Flexible Plug and Play
Low Carbon Networks
SDRC 9.6 Implementation of active voltage and active power flow management within FPP Trial area
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<td><strong>Active Network Management (ANM)</strong></td>
<td>Autonomous, software-based control system that monitors grid conditions and issues instructions to distributed generators or other field devices in order to maintain the distribution network within operating limits.</td>
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<tr>
<td><strong>Automatic Voltage Control (AVC)</strong></td>
<td>Substation level system that is used to maintain the substation voltage at a constant value and within the statutory limits.</td>
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<tr>
<td><strong>Back-haul</strong></td>
<td>The back-haul network is the communications connection between the RF Mesh Network and Active Network Management (ANM) solution for data exchange. Also, the management connection between the RF Mesh Network and GridScape management application.</td>
</tr>
<tr>
<td><strong>Canopy</strong></td>
<td>Geographical coverage of the RF Mesh Network and the consequent footprint for communications connection.</td>
</tr>
<tr>
<td><strong>Combined Heat and Power (CHP)</strong></td>
<td>Co-generation or use of power plant to simultaneously generate electricity and useful heat.</td>
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<tr>
<td><strong>Communications platform</strong></td>
<td>The communications platform installed and commissioned in the FPP trial in March 2013. It is based on the Radio Frequency wireless mesh technology.</td>
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<tr>
<td><strong>Distributed Generation (DG)</strong></td>
<td>Electricity generation connected to the distribution network.</td>
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<tr>
<td><strong>Distributed Network Protocol (DNP3)</strong></td>
<td>Communication protocol widely used currently in the utilities industry.</td>
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<tr>
<td><strong>Dynamic line rating (DLR)</strong></td>
<td>System for calculating real-time ratings of overhead lines based on actual weather data.</td>
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<tr>
<td><strong>ENMAC</strong></td>
<td>The system that UK Power Networks is using at Control Centre level to manage its distribution network in the Eastern region.</td>
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<tr>
<td><strong>Flexible Connections</strong></td>
<td>Generation customers connected to the distribution network whose output can be controlled by the DNO for operational purposes.</td>
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<tr>
<td><strong>IEC 61850</strong></td>
<td>The International Electrotechnical Committee’s Standard for the design of electrical substation automation.</td>
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<tr>
<td><strong>Intertripping</strong></td>
<td>Turning a customer’s generation equipment off at times when the electricity network requires it.</td>
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<tr>
<td><strong>Low Carbon Network Fund (LCNF)</strong></td>
<td>A funding mechanism introduced by Ofgem to promote projects that will help all DNOs understand how they can provide security of supply at value for money as Britain moves to a low carbon economy.</td>
</tr>
<tr>
<td><strong>Moden Protection Relays or Novel Protection scheme</strong></td>
<td>A protection scheme to be trialled by the FPP project to overcome the limitations Novel Protection scheme associated with the use Directional Overcurrent schemes for protection of Grid transformers.</td>
</tr>
<tr>
<td><strong>Ofgem</strong></td>
<td>The Office of Gas and Electricity Markets: regulator for the electricity and gas markets in Great Britain.</td>
</tr>
<tr>
<td><strong>PI – Data Historian</strong></td>
<td>The IT system UK Power Networks is using for collection and archiving of real-time data and events, mainly measurements from the distribution network.</td>
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<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>Point of connection (POC)</td>
<td>The interface between the UK Power Networks’ equipment (main fuse, energy meter) and the consumer’s equipment (supply panel).</td>
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<tr>
<td>RMU</td>
<td>Ring Main Unit</td>
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<tr>
<td>Quadrature-booster</td>
<td>A specialised form of transformer used to control the flow of real power on a three phase electricity transmission network.</td>
</tr>
<tr>
<td>RF Mesh Network</td>
<td>The wireless Radio Frequency Mesh Network delivered by SNN that includes all RF Mesh Nodes – Master eBridges, Remote eBridges and Relay to provided data connectivity and coverage.</td>
</tr>
<tr>
<td>RF Mesh Nodes</td>
<td>This defines the communication devices that make up the RF Mesh Network – Master eBridges, Remote eBridges and/or Relay.</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition: centralised computer-based systems that monitor and control the electricity distribution network.</td>
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1. Executive Summary

There has been continued significant growth in Distributed Generation (DG) across distribution networks from 2008 which has resulted in very limited generation capacity being available for new customers across the Eastern Power Networks network area. This has resulted in a large increase in connection requests in a relatively short space of time and has led to several challenges for UK Power Networks and other DNOs. DNOs have an obligation to offer the cheapest viable connection to a customer, also known as the minimum cost scheme; therefore each connection request is assessed to find the closest suitable point of connection. The availability of accessible and affordable capacity for generators to connect to the electricity network is continuously decreasing, due to network capacity already being fully committed to existing or planned generation projects or unless extensive and costly reinforcement works take place, paid for either by DG customers or the DNO. The closest suitable point of connection can subsequently be much further away, usually requiring lengthy cable routes or connecting customers to a higher voltage level of the network. These are both expensive options and as a result can often mean that the DG scheme becomes financially unviable.

Flexible Plug and Play (FPP) is a Second Tier Low Carbon Network Fund (LCNF) project that conducted a trial to connect DG onto constrained parts of the electricity distribution network without the need for conventional network reinforcement. To achieve this, innovative technical and commercial solutions were trialled to manage constraints and maximise network utilisation. Among a number of technical solutions, Active Network Management (ANM) was a key component that integrated the smart functionalities of all the solutions.

The ANM solution carries out real time monitoring of the network using the status and measurement information from the field devices and is able to configure a number of application thresholds at which it can take pre-determined actions. Once the threshold is breached, the ANM solution automatically issues a power export curtailment instruction to the associated generators as agreed by UK Power Networks and the flexible generation customers. ANM maintains an end-to-end connection to the generator equipment in order to perform this action. The ANM also includes fail-safe mechanisms to ensure the security of the grid in case of the failure or loss of communication with any components within the solution.

This report outlines the main trial outcomes of active power flow management and active voltage management applications using a centralised ANM system in coordination with a number of smart solutions. ANM is a fairly recent technology in the industry but is increasingly becoming a familiar concept. This report further explores the capability of the ANM in utilising the functionalities of various smart technologies that in this report are termed as smart devices.

Following the demonstration of the technical characteristics in September 2013 as part of Successful Delivery Reward Criteria SDRC 9.4, the project proved the functionalities of the technical solution over the one year trial period, using the live infrastructure comprising of the central ANM system, remote field devices and the Radio Frequency (RF) mesh based communications infrastructure.

The ANM trial was structured in various stages with a key focus on simulation and operational phases. The simulation phase was the critical part of the trial as it ensured all functionalities were tested and proven on the live infrastructure with simulated elements. As DG customers connected to the UK Power Networks distribution network under the flexible contractual terms, the system was closely monitored to ensure the
expected performance was achieved. This was the operational phase of the trial which validated the results from the simulation phase.

This trial demonstrated the capability of ANM applications to address a number of challenges. The key challenges overcome by the Active Power Flow application are the mitigation of thermal constraint on 33kV overhead line and the mitigation of reverse power flow constraint of a 132/33kV grid transformer. Due to the lack of voltage constraint scenario in the trial area, the functionality of the Active Voltage Management application was trialled via simulated experiments.

The trial also successfully demonstrated real time variation of thermal rating threshold of overhead line based on the measurements sent by Dynamic Line Rating (DLR) solution in the field as well as management of the grid in coordination with local devices such as the Automatic Voltage Control (AVC) and the Quadrature-booster Control System (QBCS). The trial also proved that the ANM was capable of dealing with changes in running arrangements/configuration of the 33kV network under study and dealing with abnormal network events.

A distinct contribution of the FPP project is that the project not only demonstrated the functionalities, but actually made it possible for the constrained network to accommodate the connection of new generation within the project timescales. A total of 14 generators were signed up during this period. These generation customers would otherwise have to pay significant reinforcement costs to connect over a significantly longer timescales if business-as-usual approaches were used, as discussed in SDRC 9.7 – Quicker and more cost effective connections of renewable generation to the distribution network using a flexible approach.

The FPP project has demonstrated a simple yet a robust concept of network management by identifying only the critical constraint points in the distribution network and actively managing them using smart applications and smart devices. While the generation power export management is the key technique used, the main philosophy of the FPP project is to unlock the capacity headroom in the network by using a portfolio of smart solutions.

1.2 Purpose
The prime purpose for the report is to provide the evidence for successful completion of the deliverables set out in SDRC 9.6, and which are repeated below. This report focuses on the remaining deliverable as outlined below:

Trial results for the Active Power Flow Management and Active Voltage Management trials. Key findings are documented in the body of this report and detailed information is included in the appendices.

It should be noted that the other deliverables set out in SDRC 9.6, which are not covered by this report, have been included elsewhere as follows:
• Pre-production functional test results for Active Power Flow Management and Active Voltage Management applications. This has been covered by the report SDRC 9.4 Demonstration of FPP Technical solutions in September 2013.

• Installation and commissioning documentation of production Active Power Flow Management and Active Voltage Management applications in accordance with the specification included in the contracts with the relevant partners. This has been covered by SDRC 9.4 Demonstration of FPP Technical solutions in September 2013.

• Suitable agreements with generators in place. This has been covered by SDRC 9.7 submitted in parallel with this report.

1.3 Document Structure
• Section 2 provides introduction to the FPP project and the trial.
• Section 3 provides background the Active Power Flow and Active Voltage Management trial
• Sections 4 and 5 describes the outcome of the trial deliverables as part of SDRC 9.6
• Sections 6 captures additional ANM trial output not covered elsewhere
• Sections 7 and 8 summarises all the key findings and lessons learnt

2. Introduction

2.1 Background

The United Kingdom (UK) government is maintaining a strong commitment to cost effective renewable energy as part of diverse, low-carbon and secure energy mix as stated in the UK Renewable Energy Roadmap Update 2013\(^1\). This is supported by the UK’s ambitious target for 30% electricity generation from renewable energy by the year 2020\(^2\).

The FPP, a trial and demonstration project, has contributed in addressing this agenda within the electricity distribution network. In 2011, UK Power Networks was awarded £6.7 million in funding from Ofgem via the LCNF to undertake the FPP project. A further £2 million was invested from UK Power Networks, with the final £1m provided by the FPP project partners making a total cost of £9.7 million.

The aim of the FPP project is to facilitate cheaper and faster connection of DG to constrained areas of the distribution network. This approach involves offering flexible connections which allow generators to connect to the distribution network without extensive reinforcement that otherwise would be required. As part of this flexible connection approach, the electricity distribution network operator is able to actively manage the output of the DG to keep the network within operating limits.

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\(^1\) Department of Energy and Climate Change, HM Government, 2013, "UK Renewable Energy Roadmap 2013"

The 700km² area of distribution network between March and Peterborough in the East of England was chosen for the FPP trial area as it had a number of characteristics which made it a suitable area for testing within FPP:

- This rural Cambridgeshire area had 90MW of connected wind generation, mostly connected at 33kV;
- Other generation technologies were already connected, such as the existing generation plant (Combined Heat and Power) at Wissington;
- Additional 57MW of generation had been consented, 34.5MW of generation had been requested and 97MW of generation were in some scoping stage; and
- Finally, existing network assets were reaching their operational limits.

The FPP project has allowed additional generation to connect in the trial area without the requirement for costly reinforcement works by unlocking the hidden capacity in this network. Since the introduction of flexible connections in the trial area in March 2013 there has been significant interest, which has seen the project achieve the following:

- 45 DG connection requests;
- Issue 39 connection offers for 176MW of generation;
- Receive with 14 or (35.88MW) customers acceptances of the flexible connection.
- As of December 2014, the project has commissioned four customer(s), totalling 2.75MW, which has given the project the opportunity to generate and implement new learning for future flexible connections that are to be commissioned.

The FPP project partnered up with a number of industry leading organisations and academic institutions who were selected for their expertise and innovative culture. Smarter Grid Solutions, who were selected to provide the ANM solution, had been involved in previous implementations of similar solutions but with different context, architecture and approach. Vodafone and Silver Spring Networks were selected to provide smart grid communications platform. Other smart devices were provided by Fundamentals, Alstom Grid and GE Power Conversion.

This report provides detailed information on the outcome the ANM trial with a key focus on the following areas:

- Learning outcomes from key ANM use cases including challenges and solutions;
- Overall approach and methodology in undertaking the trial;
- Key functionalities of the ANM solution within the FPP trial scope; and
- Key requirements, lesson learnt and future recommendations.
2.2 FPP Technical solution

The FPP technical solution involves the implementation of a smart grid architecture using smart devices and an ANM system over an Internet-Protocol (IP)-enabled communications backbone. This solution operates independently but interfaces with UK Power Networks’ existing Supervisory Control and Data Acquisition (SCADA) and related communications infrastructure.

The ANM is a software platform which runs deterministic\(^3\) algorithms to carry out monitoring, analysis and control functions. It incorporates a real time DG management system with monitoring capabilities for the network within the FPP trial area. As shown in Figure 1, the ANM architecture essentially covers two main components:

1. The ANM central controllers located at a secured infrastructure within the control centre. The central controllers comprise of SGS’s software applications hosted on a commercial off the shelf enterprise IT servers.

2. The Local generator controllers at the substation level referred to as sgs connect in this document. The local controllers comprise of SGS’s software hosted on an Intelligent Electronic Device (IED) or Remote Terminal Unit (RTU). Brodersen RTU32 devices were used in the FPP trials.

\(^3\) A deterministic system is one in which the system can only be in one of a set of pre-defined states at any point in time, and it can only move from one state to another state when defined conditions are satisfied. The future state of the system is determined by the current state and the conditions satisfied.
Figure 1: FPP Technical Solution based on information layer mapping of SGAM framework

Figure 1 shows the high level diagram of the technical solution showing the connection of the central ANM system with the local ANM generator controller at the DG substation and the smart devices at the UK Power Networks substation. This diagram is based on the use case mapping of the generator control by the ANM using the information layer of Smart Grid Architecture Model (SGAM) framework. Detailed communications architecture is shown in Appendix 1. Further details on the design and implementation of the technical solution are described within the SDRC 9.4 report. The FPP communication platform is described in detail within the SDRC 9.35 report.

4 SGAM is Smart Grid Architecture Model developed by European Standardization Organisations CEN, CENELEC, and ETSI with five interoperability layers. This diagram uses the information layer.
5 SDRC 9.3 report: Delivery of FPP Communications platform
In order to support the ANM requirements, the FPP project implemented a dedicated Internet Protocol version 6 (IPv6) enabled communications platform in March 2013. This involved deployment of a RF mesh network to cover the entire trial area supported by up to two back-haul Wide Area Network (WAN) sites linking to the ANM system at the UK Power Networks control centre as shown in Appendix 1. The RF mesh network is designed to provide a radio canopy\(^6\) over the FPP trial area in readiness for “plug and play” connection of any prospective DG substation and its corresponding generator controller.

The FPP project demonstrated multi-vendor interoperability and efficiency in the design and commissioning process using the IEC 61850 standard. The IEC 61850 standard is widely used in the industry for substation communications however, the project stretched the capabilities of the standard by trialing its use for network control application outside the substation and over the RF mesh network. Adopting a central management role in the functional architecture, the ANM system acted as the IEC 61850 client (i.e., the master) to all the field devices acting as the IEC 61850 servers (i.e. the slave). As part of this client server model, the ANM system was able to send control messages to the field devices as well as receive necessary measurements and monitoring data.

Following the delivery of the technical solution in September 2013, the project moved into a structured trial phase with seven trial cases as follows:

1. Active Network Management (ANM)
2. Dynamic Line Rating (DLR)
3. Communications
4. Automatic Voltage Controller (AVC)
5. Quadrature-booster
6. Novel Protection Relays
7. System Integration

Out of the seven trial cases, the ANM is the most comprehensive trial as it also integrates the output of the rest of trials. Trials 2 and 6 are discussed in Chapter 4 and trial 4 is discussed in chapter 5. Trials 1, 3, 5 and 7 are discussed in chapters 4, 5 and 6.

The FPP solution deployed smart devices from various vendors to address and manage existing or anticipated network constraints and operational limitations of the distribution network that either restrict the connection of new DGs or are introduced by their connection. The range of smart devices include: DLR, AVC, a Quadrature-booster and associated control system; and generation controllers. Figure 2 below shows a simplified FPP network layout and location of devices linked to the ANM and accepted flexible generations. The diagram also highlights the sections of the FPP network where additional capacity has been freed up by the implementation of these smart devices.
Flexible Plug and Play Low Carbon Networks
Successful Delivery Reward Criteria 9.6

Figure 2 – Simplified FPP network layout

2.3 Value addition to previous work

Similar work has been carried out by other DNOs, notably by Scottish and Southern Electric Power Distribution (SSEPD) as part of the Orkney project. While SSEPD has implemented similar ANM technology to mitigate the network constraints, the FPP project built upon this and has generated additional learning to the industry as detailed below.

- To our knowledge, the first implementation of a Quadrature-booster on 33kV distribution network worldwide.
- Demonstration of a capacity quota as an innovative commercial arrangement in addition to the Last In First Off (LIFO) scheme.
- The first implementation of a purpose-built DNO communications platform based on RF mesh technology in the UK.
- Use of the open standard IEC 61850 based protocol to integrate multi-vendor devices
- Implementation of an ANM solution in a control centre environment in comparison to schemes based in a substation environment.
- Integration and coordination of multiple smart solutions.
3. Trial Description

3.1 Problems and solutions

There are a number of network constraints, which were overcome by implementing smart solutions as described in this section. A detailed description of individual problem and solution has been provided in the SDRC 9.4 report in September 2013.

Thermal constraints:

Thermal overloads arising at certain pinch points, partly due to the natural flow of power through the interconnected network, which leaves some capacity underutilised. This is a common problem in the 33kV interconnected network particularly in the Eastern region.

In order to mitigate the thermal constraints, the FPP project has trialled weather based dynamic rating solution with a safety margin, since conductor temperature or sag monitoring solutions may not be economic at 33kV. Three thermal constraint zones were identified where four DLR solutions were trialled based on Alstom MiCOM P341 relays as shown below.

1. DLR_1a : Bury Primary – Farcet Primary 33kV circuit (Installed at Farcet substation)
2. DLR_1b : Farcet T2 – Peterborough Central 33kV circuit (Installed at Farcet substation)
3. DLR_2 : Funtham’s Lane Primary – Whittlesey T2/Chatteris T2 tee point 33kV circuit (Installed at Funtham’s Lane substation)
4. DLR_4 : March Grid – Whittlesey T2/Chatteris T2 tee point 33kV circuit (Installed at March Grid substation)

The main function of these relays was to use local weather data and calculate real-time ampacity ratings based on the real weather conditions. The real-time ampacity rating is provided to the ANM system, which dynamically manages thermal constraints.

Increase in reverse power flows:

Existing grid substation transformers have limits on Reverse Power Flow (RPF), which is due to the allowable Directional Overcurrent (DOC) protection settings and the size/rating of the grid transformers. The existing infrastructure within the FPP trial area consists of two 132/33kV grid sites and an interconnected 33kV network supplying ten 33/11kV primary substations as shown in Figure 1.

The ‘main’ protection on the 132kV circuits from Walpole – March – Peterborough Central is via pilot cables rented from BT. At the start of the project, the network relied on DOC as the backup to the intertripping function. The DOC was designed to detect faults just outside Walpole, which may also be fed via Walsoken, which limits the reverse power through March Grid and Peterborough Central.

The DOC protection on the 33kV side of the transformer feeders was operating with increased RPF settings of 75% instead of 50% to accommodate the backfeed from the local embedded generation. The increase in setting had degraded the sensitivity to such a point that 132kV source faults might not be cleared should the intertripping fail. This is a major problem when the fault is “back-fed” from the adjacent 132kV circuit, as the
transformers add significant source impedance to the fault. In order to mitigate the DOC constraint, the FPP project trialled the novel protection relay with Direction Negative Phase Sequence (DNPS) and Load Blinding schemes at March Grid and Peterborough Central using Alstom P142 relays.

**Voltage constraints:**

Generally, the original design of most European distribution networks occurred over four decades ago and did not consider impacts from distributed generation, such as bi-directional power flows and voltage rises. Voltage control is made more difficult particularly by reverse power flow through tap changer transformers. The connection of DG on the 11kV side at primary substations may cause voltage levels to exceed the statutory limits unless appropriate measures are taken at design stage. To increase the network capacity with regards to connection of DG it is important to allow bi-directional power flows with voltage regulating strategies equipped to handle the effects of distributed generation on system voltage profile.

At March Grid and March Primary, over 60MW of generation was planned to connect at the start of the project which is anticipated to result in high levels of reverse power flow. The project commissioned the UK Power Networks standard AVC solutions, equipped with additional functionalities to deal with the problems created by a high penetration of DG connections. The solution is based on the coordination of ANM with the Fundamentals’ SuperTAPP n+ AVC relays to optimise the voltage set point at the primary or grid substation in order to maximise the voltage headroom/legroom and accommodate additional generation capacity.

### 3.2 FPP Trial Methodology

The FPP trial was undertaken in a structured manner leading to the formulation of the overall trial delivery approach applicable for any Information and Communications Technology (ICT) solutions trial. The overall approach is represented by the diagram in Figure 3 while the key trial stages are described below.
3.2.1 Trial design

The design of the FPP trial was carried out after the completion of the delivery of the FPP technical solution in September 2013. A trial design document was developed for each of the seven trial cases providing a methodology for the structured tests and analysis required for fulfilling the corresponding Use Cases stated within the FPP High Level Use Cases document. The trial design document also ensured that the envisaged learning outcomes were covered by the trial activities. The ANM trial, as guided by the ANM trial design document, was categorised as three separate sets of use cases that were fulfilled by the trial of three separate smart applications hosted by the ANM platform as shown in Table 1.

Table 1: Use cases and smart applications

<table>
<thead>
<tr>
<th>Use case reference</th>
<th>Use case name</th>
<th>Smart application</th>
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<tbody>
<tr>
<td>U04.1</td>
<td>Active Power Flow Management</td>
<td>sgs power flow</td>
</tr>
<tr>
<td>U04.2</td>
<td>Active Voltage Management</td>
<td>sgs Voltage</td>
</tr>
<tr>
<td>U04.3</td>
<td>Thermal Ratings Estimation</td>
<td>sgs ratings</td>
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</table>

The design process of the ANM Trial considered the following elements:

- Defining hypotheses, scenarios and related experiments to meet specific objectives.
- The validation of the information gathered using the various field devices of the FPP technical solution.
- The monitoring of power flows and voltages on the various substations impacted in the area.
- The simulation of scenarios to validate the Use Cases.
- The capture, storage and retrieval of data during the operational phase.
The analyses of power flows, voltages and other relevant data from the PI historian\(^7\) during the simulation and operating phase to cover the ANM trial hypotheses.

- The optimisation and enhancement works.

### 3.2.2 Hypotheses

Twelve hypotheses were developed, each focussing on a particular set of functionalities of the ANM solution as summarised below. Section 5 addresses Use Case U04.1, Use Case U04.3 and hypotheses 1, 2, 3, 4, 5, 6, 10 and 11. Section 6 addresses Use Case U04.2 and hypotheses 3, 7, 8, 9 and 10. Section 7 covers additional learning outcomes including hypothesis 12.

1. **Hypothesis ANM001**: ANM manages DG output to mitigate reverse power flow constraints
2. **Hypothesis ANM002**: ANM manages DG output to mitigate thermal constraints
3. **Hypothesis ANM003**: ANM manages DG output considering commercial arrangements
4. **Hypothesis ANM004**: ANM is able to cope with various running arrangements to actively manage the grid
5. **Hypothesis ANM005**: ANM uses Dynamic Rating information in the power flow calculation
6. **Hypothesis ANM006**: ANM actively manages the grid in coordination with the QBCS
7. **Hypothesis ANM007**: ANM manages DG output to mitigate voltage constraints
8. **Hypothesis ANM008**: ANM manages DG output to mitigate voltage constraints in coordination with AVC
9. **Hypothesis ANM009**: ANM coordinates the management of Power Flow and Voltage
10. **Hypothesis ANM010**: ANM is able to cope with devices and communication failures
11. **Hypothesis ANM011**: The Rating Application increases the useable rating of constrained lines
12. **Hypothesis ANM012**: ANM actively manages the grid in coordination with a storage device

### 3.2.3 Trial Scenarios

The approach applied by the FPP project consisted of three scenarios, the monitoring; the simulation; and the operational scenarios as shown in Figure 3. The three scenarios were spread across a period of over 12 calendar months to cover various seasonal variations and operating conditions in order to carry out overall assessment of the ANM approach.

**Monitoring**

This scenario consisted of monitoring the status of the network, more specifically active power flows and voltages, in the trial area. It aimed to define the baseline performance to allow the comparison carried out at the simulation and operational phases. For that purpose the existing Remote Terminal Units (RTUs), already in place in the trial area and the smart devices commissioned as part of the FPP project, have been used to gather the measurements using the FPP communication infrastructure. The monitoring was conducted throughout the trial period.

**Simulation**

As the planning and delivery process of the new generator connections were not under the full control of the project, it was necessary to robustly test the concept in a simulation environment in order to build adequate trial experience. A simulation platform was designed to enable the assessment of various use cases

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\(^7\) PI is UK Power Networks data historian solution
including those network contexts which would not be possible to carry out during the project duration. This allowed a number of enhancements and optimisations to be implemented during the trial.

Operation
The purpose of the operational scenario was to undertake close assessment of the system performance after the connection of the live generators in the trial area. This allowed the system to be put under genuine constraint scenarios and observe the response of the ANM and performance of the overall system.

3.2.4 Test Platform
In addition to the ANM production platform, a simulation platform was developed consisting of the following components.

Generator simulator
The main purpose of a generator simulator was to simulate the behaviour of a generation connection with active interaction with the generator controller. It supported the following functionalities:

- Simulate circuit breaker controls and indications: This provided an indication of the circuit breaker position/status based on a trip or close signal from the ANM system.
- Simulate DG output: This simulated the real power output of the generator based on the ANM target set-point. A ramp algorithm was used to permit a gradual change of the export power towards the set-point.
- Simulate communications delay: This was used while testing the response of ANM application to field devices.

The generator simulator runs on the same hardware as the generator controller that was used to interact with DG. During the simulation phase of the ANM trial, two generator controllers were deployed into the trial area and the two additional devices were installed in a laboratory environment aiming to simulate a minimum of four generators simultaneously.

Constraint Measurement Point Simulator
A number of analogue measurement values were handled by the ANM which were referred to as Measurement Points (MP). As the ANM actions were directly linked to a constraint measurement, it was important to accurately simulate the behaviour of the constraint MP using MP simulators. With a flexibility of being operated on both the local generator controller and the ANM server platforms, the MP simulator ran a simulation algorithm for each MP.

The MP simulator was able to aggregate the real time measurements received from the trial area and the DG power output measurements received from the generator simulator to represent a simulated constraint MP as shown in Figure 4.
Both generator simulators and MP simulators were installed in the laboratory and configured to communicate with the ANM production platform located at the control centre. Two generator simulators were also implemented within the trial area in order to represent two potential DG customers communicating using the RF mesh communication infrastructure. All the relevant trial data was stored in the UK Power Networks data historian. The overall FPP simulation platform is illustrated in the Figure 5.

Figure 4: Constraint Measurement Point Simulation approach

Figure 5: FPP Simulation Platform
4. Configuration of ANM

4.1 Introduction

One of the key learning points gained from the ANM trial is the methodology of optimising the operation of ANM application in order to protect the network assets while maximising the export of generation at all times. Using the case study of the Active Power Flow application trial, studies were undertaken to establish relationship among various ANM parameters and their impact on the overall system operation which are discussed in this section of the report. It is to be noted that the same concept applies for the operation of the active voltage management application.

4.2 Factors for consideration of parameter settings for a power flow constraint

Primary factors:

The main factors that directly influence the setting of parameters of a system that manages power flow constraint include:

- **System limit:** The first step in this process is to identify the true system limit. This usually corresponds to the rating of the component in the system with the lowest thermal capacity such as an overhead line current flow rating, or a transformer reverse power flow rating. This is also the limit which needs to be updated following reinforcement and may need to be updated following any outage periods.

- **Ramp-up rate:** The major factor to consider is the maximum cumulative ramp-up rate which can occur at the constraint MP. This ramp rate depends on the amount and the combined variability effect from individual ramp rates of both firm and non-firm generations as well as the load. The faster the ramp-up rates, the higher the need to increase the separation of the ANM thresholds from the system limit.

- **Ramp-down rate:** The ramp-down rate directly impacts on the speed of constraint management by the ANM.

- **Network safety parameters:** Protection schemes and settings should also be studied to ensure the ANM operation cannot interfere with or trigger any protection system.

- **Communication network:** The system needs to be configured according to the characteristics and performance of the communication network. A sensitive ANM configuration over a communication link with high amount of short term failures can lead to an unstable system with higher levels of curtailment of DG power export for communications reasons rather than due to network constraints.

Given that some of these factors can change over time as well as the fact that initial settings should be conservative to ensure operability, it was established that the parameter settings should be regularly
reviewed and revised both to improve performance and address the dynamic nature of the network and devices connected to it.

Secondary factors:

The project undertook a thorough study of the trial network and the assets in order to establish threshold settings and system parameters and identified the following additional factors for consideration in setting these parameters.

- **Voltage step change**
  The management of multiple generators using ANM presented a challenge as they can cumulatively cause voltage step change in the event of the simultaneous loss or introduction of group of generation. The maximum step change that can normally be allowed for connection of generation is 3% at the point of common coupling. Therefore the total loss of a single generation site should not result in figures greater than this. The problem may occur when a group of generation needs to be disconnected from the network to manage a breach of a constraint. Engineering Recommendation (ER) P28 gives information on both the step change and ramp rates, so if the total loss of a number of sites will result in a step change greater than 3% then some of those sites may need to be slowly ramped down in order to prevent step changes in excess of P28 limits.

- **Tap change operation**
  The other factor in implementing a slow turndown was to allow tap change operation to compensate for loss of volts due to generation in some scenarios. The UK Power Networks standards on AVC specify a tap change operation delay of 60 seconds for grid substations and 90 seconds for primary substations. For example, it was identified during the design of the interface for one of the DG connections that the “normal” turbine ramp rate needed to be slow enough to allow the tap changer at Chatteris Primary to operate. Given the 90 second operating time of the tap changer at Chatteris primary substation, the voltage limits would be exceeded by a change in DG output of greater than 600kW in the 90 seconds timeframe. As such, a 6kW/s ramp rate was proposed for the generator to remain below the 600kW limit with a 540kW change in 90 seconds, allowing the AVC adequate time to react.

- **Generation constraints**
  Generation technologies may dictate at which speed the generation output can be curtailed. For example, solar generators can come offline without much impact but tripping a wind turbine will result in excessive mechanical stress which can limit the life of the plant. Where required, an emergency shutdown signal can be considered which can use the fastest ramp rate supported by the generation plant rather than a hard tripping signal.

- **Auto-reclose**
  Consideration should also be made for the temporary loss of circuits that can be restored by protection schemes referred to as auto reclose for 33kV and delayed auto reclose for 132kV circuits. The 33kV auto reclose protection attempts to reclose once typically 20 seconds after a trip and if unsuccessful locks out. This process can take up to a total of 30 seconds which may need to be taken into account for some ANM waiting timer configuration. Again the motivation is to avoid curtailment of DG in reaction to interruption which are about to be rectified by the recloser. The initial
conservative approach for FPP project could not accept the risk of 30 seconds waiting time and was considered for future optimisation after gaining a reasonable operational experience.

4.3 ANM configuration parameters

The ANM uses various operational parameters to carry out its analysis and decisions. The effective deployment of ANM application is dependent upon the proper setting of its configuration parameters as they pertain to the unique conditions associated with a given constraint. These parameters ultimately define the activation thresholds, time delays and response magnitudes associated with any ANM action.

For simplicity, the ANM configuration parameters can be divided into four categories as given in Table 2.

Table 2: Generic ANM configuration parameters

<table>
<thead>
<tr>
<th>No</th>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operational Thresholds</td>
<td>Operational thresholds trigger ANM to take a specific action. The ANM system makes intelligent decision to use a pre-configured static threshold or a real-time dynamic threshold for each constraint based on the requirements of each operational scenario.</td>
</tr>
<tr>
<td>2</td>
<td>Operating Margin</td>
<td>It is a safety margin between the various thresholds including the system limit. It is designed to give the system time to react and potentially solve the constraint prior to breaching the next threshold.</td>
</tr>
<tr>
<td>3</td>
<td>Operational timer settings</td>
<td>Operational timers are pre-defined sustained time periods for a system component to wait before taking any action. The calculation of timers is based on the impact analysis of an event to ensure the safest action while keeping the system stable.</td>
</tr>
<tr>
<td>4</td>
<td>Fail safe settings</td>
<td>During any abnormal condition, the ANM system is designed to take a pre-defined fail safe action in order to minimise the risk to the network.</td>
</tr>
</tbody>
</table>

As part of the implementation of the sgs power flow application in the FPP project, a number of parameters needed to be configured for MPs, generators and local ANM controllers as shown in Appendix 9. The following thresholds are defined as part of the constraint management scheme of the sgs power flow as illustrated in Figure 6.

- **Global trip threshold** – When the MP breaches this threshold, the ANM system simultaneously trips all those generators that are associated with the MP.

- **Sequential trip threshold** – ANM system trips the associated generators in the pre-defined intervals when this threshold is breached for a sufficient length of time until the MP is brought below the trim threshold.

- **Trim threshold** – When the MP breaches this threshold, the ANM system issues curtailment to associated generators in order to reduce power flow associated with the constraint to below the reset threshold.
- **Trim less threshold**: ANM system target value for power flow associated with the constraint during a release event. It is used to ensure that the release of generation does not cause power flow to breach the trim threshold immediately after.

- **Reset threshold** – Releasing the curtailment level allowing controlled ramp up

- **Reset less threshold** – The ANM system target value for power flow associated with the constraint following a trim event. It is used to ensure that curtailment is reduced sufficiently below the reset threshold.

![Figure 6: ANM thresholds](image)

**Methodology**

The ANM thresholds were calculated using the standard SGS methodology which considers all the relevant factors to define a formula for each threshold. The formula accounts for the relevant ramp rate of the MP for each threshold multiplied by the maximum duration of the time before the corresponding action can be completed. The resultant value then represents the minimum separation required between the thresholds defining their operating margins.
The computed operating margins are designed to give the system adequate time to react and solve the thermal constraint prior to breaching the next threshold. This is the theoretical approach which formed the starting point for the configuration of the ANM and yields the most conservative results. It was recognised that this approach required further optimisation at design stage based on operational experience, expert vendor knowledge and sound engineering judgement. The project team identified the following key guiding principles in setting the thresholds:

- The severity of the ANM response action should be proportional to the degree of deviation from a defined operational range of a power flow constraint;
- A global trip action should occur prior to any protective setting power flow being reached;
- The operating margins depend upon the variability of the load and generation contributing to the constraint as well as the time allocated to the ANM system to react to a breach of a particular margin.

In addition, the following threshold calculation method was developed and applied:

- The first step is to establish minimum, average and maximum figures for the variable parameters such as communication delay, ramp rates and generator response time.
- The second step is to use the relevant figures to compute the operating margins for each threshold as described above.
- The third step is an iterative one, which involves adjustment of the non-variable parameters such as observation times and communications timeouts to establish optimum threshold settings based on the size, type, behaviour and connection timescales of the expected flexible generators.

As more generators connect some parameters need to be adjusted to optimise the threshold settings in order to maximise the generation export while avoiding any possibility of a breach of system limit.

The behaviour of curtailment event can be represented by a sequence diagram showing object interactions in time sequence as per Figure 7.
Figure 7 shows the sequence of events starting from the moment when a constraint MP breaches a threshold until the moment it is brought back below the threshold. Every object in the sequence diagram represents one of participating components of the FPP project architecture while the time elements represent the parameters involved in the calculation of operating margins. The sequence diagram shows the total time of 32.2 seconds based on the parameters set on this case study. This process can be used to calculate the maximum action time criteria for the each ANM event and is represented by the formulae given in Appendix 8 and tested by the experiment described in section 5.1.

4.4 Case study 1: March Grid Reverse Power Flow constraint

Background

As explained in section 3.2, the legacy system limit for March Grid Reverse Power Flow (RPF) was DOC protection constraint which was 34MVA based on an \( n-1^6 \) condition. An assessment was carried out from five years of historic data to understand the behaviour of transformer power flow measurement. As represented by the graph in Figure 8, the duration curves show the amount of time that limits were actually threatened, the spare energy transfer capacity, and the additional energy export facilitated by ANM. The

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\( n-1 \) condition in the context of electricity networks is when one of the components of the network (e.g. a transformer, a cable or a switch) has failed and is no longer in operation. Electricity networks designed for \( n-1 \) reliability can continue to operate normally (i.e. without loss of load or voltage issues) when one of the components fails.
analysis considered 30.6MVA system limit based on an existing DOC limit of 34MVA with a 10% operating margin.

The positive half of the scale in the Y-axis of the graph represents reverse power (i.e. net export) and the negative half represents the forward power (i.e. net demand). The curves compare the duration of the reverse power flow with and without potential FPP generation of 19MW projected at the time. Two export limit scenarios with DOC (30.6MVA trim threshold based on 10% operating margin against a 34MVA DOC constraint) and without DOC (41MVA trim threshold based on 10% operating margin against a new 45MVA system limit) are considered. The curve A represents the duration of power flow without flexible generation without breaching the new export limit. The curve B shows the increased duration of reverse power with the added 19MW generation that would exceed both the system limit and the export limit. The curve C represents the duration when ANM system would take curtailment action in order to maintain the power flow below the export limit essentially, defining the ANM’s operational envelope over that period of time.

Figure 8: March Grid constraint duration curve
At March grid, the simplicity of the constraint, allowed a new principle of access (Pro-rata) to be trialled, which has proven popular. The area has seen the highest rate of connection requests over Peterborough Central grid.

Ramp rate calculation

For the calculation of ramp-up rate for the March Grid power flow, the trial data for the March Grid power flow MP were analysed. The trial data were based on the real-time measurements, without any averaging that was reported to the ANM by the March Grid RTU. Approximately three months of data sets of MW measurements were selected to analyse the step changes in MW. The calculation uses the variation in power and time between consecutive readings to determine the MW/s changes, i.e. the ramp rates. The graph in Figure 9 shows the distribution of these values, highlighting some very large outliers but the vast majority of the time the changes in MW flow are relatively small.

![Figure 9: March Grid MW Ramp rate](image)

It can be observed that nearly all the changes in MW flow are for small changes less than 0.5 MW/s with only a small percentage of bigger step changes. This suggests a maximum ramp rate of 0.5MW/s for threshold calculations based on the observation that the ramp rates above 0.5MW/s occur occasionally and do not persist over a sustained period of time. The detailed configuration settings are provided in Table 3 below.

System limit and safety operating margin

The first step was to remove the DOC protection thereby, gaining a headroom of 11MVA with a new system limit of 45MVA corresponding to the continuous transformer rating. This was achieved by the
implementation of load blinding protection as part of the novel protection relay trial described in section 3 of this document. The second step was to implement ANM to ensure the flexible DG export do not breach the new system limit.

Following factors were considered to establish the system limit of 45MVA for March Grid reverse power flow constraint.

- Continuous Rating of 45MVA when cooling fans are on (OFAF rating);
- De-rated to 22.5MVA when cooling fans are off (ONAN rating);
- Tap changers were rated to 100% reverse power flow;
- Cyclic rating of the transformer was not used by network control;
- Emergency rating 110% (49.5MVA) for 15 minutes was considered as the most conservative rating.

Based on the methodology described above, the ramp rate data and parameters settings were used to establish the March Grid constraint thresholds. An initial safety operating margin of 10% was considered with the trim threshold defined at 30.5MVA with a view of reviewing the margin after sufficient operational experience. Based on transformer emergency rating of 110% this allows for at least 20% total safety margin for a minimum of 15 minutes. This meant the highest ANM threshold the global trip, was set to 45MVA transformer rating and 42.75MVA which is 5% below the global trip.

Table 3: ANM settings for March Grid based on system limit of 45MVA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Trim</th>
<th>Sequential trip</th>
<th>Global trip</th>
<th>Release</th>
<th>Reset</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thresholds</strong></td>
<td>30.5MVA (0.9 x limit)</td>
<td>42.75MVA (0.95 x Limit)</td>
<td>45MVA (1 x Limit)</td>
<td>N/A</td>
<td>36MVA (0.8 x Limit)</td>
</tr>
<tr>
<td>Observation Times</td>
<td>6 seconds</td>
<td>5 seconds</td>
<td>4 seconds</td>
<td>10 seconds</td>
<td>N/A</td>
</tr>
<tr>
<td>Response Times</td>
<td>20 seconds</td>
<td>20 seconds</td>
<td>4 seconds</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Ramp Step</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>500kW</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The 10% operating margin was considered while defining Principles of Access and curtailment assessment for March Grid as part of smart commercial arrangements and are described in the SDRC 9.7 report. A capacity quota of 33.5MVA was agreed and publicised and the first flexible connection offers were issued with an expected curtailment level of 5.3%. The expected curtailment levels represent the duration of time when the export was expected to exceed the trim threshold as shown by the duration curve in Figure 8.
4.5 Case study 2: Peterborough Central to Bury Primary Overhead line thermal constraint

Background

The Bury Primary to Peterborough Central 33kV circuit is approximately 20.7km long and comprises of various overhead line conductor and underground cable segments:

1) 2,205m x associated cable types (mainly oil-filled)
2) 1,119m x 150SCA conductor rated 19MW (summer)
3) 17,415m x 200SCA conductor rated 23MW (summer)

![Diagram showing overhead line constraint locations with DLR]

As shown in Figure 10 the first constraint location is the section between P90 and Farcet 33kV bus bar. The combined 26MW export of existing firm generators Glassmoor (16MW) and Red Tile No.1 (10MW) is 3 MW higher than the 200SCA line summer rating. The overhead line rating is based on 50°C design temperature\(^9\).

\(^9\) “Design temperature” refers to the maximum operating temperature considered by P27/ERA experiments
The second constraint location is the 150SCA conductor and oil-filled cables between Farcet 33kV bus bar and Peterborough Central. Approximately 4MW of export from the existing 26MW export, is consumed by Farcet T1 load. Therefore approximately 22MW will be exported to Peterborough Central.

At Peterborough Central grid there were issues with voltage rise being outside of statutory limits in addition to the thermal constraints. In this case a LIFO approach was considered to be the best approach for Principles of Access as there were different constraints on different parts of the network. Therefore, not all generators would feed into the same constraint, but a curtailment order needed to be set up in case all the generators fed into a new constraint at some point in the future.

Figure 11: OHL power flow duration curve

An assessment was carried out from five years of historic data to understand the behaviour of overhead line power flow measurement. As represented by the graph in Figure 11, the positive part of the curves show duration of available export capacity and the negative part show the duration when the export was higher than the static rating. The curves for the both section of the circuits show the duration of time the power
export breached the static rating with addition of new DG. The curves also illustrate the duration of time additional DG export would be curtailed.

Ramp rate calculation

For the calculation of ramp-up rate of the Peterborough Central Grid to Bury Primary overhead line thermal constraint, the same method was used as per March Grid ramp rate calculation by analysing the behaviour of the current measurements data on the overhead line. The data was based on the real time measurements on the overhead lines, reported to the ANM by the Farcet RTU. As this circuit consists of two separate overhead line sections with separate current measurement data, both sets of data were analysed. The graph in Figure 12 shows the distribution of these values, highlighting some very large outliers but the vast majority of the time the changes in MW flow are relatively small.

![Figure 12: Overhead line ramp rate](image)

Nearly all the changes in MVA flow observed in the data were for small changes less than 0.03MVA/s and 0.04MVA/s for MP2 and MP3 respectively. Only a small percentage of changes were bigger steps.

The most likely ramp rate at the location is obtained by visualising the information near the border of the graphs, between 0 and 5th; and between the 95th and 100th percentiles.
System limit and safety operating margin

The DLR solution is based on an indirect estimation of the overhead line ratings using the local weather station information and hence, an operating margin would be required to account for the potential inaccuracies in establishing the least favourable weather conditions across the span of the overhead line. An operational assessment period of one year was recommended by the DLR trial with the adoption of most conservative settings. A 10% safe operating margin was selected as an initial conservative setting for the trim threshold. An initial setting of 130% maximum uplift was also recommended based on the trial data analysis to avoid inadvertent over-stressing of the asset.

Based on the methodology described above, the ramp rate data and parameter settings were used to establish the constraint thresholds for Peterborough Central Grid to Bury Primary overhead lines. An initial safety operating margin of 10% was considered with the trim threshold defined at 90% level of the dynamic ampacity calculated by the DLR.

Table 4: ANM settings for Peterborough Central to Bury overhead lines based on a dynamic system limit (where system limit = DLR ampacity)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Trim</th>
<th>Sequential trip</th>
<th>Global Trip</th>
<th>Release</th>
<th>Reset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thresholds</td>
<td>(0.9 x limit)</td>
<td>(0.95 x Limit)</td>
<td>(1 x Limit)</td>
<td>N/A</td>
<td>(0.8 x Limit)</td>
</tr>
<tr>
<td>Observation Times</td>
<td>6 seconds</td>
<td>5 seconds</td>
<td>4 seconds</td>
<td>10 seconds</td>
<td>N/A</td>
</tr>
<tr>
<td>Response times</td>
<td>20 seconds</td>
<td>20 seconds</td>
<td>4 seconds</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Ramp Step</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>500 kW</td>
<td>N/A</td>
</tr>
</tbody>
</table>
5 Learning outcomes for the Active Power Flow application

This section discusses the seven Use Cases related to the Active Power Flow application, following the case study for its configuration in section 4. As part of the ANM trial, the Active Power Flow management application from SGS was deployed to manage multiple thermal constraints on the distribution network in a coordinated manner. This application was designed to actively monitor the flow of real power and current measurements at key constraint points. Using the benefit of real time network visibility of the ANM system, this application calculates and issues control instructions to generators in order to maintain network loading within its capacity limits. The capability of ANM to interact with field devices locally managing the power flow, such as the QBCS, was also assessed.

5.1 The capabilities, limits and requirements of generator control as part of an active power flow management application.

What were the objectives and challenges?

The active power flow application was designed to run on a real-time deterministic ANM platform in order to achieve required response within pre-defined timescales. The algorithm was required to continuously monitor the constraint and DG MPs in order to maintain a dynamic set point for real power export of DGs. This DG set point was dynamically varied according to the individual commercial arrangement to prevent a breach of constraint thresholds.

The challenge for this application was to establish the optimum system configuration parameters that ensure safety of the assets while allowing maximum possible DG export, taking into account the fact that nothing is able to happen instantaneously. A detailed study was undertaken as described in the section 4.2 in order to produce a methodology to set and continue to maintain these parameters. The delays experienced by the DG customer projects meant that the majority of the connection dates moved towards the end or beyond the project timescales. Accordingly, the trial phase was not able to benefit from the operational testing of the application functionality with multiple DG customers. This scenario was anticipated from the early stage of the project and necessary actions were taken to prepare a simulation environment capable of thoroughly testing the functionality as described in section 3.3. However, UK Power Networks intends to keep sharing the learning from the operational phase to the industry following the completion of the project.

The trial set out the following objectives in order to demonstrate this concept:
- Curtail real power output from DG to ensure thermal loading and reverse power flow constraints are not breached.
- Establish optimum separation levels for ANM thresholds.
- Manage constraints by automatically issuing set points to DG to ramp down the generator.
- Maintain a stable operation by controlled ramping up of the generator.
- Automatic issue of control instruction to electrically disconnect DG if set points fail to manage the constraints.
- Curtail and release generator according to the pre-configured Principles of Access Maximise power export from generator at all times.
- Measure the time taken to achieve the above actions.
How was the trial conducted?

The experiments tested the philosophy of generator control by mitigating reverse power flow and thermal loading constraints respectively with multiple iterations of both simulation and operational experiments. The simulated experiment for RPF used the real power measurement of March Grid transformers with one firm (i.e. already connected DG) and four simulated flexible connections (i.e. new DGs) using "shared" POA.

For simulation purposes all the thresholds were first defined and then a set of success criteria was set for the maximum time duration for relevant actions based on the methodology described in section 4.1 and illustrated in Figure 7. Calculations were undertaken as per the formulae in Appendix 8 to set the criterion of 68 seconds to reduce the power flow from trim threshold to below reset threshold and a criterion of 260 seconds to increase the power flow to reach the trim less threshold from below the reset threshold. The criteria defined the maximum acceptable action time of each event based on the parameters set in the simulated environment. It is to be noted that, for the operational scenario, the criteria will vary depending on the ramp rates and response capabilities of the associated operational generator equipment.

The first simulated action was the increase in real power measurement by increase in firm generation as shown in Figure 13. Following this step, the trim threshold was seen to be breached after 2 seconds. After a waiting time of 7 seconds the ANM initiated curtailment instructions in steps. After the next 5 seconds it was seen that all three generators started to reduce power. Consequently, the constraint measurement dropped below the trim threshold and continued to drop until it reached the reset threshold taking the total time period of 32 seconds from constraint breach to safe level of reset threshold and well below the criterion of 68 seconds. Similarly, the action to increase the power flow to reach the trim less threshold took 185 seconds which was well below the criterion of 260 seconds.
Using the similar approach, the simulated experiment for a breach of thermal loading was examined using the constraint scenario for the overhead line between Peterborough Central to Bury 33kV with POA as "LIFO". Similar to the RPF constraint management experiment, the thermal loading constraint was successfully managed by curtailing the simulated generation to drop the current measurement from trim threshold to below the reset threshold.

**What were the key trial findings?**

It was demonstrated using a combination of simulated and operational results that the ANM system can manage both the reverse power flow and thermal loading constraint by issuing set points consistent with the theoretical calculations. The system took 32 seconds to bring the power flow at the March Grid transformer from the point of a breach to below the safe controlled level which is well within the expected time window of 68 seconds.

The experiment results showed that only the generators that were actively contributing to the constraint were curtailed, irrespective of their nominal rating. Curtailment was successfully imposed as a function of the power output of the generators contributing to the constraint while releasing (i.e. ending the curtailment) was successfully realised as a function of the rated power of the generators.
The functionality of active constraint management using generator control was also successfully demonstrated in the operational trial of the connected flexible DG customer. Figure 14 shows the actual screen-print of the event from the ANM application interface with a plot of the MP against the thresholds.

The MP was a summation of the output from a 2MW firm wind generator and a 250kW flexible generation with a trim threshold set at 2MW. It can be clearly seen that as soon as the MP breached the trim threshold it was swiftly reduced down below the trim threshold. The curve then continues to descend until it drops below the reset threshold. This demonstrated two key functionalities of the active power flow application:

1) ANM quickly acted on a breach of the trim threshold in order to avoid breaching the next threshold;
2) ANM continued to manage the constraint until the MP dropped below the Reset threshold in order to maintain stability.

![Figure 14: Operational curtailment event (screen-print of ANM interface)](image)

It was demonstrated that the amount of time used by the ANM to prevent an overload is much lower than the time constants required by the assets to “feel” that overload. The assets (overhead lines, transformers etc.) need a considerable amount of time to increase/decrease their temperature when their power flow changes. As the trim threshold was below the asset rating, the ANM system was capable of taking preventive measures before an overload is identified. In effect, the rapid ANM action time within one minute can allow the distribution network to operate closer to its limit and at the same time avoid equipment deterioration.

The key learning generated was the demonstration of the capability of ANM application to actively manage thermal loading and reverse power flow constraints. One of the additional learning outcomes was the study in setting an operational envelope to implement an optimum configuration setting for the ANM which is separately covered in section 4.
5.2 The capabilities, limits and requirements of Quadrature-booster (phase shifting transformers) as part of an active power flow management application

What were the objectives and challenges?

The capabilities of the Quadrature-booster Control System (QBCS) to effectively balance power flows on two circuits was proven earlier in the project during the commissioning stage in 2013. It was further demonstrated by the Quadrature-booster trial that the system can increase the capacity headroom at the Wissington 33kV network by approximately 10MW. To further improve the functionalities of the QBCS to take into account generation connections on the two parallel 33kV circuits under control, an innovative algorithm was developed and hosted on the ANM platform to issue optimal load sharing set-points.

On 26 July 2013, the Quadrature-booster was commissioned on the network as shown in Figure 15 to run either in an automatic or in a manual mode. The Wissington CHP generator is very sensitive to line disturbances, so it was not experimentally possible to demonstrate the interaction of the ANM and QBCS systems in the operational network. As mentioned in SDRC 9.8 report, British Sugar currently operate automatic turndown scheme on their generation which takes into account the Wissington British Sugar substation outgoing 33kV feeder circuit breakers status as well as analogue measurements on from the feeders. In order for this scheme to incorporate the Quadrature-booster operations it was necessary to
provide ‘Tapping in progress’ status information for the Quadrature-booster, to trigger the masking of the generation turndown scheme and ensure the generator ignores any changes on line currents for which it would normally initiate a reduction in generation output. To mitigate this, network conditions were simulated ensuring these actions did not impact the validity of the results.

In July 2013 the Downham Market No.2 circuit was switched off to connect the Quadrature-booster. It can be seen from Figure 16 that the imbalance in current loading between Northwold No.1 and Downham Market No.2 circuits was reduced significantly when the Quadrature-booster was brought online from 26 July 2013. There was no significant effect on the flow on the Southery line because it does not run electrically in parallel with the Quadrature-booster circuit (Downham Market line). The gap in the curves represents the time period when data was not available between 16 September and 10 October 2013 due to the technical issues related to the communications network and the data storage.

The following observations were made in reference to the graph in Figure 16 above.

- Downham Market No.2 circuit was loaded approximately twice as much as both the Northwold No.1 and Southery No.3 circuits for the period September 2012 to June 2013. With an average of approximately 800A delivered by the CHP generator, the Downham Market No.2 circuit was load at approximately 400A with both the Northwold No.1 and Southery No.3 circuits carrying approximately 200A each on average.
Flexible Plug and Play Low Carbon Networks
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- Following the commissioning of the Quadrature-booster, it is clear from Figure 16 that load profiles for Northwold No.1 and Downham Market No.2 circuits are generally closer to each other. The Northwold No.1 circuit load averaged about 200A while the load on the Downham Market No.2 reduced to an average of 250A.

Figure 17 below shows a scatter graph of recorded actual circuits loads against the recorded CHP export during the trial period.

![Figure 17: Graph showing Wissington 33kV circuit loads Vs CHP generation export](image)

By inserting lines of best fit (trend lines) and extrapolation of the trend lines it can be seen that all the three 33kV lines would be loaded below their thermal seasonal ratings up to a generation export of approximately 64MW – which is 10MW above the current 54MW (winter) export restriction.

At the inception of the project, the QBCS was based on the simplified assumptions that only power flow measurements at Wissington side 33kV on the Northwold No.1 and Downham Market No.2 circuits would be used to regulate the power sharing between these two circuits. It was also not envisaged at that time that other new distributed generation would be connected on these two lines between Wissington and Northwold or Wissington and Downham Market tee point.

The 33kV network has since changed with the connection of a new 5MW solar farm generation on the Northwold No.1 line at the half-way point of the circuit. This situation has changed the power flows, rendering in the initial assumptions on which the current QBCS algorithm as installed to be no longer valid. To correct this, it became clear that circuit load measurements at both end ends of the two lines were required to input into the control system. This was discussed in February 2014, and the project introduced...
an additional QBCS trial – picking up additional measurements at the remote ends of the lines and using ANM to calculate required inputs to feed into the QBCS as shown below.

The key measures of success for this trial were:
- Demonstrate the ability of the ANM and QBCS systems to work together to increase the utilisation of existing network assets and unlock additional capacity to connect DG; and
- Demonstrate functionality and operability of the scheme using IEC 61850 communication platform, ANM and QBCS.

The trial set out the following objectives in order to demonstrate this concept.
- Prove that the use of the Quadrature-booster can improve capacity utilisation on Downham Market No.2 and Northwold No.1 circuits;
- Prove that the central ANM system can execute intelligent algorithms to calculate an optimum load sharing ratio and provides it as input to the QBCS for use in adjusting power flows on the two circuits;
- Prove the capability of the ANM and the QBCS to efficiently interact with each other to apply the load sharing ratio using IEC 61850 communications standard; and
- Prove the thermal loading estimation of the circuits by monitoring remote measurements

**How was the trial conducted?**

The Quadrature-booster normally adjusts its tap ratio in order to share power flows in proportion to the thermal ratings of the parallel circuits, based on the local measurements. The trial explored the use of the ANM to access remote measurements and to calculate a power sharing “ratio” that, defines the proportion of power that the QBCS attempts to push through one of the two circuits. Provision to utilise dynamic rating data was also incorporated in the ANM-QBCS management scheme. Further to the successful demonstration of QBCS integration to the ANM by using IEC 61850 standard in 2013, the trial further explored the use of the standard to update QBCS load ratio setting from ANM.

Figure 18 shows the network diagram showing the proposed current transformers (CTs) at each end of each line and the information flows between ANM and QBCS.
As per Figure 18, CT1 was installed on the Downham Market (Quadrature-booster, Line2) line at the Wissington substation side, while CT3 was located (which was a simulation for the time being) at the other end of this same line2. CT2 was installed on the Northwold line (Line1) at the Wissington substation side, and CT4 was to be simulated at the other end of this line1.

The objective was not only sharing the power through the lines equally, but also to account for any generation connected on any of the lines between the two ends. Accordingly, the algorithm was designed to detect any generation between “CT1 and CT3”, and between “CT2 and CT4” and calculate the power sharing factor/ratio. The controllable power was the one that passes only through CT1 (Downham Market line Wissington substation side) and CT2 (Northwold line Wissington substation side), this was because of the position of the Quadrature-booster. Any generation that pushes power at any point between the ends of
any of these lines was considered to be forced rather than controllable; hence the corresponding line has to deal with this power regardless of the power flowing through the Wissington substation side.

The concept of the ANM to issue set-points to smart devices such as the AVC relay has been demonstrated by another use case and the innovation here is to apply to a different control device such as the QBCS. The end to end process flow of the algorithm is summarised by the flowchart in Figure 19.

![Figure 19: ANM – QBCS algorithm](image-url)
The algorithm was first tested through a desktop validation process. This was then followed by the testing in the simulation platform as follows:

1. With no DG, control power flow was observed to be the same on both circuits, which corresponded to a power sharing ratio of 0.5.
2. DG was then introduced to increase the power flow on the Northwold end of Circuit 1.
3. The behaviour of Quadrature-booster was monitored when QBCS received only local measurements at Wissington.
4. The trial functionality in ANM was enabled with additional measurements and Quadrature-booster control algorithm.
5. The behaviour of Quadrature-booster was simulated when the QBCS received a modified power sharing ratio from ANM.
6. The DG was removed and the response of ANM and Quadrature-booster was observed.

**What were the key trial findings?**

The capability of the QBCS to coordinate with the ANM to unlock additional capacity on the grid, was proven using desktop simulation. The ANM was able to interact with the QBCS to send the optimal load sharing ratio. As potential new generators connect on network in the future, it was evident that the system will need to evolve to accommodate measurements from the new generations connected. The flexibility of the centralised ANM solution enabled the processing of additional measurements and coordinate with the QBCS to enhance the powerflow balancing functionality of the Quadrature-booster.

This enabled the project to generate the following learning outcomes;

1) A centrally located application such as the ANM can be utilised to:
   a) carry out computations of control algorithms for optimal load sharing;
   b) estimate thermal loading of the circuits by monitoring remote measurements in real time; and
   c) send the optimal load sharing ratio to the QBCS.

2) It was demonstrated that actively managed QBCS with remote overhead line measurements, algorithm hosted on ANM (SGS platform) can increase 33kV capacity headroom at Wissington by approximately 10MW.

3) It was also shown that the system creates additional capacity on the Wissington 33kV network (before the network was at full capacity and could not allow further generation export). This can offer more flexible and cheaper connection for potential DG customers.

4) As a recommendation for future work, the trial also identified a potential gain in additional headroom for generation export on each line by considering the integration of DLR technology with QBCS and ANM.
5.3 Demonstrate the ability of an active power flow management application to adapt to different network running arrangements.

What were the objectives and challenges?

The main objective of this experiment was to prove that ANM can be pre-configured to automatically cope in real-time with the changing network conditions without the need of manual interventions.

The standard configuration of the ANM was based on the Normal Running Arrangement (NRA) as specified by the network outage planning team. The trial involved carrying out power system analysis to identify all possible running arrangements and their corresponding impact to the constraints and the associated DG customers connected.

Within the trial area, the Normally Open Points (NOPs) and Normally Closed Points (NCPs) were not remotely controllable and indicated. Hence, the philosophy was tested and proven using simulated network indications. The use case in the section 4.4.3 covers the integration of remotely controllable switches.

The trial successfully met the following requirements in order to demonstrate this concept:

- Analyse the network to identify all the NOPs and NCPs that can vary the running arrangement;
- Identify all possible running arrangements with their corresponding constraints and contributing DGs;
- Configure the ANM with multiple scenarios and multiple thresholds; and
- Prove that ANM can seamlessly change the association of the DGs to a constraint threshold based on variation of running arrangement.

How was the trial conducted?

The experiment involved pre-configuration of the Active Power Flow application and sequential change of running arrangements. The expected outcome was for ANM system to recognise a change in network configuration, reading the configuration data for the specific network arrangement and immediately use these to manage the network.

The experiment tested three NRAs with the associated NOP/NCP as Pole 49 (P49) isolators with simulated firm DGs and simulated flexible connections. For each NRA, the nature of constraint was varied for the flexible connections as per Table 5. The network indications monitored were March Grid circuit breaker status, P49 isolator status and Peterborough Central circuit breaker status. MP4 represents the power flow on circuits between March Grid and the P49 isolator while MP5 represents the power flow on circuits between Peterborough Central and the P49 isolator.

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10 Normal Running Arrangement refers to the distribution network configuration under normal network operating conditions.
Table 5: Running arrangement and switch status

<table>
<thead>
<tr>
<th>Running Arrangement</th>
<th>March Grid circuit breaker</th>
<th>P49 isolator</th>
<th>Peterborough Central circuit breaker</th>
<th>Constraint Associated</th>
<th>Associated DG curtailed</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRA 1 (normal)</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>No constraint</td>
<td>None</td>
</tr>
<tr>
<td>NRA 2</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Thermal limit (MP 4)</td>
<td>DG1</td>
</tr>
<tr>
<td>NRA 3</td>
<td>Open</td>
<td>Closed</td>
<td>Closed</td>
<td>Thermal limit (MP 5)</td>
<td>DG2</td>
</tr>
</tbody>
</table>

The experiment demonstrated that the flexible simulated DG was not affected on NRA1 as expected. As soon as the change occurred from NRA1 to NRA2, curtailment was issued to the DG1 that was associated with MP4 constraint. Similarly, as soon as the change occurred from NRA2 to NRA3, curtailment was issued to DG2 that was associated with MP5 constraint while releasing DG1.

What were the trial findings?

The experiment demonstrated that ANM automatically detected the change in constraint type of a MP on change of NRA and acted accordingly. This means ANM curtailed generation in the scenario when the constraint MP became an active constraint based on the specific running arrangement. It was proven that the ANM application can manage multiple running arrangements if these are pre-defined and the relevant analysis is completed.

This enabled the project to generate the following learning outcomes;

- The dynamic and flexible characteristics of the Active Power Flow management application can add value to the overall ANM functionality in detecting and responding to change in the network running arrangements.
- With the capability of the ANM to operate in different seasonal and abnormal running arrangements, DGs can be correctly associated with the real time constraint and avoid unnecessary curtailment of the power export.
- The possible changes in the running arrangements could be pre-defined and pre-configured in the ANM system to take into account any possible variation of relationships between the constraint and the contributing DG. This means constraints would always be accurately managed and again would reduce the possibility of DGs being unnecessarily curtailed.
5.4 Demonstrate the value of Ring Main Units (previously FUS in Use Case document) when deployed with an active power flow management application.

What were the objectives and challenges?

The purpose of Frequent Use Switches (FUS) trial in the FPP project area was to provide remote switching flexibility to adopt different network configurations on the existing 33kV overhead lines in a cheaper and faster way, compared to the traditional method of sending a resource to site. For clarity, it should be noted that the term FUS refers only to a switch capable of high mechanical endurance during its useful life. The FUS is not intended to be frequently switched open/close, for example several times a day.

The original scope of the project included a provision for FUS to be deployed at a strategic location on the 33kV overhead line circuits between Peterborough Central and March Grid substations to optimise the amount of DG in the trial area. At these strategic locations a business-as-usual project was taking place to upgrade the RMUs, which have the same functionality as FUSs, and therefore the FPP project decided to use these in the trial. This change was approved by Ofgem and also highlighted in SDRC 9.4.

A number of considerations were made when trialling the RMUs:

- There was a need to shift Funtham’s Lane and Whittlesey load between March Grid and Peterborough Central under n-1 condition at either grid site.
- The primary function of the RMUs installation was to enable remote switching to modify the network. The existing NOP was a manual Air Break Switch Disconnector (ABSD), and was not remotely controllable. It was therefore difficult to make network re-configurations as network conditions change from time to time.
- The FUS trials on this network tested the principle for potential application at other network locations. The benefit is mainly an improved flexibility for network configuration change.

How was the trial conducted?

Section 4.3.3 demonstrated the capability of the ANM to cope with various running network arrangements. This use case experiment demonstrated how RMUs can be used to assist the ANM system by reconfiguring network to enhance network performance or remove barriers to DG. It consisted of first simulating how the system responded to a change of switch position and secondly to demonstrate that the system could communicate with field device such as the newly commissioned RMU at Whittlesey.

Two RMUs were installed at Whittlesey Primary with Normally Open Points on the Chatteris/March Grid circuits as shown in the simplified network drawing in Figure 20.
The RMUs were installed to address an existing issue with the loading of the 33kV circuits feeding Chatteris, Whittlesey and Funtham’s Lane from March Grid. An outage affecting one of these circuits at peak load would subject the remaining circuit to a current of approximately 720A compared to the circuit rating of 575A.

The RMUs are controlled by the Control Engineers via the RTUs using DNP3 protocol over the SCADA communication network. The ANM system received the switch position indications in real time from the RTU using the IEC 61850 protocol thereby, actively updating its database to reflect the topology of the network.

What were the trial findings?

The simulated trial demonstrated in principle that RMUs could provide the flexibility to run the network with normally open points (NOPs) on the March Grid legs/circuits at Whittlesey. This could enable Funtham’s Lane and Whittlesey primary substations to be fed from Peterborough Central and overcome the loading issue referred above. Through the ANM monitoring the status of the March Grid legs of the Whittlesey RMUs, the constraint management scenarios could be altered if Funtham's Lane and Whittlesey primary substations were configured to be fed from March Grid.

The RMU equipped with automatic switching feature can also provide remote operation capability for change of switch position providing flexibility for control room staff to change the arrangement of the network without sending personnel to site. The provision of the switch indications to ANM system demonstrated functional benefits in better management of the constraint and DGs.

The key learning was that RMU can be used to implement active network configuration and thereby facilitates ANM to enhance active power flow management process. This learning compliments the use case
described in section 4.3.3 exploring the capability of ANM in utilising switch status information to detect the change in running arrangements.

This enabled the project to generate the following learning outcomes;

- The use of RMUs can offer value in reconfiguring the network to utilise the spare capacity from one circuit and mitigate thermal overloads on another circuit thereby, removing barriers to the connection of DGs.
- Based on the indications provided by RMUs, the ANM can be implemented with flexible control algorithms to increase the energy export from the DGs.

5.5 Demonstrate the ability of an active power flow management application to adapt to different network ratings as provided by DLR devices or by a thermal ratings estimation application.

What were the objectives and challenges?

The aim of the trial was to demonstrate that the ANM application was able to use dynamic asset rating information provided by DLR devices or thermal rating estimation application to dynamically change the ANM’s threshold parameters thus allowing the asset to be loaded according to its real time capacity.

The trial set out the following objectives in order to demonstrate this concept:

- Process the ampacity data calculated by both field based and server based dynamic rating solutions;
- Curtail real power output from DG to ensure thermal constraint is not breached based on the real time rating;
- Establish a safety operating margin between the ampacity values and the ANM threshold based on the reliability factor concluded by the DLR trial;
- Establish an optimum sensitivity setting for using the dynamic ratings data;
- Establish optimum separation levels for ANM thresholds;
- Manage constraints by issuing set points (curtailing) or by tripping the DG circuit breaker;
- DG is curtailed and “released” according to the configured Principles of access; and
- Maximise real power output from DG at all times.

The challenge in this case was to identify an optimum sensitivity setting for ANM application to process the dynamic rating information. This setting was required to specify how often ANM captures the dynamic rating information and what percentage of ampacity rating deviation triggers a change of threshold. Similar to the challenge in setting threshold for RPF, the separations between the various ANM thresholds should be correctly set to ensure safety of assets while maximising the DG export.

How was the trial conducted?

The trial experiments demonstrated the functionality by using data from DLR relays and thermal estimation application respectively. Alstom MiCOM P341 relays calculated the overhead line ampacity data using the weather measurements from the locally installed weather stations and continuously send them to ANM. The ANM system used sgs ratings application as described in section 3.3.1 to process these ampacity data to set the dynamic thresholds.
In order to achieve a stable system performance, various sensitivity settings were tested. The frequency of DLR data received by ANM and the rate of change of the ampacity values were closely observed to set optimum scheme in threshold variation.

The DLR data was received by ANM approximately every 2 seconds with a minimum change rate of every 4 seconds to a maximum change rate of every 15 seconds. The ANM application was configured to wait 5 seconds before calculating a new threshold. The maximum change in thresholds every 5 seconds allowed by the ANM system was 0.5A (amperes). The 5 second update rate and 0.5A maximum threshold change were chosen to ensure a smooth variation in thresholds and to filter out fast weather variations that do not affect the conductor thermal behaviour.

Figure 21 describes the process flow of updating the dynamic threshold from the point of the ANM receiving dynamic ratings data.

![Figure 21: Process flow to update dynamic threshold](image)

An optimum separation value of 20A between thresholds was established by considering the system’s selectivity to trigger the most adequate action for each situation. In one hand if the separation between thresholds was too small, it created a very sensitive system with unnecessary threshold breaches and frequent ANM actions. On the other hand if the separation between thresholds was too wide the system became too insensitive leading to system inefficiencies with generator exports to lower levels.
What were the trial findings?

The graph in Figure 22 illustrates the behaviour of ANM thresholds changing in real time in accordance to the dynamic ampacity data provided by the DLR. In this case study, the global trip threshold was equal to the DLR ampacity values which meant all the threshold values also altered dynamically while maintaining the 20A separation value.

As seen in the graph, when the constraint MP3 breached the dynamic trim threshold of 23,591kW, the set-point instructions were issued to curtail the power output of DG1. Similarly, after MP3 was safely brought below the reset threshold of 22,448kW, the set-point instructions were issued in steps to release the power output while ensuring the MP3 stayed below the trim threshold.

The experiment was also repeated to use real time ratings information calculated by the thermal estimation application hosted by the ANM. The Active Power Flow behaved in similar fashion with the data provided by thermal rating estimation application as it did with the DLR data. The comparison of the calculations between these two real time rating solutions is covered in section 4.3.6.

It was demonstrated using simulated experiment that Active Power Flow management application can manage the thermal constraint using dynamic threshold to manage power export of DG. The comparison of the ANM behaviour between DLR relay data and the thermal estimation application data proved that the concept could be applied to work with any type of data source.
Based on the results of the experiment it was verified that the Active Power Flow application is capable of using real-time thresholds to issue set-points for curtailling and releasing the generators under its control. The outcome of the trial showed that the usage of dynamic thresholds could unlock additional capacity on the network by integrating dynamic rating solutions with the ANM application.

As described in section 5.1, the Active Power Flow application was proven to manage DG active power output based on static rating or a pre-defined threshold of an overhead line. As part of this use case, the trial further demonstrated its capability to use a DLR technology to maximise DG power export allowing additional headroom beyond the static rating of the overhead line to accommodate higher power output from DG.

5.6 Demonstrate the value of DLR and thermal ratings estimation when deployed with an active power flow management application.

What were the objectives and challenges?

In addition to a site based DLR trial, the project also trialled a thermal ratings estimation application at the central ANM system providing dynamic rating information for the power flow analysis. The objective was to prove that the implementation of both site based DLR solution and server application based thermal estimation application can add value to the efficient operation of the ANM system. The functionality was trialled by the implementation of the sgs ratings application within the ANM platform.

The challenge was to assess the accuracy and reliability of each solution as there is no baseline reference available. Based on the different technologies and rating calculation methods, differences in the circuit ratings were expected but it was difficult to establish which estimation technique was more accurate.

A comparative analysis was required to be undertaken to validate application based thermal estimation with the site based conventional P341 relay dynamic line rating solution. The objective of the analysis was to identify the origin of the differences in the calculated values between the sgs ratings application and the DLR relay.

How was the trial conducted?

The line rating calculated by the sgs ratings application was compared against results from the calculations provided by the DLR relays. Both solutions used the weather information provided by the same weather station for a like-by-like comparison.

The sgs ratings application ran an algorithm to provide real-time rating estimations based on a thermal model, measurements of environmental parameters and measurements of conductor temperature and current. For the FPP project, conductor temperature was not used in the calculation.

Four different methods were used by the algorithm in a hierarchy to calculate circuit ratings as shown in Figure 23. Each method calculated ratings to a certain degree of accuracy with the more accurate method requiring more computation time. By using this principle, the application was still able to provide thermal
estimation using any one of the method if any of the methods were impacted by failures in measurements or communications link. For the FPP project, only three out of the four modules were trialled without including the temperature rating module as the temperature measurement data was not available.

The conductor thermal rating was calculated from the energy balance between heat dissipated by the Joule effect within the conductor and the heat exchange on the conductor surface, as influenced by environmental parameters and represented by the steady state energy balance equation given in Appendix 6.

Two key elements were identified that were expected to cause the differences in the calculated values between the sgs ratings application and the DLR Relay as follows.

1. **Implementation method of the CIGRE 207 standard**\(^\text{11}\): The same algorithm was implemented in both cases but there were differences in using some of the input parameters.

2. **Dynamic behaviour**: The sgs ratings application provided real-time measurements directly based on the weather inputs with no averaging whereas DLR relay provided ratings every 1 minute based on a 10-minute rolling average.

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\(^{11}\) CIGRE 207 standard provides a guide for thermal rating calculations for overhead lines
What were the trial findings?
The trial demonstrated that the sgs ratings application was capable of running a hierarchy of multiple ratings module in order of priorities, ensuring that there is always a thermal rating data available for the sgs power flow application to use as a dynamic constraint threshold. This is an extremely valuable functionality as it can avoid unnecessary curtailment of the DG by the ANM which would otherwise occur in the event of the loss of data from only one available rating data sources.

The following potential benefits were identified during the trial for implementing the server based centrally hosted thermal estimation application in conjunction with the central ANM.

- The thermal ratings application would be easier to maintain, upgrade and configure compared to field based rating solutions.
- The server based thermal estimation application could potentially be used for calculating thermal ratings for multiple conductors, using a single weather station compare to the field based DLR which calculates a single ampacity for a single conductor type.
- Similarly, further intelligence can be developed within the centrally hosted algorithm to take in to account of multiple sources of weather information in order to increase the data accuracy.

The trial investigated the calculated ampacity between the sgs ratings calculation and the DLR relay based on the same weather data provided to both solutions. As per the CIGRE standard it can be interpreted that wind speed and wind direction have the greatest influence on the calculation of ampacity.

Figure 24 shows a time series graph comparing the ampacity calculated by the sgs ratings and the DLR. The main cause for the difference between the magnitudes of the ampacity data was found to be due to the different values used for wind direction parameter in each system. The sgs ratings used a fixed value of 70 degrees (relative to the conductor’s orientation) which generated a higher ampacity compared to the DLR Relay which used fixed value of 20 degrees (relative to the conductor’s orientation).
Figure 24: Comparison of sgs ratings and DLR relay ampacity measurements

Another difference observed between the two ampacity data is the behaviour of the curves. The wind speed used by the DLR relay was based on a 10 minutes rolling average, whereas the wind speed used by the sgs ratings application was based on the real time wind speed data sent by the weather station. Due to this averaging function, the calculated ampacity from the DLR relay shows a smoother characteristics compared to the calculated ampacity of the sgs ratings (without averaging) which shows sharp fluctuations. Further learning outcomes from the DLR trial are separately covered in section 7.7.

5.7 The capabilities and limits of the communications platform to support the evolving needs of active power flow management.

What were the objectives and challenges?

As part of the analysis carried out during the bid stage, the FPP team considered a number of communication solutions that could potentially meet the initial requirements at different costs. It was concluded the RF mesh based solution can potentially meet all requirements even though the initially specified bandwidth and latency requirements of ANM solution were quite demanding. Significant learning was gained in implementing system optimisation techniques to meet the end objectives without the need of installing high bandwidth but relatively inflexible communication solutions. The added benefit of flexibility, resilience, scalability and ease of installation gained from the RF mesh network was proven to outweigh the limitations in bandwidth and latency when operating under an optimised setting.

As part of the trial, various scenarios were required to be trialled to verify ANM performs as expected in order to maintain the system under safe limits. The FPP communications solution was designed and tested with the dual hardware redundancy feature on every possible component of the architecture and where the dual redundancy was not possible to be implemented, the ANM application was designed to take fail safe
actions. The deterministic nature of the ANM solution rigorously tested the performance of the communication platform requiring the system as a whole to undergo a number of enhancements and optimisations. The design parameters of all the communicating devices were also required to be adapted to allow the best operation of the overall system.

The challenge was to understand the overall impact of communication failures to various components in the architecture. A communications system failure between the ANM system and critical MP could result in the ANM system issuing full curtailment to all associated DG to ensure that the power flows on the network remain within limits.

The RF Mesh Network was initially intended to support one second polling\(^{12}\) to meet the worst case scenario of the ANM data requirements. However, the initial lab testing showed that RF mesh network would not be able to support the data loading for a larger number of DG connections. Hence, various system optimisation actions needed to be taken to reduce the data loading on the network as detailed in SDRC 9.4 report.

The knowledge gained from the system integration testing and the ANM trial highlighted some key communication requirements as follows:

- Average latency = \(<1\) second
- Average Availability \(>99\%\)
- Bandwidth = Depends on number of devices. Refer to Table 6 for bandwidth breakdown of individual device.
- Capability of transmitting simultaneous multiple IP based protocols.
- The communications platform should be able to support IP based communications.
- Capability to operate communication devices with 48V or 24V DC.
- Ability to support time synchronisation protocols and applications. The ability for the communications equipment to carry out its internal time synchronisation is also desirable.
- Resolution of fault resulting in a loss of communications to be fixed within 24 hours.

\(^{12}\) Polling refers to a continuous messaging mechanism from one device to another device
Table 6: FPP device data utilisation statistics

<table>
<thead>
<tr>
<th>Smart Device</th>
<th>Individual device utilisation Average</th>
<th>Number of devices</th>
<th>Total device utilisation Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream</td>
<td>Downstream</td>
<td></td>
</tr>
<tr>
<td>RTU (Bytes/sec)</td>
<td>17.4</td>
<td>4.3</td>
<td>12</td>
</tr>
<tr>
<td>DLR (Bytes/sec)</td>
<td>219.5</td>
<td>52.76</td>
<td>4</td>
</tr>
<tr>
<td>QBCS (Bytes/sec)</td>
<td>16</td>
<td>18.46</td>
<td>1</td>
</tr>
<tr>
<td>AVC (Bytes/sec)</td>
<td>72.1</td>
<td>34</td>
<td>2</td>
</tr>
<tr>
<td>sgs connect (Bytes/sec)</td>
<td>30</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td>Total (Bytes/sec)</td>
<td>355</td>
<td>134.52</td>
<td>33</td>
</tr>
<tr>
<td>Total (kbits/sec)</td>
<td>2.84</td>
<td>1.07616</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 6 shows the overall data requirement for FPP trial network based on the commissioned smart devices and fourteen expected DG connections. This can be summarised as the bandwidth requirement of 18 kilobits per second with 12.856 kilobits per second data transmitted from the field to ANM while 5.1928 kilobits per second data transmitted from the ANM to the field.

How was the trial conducted?

The performance of the communications platform were tested during various field based experiments within both the ANM and smart devices trials. A structured communications trial was also undertaken in order to assess the overall performance of the platform. This involved stress testing of the network to establish the tipping point of the system i.e., the maximum data handling capacity of the platform beyond which the network underperforms or the ANM system performance is impacted.

The capability of ANM application to apply fail safe functionality under various conditions was put to test with experiments involving simulated failure of various system components during testing and commissioning process. This was further validated by observing the ANM performance during genuine fault conditions. The key fail safe actions are represented by the sequence diagram in Figure 25.
As shown in Figure 25, TCP keep alive was used as a heart-beat message to monitor the health of the communications network. The frequency of the keep alive message is configurable and was set to every 10 seconds as an optimum frequency based on bandwidth optimisation tests. The local generator controller listens to the keep alive message for a configurable time period known as communications timeout. This timeout parameter can directly impact on the level of curtailment of DG so every site needs to be carefully assessed based on the constraint, number of connected DGs and time of the year.

When the communications timeout reaches its threshold, the generator controller applies a pre-defined fail safe set-point to the DG control system\(^\text{13}\). If DG control system fails to apply the set-point within a configurable time, the generator controller opens the DG circuit breaker using a separate communications link.

The trial phase continued to enhance and optimise the performance of the communications platform as follows.

- **Data overload:** Dramatic reduction of the data traffic was achieved by changing the one second polling mechanism to reporting by exception

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\(^{13}\) DG Control system refers to the customer equipment that interfaces with the ANM local generator controller at the generator interface substation.
What were the trial findings?

The capability of the whole ANM solution including both the central system and the field device was tested and proven to identify a communications failure; take fail safe action and quickly restore the system to normal operation once the system becomes healthy.

Availability of the communications platform was found to be the highest priority performance indicator for the deployment of an ANM system. One of the attributes of the RF mesh network is the self-healing mechanism which provides multiple routes back to the destination in event of a node failure, improving the availability and resilience of the network. However, it was seen that the overall communication architecture needed to be optimally designed and thoroughly tested including the WAN architecture as the trial results demonstrated that the network can only be as strong as its weakest link. Throughput and latency were also other important parameters affecting the performance of the overall ANM system. The FPP communication platform performance results were seen:

- **Availability:** Even though both the WAN and the RF mesh availability was individually seen to attain over 99% performance levels, the end to end network suffered intermittent outages. This seriously impacted the overall network availability performance levels.
- **Throughput:** It can vary from >200kbps to <20kbps depending on the device with number of hops to the master node and link quality
- **Latency:** Multiple factors affect latency – Layer 3 routing issues, number of RF mesh hops, routing via different master node.

The trial highlighted that the quality of actions by ANM during abnormal events is crucial to maintaining quality of supply and protecting the health of distribution assets and equally in maximising the export of the DG power to the network. Table 7 represents key network events which require ANM to take specific actions under communication failure scenarios.
Table 7: Communication failure scenarios

<table>
<thead>
<tr>
<th>No.</th>
<th>Network Event</th>
<th>ANM action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Failure of communications between the Central ANM and the local ANM controller</td>
<td>Local ANM controller detects loss of communication and falls into fail safe mode which curtails the output of the DG to a predefined value that ensures that the network constraint is not breached.</td>
</tr>
<tr>
<td>2</td>
<td>Failure of communications between the Central ANM and the MPs</td>
<td>Central ANM detects loss of communication and instructs the local ANM controller to apply fail safe mode.</td>
</tr>
</tbody>
</table>

The performance monitoring of the first connected DG customer highlighted one of the hidden issues with the communications platform related to intermittent failures. This led to a series of investigation and testing on both WAN and RF mesh solutions to find the root cause of the issue generating huge learning from the project.

The basic topology of the RF mesh technology is normally based on multiple remote nodes communicating back to a central system via one designated master node. The FPP project decided to implement fully dynamic RF mesh architecture which meant any RF mesh remote node at any part of the 700km² trial area would be capable of routing via any of the four RF mesh master nodes installed at the two back-haul sites. This innovative design required synchronisation between the four master nodes using Master Failover Protocol (MFP) to achieve guaranteed failover functionality. The synchronisation mechanism determined which of the four master nodes has the best available route for each remote node and as such should be the single master to announce that route to the upstream WAN’s routing domain, disregarding the routes from the three remaining master nodes.

The investigation identified a number of factors contributing to the suboptimal performance. The main cause of the issue was related to implementation issues on the WAN infrastructure devices which hindered the ability of the master nodes to fully synchronise with each other over the WAN. This resulted in intermittent failures of remote nodes and higher latencies due to sub-optimal or conflicting routings. A number of corrective actions were taken to resolve this issue as follows.

- Removal of route summarisation in the WAN in order to prevent the loss of cost metrics in the routes announced by the Master nodes. Loss of cost led to an asymmetric routing of communications through the WAN.
- Addition of specific filter rules in the WAN routers at each backhaul sites to prevent a condition where the remote node routes learned by the WAN were then re-distributed back to the substation routers, causing a conflict with RIP that led to the loss of routes and therefore loss of end-to-end communication capability.
- Introduction of an additional Ethernet switch between the WAN router and the RF mesh master nodes at each back-haul site. This mitigated the issue caused by the interface module of the WAN routers not being able to reliably support communications required by the Master Failover Protocol.

The corrective actions led to a stable performance with high availability of remote nodes and lower latencies. The performance of the RF mesh network was further improved by network optimisation exercise which involved replacement and re-location of under-performing relays and reinforcement of additional relays in parts of the network with lower signal quality.
Figure 26 shows the improvement in the latency for some devices communicating to the ANM after a number of corrective actions were taken as part of the fault resolution process.

![Figure 26: Latency comparison before and after resolution of issues](image)

The ability of both the ANM central system and the sgs connect to identify a communications failure was demonstrated. The autonomous and fail safe characteristics increased the confidence of the solution by proving that when a communications failure occurred, the ANM managed generation export would not increase the risk of breaching the threshold of a constraint to the network.

The key learning was that the high availability of the communications network is the most important requirement for the ANM system. Other parameters such as bandwidth and latency are important to meet the performance requirement of the ANM system but a low availability network can directly lead to high levels of curtailment and loss of revenue for the DG customers.

6. Learning outcomes for the Active Voltage Management Trial

This section discusses the six Use Cases related to the Active Voltage management application. As part of the ANM trial an active voltage management application was deployed to manage multiple voltage constraints on the distribution network in conjunction with the power flow management. The aim of the application was to monitor system parameters in the areas with potential voltage constraints using real time network measurements and control the generators contributing to voltage constraints and any other smart
devices that offer a means of alleviating those constraints. The smart application was also trialled to explore its capability to interact with the AVC as well as QBCS for voltage management function using the IEC 61850 standard.

6.1 The capabilities, limits and requirements of generator control as part of an active voltage management application

What were the objectives and challenges?

As part of this use case, the Active Voltage application was trialled to test the feasibility of using generators to control voltages on a typical GB 33 kV distribution network.

High volumes of generation connecting on the FPP trial network was initially expected to affect the voltage profile, and possible unacceptable voltage rise at the point of common coupling PCC. Steady state Voltage Studies were carried out on the 33kV and 11kV network within the FPP project area using the network analysis tool, the Power Factory software from DigSILENT (with target voltage set at 1.025pu at 11kV and 1.01pu at 33kV) to identify the impact of planned generation on voltage rise, and step voltage change under network disturbance. A worst case scenario of minimum network load and maximum generation output was studied.

The results of above studies indicated that the connection of the contracted firm generation and ANM-controlled generation would not cause voltage levels to rise above the network defined limits that are even stricter than statutory limits. As real voltage constraint scenario was not present in the trial network, the experiments were undertaken in the simulation environment.

How was the trial conducted?

The trial experiment tested the mitigation of a voltage constraint using the sgs voltage application based on the philosophy of actively adjusting both real and reactive power flow as part of generator control. The sgs voltage application was configured with a series of thresholds and operation zones as defined below and illustrated in Figure 27.

- **Target value**: The value that the system will attempt to achieve when a threshold was breached for the defined observation time;
- **Release zone**: The area between release lower and release upper defining the limits that the system may release between;
- **Lower thresholds**: Two thresholds were defined to be of lower voltage than release lower. The priority of the threshold was inversely proportional to the value of the threshold;
- **Upper thresholds**: Two thresholds were defined to be of higher voltage than release upper. The priority of the threshold was directly proportional to the value of the threshold.
- **Normal zone**: The area indicating that no thresholds were being breached bounded by the lowest upper threshold and the highest lower threshold. The release zone will always be contained wholly within the normal zone;
Figure 27: Active Voltage Management thresholds

The set-point calculation was based on determining the reactive power curtailment and, if required, real power curtailment to reach the voltage target value. The formula for reactive set-point calculation is given in Appendix 8.

A voltage constraint scenario in the March Grid network was used in the experiment using a combination of live measurements from UK Power Networks RTUs and simulated generators. The following method was followed during the simulation:

1. Any constraints in the simulation were removed;
2. Simulated firm generation was increased to breach the MP first upper threshold;
3. DG was regulated using reactive and real power control;
4. Once the MP release zone was reached, the DG was released
5. Set points were issued to bring the voltage to the release upper threshold;
6. The constraint simulation was cleared; and
7. All DG was fully released.

One firm generator and one flexible generator were simulated in this scenario. Each had an associated sgs connect that simulates generator real power output and circuit breaker indications.
What were the trial findings?

Figure 22 shows the response of the ANM system to the breach of the MP upper 1 threshold. The voltage at the MP breached the upper 1 threshold of 35kV at 13:01:34 for 31 seconds. Following the breach of the upper 1 threshold, the sgs voltage application calculated and issued curtailment required to reduce the voltage observed at the MP to the target threshold. The real and reactive power set points were issued to the DG and the power output of the DG reduced in response to its new set points. Upon the voltage at the MP remaining below the target threshold for 21 seconds, the ANM scheme released the real power first and then the reactive power. The reactive power was only released after the real power was fully released.

![Figure 28: Time evolution graph for DG management based on voltage thresholds](image)

The sgs voltage application controlled the real and reactive power to bring the voltage at the MP to a value below the limit established by the ANM thresholds. The active voltage management application adopted a priority to reduce the generator’s reactive power and, only if this was not enough to bring the voltage below the target value, then it started to reduce the generator’s real power output. This, therefore, ensured that real power generation curtailment is kept to a minimum at all times.
The key learning generated was that ANM can be used to maintain voltage levels within statutory limits by actively managing the real and reactive power of DG.

6.2 The capabilities, limits and requirements of Quadrature-booster (phase shifting transformers) as part of an active voltage management application.

What were the objectives and challenges?

The objective of this experiment was to test and confirm the feasibility of using a Quadrature-booster to control voltages on a typical Great Britain 33kV distribution network.

The challenge for the experiment was to establish a method to test the capability of the Quadrature-booster as a tool for voltage management functionality on the installed 33kV trial network. A method could not be established to test this approach using the Quadrature-booster in the live network, hence desktop modelling and study was carried out to test the hypothesis.

The requirement of the experiment was to identify voltage sensitivity factors caused by Quadrature-booster varying power flow.

How was the trial conducted?

Desktop simulations studies were defined that explored how the Quadrature-booster could be used instead of, or in combination with, other methods to actively manage network voltage constraints. Voltage sensitivity studies were carried out on the interconnected 33kV and 11kV network at the inception of the FPP project and after the Quadrature-booster was commissioned. The Quadrature-booster operation in its real-world location was studied using two approaches using real-life characteristics of the installed Quadrature-booster:

- **Use of modelling data** – the Power Factory simulation tool from DigSILENT was used to run steady state load flows and on an assumption of maximum generation plus minimum summer network load. After running load flows on the existing network (Quadrature-booster on by-pass), the transformer taps for the rest of the network transformers were fixed at the optimum levels reached when the load flows converged. The busbar volts were recorded. This was used as a baseline to compare the recorded voltage with the Quadrature-booster at various tap positions.

- **Use of Power Quality Monitoring data** – to capture actual network behaviour and the Quadrature-booster voltage influence at times of tap change. The percentage busbar 33kV voltage level step changes (at substations interconnected with Wissington 33kV substation) were recorded under the following scenarios when the Quadrature-booster changed tap position:

  1. Tap10: change in voltage from network without Quadrature-booster to network with Quadrature-booster in line and placed at Tap10
  2. Tap11: % change in p.u. voltage with tap change from Tap10 to Tap11
  3. Tap12: % change in p.u. voltage with tap change from Tap11 to Tap12
  4. Tap13: % change in p.u. voltage with tap change from Tap12 to Tap13
5. Tap14: % change in p.u. voltage with tap change from Tap13 to Tap14

The simulations show that the biggest change at all studied sites within the interconnected 33kV/11kV networks occurs on transition from network with no Quadrature-booster (on by-pass) to Quadrature-booster connected and placed at Tap10. The biggest change of approximately -3% is recorded at Wissington, Southery and Littleport.

What were the trial findings?

The results showed that Quadrature-booster is more effective when utilised on power flow control compared to voltage control. The voltage change with each tap change was found to be negligible. The power flow management using the Quadrature-booster is covered in section 4.3.2.

The key learning generated was the outcome of the investigation to test if a Quadrature-booster can be used as a voltage management tool. This was only possible to be investigated by carrying out network modelling and desktop study as no immediate opportunity was available to run real-world testing, i.e. have instructions flowing from ANM to the Quadrature-booster.

6.3 Demonstrate the value of Quadrature-Booster control when deployed with an active voltage management application.

As concluded in section 5.3.2, the use of a Quadrature-booster modelled, in the trial 33kV network is not effective as part of a voltage control application. Hence, no value could be demonstrated in deploying Quadrature-booster control with an active voltage management application.

6.4 The capabilities, limits, requirements and value of transformer tap changer relays as part of an active voltage management application.

What were the objectives and challenges?

The main objective was to mitigate voltage constraints on the network contributed by the introduction of DG. The trial also addressed the challenges to optimise voltage control profile and minimise circulating current flow on the 33kV and 11kV distribution networks. Smart algorithms needed to be developed for this purpose and hosted in ANM platform.

The objective of the 33kV control algorithm was to update the voltage set points on two parallel Fundamental SuperTAPP N+ relays at a 132/33kV grid substation. The principal function of this algorithm was therefore to check the voltage set-point of each relay and maintain both relays with the same voltage set-point value.

The objective of the 11kV control algorithm was to update the load ratio on two parallel Fundamental SuperTAPP N+ relays at a 33/11kV primary substation. The principal function of this algorithm was to check the load ratio of each transformer relay and maintain both relays with the same load ratio value.
The trial set out the following objectives in order to demonstrate this concept:

- Assess the possible interaction between the local and centralised voltage regulation strategies;
- Accommodate remote measurements of voltage within the voltage control scheme using ANM and SuperTAPP n+ relay;
- Implement voltage control algorithms on ANM software platform;
- Demonstrate functionality of the system which can be employed on wider 33kV interconnected network with significant amount of DG;
- Demonstrate functionality of the system which can be employed on a typical primary substation with significant amount of DG;
- Assess complexity and challenges of implementing IEC 61850 for AVC schemes; and
- Demonstrate more robust, reliable and more accurate voltage control solution.

How was the trial conducted?

The trial has been designed to implement enhanced voltage control scheme on the existing SuperTAPP n+ relays by incorporating remote measurements on the network using IEC 61850 communications over the RF mesh network.

The trial was undertaken in three main stages: desktop simulation, off-line trial and on-line trial. Desktop studies provided an initial assessment of the proposed solution and potential challenges. When all the equipment installed and commissioned the off-line simulation was performed. With the use of real data and implemented algorithms the evaluation of the impact of the system on the network profile and performance of the voltage control schemes was evaluated. After satisfactory results of the off-line evaluation stage the system enabled and performance of the scheme was monitor for the remaining time of the trial.

Two separate trials were conducted, one at 33kV and one at 11kV voltage levels.

March Grid 33kV trial

This involved updating/sending the basic voltage target via IEC61850 from ANM to SuperTAPP n+ relay. The voltage set-point at the transformer relay was updated periodically based on algorithm hosted by the ANM. The algorithm is summarised by the flowchart in Figure 29 and the architecture is presented in Appendix 4.
The calculation of the required voltage target was based on an estimation of the maximum voltage drop on selected feeders within the interconnected 33kV network and choosing the feeder with the highest voltage drop. This feeder was then used as the representative load to calculate the required voltage boost and optimal voltage target which can be sent to all grid substations.

In order to demonstrate functionality of this ANM solution the voltage target was calculated and updated only at the March Grid substation. However it was designed to be easily extended to manage the wider interconnected 33kV network, including Swaffham, Hempton, Kings Lynn and Walsoken grid substations.

The functionality of the implemented algorithm was validated against an off-line spreadsheet-based tool developed by Fundamentals. The functional testing uses the following test cases:

- Test Case 1 – Maximum Load, No DG
- Test Case 2 – Maximum Load, Maximum DG
- Test Case 3 – Minimum Load, No DG
- Test Case 4 – Minimum Load, Maximum DG

The tool defined a set of input measurements and bandwidth ranges for each test case and produced the results. The algorithm was then tested against live measurements from March Grid substation for a period of more than seven days and the results were examined to validate that the calculated control actions were expected and within limits.

**March Primary 11kV trial**

This involved updating/sending "Load Ratio" via IEC61850 from ANM to SuperTAPP n+ relays, based on real generator output measurements. The "Load Ratio" on the relay was updated every 30 minutes by
averaging the load ratio calculations done every 60 seconds by the ANM or when the load ratio calculated by the ANM breaches a deadband. The algorithm is summarised by the flowchart in Figure 30 and the architecture is presented in Appendix 5.

![Figure 30: 11kV load ratio calculation](image)

In standard scheme, the SuperTAPPn+ relays used a fixed value for the load ratio parameter to determine the voltage target at the primary substation and eventually, the transformer tap position. This fixed value is calculated offline using data from a period that reflects different loading and generation conditions for particular 33/11kV feeders.

By gathering remote generator and feeder measurements and hosting a load ratio calculation algorithm, the ANM enabled the relays to be kept up to date with load ratio values that reflect current network conditions. To safeguard against erroneous or missing measurements, an average load ratio value was derived from measurements taken every 60 seconds over a 30 minutes time period.

The load ratio algorithm was updated when a particular deadband was exceeded, by the calculation that was done every 60 seconds, or every 30 minutes, thus maintaining a load ratio value suitable for current network loading and generator power injections. The functionality of the implemented algorithm was validated against an off-line spreadsheet-based tool provided by Fundamentals Ltd. The spreadsheet tool provided four test cases with various settings, with load and generation conditions defined for each. Test case 1 (A and B) was used as a basic test of the calculations whereas test cases 2 and 3 were performed with the purpose of testing the algorithm’s accuracy with different settings and resilience for mismatched measurements.

Upon completion of functional testing the algorithm was integrated within the FPP pre-production environment. The test environment allowed the algorithm to be tested against live measurements from
March Primary substation. The algorithm was left to run for a period of more than seven days and the results were examined to validate that the calculated control actions were expected and within limits.

**What were the trial findings?**

It was demonstrated from the results of the trial that the voltage profile could be optimised on the 33kV and 11kV network by coordinating ANM with the tap changer relays. The trial also proved successful coordination between two vendor solutions from SGS and Fundamentals using IEC 61850 standard. It was highlighted that reliable and consistent communication between ANM and AVC schemes as well as remote measurements was extremely important to maintain a stable system.

The key learning generated was the enhancement in the AVC scheme by coordinating transformer tap changer relays with ANM application. The tap changer relays conventionally perform AVC functionality within the boundary of the substation. The experiment successfully tested the philosophy of using a centrally located ANM application to monitor the impact of the distributed generation in the network and send an optimum voltage target and optimum load ratio to the remote AVC relays. A set of smart algorithms were developed and implemented in the ANM to estimate distributed generation output and total network load based on local substation measurements.

6.5 **The capabilities and limits of the communications platform to support the evolving needs of active voltage management**

This learning has been demonstrated by repeating the experiments carried out for the Active Power Flow management described in detail within section 4.3.7. Identical results were seen for both applications highlighting the same requirements for the communications platform irrespective of the application on ANM system.

6.6 **Demonstrate the value of active voltage management and active power flow management coordination.**

**What were the objectives and challenges?**

The objective was to demonstrate that the ANM system is able to co-ordinate real and reactive power control of DG to manage thermal and voltage constraints simultaneously. This tested the scenario when both the active power flow management and active voltage management applications were required to control the same devices and in this situation there needed to be a requirement for arbitration between the applications. This approach to arbitration will also be necessary to ensure that the operation of either application does not pose an operational challenge to the other, e.g. the action of one application should not result in unnecessary action of the other.
How was the trial conducted?

The success measure was based on the ANM system’s ability to issue real and reactive power set-points that remove the constraints identified by the trim and upper threshold breaches; and its compliance with the list of ANM system performance indicators. The following indicators were used to establish if the ANM system was performing correctly:

- Time that ANM took to issue a set-point after the trim/upper threshold was breached
- Communications delay
- Time duration to reduce the power flow/voltage measured from trim/upper threshold to below reset/target threshold
- Generation release duration to reach trim less/release higher thresholds.

What were the trial findings?

The coordination of two applications was achieved by calculating the set-points required to solve both constraints, by two distinct control processes (sgs voltage and sgs power flow), and issuing the most restrictive of those set-points. The advantage of approach was that it was simple and provided a conservative approach to mitigate voltage and power flow breaches.

The key learning generated was the demonstration of capability of the ANM system to carry out simultaneous management of voltage and power flow constraints, enabling the system to be manage the network more efficiently.

7 Additional Learning outcomes

7.1 The potential capabilities and limits of energy storage on 33kV networks in the FPP area.

What were the objectives and challenges?

The objective of this Use Case was to explore the potential capabilities of the energy storage in the FPP trial area. A desktop study was carried out to prove that energy storage can offer additional flexibility used with an ANM system to manage flexible connections and potentially reduce the level of their overall curtailment. The power and energy capabilities of the energy storage device in the Smarter Network Storage (SNS) project (i.e. 6MW/10MWh) were used.

Background to SNS project

UK Power Networks was awarded funding for another LCNF Tier 2 LCNF proposal, the SNS project, which commenced in 2013 and will be concluded at the end of 2016. The SNS project involves the installation of a 6MW/10MWh energy storage system at Leighton Buzzard Primary Substation in Bedfordshire, and associated hardware and software infrastructure to deliver important learning on the integration of storage into distribution networks. The SNS project builds on the experience acquired through the initial LCNF Tier 1 storage project of UK Power Networks at Hemsby and aims to trial a number of applications from energy...
storage systems including peak shaving and reactive power support to the DNO, response and reserve services to the Transmission System Operator, tolling services to energy suppliers, but also coordinate the delivery of all these services in an optimal way to improve the current business case while maintaining security of supply for the local network.

How was the trial conducted?
A curtailment assessment tool that enables the estimation of curtailment of generators was used. The effect of energy storage on the level of curtailment was assessed.

What were the trial findings?
Six case studies were defined to evaluate the effect of energy storage on the curtailment of FPP generators.

The sensitivity of that effect on micro-generation (mGen) penetration was evaluated using the three mGen penetration levels. The parameters used in all six case studies and the description of the case studies are provided in Appendix 7.

The effect of energy storage use on the curtailment of FPP generators can be shown in the following time series extract with data for the year 2011.

![Figure 31: Effect of energy storage on curtailment of FPP generators](image)
The 5-year simulation showed that energy storage was able to reduce the curtailment of FPP generators. In the absence of micro-generators, the energy storage was found to reduce the curtailment from 2,914MWh to 1,647MWh, which translates to a reduction of 1,267MWh or 43.48%. In the case of 8.374MW of mGen penetration, the energy storage was found to reduce the curtailment from 5,221MWh to 3,318MWh, which translates to a reduction of 1,903MWh or 36.45%. In the case of 11.853MW of mGen penetration, the energy storage was found to reduce the curtailment from 6,522MWh to 4,350MWh, which translates to a reduction of 2,172MWh or 33.3%. The reduction of the curtailment (in MWh) was increased with the use of storage. However the percentage reduction was shown to be reduced due to the capacity of the storage system.

The conversion losses in the energy storage system were found to increase with the increase of mGen sources, due to the higher storage utilisation. It was important to note however that the utilisation of storage was found to be below 2% for all three mGen levels. This finding suggests that the storage would be underutilised allowing more than 98% of the time available to provide other services such as energy market participation (e.g. short/long-term electricity market participation) or ancillary services (e.g. reserve, response) to the Transmission System Operator.

Table 8: Curtailment cost reduction using storage

<table>
<thead>
<tr>
<th>SNS Installed Cost (£)</th>
<th>Years of storage system’s life</th>
<th>Average Curtailment cost(£/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>£11,200,000.00</td>
<td>20</td>
<td>124.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curtailment reduction from storage</th>
<th>Energy (MWh)</th>
<th>Curtailment Cost Reduction (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No mGen</td>
<td>1267</td>
<td>157,420.14</td>
</tr>
<tr>
<td>8.374MW mGen</td>
<td>1903</td>
<td>236,440.83</td>
</tr>
<tr>
<td>11.853MW mGen</td>
<td>2172</td>
<td>269,863.10</td>
</tr>
</tbody>
</table>

The average curtailment cost of the accepted generators for flexible connections in the FPP area is £124.2/MWh. In the three scenarios used above (i.e. no mGen, 8.3MW mGen and 11.8MW mGen), it can

14 The term utilisation is used here to express the percentage of half-hourly times that the storage is used for the curtailment service, either charging or discharging
be calculated that the curtailment cost reduction from using the storage for minimising the curtailment is £157.4k, £236.4k and £269.9k respectively.

The capital expenditure (CAPEX) and operational expenditure (OPEX) for providing the curtailment minimisation service are estimated. Although the utilisation of storage as seen above (Figure 32) does not exceed 2%, it has been assumed that the storage would be reserved for one hour per day to provide this service; this equates to 4.16% and this assumption is based on:

- the current scheduling system of SNS operates in half-hourly periods (i.e. the storage system can either charge or discharge during a half-hourly period); and
- the curtailment minimisation function has been assumed to allow the storage absorb energy when required to minimise curtailment and supply that energy back as soon as possible, keeping the constrained asset within acceptable operating limits.

The installed cost of the storage system within SNS project is £11.2million. Assuming that the lifetime of the storage device will be 20 years, the contribution to the CAPEX cost is £116.6k for the 5-year simulated period.

The OPEX for the 5-year period has been calculated using the fraction of the time reserved for the service (i.e. one hour per day) on total availability related charges (these include availability, standing and metering charges) and the total utilisation-related charges from charging and discharging the device for 60 minutes each day (these include Distribution Use of System (DUoS), energy charges, Balancing Use of System (BUoS), and the remaining charges that are typically included in an energy bill). The resulting OPEX is £187,5k.

The key learning outcomes are summarised as follows:

- Energy storage can be used to reduce curtailment of FPP generators. The case studies conducted showed that a storage device equivalent to SNS, if installed in March Grid, could reduce the curtailment of generators of up to 43.5%.
- The utilisation of storage for reducing curtailment would be very low. In the March Grid area, curtailment would be required only for short periods that account for approximately 2% of the time. Delivery of other services could be considered in the remaining time.
- The power and energy characteristics of the storage need to be carefully considered. The higher the power and energy characteristics, the lower the curtailment.
- The use of storage for reducing curtailment of generators is expensive due to currently high CAPEX and OPEX. The benefit of this reduced curtailment sits with the generators, and hence storage is most appropriately considered by the developer/generators as part of their overall project business case. In a similar model to that being explored in the SNS project, a full cost-benefit analysis could consider the conflicts and synergies with other services (with their characteristics) that could be provided by the storage device alongside curtailment reduction, which could increase the potential revenue to offset this high CAPEX. The extent to which this business model could be viable would depend on a number of factors, such as connection constraints, curtailment levels and PPA arrangements and therefore need specific assessment by developers as part of an integrated business case.
### 7.2 Variation of DG connection scenarios

The trial learnt that the connection of DG will not always be a standard design as it depends on the other elements associated with the POC such as network load and firm generator. Many of the accepted FPP customers have existing firm generation and load connected on the same site. The majority of customers request that they connect their new flexible connection behind the same utility meter and therefore avoid the costs associated with a new point of connection to the UK Power Networks electricity network. This approach introduced complications in considering the resultant effect of the existing load or generation, or both. An approach was taken by the project to ensure that the customer controls the generation and export of the overall site against the existing generation and load to avoid complications.

The connection design variations can be categorised in four scenarios

**Scenario A: A new DG connection**

This is a standard scenario where a developer requests for a new power export DG connection to the DNO on a new POC

**Scenario B: Upgrade of an existing firm DG connection**

This is a scenario where an existing firm DG customer requests for additional export capacity. This can fall into two options.

- **Scenario B1:** The first option involves the provision of a separate metering circuit breaker to control the flexible connection.
- **Scenario B2:** The second option utilises the existing metering circuit breaker to control both the firm and non-firm generation. The DG customer is expected to understand and accept the possibility of the loss of total export capacity including firm and non-firm generation during abnormal network conditions

**Scenario C: Addition of export on an existing load connection**

This is a scenario where an existing load customer requests to install export capacity utilising the existing load connection infrastructure without a new POC. The delivery of this additional capacity is achieved using an flexible connection. This is expected to be for small generation sizes typically below 500kW. In this case, the ANM directly controls a given circuit breaker to implement the flexible connection.

**Scenario D: Addition of export on an existing load and firm DG connection**

This scenario is the combination of scenarios B and C.

### 7.3 Cyber security considerations for DG integration

Smart grid systems are complex systems which require careful design and management to ensure that they are resilient and robust. This requirement for care also extends to cyber security given the highly
interconnected and ICT dependent nature of these systems. The approach to smart grid cyber security for the FPP project was established at an early stage in the project, and sought to embed cyber security into the early stages of the project lifecycle itself. The cyber security management for the FPP solution was achieved largely by incorporating security related activities through the lifecycle of development, deployment and operation of the project.

As part of the cyber security management process, a security assessment was carried out on the as-built technical solution, including the security risk assessment on the communications interface of the ANM with the first connected generator. It highlighted a very limited isolation between the ANM and an untrusted network (i.e. the customer’s corporate LAN and beyond which the DNO does not have visibility). It was concluded that if the interface between the ANM and the customer’s generator controller is via Ethernet, an additional layer of security between the ANM local controller (sgs connect) and the customer’s generator controller is required. This was achieved by the deployment of an industrial Ethernet switch with security controls designed to isolate networks and restrict traffic to specific protocols and pre-defined IP addresses.

7.4 Integration of the ANM with UK Power Networks RTU

In order to maintain the fail safe feature in the ANM solution, the DG circuit breaker control interface of the sgs connect has been kept separate to the DG power management interface. This allows for the ANM to disconnect the DG connection under abnormal scenarios where the DG control system fails to respond to ANM instructions.

Where there is a UK Power Networks RTU available, the ANM instructs the RTU to carry out breaker control in order to avoid potential conflict of simultaneous control messages coming from RTU and ANM. Further security functionalities were developed on the UK Power Networks RTU to ensure the SCADA control message was given a priority should there be a simultaneous control instruction from SCADA and ANM.

7.5 System integration with IEC 61850

The ANM system required to interface with a range of “smart devices”, such as QBCS, DLR, AVC and RTUs. Integration time was greatly reduced when considering the alternative communication protocols such as DNP3, MODBUS and IEC 60870. The ANM system could send and receive data to all smart devices with less than an hour of integration time. As a specific example the DLR relay device proved more challenging to integrate with the ANM system than the other smart devices. The DLR relay required a specific set of actions to be taken before data could be transferred to/from the ANM system. Through troubleshooting this unexpected behaviour a greater understanding of IEC 61850 was gained in particular an appreciation of the different data reporting mechanisms. Although a specific issue with regards to the DLR relay has been highlighted, the general integration with third party devices using IEC 61850 has been a great success, primarily in terms of greatly reduced systems integration and commissioning effort.
7.6 Integration of DG control system with the ANM

There was a considerable amount of learning associated with the overall process of designing the DG interface and integrating it with the ANM solution. It should be noted that due to the variation of the control system technologies used by DG customers, it is likely for the ANM system to encounter issues in integrating with an un-tested platform. In earlier instances, there were challenges in finalising all the required interface details by the commissioning date due to a number of reasons such as:

- A lack of full clarity of DG control system characteristics and requirements;
- A lack of sufficient technical documentsations on customer's network; and
- Availability of the DG control system provider for testing and troubleshooting.

The above issues led to delays in the commissioning of the generator and consequently repeated visits to site. This highlighted the need to ensure that the all details regarding the interface between the ANM system and the DG control system must be agreed before beginning commissioning. The following learning outcomes were generated and were implemented for the future commissioning procedure:

1) To minimise the possibility of any technical issues that could affect commissioning, where feasible, bench testing of all interfaces need to be carried out prior to final commissioning on site with the generators control unit. Where bench testing is not possible, cold commissioning should be undertaken prior to full commissioning. This is an activity that can be completed remotely, and could identify any potential issues that could be fixed prior to the full generation commissioning day;

2) To ensure any potential technical issues that are raised during the final commissioning day can be resolved on the day, the DG customers control unit engineer needs to be present on site for the whole commissioning day. This ensures any issues with their control equipment can be dealt with quickly and preferably on the same day; and

3) There is the need to standardise the communications protocols that are used for interfacing with the generators control system. This can be achieved to a certain extent but as there are a large number of different control systems supporting different protocols, standardisation will take time.

7.7 Deployment of DLR technology

The objective of the DLR trial in the FPP project was to increase the utilisation (where possible) of the existing 33kV overhead lines at a lower cost compared to traditional conductor replacement, and to expedite the development of baseline DLR package for deployment elsewhere on the network as required. The trial utilised previous experiences from various trials of the weather based DLR systems, focusing on those undertaken within the UK. Particular reference was made to the Western Power Distribution (formerly E.ON Central Networks) trial of a weather based DLR system, which was installed on a 132kV circuit from Skegness to Boston.

The DLR trial focused on identifying suitable considerations for the design, installation, configuration and management processes associated with the implementation of indirect weather based DLR systems. This was achieved by installing a number of DLR systems across the Flexible Plug and Play area so as to gain an understanding of the installation requirements, typical system architecture and configuration requirements.
Each of the DLR systems consisted of the following components:

- An Alstom Micom P341 relay; and
- A Lufft WS501-UMB weather station complete with a digital to analogue converter;

In addition to the core system components, an Alstom BiTRONICS M871 Data Logger was also installed to provide a means of storing the data collected as part of the trial.

The main configurable elements of the DLR system revolved around the manipulation of the inputs from the weather station. Initial assumptions, based on recommendations from previous projects, were used to initially configure the system. These were further analysed to validate the approach and to identify opportunities to optimise the system and was achieved by comparing the weather data collected from each of the trial sites to identify the correlation and variance between the datasets. The summary of this comparison is as follows:

- The ambient temperature was found to highly correlate across the sites and was only subject to small changes.
- For the wind velocity it was found that a 30 minute rolling average for the wind velocity would enable ampacity comparisons to continue at an appropriate level of precision. However, improvements in the correlation peaked for a 10 minute rolling average.
- For the wind direction, there was a considerable smaller correlation across the site, which justified the approach to applying a fixed wind direction.

Based on this assessment, the final DLR system settings were:

- Wind Direction: 20°
- Solar radiation: 890 W/m²
- Wind Velocity: 10 minute rolling average
- Ambient temperature: 1 minute rolling average

In addition to the system settings, a recommended approach was identified to account for variations in weather conditions across the line. This approach included the installation of multiple weather stations at appropriate intervals along the line under consideration. The ampacity would be calculated at each location, with the values compared within the ANM system. The ANM system would subsequently utilise the smallest ampacity calculated when determining the necessary levels of curtailment of the connected distributed generation.

Considering this approach, and limiting the maximum permissible ampacity to 600A to align with the general circuit restrictions in the area, the additional capacity that could be made available through the implementation of this system was 47%. This increase was limited by the maximum permissible ampacity, with a further summary of the additional headroom that could be created through the implementation of the DLR system contained in Table 8. This additional capacity would exceed that which could be achieved by increasing the operating conductor temperature to 65°C and would mitigate any risks associated with operating the overhead line near its operational capacity.
Table 8: Summary of additional headroom that could be made available using the minimum calculated ampacity

<table>
<thead>
<tr>
<th></th>
<th>Average increase in ampacity (%)</th>
<th>Additional capacity (GWh)</th>
<th>Additional capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum ampacity</td>
<td>14.0</td>
<td>30.1</td>
<td>47</td>
</tr>
</tbody>
</table>

Using this approach there would be no known excursions from the calculated ampacity values, although it should be noted that there is still a risk that this does not fully represent the ampacity across the entire circuit. Further details on the DLR trial are described within a separate DLR trial report.
8. Key findings and lessons learnt from the overall FPP project trial

ANM Platform
- The FPP trial developed a capability of adding new generators onto the SGS ANM system without a need for system restart which was one of the constraints of the solution.
- The FPP trial also developed functionality for the time stamp data from site to be sent to the PI historian logs that was not previously available.

Communications Platform:
- Learning generated on designing, managing and testing RF mesh technology for distribution network.
- The project learnt that the RF mesh network improved its performance with the increase of its node density. That means more devices participate on the mesh the better the performance is, hence suitable for large scale deployments.
- IPv4 and IPv6: Both can be implemented in a same solution and can enable host of applications and technologies.

System Integration:
- Availability of test lab environment for the life cycle of innovation and trial projects is hugely beneficial to troubleshoot, test and enhance the functionality.
- Initial understanding of IEC 61850 standard and design process was challenging but cost and time savings were demonstrated during commissioning and upgrade process.

Smart Grid cyber Security:
- Implementation of cyber security is a process not a product. Once designed and tested, every solution needs to periodically assess for cyber security compliance.
- Cyber security is a complex and a specialist field for which smart grid designers and operators may not have adequate knowledge. A Smart Grid Cyber Security framework can help to a certain extent in providing guidance in understanding when and what security considerations should be made within a project life cycle.
- The risk management is one of the major elements of managing cyber security and it requires a different approach compared to traditional risk assessment in IT systems, due to the highly distributed nature of smart grid systems.
9. Conclusion

As an output of the FPP trials, ANM has been proven to be an effective tool to actively manage DG not only as a standalone solution but also when it is integrated with other smart solutions. The active power flow and active voltage management applications were capable of integrating and coordinating with existing and new solutions using open-standard protocols in order to make more accurate and smart decisions to enable efficient utilisation of existing network assets and to deliver additional capacity.

The capability of the ANM to simultaneously manage multiple constraints as well as various network running arrangements can create further opportunities for DNOs to relieve the additional pinch points in the network, removing barriers to the connection of DG.

A number of benefits are highlighted within this report related to the FPP’s approach of implementing a central ANM system installed at a control centre environment with direct interaction with network control and SCADA systems. This centrally managed approach has demonstrated the benefits of:

- offering a more holistic view of the network when several generator contribute the same constraint for instance;
- increasing the option for scalability to accommodate a growing demand in terms of DG connection;
- providing a centrally controlled platform for efficient operations and maintenance; and
- providing the flexibility to easily integrate and interact with other smart grid technologies by using standardised methods.
Appendix 1 – FPP communications architecture
Appendix 2 – Power flow thresholds equations

Global Trip operating margin equation

\[ OM_{GlobalTrip} = \left( \frac{dP_{existing,up,max}}{dt} + \frac{dP_{NFG,up,max}}{dt} \right) \times (TD_{GlobalTrip} + TT) \]

Equation 1 – Global Trip Operating Margin

Where,

\[ \frac{dP_{existing,up,max}}{dt} = \text{Practical maximum ramp up rate associated with the constraint (MP) from existing generation} \]

\[ \frac{dP_{NFG,up,max}}{dt} = \text{Practical maximum ramp up rate associated with the constraint (MP) from NFG (MW/s)} \]

\[ TD_{GlobalTrip} = \text{Time taken by the system to measure and process the threshold breach as well as an observation delay specific to the Global Trip Operating Margin (seconds)} \]

\[ TT = \text{Global Trip action time (seconds).} \]

Sequential Trip operating margin equation

\[ OM_{SequentialTrip} = \left( \frac{dP_{existing,up}}{dt} + \frac{dP_{NFG,up}}{dt} \right) \times (TD_{SequentialTrip} + ST) \]

Equation 2 – Sequential Trip Operating Margin

Where,

\[ \frac{dP_{existing,up}}{dt} = \text{Operator defined ramp up rate at the power export level of the operating margin from existing generation associated with the constraint (MP) (MW/s)} \]

\[ \frac{dP_{NFG,up}}{dt} = \text{Operator defined ramp up rate at the power export level of the operating margin from NFG associated with the constraint (MP) (MW/s)} \]

\[ TD_{SequentialTrip} = \text{Time taken by the system to measure and process the threshold breach as well as an observation delay specific to the Sequential Trip Operating Margin (seconds)} \]

\[ ST = \text{Sequential Trip action time (seconds).} \]
Trim operating margin equation

\[
OM_{trim} = \left[ \left( \frac{dP_{existingup}}{dt} + \frac{dP_{NFG,up}}{dt} \right) \times (TD_{trim} + RTD) \right] + \left[ \left( \frac{dP_{existingup}}{dt} - \frac{dP_{NFG,down}}{dt} \right) \times RTF \right]
\]

Equation 3 – Trim Operating Margin

Where,
\[
\frac{dP_{existingup}}{dt} = \text{Operator defined ramp up rate at the power export level of the operating margin from existing generation associated with the constraint (MP) (MW/s)};
\]
\[
\frac{dP_{NFG,up}}{dt} = \text{Operator defined ramp up rate at the power export level of the operating margin from NFG associated with the constraint (MP) (MW/s)};
\]
\[
TD_{trim} = \text{Time taken by the system to measure and process the threshold breach as well as an observation delay specific to the Trim Operating Margin (seconds)};
\]
\[
RTD = \text{Trim action time (seconds)};
\]
\[
\frac{dP_{NFG,down}}{dt} = \text{Ramp down rate of NFG caused by the trim action (MW/s)};
\]
\[
RTF = \text{Time allowed for NFG to respond before system recalculates NFG set-points (seconds)}.
\]

Appendix 3 – sgs ratings vs DLR relay

Table 9: Table of results comparing sgs ratings and DLR relay

<table>
<thead>
<tr>
<th>Percentile</th>
<th>DLR relay rating [MVA]</th>
<th>sgs ratings rating [MVA]</th>
<th>sgs ratings / DLR relay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>19.32</td>
<td>19.65</td>
<td>1.02</td>
</tr>
<tr>
<td>10%</td>
<td>19.65</td>
<td>26.43</td>
<td>1.34</td>
</tr>
<tr>
<td>20%</td>
<td>20.03</td>
<td>27.67</td>
<td>1.38</td>
</tr>
<tr>
<td>30%</td>
<td>20.36</td>
<td>28.51</td>
<td>1.40</td>
</tr>
<tr>
<td>40%</td>
<td>20.70</td>
<td>29.22</td>
<td>1.41</td>
</tr>
<tr>
<td>50%</td>
<td>21.07</td>
<td>29.83</td>
<td>1.42</td>
</tr>
<tr>
<td>60%</td>
<td>21.49</td>
<td>30.49</td>
<td>1.42</td>
</tr>
<tr>
<td>70%</td>
<td>22.03</td>
<td>31.15</td>
<td>1.41</td>
</tr>
<tr>
<td>80%</td>
<td>22.76</td>
<td>31.91</td>
<td>1.40</td>
</tr>
<tr>
<td>90%</td>
<td>23.88</td>
<td>32.97</td>
<td>1.38</td>
</tr>
<tr>
<td>100%</td>
<td>31.00</td>
<td>39.42</td>
<td>1.27</td>
</tr>
</tbody>
</table>
Appendix 4 – 33kV AVC trial diagram
Appendix 6 – Energy Balance equation

The conductor thermal rating as part of the sgs rating application, was calculated from the energy balance between heat dissipated by the Joule effect within the conductor and the heat exchange on the conductor surface, as influenced by environmental parameters and represented by the steady state energy balance equation given below,

$$Q_c + Q_r - Q_s = I^2 * R(T_c)$$

Where:
- $Q_c$ [W/m] - Convective heat exchange
- $Q_r$ [W/m] - Radiative heat exchange
- $Q_s$ [W/m] - Solar gain
- $I$ [A] - Current flowing in the conductor
- $R(T_c)$ [Ω/m] - Conductor electrical resistance at specified conductor temperature
- $T_c$ [°C] - Conductor temperature
Appendix 7 – Table for Energy storage case analysis

<table>
<thead>
<tr>
<th>Parameters used in all Cases</th>
<th>Reverse Power Flow Limit [MVA]</th>
<th>ANM Export Limit [MVA]</th>
<th>ANM Operating Margin</th>
<th>Average Sensitivity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any other FPP Generators</td>
<td>45</td>
<td>40.5</td>
<td>10.00 %</td>
<td>0.887 2</td>
</tr>
<tr>
<td>Wind Turbine Generators (MW)</td>
<td>0.5</td>
<td>21.5</td>
<td>11.5</td>
<td>33.5</td>
</tr>
<tr>
<td>PV Generation (MW)</td>
<td>33.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case Studies Description</th>
<th>Case 1 – No storage No mGen</th>
<th>Case 3 – No Storage 8.374 MW PV mGen</th>
<th>Case 5 – No Storage 11.853 MW PV mGen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2 – SNS storage No mGen</td>
<td>Case 4 – SNS Storage 8.374 MW PV mGen</td>
<td>Case 6 – SNS Storage 11.853 MW PV mGen</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 8 – Formulae

Timing criteria calculation for Real powerflow threshold

The criteria of 68 seconds to reduce the power flow from TRIM threshold to below RESET threshold, was computed using the formulae.

\[
\text{Time} = \text{Trim}_{\text{observation time}} + \text{Communications Delay} + \Delta/R
\]

Where,
- \( \text{Trim}_{\text{observation time}} \), time from breach to issuing a setpoint after
- \( \text{Communications Delay} \), time from the issue of setpoint to feedback of power reduction
- \( \Delta \) is the requested step change in generator power output,
- \( R \) is the generator ramp rate

Similarly, a criteria of 260 seconds was established to increase the power flow to reach the TRIM LESS threshold using the formula.

\[
\text{Time} = \text{Steps} \times \text{Step}_{\text{observation time}}
\]

Where,
- \( \text{Steps} \), consists of the number of steps required for the system reach the TRIM LESS
- \( \text{Step}_{\text{observation time}} \), is the amount of time that the system waits for the setpoint to be reached

Real Power control setpoint calculation

The real power setpoint required to solve the voltage breach can be calculated using the following equation:

\[
\text{Setpoint} = P_a - \left( \frac{P_a}{P_a + P_b + P_c} \right) \times \Delta \times SF
\]

- \( P_a \) – Represents the generator power output
- \( P_a + P_b + P_c \) – Represents the summation of power output of all generators under the Shared PoA contributing to the breach
- \( \Delta \) – Represents the existing power flow at the constraint minus the target power flow at the constraint, where the target is the RESET LESS threshold
- \( SF \) – Represents the sensitivity factor. In this work the sensitivity factor is equal to 1 kW/kW.

The generator setpoint when a release is required to determined by the following equation:

\[
\text{Setpoint} = (S_{P_a} - \left( \frac{RP_a}{RP_a + RP_b + RP_c} \right) \times \Delta) \times SF
\]

- \( S_{P_a} \) – Represents the generator setpoint before releasing
- \( RP_a \) – Represents the rated power of the generator in question
• $RP_a + RP_b + RP_c$ – Represents the summation of the rated power of all generators under the Shared PoA contributing to the breach
• $\Delta$ – Represents the existing power flow at the constraint minus the target power flow at the constraint, where the target is the TRIM LESS threshold
• $SF$ – Represents the sensitivity factor. In this work the sensitivity factor is equal to 1 kW/kW.

Reactive Power control setpoint calculation

The reactive power setpoint required to solve the voltage breach can be calculated using the following equation:

\[
\Delta Q = \frac{\Delta V}{SF_Q}
\]

\[
\Delta P = \frac{(\Delta V - \Delta Q \times SF_Q)}{SF_p}
\]

if $\Delta Q \geq$ system limits: $\Delta Q = \text{system limits}$ and $\Delta P = \text{system limits}$

• $\Delta Q$ – Variation in the reactive power output
• $\Delta P$ – Variation in the real power output
• $\Delta V$ – Actual voltage minus the desired value
• $SF_p$ – Sensitivity Factor, V/W, in this test is 0.00015 V/W
• $SF_Q$ – Sensitivity Factor, V/VAr, in this test is 0.00015 V/VAr

If $\Delta Q$ is greater than the equipment capacity the system caps the variation to its limit. The remaining required power is curtailed from the generator’s real power output.

The release setpoints are calculated based on achieving the RELEASE UPPER threshold with a maximum step change of 250 V, which is equivalent to 1667 kW or kVAr, each time a setpoint is issued.
Appendix 9 – MP Configuration Parameters

The following table provides a list of all MP configuration parameters for sgs power flow application.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Trip Threshold</td>
<td>ANM system trips all associated generators when breached for sufficient length of time.</td>
</tr>
<tr>
<td>Global Trip Observation Time</td>
<td>Time that the line current continuously exceeds the Global Trip threshold before an ANM response is executed.</td>
</tr>
<tr>
<td>Sequential Trip Threshold</td>
<td>ANM system trips associated generators in turn when breached for a sufficient length of time until the current has fallen back below; normal actions for a breach of the Trim threshold are subsequently initiated.</td>
</tr>
<tr>
<td>Sequential Trip Observation Time</td>
<td>Time that the line current continuously exceeds the Sequential Trip threshold before an ANM response is executed.</td>
</tr>
<tr>
<td>Trim Threshold</td>
<td>ANM system issues curtailment to associated generators in order to reduce power flow associated with the constraint to below the Reset threshold.</td>
</tr>
<tr>
<td>Trim Observation Time</td>
<td>Time that the line current continuously exceeds the Trim threshold before an ANM response is executed.</td>
</tr>
<tr>
<td>Reset Threshold</td>
<td>Safe value the ANM system attempts to bring current to following a qualifying breach of higher thresholds.</td>
</tr>
<tr>
<td>Release Observation Time</td>
<td>Time that the line current is continuously below the Reset threshold before releasing generation in succession.</td>
</tr>
<tr>
<td>Reset Less Threshold</td>
<td>ANM system target value for power flow associated with the constraint following a trim event. It is used to ensure that curtailment is reduced sufficiently below the Reset threshold.</td>
</tr>
<tr>
<td>Trim Less Threshold</td>
<td>ANM system target value for power flow associated with the constraint during a release event. It is used to ensure that the release of generation does not cause power flow to breach the Trim threshold immediately after.</td>
</tr>
<tr>
<td>Sequential Trip Response Time</td>
<td>Time delay between tripping ANM generators if the line current remains above the Sequential Trip threshold.</td>
</tr>
<tr>
<td>Trim Response Time</td>
<td>Time delay before additional curtailment is issued if the line current remains above the Trim Threshold.</td>
</tr>
<tr>
<td>Release Response Time</td>
<td>Time delay before additional network capacity is recalculated if the line current remains below the Trim Less threshold.</td>
</tr>
<tr>
<td>Release Ramp Step</td>
<td>Magnitude of released capacity allocated to generators each Ramp Time.</td>
</tr>
<tr>
<td>Release Ramp Time</td>
<td>Time delay between releasing capacity to generators.</td>
</tr>
<tr>
<td>Communications Time-out</td>
<td>Time delay following the previous successful data transfer between the measurement sensor and sgs comms hub before a communication error is set.</td>
</tr>
</tbody>
</table>