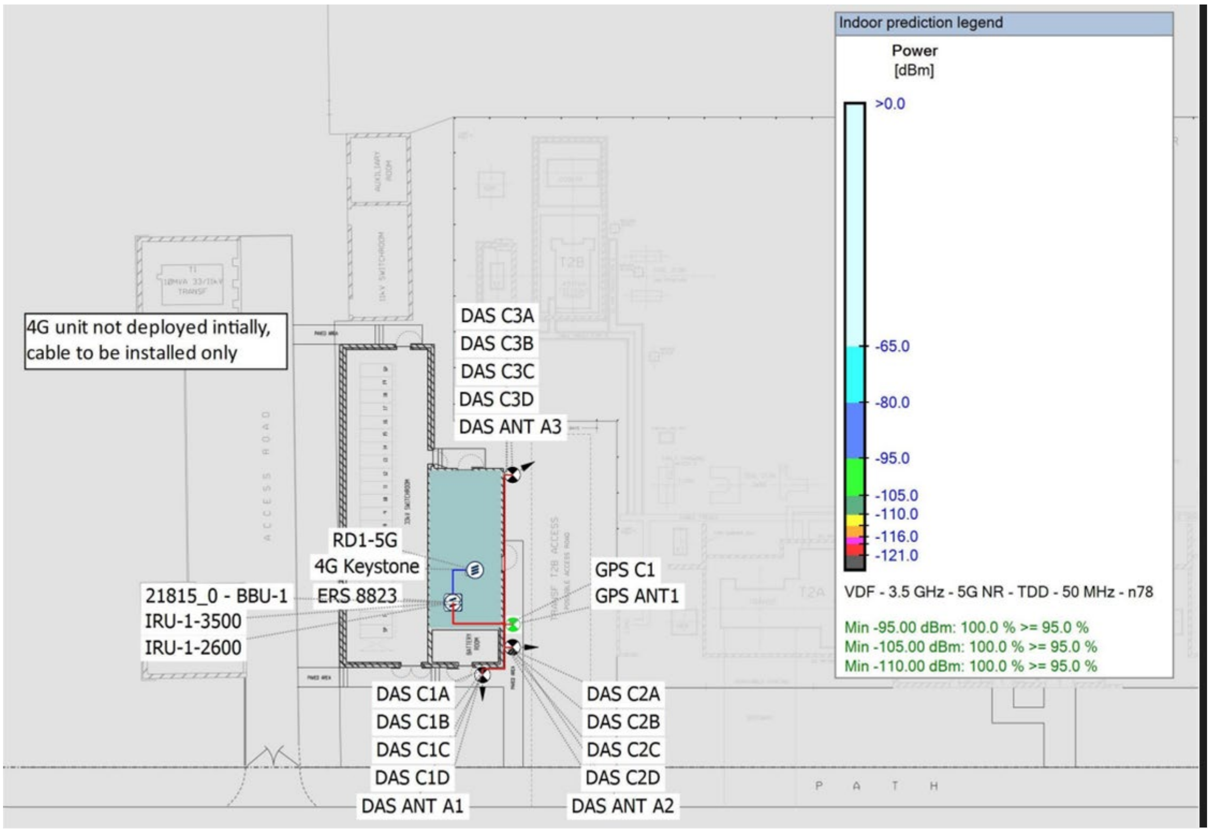


Figure 38: Thanet 33kV

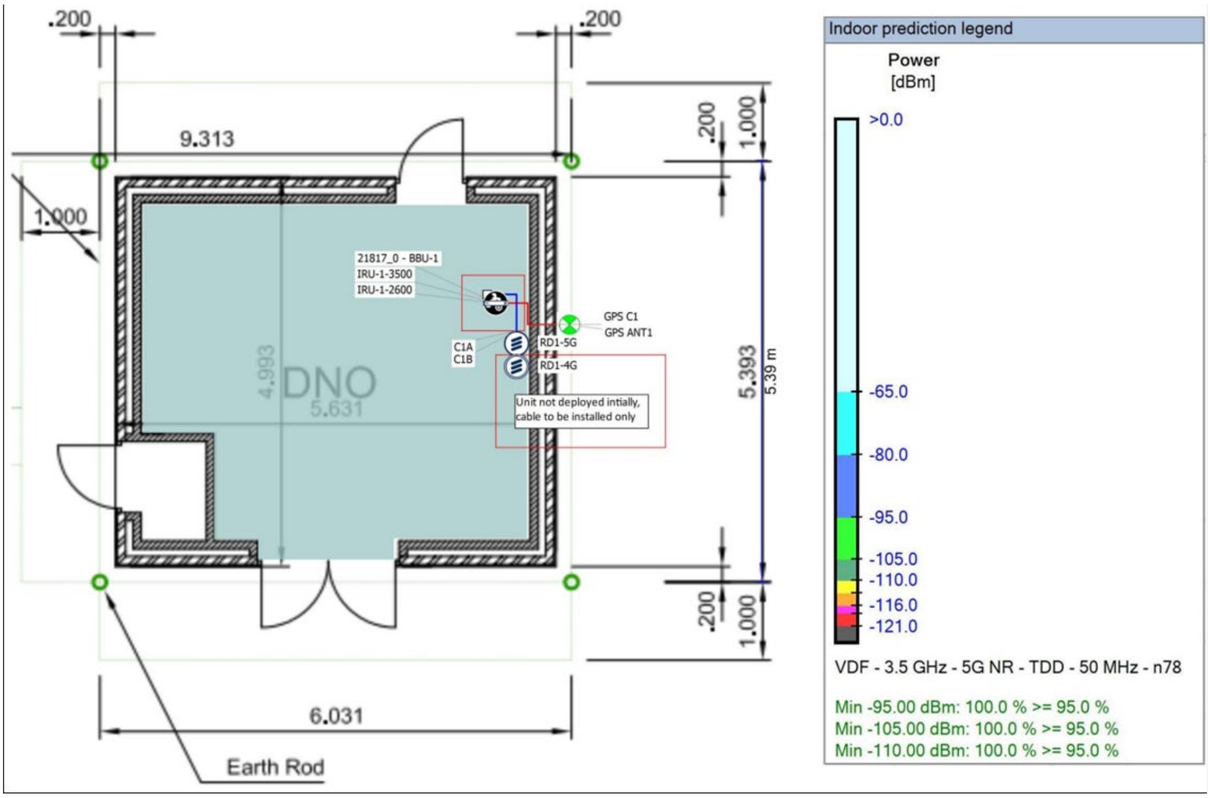


Figure 39: DER site

A.2.3 Vodafone 5G Site Survey Data Capture

The Constellation sites were surveyed by Vodafone. The surveys focused on the civil, infrastructure and hardware requirements for the Vodafone 5G equipment. Propagation modelling was done to determine the potential indoor signal strength for the 5G IoT equipment and the equipment required to implement the solution. The following are the results of the site surveys:

Maidstone Grid

- Propagation modelling indicates that Maidstone Grid site has sufficient indoor coverage.
- An Ericsson Radio DOT system will be required to provide 5G capabilities.
- Sufficient space is available for equipment installation.
- DC power supplies are required

DER site

- Propagation model indicates that the generation site has sufficient indoor coverage.
- An Ericsson Radio DOT system will be required to provide 5G capabilities.
- Sufficient space is available for equipment installation.
- DC power supplies are required

Thanet Grid (Inc. DER sites)

- The Thanet 33 kV building has sufficient indoor coverage. The smaller Thanet 132 kV building, and the DER sites have sufficient coverage for line-of-sight antennas required for the solution.
- Sufficient space is available for equipment installation in the primary building.
- An Ericsson Radio DOT system will be required, additionally a small cell will also be required to receive and send signals to Thanet's 132 kV building, and DER sites.
- Three additional antennas will be required to support the small cell system that will enable the communications to and from the three smaller buildings.
- DC power supplies are required

DER site

- Propagation model indicates that the DER site has sufficient indoor coverage, indoor area is small
- An Ericsson Radio DOT system will be required to provide 5G capabilities
- Sufficient space is available for equipment installation
- DC power supplies are required

DER site

- Propagation model indicates that the DER site has sufficient indoor coverage, indoor area is small
- An Ericsson Radio DOT system will be required to provide 5G capabilities.
- Sufficient space is available for equipment installation.
- DC power supplies are required

A.3 Site Survey Evaluation Tables

Table 15: Results from site Selection Stages 1 to 4

Stage 1 - Network requirements

Steps	Criteria	Description	Maidstone Area	Thanet Area	Lewes Area 1	Lewes Area 2	Data Source
1	Overall area suitability	An area which has a variety of site types (Grid & DER sites). One of the sites acting as the “hub” site with the other sites acting as "satellite" sites	Area consists of a Grid site and one DER site. There are also two Primary sites in the area	Area consists of a Grid site and two DER sites. There are up two more DER sites which can be connected to the Grid site, if the network is reconfigured. There is also one Primary site in the area	Area consists of a Grid site and two DER sites. There are also two Primary sites in the area. This area can also be reconfigured to be connected to another Grid site	Area consists of a Grid site and four DER sites. There are also four Primary sites in the area. This area can also be reconfigured to be connected to another Grid site	UK Power Networks network diagrams
2	Suitability network arrangement	Description of the network arrangement	Area includes a radial connection between the Grid and DER sites. The area can be connected to multiple Grid Supply Points	Area includes a 33kV ring circuit which can be reconfigured to be connected to another Grid site. This area also includes a one DER site directly connected to the Grid site and one DER site connected to a Primary site in the same area.	Area includes a 33kV ring circuit which can be reconfigured to be connected to another Grid site. The area can be connected to multiple Grid Supply Points	Area includes a 33kV ring circuit which can be reconfigured to be connected to another Grid site. The area can be connected to multiple Grid Supply Points	UK Power Networks network diagrams
3	Availability of 5G coverage in area	A high-level description of the 5G coverage in the area	Limited public 5G coverage	Limited public 5G coverage	Limited public 5G coverage	Limited public 5G coverage	Publicly available network coverage data for all UK networks

4	Feedback from key UK Power Networks experts	Overview of the area and suitability for Constellation based on feedback from commissioning engineers, outage planners, control engineers and other experts within UK Power Networks.	Excellent site for testing protection and control functionality, due to the 132kV arrangements and existing protection challenges. The DER in this area [redacted] adds further testing opportunities. This site has been used for other innovation projects due to its suitability	Complex area which is suitable for protection and control functionality testing, due to the operation of central ANM in the area. A mix of synchronous and inverter DG can be connected to the area which is essential for testing	A simple area suitable for demonstration of protection functionality, due to the 132kV arrangements. Only inverter-based generation is connected to this area	A complex area suitable for demonstration of protection functionality, due to the 132kV arrangements. Only inverter-based generation is connected to this area	Key UK Power Networks experts

Stage 2 - Constellation solution suitability

Steps	Criteria	Description	Maidstone Area	Thanet Area	Lewes Area 1	Lewes Area 2	Data Source
1	Connected DER type(s)	The DER technology type (e.g. synchronous, inverter based)	Synchronous	Synchronous & Inverter	Inverter	Inverter	Embedded Capacity Register
2	Number of connected DER	The number of DER in the area	1) [redacted]	1) 2) 3) 4) [redacted]	1) 2) [redacted]	1) 2) 3) [redacted]	PowerOn ADMS
3	DER connection type	The connection type of the DERs (firm or flexible)	[redacted]	1) 2) 3) 4) [redacted]	[redacted]	[redacted]	Embedded Capacity Register

4	Local ANM suitability	• Suitability of the constraints in the area for testing local ANM; and • Suitability to install measurement devices required as part of local ANM.	• No immediate thermal constraints. Network arrangement suitable for simulating constraints in the Grid site; and • Some measurement devices already available on site from previous initiatives. New monitoring required for a part of the area.	• A number of constraints in the area, which are managed by central ANM. Very suitable for demonstrating local ANM; and • New monitoring required for the entire area.	• No immediate thermal constraints. Network arrangement suitable for simulating constraints in the Grid site; and • New monitoring required for the entire area.	• No immediate thermal constraints. Network arrangement suitable for simulating constraints in the Grid site; and • New monitoring required for the entire area.	Distribution Network Planning assessment
5	Wide area protection suitability	• Suitability of the topology of the network for Wide Area Protection; and • Suitability of the existing DER LoM protection for Wide Area Protection.	One [redacted] DER with [redacted]. Anti-islanding protection in place and to be improved once [redacted].	Several medium size DER generators [redacted], with protection in place against loss of mains (G59/G99). Opportunity to test and prove the block of nuisance tripping with advanced Loss of Main's detection algorithms.	Two medium size DER sites in a meshed network. Anti-islanding protection in place but may not be very sensitive due to the highly meshed nature of the network.	Four medium size DER sites in a meshed network. Anti-islanding protection in place but may not be very sensitive due to the highly meshed nature of the network.	Distribution Network Planning assessment
6	Adaptive load blinding protection suitability	Suitability of the protection arrangement for demonstration of adaptive load blinding	Load blinding protection not currently installed in the area. Suitable protection arrangements for installing and demonstrating adaptive load	Load blinding protection already installed in the area. Very suitable for demonstrating adaptive load blinding protection as the existing scheme can be utilised	Load blinding protection not currently installed in the area. Suitable protection arrangements for installing and demonstrating adaptive load	Load blinding protection not currently installed in the area. Suitable protection arrangements for installing and demonstrating	Distribution Network Planning assessment

			blinding protection, due to 132kV network arrangements		blinding protection, due to 132kV network arrangements	adaptive load blinding protection, due to 132kV network arrangements	

Stage 3 - Area logistic considerations

Steps	Criteria	Description	Maidstone Area	Thanet Area	Lewes Area 1	Lewes Area 2	Data Source
1	Cost to include in Constellation trial	A high-level evaluation of the cost to prepare the area for the Constellation trials (high, medium or low)	Medium (low number of sites)	High (high number of sites)	Medium (low number of sites)	High (high number of sites)	Initial site surveys
2	Availability of space for equipment	A high-level evaluation of the space available for installation of Constellation equipment	Limited space available for the required equipment	Sufficient space available for the required equipment	Limited space available for the required equipment	Limited space available for the required equipment	Initial site surveys
3	Planned work	Evaluation of the planned work in the area which may impact the Constellation trials	[redacted]	[redacted]	[redacted]	[redacted]	Planned Outage Planning Tool (Network Vision)

Stage 4 - Other considerations

Steps	Criteria	Description	Maidstone Area	Thanet Area	Lewes Area 1	Lewes Area 2	Data Source
1	Suitability for the Open Innovation Competition	Suitability for testing solutions developed through the Open Innovation Competition	Very suitable for Open Innovation Competition due to low number of sites. This reduces the deployment effort of any additional monitoring required	Very suitable for Open Innovation Competition due to the mix of DG types in the area	Very suitable for Open Innovation Competition due to low number of sites. This reduces the deployment effort of any additional monitoring required	Moderately suitable for Open Innovation Competition due to high number of sites. This increases the deployment effort of any additional monitoring required	Key UK Power Networks experts
2	Suitability for long trial period	Suitable for long trial period to gain data and confidence at minimum scale (and cost)	Very suitable due to the 132kV reconfiguration options which are possible	Very suitable due to central ANM operation in the same area, which can be used for evaluation purposes	Very suitable due to the 132kV reconfiguration options which are possible	Very suitable due to the 132kV reconfiguration options which are possible	Key UK Power Networks experts
3	Type of customers in the area	Type of customers in the area (commercial, industrial, residential etc.)	[redacted]	[redacted]	[redacted]	[redacted]	
4	Other considerations for Constellation demonstration	Overview of any synergies with other projects / ongoing initiatives	This area was used for the testing of Unified Protection, which is the predecessor project of Constellation	This area has central ANM deployed, which allows for direct comparison with local ANM	None	None	Key UK Power Networks experts

Table 16: Results from site Selection Stage 5 - Maidstone

Stage 5A - Network assessment

Steps	Criteria	Description	Maidstone Grid	DER site	Data Source
1	Existing capacity	Evaluation of the firm capacity and maximum load currently	[redacted]	N/A	Planning Load Estimates
2	Fault history	Evaluation of the number of faults on each site	[redacted]	[redacted]	PowerOn ADMS
3	Network constraints	An overview of the constraints within the area / sites	[redacted]	N/A	Distribution Network Planning assessment
4	Network reconfiguration	Suitability of the area / sites to be reconfigured at certain times in the year	Single feeder to DER site	Single feeder to Maidstone Grid	PowerOn ADMS

Stage 5B - General site assessment

Steps	Criteria	Description	Maidstone Grid	DER site	Data Source
1	Availability of space for equipment	An evaluation of the space available for installation of Constellation equipment in each site	Ample telecoms room available for Constellation equipment. switchgear room requires detail design but merger units can be fitted on each panel.	Limited spare footprint available in the building. There are two switchgear panels with space for new merger units.	Site Survey
2	Availability of space for retrofitting IEDs	An evaluation of the space available for installation of IEDs in each site	Each panel has space to retrofit redundant IEDs with the expectation of two network rail panels.	Sufficient space available to retrofit IEDs [redacted].	Site Survey
3	Availability of IT infrastructure (including fibre links)	An evaluation of the IT infrastructure which is available on-site	Optic fibre available on site for protection on the 132KV telecoms building - can be brought to the 33kV telecoms nearby building.	Existing direct fibre optic link to Maidstone Grid which can be used for additional data transmission.	Site Survey
4	Ease of installation/retrofitting	Complexity of site works including installation,	Modern devices on site which can be replaced with existing functions and settings by IEC61850 compliant IEDs.	Modern devices on site which can be replaced with existing	Asset Management SAP database

	mechanical/numerical IEDs.	commission and decommission of IEDs if applicable.		functions and settings by IEC61850 compliant IEDs.	(Protection_Details_and_Settings)
5	5G site survey results	The 5G evaluation results following the site surveys	[redacted]	[redacted]	Vodafone network coverage site surveys. **Source file name format:** xxxxx_0_NET-CAD_Vx.pdf
6	Availability of power supply for equipment	An evaluation of the power supply available in the sites	Available power supply: 230Vac, 48Vdc and 110Vdc	Available power supply: 230Vac, 48Vdc and 110Vdc	Site Survey
7	Site accessibility/location	An evaluation of the site accessibility for equipment unloading	Site on the DNO perimeter. Site access available to authorised personnel.	[redacted]	Asset Management SAP database (Site Records)

Stage 5C - DER assessment

Steps	Criteria	Description	Maidstone Grid	DER site	Data Source
1	Connected DER type	The DER technology type (e.g. syncronous, inverter based)	N/A	Synchronous	Embedded Capacity Register URL: https://ukpowernetworks.opendatasoft.com/explore/dataset/embedded-capacity-register/information/?disjunctive.licence_area
2	DER Parameters	The relevant parameters of the DER	N/A	[redacted]	Embedded Capacity Register
3	DER export limits	The export limits for DER sites	N/A	[redacted]	Embedded Capacity Register

4	DER capacity	The generation capacity of DER	N/A	[redacted]	Embedded Capacity Register

Table 17: Results from site Selection Stage 5 - Thanet

Stage 5A - Network assessment

Steps	Criteria	Description	Thanet Grid	DER site	DER site	DER site	DER site	Data Source
1	Existing and future capacity	Evaluation of the firm capacity and maximum load currently and in the future	[redacted]	N/A	N/A	N/A	N/A	Planning Load Estimates
2	Fault history	Evaluation of the number of faults on each site annually	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	PowerOn ADMS
3	Network constraints	An overview of the constraints within the area / sites	[redacted]	N/A	N/A	N/A	N/A	Distribution Network Planning assessment
4	Network reconfiguration	Suitability of the area / sites to be reconfigured at certain times in the year	Teed feeder to [redacted]. Teed feeder to [redacted]. Single feeder to [redacted].	Teed connection to Richborough Grid and Thanet Grid. DER site can be connected to Thanet Grid directly via Richborough Grid 1 Teed, or indirectly via St Peters 1	Teed connection to Richborough Grid and Thanet Grid. DER site can be connected to Thanet Grid directly via Richborough Grid 2 Teed, or indirectly via St Peters 2	Substation has two outgoing feeders. One directly connects to Thanet Grid. The second is Connected to the 11 kV network via a 33/11 kV transformer at Thanet 11 kV substation.	Connected to the 11 kV network via Thanet 11 kV substation.	PowerOn ADMS

Stage 5B - General site assessment

Steps	Criteria	Description	Thanet Grid	DER site	DER site	DER site	DER site	Data source
1	Availability of space for equipment	An evaluation of the space available for installation of Constellation equipment in each site	Very convenient site as the telecoms rooms is ample and the switchgear panels are tall and wide.	Enough spare footprint available in the building. There are two switchgear panels with space for new merger units.	Generous spare footprint available in the building. There are two switchgear panels with space for new merger units.	Quite limited spare footprint available in the building. There are three switchgear panels with space for new merger units.	Very small pre-fabricated composite building. Enough space for a wallbox to accommodate Constellation Equipment.	Site Survey
2	Availability of space for retrofitting IEDs	An evaluation of the space available for installation of IEDs in each site	Switchroom still has many ancient mechanical relays, which require a large footprint in comparison to modern devices. Plenty of space for new IEDs.	Sufficient space available to retrofit IEDs while one panel remains nearly empty.	Sufficient space available to retrofit IEDs while one panel remains nearly empty.	Plenty of space available to retrofit IEDs as there is a top and bottom panel for protection device.	Enough space for one IED only. Space (inside the pre-fabricated building) is very limited on this site.	Site Survey
3	Availability of IT infrastructure (including fibre links)	An evaluation of the IT infrastructure which is available on-site	Optic fibre available on site for protection on the 132KV telecoms building - can be brought to the 33kV telecoms nearby building.	No relevant IT infrastructure readily available	No relevant IT infrastructure readily available	Existing direct fibre optic link to Thanet Grid which can be used for additional data transmission.	No relevant IT infrastructure readily available	Site Survey
4	Ease of installation/retrofitting mechanical/numerical IEDs.	Complexity of site works including installation, commission and decommission of IEDs if applicable.	Retrofitting activities shall be limited as there is plenty of space to fit new IEDs.	Modern devices on site which can be replaced with existing functions and settings by IEC61850 compliant IEDs.	Modern devices on site which can be replaced with existing functions and settings by IEC61850 compliant IEDs.	Retrofitting activities shall be limited as there is plenty of space to fit new IEDs.	Small space to work in but is feasible to install one new IED.	Asset Management SAP database (Protection_Details

								_and_Settings)
5	5G site survey results	The 5G evaluation results following the site surveys	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	Vodafone network coverage site surveys. **Source file name format:** xxxxx_0_NET-CAD_Vx.pdf
6	Availability of power supply for equipment	An evaluation of the power supply available in the sites	Available power supply: 230Vac, 48Vdc and 110Vdc	Available power supply: 230Vac, 48Vdc and 110Vdc	Available power supply: 230Vac, 48Vdc and 110Vdc	Available power supply: 230Vac, 48Vdc and 110Vdc	Available power supply: 230Vac and 24Vdc	Site Survey
7	Site accessibility/location	An evaluation of the site accessibility for equipment unloading	Site on the DNO perimeter. Site access available to autorised personnel.	[redacted] Site access available to autorised personnel.	[redacted] Site access available to autorised personnel.	[redacted] Site access available to autorised personnel.	[redacted] Site access available to autorised personnel.	Asset Management SAP database (Site Records)

Stage 5C - DER assessment

Steps	Criteria	Description	Thanet Grid	DER site	DER site	DER site	DER site	Data Source
1	Connected DER type	The DER technology type (e.g. syncronous, inverter based)	N/A	Inverter	Inverter	Synchronous	Synchronous	Embedded Capacity Register
2	DER Parameters	The relevant parameters of the DER	N/A	[redacted]	[redacted]	[redacted]	[redacted]	Embedded Capacity Register (Enterprise Way not available on ECR, used PowerOn instead)
3	DER export limits	The export limits for DER sites	N/A	[redacted]	[redacted]	[redacted]	[redacted]	Embedded Capacity Register
4	DER capacity	The generation capacity of DER	N/A	[redacted]	[redacted]	[redacted]	[redacted]	Embedded Capacity Register

A.4 Factory Acceptance Test Procedures (Examples)

A.4.1 GE (Method 1, Local ANM)

Table 18: Initial set of DER Tests

ID	Description	Change under test	Pre-Requisites
DER-002-008-T	Transition from Direct Distributed L-ANM into Holdover when constraint point to DER site communication fails	Constraint point (CP) to DER site communication fails	L-ANM is in direct distributed and timeout will not occur during the test
DER-004-001-T	Transition into Holdover L-ANM from Central ANM when DER site to central ANM communication and DER site to constraint point communication is lost	DER site to central communication fails	DER is controlled by central, DER site to CP communication is unavailable
DER-004-002-T	Transition into Holdover L-ANM from Central ANM due to operator instruction	Operator instruction issued	All communication is healthy, DER is controlled by central no constraints are violated
DER-005-001-T	Transition from Holdover L-ANM into Central ANM due to operator instruction	Operator instruction issued	All communication is healthy, DER is in holdover, no constraints are violated
DER-005-002-T	Transition from Holdover L-ANM into Central ANM when communication between DER site and Central ANM is restored and communication between constraint point site and Central ANM is available	DER site to central communication restored	DER is in holdover, DER site to CP communication is unavailable and DER site to central communication is unavailable
DER-005-003-T	Transition from Holdover L-ANM into Direct Distributed L-ANM when communication between DER site and constraint point has been restored but communication between constraint point site and Central ANM is unavailable	DER site to CP communication restored	DER is in holdover, communication between the DER site and CP is unavailable, CP to central communication is unavailable

ID	Description	Change under test	Pre-Requisites
DER-005-004-T	Transition from Holdover L-ANM into Direct Distributed L-ANM when communication between DER site and constraint point has been restored but DER site to central ANM communication is unavailable	DER site to CP communication restored	DER is in holdover, communication between the DER site and CP is unavailable, DER site to central communication is unavailable
DER-005-005-T	Transition out of Holdover L-ANM into Learned Limit L-ANM when timeout is exceeded	None	DER is in holdover and timeout will expire during test
DER-005-006-T	Transition out of Holdover L-ANM into Learned Limit L-ANM when upper limit of uncertainty violates constraint and no further Plim changes are available	None	DER is in holdover, Plim is at relevant limit and upper limit of uncertainty will violate constraint during test
DER-005-007-T	Transition out of Holdover L-ANM into Learned Limit L-ANM when lower limit of uncertainty violates constraint and no further Plim changes are available	None	DER is in holdover, Plim is at relevant limit and lower limit of uncertainty will violate constraint during test
DER-005-008-T	Transition out of Holdover L-ANM into Failsafe when any local area event is detected	A local area event occurs	DER is in holdover, timeout will not expire during test and uncertainty will not cause holdover to expire
DER-006-001-P	Adjustment of Plim when upper limit of uncertainty violates constraint and Plim range is not exceeded	None	DER is in holdover, Plim is not at relevant limit and upper limit of uncertainty will violate constraint during test
DER-006-002-P	Adjustment of Plim when lower limit of uncertainty violates constraint and Plim range is not exceeded	None	DER is in holdover, Plim is not at relevant limit and lower limit of uncertainty will violate constraint during test
DER-007-001-T	Transition into Learned Limit L-ANM from Central ANM due to operator instruction	Operator instruction issued	All communication is healthy, DER is controlled by central

ID	Description	Change under test	Pre-Requisites
DER-008-001-T	Transition from Learned Limit L-ANM into Central ANM due to operator instruction	Operator instruction issued	All communication is healthy, DER is in learned limit and timeout will not occur during the test
DER-008-002-T	Transition from Learned Limit L-ANM into Central ANM when communication between DER site and Central ANM is restored and communication between constraint point site and Central ANM is available	DER site to central communication restored	DER is in learned limit, DER site to CP communication is unavailable and DER site to central communication is unavailable, timeout will not occur during test
DER-008-003-T	Transition out of Learned Limit L-ANM into Failsafe when any local area event is detected	A local area event occurs	DER is in learned limit, DER site to CP communication is unavailable and DER site to central communication is unavailable, timeout will not occur during test
DER-008-004-T	Remain in learned limit L-ANM when a remote event occurs	A remote event occurs	DER is in learned limit, DER site to CP communication is unavailable and DER site to central communication is unavailable, timeout will not occur during test
DER-008-005-T	Transition out of Learned Limit L-ANM into Failsafe when timeout occurs	None	DER is in learned limit, DER site to CP communication is unavailable and DER site to central communication is unavailable, timeout will occur during test

Table 19: Initial set of Substation Server Tests

ID	Description	Change under test	Pre-Requisites
STA-001-001-T	Successful transition into Direct Distributed L-ANM from Central ANM due to operator instruction	Operator instruction issued	All communication is healthy, L-ANM is inactive and no constraints are violated
STA-001-002-T	Rejected transition into Direct Distributed L-ANM from Central ANM after operator instruction due to existing failure of constraint point to DER site communications.	Operator instruction issued	Constraint point to DER site communication unavailable, L-ANM is inactive and no constraints are violated
STA-001-003-T	Transition into Direct Distributed L-ANM from Central ANM due to a failure of communication between DER site and Central ANM (but DER site to constraint point communication is still available)	Failure of DER to Central ANM communication reported by RTU	All communication is healthy, L-ANM is inactive and no constraints are violated
STA-001-004-T	Transition into Direct Distributed L-ANM from Central ANM due to a failure of communication between constraint point site and Central ANM (but DER site to constraint point communication is still available)	Failure of constraint point to Central ANM communication recognised by L-ANM	All communication is healthy, L-ANM is inactive and no constraints are violated
STA-001-005-T	Transition into Direct Distributed L-ANM from Central ANM due to a constraint violation that Central ANM has failed to correct	A constraint becomes violated	All communication is healthy, L-ANM is inactive and no constraints are violated
STA-002-001-T	Successful transition from Direct Distributed L-ANM into Central ANM due to operator instruction	Operator instruction issued	All communication is healthy, L-ANM is in direct distributed and no constraints are violated
STA-002-002-T	Rejected transition from Direct Distributed L-ANM into Central ANM due to operator instruction	Operator instruction issued	Central ANM to DER communication is unavailable, L-ANM is in direct distributed and no constraints are violated
STA-002-003-T	Transition from Direct Distributed L-ANM into Central ANM when communication between DER site and Central ANM has been restored and constraint point site to central ANM communication is still available	Central ANM to DER communication is restored and reported by RTU	Central ANM to DER communication is unavailable, L-ANM is in direct distributed and no constraints are violated

ID	Description	Change under test	Pre-Requisites
STA-002-004-T	Transition from Direct Distributed L-ANM into Central ANM when communication between constraint point site and Central ANM has been restored and DER site to Central ANM communication is still available	Constraint point to Central ANM communication is restored	Central ANM to constraint point communication is unavailable, L-ANM is in direct distributed and no constraints are violated
STA-002-005-T	Transition from Direct Distributed L-ANM into Failsafe when timeout occurs	None	L-ANM is in direct distributed and the time in direct distributed is sufficiently close to the timeout value that timeout will occur during test duration
STA-002-006-T	Transition from Direct Distributed L-ANM into Failsafe when an unrecoverable local area event is detected	A non-recoverable local event occurs in the PMU data	L-ANM is in direct distributed and timeout will not occur during the test
STA-002-007-R	Successful report by Station Substation Server to Central when CP to DER comms fail	constraint point to DER site communication fails	L-ANM is in direct distributed and timeout will not occur during the test
STA-002-009-R	Failed report by Station Substation Server to Central when CP to DER comms fail	constraint point to DER site communication fails	L-ANM is in direct distributed, communication between central and CP is unavailable and timeout will not occur during the test
STA-003-001-P	Proper management of a constraint violation occurring, e.g. for a reverse power flow limit a load decrease causes the constraint to be violated so DER must be limited	Load reduction causes reverse power flow limit to be violated	L-ANM is in direct distributed and timeout will not occur during the test
STA-003-002-P	Proper management of a constraint violation being removed, e.g. for a reverse power flow limit a load increase causes the constraint to violation to be removed so DER limit can be relaxed	Load increase causes reverse power flow limit to be relieved	L-ANM is in direct distributed and timeout will not occur during the test
STA-003-003-C	Proper detection of DER disconnection via P and Q measured at DER site	DER disconnects	L-ANM is in direct distributed and timeout will not occur during the test

ID	Description	Change under test	Pre-Requisites
STA-003-004-C	Proper detection of DER reconnection via P and Q measured at DER site	DER reconnects	L-ANM is in direct distributed and timeout will not occur during the test. One DER is not exporting power
STA-003-005-P	Local event recovery initiated after a recoverable local area event is detected	A local, recoverable event occurs	L-ANM is in direct distributed and timeout will not occur during the test

Test ID STA-001-001-T	**Test Name: Successful transition into Direct Distributed L-ANM from Central ANM due to operator instruction**	
Objective	Confirm the L-ANM solution will receive and respond to an operator instruction to enter Direct Distributed	
Set-up	Using the substation site test setup: • Apply the standard configuration to the Substation Server • Ensure all communication links are healthy • Selected and prepare the appropriate playback signals • Ensure the output capture is healthy	
1. Procedure	Start signal playback	
2. Verification	At time equal to 5 seconds a command to enter direct distributed will be received	☐
3. Procedure	Wait	
4. Verification	Observe as the shift to direct distributed is communicated to the DER site as part of the substation site outputs.	☐
Comments		

Outcome ☐ GE Reporting ☐ Customer witnessed ☐ Approved ☐ Not Complete ☐ Failed	GE Responsible Signature Date	Customer Responsible (if applicable) Signature Date

Figure 40: Example of GE's Intended Test Procedure Template

A.4.2 Siemens (Method 2, Adaptive Protection)

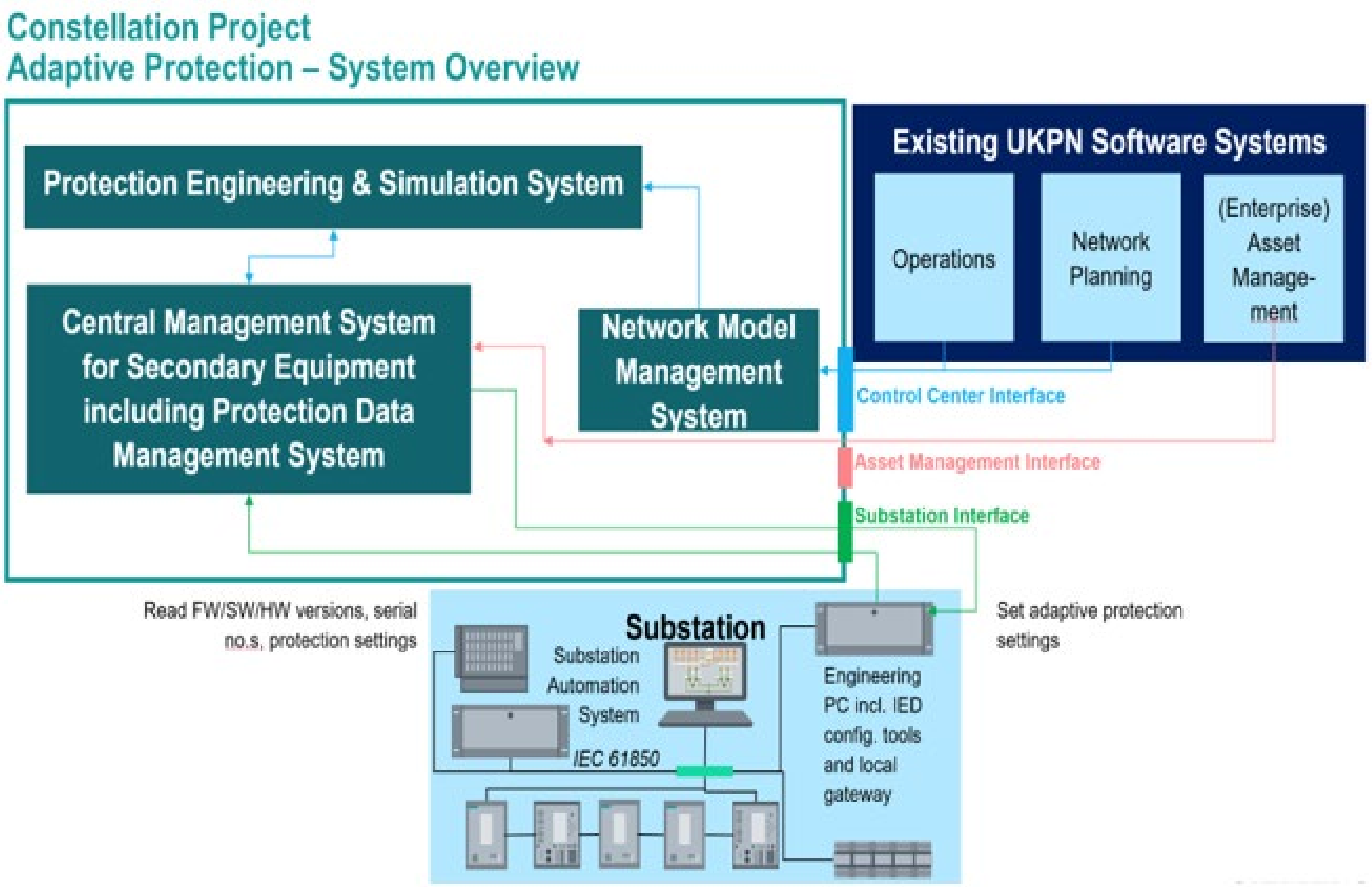


Figure 41: Whole System Architecture (Adaptive Protection FAT)

A.4.3 ABB (Method 2, Wide Area Protection)

Test	**Three-Phase non-directional overcurrent protection function**	**Customer**		UK Power Networks			**Date**	[DATE]	
		Project		Constellation					
		Substation		[SUBSTATION NAME]				33	**[kV]**
		Bay		[BAY NAME]			**DUT**	[RELAY & SSC	
Step	**Description**	**Checklist**							
		Testset		**[RELAY TK]**		**[SSC600 TK]**		**SCADA**	
		Check	**N/A**	**Check**	**N/A**	**Check**	**N/A**	**Check**	**N/A**
1	In the protection IED enable only the protection function to be tested and disable all other protection functions in protection IED and SSC600 respectively								
2	Verify that the CB is closed and all alarms are cleared on the protection IED, SSC600 and SCADA system								
3	Inject secondary measurement values to the protection IED and increase progressively the phase(s) current magnitude until the protection function START signal is triggered on the protection IED								
4	Verify that the protection function START signal is triggered on the protection IED alarms/events/LEDs/Disturbance Recorder								
5	Verify that the protection function START signal is NOT triggered on the SSC600 alarms/events/LEDs/Disturbance Recorder								
6	Verify that the protection function START signal is reported on the SCADA system from the protection IED								
7	Verify that the protection function START signal is NOT reported on the SCADA system from the SSC600								
8	Clear all the alarms/events/LEDs/Disturbance Recorder on the protection IED, SSC600 and SCADA system respectively								
9	Create a test file document and Inject secondary measurement values to the protection IED and increase progressively the phase(s) current magnitude until the protection function START & OPERATE signals are triggered on the protection IED and the CB is opened by the protection IED								
10	Verify that the protection function OPERATE signal is triggered on the protection IED alarms/events/LEDs/Disturbance Recorder								
11	Verify that the protection function OPERATE signal is NOT triggered on the SSC600 alarms/events/LEDs/Disturbance Recorder								
12	Verify that the protection function OPERATE signal is reported on the SCADA system from the protection IED								
13	Verify that the protection function OPERATE signal is NOT reported on the SCADA system from the SSC600								
14	Check the operation time of the protection function and asses if retesting is needed								
15	Save the test file document								
16	Close the CB and clear all alarms on the devices								
17	In the SSC600 enable only the protection function to be tested and disable all other protection functions in protection IED and SSC600 respectively								
18	Verify that the CB is closed and all alarms are cleared on the protection IED, SSC600 and SCADA system								
19	Create a test file document and Inject secondary measurement values to the protection IED and increase progressively the phase(s) current magnitude until the protection function START signal is triggered on the SSC600								
20	Verify that the protection function START signal is NOT triggered on the protection IED alarms/events/LEDs/Disturbance Recorder								
21	Verify that the protection function START signal is triggered on the SSC600 alarms/events/LEDs/Disturbance Recorder								
22	Verify that the protection function START signal is NOT reported on the SCADA system from the protection IED								
23	Verify that the protection function START signal is reported on the SCADA system from the SSC600								
24	Clear all the alarms/events/LEDs/Disturbance Recorder on the protection IED, SSC600 and SCADA system respectively								
25	Inject secondary measurement values to the protection IED and increase progressively the phase(s) current magnitude until the protection function START & OPERATE signals are triggered on the SSC600 and the CB is opened by the protection IED								
26	Verify that the EXTERNAL TRIP signal is triggered on the protection IED alarms/events/LEDs/Disturbance Recorder								
27	Verify that the protection function OPERATE signal is triggered on the SSC600 alarms/events/LEDs/Disturbance Recorder								
28	Verify that the protection function OPERATE signal is NOT reported on the SCADA system from the protection IED								
29	Verify that the protection function OPERATE signal is reported on the SCADA system from the SSC600								
30	Check the operation time of the protection function and asses if retesting is needed								
31	Save the test file document								

Test	**Wide area protection scheme - Hardware-in-the-loop (HIL) simulation - draft 1**	**Customer**		UK Power Networks			**Date**	[DATE]	
		Project		Constellation					
		Substation		[SUBSTATION NAME]				33	**[kV]**
		Bay		[BAY NAME]			**DUT**	[RELAY & SSC	
Step	**Description**	**Checklist**							
		Testset		**[RELAY TK]**		**[SSC600 TK]**		**SCADA**	
		Check	**N/A**	**Check**	**N/A**	**Check**	**N/A**	**Check**	**N/A**
1	Open the "phasor diagrams" view in the web HMI. Check that current and voltage measurements match with the values simulated in RTDS.								
2	Check that the circuit breaker statuses during healthy state match with the simulated circuit breaker statuses.								
3	Simulate switching events that will cause DG units 1-4 to be islanded, one or several DG units at the time. Check that the functioning of the intertrip logic. Verify that the correct DG unit has been disconnected by the intertrip logic. There is an additional tripping criterion in the intertrrip logic for Feeders connected via circuit breakers SPENS 03 and SPENS 04. These two feeders, which both accommodate PV generation (DG units 3 and 4), can be supplied from Richborough instead of Thanet, if desired. An intertrip command from the main area substation computer to trip DG units 3 or 4 is therefore only sent the circuit breaker is opened due to a fault. Verify the proper functioning of this feature by inflicting a fault on feeders SPENS 03 and SPENS 04, which results to a general operate from the tested SSC600. Check that there is a suitable protection function (e.g. overcurrent protection) active on bays SPENS 03 and SPENS 04 in the PCM600 configuration.								
4	Check that the communication supervision logic is enabled as set as intended for all DER site computers and the Main area site computer. The associated communication link supervision pulses can be observed from RTDS runtime graphs.								
5	Test the communication supervision logic. When causing a communication break, does the supervision logic detect the communication break in the set time? Check also the reset time functionality, i.e., that reset time seen in RTDS matches with the setting used in the tested SSC600.								
6	Test the functioning of the wide area protection scheme by causing suitable changes in the frequency of the supplying 132 kV voltage source (i.e. which represents a national grid connection point). Change the frequency with rate lower rate than the the rate of change of frequency value used for triggering the wide area protection logic. Verify that no erroneous blocking occurred.								
7	Test the functioning of the wide area protection scheme by causing suitable changes in the frequency of the supplying 132 kV voltage source (i.e. which represents a national grid connection point). Change the frequency up/down with a rate higher than the the rate of change of frequency value used for triggering the wide area protection logic. Verify that the BLOCK ROCOF message was sent and that no false tripping of DG units occurred. Perform a similar test when causing a "wide area disturbance" of opposite ROCOF polarity.								
8									

Figure 42. Example ABB Test Procedure

A.4.4 5G Site-to-Site Communication Testing (Vodafone)

Table 20: Example Vodafone Test Process

S.No	Test Case	Method of testing	Check, result, comment
1	Health Check of Constellation Slice	Check health of AMF, SMF and UPF (Dedicated), check interface status between AMF-SMF, SMF-UPF, AMF-AUSF/UDM and SMF-UDM	Pass
2	Health check of Core-RAN connection for Constellation sites	Check gNb status in AMF (N2) and UPF (N3)	Pass
3	Provisioning of Constellation devices with new slice, DNN, static IP, UPIP etc	Vodafone to provide secured SIM card (SUCI enabled) with security details which will be provisioned in the UDR using EDA-2 (Provisioning gateway) together with Slice number and static IP of each device	Pass
4	Register Constellation 5G Device in 5G Network (5G Signal in Device)	The 5G SIM card should be inserted into the 5G device and switched on; the 5G device should then be authenticated in the 5G Core and registered in the 5G network; Printing the data in AMF and UDR should show that the 5G device is authenticated and registered in 5G network; there should be 5G signal bars showing in the 5G device	Pass
5	PDU Session Establishment with associated DNN for Constellation device (Mobile data ON)	The 5G device should be configured with APN configuration (Agreed APN) and “Mobile Data” should be switched on so that the device initiates a PDU Session; verify the PDU session establishment by printing data in SMF, UDR and UPF (Dedicated for UKPN)	Pass
6	Check data transmission from one device to another (measure latency and throughput)	5G device to trigger sending of data using router to another 5G device connected to the 5G network. The 2nd device should receive the data via the 5G Core (UPF). Latency, jitter and throughput using statistics in UPF.	Pass
7	Activate UPIP and Check data transmission from one device to another (measure latency and throughput)	Activate User plane integrity protection in the 5G Core (SMF) and compare latency with and without UPIP.	Pass
8	Compare latency against L2TP and L3 (Config by UKPN in Ruggedcom)	UK Power Networks to configure the router with and without L2TP and latency compared with both options	<10ms

9	Speed test	A Samsung galaxy S21 5G handset using an app such as OOKLA with a number of tests to be taken close to the DOT and in the target areas (if an RU with external antenna is utilised).	=>100mb/sec
10	Coverage checks	A dedicated tablet connected to a PCTEL IBFLEX scanner recording VF 5G coverage levels from the scheme.	> -80dBm

A.5 PNDC Test Cases

This appendix presents one PNDC test case in full (Test case TC-01) and then provides summary details on the remainder.

A.5.1 Test Case – TC01

Project : Constellation Method - 1: Local ANM
Name of the Test Case
Test the decentralised, virtualised Local Active Network Management application in the event of communication loss between Central ANM and Grid/DER site.
Method Overview
The objective of Local Active Network Management designed in the Constellation project is to develop a distributed intelligence-based solution, resilient to loss of communication which has visibility over network constraints and the state of the network using local, time synchronised measurements. Data analytics and machine learning technology utilise these measurements to deliver a solution that allows the DERs (Distributed Energy Resources) to continue operation through communication outages with minimal interruption. An autonomous, virtualised and decentralised application referred to as Local ANM is installed on the Constellation platform i.e., Substation Server (including virtualised PDC (Phasor Data Concentrator), WAMS DE Edge and Phasor Controller) at Grid/DER sites). A WAMS (Wide Area Measurement System) Digital Energy (WAMS DE) application will run as the central Azure cloud server including the computationally intensive ML (Machine Learning) model building processes. The Local ANM is intended to process state estimation, advanced data analytics and machine learning based forecasting using local synchrophasors. When the DER site Substation Server loses all communication learned limit or holdover Local ANM will be applied. These methods are based on machine learning models that estimate the headroom available In the normal state, the local intelligence is trained as to what is “normal” and the acceptable operating parameters at different times. It will also learn from remote sites, via 5G, how its output impacts network constraints. On communication loss to central ANM, the Substation Server will coordinate the DER sites using local intelligence that draws on both local and remote measurements over 5G to provide the maximum safe output through the application of direct distributed Local ANM. Under direct distributed Local ANM, the application directly measures/derives network constraints and calculates available headroom to maintain the optimal DER asset operational, when the communication to central ANM system is unavailable (or as and when selected for operation manually through enable/disable button in ADMS). On loss of all communication, the local intelligence will rely purely on local measurements to safely maximize DER output, as the central ANM would, through the application of either holdover or learned limit Local ANM as applicable. As a last resort, fail-to-safety principle, in a rare event of failure of all intelligent functionalities, the solution will apply the most conservative fail-safe action to prevent damage to the network.

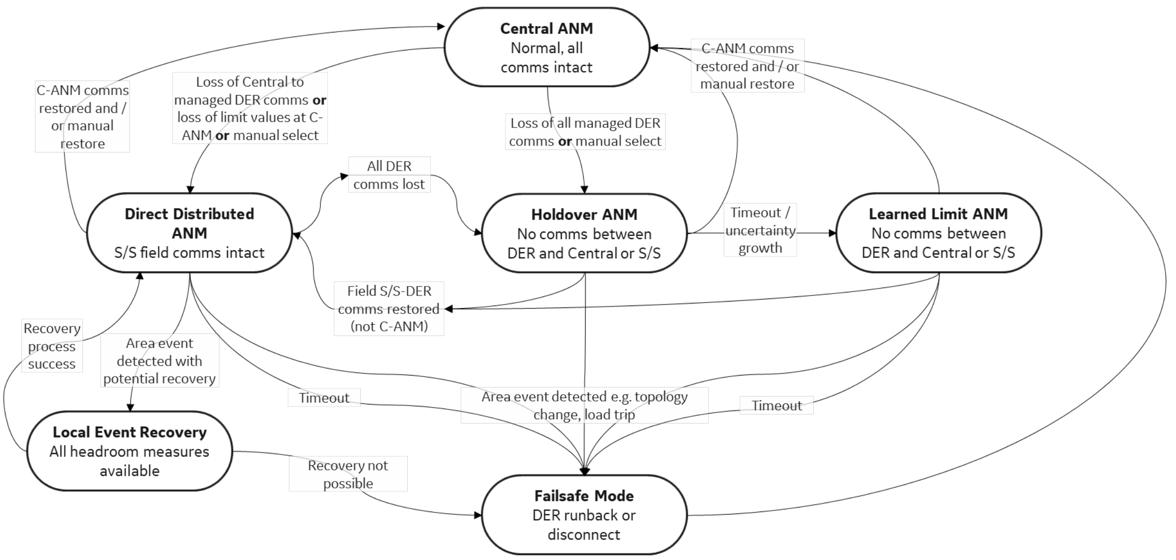


Figure 43 : Different modes of operation as per approved design (ref: GE design document)

Function(s) under Test (FuT) (*A brief overview of the functions considered for testing is covered here, detailed test steps, test metrics and expected outcomes shall be covered in the test specifications that follow the test case document*)

Test Category 1: Integration Tests –

The integration test shall comprise:

- Establishing and testing the integration and communication of different hardware components/virtualised modules of the Local ANM application including the relevant networking and security elements, as a combined entity. This shall focus mainly on launching the interfaces & data flow between the modules as per approved architecture, together with documented operational settings & parameters and access credentials.
- Establishing audit trail and event logging capability is also an integral part of the integration, while the list of alarms/events as reporting at SCPs/ADMS (Advanced Distribution Management System – GE PowerOn) shall be verified during the functional/performance verification. The comprehensive alarm/event list shall be tested during UK Power Networks live trials.

The data flow from testing hardware and software modules including test system modelled in RSCAD shall be established under the integration test at PNDC.

Test Category 2: Functional Tests –

- Measurement, aggregation and visualisation of C37.118 WAMS data at the virtualised applications in Grid Substation Server (including via 5G), at local WAMS DE in the SCPs and central WAMS DE server.
- Seamless switch over between three modes (Direct Distributed, Learned Limit and Holdover) during communication failure of Central ANM (Central to Local/Grid SS to Local) or manual enable/disable from ADMS.
- Ability of the Local ANM application to measure/derive constraint headroom to maintain the optimal DER asset operation and maximise the DER output, in the event of communication loss to Central ANM. This shall cover the functional requirements covered as per ETS 05-1603.
- Fail safe response on inadequate/unwarranted response to a regulation action/ issue

aggravated by ANM (e.g. if a DER is subject to a Plim command but it is unresponsive within the specificied time limit)

- Interactions with protection/other control schemes– under/over voltage/frequency, AVC (Automatic Voltage Control) using OLTC.
- Multiple DER sites to be associated with multiple power network constraints, arbitrations to avoid conflicts among instructions.
- Audit Trail/Event log at Substation Server - DER acknowledgements and watchdog alarms, alarms and indications at the Substation Computer level, DER exceeding the maximum setpoint limit, application-level system changes, monitor DER ramp up/ramp downtimes and provide alarms in case of no compliance from the DER site.

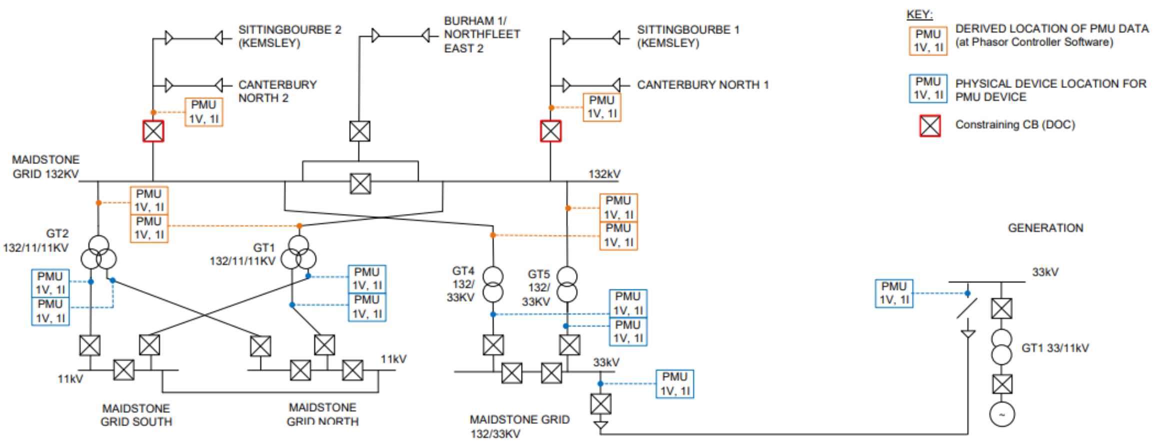
It is expected that each Constellation Method would have its own time stamped event log/operational log capability for alarm/indication at the Substation Server level. Alarms/events/audit trail at RTU (Remote Terminal Unit) level and/or the UK Power Networks central control system level (for e.g. UKPN ADMS) shall be tested during live trials (against an approved alarm list, if available).

Test Category 3: Performance Tests –

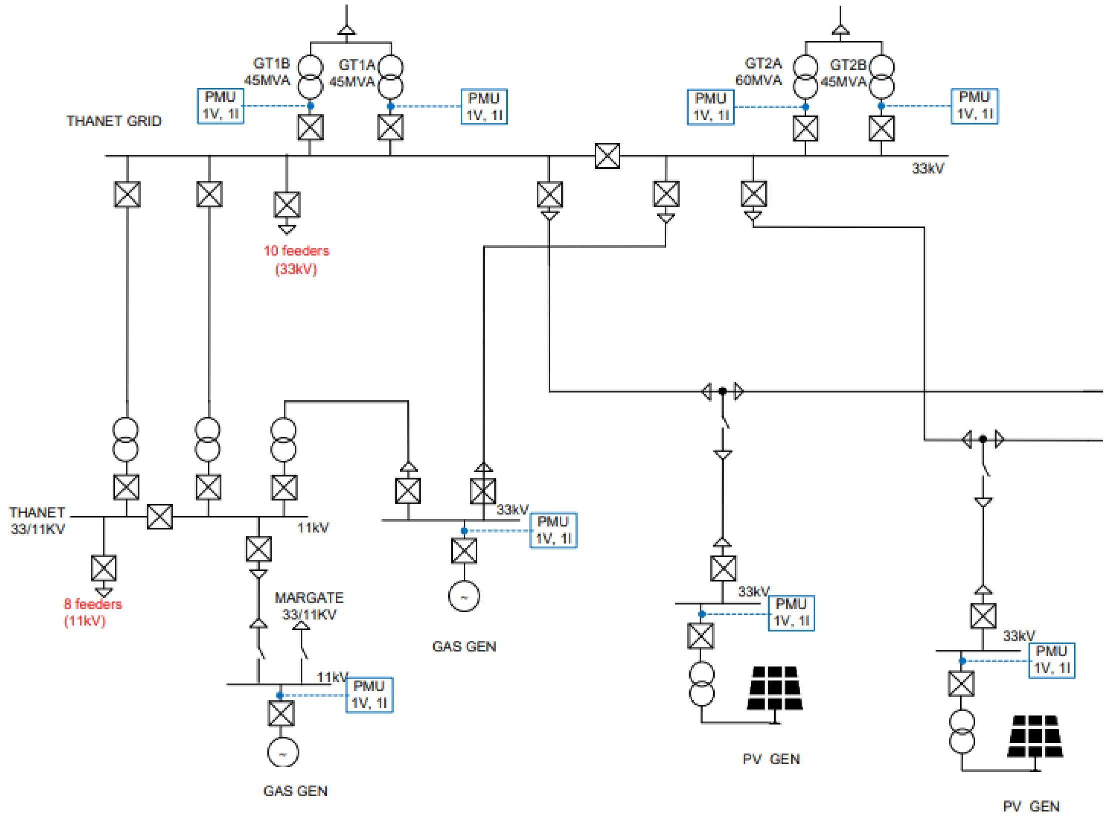
- Communication network tests - bandwidth, latency, effect of congestion on prognosis of network condition & reliability of Local ANM functionality.
- Effect of loss of time synchronisation on reliability of the Local ANM function.
- Effect of quality of measurement on sensitivity of Local ANM function.
- Fail safe response on failure of network nodes, substation computer, Merging Unit, PMUs etc.
- Configurable timeout capability to relinquish control to Central ANM during testing.
- Removal of non-participating DER from Local ANM.

System under Test (SuT)

A simplified SLD (Single Line Diagram) of Maidstone and Thanet showing measurement locations (might be revised based on final design document), network boundaries and point of constraints [7] are shown below.



Trial site 1 – Maidstone



Trial site 2 – Thanet

Testing Principle (TP)

1) System modelling of the selected UK Power Networks trial sites (Maidstone & Thanet), considering equivalent models at the agreed boundaries of the power system network, in RSCAD.
2) Duplicate the UKPN ADMS capabilities at PNDC PoA ADMS, as relevant to the test set up of project Constellation. While the system model in RSCAD duplicates the trial sites and communicates to other hardware components/software modules of Local ANM application, using the capabilities of RTDS to realise the interfaces.
3) Integrate and interface all the hardware components/software modules of the Local ANM application to establish the data flow as per approved architecture.
4) Integrate and interface with the test set up, to establish communication of test signals, to realise the use cases elaborated in each of the test specifications.
5) Simulate use cases in RSCAD to realise constraint violations and other operational conditions to demonstrate the capability of Local ANM application against approved design and functional requirements specified in ETS-05-1603.
6) Simulate use cases to establish the limits of Local ANM application (stress testing).
7) Gather mandatory documents to be submitted by OEM & document test results and analysis as per common data management plan to ensure efficient exchange and interpretation of trial results.

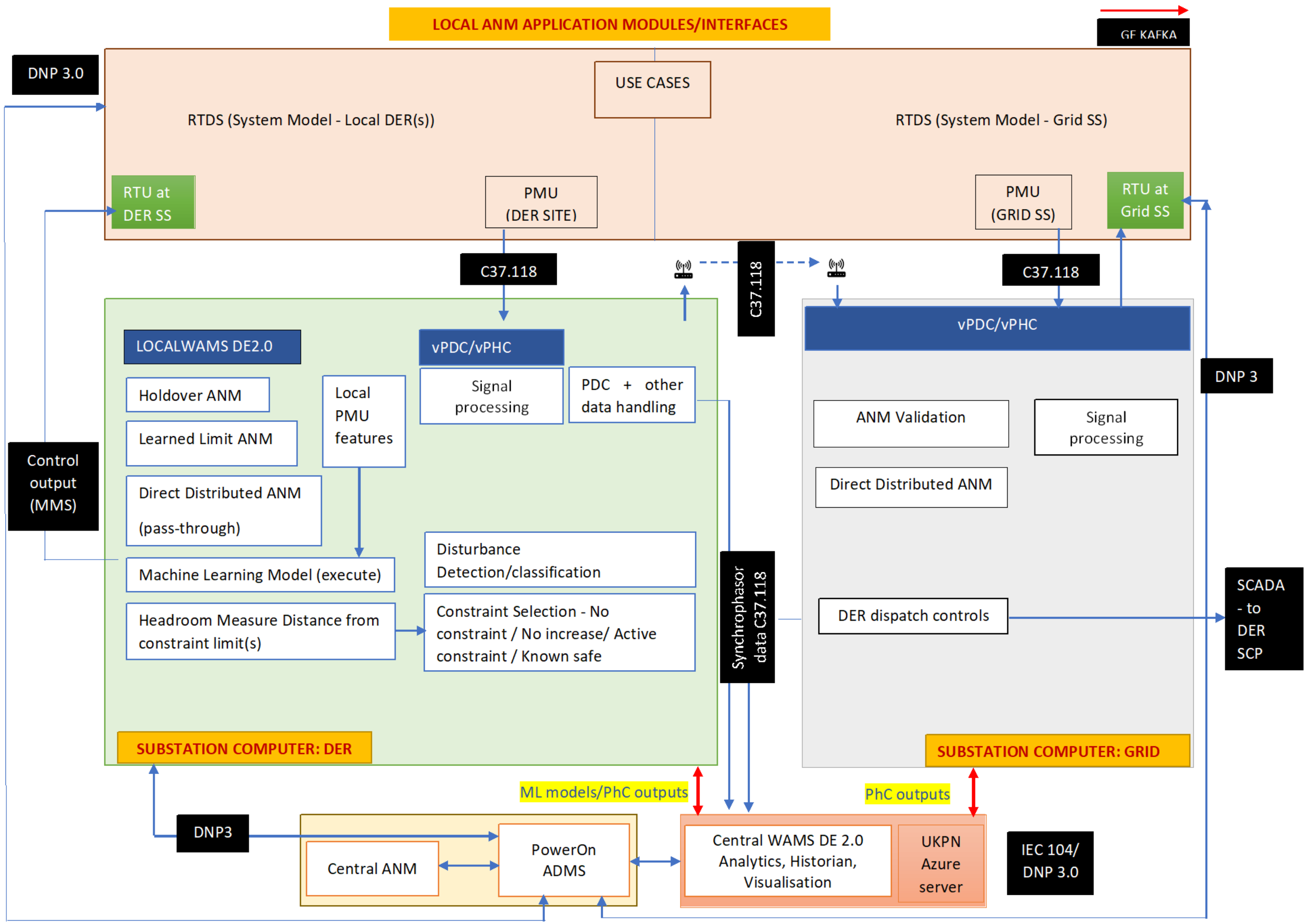
Test Metrics (TM)	1) Deviation from statutory operation limits

	2) Response times 3) Bandwidth, Propagation delays, Latencies 4) System parameters (V,P,Q,f) at GSP/Grid/DER bus, GT before and after control action 5) Reference set points issued by Local ANM 6) Variation in forecast/decision making by local solution vs when communication available (provided Central ANM (CANM) decisions available) 7) Interoperability and arbitration among the virtualised modules/hardware components of the application 8) Interoperability and arbitration with Central ANM and among the existing protection and control schemes in place at Grid/DER sites
Test Variables (TV) Uncontrollable attributes beyond the purview of defined test design	1) Different types of DERs and characteristic curves all of which might not be comprehensively covered in the trial sites 2) Different control modes of the DER and scope of controllability from Local ANM which may not be available in the solution under consideration 3) Varying generation/load profile or summer/winter ratings all of which might not be comprehensively covered in the model 4) OEM specific configuration and settings of Local ANM which form part of the black box 5) 5G Communication Network parameters
Quality Attributes (QA) threshold levels for test result quality as well as pass/fail criteria.	1) The Constellation Method 1 hardware components and virtualised applications integrate, arbitrate and interoperate with each other and with Central ANM and the other existing P&C schemes in operation. 2) DER output managed within technical limitations at all times. [8, 9] 3) Switch on Local ANM control from Central ANM within 750 ms of loss of communication. 4) Update the DER generation setpoints within 750 ms of fault/disturbance inception. 5) Failsafe response is instructed when applicable. 6) Relinquish control with Central ANM on restoration of communication/when disabled by operator. 7) Engineering Documents as per ETS 05-1603A.

A.5.1.1: Test Specification – TS1.1 : Integration Test

Test Case Reference
TC01 – Test Category 1 : Integration Test
Test Objective
Bench test the integration, interfaces and data exchange between different hardware components/virtualised modules of the Local ANM application including the relevant networking (5G, layer 2, layer 3) and security elements, as a combined entity, as per approved architecture in ETS-05-1603. Verify the input/output mapping to cover full integration test prior to functional/performance verification/validation and on-site testing. Verify audit trail and event logging capability.

Specific Test System (graphical)



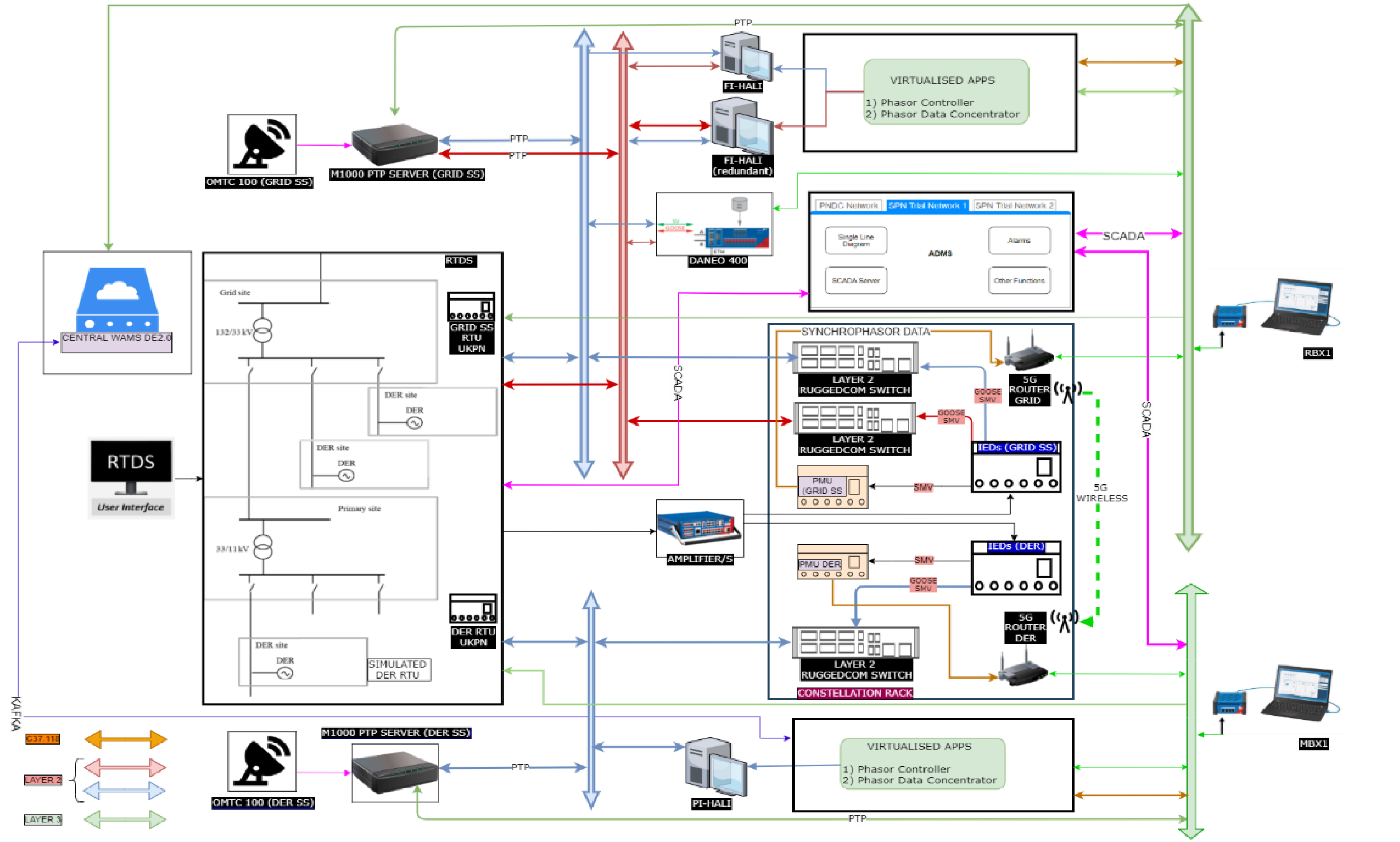
Local ANM solution and interfaces

Pre-Requisite
The unit tests including configuration of operational parameters & settings and access credentials in the hardware/software modules are assumed to have been completed in the FAT/SAT. The integration tests shall be conducted construing the documented operational parameters & settings and FAT and SAT results.
Test Design (Use Cases (UC))
UC 1: Establish the interfaces and communication links between the hardware components and virtualised modules and ensure end to end healthy poll. **UC 2:** Check security access points e.g., authorised user access. **UC 3:** Verify the measurement points (AI) and status values (DI) in the relevant IED, HMI/WAMS application/ADMS/other visualisation tool. Ensure the quality of data. Force binary input values to check change of status and updating of event logs. **UC 4**: Simulate varying binary outputs from Local ANM to RSCAD and analogue outputs (e.g., network constraint measurements to ADMS) from RSCAD, to ensure the data flow through RTDS interface and updating the same in relevant applications. **UC 5:** Verify dataflow using DANEO 400 which serves as the multimeter for digital signals /using a traffic monitor like Wireshark. **UC 6**: Force change various output levels in DER to verify updating of alarms/audit trails. **UC 7**: Turn off and reinitialise all applications.
Test Metrics
Proper mapping of Analogue/Digital Inputs/Outputs between various applications. Proper responses to state of change/commands, e.g., in visualisation tools/audit trails, enable/disable commands etc. Configuration of interfaces as per approved architecture.
Expected outcome
• Local ANM application hardware components and virtualised modules integrate, arbitrate and interoperate with each other and with the existing monitoring and control schemes, through proper communication of analogue and digital input and output data as per approved architecture. • Documented outcome – Digital and Analog I/O map with details of interface.
Source of uncertainty
Configuration parameters/settings specific to the solution, the virtualisation platform or communication infrastructure.

A.5.1.2: Test Specification – TS1.2 : Functional Test

Test Case Reference
TC01- Test Category 2 : Functional Test
Test Objective
This shall verify the relevant functional requirements as per ETS 05-1603. Simulate use cases, test and demonstrate the Local ANM application ability to: 1) Measure/derive voltage/thermal constraints and calculate available headroom. 2) Issue the correct operational set points to DER from virtualised Local ANM application in Substation Server (Grid/DER as per the relevant case) for different DER control strategies (i.e., Power Factor Control-Voltage Control (PFC-VC), Volt-Watt and Frequency-Watt). 3) Switch to fail-safe mode: predetermined fail-safe settings (active power limit, reactive power limit/set point) or keeping the DER energized with zero output or trip DER, when required. 4) Maintain the optimal DER asset operation and maximise the DER output within contractually defined PQ envelope, during loss of communication & visibility at central ANM. 5) Report health and control actions – audit log at Substation Server.

Specific Test System (graphical)



Pre-Requisite
The nature and location of constraints already identified at the trial sites shall be shared by the utility. Based on the data shared, steady state voltage/power flow studies can be carried out on the modelled trial areas (Maidstone and Thanet) (truncated above 132 kV at Grid supply points to the trial areas and below 11 kV as equivalent loads at the trial areas) to validate the constraints identified & to understand any violations beyond statutory limits.
Test Design (Use Cases (UC))
The following use cases are simulated in the system model in RSCAD **UC1:** Simulate positive and negative step changes in voltage of 1.05 pu at 132 kV GSP bus to probe the Local ANM response [10]. **UC2:** Simulate negative and positive progressive ramps in voltage at 132 kV GSP bus to probe the Local ANM response [10]. **UC3:** Simulate varying generation & load profile (maximum generation-minimum load, maximum generation-maximum load, minimum generation-maximum load, minimum generation-minimum load, typical generation-load profile) with simulated ANM lower and upper threshold violations and management of constraints among multiple DER sites. [11]. **UC4:** Simulate maximum generation - minimum load (11 kV) scenario (with additional DER in case of Maidstone)/simulate case to realise reverse power flow violating transformer rating/RPF limit at GT. **UC5:** Simulation of N-1 contingencies at GTs during minimum DER output, tripping of a heavily loaded incomer at 132 kV bus during minimum DER output, internal and external short circuit faults. Verify post-fault operation where the network operates above its firm capacity and ANM manages the constraints immediately after a network fault to bring the system back within its thermal limits. In the time between the fault and the curtailment, network assets may be operating above their thermal limits. **UC6:** Simulate transient overvoltage scenario by delayed clearance of a ground fault in a feeder during maximum penetration. **UC7:** Simulation of conditions to violate under/over voltage G99 settings. **UC8:** Simulation of fail-safe conditions – a) non-responsive DER b) network weakening event (e.g.: failure of protection system to respond to a fault). All use cases are to be simulated for: • Communication from Grid site to DER site available • All communication unavailable • Varying running arrangements/layouts if any, at the trial sites
Test Metrics
1) During steady state studies, verify measurement, aggregation and visualisation of C37.118 WAMS data at the virtualised applications in Grid Substation Server (including via 5G), DER Substation Server in local WAMS DE and central WAMS DE2.0 server

2) Response times of switching between operating modes – auto/manual
3) Reference set points issued by Local ANM against each simulated use case
4) Voltages at GSP, Grid, DER site buses, GTs before and after instruction from ANM
5) Active power at the measurement points before and after instruction from ANM
6) Reactive power at the measurement points before and after instruction from ANM
7) Time taken by ANM to respond (issue of set point) to a threshold violation
8) System frequency at GSP, Grid, DER site buses
9) Audit trails/Event logs
10) Interaction with AVC through OLTC
11) Interaction with other protection functions
12) Interoperability and arbitration among the virtualised submodules of Local ANM application to realise the core objective
13) Time taken to reinstate control with Central ANM on recovery of communication/manual disable
14) Establish the limits of the machine learning model by comparing with CANM decisions during various scenarios (can be checked at PNDC if previous test results available from UK Power Networks, else shall be taken up during live network trials)
15) Configurable timeout capability to relinquish control with Central ANM (for live network trials)

Expected outcome

Local ANM manages DG output within contractually defined PQ envelope and mitigates voltage & thermal constraints in the event of loss of communication with Central ANM, to maintain operation within statutory voltage limits. Any Demand Unit must remain connected and operate normally in accordance with the following table [8, 9].

Voltage Level	Operational Standard
132kV	±10%
33kV	±6%
≤11kV	+10%, -6%

Statutory Voltage Requirements

Frequency Range	Requirement
47Hz - 47.5Hz	Operation for a period of at least 20 seconds is required each time the **Frequency** is below 47.5Hz.
47.5Hz - 49.0Hz	Operation for a period of at least 90 minutes is required each time the **Frequency** is below 49.0Hz.
49.0Hz - 51Hz	Continuous operation is required
51Hz - 51.5Hz	Operation for a period of at least 90 minutes is required each time the **Frequency** is above 51Hz.
51.5Hz - 52Hz	Operation for a period of at least 15 minutes is required each time the **Frequency** is above 51.5Hz.

Switch to Local ANM control from Central ANM within 750 ms of loss of communication.

Update the DER generation setpoints within 750 ms of onset of constraint.

Local ANM doesn't interact adversely with protection system operation.

Local ANM doesn't interact adversely with OLTC AVC or other control/SP schemes, if any.

Local ANM shall log alarms/events and report health and control actions to the ADMS for audit.

Local ANM shall resort to fail safe mode on inadequate/unwarranted response to a regulation action, issues aggravated by ANM.

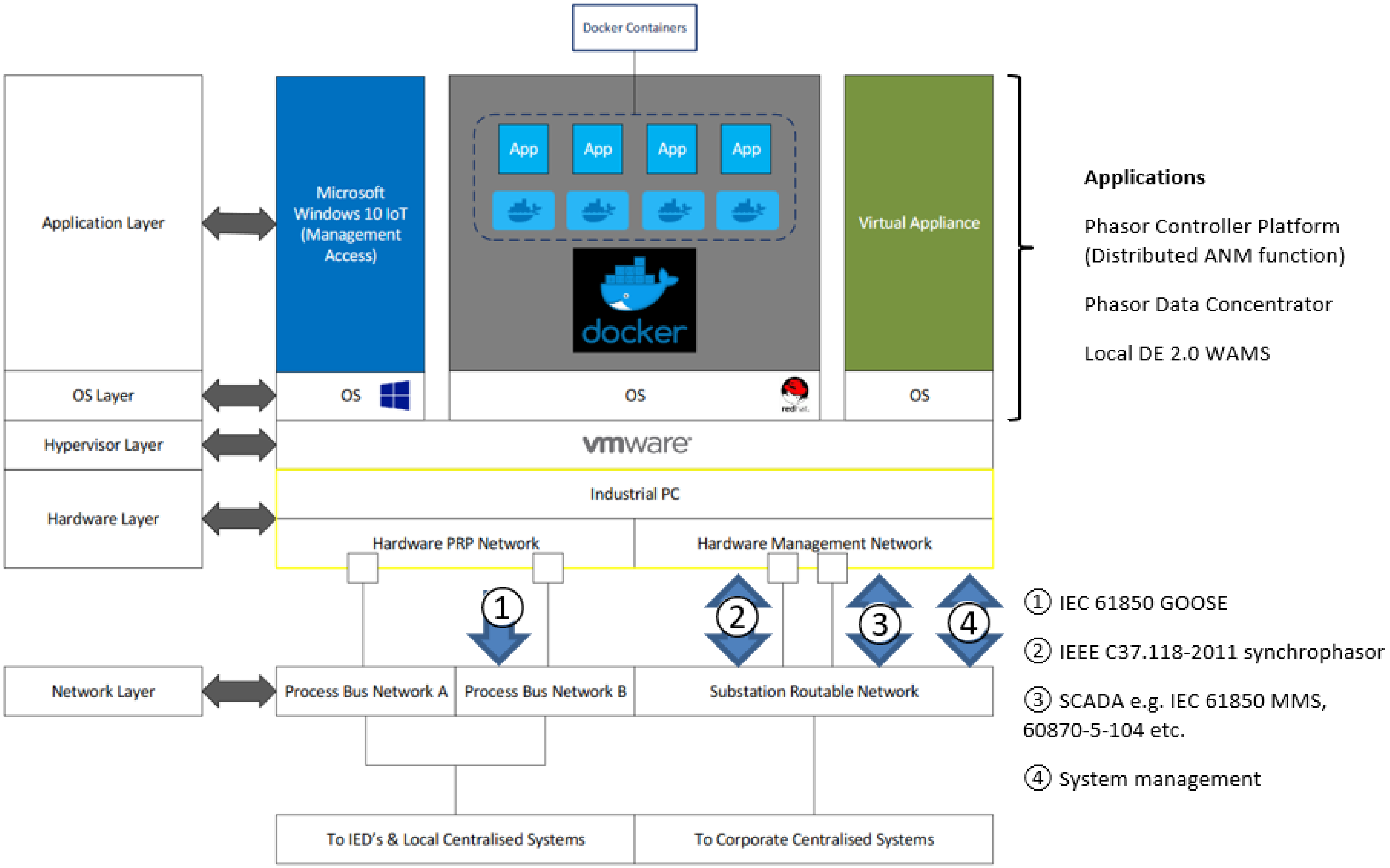
Source of uncertainty

- System Modelling uncertainty (modelling choices/assumptions made where data is incomplete/not available from UKPN/partners).
- Resource allocation and resource controls in the virtualised solution.
- Interference and latency in measurements relayed through 5G.
- Added latency due to virtualisation of solutions.
- Effect of variability in training and test datasets on prediction accuracy and uncertainty estimation.

A.5.1.3: Test Specification – TS1.3 : Performance Test

Test Case Reference
TC 01-Test Category 3: Performance Test
Test Objective
Verify the performance of LANM application during the following scenarios 1) Simulated communication network congestion – throughput, latency and effect on reliability of the function. 2) Loss of time synchronisation – effect on reliability of the function. 3) Availability and resilience of the network (on loss of communication to DER site, the local network within the DER site shall be considered) - Self-healing/redundancy of the network to provide multiple data path in case of failure of a single node and fail-safe actions, where redundancy is not available. Effect of quality of measurements on the sensitivity of the function.

Specific Test System (graphical)



Substation PC Design and network interfaces (ref: GE design document)

Pre-Requisite
The communicating/networking hardware components and the associated parameters in the virtualised solutions to be configured with accepted optimal configuration. Documentation of settings & parameters to be available (for e.g. FAT test results/approved documentation specified as per ETS-05-1603) to manipulate and test the effects on application reliability.
Test Design
The following use cases are simulated 1) **UC1:** Simulate failures of nodes in communication network, to assess the impact of failures nodes in the architecture, on the reliability of LANM solution. 2) **UC2:** Simulate data loading (for e.g.: equivalent to having a larger number of DG connections), ensuring the data is flowing through the relevant channels as equivalent to a real scaled deployment, to assess the maximum data handling capacity of the platform (stress test) beyond which the network underperforms or the LANM system performance is impacted. 3) **UC3:** Simulate failure of time synchronisation at various nodes in the LAN and WAN. 4) **UC4:** PMU data from simulation studies (zero-noise signals free of unknown or uncontrolled measurement error) can be modified to add certain levels of errors (e.g., certain levels of noise or frequency error). Modifications made on the data shall be - different types of measurement errors, introducing data losses and drop-outs to test the impact of data sparsity, loss of specific PMUs, mislabelling data channels, erroneous or duplicative timestamps, forcing delays in data delivery to the application etc. Simulate and test diverse types/combinations of data errors and quality problems.
Target measures
• Throughput and Latency • Reliability of LANM • Sequentially compare LANM application performance with ‘perfect dataset’ vs ‘flawed dataset’ • Audit trail/event log
Expected outcome
1) LANM application shall switch to fail safe mode under various conditions involving simulated failure of various system components/network nodes. 2) LANM application shall switch to fail safe mode on failure of substation computer, Merging Unit, PMUs / failure of the central ANM system.
Source of uncertainty
• Resource allocation and resource controls in the virtualised solution. • Interference and latency in measurements relayed through 5G. • Added latency due to virtualisation of solutions.

A.5.2 Summary of Other PNDC Test Cases

Test Case Number	**TC02.1: Wide Area Protection**
Overall Test Objectives	To test and validate the wide area LoM protection based on R-GOOSE through 5G communication and anomaly detection function running on the virtualised environment
TC02.1 Integration Tests	
Test Design (Use-Cases)	**UC 1:** Establish the interfaces and communication links between the hardware components and virtualised modules and ensure end to end healthy poll. **UC 2:** Check security access points e.g., authorised user access for function settings and logic functions in the virtualised IEDs. **UC 3:** Verify the measurement points (AI) and status values (DI) in the relevant IED. Ensure the quality of data. Force binary input values to check change of status and updating of event logs. **UC 4**: Simulate binary outputs from Wide Area Protection to RSCAD and analogue outputs (e.g., sampled values for anomaly detection) from RSCAD & R-GOOSE between Grid and DER servers, to ensure the data flow through RTDS/other interfaces and updating the same in relevant applications. **UC 5:** Verify the dataflow using DANEO 400 which serves as the multimeter for digital signals/using a traffic monitor like Wireshark. **UC 6:** Verify data exchange with the adaptive protection application and central protection management system developed by another supplier. **UC 7:** Verify updating of alarms/audit trails at server level. **UC 8:** Turn off and reinitialise all applications.
Expected Outcomes	Wide Area Protection application hardware components and virtualised modules integrate, arbitrate and interoperate with each other, with the adaptive protection application and central protection management system developed by another supplier and with the existing monitoring and control schemes, through proper communication of analogue and digital input and output data as per approved architecture.
TC02.1 Functional Tests	
Test Design (Use-Cases)	The following use cases are simulated in the system model in RSCAD. Thanet trial site provides a mix of conventional generation and inverter-based DER: 1) **UC1:** Simulate ramp in frequency of >1Hz/s for >500ms, triggered at Grid level, to initiate a RoCoF event at DER site, with communication to Grid site available. 2) **UC2:** Simulate ramp in frequency of >1Hz/s for >500ms, triggered at Grid level, to initiate a RoCoF event at DER site, with communication to Grid site unavailable. 3) **UC3:** Simulate genuine loss of mains events i.e. outage of incomers to 33 kV bus at Grid site, for varying running arrangements for operation and maintenance at the trial sites, with communication to Grid site available. 4) **UC4:** Simulate genuine loss of mains events i.e. outage of incomers to 33 kV bus at Grid site, for varying running arrangements for operation and maintenance at the trial sites, with communication to Grid site unavailable. 5) **UC5:** Simulate external disturbances/transient events at 132 kV bus upstream, three phase

	faults / short circuit faults in adjacent feeders, N-1 contingencies at GTs during minimum DER output, tripping of a heavily loaded incomer at 132 kV bus during minimum DER output. This is tested during 5G communication available. 6) **UC6:** Repeat simulation of external events to test self-supervision of communication and disregard of RoCoF block logic on communication loss. 7) **UC7:** Repeat simulation of external frequency excursions along with genuine loss of mains events. 8) **UC8:** Simulate varying generation & load profile - maximum/minimum generation-maximum/ minimum load, islanded generation balancing the local load). 9) **UC9:** Simulation of use cases for anomaly detection.
Expected Outcomes	• Virtualised Wide Area Loss of Mains logic detects external events and blocks RoCoF to prevent unintended power islanding of DER, when 5G communication available. • Virtualised Wide Area Loss of Mains logic self-supervises the health of communication and disregards RoCoF block signal when communication unavailable. • DERs stay connected to the distribution network & operate at rates of change of frequency up to 1 Hzs^{-1} as measured over a period of 500 ms unless disconnection is triggered by the intertrip enhanced loss of mains protection or by the DER's own protection system for a co-incident internal fault. • The virtualised Wide Area Protection logic sends transfer trip as R-GOOSE over 5G communication to disconnect DER generation in case of genuine loss of mains. • Virtualised wide area LOM protection detects islanding and disconnects islanded DG units rapidly enough (< circuit breaker open time used in fast automatic reclosing) for the fault arc to extinguish during fast automatic reclosing. • The local virtualised RoCoF operates during internal events in the case of loss of communications with Grid site. • Disturbance records are triggered to give early indications of an evolving faults on detection of anomalies. • The alarms/events are logged for audit trails.
TC02.1 Performance Tests	
Test Design (Use-Cases)	The following use cases are simulated and network traffic monitored by a network protocol analyser namely, DANEO 400. **UC1:** Base case test during network steady state with R-GOOSE signal transmission simulated to measure network propagation latency, asymmetrical latency and throughput. This can be compared with the latency measurement done during functional tests with power system events simulated to initiate R-GOOSE transfer trip & blocking. **UC2:** Artificially introduce network congestion and repeat R-GOOSE transmission in a steady state power system network to measure network propagation latency, asymmetrical latency and throughput. **UC3:** Artificially introduce network congestion and simulate use cases from functional tests to initiate R-GOOSE transfer trip and blocking signals to measure network propagation latency, asymmetrical latency and throughput. **UC4:** Simulate failure of network nodes to analyse the impact on reliability of Wide Area Protection solution **UC5:** Simulate network switching from main to redundant path wherever applicable to analyse the impact on reliability of Wide Area Protection solution and transmission of R-GOOSE

	UC6: Simulate failure of time synchronisation at various nodes in LAN and WAN **UC7:** Simulate unknown CB status to analyse the effect on reliability of Wide Area Protection solution
Expected Outcomes	The performance characteristics of 5G communication including the architecture used and configuration are suitable for transmitting multicast R-GOOSE messages and for use in time-critical wide area LoM protection functions. Deterministic communication parameters are expected.
Test Case Number	**TC02.2: Adaptive Protection Settings**
Overall Test Objectives	Test and validate the capability of Adaptive Protection System (APS) application to adapt, dynamically validate and set the virtual load blinding function, installed in the Substation Computer (by ABB), according to the grid operational state
TC02.2 Integration Tests	
Test Design (Use-Cases)	**UC 1:** Establish the interfaces and communication links between the hardware components and virtualised modules as per system under test above and ensure end to end healthy poll. **UC 2:** Check security access points e.g. authorised user access. **UC 3:** Verify the measurement points (AI) and status values (DI) in the relevant IED, HMI/other visualisation tools. Ensure the quality of data. Force binary input values to check change of status and updating of event logs. **UC 4**: Simulate and ensure the data flow from system model in RSCAD through RTDS interface and updating the same in relevant applications. **UC 5:** Verify dataflows using DANEO 400 which serves as the multimeter for digital signals/a traffic monitor like Wireshark. **UC 6**: Verify updating of logs/audit trails for e.g. manual approval of new calculated settings in CMS or deployment of adapted settings in the virtualised DOC IED. **UC 7**: Turn off and reinitialise all applications.
Expected Outcomes	Adaptive Protection application hardware components and virtualised modules integrate, arbitrate and interoperate with each other, with the virtualised protection function under Wide Area Protection application and with the existing monitoring and control schemes, through proper communication of analogue and digital input and output data as per approved architecture.
TC02.2 Functional Tests	
Test Design (Use-Cases)	The following use cases are simulated in the system model in RSCAD with Adaptive Protection enabled. All use cases are to be simulated for varying operational topologies/running arrangements at the trial sites. **UC1:** Simulate varying reverse power flow conditions (high power export maximum generation-minimum load, maximum generation-normal load, high reactive power export) at the two Grid transformers. The increase in generation can be simulated for conventional DERs and inverter based DERs, where inverter based DERs show different capabilities based on the control logic. **UC2:** During each of the above varying power flow cases simulate, • Symmetrical 3 phase, 2 phase and single phase to ground faults upstream to verify the sensitivity of the DOC/blinder setting

	• Simulate high resistance faults (3ph-g, 1ph-g) upstream to evaluate any non-detection zones **UC3:** Simulate intermittent/varying generation of inverter-based resources to analyse sensitivity towards worst-case scenarios. Analyse high resistance short circuit fault scenarios during varying/intermittent/nil generation from inverted based resources i.e. minimum fault contribution from the inverter-based resources. **UC4:** Simulate external fault- scenario where DER is connected to a specific feeder and a fault occurs on an adjacent one during maximum generation scenario. **UC5:** Grading with 132 kV overcurrent or distance protection, the 33kV overcurrent protection and the transformer earth fault protection and impact on recloser. **UC6:** Test the Adaptive Protection algorithm with any evolving fault case (e.g., phase-to-ground a-g fault evolving to two phase-to-ground a-b-g fault in a few milliseconds).
Expected Outcomes	• The Adaptive Protection application shall adapt relay setting groups dynamically according to grid mode variations and detect all faults with maximum sensitivity and no non-detection zones. • The Adaptive Protection application shall adapt load blinder settings to prevent unwarranted operation during reverse power flow/export conditions. • The operation timing shall be graded with 132 kV overcurrent or distance protection, 33 kV feeder protection/transformer earth fault protection.
TC02.2 Performance Tests	
Test Design (Use-Cases)	The following use cases are simulated: 1) **UC1:** Simulate failures of nodes in communication network, to assess the impact of failures nodes in the architecture, on the reliability and availability of Adaptive Protection. 2) **UC2:** Simulate failure of time synchronisation at various nodes in the LAN and WAN. 3) **UC3:** Simulate network congestion in LAN to assess if the Adaptive Protection system capability to adapt the protection logical nodes of virtualised protection function is impacted.
Expected Outcomes	Adaptive Protection solution shall switch to fail safe mode – most recent adapted & validated setting (roll back/alternate back up setting group) - under conditions involving simulated failure of various system components/network nodes/synchronism.
Test Case Number	**TC02.2a: Central Management System**
Overall Test Objectives	Test and validate the functionality of Central Management System (CMS) application to enable data exchange from the IEDs on site and the central management system database
TC02.2a Integration Tests	
Test Design (Use-Cases)	**UC 1:** Establish the interfaces and communication links between the hardware components and virtualised modules as per system under test above and ensure end to end healthy poll. **UC 2:** Check security access points e.g. authorised user access. **UC 3**: Verify updating of logs/audit trails **UC 4**: Turn off and reinitialise all applications

Expected Outcomes	CMS solution components and virtualised modules integrate, arbitrate and interoperate with each other and with the protection devices/secondary devices in the SS LAN through proper communication across interfaces as per approved architecture.
TC02.2a Functional Tests	
Test Design (Use-Cases)	Demonstration of **UC 1:** user authentication process including user management – e.g. user classification and authentication in the web-based software for different roles, CMS admin configuration **UC 2:** send/receive/storage of protection settings with time stamp **UC 3:** storage/management/visualisation of FW versions, serial numbers, installed protocols, installed modules, and protection settings of all secondary devices and protection & control assets in Grid substations **UC 4:** bidirectional synchronisation & transfer/file management in a file directory Substation Server with files in a file directory on the CMS (Machine 1) in central platform via SFTP link **UC 5:** auto/manual retrieval of disturbance record
Expected Outcomes	• Management of assets in the Grid substations i.e. a) protection devices in substation LAN via IEC61850 protocol b) secondary devices e.g. switch router etc. via SNMP protocol, including visualisation in a web interface. Data exchange includes asset information, settings and configuration. • Management of files (e.g. manuals) between Grid substation and CMS at central platform.
TC02.2a Performance Tests	
Test Design (Use-Cases)	The following use cases are simulated 1) **UC 1**: Simulate network congestion in LAN to analyse VLAN/Multicast address filtering-based prioritization of traffic/logical segregation and to assess if the CMS system capability is impacted. 2) **UC 2**: Simulate failures of nodes in communication network, to assess the impact of failures nodes in the architecture, on the reliability of CMS. 3) **UC 3**: Simulate failure of time synchronisation at various nodes in the LAN and WAN.
Expected Outcomes	100 % availability of CMS solution/fail-safe action in the event of non-availability of redundancy during node failures (e.g. load last verified and validated settings available at CMS database in the event of node failure during data exchange).

A.6 UK Power Networks General and Mode Specific Test Goals

A.6.1 Method 1

Table 21: General Method 1 Test Goals

General test goals	Assessment conditions
Check the status of PTP synchronization network	Ensure all components in the system are synchronized to the same time reference and all failures are notified as alarms to RTU/ADMS.
Measurements verification from real PMU and Sampled Values data	Compare ratio, accuracy, phase sequence for currents, voltages, frequency, TAP positions.
Automatic and manual triggers for Local ANM modes and restoration to Central ANM	Simulate failures scenarios between Central ANM and the RTU in substation Grids and DER sites, PhC shall automatically detect them and switch to Local ANM. Also, execute manual control from RTU/HMI/ADMS.
Power system event detection and classification	Simulate different topology changes, power rate-of-change or faults and check if PhC detect them accordingly.
Failsafe conditions triggers	Simulate power system events, Headroom limits, or life expectancy timeout and check the PhC decisions to Failsafe.
Offline test methodology	Check the test sequence to run offline test, with new power system scenarios, using test sets instead of real power system data.

Table 22: Specific Method 1 Test Goals

Direct Distributed Local ANM Test Goals	Assessment conditions
Headroom verification	Compare the calculated Headroom values against the real values measured at each constraint point.
Sensitivity Factor test	Check the power change responses at each constraint point as result of one MW change at each DER.
Validate the Headroom freeze condition	Simulate failures with the Headroom measurement and check Headroom freeze status.
Test the control command to RTU at DER sites	Simulate changes in the power flow to curtail generation when one constraint point reaches its limits, and to release generation when there is a positive Headroom in the constraint points, check the commands accordingly.
Hybrid system: Local ANM and Holdover in the same Grid trial area	Switch one DER site to Holdover mode and all others DERs within the same Grid area are managed under Direct Distributed Local ANM mode. Simulate changes in the power flow and evaluate the PhC logic.

Holdover Local ANM Test Goals	Assessment conditions

Triggers to Holdover mode	Simulate failures scenarios between Grid site and DER sites, PhC shall automatically detect them and switch to Holdover Local ANM. Also, execute manual control from RTU/HMI/ADMS.
Headroom uncertainty verification	Simulate different load scenarios and validate the Headroom uncertainty calculation against the system model.
Test the control command to RTU at DER sites	Simulate changes in the power flow to curtail or release generation to adjust the Headroom´s offset, check the commands accordingly.
Check the Holdover Life expectancy given a maximum possible curtailment	Simulate conditions to move the system to maximum possible curtailment, then check the life expectancy timeout.
Test the system when multiple DER sites are in Holdover mode	Simulate a communication failure in the Grid site or using manual commands switch all DERs to Holdover mode, then simulate different power flows and evaluate their logic and control decisions.

Learned Limit Local ANM Test Goals	**Assessment conditions**
Triggers to Learned Limit mode	Simulate conditions to move the system to life expectancy timeout and verify the triggers conditions for switching to Learned Limit mode.
Estimated Headroom verification	Compare the estimated Headroom values against the real values measured at each constraint point.
Test the control command to RTU at DER sites	Simulate changes in the power flow to curtail or release generation to adjust the estimated Headroom´s offset based on Learned values.

A.6.2 Method 2

Table 23: Test Goals

General test goals	**Assessment conditions**
End-to-End encryption check	Check if communication between Central Management System and the substation Grids are managed using TSL certificates and passwords.

Adaptative Protection Settings test goals	**Assessment conditions**
CIM files verification	Import a UKPN´s CIM file and verify the capability to detect and validate a new network model via CIM files.

Load blinder settings calculation	Check the new settings calculation for the load blinding protection accordingly with the imported network model in PSS®CAPE and passed to Central Management System.
User approval condition	Check if settings are not transmitted to Protection IEDs till they are manually approved.
Settings management system	Verify if settings are stored as new reference settings in the Central Management System before transmitting it to protection IEDs.
Download settings to protection IEDs	Check if the new settings are downloaded automatically in the corresponding protection IED, after approval.
Testing new settings in protection IEDs	By injecting sampled values in the virtual IED, Test the new operational zones.
Central Management System test goals	**Assessment conditions**
Database scope	Verify if CMS contains protection settings for all IEDs included in trial areas, Thanet and Maidstone.
Database historical data	Verify if old settings remain available when new reference settings are stored in the CMS.
Database Logs	Check if every change in the settings is registered in the CMS log.
Export Database	Validate if a new CSV file is created, with all IEDs part of the trial area, including the new reference settings.