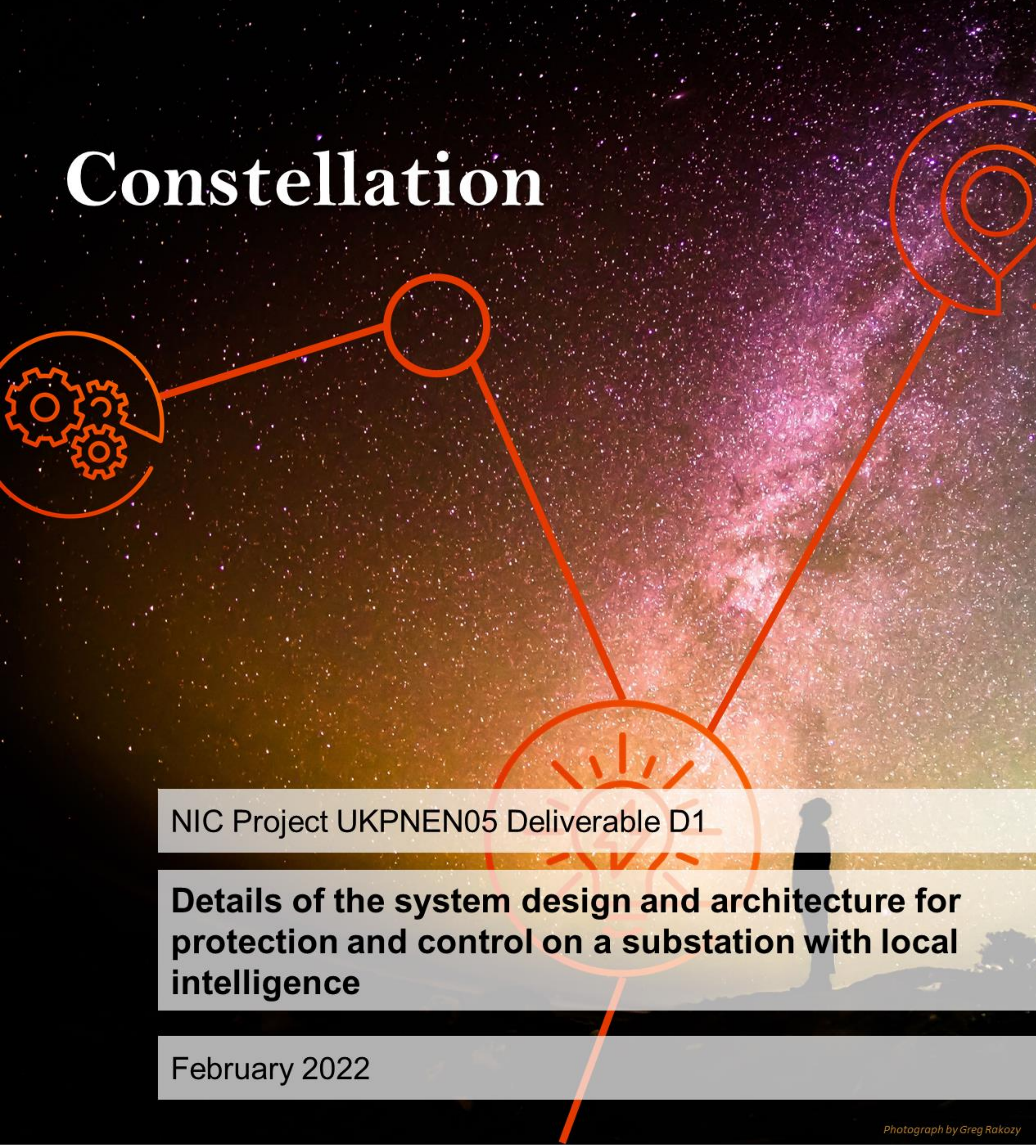

Constellation

NIC Project UKPNEN05 Deliverable D1

Details of the system design and architecture for protection and control on a substation with local intelligence

February 2022

Photograph by Greg Rakozy

Constellation Partners

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	4^{th} Generation Mobile Network
5G	5^{th} Generation Mobile Network
5G-GUTI	5G Globally Unique Temporary Identifier
5G NR	5G New Radio access technology developed by 3GPP
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
ADSL	Asymmetric Digital Subscriber Line
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
BS EN	British Standards European Norm
CAPE	Computer Aided Protection Engineering
CAPEX	Capital Expenditure
CCDM	Cloud Core Data Management
CCRC	Cloud Core Resource Controller
CCSM	Cloud Core Session Management
CIA	Confidentiality, Integrity & Availability
CLASS	Customer Load Active System Services
CMC	Universal Relay Test Set & Commissioning Tool
CMFD	Cumulative sum of Frequency Difference
CMS	Central Management System
COMTRADE	Common format for Transient Data Exchange
CoRoCoF	Comparison of Rate of Change of Frequency
CPU	Central Processing Unit
CT	Current Transformer
D1	Deliverable 1
D2	Deliverable 2
DANEO 400	Hybrid Measurement System (Omicron)
DDoS	Distributed Denial of Service
DER	Distributed Energy Resource
DERMS	Distributed Energy Resource Management System
DG	Distributed Generation
DN	Data Network
DNO	Distribution Network Operator
DNP3	Distributed Network Protocol 3

Acronym	Full form
DOC	Directional Over Current
DSO	Distribution System Operator
EAM	Enterprise Asset Management
EDA	Ericsson Dynamic Activation
eMBB	Enhanced Mobile Broadband
ENA-TS	Energy Network Association Technical Specification
ER	Engineering Recommendation
ETS	Engineering Technical Specification
FAT	Factory Acceptance Test
FSP	Full Submission Pro-forma (in reference to the project proposal)
FW	Firmware
Gbps	Gigabits per second
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
I>, I>>	Low, and High-Set Stages of an Overcurrent Function
I2	Negative-Sequence Current
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IGMPv3	Internet Group Management Protocol v3
IM	Instant Messaging
IP	Internet Protocol
IT	Information Technology
kV	Kilovolt
L2TP	Layer-2 Tunnelling Protocol
LAN	Local Area Network
LED	Light Emitting Diode
LoM	Loss of Mains
LTE	Long Term Evolution
LV	Low Voltage
LVRT	Low Voltage Ride Through
Mbps	Megabits per second
MBX	Mobile Branch Exchange
MMS	Manufacturing Message Specification
MoSCoW	Must Have, Should Have, Could Have, Won't Have (*at this time*)
MPLS	Multi-Protocol Label Switching
ms	millisecond
MW	Megawatt
NFVI	Network Functions Virtualisation Infrastructure
NIC	Network Innovation Competition
NR	New Radio
NRF	Network Repository Function
NSSAI	Network Slice Selection Assistance Information
NSSF	Network Slice Selection Function
NTP	Network Timing Protocol
ODMS	Open Data Management System

Acronym	Full form
OIC	Open Innovation Competition
OS	Operating System
OTA	Over-the-Air
P	Active Power
PAC	Protection and Control
PCC	Packet Core Controller
PCF	Policy Control Function
PCG	Packet Core Gateway
PDC	Phasor Data Concentrator
PF	Power Factor
PhC	Phasor Controller
PIM	Protocol Independent Multicast
PMU	Phasor Measurement Unit
PNDC	Power Network Demonstration Centre
PPCA	Probabilistic Principal Component Analysis
PRP	Parallel Redundancy Protocol
PSS	Power System Simulation and Modelling Software
pu	Per Unit
PV	Photo-Voltaic
PTP	Precision Time Protocol
Q	Reactive Power
QoS	Quality of Service
R-GOOSE	Routable Generic Object Oriented Substation Event
RAM	Random Access Memory
RAN	Radio Access Network
RAT	Radio Access Type
RBX	Radio Branch Exchange
RJ45	Recognised Jack-45
RoCoF	Rate of Change of Frequency
RTU	Remote Terminal Unit
SAPC	Standalone Policy Control Function
S-NSSAI	Single Network Slice Selection Assistance
SA	Stand Alone
SCADA	Supervisory Control and Data Acquisition
SFP	Small Form Factor Pluggable Transceiver
SFTP	Secure File Transfer Protocol
SIM	Subscriber Identity Module
SMF	Session Management Function
SMS	Short Message Service
SMV	Sampled Measured Value
SNMP	Simple Network Management Protocol
SNTP	Simple Network Time Protocol
SSD	Solid State Drive
SUCI	Subscription Concealed Identifier
TCP/UDP	Transmission Control Protocol/User Datagram Protocol
TLS	Transport Layer Security
TWh	Terra Watt Hours
UDM	Unified Data Management
UDR	Unified Data Repository
UE	User Equipment

Acronym	Full form
UID	Unique Identifier
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
[Redacted]	
V2G	Vehicle to Grid (Electric Vehicles)
VLAN	Virtual Local Area Network
VM	Virtual Machine
VoLTE	Voice over LTE
VoWiFi	Voice Over WiFi
VPAD	Voltage Phase Angle Drift
VPN	Virtual Private Network
VSAPC	Virtualised 5G Standalone Policy Control Function
WAM	Wide Area Management
WAMS DE	Wide Area Management System Digital Edge
WAP	Wide Area Protection
WG	Working Group
WMG	WiFi Mobile Gateway
WS	Workstream

Table 2: Glossary of terms

Term	Definition
5G Slice	A network slice is an independent end-to-end logical network that runs on shared physical infrastructure, capable of providing a negotiated service quality
Area	A geographical area that has a number of substation sites within close proximity. The areas considered in this document are given in the scope
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 and reduce system balancing costs by allowing DER to ride through transient instability events.

This report, which provides the first Constellation deliverable, D1, covers the activities undertaken since project commencement until mid-January 2022 by all project partners. It provides evidence that the system architecture and solution designs have been finalised, in accordance with the Full Submission Proforma (FSP) document requirements[1]. These designs can now be used to develop, build, install and test the solutions demonstrated as part of Constellation.

This report starts to address the three key project questions, detailed below, and each question will be further elaborated upon as the project progresses through each subsequent phase.

1) How do we ensure services to the network (e.g. flexibility) are resilient to loss of communication with central systems?
2) How do we ensure the services we obtain from DER assets are protected from transient instability events?
3) What is the future-proof architecture and virtualisation approach for network control and real-time protection functions?

Given that Constellation is a multi-faceted project requiring specialist contributions from each project partner, the initial stages of Constellation involved:

- Extensive collaboration and knowledge sharing through a series of virtual workshops and technical meetings. This provided a suitable environment within which the project partners developed and agreed their designs and system interfaces;
- Undertaking an assessment of current industry best-practice relating to the core technology subjects within Constellation; and

[1] Full Submission Proforma, Section 9, Table 11.

- Assessment of previous and ongoing DNO innovation initiatives which comprised similar functional and/or technical aspects, in order to leverage their lessons learned and how they could be applied to Constellation's design.

In addition to the above, the basis of design was further developed to address key challenges associated with aspects of the various elements of Constellation. These included the hardware build, architecture, virtualisation, cyber security, and the individual design for each Constellation solution.

Therefore, this report confirms that:

- The detailed designs for Methods 1 and 2 and 5G slicing are complete, with an agreed suite of integrated design and architecture documents now prepared which, pending final reviews and closure of a few minor ongoing activities, are forming the basis of the Constellation design;
- The Constellation design ensures cyber resilience utilising a secure by design approach;
- The project team has commenced the next Constellation project phase which will provide closure of the site selection and trial design activities. This will be reported upon under project Deliverable 2, due in August 2022; and
- Significant learning has already been generated whilst undertaking the design of the Constellation solutions and these are detailed within this report.

Section 1 of this report details the project background and purpose. **Section 2** details the overall approach of how the design was managed between the partners. **Section 3** provides concise details pertaining to the trial areas whilst **Section 4** details the overarching design of Constellation. **Section 5** provides the details of the designs of Methods 1 and 2, as well as the 5G slicing. **Section 6** details the ongoing activities and next steps required to progress Constellation through the next project stages and **Section 7** focuses on the BaU considerations that have been identified to date. **Section 8** provides the conclusions that can be documented at this stage in the project. Finally, the **Appendices** will present additional design data from each project partner which can be used for reference.

Table 3: Deliverable 1 Requirements

Deliverable D1: Details of the system design	
Evidence item	**Relevant section of the report**
Report on the:	
System design of Constellation	• Details can be found in sections 2, 4.5, 4.6 and 4.7 relating to WS1 and WS2.
Associated architecture for communication, protection and control across Methods 1 and 2	• Details of the overarching architecture can be found in sections 2, 4.2 and 4.3 relating to WS1 and WS2; and • Architecture details for each Method can be found in sections 4.4, 5.3, 5.4, 5.5 and 5.6 relating to WS1 and WS2.

1 Project Background and Purpose

1.1 Project Overview

The United Kingdom (UK) Government has set legally binding carbon budgets under the Climate Change Act 2008[2] 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 production activities currently account for approximately 24%[3] 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[4]. 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 PV, BESS, 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, or DER) has risen from approximately 70TWh to 180TWh[5]. The introduction of this has created some significant challenges for the energy industry, in particular the 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 centralised Active Network Management (ANM) system, utilising standard Supervisory Control and Data Acquisition (SCADA) capability, 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 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 DER and DERMS is lost (e.g. due to telecommunications failure) then the DER is required to automatically curtail to a known safe level, or even to disconnect entirely to protect the integrity of the distribution network. Additionally, when local network fault conditions occur, the existing protection arrangements may cause DER to be disconnected even if not directly impacted by the fault. A method of preventing such disconnections 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.

[2] https://www.legislation.gov.uk/ukpga/2008/27/section/14
[3] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/972583/2020_Provisional_emissions_statistics_report.pdf
[4] https://www.gov.uk/government/publications/net-zero-strategy
[5] https://www.gov.uk/government/statistics/uk-energy-in-brief-2021

With the anticipated exponential rise in connected DER in 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 potentially influence grid frequency and electricity network loading.

The primary aim of Constellation is therefore 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 of operation 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 out 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 very low latency 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).

1.2 Project Structure

To achieve the primary aims detailed in Section 1.1, Constellation will develop and trial two distinct project Methods, as summarised below.

Method 1: Local ANM
This project Method will provide localised control of DER operation to efficiently use the network capacity without risk of overload. The Method provides resilience for DER operation against loss of communication with the central ANM system. 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 results in improved DER asset operation during events when the central ANM system and/or DER communication links are unavailable.

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:

- Prevent DER protection being unnecessarily activated when transient instability events occur elsewhere on the network, by using sophisticated protection. This will rely on site-to-site communications via a low-latency 5G telecommunications network to transmit Routable Generic Object-Oriented Substation Event (R-GOOSE) messages.
- Carry out dynamic collection, calculation and deployment of protection settings for load blinding to release capacity for more generation to connect to the distribution network.

The above project Methods are further elaborated upon within Section 1.4.

Six workstreams have been implemented to manage the project Methods, detailed in Table 4 below, as there is some technical, testing and learning overlap between the two project Methods:

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 the 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

The responsibility for delivering and managing each individual workstream has been assigned to a specific partner on the project, as described in the Section 1.3.

1.3 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 1.

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 the 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.

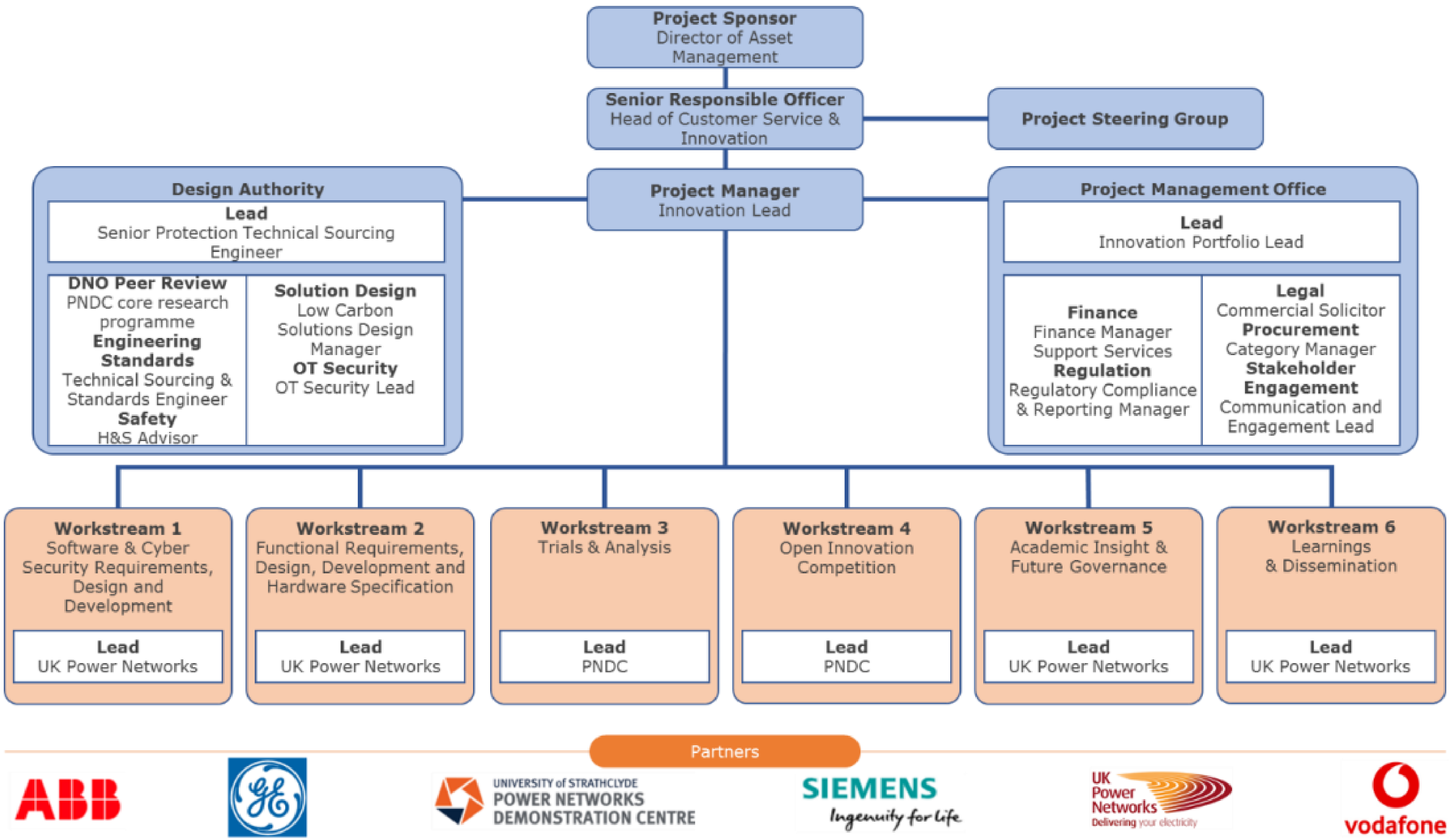

Figure 1: Project Organisation and Workstream Leads

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, the 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 Advanced Distribution Management System (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 (Join Radio Committee) will provide technical support on the 5G Slice design and 5G site specific design.

1.4 Details on Individual Project Elements

As stated in Section 1.2, 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:

1.4.1 Method 1: Local ANM

Method 1 (Local ANM) 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.

This concept is shown graphically in Figure 2.

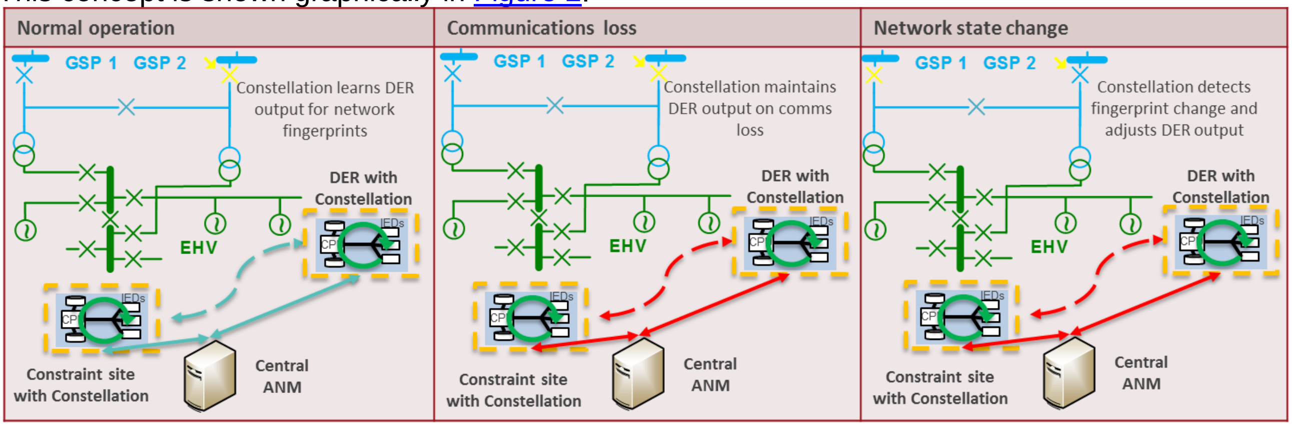

Figure 2: Local ANM (Method 1) Summary Diagram

1.4.2 Method 2: Wide Area and Adaptive Protection

<u>Wide Area Protection</u>

Wide area protection provides resilience to 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. This will be achieved with the application of low latency communications utilising via 5G slicing techniques between sites.

The above approach is in line with Engineering Recommendation (ER) G99[6] which provides the requirements for connecting generation equipment in parallel with public distribution networks, as well as complement ER G59/3-7[7], 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 3.

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

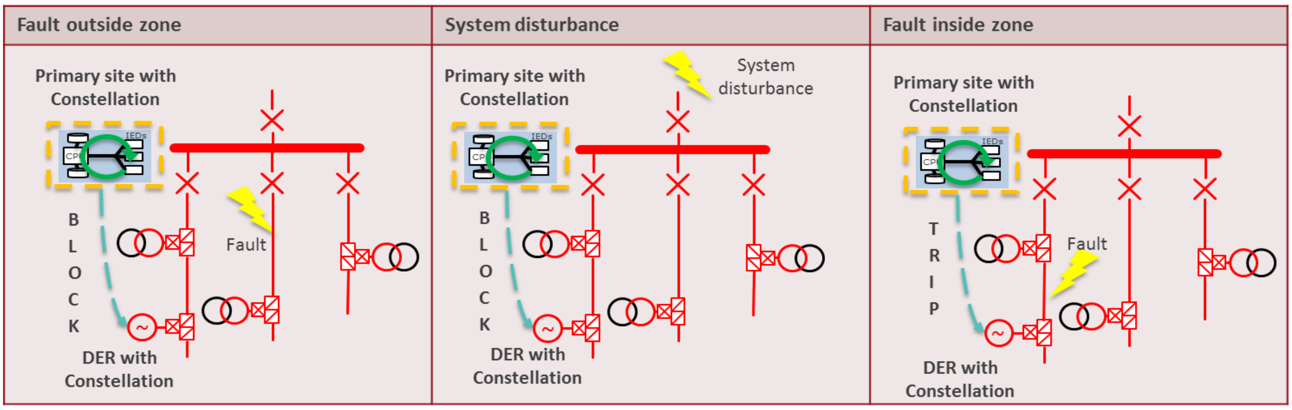

Figure 3: Wide Area Protection (Method 2) Summary Diagram

Adaptive (load blinding) Protection

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 will allow the load blinding protection function to adapt to the different topologies of the network and correctly discriminate between genuine faults and generation/load.

The adaptive protection element of this Method provides dynamically verified and configured protection settings. 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.

This concept is shown graphically in Figure 4.

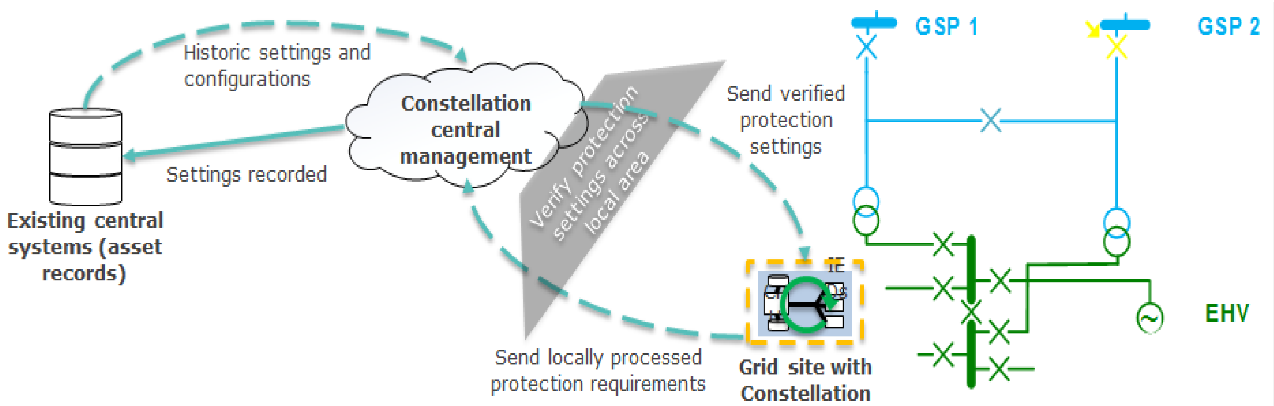

Figure 4: Adaptive Protection Settings (Method 2) Summary Diagram

2 Approach to Design

2.1 Collaboration and Working Ethos

Constellation is an ambitious and complex project with five partners delivering aspects of the solution. Our partners are global leaders in protection, control and telecommunication and have demonstrated they are at the cutting edge of development in their fields. In bringing this consortium (of partners) together, we genuinely believe that the outcomes of the project will demonstrate transformational approaches for the industry that can readily be rolled out by DNOs both in GB and globally. To achieve that, it is therefore essential to have continued and open communication between UK Power Networks and all partners in order to ensure that we are working together as a single unified collaborative team to deliver the project objectives.

Project works undertaken to date have concentrated on the definition of the requirements and development of the designs for each Constellation element, with workstream 1 focusing on the non-functional requirements and design and workstream 2 focusing on the functional requirements and design.

To achieve the outputs of workstreams 1 and 2, we have carried out extensive all-partner collaboration through workshops and brainstorming meetings. This is evidenced by the robust engagement structure that was employed to manage the project and has included the following:

- Weekly one-to-one sessions with each individual partner to discuss progress and highlight any potential challenges or risks;
- Fortnightly sessions with all partners to discuss upcoming priorities and any areas where support is required from another partner;
- Monthly review sessions with all partners to review the plan, risks and issues log; and
- Leadership sessions with the project sponsors from each partner organisation to set overarching project direction.

In addition to the continuous management sessions above, there have been numerous technical discussions and brainstorming meetings between the partners, which were scheduled as required. Figure 5 below, summarises the approach taken amongst project partners to progress the design of each element across both workstreams.

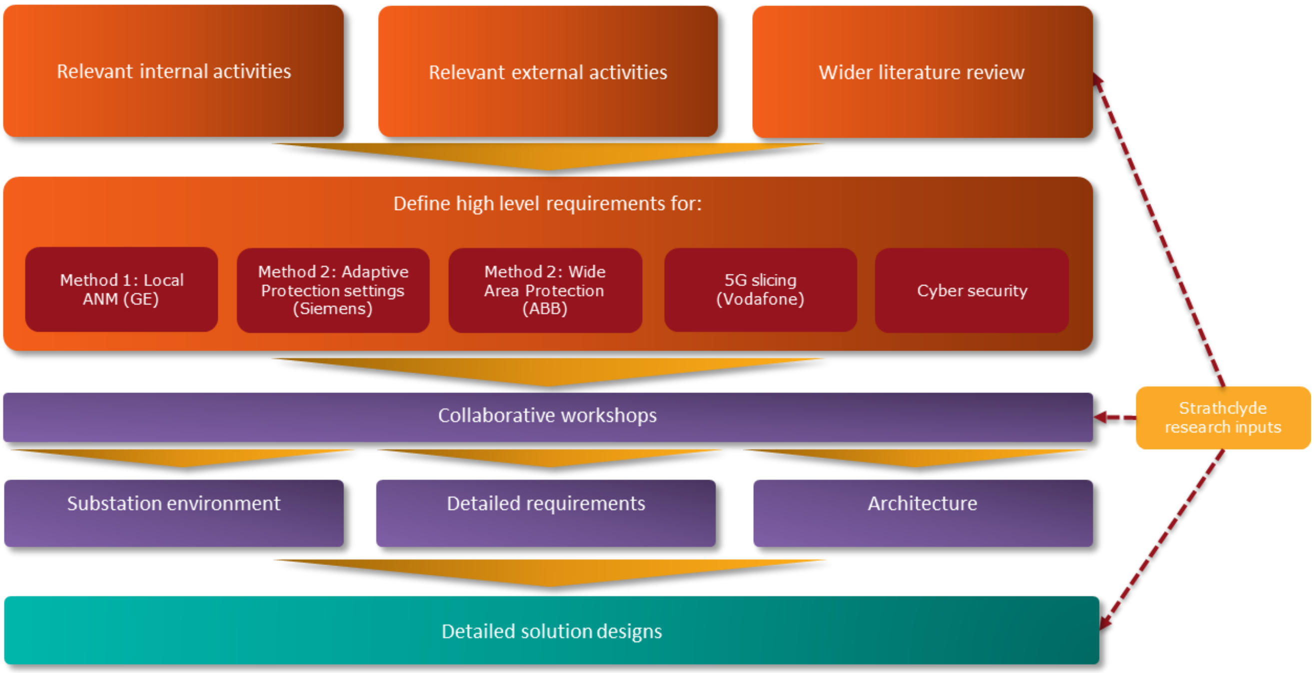

Figure 5: Approach to Definition of the Requirements and Design for Workstreams 1 and 2

2.2 Building on Previous Project Learnings

Constellation is providing a significant step towards demonstrating a robust distributed control architecture that combines the benefits of centralised situation awareness and network state verification, along with local fast-acting control and protection.

To assist with such a step, Constellation has incorporated learnings generated from a variety of previous and current ongoing projects such as those detailed within Figure 6 below:

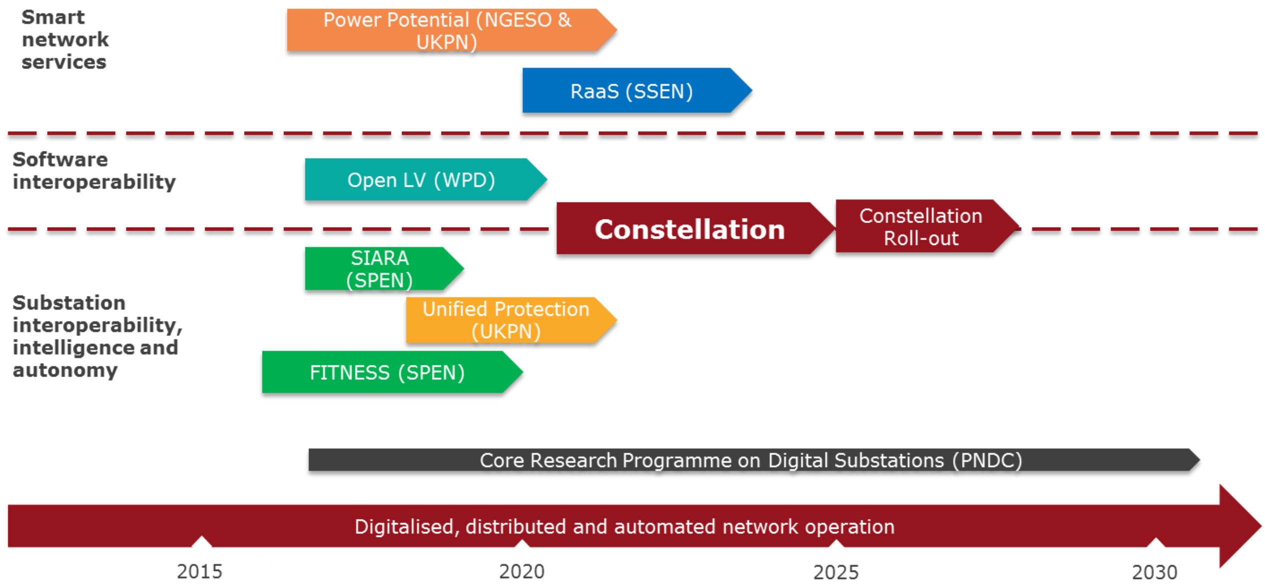

Figure 6: Constellation fit within wider industry work on digitalised system operation

In particular:

- FITNESS, SIARA and OpenLV have focused on "digitalised network operation", providing interoperability and multi-vendor interaction learnings. These innovation projects have provided valuable learnings related to implementing an open and flexible platform for distribution substation protection and control (PAC) equipment;
- Unified Protection has provided learnings on initial concepts associated with virtualisation and centralising PAC systems within substations. This innovation project demonstrated that software applications from a single vendor could be containerised on the same vendor's hardware, which Constellation is progressing to demonstrate such containerisation can be achieved on an open platform; and
- RaaS and Power Potential have provided valuable learnings on "smart services" demonstrating the value of utilising distribution connected resources to support the network.

Additionally, with the participation of some of the global leading protection, control and telecommunication vendors, Constellation is also leveraging their existing expertise and systems, many of which already provide an existing BaU solution.

With the combination of learnings from all the initiatives described above, the baseline "starting point" for Constellation is reasonably well advanced. This provides confidence that the advances in design required for Constellation to evolve in the manner expected, can be achieved.

Ultimately, the project trials will provide the learning and confidence necessary to accelerate the development of the Constellation system and Methods, increasing the success of adoption by the wider industry.

2.3 Initial Research

To ensure that Constellation delivers a solution suitable for BaU rollout, we have identified four research streams that will be progressed throughout the project.

These research streams are:

- Communication and data architecture: an optimised communication architecture, combining wired and wireless components;
- System reliability and distributed control: a set of system study results to enhance understanding of the impact of large-scale implementation of the distributed control;
- Adaptive and LoM Protection: comparative off-line modelling and testing studies to provide assurance; and
- Governance: insights and recommendations for the industry on the commercial and contractual arrangements needed for interoperable solutions for protection and control.

In order to support the initial requirements and design phase of Constellation, and complement the learning from other projects, two of the research streams started work at project commencement.

2.3.1 Communication and Data Architecture

This activity has outlined options for resilient and secure communication architectures required for the Constellation Methods. In addition, requirements for site-to-site communications, and the configuration and management of the virtualisation platform for the Constellation Methods has been considered.

The communication research team conducted a state-of-the-art review of digital substation connectivity. This review encompassed aspects related to network security, resilience and quality of service. The research team has also supported the development of the 5G requirements pertaining to slicing and achievable performance particularly related to latency. Finally, the team provided expert input during the requirements workshops covering 5G and site to site communication, cyber security and the virtualisation platform.

2.3.2 Adaptive and LoM Protection

This activity has focused on the systematic evaluation of the operation of these protection schemes to understand their performance envelope and inform the requirements and design phases of Method 2. Furthermore, this work provided a wider perspective on possible protection solutions which can be implemented using a Constellation system.

The protection research team conducted a state-of-the-art review of wide area LoM protection and adaptive directional overcurrent protection. The research team carried out a set of simulation studies to evaluate three communication enabled LoM protection techniques identified in the literature. Initial results demonstrated the superiority of the communication based LoM techniques. Final results will be reported in the sixth Constellation Deliverable as well as in a dissemination meeting with stakeholders.

A new adaptive distance protection method is also currently under investigation to evaluate the feasibility of extending Method 2 into other adaptive protection functions utilising the same virtualisation platform. Finally, the team provided expert input during the requirements workshops covering wide area LoM protection and adaptive protection.

2.4 Requirements Capture Approach

As shown in Figure 5, the requirements development exercise has involved the active participation of all project partners and covered an extensive agenda.

In essence, the project team commenced by researching previous and ongoing relevant projects nationally and globally whilst, in parallel, capturing industry best practice relevant to the specific project areas. This enabled a start to creating the high level requirements for each Constellation element. This provided a strong starting point and ensured learning from other industry initiatives is taken on board (refer to Section 2.2).

A number of collaboration technical workshops with the partners have been ongoing on a regular basis to define the functional, non-functional, cyber security and architecture requirements as well as the high-level designs for Constellation. A selection of such workshops is summarised within Table 5 below.

Table 5: Summary of Workshops Completed to Date

Workshop Title	Date
Constellation 5G requirements workshop 1	15 July 2021
Constellation Local ANM requirements development workshop	11 August 2021
Constellation Wide Area Protection and Virtualised Protection requirements workshop	25 August 2021
Constellation Software Platform and Security workshop	6 September 2021
Constellation Adaptive Protection Settings requirements workshop	8 September 2021
Constellation 5G requirements workshop 2	30 September 2021

In parallel to the above, University of Strathclyde's two research streams (Section 2.3) were using their research findings to ensure the Constellation requirements are scalable and fit for BaU.

The outputs of all the requirements capture works have been formulated into a suite of Engineering Technical Specification (ETS) documents which form the basis of the detailed designs currently being produced by the partners. These ETS documents are defined as follows:

- ETS 05-1601: Constellation Overall System Requirements;
- ETS 05-1502: Specification for IED Hardware Requirements in line with IEC 61850-3;
- ETS 05-1603: Constellation Requirements – Method 1: Local ANM/DERMS;
- ETS 05-1604: Constellation Requirements – Method 2: Adaptive Protection Settings;
- ETS 05-1605: Constellation requirements – Method 2: Wide Area Protection and Virtual PAC Functions; and
- ETS 05-1606: Constellation Requirements – 5G Communications.

To complement these ETS, UK Power Networks identified the requirements for each project Method, and prioritised them using the MoSCoW (Must Have, Should Have, Could Have, Won't Have) principles.

All the newly created ETS documents have been used as a basis for the design and ETS 05-1601, ETS 05-1502 and ETS 05-1603 have been issued in BaU. The remaining ETS documents and associated Requirement Statements are all undergoing final review before publication to BaU.

D1 Section 2 : Lessons Learnt	
1	Constellation is a large multi-faceted technology project requiring significant specialist input from a number of different project partners. An appropriate level of engagement between all partners was required, especially in the initial project stage, in order to define and agree the project technical issues, especially those relating to interfacing between the respective vendors solutions. Key to success was the rapid organisation of all-partner workshops and technical conference calls, especially given the inability to physically meet whilst under COVID-19 restrictions.
2	Assessing all previous projects that included elements similar to those required to be developed under Constellation was vital in order to ensure a robust starting point for Constellation and avoid unnecessary duplication.

D1 Section 2 : Lessons Learnt	
3	Launching the two research activities at the beginning of the project served as a valuable resource to aid in developing and scrutinising the solution requirements and designs. The contribution of the academic teams served to: • Ensure lessons from other activities in the digital substation domain are captured via a comprehensive review of state of the art and best practice; • Perform an early evaluation of the Constellation concepts and proposed Methods by conducting modelling (protection studies) and laboratory work (5G technology testing); • Independently review requirements and partner designs and provide input shaping key design decisions (e.g. choice of virtualisation architecture); and • Future proof Constellation concepts and Methods by considering future network operating scenarios. For example in relation to the longevity of the virtualisation architecture, or in relation to considering the supply chain maturity and lifecycle management of the Substation Servers.

3 Trial Site Selection

In order to maximise the benefit and learning from implementing the Methods on a live distribution network, UK Power Networks have assessed the network in order to identify where it may be most appropriate to implement the Constellation solutions.

Two areas within different geographical locations have been identified as provisional trial areas, Maidstone and Thanet, this will be finalised as part of D2. Each of these areas has a main area substation (Maidstone Grid and Thanet Grid respectively) and a number of dedicated substations which are connected to DER.

By implementing and testing the project Methods on two significantly different portions of the power network, we are able to demonstrate different aspects of the project designs and their respective functionality in stages, commencing with Method independent testing and then expanding to test the interactions between them.

Whilst full details of the trial site selection process will be provided within project deliverable report D2, it is considered beneficial to summarise within this D1 report the sites selected, and, from a design process perspective, the main reasons why, as summarised below:

- 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, currently operating under a firm generating agreement.

  This area is considered to provide a relatively complex 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.

- Thanet Grid, on the other hand, provides a reasonably complex environment for testing the local ANM design as this substation can be connected to multiple DER, depending on the running arrangements, some of which are connected to the central ANM and are operating under flexible generating agreements.

  In addition, as the mix of generation provides both inverter and synchronous generation, we are able to test how the local ANM and Wide Area Protection designs accommodate the different responses to frequency changes. The Thanet area is also constrained due to DOC protection on the grid transformers, which makes it suitable for demonstration of the Adaptive Load Blinding Protection (project Method 2).

Table 6 and Table 7 below summarise the substations provisionally selected within each geographical area:

Table 6: Sites in Maidstone

Maidstone Area Sites		
Site	**Site Type**	**DER Type**
Maidstone Grid 132/33kV	Grid	-
[Redacted] Generation 33kV	DER	Waste Generation

Table 7: Sites in Thanet

Thanet Area Sites		
Site	**Site Type**	**DER Type**
Thanet Grid 132/33kV	Grid	**-**
[Redacted] Generation 11kV	DER	Gas
[Redacted] Generation 33kV	DER	Gas
[Redacted] PV 33kV	DER	PV
[Redacted] PV 33kV	DER	PV

Appendix A.1 provides the basic Single Line Diagrams (SLD) for each trial area. Further SLD are provided in later chapters of this report, detailing where the project partners are intending to locate their equipment (e.g. GE's PMUs).

It should be noted that all of the sites discussed are subject to final selection before the submission of the D2 report.

D1 Section 3 : Lessons Learnt	
1	For Constellation to be a success, and hence provide the forecasted benefits and learning anticipated, careful attention had to be applied when considering the potential sites for implementing the "live network trials". Given that both Methods required differing network configurations and blend of connected DER and central ANM connectivity, many areas were assessed which was relatively time-consuming. Apart from the aforementioned criteria, considerations relating to physical space availability and the availability of a 5G network in the trial site area also had to be identified. We carried out multiple site surveys to ensure the trial sites are suitable. It was important to conclude the trial site selection at an early stage to ensure Constellation had two areas which can be considered as part of the design activities.

4 Overarching Project Design

4.1 Introduction

This section provides an overview of the project design aspects which enable the successful implementation of the two Methods. The aspects described herein cover the following:

- Description of Constellation Elements
- Overarching Architecture and Requirements;
- Insights from Academic Research;
- Substation Server and Associated Hardware (the “Equipment”);
- Virtualisation; and
- Cyber Security.

Section 5 provides a summary of the specific design details associated with each Method, and those associated with the 5G site-to-site telecommunications slicing.

4.2 Description of Constellation Elements

In summary, the various hardware and software components of the complete Constellation project that require to be integrated comprise the following:

a) Hardware components of Constellation include (but are not limited to):
   - PAC IEDs (Merging Unit devices);
   - GPS synchronised Clock Servers (NTP and PTP time server);
   - Industrial grade Substation Server and associated HMI;
   - Network Switches (layer 2 and 3 managed switches);
   - Testing devices (e.g. signal analyser);
   - Connection cables (Ethernet and optic fibre);
   - Substation free-standing cubicle (to house the hardware devices); and
   - 5G communication devices.

b) Software components of Constellation include (but are not limited to):
   - Operating system (host and Virtual Machine) at a Substation Server;
   - Virtual Machine and/or container orchestration software;
   - Software applications for Methods 1 and 2;
   - Third-party software applications to configure and manage their respective hardware devices;
   - Applications that analyse network protocols and data exchange. These applications may check the network for data acquisition;
   - Cybersecurity applications; and
   - Common operating system applications (e.g. browser, document viewer/editor)

Each component may require integration/interfacing with one, or more other hardware or software components and further details relating to such integration is provided within Section 5.

4.3 Overarching Architecture and Requirements

The overarching architecture for the Constellation project is shown in Figure 7. The system will include a new central settings database management system, new 5G communications between sites within the same area, the transition of PAC functions to a virtual platform, development of new PAC functions and deployment of IEDs and software (virtualised) platform.

Furthermore, these new Constellation systems and sub-systems will interface with existing UK Power Networks systems, such as central ANM (DERMS) and ADMS. Together, all of the elements in the architecture, will work together to achieve the Constellation aims (refer to Section 1.1).

The detailed architectures for the individual Methods are presented in Section 5.

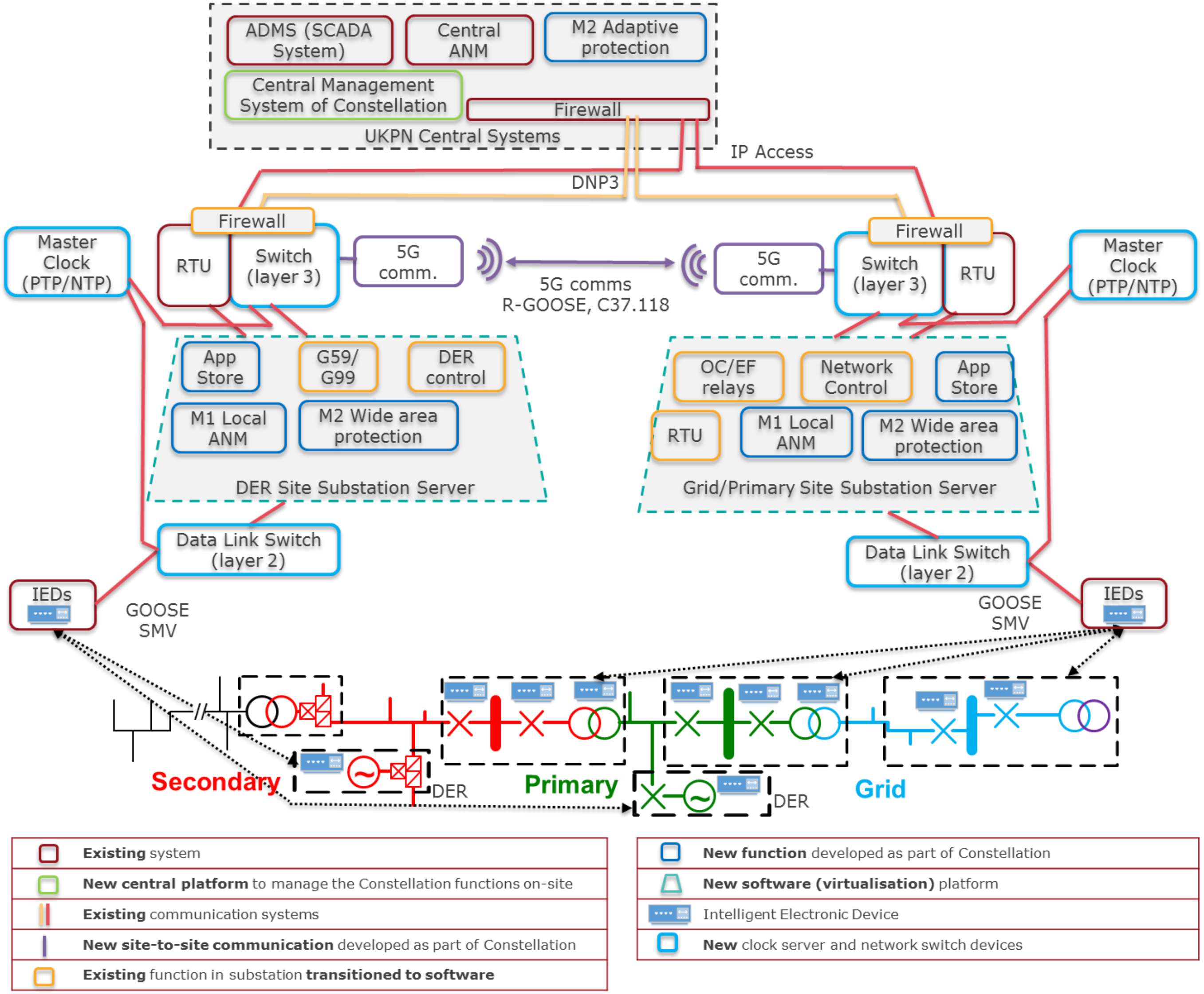

Figure 7: Constellation Architecture

The new Equipment, software and systems as shown marked with blue and green borders will be provided by the following project partners:

1) UK Power Networks: Layer 2 Data Link Switch, Layer 3 Network Switch, Master Clock (PTP/NTP), IEDs, Substation Server;
2) ABB: Method 2 Wide Area Protection;
3) GE: Method 1 Local ANM;
4) Siemens: Method 2 Adaptive Protection and central management system; and
5) Vodafone: 5G Telecommunications between distribution substation sites.

It should be noted that ABB, GE and Siemens will be providing their solutions as software. However, during some of the initial testing, hardware may be used as part of the tests.

The main design features associated with this project architecture have been agreed between all project partners and assimilated into an approved BaU Engineering Technical Specification (ETS 05-1601). These are summarised as follows:

1) IEDs will be installed and configured to get plant data (such as hardwired signals, voltage and/or current measurements) and be able to exchange data with a Substation Server located at the same site;
2) The communication between devices at the substation level will occur over an Ethernet network using managed switches or routers;
3) The Grid Substation Server will be able to exchange data with DER Substation Servers within the same network area over a communications medium;
4) The Substation Servers will be able to exchange data with the UK Power Networks control centre via a Remote Terminal Unit (RTU) application or device;
5) PAC functions will run as software applications in allocated containers and/or in a Virtual Machine environment;
6) All the PAC software applications will be installed in a Substation Server except for a limited number of backup functions that may be installed at IEDs;
7) Grid Substation Servers will have redundant topology whereas at DER sites, only one Substation Server will be required;
8) Phasor Measurement Units (PMUs) will be installed at DER and Grid Substation sites in order to capture samples from a waveform in quick succession and reconstruct the phasor quantity (angle and magnitude measurement);
9) Site-to-site communication will be designed to be under 10ms via 5G slicing;
10) Software PAC functions for local ANM and WAP will be able to run in the event of loss of communications to central systems (e.g. central ANM/DERMS);
11) The indications or alarms will be available locally (via display or LED indication) and centrally via SCADA (DNP3);
12) Control of the circuit breakers and switches within an area will be available on the Substation Server;
13) Communication and data exchange between devices located at the various sites shall accommodate the following communication protocols:

- IEC 61850-7-2 (GOOSE protocol);
- IEC 61850-8-1 (MMS protocol);
- IEC 61850 9-2 (SMVs);
- IEC 61850-90-5 (R-GOOSE and synchro phasor/PMU data);
- IEEE C37.118.1/2 (Synchrophasor data);
- DNP3 (Continuous polling) (SCADA);
- IEC 60870-5-103 (SCADA); and

14) Be compliant with the PTP, NTP, DNP3 and the SNTP time protocols.

4.4 Insights from Academic Research

As described in Section 2.3, in order to ensure that Constellation delivers a solution suitable for rollout, two research streams (covering the new communications and protection aspects) started work upon project commencement, tasked to complete:

- An industry-wide data-gathering exercise in order to gain knowledge on how the new communication and protection functional designs proposed for Constellation should be best-realised in practice; and
- To review the literature and lessons learnt from all previous and ongoing relevant projects.

The output from these two research streams has been used as inputs to the 5G communication and wide area and adaptive protection design. A summary of the outputs obtained from this design validation process, for each research stream, is provided below.

4.4.1 Communication and Data Architecture

As electrical generation becomes increasingly decentralised, and DNOs transition to Distribution System Operators (DSOs), the need for reliable and secure communication networks, allowing independent assets to coordinate and protect life of assets over wide geographical areas, has become even more important.

Existing communication technologies such as Multi-Protocol Label Switching (MPLS) and dedicated computational hardware has historically been used to fulfil these requirements. However, as the number of sites increases the cost of deployment becomes prohibitively expensive. Therefore, one Constellation research stream has investigated how recent advances in communication technologies may now provide appropriate solutions to facilitate reliable communications between dispersed substation sites at a reduced cost.

As the risk of a cyber security attack has escalated tremendously in recent years, mainly due to the increased application of open networks (e.g. not dedicated hardwired communication infrastructures) and the introduction of modern computerised devices integrated into the operational networks at remote and dispersed sites, the research stream placed prime importance on evaluating how the Constellation communications technology and data architecture would be designed to mitigate these risks.

University of Strathclyde has therefore conducted several workshops with stakeholders and industry partners to establish baseline security and architecture requirements to feed into UK Power Networks' overall requirements for the Constellation communication system. These workshops highlighted a number of gaps between the initially proposed system and an ideal system for future DNO/DSO environment, and these changes were adapted into the design.

Additionally, the analysis undertaken by the PNDC relating to the overall requirements also resulted in architectural considerations being highlighted to the project partners, and led to on-going discussions on the complexity versus benefit. The results from these discussions and assessments has helped shape the design of Constellation.

As a result of all this research, utilising 5th Generation Mobile Networks (5G) was identified as the preferred communications technology for use within Constellation, as it offered the potential to securely connect dispersed sites using a wide-area private network with lower latencies than any previous point-to-multi-point wireless communication technology at a reduced cost.

The PNDC then conducted preliminary 5G latency and reliability testing in order to demonstrate the end-to-end communication within the intended use cases. This was essential as latency requirements are crucial to the validation of the proposed 5G architecture. These results were demonstrated to project partners which confirmed the average latency was suitable for the intended use case (Wide Area Protection). However, the results also showed a significant long tail of higher latency measurements, which was also found by ABB in separate tests on 4G equipment, and these characteristics will require further investigation in order to ensure suitable reliability for the intended use case.

4.4.2 Adaptive and LoM Protection

The review of technical literature identified a variety of methods with a potential to improve resilience of power system protection against the changes that electricity systems are currently experiencing. Considering Constellation as a key enabling platform, the academic research effort within the project has undertaken a number of detailed simulation-based studies to establish technical requirements for each of the considered solutions, as well as to validate their performance against standard protection practice.

The adopted research methodology can be summarised by the following five steps:

1. Development of the representative power network model;
2. Development of a protection scheme model to represent each tested solution;
3. Definition of the test scenarios for benchmarking protection performance;
4. Simulation and comparative analysis of the results, and
5. Development of recommendations for Constellation trials and future developments.

In the first stage, for the purposes of investigating Loss-of-Mains (LoM) protection, four islanding detection schemes were selected. Their performance was assessed in terms of sensitivity to genuine islanding events, and stability under non-islanding disturbances such as system wide events and short-circuit faults. Moreover, generating technology, which is a known influencing factor when it comes to islanded operation, has also been considered in the studies. Various proportions of synchronous vs. converter-based distributed generation were therefore also included.

The key outcomes for the four studied methods can be summarised as follows:

1. Comparison of Rate of Change of Frequency (CoRoCoF) – the utilisation of a blocking signal communicated from an upstream substation greatly enhances the stability aspect of the LoM protection. However, the sensitivity is not improved compared to conventional RoCoF method. A method very similar in principle, developed by ABB, is already included in the Constellation trial programme;
2. Voltage and Frequency protection with the settings specified by G99 engineering recommendation – this is a standard requirement for all distributed generators, which although has low sensitivity and no ability to block system wide events, offers additional level of protection against islanding and/or any other prolonged operation under abnormal voltage or frequency conditions;
3. Rate of Change of Frequency (RoCoF) – a passive, local measurement based, standard LoM method most widely used in UK, included in the test to provide a benchmark case for protection assessment purposes; and
4. Voltage Phase Angle Drift (VPAD) – a communication assisted method utilising synchronised measurement of system frequency at two locations to derive voltage phase angle difference, which is then compared against a fixed threshold. This method delivers the best performance as it provides significant improvement both in terms of islanding detection sensitivity and stability under non-islanding disturbances. This method could be included in the Constellation trial after additional practical implementation effort by a manufacturer, or considered in an Open Innovation Competition[8] use case for implementation as a Constellation app.

The outcome of the study makes it evident that performance of the LoM protection can be significantly enhanced by the utilisation of communications, as demonstrated through Wide Area Protection.

The Strathclyde team participated in the stakeholder technical workshops and provided necessary input to the definition of Constellation platform requirements, so that the considered communication based LoM approaches could be implemented.

In the second stage of academic research, a case study of distance protection of a three-ended transmission feeder using similar simulation-based methodology is being undertaken.

The aim of this study is firstly to determine, under a range of realistic network and generation conditions, the extent of compromised protection performance using the existing protection practice (i.e. conventional communication-aided distance protection scheme), and secondly, to demonstrate how the problem can be mitigated using adaptive distance setting approach.

The adaptation strategy considered solutions found in technical literature, as well as available functionality of the Constellation digital platform in terms of real-time data collection, algorithm deployment and communication. The outcome of the study will identify whether there are opportunities to effectively expand the adaptation of settings to distance protection. The outcome can also open similar opportunities for other existing protection schemes enabled by the Constellation platform.

[8] Refer to Full Submission Proforma, Section 2.1.3.1

4.5 Substation Server and Associated Hardware (the "Equipment")

4.5.1 Overview

As part of Constellation, Equipment in substations (Grid and DER) is required to provide the physical resources for the data collection, processing, communication, and security of operation, and to host the software applications developed for Methods 1 and 2. This Equipment, which will be procured by UK Power Networks and be based around ruggedised Substation Servers, communication switches, 5G hardware, Intelligent Electronic Devices (IEDs) and test equipment, for the duration of the trial, will be deployed in two forms:

- Full intelligence deployed at grid and primary sites: two Substation Servers, for resilience, with full processing and memory capabilities, and ability to extend the interface to IEDs based on the site requirements
  - It should be noted that during the Constellation trials, it is unlikely that any primary sites will be equipped with any Equipment (full or partial); and
- Partial intelligence deployed at DER and secondary sites: single Substation Server with lower processing capabilities and limited number of interfaces
  - It should be noted that during the Constellation trials, it is possible for the Substation Servers in DER sites to be the same as the ones in Grid sites. This will be determined during the trial design and site preparation phase of the project.

The Equipment required at each type of site is detailed in Table 8 below. Figure 8 and Figure 9 detail the current cubicle build configurations for each substation type.

In addition to the Equipment currently intended to be mounted within these cubicles, each site will comprise Constellation Equipment located separately from the cubicle, as follows:

- 5G antenna (located on the external building façade as per Vodafone's 5G coverage design)
- IEDs acting as Merging Units (MU) (located within the switchgear panels)
- Phasor Measurement Units (PMU) (located within the switchgear panels)
- Phasor Data Concentrator (PDC) (location to be confirmed as part of trial preparation)

  (Note: Intent is to migrate the PDC equipment from a hardware solution to a virtualised solution as the project progresses)
- Equipment which will be used for testing purposes, removed upon completion.

The Constellation team is committed to minimise the hardware requirements and maximise the project learning as much as possible through using virtualised solutions, wherever possible within the project budget and timescales. As noted above, examples include the provision of a substation RTU and Phasor Data Concentrator, which as part of the project may ultimately be provided as software solutions within the Substation Server instead of contained within individual hardware containers. The ability to implement such cost-efficient solutions will be progressed during the forthcoming project trial period.

4.5.2 Details

Substation Server

The software requirements of all the Constellation solutions dictated that Substation Servers with an enhanced performance are required, especially with regards to the Central Processing

Unit (CPU) operating speed, Random Access Memory (RAM) and Solid State Drives (SSD). This is due to the adoption of a virtualisation design approach and the real-time requirement of several of the software applications (e.g. protection applications) to run in a real-time environment, processing fast protection and control data over a number of dispersed sites.

In addition to this, the servers are required to be of industrial/ruggedised quality to suit installation within a harsh environment susceptible to temperature changes, dust, electrical and magnetic noise.

Each server will be equipped with a monitor, keyboard and mouse to permit local operation by an engineer with the appropriate access rights.

We have identified the details of each software application running on the Substation Servers (see Appendix A.1). We then dedicated a workshop to understand what additional hardware is required to ensure security and resilience. The results of this initial assessment are currently, as part of the trial preparation, being used to identify the most suitable hardware configuration for the Substation Servers.

Network Switches

The network switches will connect all the measurements and devices within a substation as well as connect all the dispersed Substation Servers across all sites within each project trial area. These network switches will be sourced from Siemens (RuggedCom) and are of prime importance for the following reasons:

1) They will contain in-built Layer 2 and Layer 3 cyber security functionality to protect the UK Power Networks' central systems from un-authorised intruder access via any system installed locally at the Grid Substation or DER site; and
2) They will be connected to the 5G network and will be facilitating the 5G slicing functionality.

Other equipment (communication, synchronisation and testing)

Each Constellation site will be equipped with a 5G aerial and Global Positioning System (GPS) time management server. This will ensure all connected sites are able to maintain accurate time synchronisation between devices and permit the processing of accurate chronologically ordered alarm and event messages.

For the purposes of executing the testing phase, substation simulator equipment sourced from Omicron will also be provided, possibly located in a standalone/temporary cubicle, or permanently installed in the main Equipment cubicles.

All Equipment contained within each cubicle will be connected to a local area network (LAN), which shall also be redundant at the Grid Substation sites to provide us with the necessary resilience.

Given that there are space limitations at DER sites, consideration has been given to identifying and procuring a minimal set of Equipment for the DER sites (which is still capable of providing the necessary functionality and performance) and can be accommodated within a smaller cubicle. We will use the learning from the trials to understand how much the DER Equipment can be minimised before BaU deployment.

Table 8: Equipment Required per Type of Substation Site

Equipment category	Purpose
Substation PAC cubicle	Contain the Substation Server and associated network switches and wiring
Substation Server	Host the solutions developed as part of Method 1 and Method 2
Interface (screen, keyboard)	Enable operator interaction within the substation
Network switches (Layers 2 and 3)	Enable the communication within the substation and between substations
5G communication equipment	Enable 5G communication
Time source	Enable time synchronisation
Testing equipment	Carry out testing to verify performance
Phasor measurement	Collect measurements from the distribution network and send them to the Substation Server
Merging units	Collect measurements from transducers

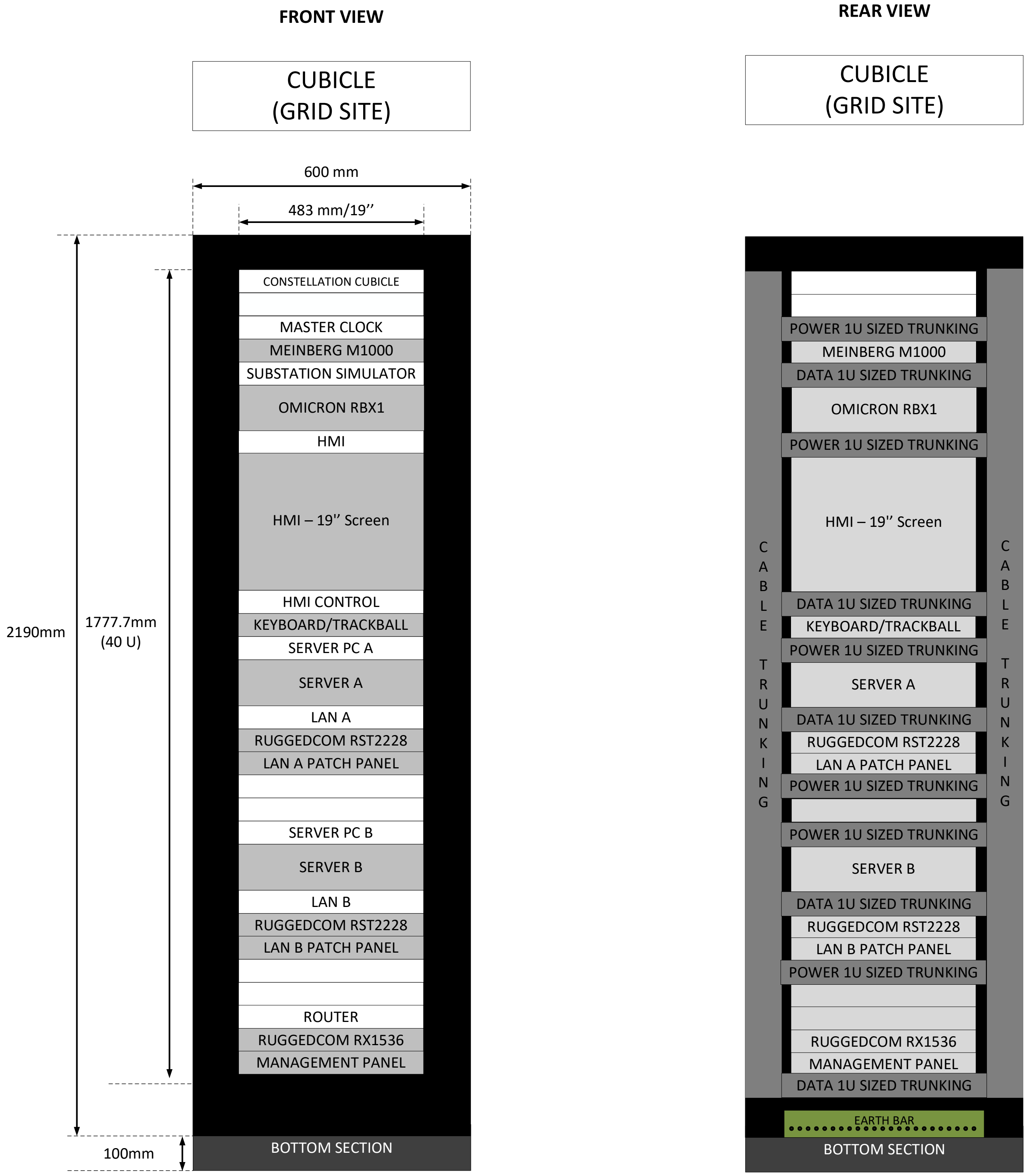

Figure 8: Cubicle Build for the Grid Substation Sites

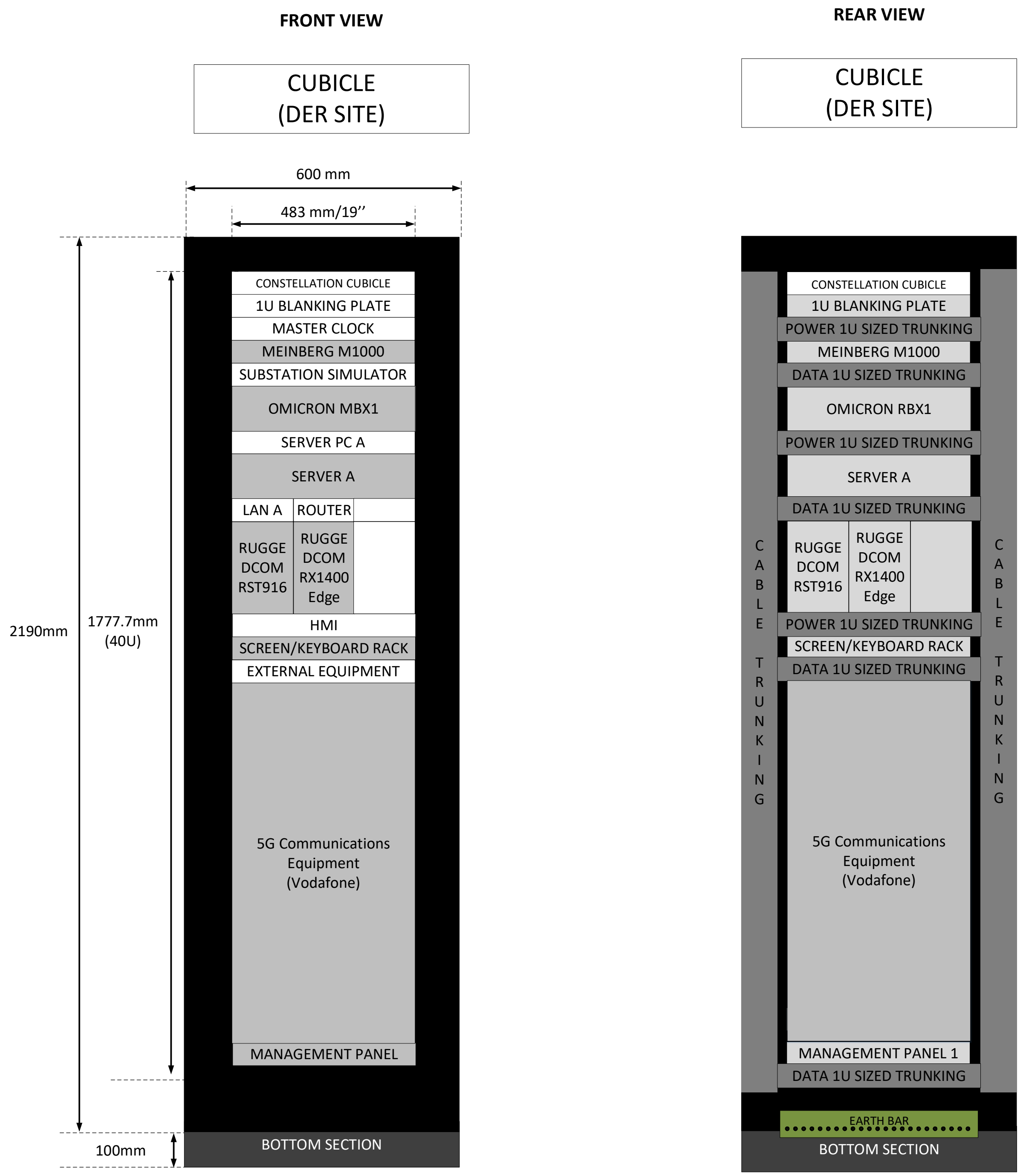

Figure 9: Cubicle Build for the DER Sites

4.6 Virtualisation

4.6.1 Overview

In traditional substation hardware, a physical server runs a single operating system (e.g. UNIX, Windows) and is dedicated to a specific application, managing, via a single kernel portion of the operating system code always resident in memory, all interactions between the hardware and software components. This often results in wasted capacity and an increase in overall IT costs as, for a typical power utility company, separate devices may be required to run and manage applications from a variety of different vendors requiring differing operating systems.

Constellation is migrating away from this traditional design approach and developing a new design for digitising distribution substation utilising virtualisation techniques. Virtualisation is widely used in the wider IT sector as a way to decouple application functionality away from specific hardware and make it easier to manage networked applications – a hypervisor platform can provide remote management and more functionality for managing Virtual Machines at scale, which is not possible when interacting with hardware servers. For example, Virtual Machines can be snapshotted, migrated between servers.

For Constellation, two virtualisation techniques are being implemented, as follows:

- Hardware virtualisation: Where the PAC functions will run on Virtual Machine (VM) platforms.

  With this technique, software is used to create an abstraction layer over the physical (server) hardware, thus creating virtual computer systems known as VMs. One main advantage of this is that it permits a single server to operate and manage multiple different "virtual operating systems", running applications from a variety of vendors, in isolation from each other. This permits the introduction of "interoperable solutions" and maximises the utilisation of the available server capacity and ultimately reduces the capital cost of deploying dedicated servers.

  To manage the VMs, further software known as a "hypervisor" is required to allow the multiple operating systems to run alongside each other and share the same physical computing resources. In essence, the hypervisor assigns each VM its own portion of the underlying computing power, memory, and storage and prevents the VMs from interfering with each other.

- Operating system level containerisation: Where PAC functions will run on a container platform

  A container is an isolated, "lightweight silo" (smaller in size and hence quicker to start that a VM solution) for running an application on the host operating system. Containers build on top of the host operating system's kernel and contain only apps and some lightweight operating system Application Programming Interfaces (APIs) and services that run in user mode.

With application of the above virtualisation techniques, the overall intent is therefore to demonstrate that:

- The virtualisation approach, including the concept of containerisation, is suitable for providing the necessary hardware, software and cyber security requirements for protection, control and management functions;

- The virtualisation platform will provide the environment upon which GE, ABB and Siemens can successfully implement all software required, in an interoperable manner, for both Methods 1 and 2; and
- It is possible to run all necessary software applications (“virtualised “apps”) at each site on VMs on a single server. (Note: If, after completing the server procurement exercise this is demonstrated to be inappropriate, then duplicated server configurations will be considered although cost savings are still expected).

As well as procuring the Equipment, UK Power Networks are procuring a VM solution from the open market, upon which the project partners (ABB, GE and Siemens) will deploy their proprietary virtualised software (application) solutions.

4.6.2 Details

The concept of virtualisation has been demonstrated previously by UK Power Networks within project “Unified Protection”. However, within that project, applications from only a single vendor were successfully demonstrated to be containerised on a Substation Server.

As described above, Constellation will progress this success to the next level by demonstrating that it is possible to integrate software applications from a variety of vendors within a single third party hardware platform using both full virtualisation (where the VMs run a complete operating system including their own kernel) and the lightweight containerisation solution. This will provide a “hybrid” virtualisation concept that Constellation will be able to demonstrate and trial.

The following form the key functional and non-functional requirements identified for Constellation’s proposed hybrid virtualisation solution:

a) Functional requirements

- Virtual Machine based solutions should utilise Type 1 hypervisors;
- The PAC functions will operate as software applications and run within the VMs or as containerised applications;
- Virtualised environment will be capable of running third party software solutions as part of the Open Innovation Competition;
- The virtualised environment will provide monitoring information on hardware usage;
- Data exchange and/or settings updates will not affect operation or performance; and
- Virtualisation software should operate VMs independently from each other with appropriate isolation.

b) Non-functional requirements

- The applications running in the virtualised environment are to perform as they would in a non-virtual system on physical hardware;
- All systems should be capable of coping with periods of intensive workloads;
- Reliably perform tasks with little to no downtime, similar to critical infrastructure such as SCADA and protection systems;
- Software updates and/or system security patching will be performed in standardised and efficient manner in line with existing BaU processes; and

- Verify the compatibility between virtualised software functions and external applications.

The current intention is for the protection aspects of Constellation to run as VMs due to their critical real time requirements, whereas aspects of Method 1 and the OIC apps to be either containerised, for ease of configuration and deployment, or also run as VMs.

Figure 10 below details the current virtualisation hybrid software design, which shall be installed on the Substation Servers.

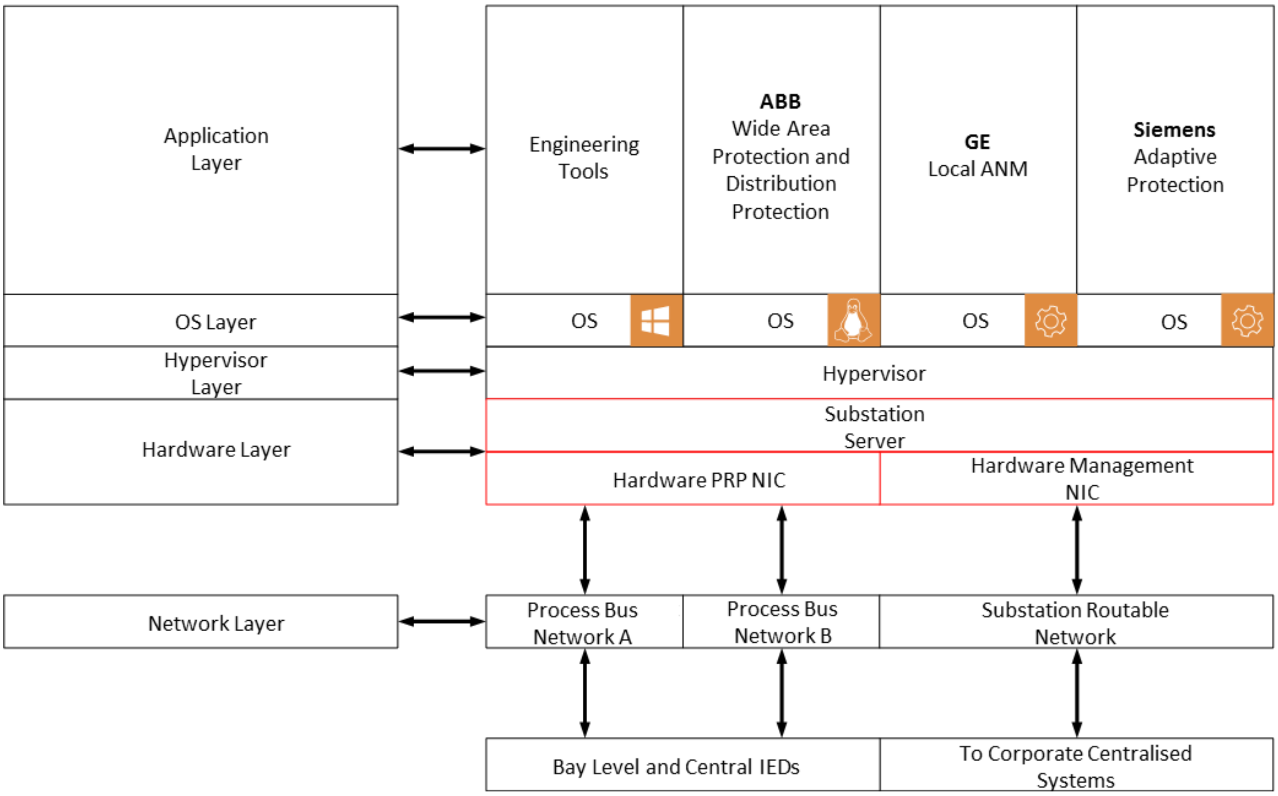

Figure 10: Hybrid Virtualisation Design

In Constellation, the three PAC partners will be utilising the following:

- ABB will be implementing their SSC600 product;
- GE will be implementing their Phasor Controller (PhC) and Phasor Data Concentrator (PDC) product, and their Wide Area Management System Digital Edge (WAMS DE) product; and
- Siemens will be implementing their Sicam Grid Edge product.

Appendix A.1 provides a summary of the requirements for the software.

Virtualisation in the central system
The Local ANM and Adaptive Protection functions both require information from a central system to function as intended. To support this, Azure cloud servers will be deployed as an interface with the necessary systems and databases, configured as shown below in Figure 11.

- GE's Local ANM solution requires an Azure server for hosting the WAMS DE platform and includes a central PDC, which is required for managing large quantities of phasor data collected from the PDCs at Substation Servers; and
- Siemens's Adaptive Protection System requires systems to interface with and gather data from UK Power Networks systems such as the ADMS. Power system simulation and modelling software (PSS) will also be installed for data ingress.

Further details associated with the central systems is provided within Section 5.

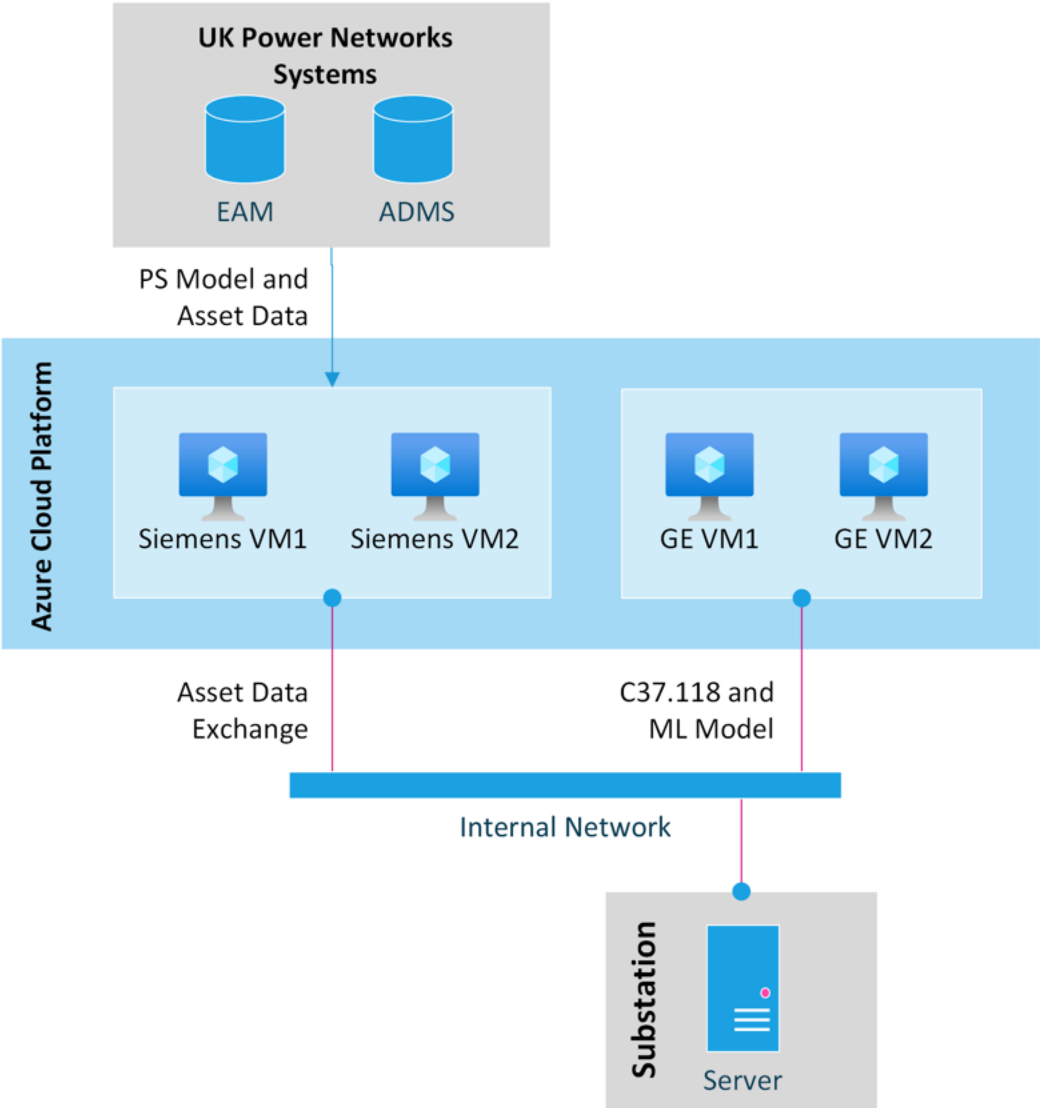

Figure 11: Simplified Block Diagram for the Azure Servers

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5 Specific Design (Methods Details, Architectures and Integration)

5.1 General

While Section 4 is focused on the overarching design, which is applicable to all Constellation aspects, Section 5 is dedicated to the design of each Method, as well as the 5G slicing communication. The following sections provide concise details relating to each project partner's specific design. Further supporting literature is provided within the Appendices.

5.2 Overarching Project Method Requirements

The high-level design features associated with each Method that have been agreed between all project partners and assimilated into an approved Engineering Technical Specification, ETS 05-1601[9]. As described in Section 2.4 of this report, these design requirements were then detailed further and individual ETSs were developed.

Reference to these high-level and detailed design features have remained pivotal throughout all design considerations by the project partners.

5.3 Project Method #1 (Local ANM)

5.3.1 Brief Introduction to the Project Method

The purpose of Method 1 is to demonstrate that Local ANM, at substation level, will provide resilience to DER operation against loss of communication with the central ANM/DERMS system by implementing local control and optimisation techniques.

The existing central ANM/DERMS system requires continuous monitoring of both the DER and the network constraints on the distribution network. When the central system loses connection with either of those, the network can no longer be managed through central ANM/DERMS. To manage that risk, the central ANM/DERMS solution defaults to a conservative fail-safe state which may be to disconnect the DER completely. As part of Constellation a new solution is developed to complement central ANM/DERMS. It uses phasor measurements at key points of the network (fingerprints) and retains as much DER availability as possible within situations when central ANM/DERMS is unavailable. This approach will use fast, time synchronised phasor measurements along with analysis processes and machine learning that allows the DERs to continue operation in events where there is a loss of communication with the central platform with minimal interruption.

GE is delivering the PhC platform for real-time control together along with the GE WAMS DE infrastructure for data management, historian, visualisation and applications for advanced analytics and machine learning. The PDC, PhC and WAMS DE systems together form the Local ANM system which will be demonstrated as part of Constellation. The present implementation of PhC software and logic environment runs on dedicated hardware with a deterministic cycle time. Over the course of the Constellation project, it will be virtualised to run on the Substation Server.

[9] UK Power Networks Engineering Technical Specification document ETS 05-1601 entitled "Constellation Overall System Requirements", v1 dated 28th July 2021.

5.3.2 Design Objectives

The objectives of the architecture and design of the Local ANM scheme are to:

- Implement three operating modes of local ANM to apply if the central ANM/DERMS system loses communication and control of a managed DER site, thus reducing the need to curtail DER unnecessarily. The three operating modes are described in Section 5.3.3:
  - Direct Distributed ANM;
  - Holdover ANM;
  - Learned Limit ANM;
- Provide flexible local intelligence and control through the Substation Server, in parallel with the other Constellation applications (e.g. Method 2); and
- Introduce the infrastructure for synchrophasor measurements in UK Power Networks' distribution network, enabling measurements, analytics, data sharing and applications for monitoring and control.

The layout of the Local ANM Method 1 is shown diagrammatically in Figure13.

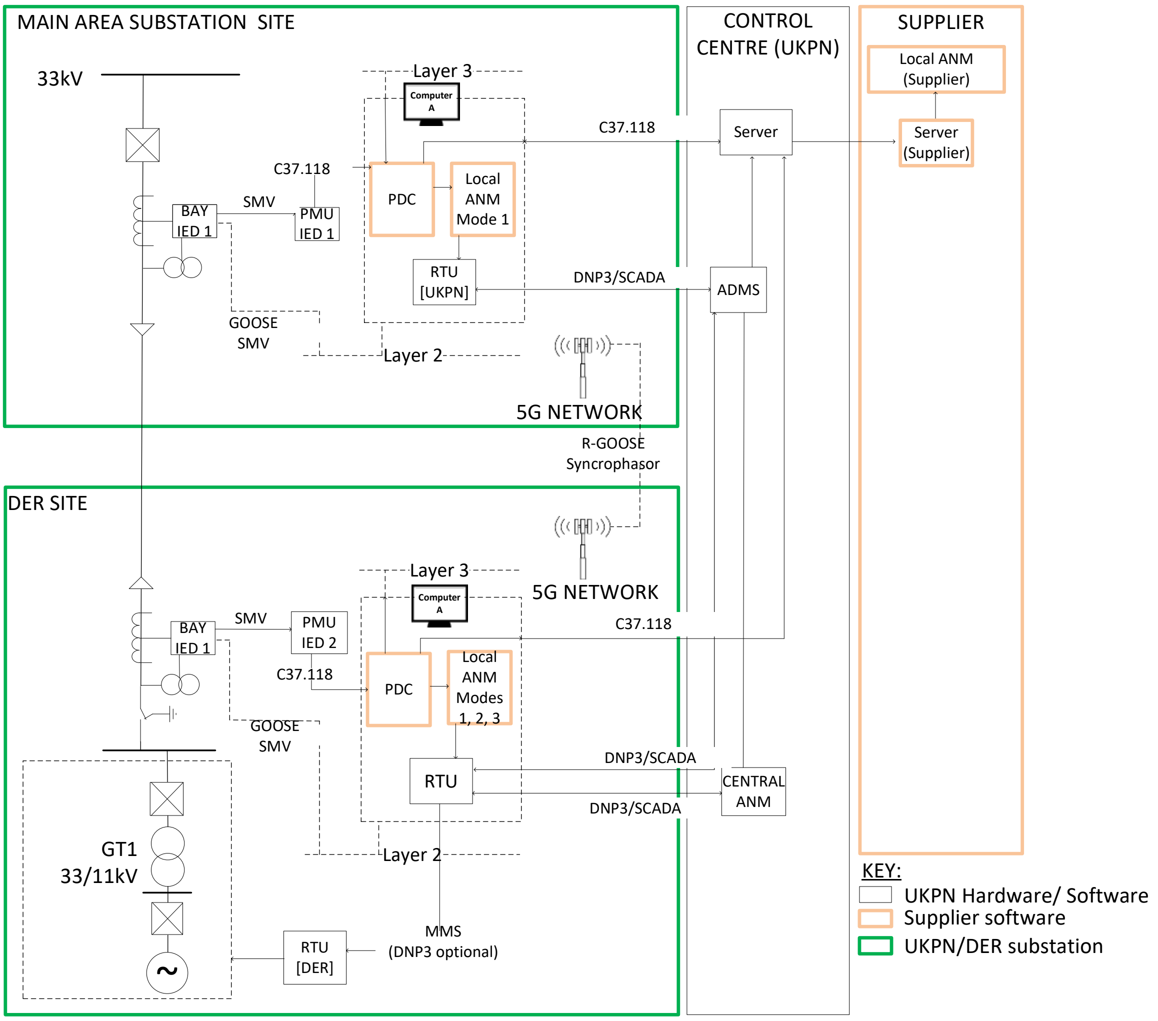


Figure 12: Conceptual Local ANM Architecture

5.3.3 Specifics of Current Design

This section provides further detail on the current design for the implementation of the Local ANM intelligence for Constellation.

5.3.3.1 Architecture

The Grid Substations and managed DER sites will require the installation of the industry standard PMUs which will feed into the PDC functionality of the PhC, which can also receive any relevant SCADA/RTU data.

The architecture of the Local ANM Method is made up of two components described below and shown diagrammatically in Figure 14.

- Grid Substations: Phasor measurements are recorded at the substation through the PhC, which will be integrated as software on the Grid Substation Server. The PhC logic platform will apply analytic processes to the data and will forward both the raw measurements and analysed data to the GE WAMS DE central platform (see Section 4.6.2) where analytics services and machine learning model building functions will be applied. Both UK Power Networks and GE will have access to the WAMS DE central platform.

  The Grid Substation Server will be configured to run the Direct Distributed ANM operating mode where site-to-site communication is available. The Grid Substation Server will execute control signals to the DER site to apply constraints as required. The constraint level is communicated to the local DER site using a SCADA protocol. This allows multiple DER sites to be managed by the Grid Substation; and

- DER Sites: Similar to the Grid Substations, the PhC/PDC software will be hosted on the DER Substation Server. The DER Substation Server will be configured to run the Holdover and Learned Limit ANM operating modes, which is applied when all communication is lost to the DER site, including to the Central ANM and the Grid Substation Server. The DER Substation Server will also host a version of the WAMS DE platform which executes a machine learning model that is built and transferred from the UK Power Networks' Central WAMS DE which estimates network headroom at measured points of constraint boundaries. The infrastructure providing local measurement will be used to test the three Local ANM approaches (Holdover, Direct and Distributed ANM).

The functionality of the PDC, PhC and WAM DE components that form the Local ANM Method are described in Section 5.3.3.2 and Section 5.3.3.3.

The three operating modes of Local ANM that will become active when the Central ANM is lost can be summarised as follows:

- Direct Distributed ANM: This control mode is hosted on the Grid Substation Server. It is activated when communication between the Grid Substation and managed DER site is available while communication from the central ANM platform is lost. This method measures or derives network constraints from the Grid Substation, which allows the distribution of power setpoints to one or more managed DER sites to control the output;
- Holdover ANM: In cases where a managed DER site has no communication to the central ANM and Grid Substation, the local ANM system will revert to Holdover ANM that will continue operation of the DER. This is hosted on the DER Substation Sever at the managed DER site and accounts for an increase in uncertainty in network headroom. It also identifies through local measurements at the DER site if any network

faults reduce the assumptions relating to the uncertainty in how much network headroom is available. Once the Holdover times out, the local ANM will either send a signal to return to failsafe operation of the DER output or will switch to the following local ANM control mode; and

- Learned Limit ANM: This is a further control mode which will be applied when the managed D ER site has lost communication to the central ANM and the Grid Substation. This control mode is developed with a view to continue DER operation indefinitely. The aim of the Learned Limit ANM is to estimate network headroom from local measurements provided at the DER site by learning over time how the network behaves during normal operation and when the network develops a fault and executes a machine learning model, provided from the central WAMS DE server.

Appendix A.2.1 provides further details on the Local ANM operating modes and Appendix A.2.2 provides details on how Method 1 (Local ANM) has been applied to the Constellation trial sites.

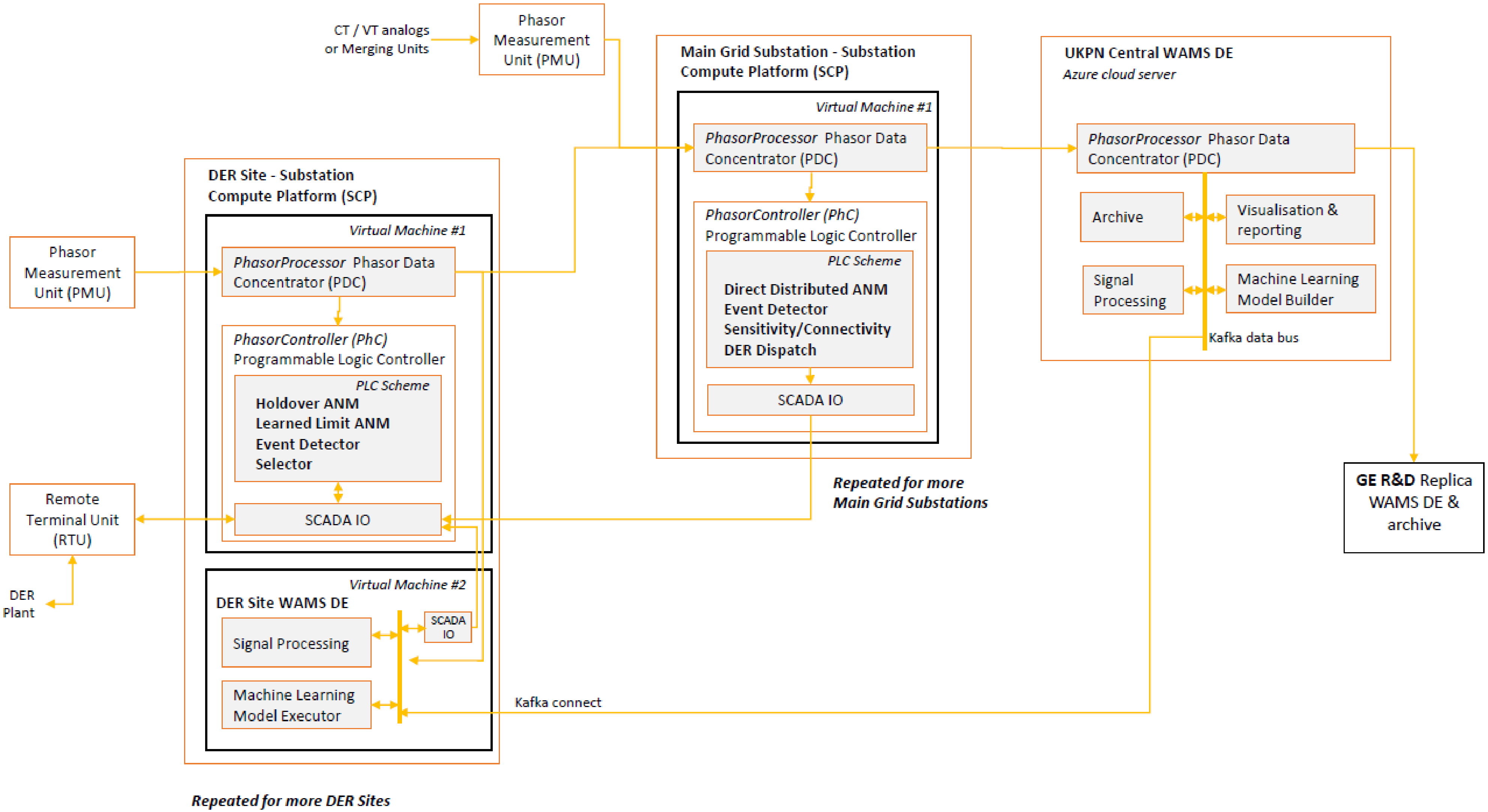


Figure 13: Local ANM Layout Structure

5.3.3.2 Hardware

The hardware Equipment to be installed by UK Power Networks in order to implement Method 1 is as follows:

- PMUs: This is a measurement technology commonly used in electric systems to improve system operator's visibility on the condition of the grid network. A PMU is a device that accurately measures instantaneous voltage and current at a specific location on the grid. This information can be used to determine the frequency as well as voltage and current phasors in that location. Other variables that can be derived from the phasors are active and reactive power. The PMU output data rate is typically one sample per cycle, which is much faster than traditional SCADA and presents dynamic changes in the network in much more detail. The potential areas of constraints at the selected Grid Substations and managed DER sites will be measured using PMU measurements, and GE will provide support on this. These shall be capable of capturing samples from a waveform in quick succession and reconstructing the phasor quantity, which will be streamed to the PDC, where logic control is applied and to the central server for processing, recording and visualising. This data can be used in control schemes for active management with the benefit to respond quickly to power network and communication network changes; and
- PDC: This will receive and time-synchronises phasor data from multiple PMUs to produce real-time, time-aligned output data. The PDC can exchange phasor data with PDCs at other locations by providing routing points using the PDC software which can be standalone or integrated with other elements of the monitoring and control scheme. This will be available in dedicated hardware format initially but over the course of the Constellation project, this will be virtualised into the Substation Server.

5.3.3.3 Software/Firmware

The software to be integrated over the course of the Constellation project to implement Method 1 is as follows:

- PhC: This is a dedicated software platform designed for real-time control. It analyses phasor data and produces protection and control outputs for monitoring, management and protection applications. The function shall have a number of operating modes as described above depending on the availability of communication. It is a flexible Programmable Logic Controller (PLC) that can be applied to many wide area control and protection applications. The PDC is an application hosted together with the PhC platform.
- The PDC is based in on the GE PhC software, which is a highly scalable and efficient software for synchrophasor data processing in the main central WAMS DE platform, right down to substation scale. The software will be integrated with the PhC platform later in the project and will be included in the virtualisation at the Substation Server. The PDC software will be implemented on the Substation Server initially for data gathering and will be one of the first components made available on the Substation Server for full local ANM functionality; and
- WAMS DE will be based on the next generation of WAMS DE platform infrastructure, in which synchrophasor and other data that is made available on a data bus (Kafka) to applications that are built as microservices. The architecture is modular and extensible and supports the development of the Constellation Local ANM machine learning applications. A version of WAMS DE will run as the central Azure cloud sever where

there is access to the processing power needed for intensive machine learning model building. An instance of the WAMS DE platform will be incorporated onto the DER Substation Server. The WAMS DE software at the central UK Power Networks' centre will manage all of the incoming data from the PMU installation and will provide visualisation and archiving of all phasor data, while executing the machine learning model in the background.

5.3.3.4 Communication Requirements

The communication requirements for the Local ANM design are as follows:

- As phasor measurement data is transferred from the substation PDC to the central WAMS DE platform for processing and machine learning, an Azure server has been designed for the central data collection point. This will be achieved through the industry standard IEEE C37.118.2-2011 protocol. The PDC at the Grid Substation will continue to exchange phasor measurement data with the Central WAMS DE server to ensure visualisation of the data at UK Power Networks' control centre;
- The local WAMS DE platform at the DER site must interact with the central WAMS DE platform by sharing data and models while communication between them is available. This is to ensure that the latest development of the machine learning model from the central platform is sent across to the DER site to execute in the event of loss of communication. The machine learning exchange and signal processing data exchange between the Central and Local WAM DE sites uses Kafka Connect linking the Kafka data bus in the two units;
- In the event of loss of communication with the main central ANM server, PDC at the DER site should send across phasor data to the Grid Substation Server, which is configured to run in Direct Distributed ANM operating mode. From there, the Grid Substation Sever and Direct Distributed ANM logic will execute control decisions to the DER site to apply output curtailment as required. Information exchange between the ADMS and Grid Substation Sever and DER Substation Server is achieved via a SCADA protocol; and
- The basic intention of the Local ANM approach is to remove the dependency on communication between the central systems and the Grid Substations and DER sites, so that in event of loss of communication, the Local ANM will continue to operate regardless. However, there is interaction required between the Local ANM and central ADMS and/or central ANM platform to provide observability of the status of key operational network areas that have known constraints, which allows system operators to change the mode of operation of the network.

5.3.4 Lessons Learned

D1 Section 5 : Local ANM Lessons Learnt	
1	**Accommodating remote network constraints with Local ANM:** the constraints impacting Thanet Grid include some network constraints that cannot be measured (section 5.3.3.1) or derived from the Thanet Grid Substation (refer to network diagram in Appendix A.1.2). These include Super Grid Transformer reverse power flow at Richborough. The original design concept assumed all relevant constraints could be measured with PMUs and sent back to the relevant Grid Substation. However, there is uncertainty in providing the monitoring at a Richborough Grid due to complexity and availability of outage periods, which impact the implementation time. The solution is to undertake a live implementation which will be trialled based on the Thanet Grid constraints only, coupled with PNDC testing to investigate using recorded (and simulated) SCADA/RTU/syncrophasor data from Richborough Grid using existing monitoring sources and the Thanet area Constellation monitoring.
2	**Accommodating network topology changes:** the network topology can change during Local ANM operation, and this can impact on the available network capacity to be allocated to DER sites. Local ANM will not have full observability of the distribution network; however, as part of Constellation this can be addressed in several ways: ➢ Event detection and classification using signal processing on the high-resolution data is a technique that can be used to sense network events or conditions, even if the network event is not directly monitored; ➢ Use analysis of sensitivities and connectivity between the measured network constraint and the DER site using high-resolution data; and ➢ Define boundaries of Local ANM zones where the possible combinations of relevant network topology changes are manageable by Local ANM.

5.4 Project Method 2 (Wide Area Protection)

5.4.1 Brief Introduction to the Project Method

The increasing amount of distributed generation (DG) connected to distribution networks calls for new protection functionality. DG operation needs to be considered in protection planning as it can alter the distribution network fault levels and disturb traditional protection schemes. The Wide Area Protection Method that Constellation will trial will address these challenges through the use of communications between sites to improve detection of Islanding.

Islanding refers to a situation where a network section including generation and loads becomes isolated from the electrical grid. In GB, a generator cannot be islanded from the grid under GB codes. For this reason, the use of loss of mains (LoM) protection is standard. Research of LoM protection identified solutions divided into local active, local passive and remote methods. Rate of change of frequency (ROCOF) is perhaps the most widely utilised LoM protection method worldwide and required also by the GB codes. This function significantly improves the capability to detect islanding in comparison to plain voltage magnitude and frequency protection. However, the additional sensitivity gained by using ROCOF unfortunately also increases the risk for unwanted tripping of DER. In the worst case, it may even result in cascading disconnection of DERs in the power system.

It is also good to bear in mind that inverter coupled DERs do not contribute to the system inertia unless dedicated virtual inertia control is implemented. As the inertia of a power system decreases, the fluctuations in frequency followed by disturbances in transmission grid are likely to be magnified. Consequently, the risk of false ROCOF protection operations also increases. On the other hand, the increase of DER capacity in distribution network level also increases the probability that local generation can more often match the local demand closely enough for causing local LoM protection to fail to detect islanding. This is because the performance of local passive LoM detection methods is dependent on the power imbalance between the islanded generation and loads. It is therefore challenging to find a balance between avoiding false LoM operations and managing the risk of non-detected islanding.

The wide-area protection designed as part of Constellation can improve the operation of LoM protection through utilising messages exchanged between the Grid Substation and DER sites equipped with Substation Servers. Protection logic located at Grid Substations differentiates between events when the DER feeder is faulty (and the DER unit should be disconnected) and when the disturbance originates from the regional transmission system or adjacent feeders (in this case, the DER unit should remain connected). R-GOOSE over 5G technology will be used to send transfer trip and block signals to the DER units. As a result of this new functionality, the DER benefits from reduced outages, while the electricity network benefits from the increased reliability of the intelligent services provided by DER.

Appendix A.3.1 provides details on how Method 2 (Wide Area Protection) has been applied to the Constellation trial sites.

5.4.2 Specifics of the Current Design

Figure 15 below details the protection concept with virtualised protection functions and communication based wide-area protection, Figure 16 details the Wide Area Protection functionality and Figure 17 details the signal paths for the wide area protection system.

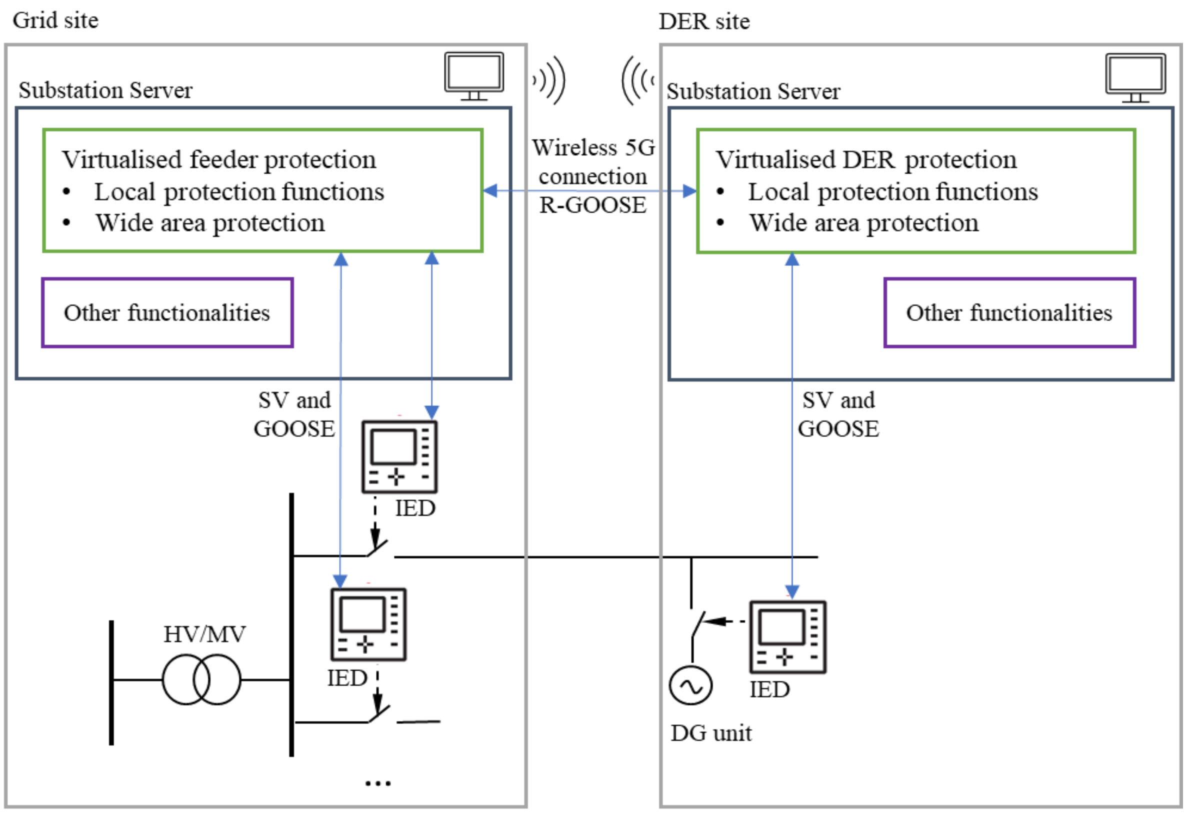


Figure 14. The protection concept with virtualised protection functions and communication based wide-area protection.

The Wide Area Protection LoM scheme includes the following functionality:

- **Transfer Trip** that aims to prevent unintentional islanding. The transfer trip-based LoM protection solution is based on predefined combinations of switch statuses and detection of faults on the DER feeder. In this project the transfer trip command is sent to the protected DER(s) whenever the DER feeder in question becomes islanded. In most cases the islanding is declared by monitoring circuit breaker statuses. That is, islanding is detected by monitoring whether the DER feeder becomes separated from the connecting busbar section at the Grid Substations or when busbar section(s) in question at the Grid Substation become de-energised themselves.
- A **ROCOF based blocking scheme** to prevent disconnecting DERs during wide-area disturbances; and
- A **Safe Reclosing Function** to prevent unsynchronised reclosing. Unsynchronised reclosing is often mentioned as one of the key concerns related to DG protection. This is because islanded DER and other network components may experience severe damage due to out-of-phase reclosure. This concern may be tackled by ensuring that all DER are disconnected within the open time of automatic reclosing. In this project the DER IED is configured to send its circuit breaker status to the Grid Substation IED, where this information is used for determining whether the DER is online or not. However, as the automatic reclosing open time is long in the UK Power Networks network, this information will only be used for raising an alarm to SCADA.

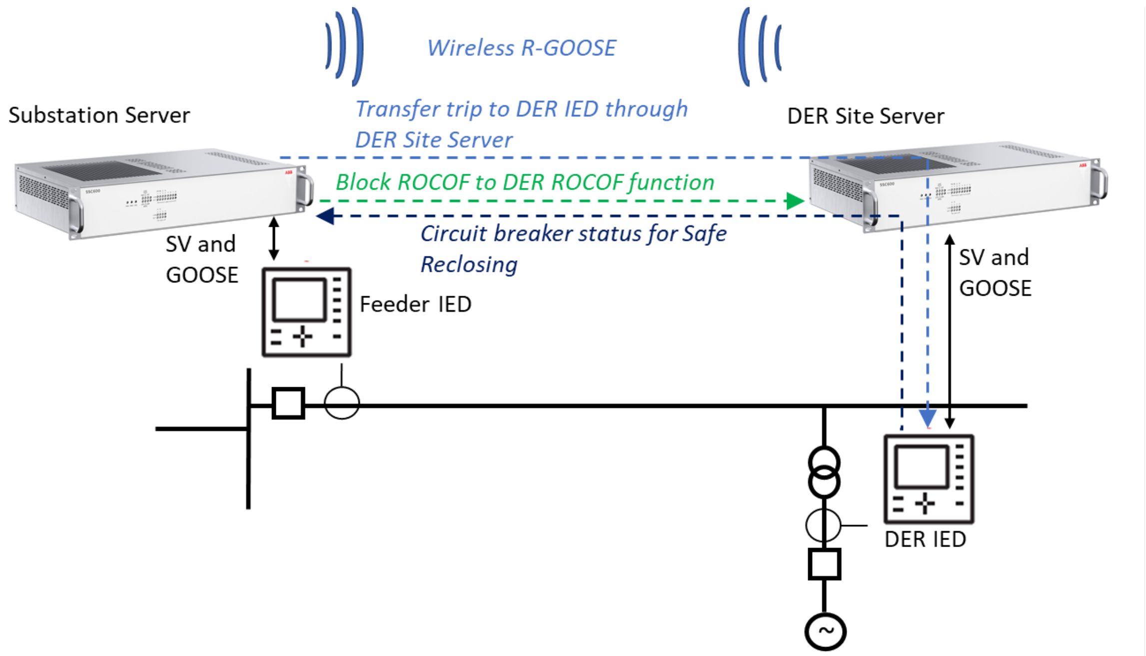


Figure 15: Wide Area Protection Functionality

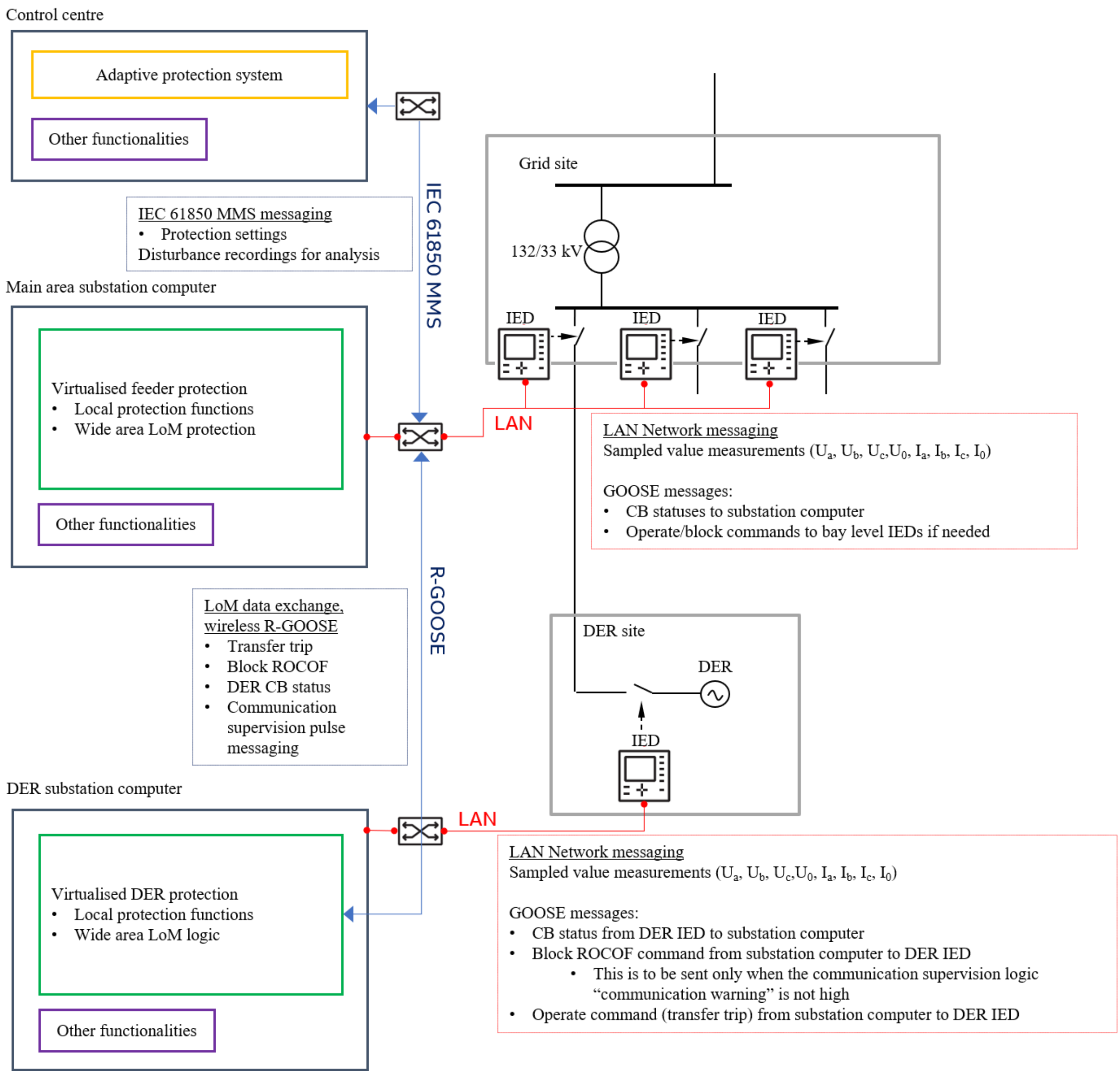


Figure 16. Wide Area Protection Signal paths

Two local protection functions will also be trialled in Constellation:

- A Load Blinding, or Load encroachment, function used to block the directional overcurrent protection on the 33kV side of the grid transformers. The aim of this function is to avoid incorrect tripping in the case of a heavy loading condition in a network whose power factor is close to 1.00. The operating principle is based on calculating the positive sequence impedance, and then provides a blocking signal if this impedance is in the load blinder forward or reverse area. This function will be adapted as part of the Adaptive Protection solution (Section 5.5); and

- An anomaly detection algorithm that identifies atypical events, which could potentially be indicative of future performance degradation or fault occurrence. The algorithm uses raw sampled current and voltage measurements as inputs and triggers a disturbance recording when it notices exceptional situations. The disturbance recordings can then be used for further offline analysis possibly in combination with data from other sources also (e.g. weather data). The analysis results can provide information on evolving faults, in addition to information for longer term predictive maintenance activities, but will not be used for protection.

5.4.3 Communication Requirements

All communication between the virtualised wide area protection (part of SSC600) units will be implemented using wireless R-GOOSE. R-GOOSE follows the principles and configuration of GOOSE extending the transport medium to allow routing over IP networks. R-GOOSE messages are sent connectionless using IP multicast and UDP. R-GOOSE uses IGMPv3 to allow routers to determine the routing path through the network.

When blocking protection functions over wireless 5G network, it is of utmost importance that the blocking messages are up to date. This is because outdated block messages could potentially result to impaired LoM protection performance. To negate this risk, a dedicated communication supervision logic based on continuous R-GOOSE messaging between the two IEDs is designed. In this approach, the DER end IED is configured to send a continuously changing binary pulse to the Primary Substation IED via R-GOOSE. The Primary Substation IED detects the rising edges of this R-GOOSE message and replies to these by similar R-GOOSE pulse messages. The DER end IED then subscribes the replies from the Primary Substation IED and raises a communication down alarm if no replies have been received for a predefined period that will be determined during testing. This alarm is held high for a predefined reset period starting from the first received communication supervision pulse from the other end. Whenever the communication down alarm is high, the block ROCOF messages are disregarded.

5.4.4 **Lessons Learned**

D1 Section 5 : Wide Area Protection Lessons Learnt	
1	**Virtualisation:** the key challenges of the Wide Area Protection Design are related to virtualising functionality that has strict real-time requirements. Protection in electricity distribution must be quick and reliable to operate whenever necessary. However, on a Substation Server running multiple software environments it is essential protection functions can always have access to adequate server resources to ensure reliable operation. As part of the trial preparations, testing is ongoing to determine if the virtualisation approach (Section 4.6) can accommodate this requirement.

5.5 Project Method 2 (Adaptive Protection)

5.5.1 Brief Introduction to the Project Method

Traditionally protection settings are manually calculated and applied to protection relays. By design they are based on all running arrangements and are conservative to ensure that as the network is reconfigured the protection continues to operate reliably. This is necessary as 71% of protection uses electromechanical relays with no ability to remotely change settings.

However, this poses a challenge to connecting generation to the distribution network. Specifically, directional overcurrent (DOC) protection is essential to ensuring network capacity is maximised. DOC protection is designed to protect the network from back-feeding faults. In some cases, DOC limits the amount of DG that can be connected downstream of the relaying position.

The traditional solution to this is load blinding. This uses a pre-calculated power factor to differentiate between network faults (e.g. a 132kV high resistance fault) and normal generation/load (e.g. high reverse power flow into 132kV). In sites which can be supplied through multiple Grid Supply Points, either directly or through loose couples, the changing power flows present challenges for a fixed protection setting application and need to be managed dynamically.

As networks look to move to DERs providing voltage control services and utilising CLASS functions, the load blinding solution will face further challenges with fixed settings. As a result, there will be areas on the distribution network, where DOC settings could be the limiting factor to the available capacity rather than the rating of the assets. Parts of the network may therefore have spare capacity which cannot be utilised to connect more DER to support the transition to Net Zero.

For the Constellation project, Siemens will develop an Adaptive Protection System (APS) which adapts the DOC load blinder protection settings in each Grid Substation according to the operating topology in that trial area. A Central Management System (CMS) will be provided to collect, manage, and change protection device settings as well as for management of other secondary devices, i.e. non-protection devices. The APS and CMS are deployed as a central platform with communication to each trial Grid Substation via an MQTT protocol and the Local Gateway which will be installed in each trial Grid Substation on the Substation Sever.

Appendix A.4.1 contains further details on the software applications used in the adaptive protection solution and Appendix A.4.2 provides details on how Method 2 (Adaptive Protection) has been applied to the Constellation trial sites.

5.5.2 Specifics of the Current Design

5.5.2.1 APS Process

The Adaptive Protection System process is shown diagrammatically in Figure 18 and Figure 19 below and described as follows:

1. ADMS decides to start the APS process. The ADMS trigger to this decision can be made manually, scheduled-base, time interval based or event-based by operators, automatic SCADA scripts for network reconfiguration, etc. In all such cases, ADMS

send primary network operational data (load, generation, and switch status) as a file to a monitored file directory detecting the start of APS process;

2. Receive an up-to-date primary network model inclusive of the latest operational data (circuit breaker and switch status, load and generation status (MW/MVAr). This is illustrated by the black arrows in Figure 18;
3. Check the primary network model by the Network Model Analysis System implemented in PSS®ODMS. The role of the Network Analysis System is to consume primary network model data updates from ADMS in CIM16 XML format, run State Estimator/Power Flow analysis in PSS®ODMS and Short Circuit analysis in PSS®CAPE. This process will be automated through Python scripting;
4. Retrieve the latest protective relay settings from the relay asset database; and
5. Perform the adaptive protection settings calculations for load blinding protection based on this latest network model and protection settings, as follows (illustrated in Figure 19):
   a) From the 33kV substation trace down and find all connected DERs;
   b) Complete load flow and find the back-feed to the upstream network at the 33kV incomer;
   c) Determine load blinder parameters (e.g., Cos Phi, I>, I2>, V<);
   d) Decide the study area for Protection Security Assessment (PSA) analysis each 33kV incomer (e.g. 5 buses on upstream and downstream feeders). This will be pre-determined for each trial zone;
   e) Decide solid/resistive fault scenarios (upstream and downstream). Again, these will be pre-determined for each trial;
   f) Run the PSA and validated adapted settings as well as overall security and dependability of other protections in the defined PSA study area;
   g) Save the adapted settings back to the database for subsequent communication to the Central Management System; and
   h) Send the Adapted settings to the Protection IEDs

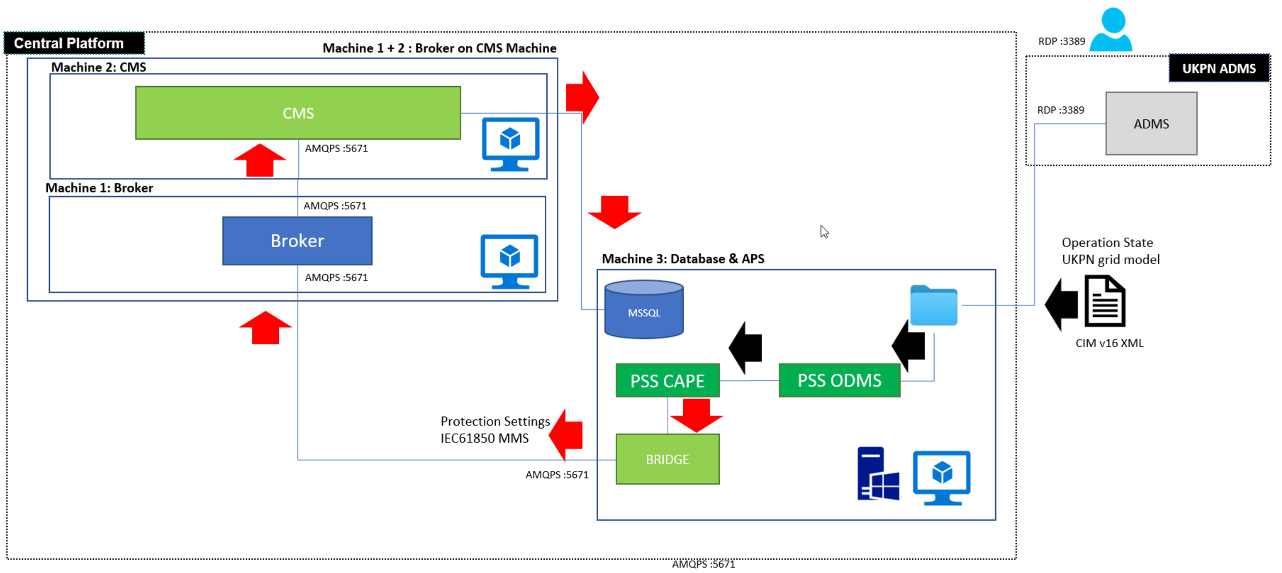


Figure 17. APS Process - New operation state, new protection settings calculation, and storage at the Central Platform

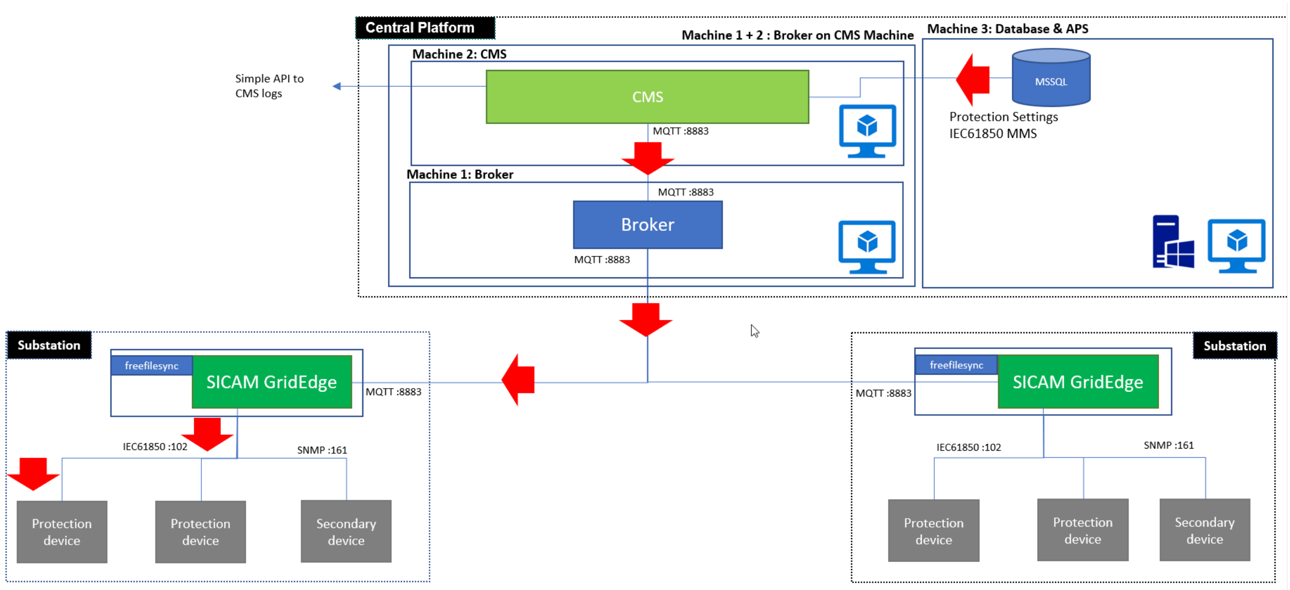


Figure 18. CMS Process - Get new protection settings from the Central Platform and adapt IEDs in substations

5.5.2.2 The Central Management System

The Central Management System (CMS), a web-based software, will be used to manage the protection settings adaptively and view assets in Grid Substations. The CMS incorporates the following features:

- Topology Management Feature: Displaying the substation model hierarchy (Substation, Voltage, Bay, IEDS) and allowing editing and management of functions;
- Protection Settings Manual Deployment Feature: allowing the user manual control over the deployment of Adapted Protection settings;
- Protection Settings Automatic Deployment Feature: allowing automated deployment of Adapted Protection settings; and
- Protection/Non-Protection Settings Monitoring Feature as shown in Figure 20, giving user access to read and alter device settings and settings export to other systems.

CMS communicates with the Substation Server through a gateway software (called SICAM GridEdge) in the Grid Substation, as illustrated in Figure 21 below. The SICAM GridEdge communicates with protection/non-protection devices in each Grid Substation.

- 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;
- Protection settings will be read through the protocol IEC 61850;
- The SICAM GridEdge software will exchange and synchronise data (actual protection settings and version information) toward the Central Management System, by using MQTT protocol;
- The SICAM GridEdge software will deploy protection settings received from the Central Management System over substation LAN through IEC 61850 to the protection relays in the substation;

- One SICAM GridEdge software handles one Grid Substation; and
- For each device in a substation, the SICAM GridEdge creates an asset file containing the device hardware version, device firmware version and software version information.

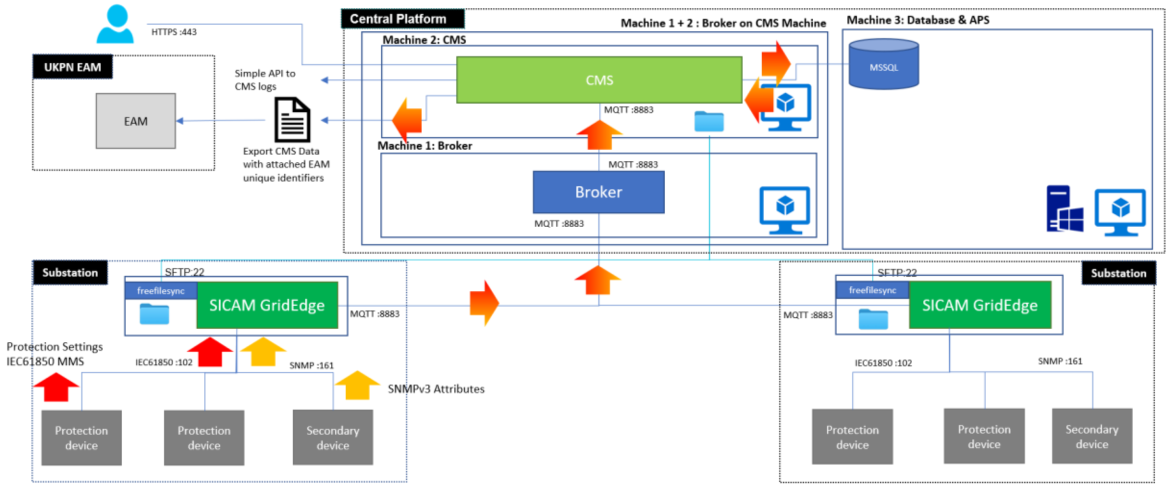


Figure 19. CMS Process - Protection/Non-Protection Settings Monitoring

5.5.2.3 System Structure

The Method will be implemented via the system structure shown in Figure 21, with the interfaces to the UK Power Networks Enterprise Asset Management and Advanced Distributed Management System included. The Central Platform (comprising the APS and CMS) is shown in the middle of the diagram, and the connection to the two trial substations is shown at the bottom. Data flows, and the communications protocols between the hardware devices are also shown.

An interface to UK Power Networks' existing asset management system will provide an up-to-date list of enterprise assets each with a unique identifier (UID) in a suitable agreed format (such as CSV file) to the Central Management System. An interface to UK Power Networks' existing ADMS software system will provide an up-to-date network model in a suitable agreed format (such as CIM V16) to the Network Model Analysis System (not to the Central Management System). Using an up-to-date network model, the Protection Engineering and Simulation System (PESS) will adapt protection settings, if needed, and provides up-to-date adapted protection settings to the Central Management System database.

The CMS and its database serve as Protection Data Management System at the Central Platform, and the Broker interface to the Local Gateway enables – for supported devices – online reading of the mentioned data and writing of adapted settings for protection devices.

In addition to the Local Gateway interface, the Central Management System will use a file transfer interface and a file synchronisation software for synchronisation of files (configuration files, commissioning reports, firmware (FW) binaries, as additional attributes to these assets) between each Grid Substation and the central platform via a third party software component for file synching.

The SICAM GridEdge communicates with the Central Management System by using MQTT protocol. 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 (to the extent supported by the devices/software components).

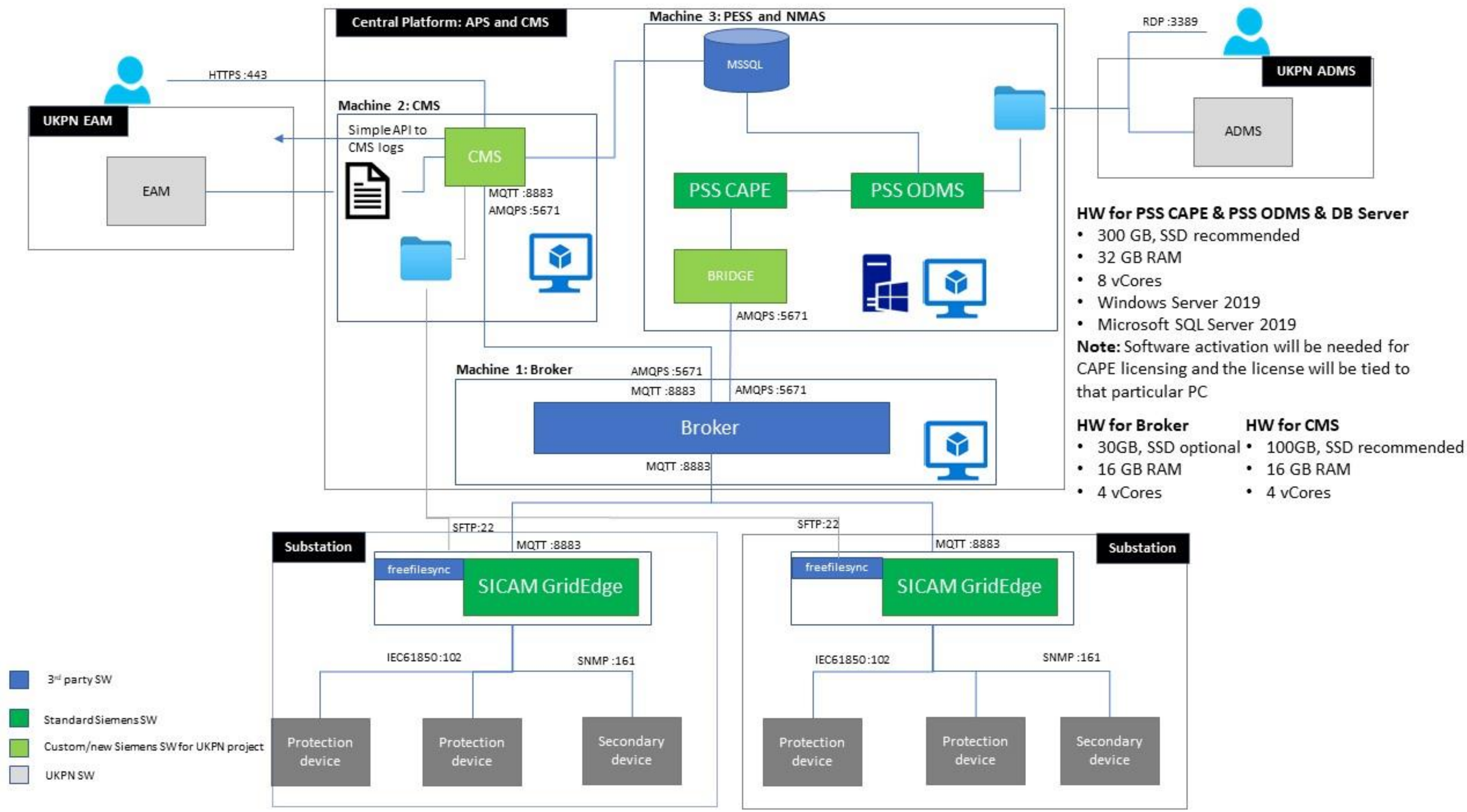


Figure 20 - APS and CMS Deployment

5.5.3 Lessons Learned

D1 Section 5 : Wide Area Protection Lessons Learnt	
1	A key challenge of the Adaptive Protection System development that has been overcome in the Constellation project is ensuring component interoperability from a standardised product portfolio. This includes: • ODMS – CAPE (Open Data Management System – Computer Aided Protection Engineering); • CAPE – New central management controller; • Central management controller – Developed and modified substation gateways. Overcoming these challenges has been achieved through detailed technical coordination and the engagement of independent product lifecycle managers, together with the technical teams under their control. Clear documentation is being created to define individual product function and interoperability for the whole system Constellation design deliverables.
2	The close collaboration between the whole consortium has inspired and maintained project momentum, with shared investment in overall programme success, additionally; The Siemens internal development of a technical forum with clear activities and progress tracking has been highly effective in programme management and success evaluation. Innovative and agile, weekly and fortnightly stand-ups for whole systems engineering evaluation has encouraged full ownership and accountability for each technical deliverable.
3	The availability of network information and data sources in compatible digital formats has required tweaks and modifications to the original design proposal, as an example: Original Network model and analogue information, all expected from the existing Distribution Management System, has required the addition of systems exports from the design tools and existing operational analogue databases.

5.6 Site to Site Communications (5G Slicing)

5.6.1 Introduction

To enable the wide area protection and control functionality in Methods 1 and 2 to be implemented successfully, a reliable and low latency 5G Slice infrastructure will be implemented for the site-to-site communications.

This is because:

- For Method 1, should the connection to the central ANM system be lost, the local intelligence is required to draw on both local and remote measurements to provide the maximum safe output and this functionality must be achieved quickly to avoid DER curtailments; and
- For Method 2 (Wide Area Protection), the DER LoM protection details must be identified and shared between all connected sites quickly (under 500 ms) and reliably to avoid un-necessary DER curtailments.

Whilst a reliable and low latency 5G Slice infrastructure could have been implemented using traditional microware, fibre optic or Multi-Protocol Label Switching (MPLS) technologies, with associated/dedicated hardware, the cost of doing so would have been prohibitive considering the project budgets. Furthermore, the level of disruption that would have been imposed upon UK Power Networks' network services was considered un-acceptable given the innovative nature of the project.

Therefore, given the recent developments in 5G mobile radio communication technologies, in particular when considered in conjunction with implementing a network slicing design, it was determined that an economically scalable Very Low Latency solution could be introduced for site-to-site telecommunications between distribution substations, based on this technology, while simultaneously improving the cyber security of the system.

5G offers the potential to connect various sites using a wide-area network with lower latencies than any previous point-to-multi-point wireless communication technology. Additionally, it has the ability to share infrastructure between various users and use cases reducing the capital and operational cost of implementation. However, whereas private fixed line networks can offer extremely reliable communication with little marginal cost for additional capacity, mobile networks must consider the cell coverage and capacity to ensure each user receives a reliable and sufficient service.

With due consideration to all the above, and following industry consultation and a procurement exercise, UK Power Networks engaged Vodafone to design and implement a 5G Slice design based on reliable and low latency 5G Slice principles for Constellation.

Vodafone are actively rolling-out a 5G network throughout the UK and are committed to prioritising such implementations not only for Constellation sites, but for wider roll-out across all UK Power Networks' licence areas by 2025.

It is acknowledged that whilst 5G networks are not new, implementing a 5G Slice design within an electricity distribution utility, and in the manner required for Constellation, is innovative and presents a step change in electricity protection and control processes.

Significant learning is therefore expected to be obtained during the 5G Slice design and off-site and on-site trial stages of Constellation. Vodafone are working with Ericsson as 5G network partner, to support the hardware, software and technical delivery of 5G slicing and site-to-site communication

Appendix A.5.1 and Appendix A.5.3 provides further details relating to the 5G Solution and High Level Architecture.

5.6.2 Design Objectives

Implementing a 5G Slice network essentially means that distinct virtual (logically independent) telecommunication networks for the services required under project Methods 1 and 2 are able to run over a dedicated and/or the same physical infrastructure, designed and configured to ensure that priority is given to achieving independent reliable and low latency 5G Slice networks.

These design objectives can be summarised below:

- Specific/custom network instances (slices) can be provided for different services;
- Slices can offer flexible configuration of throughput, latency, scalability, reliability, and topology requirements;
- Network functions can be shared or allocated exclusively, offering service isolation, through service delivery automation; and
- In a longer run, exploits Network Functions Virtualisation (NFV) to create and monitor/tune network slices dynamically/in real time.

To implement this design, a new and dedicated network control and user plane slice involving both Radio Access Network (RAN) and 5G Core will be provided which will integrate with Vodafone's existing Gravelly Hill Data Centre and handle the Constellation workloads associated with both project Methods. This design solution uses connectivity with the central Vodafone data centre through a 5G New Radio (5G NR) and 5G Standalone (5G SA) solutions.

To achieve the above, the 5G Slice design is required to comply with the following requirements:

1) Provide connectivity between UK Power Networks sites over 5G;
2) Provide a dedicated Network Slice for Constellation (Method 1 and 2) workload;
3) Provide up to 5 Gbps total throughput in the new slice user plane;
4) Achieve 10-15 Mbps throughput per device, upload and download, round trip time delay – this will be verified during the forthcoming trial period;
5) Ensure that no enhanced mobile broadband (eMBB) 5G subscriber is able to attach to 5G using the Constellations 5G NR sites; and
6) Ensure that no Constellation devices can attach to Vodafone UK 5G eMBB network.

One further important design objective is to ensure that cyber security measures are accommodated within the overall 5G design in order to mitigate un-authorised access to UK Power Networks' operational systems, and to the DER sites.

Within Constellation we are mitigating such concerns by designing a closed 5G network and deploying specialist Layer 3 network switches with in-built cyber security defences at the Grid Substation and DER sites, sourced from Siemens (RuggedCom), to provide the 5G router capability.

As the project moves from the design to the test stage, it will be an important consideration to understand the contribution/impact that the RuggedCom routers will have on the services (e.g. Quality of Service (QoS) and performance).

To achieve the required design, the following design specifics have been addressed:

- E2E network slicing is a logical network that provides specific network capabilities and network characteristics with logical isolation;
- It is a cross-domain technology that span across RAN network, Transport network, Core network and terminal domains;
- Each of these domains comprises of functions, platforms, protocols as well as resources; and
- 5GSA Core architecture is based on 3GPP Release 15. The upgrade to release 16 will be performed as soon as the product becomes available.

Appendix A.5.2 provides details on the hardware and software that will be provided as part of the 5G Slice for Constellation.

5.6.3 Security

Considering the security requirements of Constellation, we will use state-of-the-art 5G security of the user identity. 5G brings a new security capability whereby the identity of the user (e.g. IMSI) does not flow unencrypted over the air interface.

This is made possible by use of SUCI – "Subscription Concealed Identifier" where the subscriber identity is encrypted and can only be decrypted at the 5G Core.

Please refer 3GPP[10] for structure of SUCI. Please refer 3GPP[11] for SUCI de-concealment procedure.

5.6.4 Site Survey Activities

Initial site surveys have been completed by both Vodafone and UK Power Networks on all proposed trial sites to validate their suitability with regards 5G coverage and ability to physically install and connect, e.g. power supply available capacity, the required equipment inside the available site buildings in the telecommunication rooms or the relay rooms.

These site surveys have confirmed that 5G coverage and ability to install the necessary equipment inside the site buildings is acceptable and hence the 5G Slice infrastructure designs required for each site have been progressed.

[10] Refer to TS 23.002
[11] Refer to TS 33.501

5.6.5 Lessons Learned

D1 Section 5 : Lessons Learnt	
1	Provision of 5G coverage: Timelines on 5G DOT (in building solution) meet the technical programme requirements compared to the longer lead times on macro cell upgrades to service the trial site locations. 5G macro upgrades will be deployed later in the programme.
2	Sharing the Network Slice with public 5G SA users is not possible in the initial phase of the trial as this will require a Network Sharing agreement with Vodafone's partner Virgin-Media O2 (VMO2).
3	Providing the Radio Coverage to various UK Power Networks' sites is challenging due to remote locations and physical structure. Vodafone is working on multiple radio coverage solutions (e.g. Ericsson Dots, Mini-Macros, etc) as appropriate to maximise the numbers of sites with 5G coverage.

6 Ongoing Activities & Next Steps

6.1 Ongoing Activities

The high-level project plan for Constellation is as detailed within Figure 22, where each of D1 to D7 represents a Constellation Deliverable.

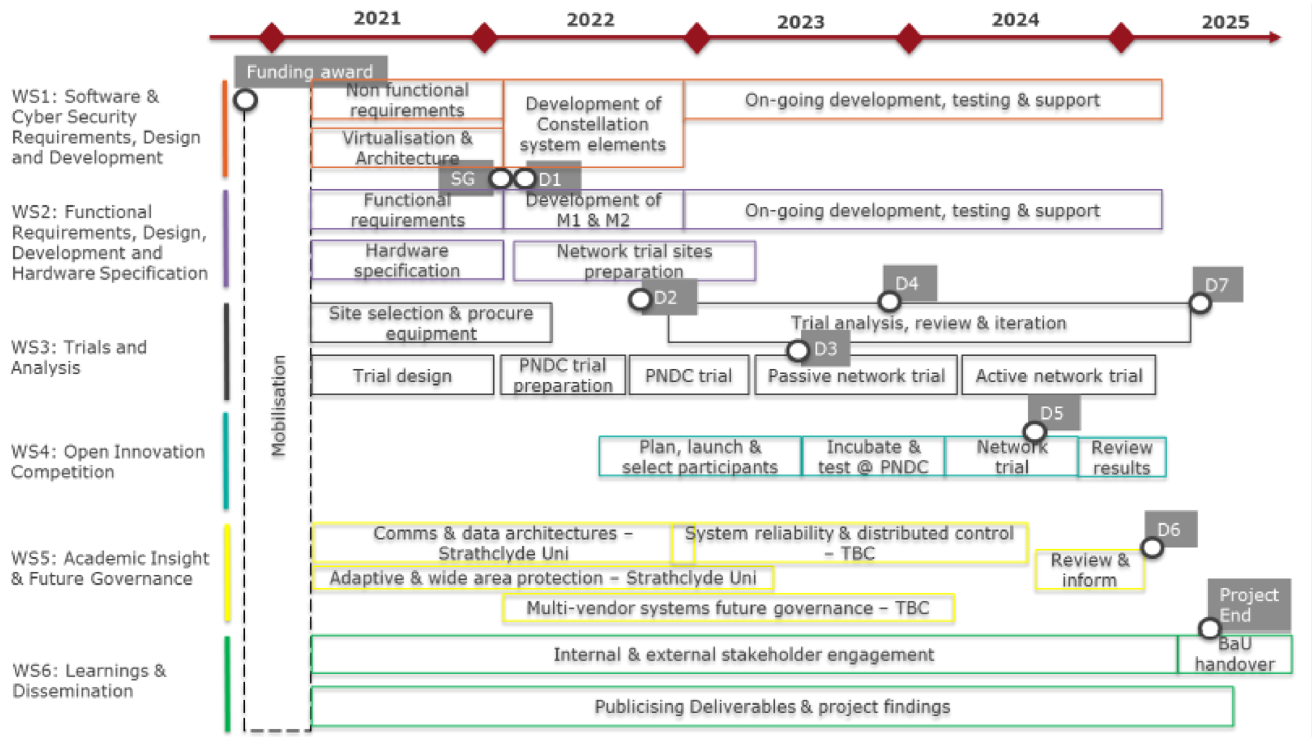


Figure 21: Constellation High-Level Project Plan

From this, it can be shown that after completion of Deliverable 1, the next stage of the project focuses on:

- Development of Methods 1, 2 and the 5G slicing; and
- Preparation for trials in PNDC and UK Power Networks.

In order to progress the next project stage, several activities which remain ongoing at the time of this deliverable report D1 being prepared, identified within Table 9 below, will be progressed and concluded and several activities required to progress the next stage of the project will commence, as summarised in Section 6.2.

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

Table 9: Summary of Ongoing Activities

Description of Ongoing Activity	Planned Actions
OMICRON currently does not support R-GOOSE testing and/or monitoring.	This capability will be developed during the project for the latter stages of trials on the live network.
The adaptive protection solution requires specific network parameters, live measurements and live network topology (in order to define the running arrangement)	UK Power Networks and Siemens will continue the data integration activities.
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.
Investigations by ABB to verify how they are able to implement their software in a virtualised environment in parallel with other project partners' software is ongoing.	If it is evidenced that such integration is not possible, then additional hardware may be required for ABB's real time functions.
There is a risk that the deployment of the 5G coverage within the trial sites takes longer than anticipated due to delays in land acquisition in the DER sites.	To manage this Vodafone and UK Power Networks have begun the legal process immediately after the trial sites were shortlisted. The two legal teams are currently working together to ensure minimal disruption to DER customers.
Procurement of electronic components – equipment Suppliers have made us aware of issues with their supply chains.	To manage this risk we have agreed to test the initial 5G solutions on an existing release of 5G (v15) initially and move to a more advanced release of 5G (v16) only after the components are available, during the network trials.
Cubicle sizing for Grid Substation and DER sites.	UK Power Networks will carry out detailed site preparation designs and identify opportunities to reduce the size of the cubicle for DER sites.
The containerisation approach may need to be adopted at the DER sites, where space constraints are dictating that the RTU functionality and Phasor Data Concentrator may need to be containerised and run on the Substation Server (rather than being provided as a separate physical hardware device).	Investigations relating to this are currently ongoing and will be reported upon within the next deliverables.

6.2 Next Steps

The following section details the next steps which the project partners shall embark upon in order to progress Constellation through the next project stages.

Project Quality Control

- All project partners' design documents will undergo a final review prior to approval and closure by UK Power Networks. To facilitate this:
    - The UK Power Networks ETS documents will be used as a baseline against which to complete this final review;
    - A formal design review by the Technical Design Authority will be carried out; and
    - Feedback from the design review will be implemented before each design is approved.
- The aim is for all ongoing actions (summarised in Table 9) to be addressed, actioned and closed as appropriate;
- As the project progresses and further learning is generated, we anticipate that the design described in Section 4 and Section 5 will continuously evolve. The project team will record and manage these changes; and
- The project partners will continue working together to ensure successful development, integration and testing in the subsequent phases of Constellation.

Project Scheduling

- With the successful completion of deliverable 1, works related to project deliverable 2 and 3 will be continued. In particular, the site selection activities will be progressed and closed, including any required final discussions with the concerned DER site owners; and
- The requirements relating to the "off-site" (PNDC test facility) and live "on-site" trials will be developed. Additionally, the overarching trial objectives will be finalised;

Equipment Procurement

- UK Power Networks will conclude the trial site preparation (including finalisation of the Equipment), after which procurement will be started;
- In order to ensure the Substation Servers are capable of hosting the solutions described in Section 5 and meet the requirements in Section 4 we will obtain a sample Substation Server to carry out preliminary testing. While not accounted for as part of the NIC bid preparation, this early testing is essential to ensure the right Equipment is procured;
- In order to ensure the virtualisation medium is capable of hosting the solutions described in Section 5 and meet the requirements in Section 4 we will proceed with the preliminary testing. More specifically, ABB will continue testing of PAC functions to confirm suitability; and
- The current specification for the required Substation Server and associated hardware (the "Equipment") is detailed within Appendix A.1. It should be noted that it is subject to change as the detailed trial site engineering is completed during the next project phase.

General Project Activities

- UK Power Networks will proceed with:
  - Progressing the procurement of a “second Supplier” for Method 1 and Method 2 (Wide Area Protection). The intent of this is to prove the interoperability of the platform and the existence of a market by having two solutions for each Method; and
  - Beginning trial site preparation (outages, installation, commissioning);
- PNDC will proceed with:
  - Developing detailed trials specification based on the finalised designs. This will encompass both the PNDC and UK Power Networks trials;
  - Building the trial environment;
  - Identifying logical and physical interfaces between the partner solutions required for the full system integration and trials. This is being overcome by continuous engagement with the partners during the design phase and communicating the PNDC trials methodology with the partners so that there is a common understanding of the trial objectives and testing capabilities being used.
  - Ensuring that 5G latency meets critical protection requirements. This is currently being de-risked by performing laboratory tests to characterise the latency, as well as engaging with ABB and Vodafone to ensure findings are shared and validated.
- Vodafone will proceed with:
  - Setting up the 5G coverage and developing the 5G Slice;
  - Refining the design to ensure trial delivery; and
  - Validating the above design by testing some of the device/networks capability in Vodafone’s controlled environment;
- ABB, GE and Siemens will proceed with:
  - System integration activities through working closely with UK Power Networks;
  - Developing the Methods following successful completion of the project design phase;
  - Preparing for the FATs with the support of Omicron and PNDC;
- UK Power Networks, Siemens and GE will work on setting up central environments for their software (the software that sits outside the substations); and
- PNDC and GE will work on ensuring the PNDC ADMS is updated and ready for the Constellation trial.

Cyber Security

- The cyber security measures for each major component of Constellation will be implemented. This will be based on the security requirements and risk assessment carried out as part of the secure by design approach;

- Secure by design document will be updated and treated as a detailed design document for cyber security; and
- Continuous risk assessment and monitoring of project partners' hardware/software solutions and architecture will take place to ensure the cyber security measures in secure by design are still fit for purpose.

7 BaU Design Considerations

Progressing the overall Constellation design to date has identified that several technical challenges and business decisions associated with two key project technologies, namely the 5G telecommunications infrastructure and the adaptation of advanced protection functionality, need to be addressed, as discussed in the sections below.

7.1 5G Telecommunications

Constellation is investigating if technological advances can reduce the operational costs of reliable telecommunication while simultaneously improving the overall system cyber security. To address this challenge, a 5G mobile telecommunication technology is being trialled to assess the benefits of connecting various sites using a wide-area network with lower latencies than any previous point-to-multi-point wireless telecommunication technology in a secure manner.

As part of the overall research and design process, testing of the proposed 5G implementation has been undertaken at PNDC's in-house testing facility in order to assess the suitability of using this new technology with the Constellation Methods. Whilst the initial tests suggested that overall latency may present an issue, further testing provided some improvements after the testing configuration was optimised. In parallel with this, it is agreed to continue building upon the strong design foundation through the secure by design framework.

7.2 Protection

In order to take the outcomes of the protection research forward, towards a business-as-usual scenario, it is acknowledged that additional implementation effort will be necessary.

The amount of effort needed will be determined by the requirements of each individual protective scheme. However, in general terms, most of the schemes will fall into one of the three categories:

- Low implementation effort – this category will include all protective schemes where no additional algorithm or hardware development is required. The Constellation provides logical/inter-tripping signal exchange platform only, i.e. all protection devices utilised in the scheme are commercially available. An example of such scheme is a CoRoCoF LoM protection;
- Medium implementation effort – protective schemes where real-time exchange of analogue measurements is used (e.g. PMU data) but no additional hardware or algorithm development is needed. An example of this could be a VPAD LoM method, assuming the existing PAD relay was utilised with minor modifications only. Other LoM possibilities identified in the literature include Cumulative sum of Frequency Difference (CMFD) and Probabilistic Principal Component Analysis (PPCA); and
- High implementation effort – in this category all new protective methods are included, where a new algorithm needs to be implemented on a numerical relay or running as a virtual protection app on the Constellation platform.

It is reasonable to expect that in most cases the selection of methods for practical implementation should prioritise those with lower implementation cost, so long as they meet acceptable protection performance standards. However, at the same time, it is important to bear in mind long term operation of such schemes under ever changing power system landscape, electricity generation technologies, and continual development of digital substation platforms.

Considering the above approach, Constellation is well placed to demonstrate novel protection solutions fit for BaU roll-out.

8 Conclusions

This deliverable report, D1, provides the detailed evidence that the system design and architecture required to implement new PAC functionality with local intelligence within distribution substations, and covering both Methods 1 and 2, has been successfully delivered.

The design activities carried out and described in this report demonstrated that the Constellation project team has successfully fulfilled the deliverable 1 requirements. The approach (Section 2) was focused on providing the correct blend of specialist resource and on collaborative work. 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 Supporting Literature (General)

This appendix provides summary tables detailing:

- 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: Current Application Requirements (Grid Sites)
- Figure A.1.4: Current Substation Server Requirements (DER Sites)
- Figure A.1.5: Example Tables from Risk Assessment Evaluation

A.2 Supporting Literature (GE)

A.3 Supporting Literature (ABB)

A.4 Supporting Literature (Siemens)

A.5 Supporting Literature (Vodafone)

A.1 Supporting Literature (General)

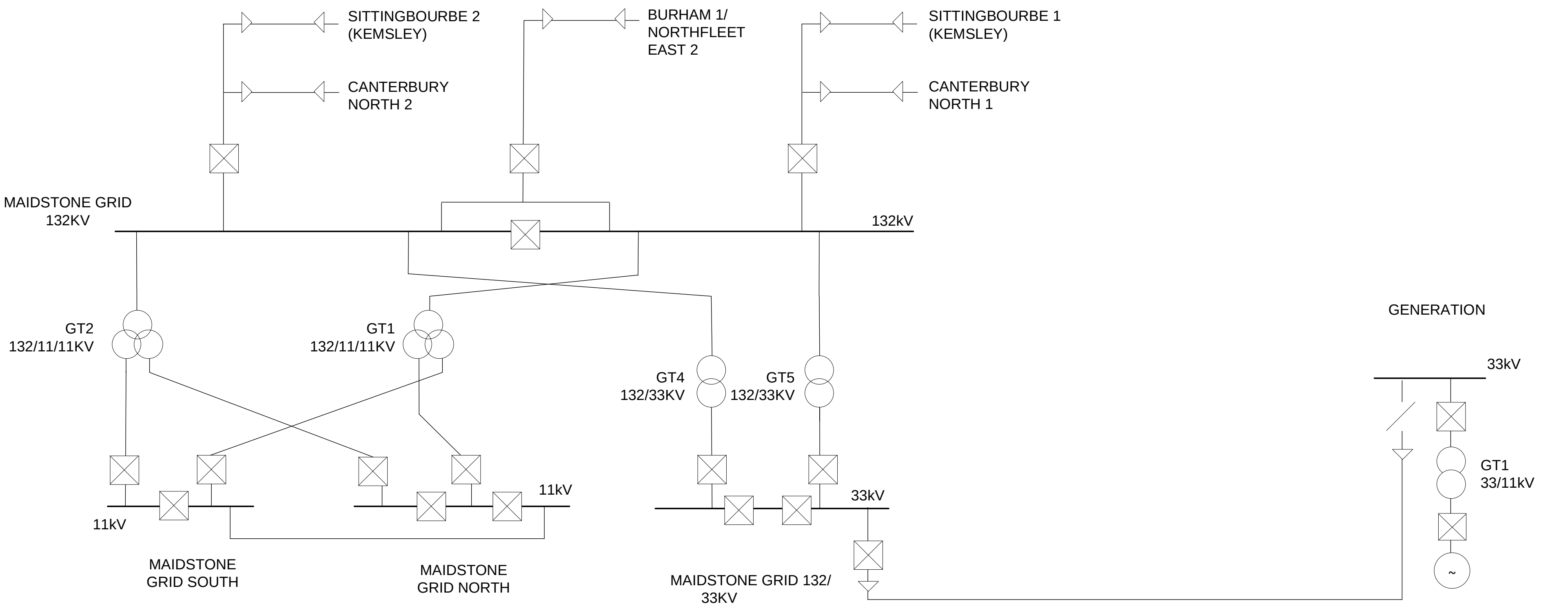


Figure A.1.1: Maidstone Grid Trial Area Single Line Diagram

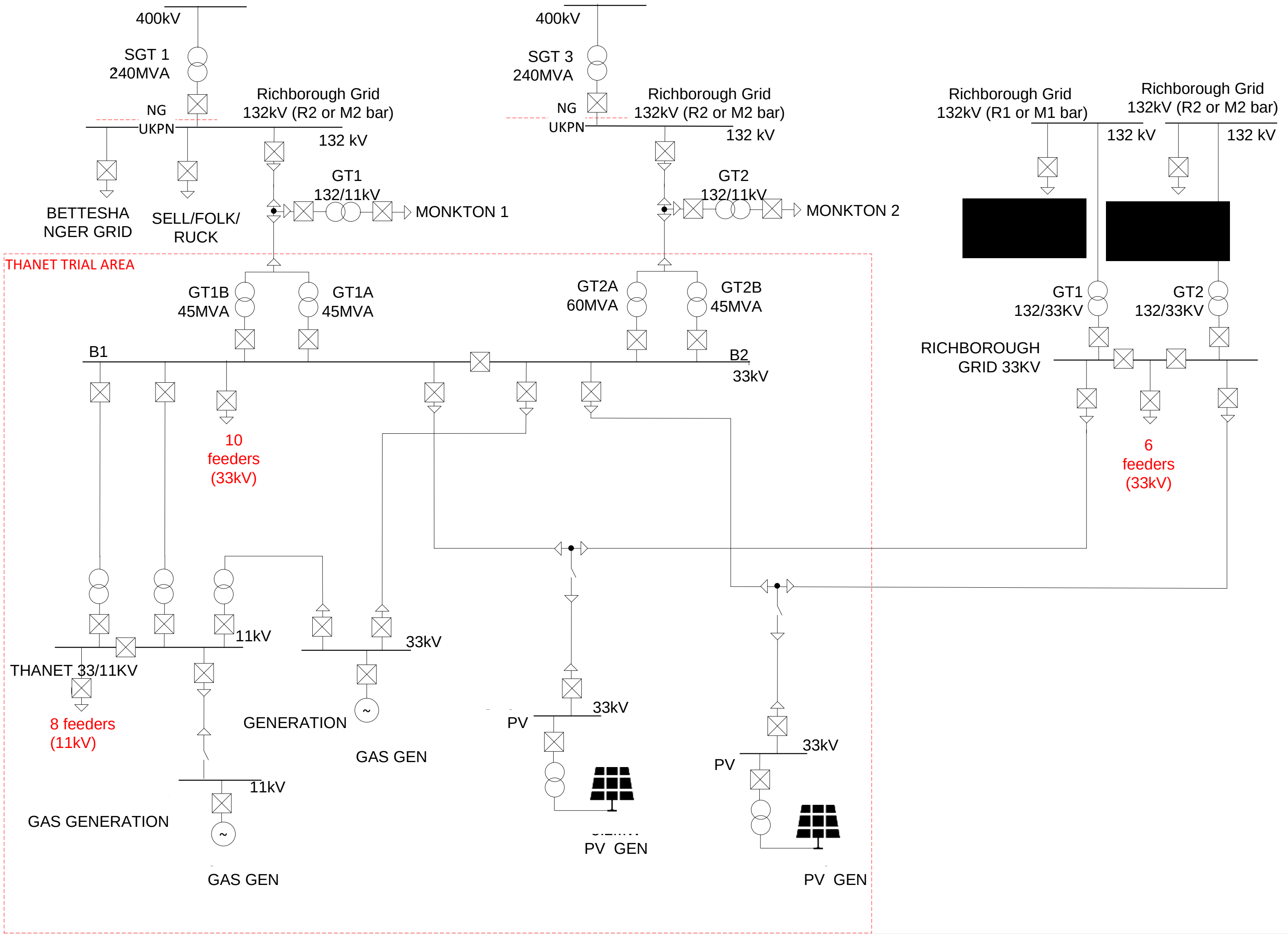


Figure A.1.2: Thanet Grid Trial Area Single Line Diagram

Figure A.1.3: Current Application Requirements (Grid Substation Sites) – Redacted

Figure A.1.4: Current Application Requirements (DER Sites) – Redacted

Figure A.1.5: Example Tables from Risk Assessment Evaluation – Redacted

A.2 Supporting Literature (Local ANM)

A2.1 Operating Modes of Local ANM (Additional Information)

The Local ANM system can apply three operating modes of control that becomes active when communication to the central AMN/DERMS is lost. Direct Distributed ANM is the operating mode that will be activated while site-to-site communication is still available after Central ANM/DERMS connection is lost. In cases where a managed DER site has no communications to the Grid Substation, the Local ANM system will first revert to Holdover ANM that will continue operation of the DER, accounting for the increasing uncertainty due to drift in loading and generation over time. It also identifies (using local measurements) disturbance events that may invalidate the underlying assumptions related to the uncertainty in constraint headroom. Once the Holdover validity times out, the Local ANM will either initiate a return to fail-safe DER output level or switch over to Learned Limit ANM.

Learned Limit ANM is a further control under investigation to be applied when the managed DER has no communications to the Central ANM nor the substation. This control mode is explored with a view to continuing DER operation indefinitely. While Holdover ANM has a timeout due to the uncertainty in the system headroom, the target of Learned Limit ANM is to relate the measurable steady-state and dynamic features observed at the local point to predict the constraint headroom in the network. A successful outcome of Learned Limit ANM would be that the headroom values can be estimated from local measurements provided there is no significant change to the surrounding network, and that the occurrence of relevant network changes can be extracted from the local measurements.

The states in which the ANM Methods apply, and the conditions for transition between them are illustrated in Figure A.2.1 below.

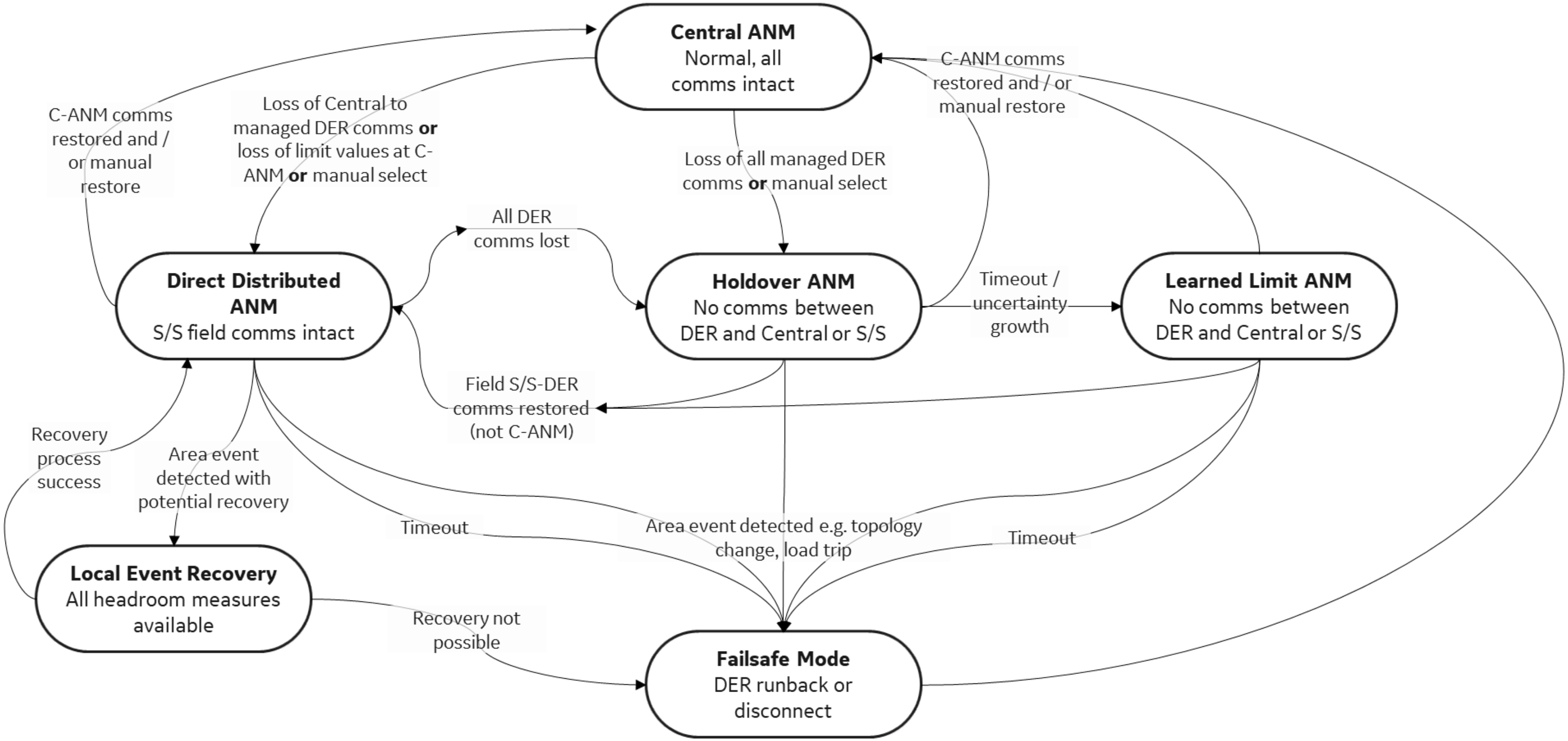


Figure A.2.1: An illustration of the three operating modes of operation of the Local ANM, which shows how each one is activated when a loss of communication is encountered

A2.2 Application of the Local ANM Method to the Constellation Trial Areas

At the trial sites selected to demonstrate the Local ANM Methods, the critical area of the grid where network constraints are encountered will be measured to collect phasor data using the PMU devices.

Two physical PMU measurements will be available at the 33kV network side of the Maidstone Grid Substation, and an additional four PMUs will be located on the 11kV side of Maidstone Gird. Virtual phasor measurements will be derived for the 132kV network side using the 33kV and 11kV phasor measurements in the circuits to the transformers and by using the transformer models. Thus, a voltage and current measurement can be derived on the 132kV side of Maidstone Grid. Phasor measurements will be located locally at the [redacted] Generation DER site, where the Local ANM Method will be trialled to control its output. The local measurement at the DER site will be used to demonstrate control methods, and along with measurements at the Grid Substation at Maidstone Grid, the measurements will be used for machine learning development. A further PMU measurement will be taken at Maidstone Grid at the circuit to [redacted] Generation in order to gather data for the Local ANM development as soon as the measurements are in place at Maidstone Grid as it is likely that Maidstone Grid Substation will be measured first before the DER site.

For Thanet Grid, Local ANM will be used to manage the constraints across the four Grid transformers by measuring the constraints on the 33kV side of the Grid transformers. [Redacted] and [redacted] DER sites will be managed to address the network limits by also recording phasor measurements. A live demonstration will be undertaking to show that network headroom at the Thanet Grid can be measured and estimated in accordance with the principles of the Local ANM Method. A further offline study will be carried out using SCADA/RTU measurements at Richborough Super Grid Transformer.

The location of the PMU measurements at both trial sites are provided in Figure A.2.2 and Figure A.2.3 below.

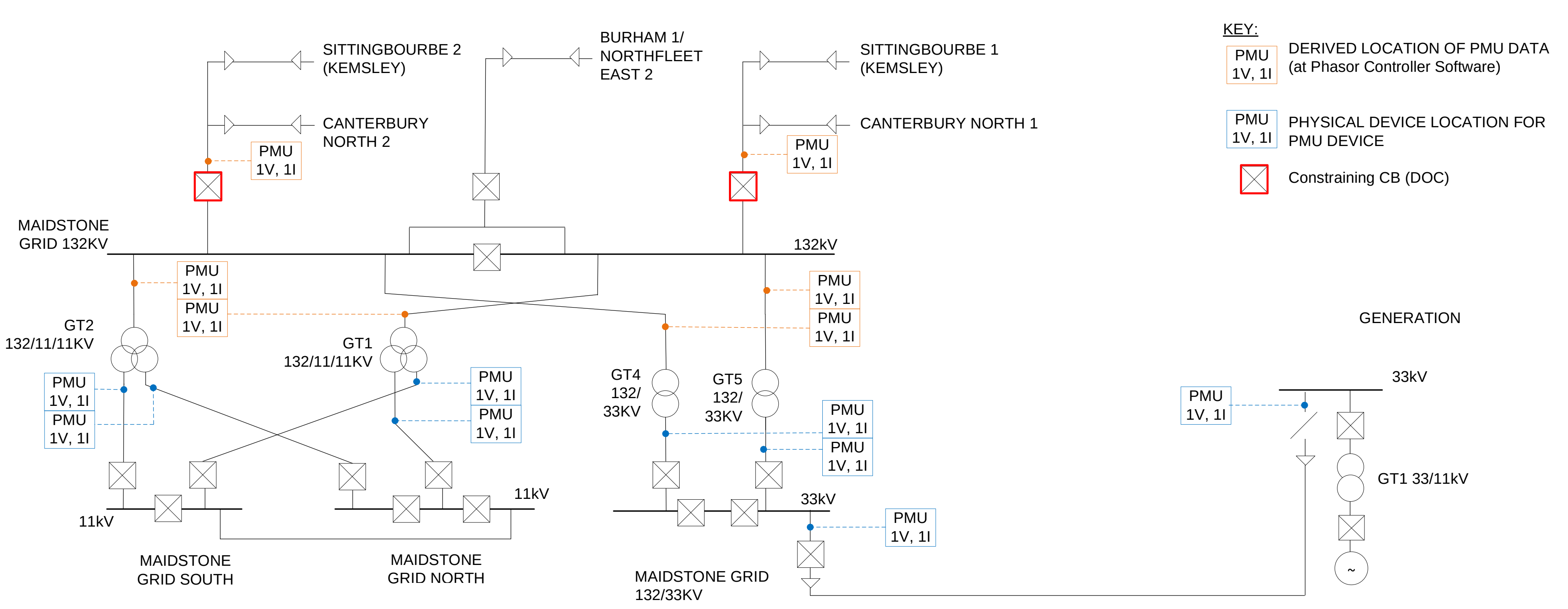


Figure A.2.2: PMU Measurements and Virtual PMU Measurements in the Maidstone Grid Substation Network Region

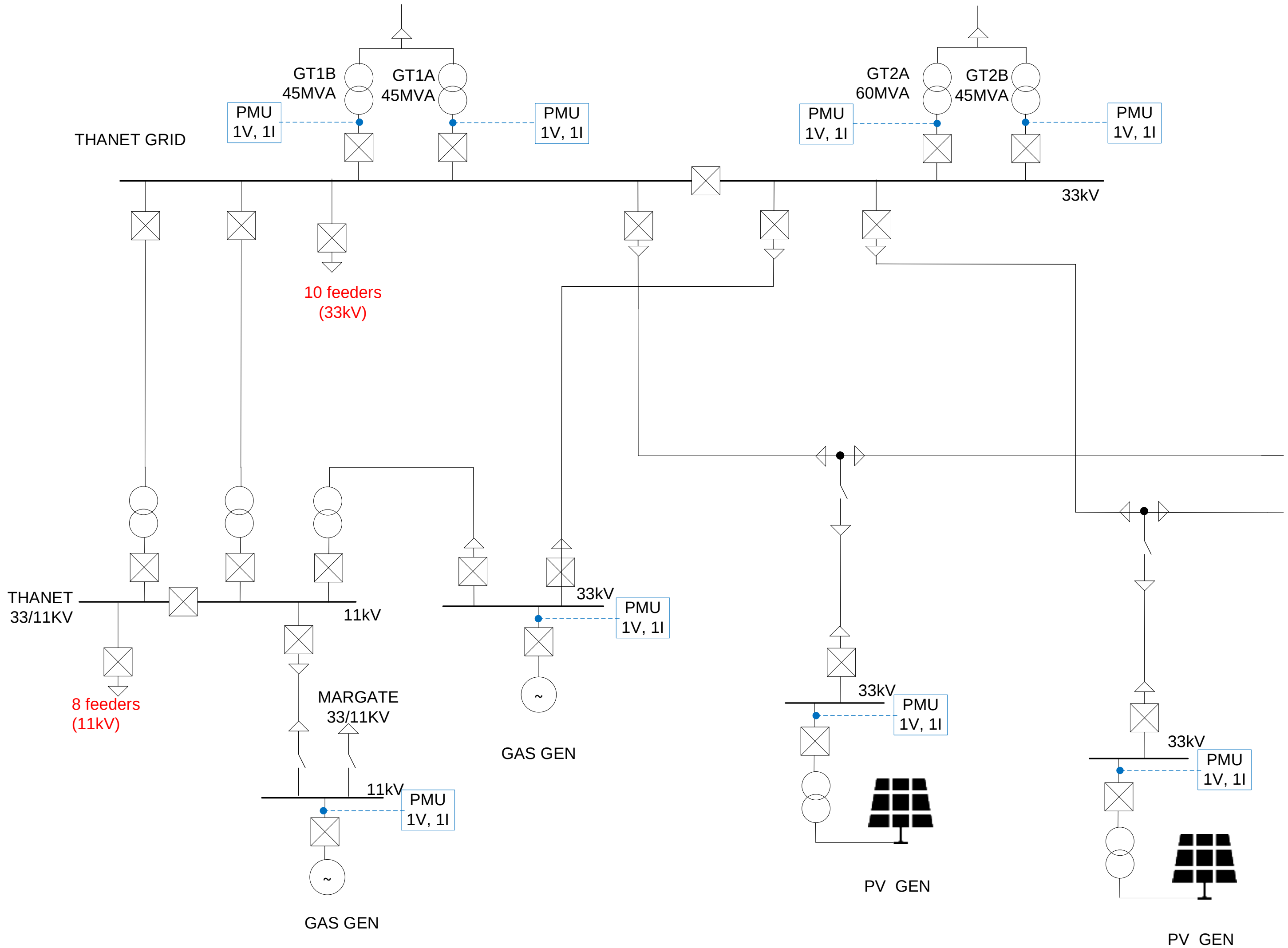


Figure A.2.3: PMU Measurements in the Thanet Grid Network Location

A.3 Supporting Literature (Wide Area Protection)

A3.1 Application of Wide Area Protection (Method 2) to the Constellation Trial Areas

A3.1.1 Maidstone

The Maidstone trial area, as described in Section 3, consists of one grid site (Maidstone 132/33kV Grid Substation) and one DER site. The trial area and a general overview on protection functionality to be implemented during Constellation is depicted in Figure A.3.1.

Both the Grid Substation and the DER site include local and wide area protection functions. All the protection functionality is virtualised and running on the software environment on the Substation Server.

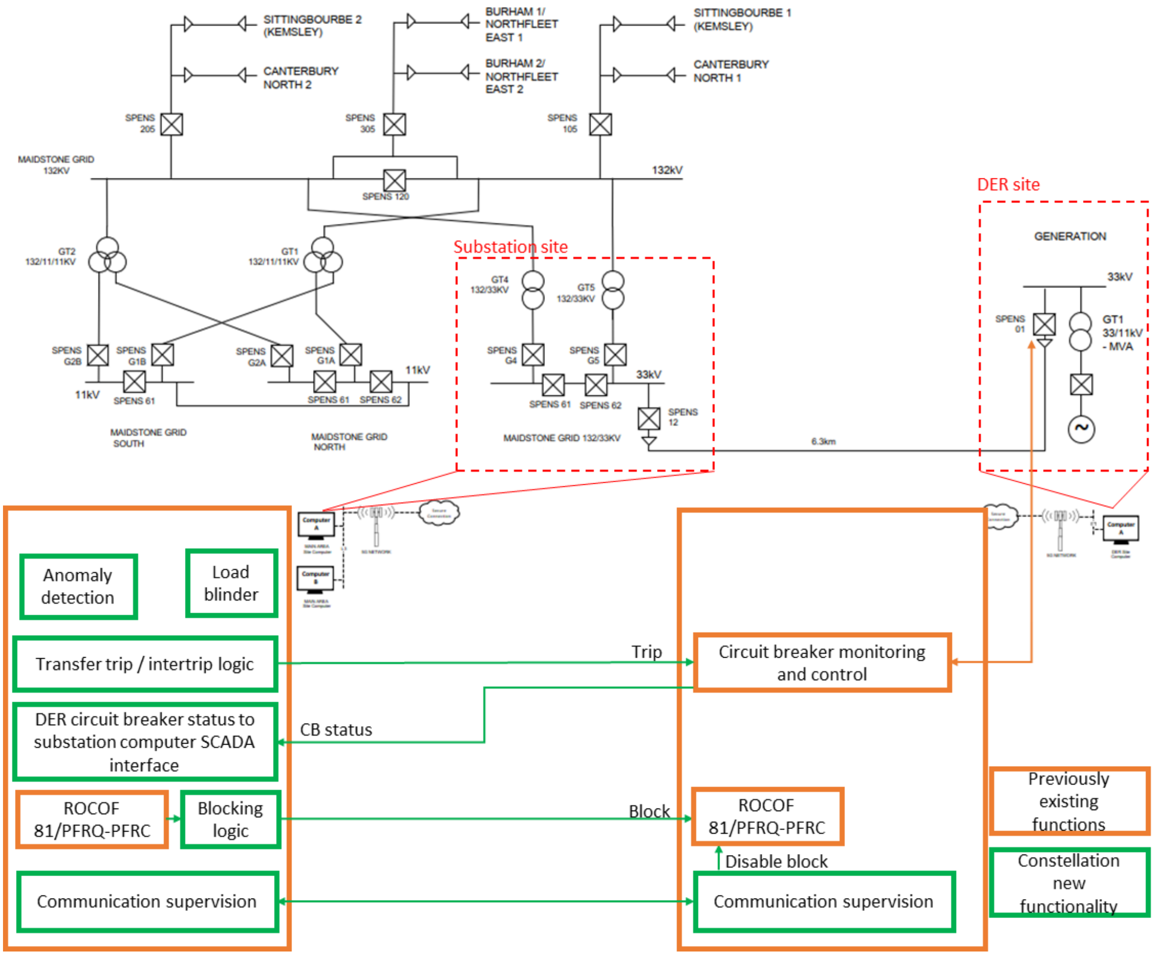
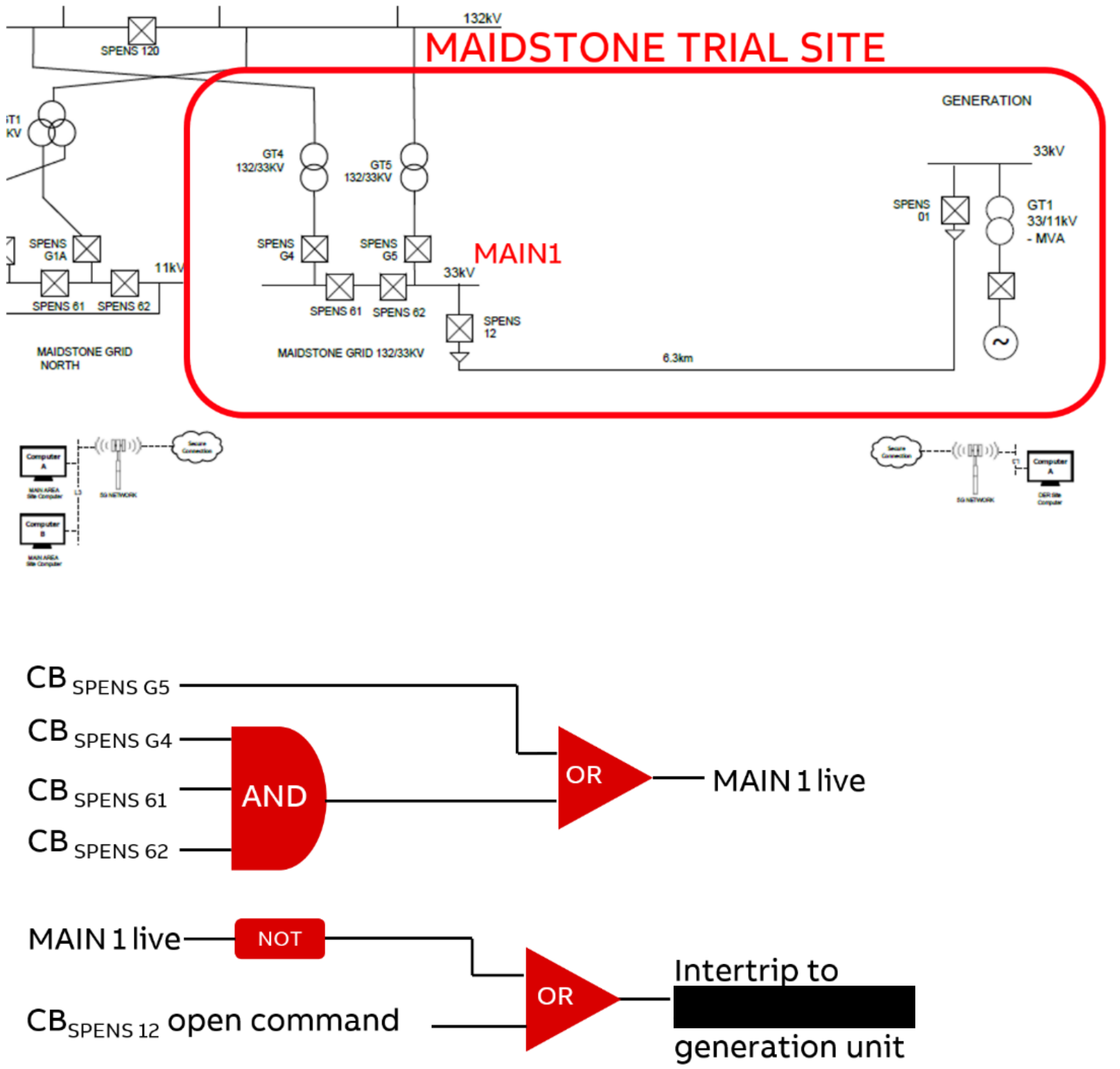


Figure A.3.1: Maidstone Trial Area and Wide Area Protection Functionality

A3.1.1.1 Maidstone Area Protection Transfer Trip Logic

There is only one generating unit in the Maidstone trial area, and the generating unit is connected via a radial line. Figure A.3.2 illustrates the principle of the proposed transfer trip logic for Maidstone.

The principle is to issue a transfer trip command for isolating the generating unit if the connecting 33kV busbar section at Maidstone Primary Substation becomes separated from the national grid or if the DG unit feeder circuit breaker (SPENS 12 in the figure) is opened. The circuit breaker control (CBXCBR) function is used for validating and providing the status of all the circuit breaker status indications for the transfer trip logic.



FigureA.3.2: Principle of the Transfer Trip Logic in Maidstone Trial Site

A3.1.1.2 ROCOF Based Blocking for Maidstone

The ROCOF index is computed from frequency, which in turn is computed from the voltage signals. There is dedicated voltage monitoring equipment in place at Maidstone busbars. The DG unit is connected to main bar section MAIN 1 as represented in Figure A.3.2 and the monitored voltage at MAIN 1 is used to compute the ROCOF index for blocking.

The threshold for the ROCOF protection at the substation site computer should be more sensitive than what is used at the DER sites. If a ROCOF protection threshold of 1 Hz/s is used at the DER sites, then a suitable value for the Grid site ROCOF instances could be 0.8

Hz/s. A more sensitive threshold is justified since the wireless transfer trip, which serves as the main LoM protection function, is in operation whenever the wireless communication link is up. Moreover, the ROCOF based blocking scheme is disabled whenever the communication supervision logic described in Section 5.4.3 indicates that the latency is too high.

A3.1.2 Thanet

The Thanet trial area consists of one grid site (Thanet 132/33kV Grid Substation) and four DER sites, namely:

- [Redacted] Gas generation 11kV;
- [Redacted] Generation 33kV;
- [Redacted] PV 33kV; and
- [Redacted] PV 33kV.

PV units are normally fed from Richborough 132/33kV Grid Substation but for the trial the network can be switched such that also these generation units are connected to Thanet Grid Substation.

The trial area and a general overview on protection functionality to be implemented during Constellation is depicted in Figure A.3.3.

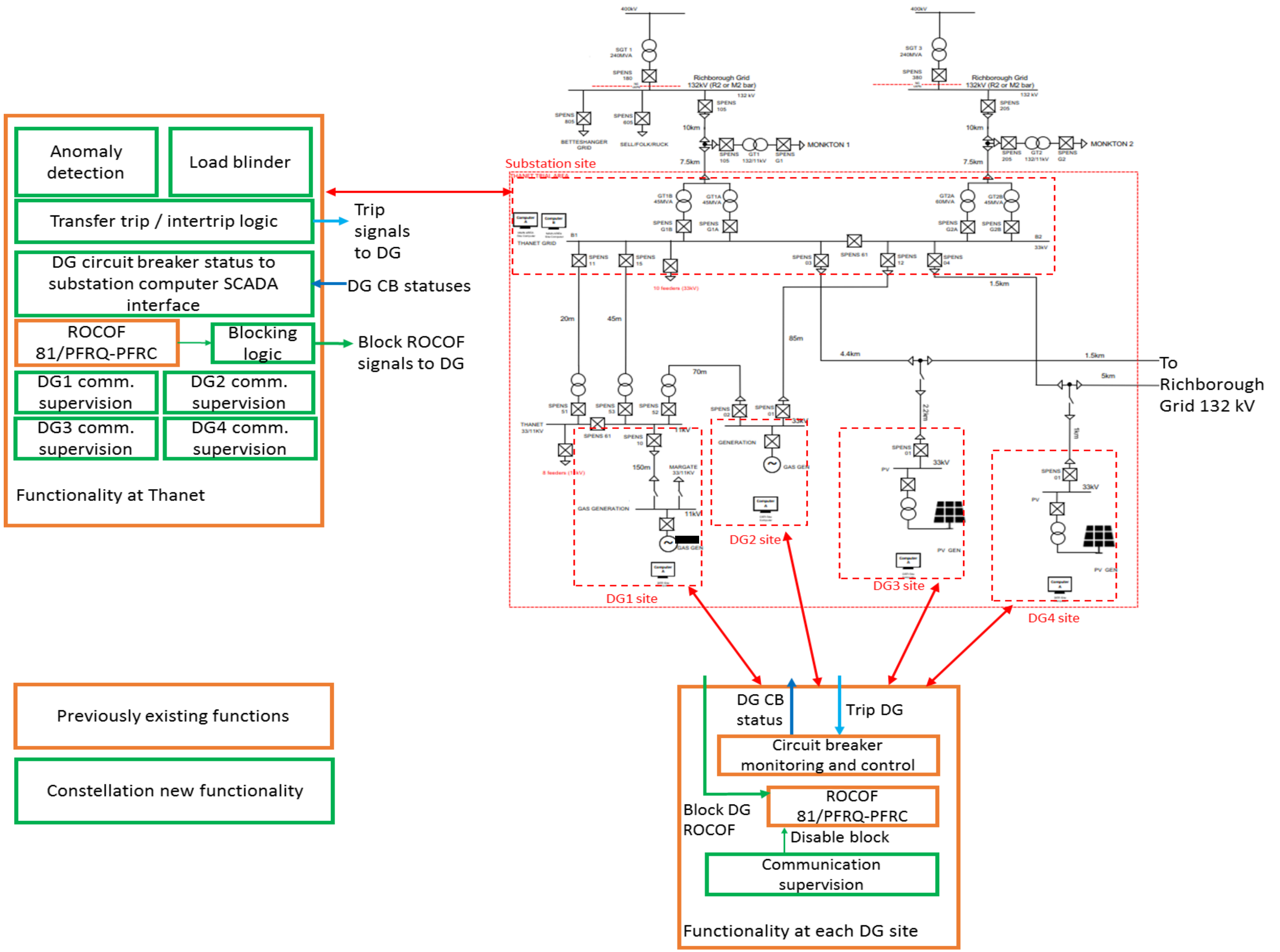


Figure A.3.3: Thanet Trial Area and Wide Area Protection Functionality

A.3.1.2.1 Thanet Wide Area Protection Transfer Trip Logic

An overview of the Thanet trial site, including the transfer trip logic, is depicted in Figure A.3.4.

The two 33kV bus sections are referred to as “MAIN 1” and “MAIN 2” in the figure for facilitating the description of the logic. Similarly, the generation units are referred to as DG unit 1 – 4. Note that Richborough is not included in the wide-area-protection trial site area, but the back-up supply connections are considered in the logic.

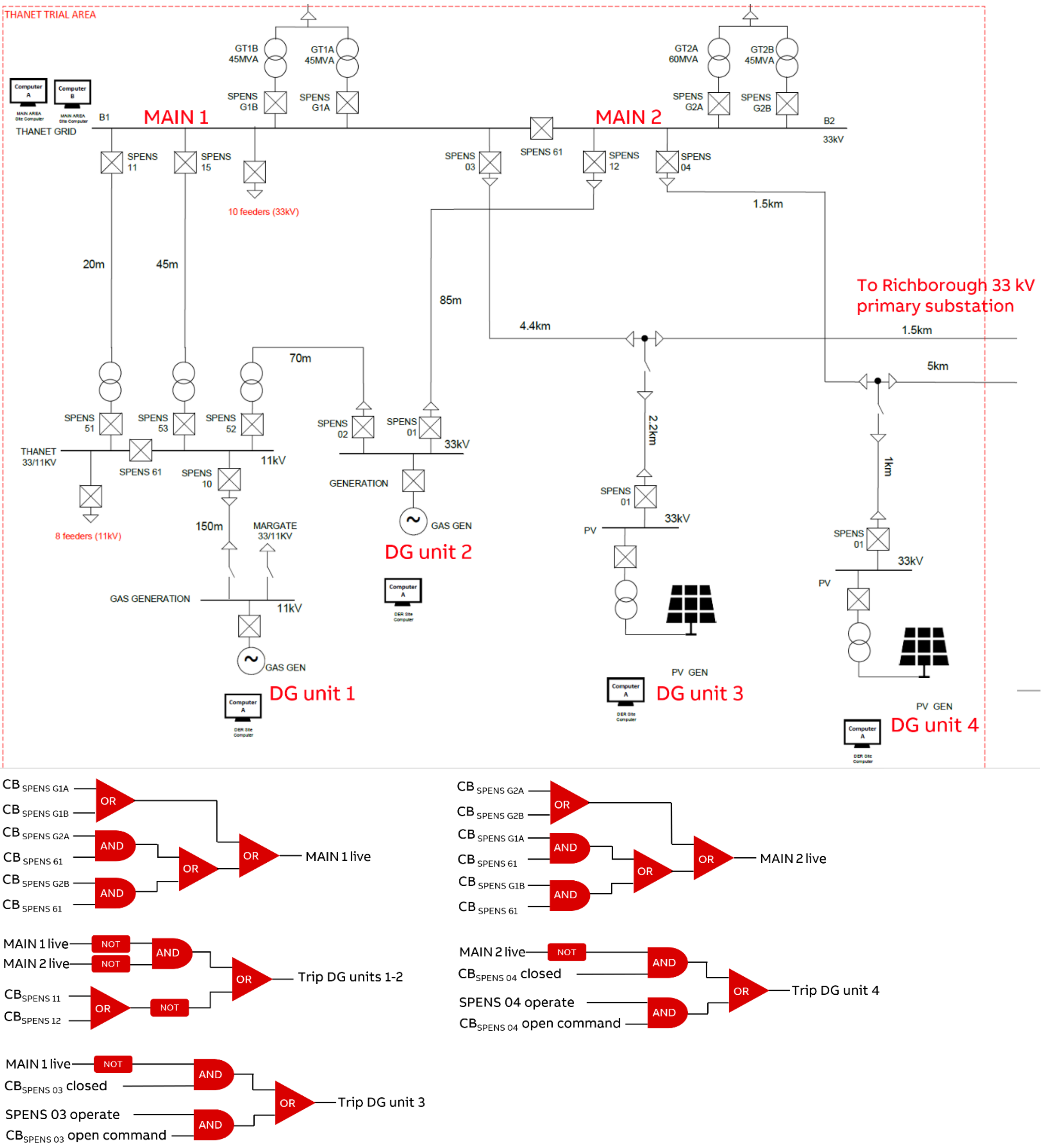


Figure A.3.4. Principle of the Transfer Trip Logic in Thanet Trial Site.

Here the idea is to firstly detect whether busbar sections “MAIN 1” and “MAIN 2” (are live or not, which together with other conditions is used for determining if islanding has occurred. The principle is to issue a transfer trip command for isolating a generating unit if the feeding 33kV busbar section at Thanet Primary Substation becomes separated from the national grid or if the circuit breakers at the beginning of the feeder or feeders connecting the DG unit to the substation busbar are opened.

The fact, that the two PV generation-based DG units can also be configured to supply via Richborough 33kV substation instead of the Thanet 33kV busbar, is considered by requiring an operate signal and an open CB command from the PV feeder in question (SPENS 03 or SPENS 04) for a transfer trip command to be issued. Alternatively, a transfer trip signal to the PV units is also sent if “MAIN 1” or “MAIN 2” is dead while the PV feeder in question is connected to Thanet 33kV busbar (via $CB_{SPENS\ 03}$ or $CB_{SPENS\ 04}$).

If the operator manually opens either CB SPENS 03 or CB SPENS 04, no transfer trip signal to the PV units is sent even if the manual opening of the CB(s) would result in islanding. However, the local LoM protection (ROCOF) would still be in operation in such a scenario.

A.3.1.2.2 ROCOF Based Blocking for Thanet

The ROCOF index is computed from frequency, which in turn is computed from the voltage signals. There is dedicated voltage monitoring equipment in place at both Thanet busbars (Main 1 and Main 2), either of which could be used for blocking purposes as long the main bars are not islanded themselves. The DG units 1 – 3 in Thanet are connected to main bar section MAIN 1 while DG unit 4 is connected to MAIN 2 bus section. Thus, it is better to use the ROCOF index computed from MAIN 1 for blocking DG units 1 – 3 and the ROCOF index computed from MAIN 2 bus section voltages for blocking DG unit 4.

The principle of the blocking logic for Thanet trial site is illustrated in Figure A.3.5.

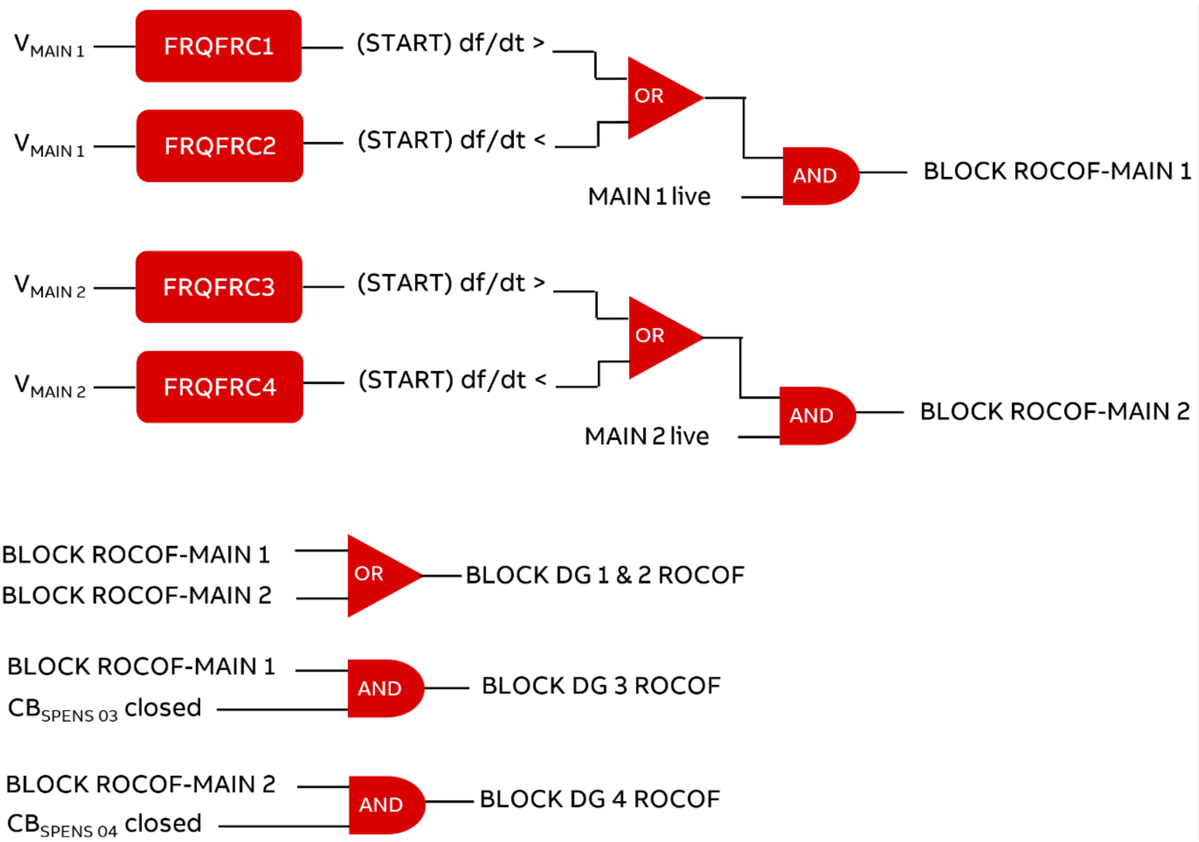


Figure A.3.5. Principle of the ROCOF Blocking Based Wide Area Protection Scheme for Thanet.

As noted earlier, DG units 3 and 4 can supply via Richborough. Additional logic is therefore included for allowing the blocking of local ROCOF at these PV sites only when they are connected to Thanet as illustrated in Figure A.3.5.

A.4 Supporting Literature (Adaptive Protection)

A4.1 Additional Details of the Software Applications in the Adaptive Protection Solution.

1. **Central Management System (CMS)** application enables a user to:
   - Manage asset information in Grid Substations by linking IDs of the 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;
   - Enable a user to upload, display and synchronise files between Substation Server and the Azure Server on which Central Management System runs; and
   - Enable user to investigate and act by using event logs.
2. **FreeFileSynch** is a third party software application.
   - It will be installed on the Substation Server in each Grid Substation. A file directory on this machine is devoted for file synchronisation;
   - It will be connected to a file directory on CMS via a SFTP link for file synchronisation;
   - It synchronises files between the file folders at the Substation Server and at the CMS; and
   - More information on this software is available under. https://freefilesync.org/faq.php#operating-systems
3. **SICAM GridEdge** Software:
   - The SICAM GridEdge software exchanges and synchronises data (actual protection settings and version information) toward the Central Management System, by using MQTT protocol; and
   - The SICAM GridEdge software deploys reference protection settings received from the Central Management System over substation LAN through IEC 61850 to the protection relays in the substation.
4. **PSS®ODMS** is a software application that enables a user:
   - To receive up-to-date network models from UK Power Networks centre;
   - To run State Estimator/Power Flow analysis for analysis and validation of received network models; and
   - To trigger PSS®CAPE for updating its network model with the new data.
5. **PSS®CAPE** is a software application that enables a user:
   - To run short circuit analysis, protection settings calculation, simulation, and validation;
   - To transfer results to CMS via Bridge and Broker software applications; and
   - To receive protection setting changes in Grid Substations via CMS application.
6. **RabbitMQ** is a third party software application used for the Broker Software.
   - It enables to exchange messages and events between SICAM GridEdge, CMS, and Bridge applications; and

- Constellation will use two additional "Tier 1" (https://www.rabbitmq.com/plugins.html#tier1-plugins) plugins, they are:
    - rabbitmq_mqtt; and
    - rabbitmq_tracing

A4.2 Application of Adaptive Protection (Method 2) to the Constellation Trial Areas

The two trial areas which have been selected in Constellation are Maidstone 33kV and Thanet.

At Maidstone 33kV APS will be applied to DOC on SPENS G4 and G5 in Figure A.4.1.

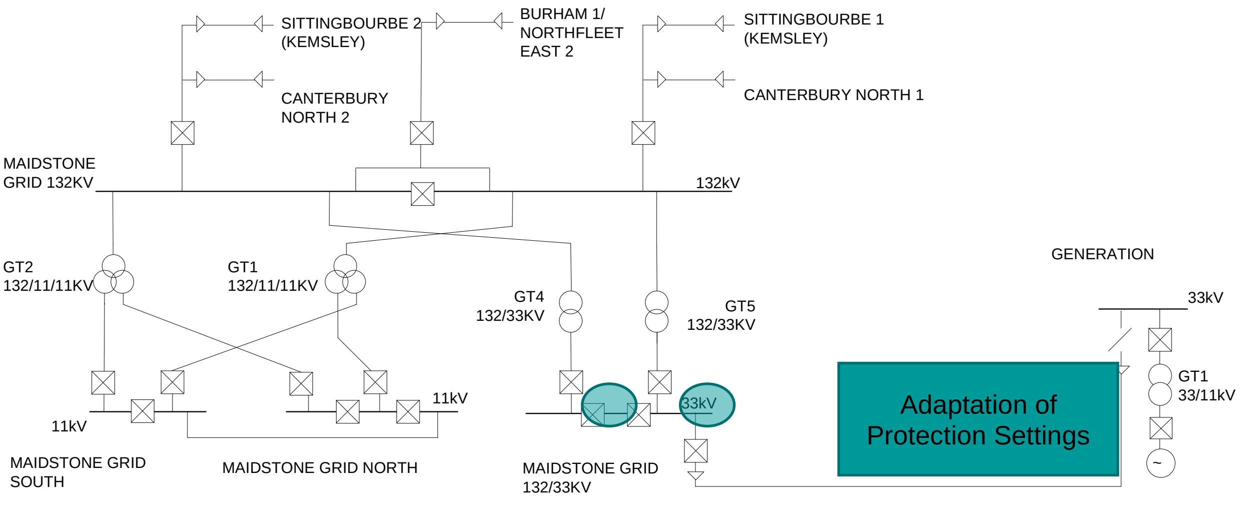


Figure A.4.1: Maidstone Trial Area Overview

At Thanet 33kV APS will be applied to DOC on SPENS G1A, G1B, G2A and G2B, as shown in Figure A.4.2.

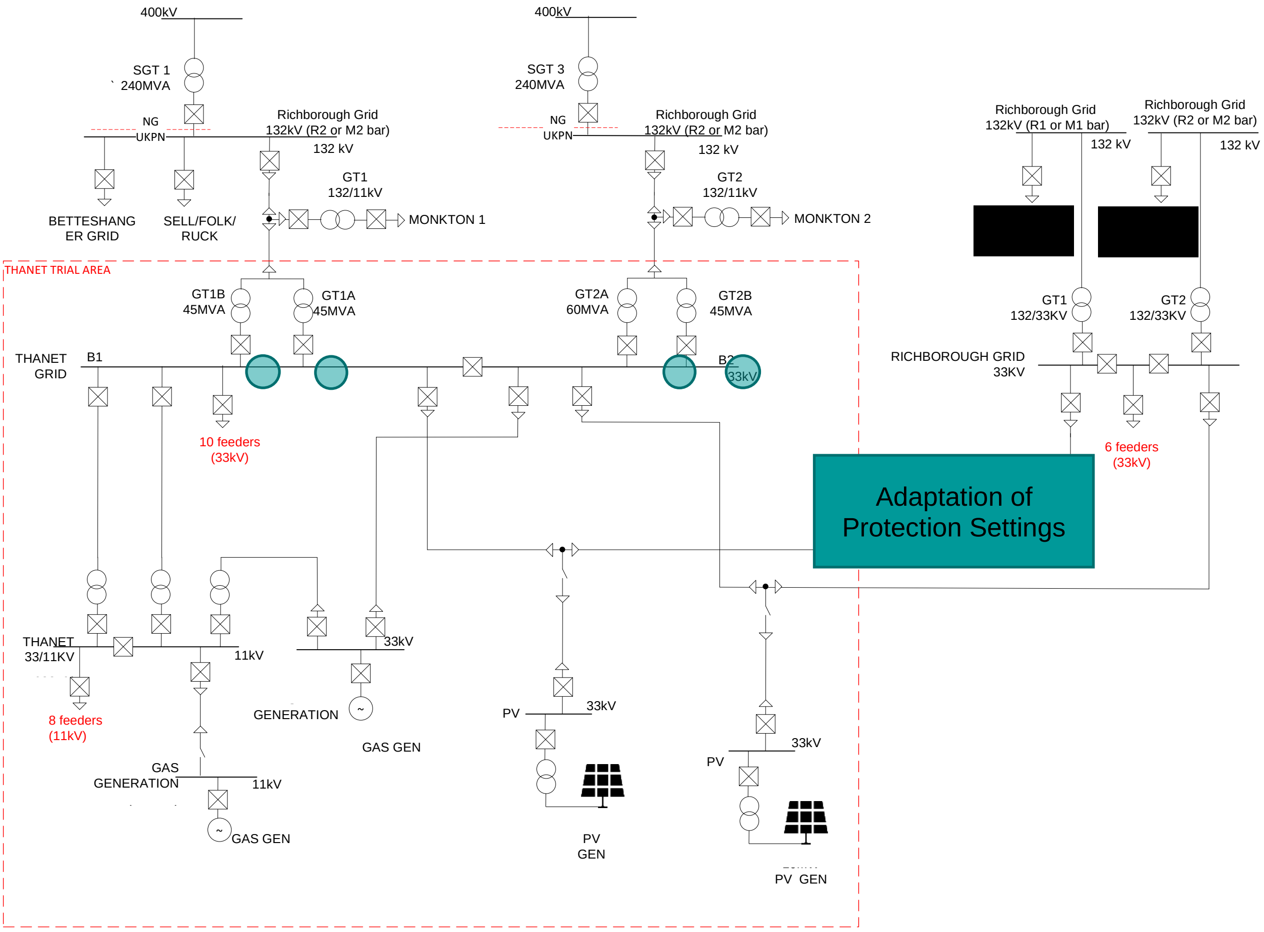


Figure A.4.2: Thanet Trial Area Overview

A.5 Supporting Literature (5G Slicing)

A.5.1 5G Solution and High Level Architecture

A summary description of Vodafone's 5G slicing design and high-level architecture is as described below.

The high level architecture for the 5G Slice design is as shown in Figure A.5.1 below.

Core Network Slices

- Common Slice – UDR, UDM, AUSF, NRF, NSSF and PCF
  - ➢ Slice-A: eMBB (Internet) for public Vodafone users
    - NSSAI=1-000001; AMF-1, SMF-1 and UPF-1 (Central)
    - Central UPF – towards internet
  - ➢ Slice-B: UK Power Networks (Slice ID #3 for the constellations data, and Slice #2 for the signalling)
    - NSSAI=1-000003; AMF-2, SMF-2 and UPF-3 (DUPF), exact slice ID is subject to change
    - DUPF – 5 Gbps, N6 towards Application Server will be possible

The Constellation POC is proposed to be provided with a dedicated network slice for the Traffic Data. The existing 5G Core in Vodafone UK datacenter has two slices:

- Slice-1: eMBB – For all 5G eMBB use cases like data, mobility (5G/4G, WiFi etc.), charging, Voice and SMS; and
- Slice-2: Low Latency – For low latency use cases, the user plane of Slice-2 is place within customer premises (Coventry University) to provide to low latency data path between Device, RAN, 5G Core and the Application.

As part of project Constellation, Slice-3 is proposed with the following characteristics:

- Control plane shared with Slice-2 AMF and SMF,
- Common components: PCF, UDM, UDR, NRF and NSSF are shared across Slice-1, 2 & 3
- Dedicated user plane (UPF) for Slice-3
- N6 (Data Network) for Slice-3 should only be towards DC-GW which will re-route the traffic back to UPF; UPF will then send the traffic to destination 5G UE using the N3 path
- Specific DNN (Data Network Name) should be used together with associated UE IP Pool to enable Slice-3 Control Plane (SMF) to select Slice-3 user plane (UPF) for the Constellation 5G devices; separate DNN is also recommended for differential charging which in this case is not charging; this DNN must then be configured manually in the 5G device (UE)
- The N6 path from UPF will route destination IP which will be of another UE to DC-GW which in turn will route it back to UPF

- UPF will then use N3 towards destination UE over the N3 path; UPF will have UE-UE communication enabled to allow this communication

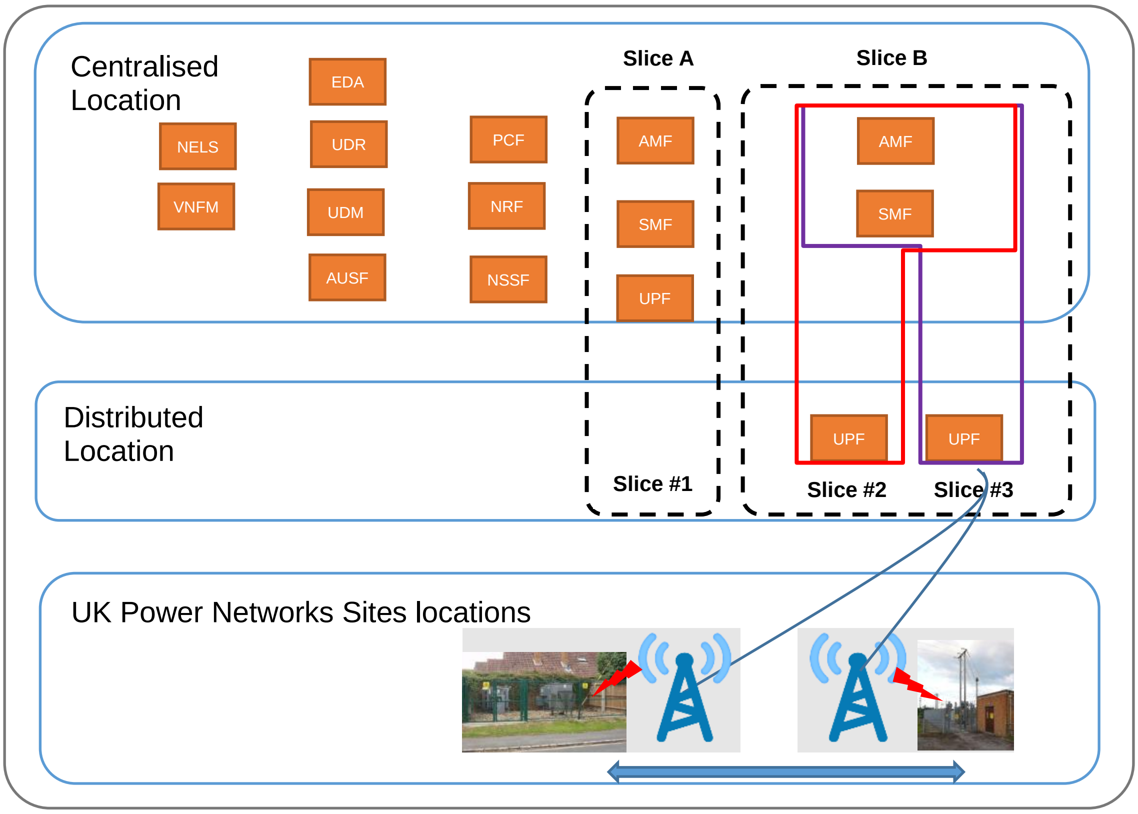


Figure A.5.1: 5G Slicing Design Architecture

In summary, the 5G Slice design will operate via this architecture as follows:

- The S-NSSAI based User Plane Function (UPF) will be fully dedicated for Constellation workload;
- 5G SA device SIM cards will be registered allowing end-to-end user plane connectivity between the User Equipment (UE) and the Data Network (DN) to proceed (e.g. upload and download of data can proceed); and
- S-NSSAI "3" will be mapped to Quality of Service (QoS) profile which Radio Access Network (RAN) can use to prioritise the Slice-3 and so the transmission network can prioritise packets for Slice-3 using a DSCP marking.

A.5.2 Hardware and Software

Table A.5.2.1 below details the hardware products that will be provided by Vodafone to deliver the required functionality for the complete 5G Slice design:

Table A.5.2.1: Active Radio Access Network Hardware Provided by Vodafone

5G Item	Item	Description
BBU	BB 6630, inc. 6 x CPRI Ports	BB 6630 (inc. up to 6 x CPRI ports, 150DL Mbps/75 UL Mbps or 288 ChE DL/288ChE UL 480ChE EUL/90HS Codes or 48 TRX. VF Standard BBU
5G IRU	IRU 8846 RDS Indoor Radio Unit (IRU)	IRU 8846 RDS Indoor Radio Unit, 8 Ports HC
Radio DOT & Mounting Options	5G DOT 479 clip on shroud	Clip on Shroud for ICNIRP Compliancy (1 Required for each DOT)
	5G DOT 4479	Dot 4479, B78A
	5G DOT bracket	Radio Dot 4479 Bracket (ceiling, wall, pipes)
GPS	GPS radio antenna (Rosenburger)	GPS, KRE1012395/1 with Mounting Bracket
	GPS Receiver	GPS Receiver GRU 04 01 GPS Decoded
	RJ45 Cable GPS - BBU	Primary Cable – RPM 113 6127/2000 (2m) – Standard Stock Item
	Rf Jumper Cable	1.5n Jumper – Main Coax to GPS Receiver N-Type (f) to SMA (m)
Misc	SFP for 10G Usage	10GB/s SFP Optical Transceiver (SFP + SM 10.3 GB/s 1.4km 1310 nm -40/+85C 3.3V) - 2 Required per IRU

Table A.5.2.2 below details the software products that will be provided by Vodafone to deliver the required functionality for the complete 5G Slice design:

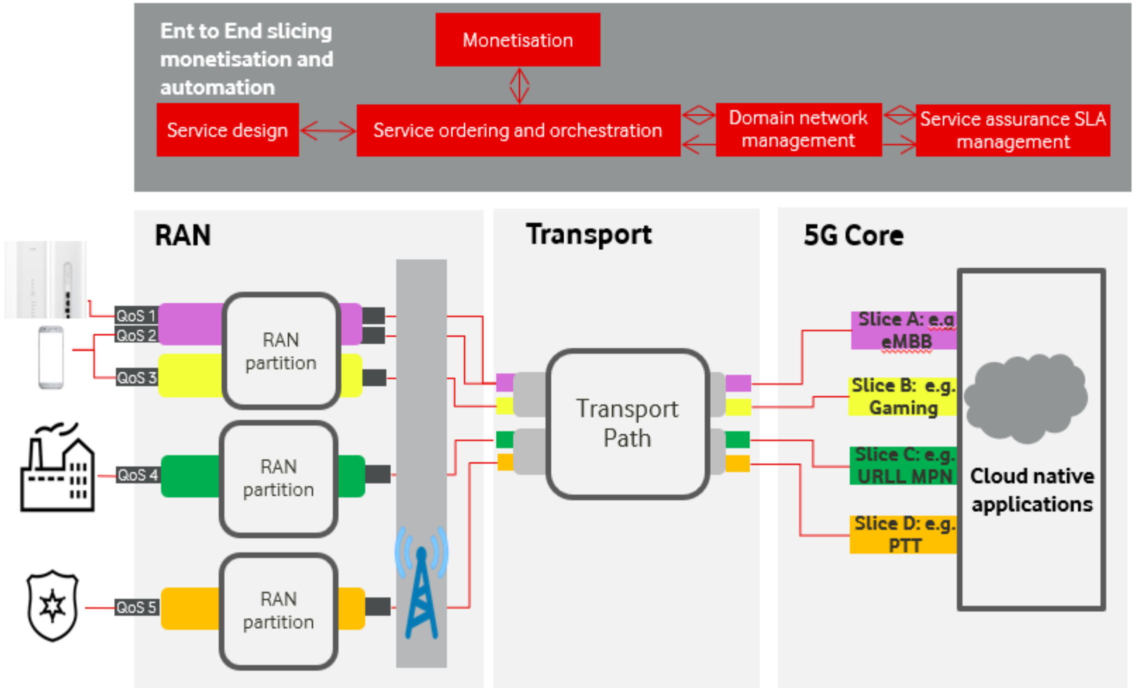
Table A.5.2.2: Software Provided by Vodafone

Network Function	Version	Comment
PCC	1.18 (To be upgraded from 1.16)	5G Control Plane (AMF & SMF); shared slice (Slice-2 & Slice-3)
PCG (*New)	1.11	5G User Plane (UPF); dedicated (Slice-3) user plane path for Constellation workload
vSAPC	1.16	5G Policy Control Function (PCF)
CCSM	1.6	5G UDM; Authentication for 5G devise including SIM identity decryption (SUCI)
CCDM	1.6	5G UDR; store the constellation device/SIM parameters which will be provisioned either manually or by Vodafone UK IT system; this also stores the new Slice profile for Constellation devices

Network Function	Version	Comment
EDA-2	2.7	Provisioning client to provision the 5G SIMs in UDR
CCRC	1.6	5G NRF and NSSF; NSSF is the Network Slice Selection Function used to place the 5G devices in correct slice (Slice-3 for Constellation devices)
NFVI	9.3	Has several components including hypervisor (Openstack), SDN, SDI and Kubernetes (Ericsson CCD)

A.5.3 5G Slice Design Basics

QoS on 4G and Network Slicing on 5G SA can be used to differentiate Services / propositions



Unique multi-dimensional service differentiation by dynamic RAN resource sharing at 1ms with slice-aware QoS and observability for SLA fulfilment

5G SA e2e slicing support for dynamic resource management & orchestration

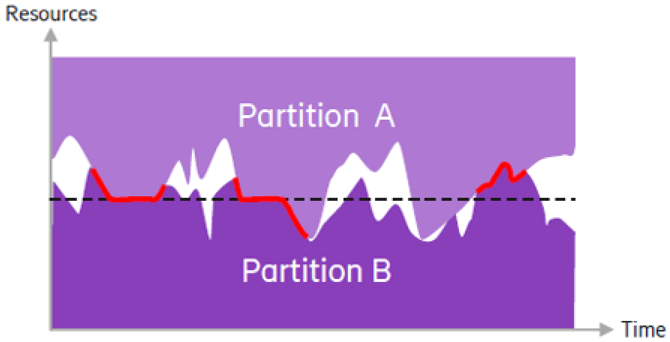
- Unique multi-dimensional service differentiation by dynamic RAN resource sharing at 1ms with slice-aware QoS and observability for SLA fulfilment

Software solution offers:

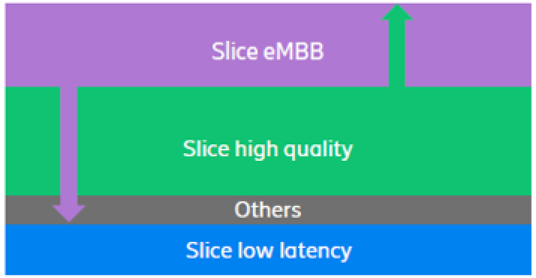
- Dynamic Radio Resource Partitioning
- Slice-aware QoS Differentiation
- Slice-aware observability
- Slice orchestration support
- RAN transport slicing support

Dynamic Radio Resource Partitioning

Resource sharing sub 1ms for best spectrum efficiency



Dynamic resources sharing at 1ms level



Flexible partition sharing policy

Radio resource partitioning distributes available spectrum resources across network slices

- Dynamically when there is no resource contention
- Enforces configured resource share during contention

Benefits

- Protection of services and business
- Provides services meeting SLAs
- Provides resource guarantees during times of contention