Scottish & Southern Electricity Networks

LEAN | Low Energy Automated Networks

Low Energy Automated Networks (LEAN)

SDRC 9.5 Monitoring & Analysis

Scottish and Southern Electricity Networks (SSEN) is the trading name of Scottish and Southern Energy Power Distribution (SSEPD), the parent company of Southern Electricity Power Distribution (SEPD), Scottish Hydro Electricity Power Distribution (SHEPD) and Scottish Hydro Electricity Transmission. SEPD is the contracted delivery body for this LCNF Project.

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Version Control

Version	Date	Authors	Change Description
1.0	25/02/2019	Sarah Rigby / Maciej Fila	Final version for submission following internal review and sign-off

SDRC Report Specification

Criterion 9.5 Monitoring & Analysis	• In depth review of the techniques used to monitor transformer health. • Interim feedback on the performance of the implemented sites. • Initial assessment of asset health before and after TASS operation. • Data to quantify the electrical impact on the network in terms of power quality.
Evidence	Evidence: An interim report will be provided in conjunction with appropriate evaluation of the various transformer health monitoring techniques employed.
Date	25th February 2019

Executive Summary

The Low Energy Automated Networks (LEAN) project has developed and applied Transformer Auto Stop Start (TASS) technology to reduce losses at 33/11kV primary substations.

The key principal of TASS is to switch off one of a number of transformers in a primary substation at times of low demand to avoid the fixed iron losses associated with that transformer - akin to turning off a car engine when the vehicle isn't driving anywhere.

The TASS system provides local, automated control within the substation to monitor the loading and control this switching, and to respond to SCADA alarms and status information from other network assets. In addition, commands incorporated into the Distribution Management System (DMS) provide the central network Control Room with remote supervision and management capability. The technology has been deployed in primary substations on the SEPD network since June 2018, and over the seven months to date has achieved energy savings of around 40 MWh in total across the two trial sites.

This report presents an appraisal of the techniques used to monitor asset health, together with an evaluation of the implications of increased switching due to TASS operation on both network assets and power quality, in accordance with the Project Direction and to meet the requirements of SDRC 9.5. To date, no impacts on asset health due to TASS operation are evident. Analysis of the electrical impact of TASS switching on the network indicates that to ensure best practice compliance with ER P28 voltage fluctuation limits, TASS operation with controlled Point on Wave switching would be of benefit for some sites, however other sites may operate acceptably without controlled switching.

The monitoring and analysis aspects of the trials are essential in managing risks, assessing the performance of the TASS technology, and ensuring that the system maintains compliance with relevant codes and standards. The approaches used have proven to be practicable, effective and thorough in providing a comprehensive understanding of the implications of integrating the TASS scheme with existing network assets.

In addition, the approaches used represent enhanced monitoring and analysis techniques that would bring benefits to wider network operation and investment in the context of improved data management and risk based decision making. The experience from their application during the LEAN project contributes to the consideration of enhanced levels of monitoring as the industry transitions to the world of DSO with increasingly dynamic operation of GB electricity networks.

The ongoing operation of TASS provides clear evidence of how this system can be used to reduce technical losses on the distribution network.

An overview of the LEAN project and the context of this SDRC 9.5 report is given in **Section 1**.

Section 2 sets out the objectives for monitoring different assets and systems during the TASS trials. This provides an overview of what's being monitored, why it's being monitored and how the data obtained is used to meet project requirements.

Section 3 describes the techniques used to monitor the health of key primary substation assets during the trials, and ascertain whether the application of TASS has any implications for asset health.

➡ The content provides detail to inform the use of these approaches by DNOs or other electricity network stakeholders when monitoring asset health during innovation trials, or for enhanced risk based asset management, together with conclusions regarding the sustained health of the assets within the TASS trial substations.

Section 4 presents an evaluation of the effects of TASS switching on power quality through the analysis of data monitored during transformer energisation both with and without the use of controlled Point on Wave switching.

➡ This provides information to support decisions by DNOs considering the application of TASS or other automated switching technologies on their networks, and decisions by product vendors on the application of controlled switching.

Section 5 describes the approaches used to monitor TASS operation throughout the trials and validate that the system operates as designed to provide an effective, reliable solution for reducing network losses.

➡ This is aimed at those considering the application of TASS at scale across a given network, and those developing operational review processes to assess technologies use during electricity network innovation projects.

Section 6 provides an assessment of the performance of TASS to date with regard to the automated switching activity seen and the associated reduction in losses.

The next steps for the project are set out in the concluding **Section 7**, and subject to continued successful operation, the system will be trialled for a period of 12 months to assess performance with changing seasonal electricity demands.

Interested parties are very welcome to contact the LEAN project team with any enquiries via lean@sse.com.

Contents

Acronyms

ANT	Active Network Topology
AC	Alternating Current
ACO	Automatic Changeover (of LVAC system)
AVC	Automatic Voltage Control
CB	Circuit Breaker
CBA	Cost Benefit Analysis
CBRM	Condition Based Risk Management
CoP	Crossover Point for TASS
CMZ	Constraint Managed Zones
DC	Direct Current
DF	Dissipation Factor
DFR	Dielectric Frequency Response test
DG	Distributed Generation
DGA	Dissolved Gas Analysis
DMS	Distribution Management System
DNO	Distribution Network Operator
DRM	Dynamic Resistance Measurement test
DSO	Distribution System Operator
ER	Engineering Recommendation
FAT	Factory Acceptance Testing
FRSL	Frequency Response of Stray Losses test
HVPR	High Voltage Protection Relay
LCNF	Low Carbon Networks Fund
LEAN	Low Energy Automated Networks
LRT	Leakage Resistance Tests
LVAC	Low Voltage Alternating Current system
LVPR	Low Voltage Protection Relay
MCB	Miniature Circuit Breaker
NMC	SSEN's Network Management Centre
OLTC	On-Load Tap Changer
PD	Partial Discharge
PF	Power Factor
PLC	Programmable Logic Controller
PoW	Point on Wave switching
PPE	Personal Protective Equipment
RFCT	Radio Frequency Current Transformer
RTS	SSEN's Real Time Systems team
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SDRC	Successful Delivery Reward Criteria
SEPD	Southern Electric Power Distribution
SFRA	Sweep Frequency Response Analysis
SLC	Standard Licence Condition
SSEN	Scottish and Southern Electricity Networks
TASS	Transformer Auto Stop Start
TEV	Transient Earth Voltage
TTR	Transformer Turns Ratio test
TX	Transformer
VLF	Very Low Frequency

1 Introduction

1.1 Overview of LEAN

The Low Energy Automated Networks (LEAN) project aims to establish whether it is technically feasible and economically viable to implement the proposed energy efficiency methods at 33/11kV primary substations on the Southern Electric Power Distribution (SEPD) network. It is a £3.1m project supported by Ofgem's Low Carbon Networks Fund (LCNF).

The two methods considered within LEAN are:

- Transformer Auto Stop Start (TASS) - this is the automated switching out of one of the transformers in a primary substation at times of low demand to reduce energy losses
- Alternative Network Topology (ANT) - this would make use of existing 11 kV feeder automation where available to allow a TASS site to operate in parallel with an adjacent primary substation

Prior to developing and trialling these technologies, the first phase of the project assessed the costs, benefits and risks associated with their application.

Within this, the work to validate the business case for the technologies indicated that TASS may be suitable for implementation at around 430 primaries across the GB distribution network, providing an energy saving in the region of 1,185,000 MWh over 45 years, equating to around 467,000 tonnes of CO_2e. The cumulative discounted net benefit associated with this saving would be in the region of £18 million[1]. This work also concluded that it is not considered financially viable to deploy ANT with TASS[2].

Accordingly, the decision was taken to proceed with developing and demonstrating the TASS technology on the SEPD network[3].

[1] derived using Ofgem's RIIO-ED1 CBA figure for the value of losses and the 2016 Electricity GHG conversion factor and 2016 traded carbon price
[2] as reported in LEAN SDRC 9.2 'Business Case Validation', March 2016 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents
[3] as reported in LEAN SDRC 9.3 'Phase Two Decision Point', July 2016 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents

1.2 Project Structure

The project has three distinct phases:

Phase One comprised the development of a comprehensive understanding of the costs, benefits and risks associated with deployment of the LEAN technologies. The information obtained during this phase supported evaluation of the business case, and a methodology for undertaking Cost Benefit Analysis on a site by site basis was created.
Phase Two focuses on validation of the technology through deployment and demonstration at primary substations selected to be representative of SEPD and GB distribution network scenarios, but also ensuring that there is minimal risk of supply interruptions.
Phase Three encompasses monitoring of the transformers at the substations selected for technology deployment over the trial operational period to capture relevant learning.

A Decision Point was incorporated into the project plan to ensure that there was value in proceeding from Phase One to the trial stages. To inform this decision, the findings from Phase One and the conclusions regarding the business case for the technologies were presented to both internal and external stakeholders, including GB DNOs. The responses received through this consultation supported SEPD's decision to continue the project and develop the TASS technology for trial on the SEPD network.

1.3 Overview of SDRC 9.5

This report presents the approaches used within the LEAN project to assess the health of transformers and other substation assets, and to evaluate both the performance of TASS and any potential implications associated with its application.

The technical analysis undertaken during Phase One of the project identified the potential risks to existing substation assets and to quality of supply from the application of TASS, and these informed both the design of the TASS scheme and the requirements for monitoring different aspects of the system to manage these risks. These considerations have been further refined during development of the trial stages of the project, and the monitoring and analysis techniques subsequently implemented provide data which closely track asset health and TASS operation.

The Successful Delivery Reward Criteria (SDRC) are defined in the LEAN Project Direction. In accordance with the SDRC 9.5 evidence requirements, this report provides:

- A review of the techniques used to monitor the trial transformers and assess the effects of TASS switching
- An initial assessment of asset health prior to the installation of TASS and following a period of trial operation
- A review of the electrical impact of TASS switching with regard to network power quality
- Interim feedback on the performance of TASS to date with reference to the automated switching activity seen and the associated reduction in losses

To provide context for the scope of SDRC 9.5, the following companion SDRCs relate to the development and trial of the TASS technology through Phase Two and Phase Three of the project:

- SDRC 9.4 'Initial Learning from Trial Installation and Integration' - comprehensive information on the technology developed, its integration with existing network assets, the operational principles designed into the scheme, and the factors relevant to the scalability and replicability of the system for wider deployment across other network areas, together with an initial assessment of the performance of TASS

- SDRC 9.6 'Site Performance to Date' - a detailed review of the losses savings achieved through TASS operation, and evaluation of both the benefits of the technology and costs of deployment to refine the business case

- SDRC 9.7 'Network Losses Evaluation Tool' - refinement of the tool developed to allow DNOs to undertake a site by site cost benefit analysis on the deployment of the technology, reflecting experience gained from trial implementation

- SDRC 9.8 'Knowledge & Dissemination' - the project closedown report, including consideration of the wider deployment of the technology across the SEPD network if applicable

SDRC 9.4 was published in September 2018, with SDRCs 9.6 to 9.8 to be published over the course of the project as further experience is gained from trial operation.

2 TASS Trial Monitoring & Analysis Requirements

This section sets out the objectives for monitoring different assets and systems during the TASS trials, providing an overview of what's being monitored, why it's being monitored and how the data obtained is used to meet project requirements.

The content is relevant to innovation teams and other stakeholders interested in managing risks and assessing the performance of innovative, automated control technologies to be deployed on electicity networks.

The design considerations identified during Phase One of the LEAN project[4] informed the choice of monitoring and analysis techniques used to evaluate the performance of the TASS technology and to track the health of the transformers and other assets.

In addition to designing the TASS system and control algorithm to mitigate risks to security of supply, asset health and quality of supply[5], monitoring and analysis throughout the trials is fundamental to demonstrating the technology without compromising our priority to provide a safe and reliable supply of electricity to our customers.

Accordingly, the approaches used during the trial stages provide information relevant to the aims of the project, including:

- the assessment of any potential impacts to network assets from TASS switching
- minimising risks to asset health or security of supply
- assessing and ensuring compliance with relevant codes and practices regarding quality of supply

The monitoring systems and data sources used are set out in Table 1, with brief descriptions given as to how the data is used within the project. To reflect the different aspects of TASS implementation considered within the project, further detail is then provided in the **Asset Health**, **Quality of Supply**, and **TASS Operation** sections of the report as applicable.

[4] as reported in LEAN SDRC 9.2 'Business Case Validation', March 2016 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents

[5] as reported in LEAN SDRC 9.4 'Initial Learning from Trial Installation and Integration', September 2018 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents

Table 1 - TASS trial monitoring systems and data sources

Monitoring System / Data Source	Application During the TASS Trials
• Point in time condition assessment tests	A range of specialist techniques have been used before and during the trials to provide detailed information on asset health and monitor for any changes which may indicate that TASS operation is having an impact on the health of substation assets such as transformers, circuit breakers, or tap changers.
• Oil samples and DGA	In addition to conventional transformer oil sampling, online Dissolved Gas Analysis (DGA) monitoring equipment has been installed to keep a close eye on the transformers and provide early indication of any potential issues due to the operation of TASS.
• Protection Relays	Power quality monitoring via the disturbance recording functionality of the existing 33 kV and 11 kV protection relays provides information on the inrush current and voltage waveforms, current and voltage magnitudes, and harmonic distortions seen on different phases during transformer energisation and switching, allowing an assessment to be made of any impact on power quality due to TASS switching.
• Synchronising Relays	The new synchronising relays incorporated into the TASS scheme to provide controlled Point on Wave switching also record current and voltage waveforms during each transformer energisation event, and periods of TASS operation both with and without the use of controlled switching allow the effectiveness of these devices to be assessed.
• PI data historian	Key TASS information has been incorporated into SSEN's data historian system, PI, and daily reviews of data via the PI ProcessBook and PI Datalink tools are being used by the project team to monitor the operation of TASS and pick up on any potential issues with its responses to different network situations.
• DMS	Information on the status of the TASS system is displayed alongside existing SCADA data in SSEN's Distribution Management System (DMS), PowerOn Fusion, to allow supervision by the Network Management Centre (NMC) Control Engineers who can then respond as necessary to alarms from TASS or other networks assets, and manage operational situations such as storms or reports of trespassers in a substation. The DMS is also used by the project team to obtain information regarding network configuration or SCADA alarms when reviewing TASS operation.
• TASS control device	More detailed, supplementary information is recorded by the TASS control device in each trial substation to complement the data available within PI, in addition to providing a back-up data source in the event that a SCADA comms issue temporarily prevents data acquisition to PI - the three data logs held are as follows: • event log - data points such as statuses, alarms, flags, timers and commands issued • fault log - TASS system faults together with data denoting the cause • load data - 10 minute average, minimum and maximum values for load measurements
• Substation comms logs	The Real Time Systems (RTS) comms logs record data flows from the substation Remote Terminal Units (RTUs), and this data is obtained when required to support investigations into the TASS system's automatic response to situations such as a loss of SCADA comms.

3 Monitoring - Asset Health

This section describes the techniques used to monitor the health of primary substation assets during the trials and ascertain whether the application of TASS has any implications for asset health.

The content provides detail to inform the use of these approaches by DNOs or other electricity network stakeholders when monitoring asset health during innovation trials, or in delivering enhanced risk based asset management, together with conclusions regarding the health of the assets in the TASS trial substations.

The data obtained presents no evidence of any increased risks to asset health due to the deployment of TASS.

The approaches used are presented under the following subsections:

- Site Inspections
- Partial Discharge Surveys
- Transformer Condition Assessment Tests
- Oil Sampling & Online DGA Monitoring
- Conclusions & Recommendations

The strategic management of network asset health is fundamental to providing a safe, secure and cost-effective electricity distribution system.

TASS is designed for deployment in primary substations and interacts with a number of network assets to provide the automated switching functionality which reduces energy losses from the transformers. It is therefore important to understand and to minimise any risk of damaging assets through the operation of TASS, particularly where this may result in a loss of supply to customers.

The electrical assets central to TASS operation are the transformers and circuit breakers, together with associated equipment such as tap changers, Low Voltage Alternating Current (LVAC) schemes and comms system Remote Terminal Units (RTUs). Phase One of the project assessed the key risks and mitigation measures associated with the application of TASS, as summarised below:

- Transformers

  The two major risks to transformers relate to:

  - physical damage due to the inrush currents that occur during energisation
  - migration of moisture from the oil to the paper insulation due to the increased thermal cycling of a transformer, which may cause the cellulose insulation to eventually breakdown

  The Phase One work concluded that there is a low risk of transformer damage due to inrush currents[6]. However, as described in Section 4 'Monitoring - Quality of Supply', the synchronising relays deployed at the trial sites can act to minimise inrush currents and switching transients.

[6] as reported in LEAN SDRC 9.2 'Business Case Validation', March 2016 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents

- Switchgear

  The major risk to circuit breakers relates to the increased number of switching operations due to TASS. Whilst increased switching will increase mechanical wear on the circuit breakers, the number of additional operations associated with TASS trials is well within the number of switching operations that circuit breakers are designed to accommodate. In addition, the TASS scheme is designed to switch at times of low substation loading, and consequently the risk of causing damage to the contacts within the circuit breakers is minimised. The conclusions from both Phase One of the project and subsequent conversations with the SSEN Protection team are that TASS presents minimal risk to 11 kV or 33 kV vacuum circuit breakers.

- Tap Changers

  As TASS de-energisation and re-energisation will occur at similar low load levels, the overall number of tap changer operations will remain within conventional operational ranges.

The TASS control system has been designed and tested to respond to SCADA alarms from existing network assets in a way that will minimise the consequence of any issues with those assets, whether caused by increased switching due to TASS or whether unrelated to the trials.

However, visibility of key data is also key to understanding and managing any risks to network assets.

A range of techniques have been used before and during the trials to provide detailed information on asset health and monitor for any changes which may indicate that TASS operation is having an impact on the health of substation assets. The following subsections detail the approaches used.

Site Inspections

Visual inspection is a useful means of assessing the physical appearance of network assets to identify anything which is not as expected and would therefore merit further examination. Accordingly, substation inspections are regularly carried out as part of standard maintenance activities.

Use within the LEAN Project

The site surveys undertaken to refine the TASS design requirements and select the trial sites, as reported in SDRC 9.4 'Initial Learning from Trial Installation and Integration'[7], allowed for visual inspections of the substation equipment to check for any issues. This included inspection of detailed features such as the tap changers, oil tanks, and transformer breathers.

[7] LEAN SDRC 9.4 'Initial Learning from Trial Installation and Integration', September 2018 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents

The surveys were completed in April & May 2017, with each visit attended by the LEAN Project Engineer alongside the consultants engaged for this work, to allow the suitability of the sites to be assessed and discussed.

Experience from Implementation

Visual site inspections can be undertaken by anyone with the relevant authorisations for substation access and competencies to know what to inspect and what may raise concerns. As with all site based activities, Operational Safety Rules and relevant safety and operational processes must be adhered to (inc. PPE, Method Statements, Risk Assessments, etc.). Further, site access may need to be planned and scheduled in advance in line with any relevant business procedures.

Results and Key Findings

No asset health issues were identified during the inspections at any of the eight substations that had been shortlisted for survey to select the TASS trial sites.

Partial Discharge Surveys

Partial Discharge (PD) is localised electrical activity that occurs over a small area of the solid or fluid insulation of medium and high voltage assets, and does not span the entire distance between the two insulated electrodes - hence the terminology 'partial'[8]. PD indicates an initial breakdown of the insulation within the equipment, and this deterioration may worsen with time.

Electrical assets that can be tested for PD include transformers, circuit breakers or switchboards with metal casings, bus ducts around busbars, bushings, cables and overheard insulators. PD occurring within insulating material emits high frequency Transient Earth Voltages (TEV) which can be detected via TEV probes placed on the outside of an asset whilst it is in service. Surface PD tracks across the surface of the insulation and typically generates high frequency, low amplitude ultrasonic acoustic frequencies, therefore an ultrasonic sensor provides an effective means of detection for above ground assets. For cables, Very Low Frequency (VLF) mapping or use of a Radio Frequency Current Transformer (RFCT) on an earth connection to the cable sheathing may be used to detect PD.

Surveys can be undertaken by a trained specialist whilst the equipment is operational, subject to compliance with all relevant safety requirements, such as risk assessments and appropriate PPE. Readings from the TEV probe and ultrasonic sensor are taken at different locations on the assets to detect internal and surface PD activity, and two

[8] the IEC 60270 'Partial Discharge Measurements' definition for Partial Discharge is "localised electrical discharges that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor"

coupled TEV probes can be used to locate the source of internal PD activity using time-of-arrival measurements between the two probes.

Data is interpreted based on reference values, or where historic data is available the results can be compared with previous readings taken from the same point, or results taken from other, similar assets of the same type and manufacture. In addition, supplementary information can be factored into the assessment as relevant, including environmental conditions such as ambient temperature, relative humidity and atmospheric pressure which each influence PD activity, or readings of localised temperatures which indicate hot spots within an asset.

Regular testing can be used to monitor a given asset and forecast maintenance requirements. Online PD systems can also be used to continuously monitor more critical assets, or those of particular interest due to unusual operating conditions, including the application of new technologies within an innovation project.

PD surveys are therefore an effective, non-intrusive monitoring technique for detecting emerging defects which may represent an increased risk of future faults.

Use within the LEAN Project

As PD is indicative of mechanical, thermal, or moisture issues within electrical equipment, PD surveys are an effective monitoring approach for detecting a range of issues which may be related to the application of TASS and increased transformer switching.

PD surveys were undertaken at the two TASS trial sites in May 2017 by an SSEN colleague with specialist expertise in PD assessment. The surveys were conducted using EA Technology's UltraTEV Locator[9] equipment with TEV and ultrasonic contact probes, and assessed the 11 kV & 33 kV switchboards and the external transformers and their cable boxes.

Figure 1 shows a PD survey underway at one of the TASS trial sites, with readings being taken from a transformer cable box.

[9] www.eatechnology.com/engineering-products/partial-discharge-solutions/ultratev-locator/

Figure 1 - Photograph taken during a PD survey

Further PD surveys will be carried out on completion of the TASS trials, with any differences in results assessed to identify whether or not these changes may be due to TASS operation.

Experience from Implementation

Around 3-4 hours per substation were required to obtain PD readings from relevant points across the site.

A range of PD detection systems are available from different product vendors, with differing user interfaces designed to effectively display relevant readings and information. However, training and experience are key to ensuring that the devices are used correctly to provide valid readings, and that the results are correctly interpreted based on a qualitative as well as quantitative understanding of the measurements.

The UltraTEV Locator used within the LEAN project is portable, and with appropriate training can be easily used to obtain a suite of PD measurements at a site. The device displays the magnitude of PD detected, together with a traffic light indication of the level of PD activity - Green indicating no significant PD, Amber indicating some activity which merits more frequent monitoring, and Red indicating a level which requires immediate investigation, and may present a risk to equipment or personnel.

In addition the ultrasonic signal is processed via heterodyning, which combines two frequencies to shift a signal from one frequency range to another, to provide audible signals which can be heard as 'ticks' and 'crackles' from the device. When listening to this output, a 'tick' indicates the presence of capacitive discharge, with a 'crackle' indicating

corona discharge associated with the ionisation of a fluid, including air which may be present within voids in the insulation.

All of the measurements taken by the UltraTEV Locator, including the audio output created from the processed ultrasonic signal, are saved to the system's internal memory for later download via the USB port. The measurement data can then be accessed for assessment and display in generic spreadsheet software.

Results and Key Findings

A summary of the conclusions from the surveys was provided to the LEAN project team by email on the day following the surveys, with full reports subsequently prepared for each site[10]. The reports, which include the TEV histograms and plots indicating the levels of ultrasonic activity at different locations within the substation, are provided as Appendix A.

The surveys indicated that the level of PD activity detected across the two TASS trial sites represents a low risk with regard to asset health. Consequently, it is acceptable to continue normal surveillance procedures upon entry to the substation.

The key findings are as follows:

- No significant TEV signals were detected on the switchgear or the transformers and their cable boxes at either trial site. All histograms record TEV below 15 dB, well within the 20 dB upper limit for the Green zone.
- At both sites, the ultrasonic readings from the 33 kV & 11 kV switchboards were suggestive of some low level capacitive discharge associated with the busbars, and this could be heard as a low rate of 'ticks' in the processed audible signal. The amplitude and frequency of the signals was not significant enough to be of concern, however, and is comparative with the results from PD surveys on similar switchboards. At one of the sites, a low 'crackling' sound could also be heard, indicative of some low level corona discharge associated with the busbars.
- No significant ultrasonic activity was detected on either the transformers or their cable boxes at either site. However, differences could be identified between assets, for example at one site the hum from the core of one transformer was more detectable than the other, though neither was significant in amplitude, and a low rate of 'ticks' was picked up on the second transformer, indicative of some capacitive discharge.
- At the site which displayed corona activity in both the 33 kV busbar sections and the transformer cable boxes, the intensity of the ultrasonic signals suggests a low level of PD activity within these compartments, equating to a low risk. However, the extent of this activity could only be confirmed through disassembly of the cable boxes and visual inspection, therefore a recommendation has been made that the cable box connections be examined during the next planned outage to check for and to eliminate any sources of PD activity associated with the connections (such as a loose connection, inadequate clearances, or incorrect cable sleeving, routing or earthing).

[10] 'PD Survey on Gillingham 11KV and 33KV' and 'PD Survey on Hedge End 11KV and 33KV', SSEN, August 2017

Curiously, the background TEV reading near to the door to one of the substations was found to be higher than the readings from the switchboards, and this finding is attributed to the detection of extraneous signals coupled into the building from outside sources. This further illustrates the need for training and experience in undertaking and interpreting the results from PD surveys.

Transformer Condition Assessment Tests

A range of specialist transformer condition assessment tests are available for use in monitoring asset health or diagnosing issues with specific elements of a transformer, including the transformer core, windings, insulation, bushings and tap changers.

In addition to assessing the current condition of an asset, many of these tests provide a benchmark or 'finger print' of a transformer so that the same tests can be run at a later point in time and the results compared to identify any changes.

The tests used within the LEAN project are set out in Table 2, with information given on the purpose of the test and the methodology used to obtain and interpret the results. Each of these tests must be undertaken with the transformer off load to allow test equipment to be connected and/or measurement currents and voltages to be applied, therefore transformer outages must be scheduled in line with standard outage planning processes.

Table 2 - Transformer condition assessment tests used within the LEAN project

	Description & Use	Process & Interpretation
Sweep Frequency Response Analysis (SFRA)	This technique is a well established, non-invasive method for assessing the mechanical integrity of transformers on the basis that the distributed RLC (resistance, inductance, capacitance) properties of a transformer are dependent on material properties and geometries. Where it may be considered beneficial to track the health of a given transformer, it is typically recommended that these tests be carried out every 5 to 10 years. Any changes can be further investigated through the use of other condition assessment approaches such as Winding Resistance tests, LRT, TTR or FRSL measurements.	An excitation voltage with a continuously increasing sinusoidal AC frequency is injected into one end of a transformer winding, and the test device measures the response signal returned from the opposite end. The difference between the input and output signals provides a unique 'frequency response' for the transformer. Changes to the mechanical structure within a transformer's core or windings are identified by comparing the results of the latest test with previous results from the same asset, however where a fingerprint of a given asset is not available, results from a similar transformer may be used. Variations in SFRA results from two different points in time will relate to variations in asset health, as damage or movement of internal components will change this frequency response signal.
Winding Resistance tests	These tests are used to detect faults with transformer windings (e.g. open winding, shorted turns or poor contacts) by measuring the resistance of each winding, and to verify the integrity of components such as the on-load tap changer. They are a useful diagnostics tool to provide additional information which may indicate issues due to poor design or assembly, or damage during transit or as a result of the transformer's environment or operational duty. Where an issue is suspected, SFRA can be used to confirm contact problems, and TTR measurements can be used to confirm an open circuit.	A known DC current is injected into the winding under test and the resulting voltage drop across the winding is measured and used to calculate the winding resistance. The resistance measurements are typically taken phase-to-phase, with the results compared to ascertain whether or not the results from the different phases agree well - differences of less than 3% between phases should be expected. The readings can also be compared with previous results, however measurements must be temperature corrected for comparison, with the typical reference temperature being 75°C - the results shouldn't vary by more than 1%. Poor correlation is indicative of issues within the transformer or tap changer. The DC current will also flow through the on-load tap changer (OLTC) and other mechanical connections, and so will detect changes with these components, however a DC test current may also be applied during OLTC operation to provide Dynamic Resistance Measurement (DRM) which fully assesses the operation of the OLTC to indicate the condition of the contacts and diverter switch transit time. The measured voltage may take some time to stabilise due to winding inductance, and this must be considered when taking measurements. For tapped windings, each tap position should be tested.

Magnetising Current tests	The magnetising current is proportional to the energy required to induce a voltage in the opposite winding, and so defects in the transformer core can be detected by assessing the current required to establish a magnetic flux in the core. As it is relatively simple to measure the magnetising current, these tests are an effective approach for identifying issues within the core structure, such as faults with the laminations or windings. Short-circuited turns can also be confirmed by TTR measurements, while SFRA tests can also be used to confirm or further diagnose problems in the core.	A known AC voltage is applied to one side of the transformer (typically the primary/high voltage side) whilst the opposite (secondary/low voltage) side is open circuited, and a reading is taken of the magnetising current drawn to energise the transformer. The test connections are made according to the transformer construction and winding configuration. Measurements are taken for all phases and all tap positions and a comparison is made between the results. The two outer phases of a three-phase transformer should display similar results - with deviations of less than 5%-10% - though the centre phase will differ. A similar pattern should also be seen across all tap positions for all phases. If any issues are present, the results will not show these expected patterns. Residual magnetism in the core can affect the results, and so the transformer should be demagnetised and the tests repeated if this is suspected.
Winding Capacitance & Power Factor tests	These tests are used to assess the overall dielectric condition of the transformer and the condition of the transformer insulation - capacitance readings can indicate mechanical displacements of windings or partial breakdown of bushings, and power factor tests, also known as dissipation factor or tangent delta tests, can indicate degradation of the transformer insulation or the ingress of water. Where high power factor/dissipation factor values are obtained, DFR tests, or oil sampling, can be used to indicate a breakdown of the oil insulation or the presence of moisture.	For transformers, both the insulation between the separate windings and the insulation between the windings and the tank are assessed. The windings must be shorted, and an AC test voltage is then applied to one winding with a current measurement taken on the opposite winding or on the tank. Impedance and capacitance are then calculated from the voltage and current readings, and the power factor (PF) and dissipation factor (DF) are calculated from the angles of the phase shift between the reference/test current and the measured current. Capacitance results are expected to agree well with any available reference results. PF results between windings are typically 0.2-0.3% for large & medium sized transformers when new, with values increasing during service. Values above 0.5% may indicate a poor dielectric condition; for values above 1% remedial action is required to improve the dielectric condition. For bushings, an increase in capacitance of more than 10% would be considered significant and would merit further investigation and remedial action. PF measurements taken at the standard frequency of 50 Hz are less sensitive to issues, and the use of a wider frequency range during testing will allow issues to be detected at an earlier stage. PF measurements between windings are considered to be reliable, however judgement must be used when interpreting power factor measurements between windings and earth, as these can be affected by dirt or moisture and so may not correctly reflect the condition of the transformer.

Dielectric Frequency Response (DFR) tests	These tests provide a reliable means to non-invasively estimate the moisture content of the transformer's solid insulation (cellulose) as the presence of moisture affects the frequency dependence of the winding power factor. The test directly determines the moisture content in the solid insulation, and therefore provides an alternative to inferring moisture levels from standard oil samples which may be affected by temperature.	The output of the measurement device is connected to the primary/high voltage winding and the input to the secondary/low voltage winding, and a low voltage is applied with a frequency ranging from kHz to a few mHz. The readings are used to calculate capacitance and power factor across the frequency range, and specialist software is used to compare the resulting curve with modelled curves to derive the moisture content in accordance with IEC 60422 'Mineral Insulating Oils in Electrical Equipment - Supervision and Maintenance Guide'. The results from the low test frequencies indicate moisture within the solid insulation, and the results from the mid-range frequencies indicate the conductivity of the fluid insulation.

A number of further transformer condition assessment tests are available, including those described below, however these have not been used within the LEAN project as the scope of the tests which have been undertaken provides sufficient information to assess any potential impacts of TASS operation on transformer health.

- Leakage Resistance Tests (LRT) - these may also be referred to as short-circuit impedance measurement tests, and the measurements can be compared with the values provided by the manufacturer following factory acceptance testing (FAT) to ascertain whether there have been any changes which may indicate deformation or displacement of windings, potentially caused by severe short-circuits or damage during transportation of the transformer - typically the tests provide a reading which represents the average across all three phases, however individual phase measurements can also be taken to support diagnosis of any issues with the windings
- Transformer Turns Ratio (TTR) tests - these measure the ratio and phase angle of a winding to detect open circuits or shorted turns within the windings, and can be compared with the turns ratio determined during factory acceptance testing to assess any changes - these tests can provide additional information in light of unusual Power Factor tests or Dissolved Gas Analysis (DGA) readings
- Frequency Response of Stray Losses (FRSL) measurement - this is an advanced diagnostics tool which measures the resistive component of short-circuit impedances at a range of frequencies to identify short-circuits between parallel strands within windings, or localised overheating as a result of high eddy current losses - measurements can be obtained through three-phase or individual phase tests

Use within the LEAN Project

The condition assessment tests used to monitor the transformers in the TASS trial substations have been completed by a specialist consultancy with expertise in undertaking and interpreting the results of these tests, Doble Engineering. Figure 2 shows the testing underway on one of the trial transformers.

Figure 2 - Transformer condition assessment testing

Prior to installing the TASS equipment and commencing the trials, the first round of tests were undertaken at the trial substations in October 2017. In addition to assessing asset health at that point in time, the results from these tests provide the benchmark against which future results can be compared.

Mid-trial tests were then undertaken in October 2018, over 4 months into trial operation, and the results reviewed to ensure that there are no points of concern relating to continuing the trials.

A further suite of tests will be carried out on completion of the trials following 12 months of TASS operation, and the results will be compared to the pre- and mid- trial tests to identify and assess any changes that may be a consequence of the application of TASS.

The findings from the pre- and mid-trial tests are presented in the 'Results and Key Findings' subsection below.

Experience from Implementation

For each transformer, a one day outage was scheduled and the suite of tests were then undertaken over a period of around 4-5 hours per transformer.

Specialist knowledge and expertise is key to both undertaking the transformer condition assessment tests and interpreting the results. For many of the tests, there is no definitive pass/fail distinction, or no universally agreed acceptable result, and a detailed understanding of both the transformers and the testing procedures supports the use of expert judgement when attributing findings to likely causes, and in assessing the implications and risks.

The importance of this is evident with the transformer condition assessment tests undertaken for the LEAN project. Both the pre-trial and mid-trial reports provided by the consultants conclude that there are no indications of any issues with the transformers, and the key recommendation is that repeat tests be run at the end of the trial period for further comparison. However, in detailing the work the reports include the following points of judgement in undertaking the tests and analysing the results:

- The pre-trial SFRA tests generally show good agreement across the measured frequency range, other than at the higher frequencies on one phase of one transformer. This irregularity is attributed to a measurement issue rather than a problem with the transformer, and indeed the mid-trial tests do not present the same issue.
- In light of unusual patterns seen in the results from the pre-trial Winding Resistance tests on one transformer, before the mid-trial tests were run the tap changer was exercised through its range to wipe the contacts and remove any deposits that may have been present. Consequently the winding resistance values were no-longer elevated, and it can be concluded that the results from the pre-trial test were affected by surface deposits, rather than indicating deterioration of the tap changer contacts or any issues with the transformer windings, and that this 'cleaning' process allowed the true contact resistance to be assessed.
- A similar issue was seen with the mid-trial Winding Resistance tests on another transformer where it was necessary to exercise the tap changer between positions 2 and 4 a number of times before a sensible HV winding measurement could be obtained, again attributed to contamination deposited on the tap 3 contact.
- With the Winding Capacitance & Power Factor tests, the mid-trial results at one site indicated slightly elevated power factors for the 'HV winding to earth' when compared to the pre-trial tests, however this is attributed to an effect of the adverse weather conditions at the time of testing, rather than an issue with the transformers.
- Similarly the mid-trial Winding Capacitance & Power Factor tests at the other trial site indicated slightly elevated 'HV winding to LV winding' power factors compared to the pre-trial results. This finding is attributed to the fact that a higher test voltage was applied, and this conclusion can be validated during post-trial testing.

Results and Key Findings

A summary of the conclusions reported for the pre-trial and mid-trial transformer condition assessment tests is given in Table 3. The full reports prepared by the consultants for the two rounds of tests[11, 12] are provided as Appendix B.

The pre-trial results suggested that there were no significant issues with any of the transformers at that point in time.

The mid-trial tests indicate that the transformers remain in good condition, with the results agreeing reasonably with those obtained from the pre-trial surveys, thereby indicating no changes due to TASS operation.

[11] 'Report on Condition Assessment Tests on C1MT and C2MT at Gillingham Substation' and 'Report on Condition Assessment Tests on C1MT and C2MT at Hedge End Substation' reports, Doble, October 2017

[12] 'Report on Condition Assessment Tests on C1MT and C2MT at Gillingham Substation' and 'Report on Condition Assessment Tests on C1MT and C2MT at Hedge End Substation' reports, Doble, October 2018

Table 3 - Conclusions from the two rounds of transformer condition assessment tests

	Conclusions from Pre-trial Tests		Conclusions from Mid-trial Tests	
Sweep Frequency Response Analysis (SFRA)	no indication of any problem	At both sites the results from the two transformers generally show good agreement across the measured frequency range.	no indication of any changes due to TASS	At both sites the results from the two transformers continue to show good agreement across the measured frequency range. The results compare well with the reference data from the pre-trial tests, with only minor differences.
Winding Resistance tests	no indication of any problem	As the transformers at both sites were installed at the same time, and are of the same manufacture and age, measurements were taken on one transformer only at each site - results from different phases agree well and are as expected.	no indication of any changes due to TASS	For the mid-trial tests, both transformers at each site were assessed, and measurements on all transformers show good agreement between different phases and consistency across the tap range on the HV side. The results compare well with the reference data available from the pre-trial tests, with only minor differences.
Magnetising Current tests	no indication of any problem	At one site the results from the two transformers agree closely, and show the expected pattern, at the other site differences in the Magnetising Current results from the two transformers are seen, however this is due to the tests being run on different tap positions.	no indication of any changes due to TASS	At both sites the results from the two transformers indicate good agreement, and show the expected pattern. Comparison with the results from the pre-trial tests shows negligible differences.
Winding Capacitance & Power Factor tests	no indication of any problem	At both sites the results for the two transformers agree well, with all power factor results within the accepted limits.	no indication of any changes due to TASS	At both sites the results for the two transformers agree well, with all power factors within the accepted limits. The winding capacitance results agree well with the reference data from the pre-trial tests. The power factor results generally agree well, however at one site the 'HV winding to ground' power factor was slightly elevated for both transformers, expected to be due to adverse weather conditions present at the time of testing, and at the other site the 'HV winding to LV winding' power factor for one transformer is slightly elevated, expected to be due to the increase in test voltage used, therefore there are no clear indications of any changes due to TASS operation.
Dielectric Frequency Response (DFR) tests	no indication of any problem	These were carried out at one site only due to the availability of test equipment - the results from the two transformers agree well, and the moisture content in the solid insulation is only slightly above the level that may be expected for a new transformer.	no indication of any changes due to TASS	At both sites the results from the two transformers agree well, and the moisture content in the solid insulation is only slightly above the level that may be expected with a new transformer, with the readings considered good for a transformer of this type and age. For the site with pre-trial DFR reference data, the results agree will, and at the other site the capacitance and power factor readings for inter-winding insulation capacitance align well with the comparative readings from the Winding Capacitance & Power Factor tests.

Oil Sampling and Online DGA Monitoring

Oil sampling is commonly used to assess transformer health as faults present within a transformer can change the composition of the insulating oil and lead to the formation of different gases.

Transformer oil samples can be tested directly for a number of factors, including:

- moisture content
- dielectric breakdown voltage
- acidity
- surface/interfacial tension
- contaminants (e.g. PCBs (polychlorinated biphenyls) or metals)
- furfuraldehyde (which indicates the breakdown of solid insulation)

Dissolved Gas Analysis (DGA) then provides additional information for identifying and diagnosing issues as the volumes and ratios of any detected gases can be used to indicate different types of fault activity within the transformer.

Conventional oil samples are taken manually from transformers and analysed within a lab to provide oil quality and DGA results. These results can be used to track asset health indices and inform decisions on maintenance and replacement. Where routine sampling is used on transformers which are not otherwise demonstrating any issues, this is typically based on a sampling schedule, such as once per year, with the results providing point in time values only.

In contrast, online multi-gas DGA systems provide continuous monitoring of transformer oil quality with the results available remotely and in real-time. A number of systems are now available on the market to measure key gases or provide results for the full suite of fault gases. Different manufacturers apply different technologies for analysing the oil samples within the equipment installed on site, and different communications methods can be used to access the data remotely. Web based user interfaces are typically used to display results, including charts which track the individual gas readings through time together with diagnostic tools to support the analysis and interpretation of any data which may indicate the presence of a fault.

These diagnosis techniques are based on empirical evidence that different types of fault produce different effects within a transformer, which result in the formation of different combinations of fault gases. Accordingly, when an increase is seen in one or more of the DGA readings, the respective levels of the different gases can be analysed and the diagnostic tools can be used in combination to draw conclusions on the likely cause of the fault, and assess the level of risk.

The web interface of the online monitoring system used within the LEAN project incorporates the three techniques

described below. Each of these approaches is included in IEC 60599 'Mineral Oil-Filled Electrical Equipment in Service - Guidance on the Interpretation of Dissolved and Free Gases Analysis'. The Rogers Ratios and Key Gas Method techniques are also included in the IEEE Standard C57.104-2008 'Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers'.

- Duval Triangles

  gas readings required - CH_4, C_2H_4, C_2H_2

  An illustration of a Duval Triangle taken from the TOTUSPRO system being used to monitor the TASS trial sites is given in Figure 3.

  These triangular charts provide a graphical representation of DGA readings to support fault diagnosis. The original chart, known as Triangle 1, was developed to assess DGA data from transformers, bushings and cables filled with mineral oil. The three sides of the triangle represent Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2), with the axes being 0% to 100% in each case, and the DGA readings for each gas expressed as a percentage of the ppm sum of the three gas readings. The triangle is subdivided into prescribed fault zones indicating the following thermal and electrical faults:

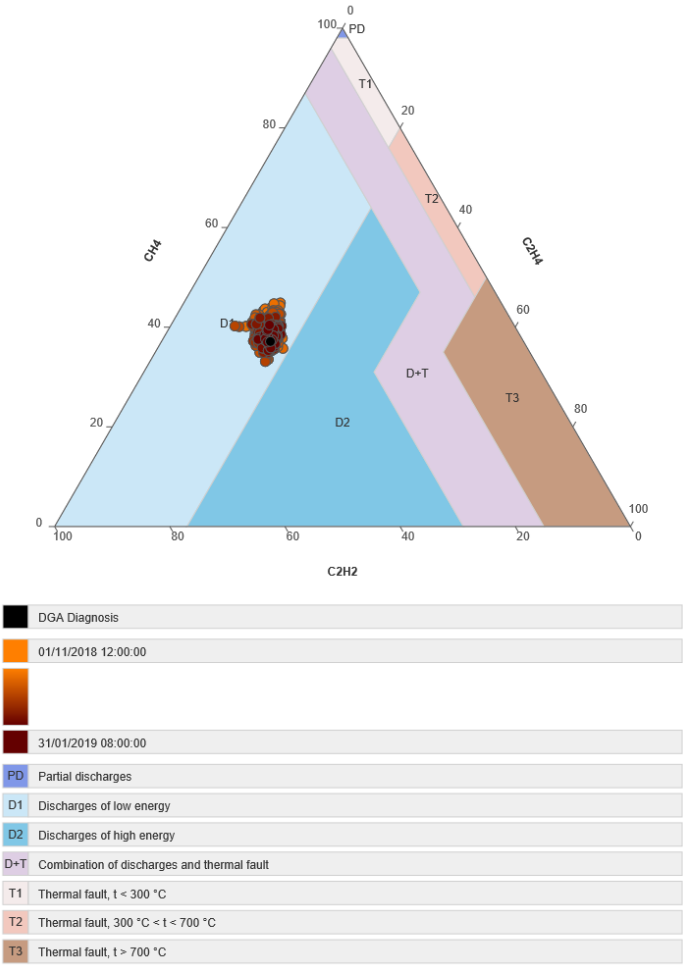
  - T1 - thermal fault less than 300°C
  - T2 - thermal fault between 300°C and 700°C
  - T3 - thermal fault greater than700°C
  - PD - Partial Discharge
  - D1 - low energy discharge - sparking
  - D2 - high energy discharge - arcing
  - DT - a combination of thermal and electrical faults

  The position of the plotted DGA reading within the fault zones indicates the type of fault present, however allowances should be made for measurement error by considering an uncertainty polygon around the plotted values when interpreting the data. Readings from different points in time can be presented on the same chart to monitor the development of a fault.

  The approach was first developed in the 1970s[13] based on empirical observation of transformer failures. A set of complementary Duval Triangles have subsequently been developed, with differing fault zones or representing a different combination of fault gases, to provide an increased scope of diagnosis including low temperature faults, faults with onload tap changers, and faults in different oil types (e.g. mineral, bio or silicone oils).

[13] 'Fault Gases Formed in Oil-Filled Breathing EHV Power Transformers - The Interpretation of Gas Analysis Data' (IEEE PAS Conference, Paper No. C 74 476-8), Michel Duval - Hydro Quebec, 1974

Figure 3 - Duval Triangle showing data points over a 3 month period for one of the TASS trial transformers



- Rogers Ratios

  gas readings required - H_2, CH_4, C_2H_6, C_2H_4, C_2H_2

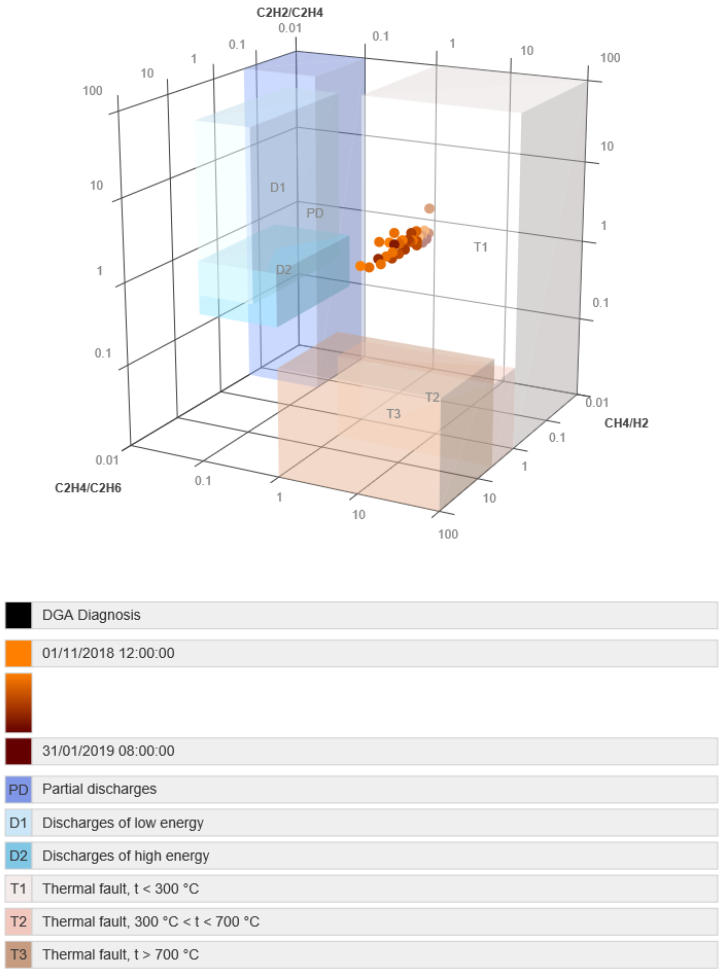
  An illustration of a 3D Gas Ratios cube taken from the TOTUSPRO system is given in Figure 4.

  This methodology can be used for fault diagnosis as different permutations of the ratios between pairs of fault gases can be attributed to different types of fault. The DGA readings of 5 key gases are used to calculate ratios, which are then assessed against specified reference ranges to infer the type of fault causing the formation of the gases. The derived fault types are in line with the thermal and electrical classifications associated with the Duval Triangle described above.

  This methodology was developed in the 1970s[14], and is a refinement of the Doernenburg Ratios method. The three ratio approach is included in IEC 60599 (and may be referred to as the 'IEC Ratio Method'). A fourth ratio may also be included, although this only represents a limited temperature range of decomposition. The ratios can also be displayed as a 3D cube, with each axis corresponding to one of the three ratios, to provide a visual representation of the data and to track changes in the readings through time.

[14] 'IEEE and IEC Codes to Interpret Incipient Faults in Transformers Using Gas in Oil Analysis' (IEEE Transactions on Electrical Insulation - Vol. EI-13, Issue 5), R. R. Rogers - CEGB, 1978

Figure 4 - 3D Gas Ratios cube showing data points over a 3 month period for one of the TASS trial transformers



- Key Gas Method

  gas readings required - CO, H_2, CH_4, C_2H_6, C_2H_4, C_2H_2

  An illustration of the Key Gas Methods charts taken from the TOTUSPRO system is given in Figure 5.

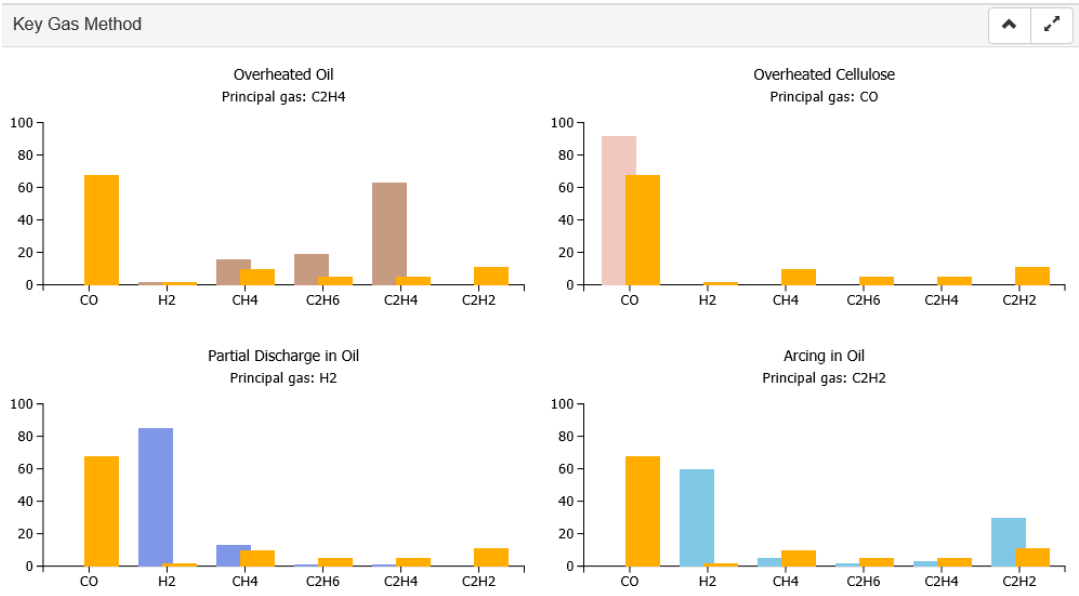
  This approach compares the pattern of individual gas readings to reference levels which denote thermal or electrical faults. Different concentrations of specific gases infer a corresponding fault diagnosis as follows:

  - thermal fault in the oil
  - thermal fault in the oil & cellulose
  - low energy partial discharge
  - high energy arching

  Appropriate reference levels were proposed in the 1970s[15], however the approach was developed primarily using sealed or blanketed transformers therefore its application to breathing conservator-type transformers should be carefully considered.

[15] 'Advances in Fault Diagnosis by Combustible Gas Analysis' (41st International Conference of Doble Clients - Minutes, Section 10-1201), D.R. Pugh - Doble, 1974

Figure 5 - Key Gas Method charts showing DGA readings for one of the TASS trial transformers



Use within the LEAN Project

Conventional oil sampling is routinely used within SSEN, however project specific oil samples have been taken from the transformers at the TASS trial sites and analysed to provide a reference point for comparison with subsequent oil samples.

In addition, online DGA equipment has been installed at the trial substations to provide ongoing monitoring of transformer health throughout the TASS trials and provide early indications of any emerging issues.

Following the comparison of alternative systems as part of a standard procurement process, the system selected for use during the TASS trials was Camlin's TOTUS DGA product. This system takes oil samples every few hours, and Photo-Acoustic Spectroscopy[16] is used to analyse the oil and give readings for the following 9 fault gases & moisture:

H_2 - Hydrogen	CO - Carbon Monoxide
CH_4 - Methane	CO_2 - Carbon Dioxide
C_2H_6 - Ethane	O_2 - Oxygen
C_2H_4 - Ethylene	N_2 - Nitrogen
C_2H_2 - Acetylene	H_2O - moisture

Site surveys for the DGA system were undertaken at both trial substations in July 2017, and the units were then installed on each transformer during September 2017. Figure 6 shows one of the DGA units installed on site.

[16] this applies acoustic detection to measure how much electromagnetic radiation (in this case infrared light) has been absorbed by the gases present to increase the pressure within the sealed unit

Figure 6 - Online DGA unit installed at a TASS trial site

The DGA data is viewed by logging in to the secure TOTUS system via a normal web browser.

Users can also opt to receive alarms by email and/or text message in the event that any readings rise above the thresholds that have been set.

To monitor the transformers at the TASS trial sites, both the LEAN project team and key Control Room staff have access to the web system and will receive any alarms raised, and the data is reviewed regularly by the project team to identify any trends in dissolved gas and moisture readings. In addition, significant interest in the system has been expressed by Asset Management colleagues as a result of project dissemination activities, and access to the system has been requested to allow the consideration of other potential uses for the information available.

In the event that any potential issues are identified with any of the TASS trial transformers, investigations can be undertaken, drawing on specialist expertise as required. Similarly, the trials can be halted if necessary to ensure that any changes which may be due to TASS having an adverse impact on the transformers, are understood and addressed prior to any incident, particularly a loss of supply event, occurring.

To provide further insight into the data, the SAPIENT[17] intelligent analytics service has also been procured with the TOTUS DGA system. This gives access to expertise in the event that any issues are identified, together with regular technical reports which contain observations from the tracked data, to inform conclusions regarding any effects that TASS operation may have on transformer health.

Experience from Implementation

The TOTUS units selected for use during the TASS trials provide a compact monitoring solution with straight forward installation. The site surveys undertaken to identify suitable points of installation and take relevant measurements required around 1 hour per transformer. Installation of the units, including attachment of the supporting brackets to the transformer compound, mounting of the DGA equipment and connection to the transformers, took around 1.5 days per site (2 transformers).

It had been indicated by the product vendor that it should be possible to install the units live, however for safety planned outages were booked for each transformer, and scaffolding was used to allow safe access to the top oil valves. Details on the system selection process and site survey and installation activities are provided in SDRC 9.4 'Initial Learning from Trial Installation and Integration'.

The DGA data is cloud hosted, and SSEN's standard data security assurance processes were followed to obtain approval for use of the system. This included ensuring both vendor and system compliance with SSEN's Information Security Policy, Cloud Operating Standard, Third Party Standard and Operational Technology Security & Risk Standard.

The TOTUS web interface gives an overview of the present status of each transformer and provides charts showing the DGA readings through time, with further information available through Duval Triangle and 3D Gas Ratios advanced visual diagnostics tools, which track historic values to identify emerging patterns, together with Rogers Ratios values and Key Gas Method charts, as described above.

This system provides an intuitive interface for viewing the data, and has proven to be highly reliable. Expertise is required in the interpretation of the data, however, and for the purposes of the TASS trials the SAPIENT analytics service has provided valuable access to specialist knowledge for assessing the data together with an impartial view on any potential changes to the transformers which may be linked to the application of TASS.

The default alarm thresholds applied are typically based on the Condition 1 and Condition 2 levels set out in the associated IEEE C57.104-2008 standard. For the purposes of the LEAN project, however, the thresholds have been set at 50% above the maximum value seen for the transformer in question prior to commencing the TASS trials. These are typically much lower than the Condition 1 values, with the specific purpose of drawing immediate attention to any notable changes in measurements during the trials.

[17] www.camlingroup.com/sapient

Whilst advanced DGA diagnostics have not yet been required within the project, it's recognised that having the analyses and visual representations of the data readily available within the web system would be of significant value where an issue is identified, and removes the need to process the data manually. The presentation of all diagnostics tools in one view is also useful to allow the results from the different methodologies to be considered in combination and conclusions to be drawn.

A detailed operating manual for the TOTUS web interface was available, however to support the use of the system by operational colleagues the project team created a 'Quick Intro Guide'[18] for issue to SSEN staff. This set out key information on how to request a user account, how to log in, where to find the key information relevant to the TASS trials, and how to set up alarm options.

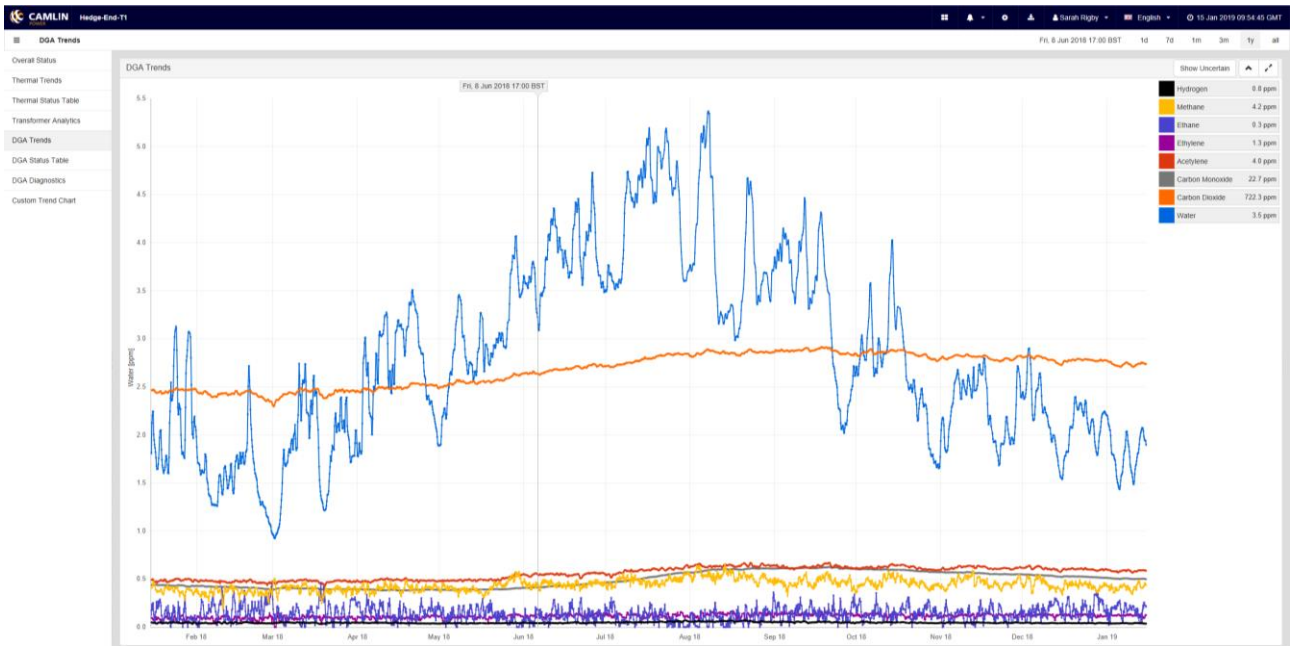
Results and Key Findings

During installation of the DGA equipment, conventional oil samples were taken for comparison with the results from the online system. Whilst the concentrations of a number of the dissolved hydro-carbonate gases were found to be too small to allow a precise comparison, convergence of the results obtained from laboratory analysis of the oil samples and from the DGA units was generally found to be acceptable by Camlin, with the exception of Acetylene and Ethane. More detail on the Acetylene readings is given below, and further oil samples will be taken following conclusion of the trials to give further consideration to the differences in readings from the two approaches. Tables presenting the two sets of results for each transformer are given as Appendix C[19].

Figure 7 shows a complete year of DGA trend data from one of the TASS trial transformers. Charts for each of the four transformers are given in Appendix D. The date that TASS operation commenced, 8 June 2018, is marked by the vertical line. Data collected prior to the TASS trials provides a benchmark for comparison with readings obtained during the trials.

[18] 'Quick Intro Guide to the TOTUSPRO system for SSEN's TASS Trials', SSEN, May 2018
[19] 'SSEN Device Operational Check', September 2017, Camlin

Figure 7 - DGA trend chart from the TOTUSPRO system



Though the y-axis in the chart relates to water in this example, and therefore does not reflect the scale of, for example, the carbon dioxide readings, it can be seen that the gas levels remain relatively stable with some fluctuations through time. Reviewing the patterns seen in the trend data from each of the transformers, all four have similar DGA profiles, and the following observations are made:

- A clear, and expected, seasonal effect can be seen in the water readings as moisture migrates from the solid cellulose insulation to the oil with increased temperatures, however the respective levels are satisfactory and indicate a good oil preservation system. Whilst moisture can be 'hidden' from oil DGA readings, advanced analysis undertaken by the SAPIENT team has been used to evaluate and confirm reasonable moisture in cellulose content.
- An increase in the rates of change of Carbon Monoxide and Carbon Dioxide can been seen during the summer as the higher seasonal temperatures act to accelerate degradation, however values remain well within acceptable levels. Further, these gases also migrate between the cellulose and oil, and such patterns are commonly seen in online DGA data.
- All four transformers have relatively high Acetylene readings, and for one transformer a notable increase in the Acetylene reading is apparent between May and August 2018, however this is in the absence of any other related fault gases. This is discussed in more detail below.
- The results raise no concerns regarding possible low, medium or high temperature faults within the transformers, and no changes linked to the TASS trials are evident.

Figure 8 presents charts configured to show ambient temperature (red line), top oil temperature (yellow line) and moisture (blue line) for one transformer from each site over a 3 month period from mid-November 2018 to mid-January 2019. The variation in moisture (readings ranging between 1.4 and 3.4 ppm) with temperature clearly illustrates the effect of temperature on the migration of water between the solid insulation and oil. The sites are situated around 40 miles apart in southern England, also indicating a correlation with the weather in this region.

Figure 8 - Screenshots from the TOTUSPRO system - Gillingham (top) & Hedge End (bottom)

Two SAPIENT reports[20, 21] have been prepared to date, as given Appendix E. These present an overview of the transformer condition based on analysis of the oil quality and DGA data obtained up to November 2018. This information is used to determine the Condition Group[22] of each transformer (ranging from Condition 1 - Good, to Condition 5 - Short-term risk), and provide a wider view on transformer health. Within the reports, values are colour coded to identify the readings which influence the Condition Group assigned to each transformer.

Based on the online DGA monitoring data from the TASS trial sites, the latest SAPIENT report assigns Condition Group 3 (yellow) to three of the transformers and Condition Group 4 (amber) to one of the transformers. The data set for each transformer indicates that for all transformers the driver for this categorisation is the Acetylene reading, as discussed in more detail below. In addition, the reports note that the cellulose moisture content is good for free breathing transformers (with desiccant breathers), however the value is formally judged as Condition 3 (yellow). No reference is made to the advanced fault diagnostics tools such as Duval Triangles, as the readings obtained do not indicate the presence of a fault. Consequently, the recommendation given is to continue to monitor the transformers.

To provide further information for consideration alongside the DGA data, information from the suite of transformer condition assessment tests undertaken at the trial sites was also made available to the SAPIENT team. Whilst the observations and recommendations included within the SAPIENT reports are broadly similar to those from the transformer condition assessment reports, some differences are apparent as to what constitutes an acceptable reading, again highlighting the role of expertise and considered interpretation of results within the broader suite of information available.

One notable change identified by the online DGA system was a steady increase in Acetylene readings on one of the trial transformers between May and August 2108. Acetylene is of significant importance as it is typically associated with high energy arcing (temperatures >700°C) occurring within a transformer, and can indicate a high level of risk due to combustibility.

Acetylene readings for each of the trial transformers have always been untypically high, attributed initially to the possible use of regenerated oil to top up the oil levels of the main tanks or tap changer conservators, however in May 2018 the readings for one of the transformers began to gradually increase, as shown in Figure 9.

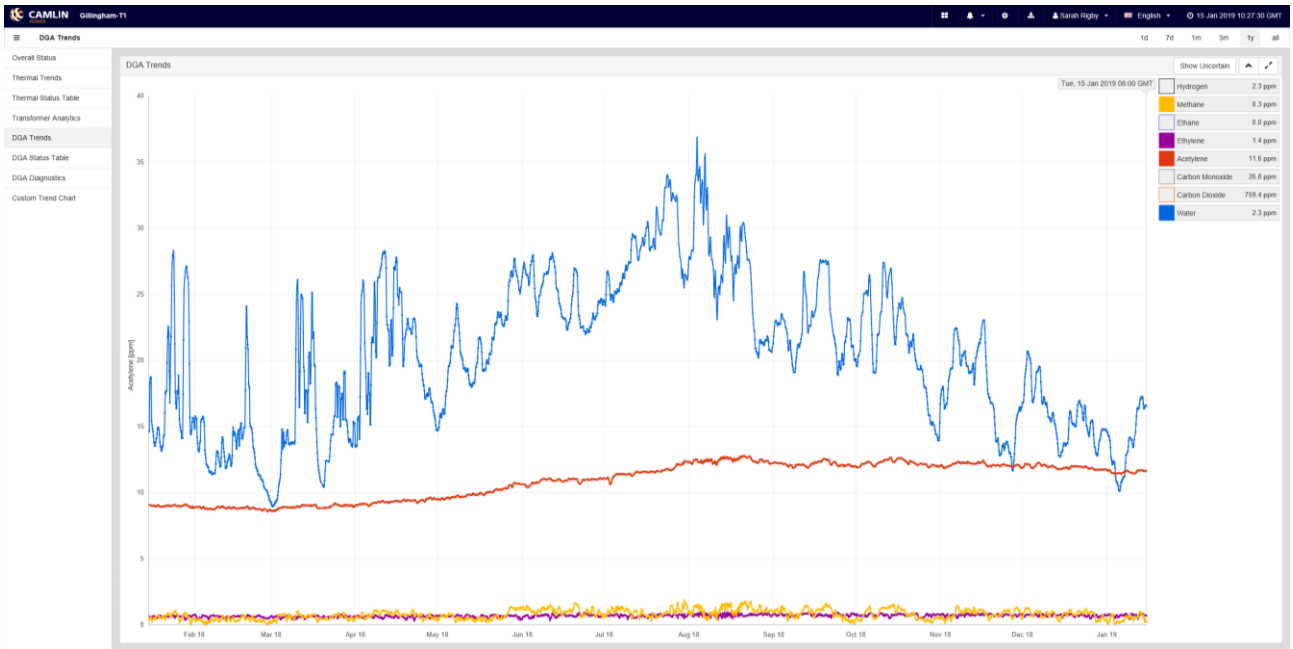
[20] 'Transformer Condition Report #1a - Gillingham and Hedge End Substations', Kelvatek (Camlin Group), July 2018

[21] 'Transformer Condition Report #2 - Gillingham and Hedge End Substations', Kelvatek (Camlin Group), November 2018

[22] Kelvatek Condition Groups are informed by the 5 categories indicated in CIGRE TB227, as follows:

Condition 1: Good	Condition 4: Mid-term risk
Condition 2: Normal for service	Condition 5: Short-term risk
Condition 3: Long-term risk	

Figure 9 - Trend chart presenting the pattern of DGA readings for Acetylene on one of the TASS trial transformers



The highest value between Oct 2017 and May 2018 was 10.7 ppm, then from early June the readings gradually crept up with the highest value of 12.8 ppm seen in mid August. These increasing readings eventually triggered text & email alarms from the system in July, as the values were higher than the alert threshold set at 50% above the maximum value seen prior to the trials. The readings subsequently stabilised towards the end of August at around 12 ppm.

This represents a curious observation as these unusual Acetylene levels were in absence of accompanying fault gases which would also typically be generated by faults associated with the formation of Acetylene, and no significant changes were apparent in any of the other fault gas readings.

This matter was investigated by the LEAN project team in collaboration with operational colleagues and drawing on expertise available through the SAPIENT analytics service procured with the TOTUS system, and the following investigations were used to examine and understand the issue:

- site inspection of the oil levels and breathers on both the main tank and tap changer to identify anything which may affect the oil pressures and allow deteriorated oil to flow from the tap changer into the main tank
- conventional oil sample analysis
- winding resistance tests - undertaken within the suite of mid-trial transformer condition assessment tests

No issues were found through any of these investigations, and the DGA Acetylene readings have remained stable since September, with no increase in the levels of any associated fault gases. Consequently the conclusion is that the cause of the high Acetylene readings is external and not related to any fault activity within the transformer. Examples of such external influences include:

- a top up of oil in the main tank or tap changer with oil already containing some acetylene (i.e. regenerated oil)
- migration of oil or air from the on-load tap changer diverter switch to the main tank

  or
- welding on the tank (though no welding activity has been reported at this site)

The project team will continue to monitor the online DGA data throughout the remainder of the TASS trials to ascertain whether the Acetylene levels, or any other gas levels, show any emerging patterns, and if so further work will be undertaken to investigate how the findings relate to specific operational conditions or the application of TASS.

Conclusions & Recommendations on Monitoring Asset Health

The techniques used to monitor asset health during the TASS trials serve two functions:

- to gather data for use in assessing any potential impacts to assets from the deployment of TASS
- to quickly identify emerging issues with asset health and minimise risks to security of supply during the trial of a new network technology

The combination of approaches used provides valuable information on differing aspects of asset health to build a comprehensive representation of the condition of the electrical assets integrated into the TASS scheme, including the circuit breakers and the core, windings, insulation and tap changers of the transformers. The point in time data obtained before, during, and eventually after, the trials can be compared to examine any changes which may be linked to increased switching due to TASS, and assess any risks to asset health. Ongoing monitoring then provides assurance to the project team and operational colleagues that any changes associated with TASS operation will be identified prior to any incident, particularly a loss of supply event, occurring.

For the majority of approaches used within the LEAN project, specialist expertise has been required to undertake tests, install equipment or interpret the results obtained to assess any implications and risks. These services can be readily procured from third parties, however, internal resources may also have the capabilities or knowledge to undertake surveys or assess results. Similarly, for wider adoption of certain techniques within a business, training may be provided to develop skills amongst relevant staff.

Where monitoring or testing services are sourced through standard procurement processes, costs are influenced by a range of factors including the suite of tests required, the functionality required, the number of sites to be assessed and the geographical locations of these sites.

At this point in time, there is no evidence of any increased risks to asset health due to the deployment of TASS. A further suite of transformer condition assessment tests and PD surveys will be undertaken following the conclusion of the trials, and findings will be presented in the project closedown report SDRC 9.8 'Knowledge & Dissemination'.

On this basis, prior to the installation of TASS it is recommended that visual inspections of the substation assets be undertaken. In addition, a suite of pre-installation oil samples, PD surveys and/or transformer condition assessment tests may be considered of value to validate that there are no pre-existing issues with the assets, and to provide a set of reference data for any subsequent tests. Once the system is operational, the business's standard approaches to asset health monitoring, including scheduled inspections and oil sampling, are expected to be sufficient to monitor any substations where TASS is applied, with more specialist techniques then used if any potential issues are identified which merit further investigation. However, this will be subject to further consideration during future decisions on the potential roll out of TASS technology.

Considering the online DGA monitoring system specifically, whilst it is not currently anticipated that this would be required as part of the wider roll out of TASS, the use of this technology during the LEAN project has provided valuable insight into the information that can be obtained from such systems, and how the data can be used with reference to available standards and diagnostic techniques to evaluate asset health.

To develop a broader view of how such technology could be applied to bring benefits to distribution network operation and investment, discussions have been held with asset management colleagues within the business as part of the project's internal dissemination activities. Through this, the following proposals have been made as to how else online DGA monitoring could be applied, with each representing a temporary installation of the technology at a given site to support cost-effective deployment:

- assess any specific transformers which may be of concern to Field Staff
- assess any impacts on transformer health at sites with significant levels of variable Distributed Generation (DG)
- monitor sites where there is a risk that a transformer may be overloaded for a period of time, for example in designated Constraint Managed Zones (CMZ) areas prior to a CMZ scheme being commissioned
- deploy the equipment on a range of different transformers for given periods to collate data that can be used to increase the business's understanding as to how such enhanced data relates to conventional approaches for tracking transformer health (such as point in time oil samples), and how this information could be incorporated to better define health indices, or utilised in some other way in the context of planning maintenance and replacement activities
- monitor new grid transformers during their first year of operation/warranty period to ensure there are no initial faults (e.g. due to manufacture or transport) and to establish a baseline (including seasonal effects) for comparison with future DGA readings, whether from point in time oil samples or online monitoring
- assess substations where the operational duty of the transformers has been altered - as with the TASS trials

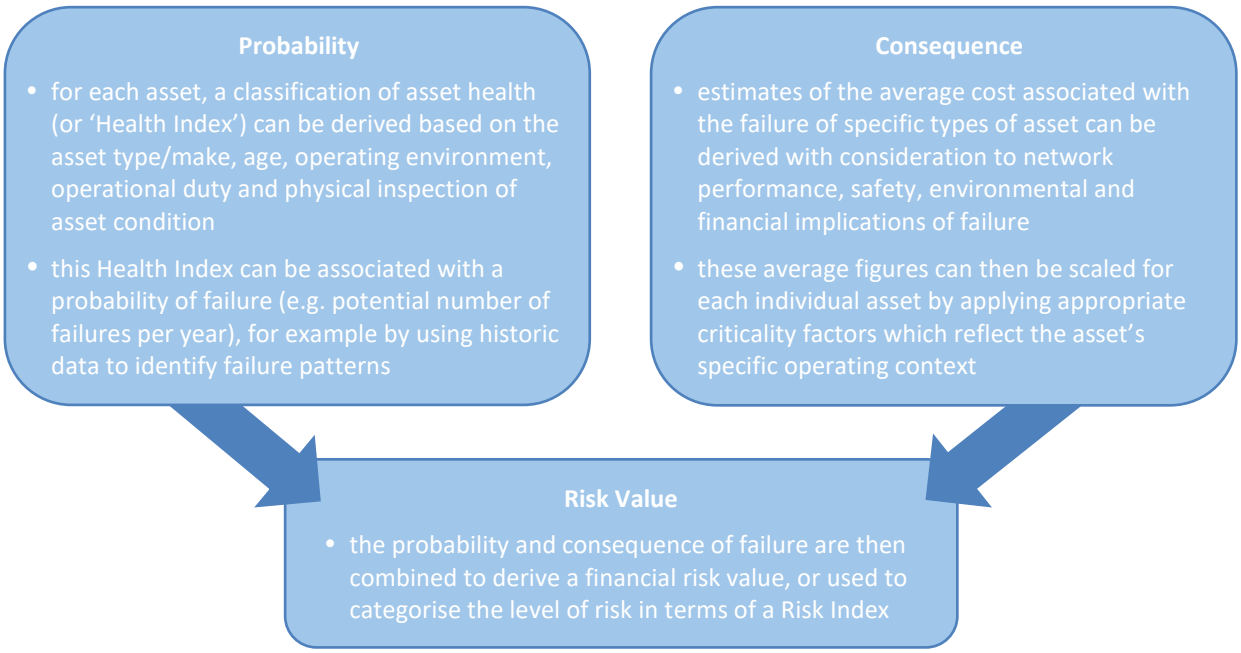
As the 4 units procured for use during the TASS trials have straight forward connections to the transformers via existing valves, it should be possible to remove and relocate the devices to other substations to investigate these alternative applications following conclusion of the LEAN project. Although the associated cloud hosting and SAPIENT services have only been procured up to the end of the TASS trials, in June 2019, those adopting the technology within the business would have the option to extend those services should they wish to.

With regard to the wider incorporation of the techniques presented here into standard business processes, increased levels of monitoring and testing typically incur higher costs, and require resources to gather and analyse data, but offer greater advantages, as follows:

- point in time measurement or inspection supports effective asset management by informing refurbishment or replacement investment decisions
- ongoing monitoring (whether permanent or for a temporary period) provides additional information under a range of operational or environmental conditions to provide a broader view of trends and influencing factors for asset management decisions
- online monitoring, with data available in real time, then adds the capability to quickly identify any emerging issues, allowing a situation to be investigated and managed to further minimise any risks to asset health or security of supply

As with any investment decision the appropriate level of monitoring for a given situation represents a balance between the costs and benefits of implementation. To allow the business case to be assessed, it is recommended that the economic benefits of different types of monitoring or levels of detail are quantified in terms of the associated reduction in risk. This is in line with the industry's progression to Condition Based Risk Management (CBRM)[23], and considers both the probability and consequences of asset failure, as outlined in Figure 10.

Figure 10 - Economic quantification of a reduction in asset risk



The derived financial risk values and information on the Capex and Opex costs of a given monitoring technology can then be used in a Cost Benefit Analysis (CBA) to determine the level of monitoring required for a given asset.

Further, the CBRM process applied by DNOs to target refurbishment, replacement and maintenance activity could be developed to incorporate an assessment of monitoring requirements. It is recommended that consideration be given to the inclusion of monitoring within a CBRM framework to automatically identify which assets may merit the use of enhanced monitoring to track the condition of the asset, or to assess the operational stress on the asset. This will support DNOs and other stakeholders in cost effectively reducing and managing risk.

[23] CBRM was first introduced to GB electricity distribution network operation by EA Technology Ltd and Electricity North West Ltd in 2002, and provides an enhanced approach to asset management which can improve reliability and reduce overall maintenance costs - subsequently, to meet the requirements of Electricity Distribution Standard Licence Condition 51 (SLC 51) for RIIO-ED1 and promote a common approach to the application of CBRM by all DNOs, a methodology has been collaboratively developed by the six GB DNO groups, as presented in 'DNO Common Network Asset Indices Methodology' v1.1, January 2017 - available at www.ofgem.gov.uk/system/files/docs/2017/05/dno_common_network_asset_indices_methodology_v1.1.pdf

4 Monitoring - Quality of Supply

This section presents an evaluation of the effects of TASS switching on power quality through analysis of data monitored during transformer energisation both with and without the use of controlled Point on Wave switching.

The content provides information to support decisions by DNOs considering the application of TASS or other automated switching technologies, and decisions by product vendors on the application of controlled switching.

The analysis indicates that to maintain best practice compliance with ER P28 voltage fluctuation limits, PoW switching would be necessary at some TASS sites, however other sites may operate acceptably without controlled switching.

Three subsections are presented:

- Inrush Current & Voltage Waveform Monitoring
- Analysis to Quantify the Effect of TASS Switching on Power Quality
- Conclusions & Recommendations

Inrush Current & Voltage Waveform Monitoring

The switching in of power transformers can result in large current and voltage transients. If not managed, these transients may cause quality of supply issues on the network which can affect customers' equipment, and may cause electrical or mechanical stress to the transformer itself or to other network assets.

Switching transients are associated with the inrush current created when energising a transformer. When using existing network switchgear, the probability of experiencing a high inrush current is associated with the amplitude of the residual flux within the transformer core (determined by the position on the voltage wave at which the transformer was switched out) and the prospective flux when the transformer is energised (determined by the position on the voltage wave at which the transformer is switched in). Where the residual flux matches the prospective flux, the inrush current is minimised, however the greater the difference between the residual flux and prospective flux, the greater the inrush current and resulting voltage step change.

Power quality monitoring can provide information on the magnitude and frequency of inrush currents and voltage variations to allow any impacts on the quality of supply to be assessed, and evaluate compliance with Engineering Recommendation P28 (ER P28)[24].

[24] Engineering Recommendation P28 'Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the UK', The Electricity Council, September 1989

Use within the LEAN Project

Whilst ER P28 relates to voltage fluctuations caused by industrial, commercial and domestic equipment, and not specifically to DNOs, industry best practice is to work to this recommendation, which permits infrequent voltage fluctuations of up to +/-3%. The TASS scheme has been designed in accordance with this objective.

The TASS control device can switch by operating the 33 kV and 11 kV circuit breakers through the existing RTUs and protection relays, however a synchronising relay with Point on Wave (PoW) switching capability has also been incorporated into the system architecture, as described in SDRC 9.4 'Initial Learning from Trial Installation and Integration'[25]. The synchronising relay selected for use during the trials is Vizimax's SynchroTeq MVX unit, and this device monitors the AC wave patterns on the 33 kV busbar and can be used to ensure that switching of the 33 kV circuit breaker to energise a transformer occurs at a point which minimises the inrush current and voltage transients.

In addition, the TASS control device monitors the voltage difference between the 11 kV busbar and the transformer being restored, and once the TASS transformer has been energised it uses this data to avoid any risk of a high voltage change when closing the 11 kV circuit breaker to put the transformer back on load. Should these measurements ever indicate that there is a risk of excessive voltage change on the downstream network, the TASS control device will not switch the 11 kV circuit breaker, and will instead raise a 'TASS Failed to Operate' alarm in the DMS to notify the network Control Room, who can then review and address the situation taking into account other alarms and status indications.

To assess the extent of any impact of TASS switching on quality of supply, and to compare the inrush currents and voltage variations seen both with and without the use of the synchronising relays, the following data is obtained from the trial substations:

- protection relays - the disturbance recording functionality of the existing MiCOM protection relays provides information on inrush current and voltage transient data and waveforms, together with current and voltage magnitudes and harmonic distortion seen on different phases during each switching event, at both 33 kV and 11 kV level
- synchronising relays - the SynchroTeq MVX units also record inrush current and voltage transient data and waveforms measured within the substation

This data is retrieved manually from the devices during site visits by the project team.

[25] LEAN SDRC 9.4 'Initial Learning from Trial Installation and Integration', September 2018 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents

The data obtained over the course of the trials has then been analysed to determine the effect of each TASS transformer energisation event on power quality. This analysis has comprised:

- comparing and validating data from the two monitoring sources - protection relays and synchronising relays
- determining the maximum inrush current for each transformer energisation event
- determining the voltage drop on the 33 kV busbar caused by the inrush current during each event
- comparing the range of inrush currents and voltage variations seen with and without the use of controlled PoW switching
- evaluating compliance with ER P28 and the probability of exceeding the specified limits (both ER P28 Issue 1 (1989) and expected refinements in the forthcoming Issue 2)

Further, a study has been undertaken to model the impacts of switching through time domain based simulation using the data obtained. This takes forward the technical analysis completed during Phase One of the LEAN project, allowing the original findings to be assessed and verified in light of operational experience. This work was commissioned from a consultancy with specialist expertise in power systems modelling, Mott MacDonald.

The aims of this study are to:

- assess the impact of inrush currents during transformer energisation on the upstream and downstream networks for the two TASS 33/11kV primary substations
- validate conclusions regarding the maximum impacts and voltage disturbances from transformer energisation

To meet these aims, the approach taken for the work included:

- creating detailed PSCAD-EMTDC[26] models for each of the two sites based on SSEN's PSS/E[27] network models for the relevant SEPD areas, together with configuration information and transformer data
- running 'worst case' simulations, in line with the modelling approach taken for Phase One
- comparing the worst case simulations with site data obtained from TASS transformer energisation events which resulted in high inrush currents
- modelling the impact of inrush currents on the upstream and downstream networks considering data obtained from low, medium and high impact transformer energisation events during the TASS trials
- assessing the potential for transformer energisation events to exceed ER P28 voltage step change requirements

The findings from this analysis and modelling work are presented in the 'Analysis to Quantify the Effect of TASS Switching on Power Quality' subsection below.

[26] https://hvdc.ca/pscad
[27] https://new.siemens.com/global/en/products/energy/services/transmission-distribution-smart-grid/consulting-and-planning/pss-software/pss-e.html

Experience from Implementation - Protection Relays

MiCOM protection relays have a disturbance recording functionality which can be used to log power quality data over periods when voltage or current fluctuations are experienced. Within the trial substations the High Voltage Protection Relay (HVPR) continually monitors the 33 kV circuit breakers and the Low Voltage Protection Relay (LVPR) monitors the 11 kV circuit breakers, and when disturbance recording is enabled any 'close' operation of a circuit breaker will trigger the device to retain data recorded over the associated period of time (in this case 500 ms before and 1000 ms after). Though it would have been useful to have the capability for a 33 kV circuit breaker operation to trigger LVPR recording, this was not possible.

The process for setting up the protection relays to capture data during the TASS trials was straightforward since all relevant data points to provide relevant status information and analogue values are already available within the MiCOM relays. However, in line with standard business processes, approval from the SSEN Protection team was required to alter the configuration of each device and enable disturbance recording.

This data provides voltage and current waveforms, current and voltage magnitudes, and harmonic distortion information for all TASS transformer energisation events, both with and without the use of PoW switching. This information can then be used to calculate the associated voltage step change for each event.

To download data, a laptop is connected to the protection relay via serial cable, and GE's S1 Agile[28] software is used to access the data and allow configuration of the MiCOM units.

The S1 Agile software is also used by the LEAN project team to view and analyse the power quality data from TASS switching events, with data also retained for further use in modelling the effects of TASS switching on the network.

This data logging process has been found to be reliable during the trials, however it is acknowledged that there may be a low risk of losing some periods of data in the event of maloperation or failure of a protection relay.

Experience from Implementation - SynchroTeq Unit

The synchronising relay selected for use during the trials is Vizimax's SynchroTeq MVX unit. These are compact devices which allowed straightforward installation within switchgear panels at the trial substations, and the processes for installing and integrating this with TASS and the existing substation assets are detailed in SDRC 9.4 'Initial Learning from Trial Installation and Integration'.

[28] www.gegridsolutions.com/multilin/catalog/engineering-tool-suite.htm

The relays offer very good functionality and meets the TASS requirements for transformer energisation using bank operated 33 kV circuit breakers, however, the MVX relay does not directly support the DNP3 protocol and so an auxiliary comms module is required for DNP3 data exchange.

To commission the units, a detailed understanding of PoW switching and operation of these devices was required to assess data obtained from a series of test switching operations and establish appropriate settings as the basis for ongoing optimisation. This expertise was provided by the product vendor, UK distributor Enspec Power. In service, the units continue to refine operation in response to switching characteristics and variations in circuit breaker timing observed.

Again, these devices monitor all TASS switching events whether or not the synchronising relay is used to provide PoW switching. Data recorded includes inrush currents and 11 kV voltage waveforms for all three phases, waveforms for the 33 kV single phase reference voltage, and information on the timings of both the PoW switching signal and 33 kV circuit breaker operation during transformer energisation. No data is provided on harmonic distortions, however this supplementary information is available from the existing protection relays.

To download data, a laptop is connected to the relay via Ethernet cable and a web browser interface is used to manage the data transfer. As the Ethernet port is positioned at the rear of the unit, rather than the face plate on the front of the unit, the switchgear panel must be opened to access the Ethernet port.

Vizimax's Event Analyzer software is then used to display the waveforms and circuit breaker operation, providing a visual representation of the changing voltages and currents during switching, as illustrated in Figure 12 and Figure 13. This provides a useful and intuitive means for the project team to analyse and assess the effects of TASS operation on power quality, both with and without use of controlled PoW switching.

Analysis to Quantify the Effect of TASS Switching on Power Quality

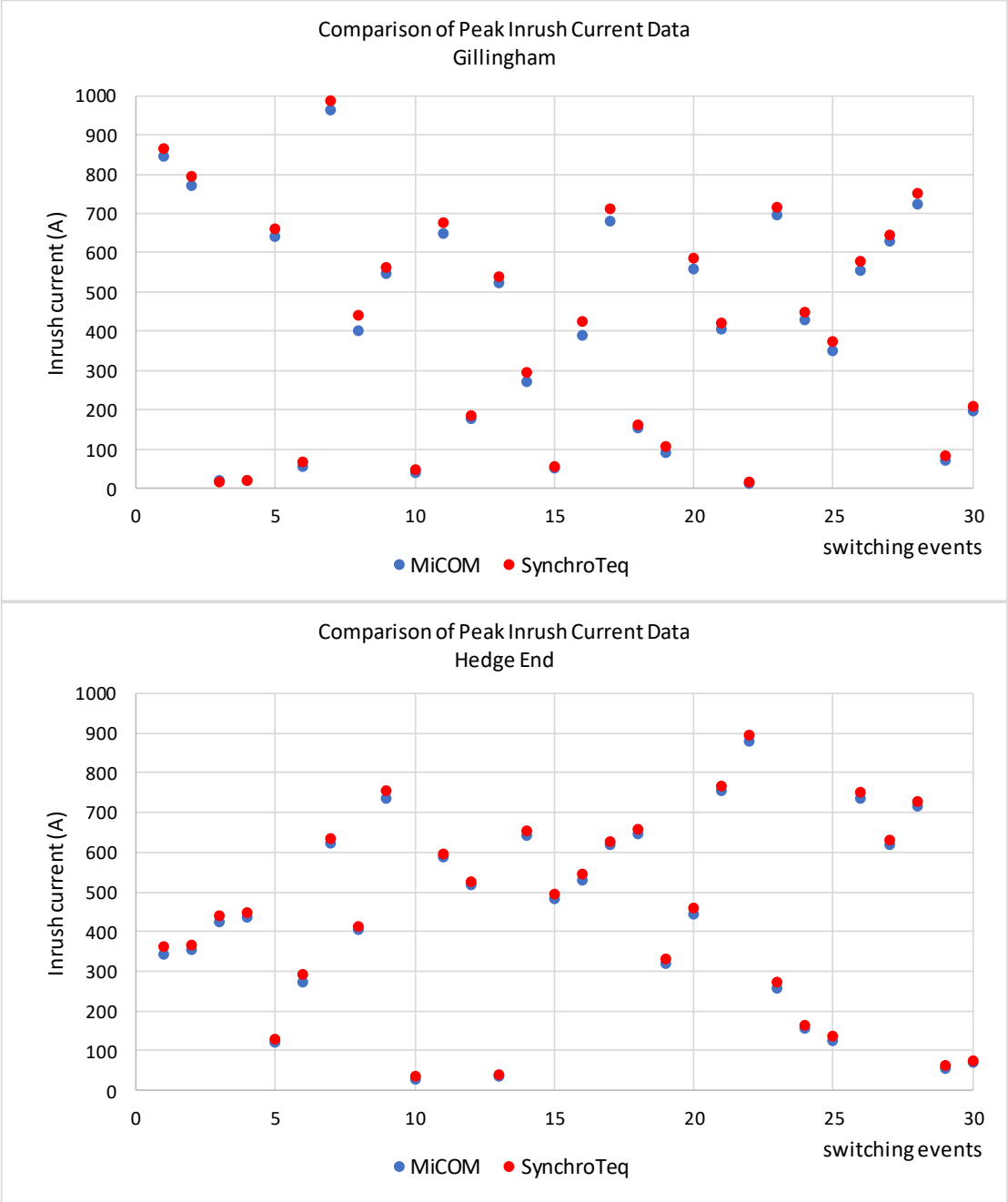
Data Set Analysed

Up to 15th January 2019, data for 30 transformer energisation events at Gillingham and 45 events at Hedge End have been obtained from both the protection relays and synchronising relays. The majority of these events have occurred without PoW switching, providing a valuable data set for use in assessing any potential impacts on power quality without the use of controlled switching, and around ~17% include the use of the synchronising relay to allow the effectiveness of these devices to be assessed.

Comparison of Data from the MiCOM Protection Relays & SynchroTeq Relays

Data from the protection relays and synchronising relays have been compared for each transformer energisation 33 kV circuit breaker (CB) closure switching event. It is evident that data on the inrush current magnitude and waveform, voltage magnitude and waveform, and timing of the switching sequence obtained from the MiCOM protection relays and SynchroTeq relays correspond well. The peak inrush current magnitudes recorded by each device agree within 30 Amps, and the timestamp for occurrence of the peak is very accurate. Figure 11 presents the comparisons of peak inrush current magnitude data from the two sources for 33 kV CB operation without controlled PoW switching.

Figure 11 - Peak inrush current magnitude data (without PoW switching) from the HVPRs and synchronising relays at the two trial sites - Gillingham (top) & Hedge End (bottom)



As this data corresponds well, the data set from the synchronising relays has been used for the detailed analysis since the Event Analyser software provides a swift data export facility to obtain the data in a transferable file format.

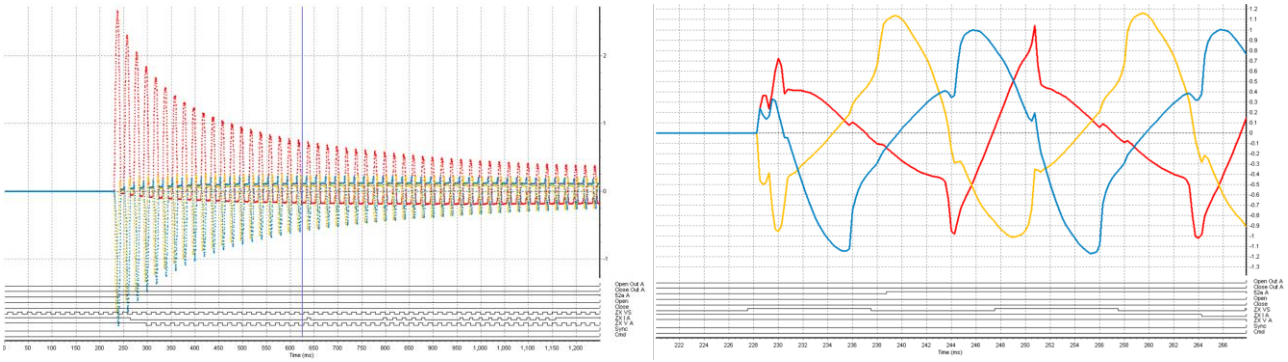
Transformer Energisation without PoW Switching

It can be seen in Figure 11 that the peak inrush currents observed at Gillingham ranged between 10 and 1000 Amps, with the highest peak inrush current experienced being 986 Amps. The inrush current waveform and corresponding voltage waveform from this high inrush current transformer energisation event are presented in Figure 12, as displayed in Vizimax's Event Analyzer software.

The range of peak inrush current measurements at Hedge End was between 10 and 900 Amps, with the highest recorded value being 894 Amps. The inrush current waveform and corresponding voltage waveform from this high inrush current event are presented in Figure 13.

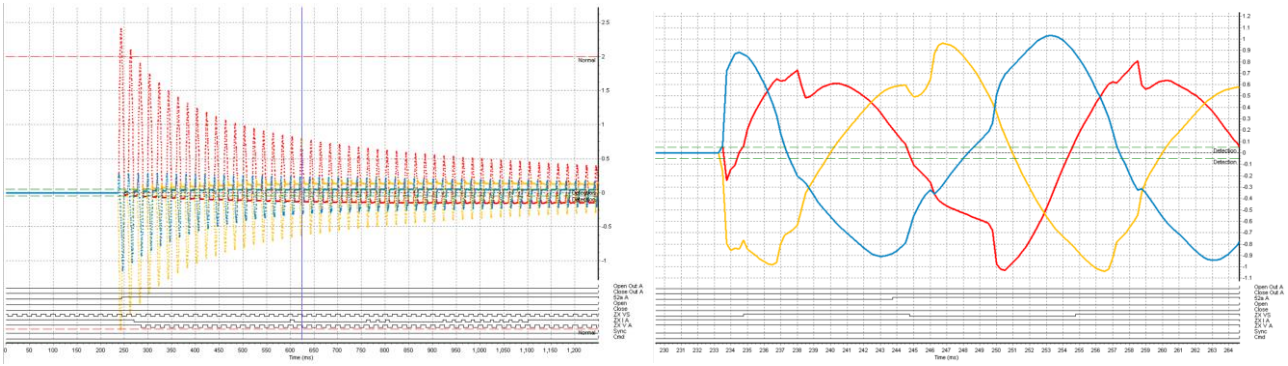
This variation reflects the fact that the probability of experiencing a high inrush current is associated with the both amplitude of the residual flux within the transformer core and the prospective flux seen as a result of the position on the voltage wave at which the transformer is switched in and energised.

Figure 12 - Highest inrush current event - 33 kV CB close operation without PoW switching - Gillingham



a) Inrush current waveforms b) Corresponding voltage waveform

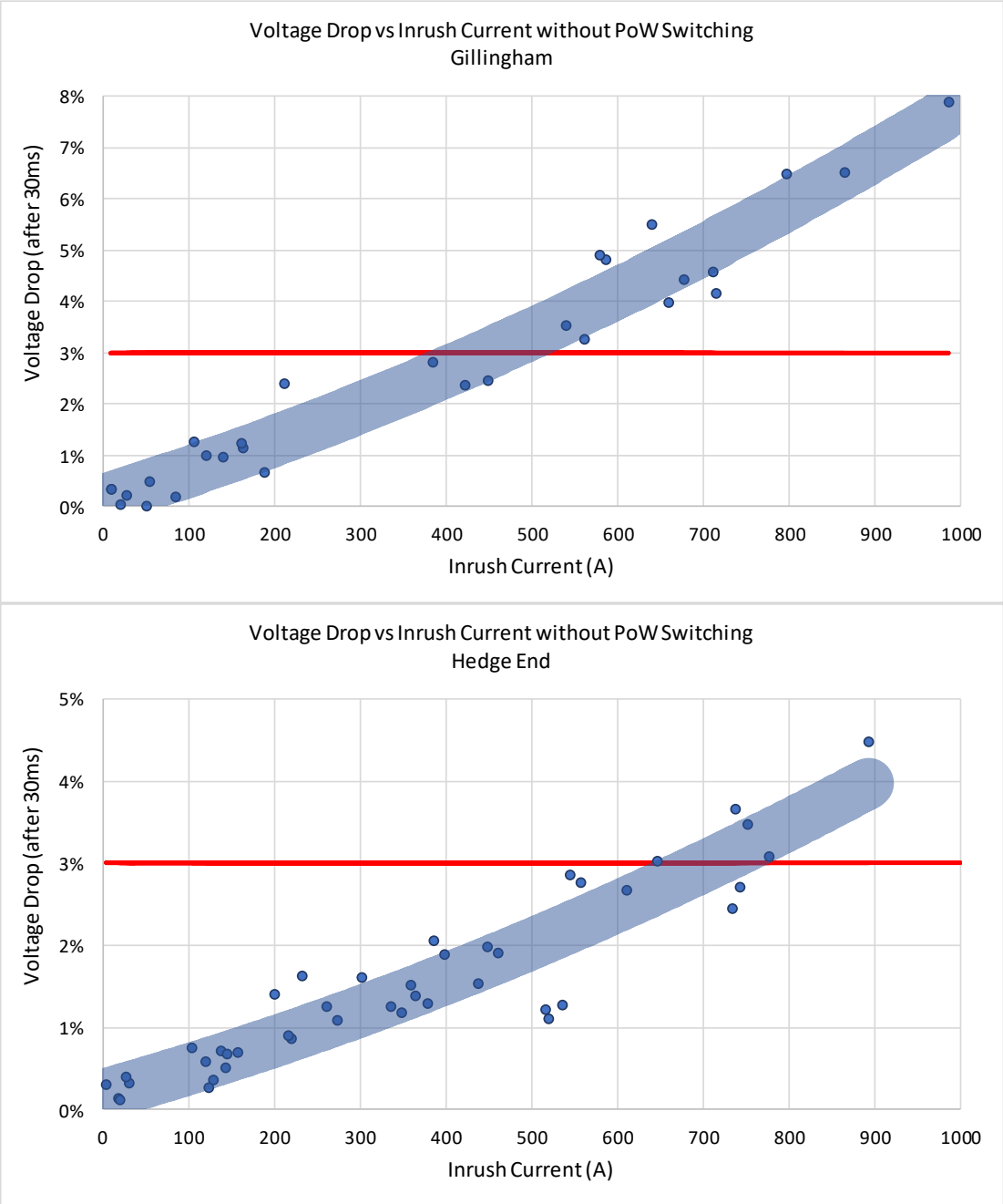
Figure 13 - Highest inrush current event - 33 kV CB close operation without PoW switching - Hedge End



a) Inrush current waveforms b) Corresponding voltage waveform

The data has been analysed to determine the voltage drop at the 33 kV busbar both 30 ms and 100 ms into each transformer energisation event, and the results at 30 ms are presented in Figure 14. The red lines in these charts represent the ER P28 reference point of 3% RMS voltage change over a duration of 30 ms.

Figure 14 - Peak inrush current and corresponding voltage drop at 30 ms for 33 kV CB close operation without PoW switching - Gillingham (top) & Hedge End (bottom)



At Gillingham the RMS voltage drop at the 33 kV busbar ranged between 0% and 7.9%. It can be seen that at this site a peak inrush current of ~400 Amps or above may result in a voltage drop exceeding 3%. In line with this, 40% (12 out of 30) 33 kV CB close operation switching events fall above the present ER P28 limit. Considering ER P28 Issue 2, this is

expected to include a modification of the acceptable limit to 6% for 100 ms and 3% thereafter for frequent switching events, and the data shows that 37% (11 out of 30) fall above this revised limit.

At Hedge End the relatively similar range of peak inrush current magnitudes results in a lower range of RMS voltage drop values between 0% and 4.5%. Here, a peak inrush current of ~630 Amps or above may cause a voltage drop exceeding 3%, and just over 10% (5 out of 45) 33 kV CB close operation switching events fall above the present ER P28 limit. Considering ER P28 Issue 2, only 2% (1 out of 45) of these switching events exceed the revised limit. This difference in compliance relates to the higher fault level[29] at Hedge End, as a higher fault level corresponds to a lower impedance which results in a smaller voltage drop for the same level of inrush current.

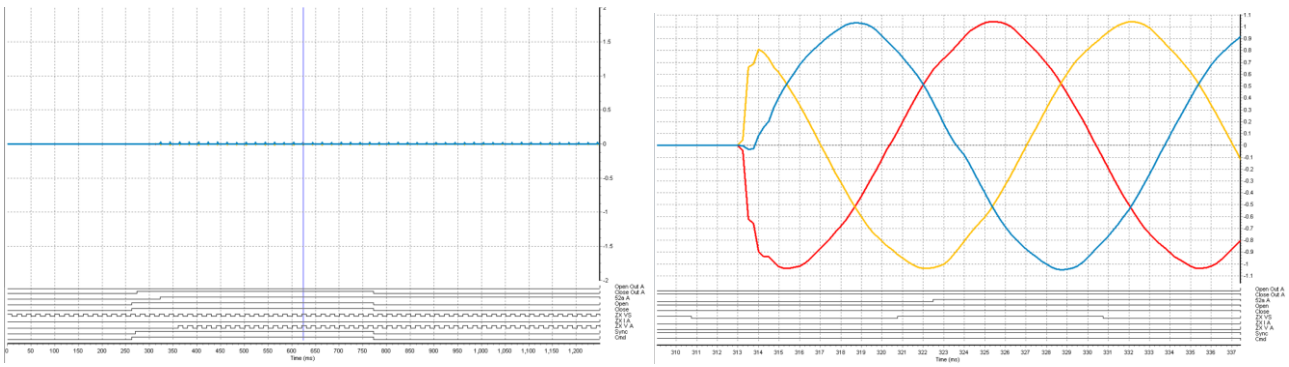
Transformer Energisation with PoW Switching

At the time of writing, PoW switching has been used for 13 TASS transformer energisation events.

Within these controlled switching events, the highest impact event at Gillingham resulted in a peak inrush current of 111 Amps (0.3 pu) and a corresponding voltage drop of 0.79%, and at Hedge End, the highest impact event saw a peak inrush current of 183 Amps (0.5 pu) with a corresponding voltage drop of 0.8%. At both sites, the lowest recorded peak inrush current was 3 Amps. These figures are consistently within the lowest ranges recorded without controlled switching, and as the devices continue to optimise operation and refine the timing of the switching signals, further improvement can be expected.

The inrush current waveforms and corresponding voltage waveforms from these highest impact events with PoW switching are presented in Figure 15 and Figure 16 for each site respectively. The contrast with the waveforms obtained from the highest inrush current events without PoW switching, as shown in Figure 12 and Figure 13, is clear.

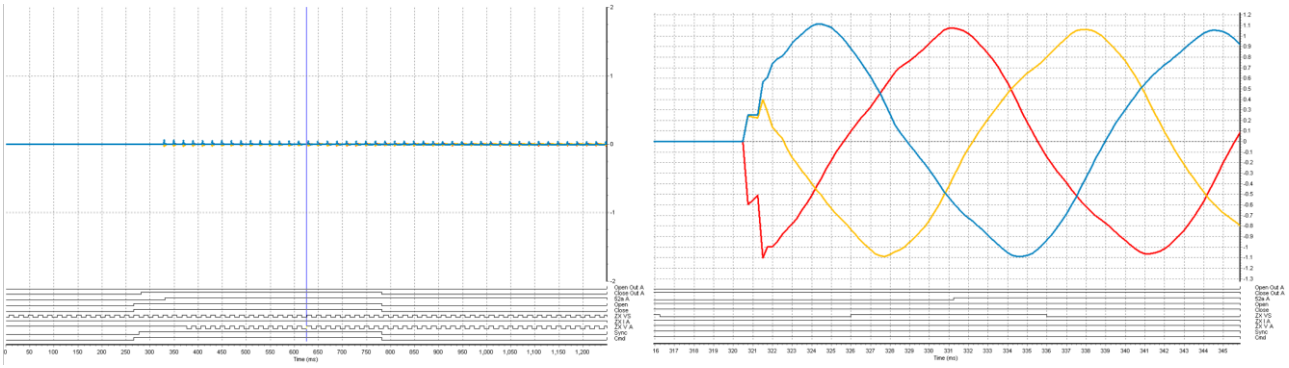
Figure 15 - Highest inrush current event - 33 kV CB close operation with PoW switching - Gillingham



a) Inrush current waveforms b) Corresponding voltage waveform

[29] the fault level for an electrical system, or item of equipment, relates to the current that the system would allow to flow in the event of a fault which results in a short circuit current, and the impedance of the system limits this current

Figure 16 - Highest inrush current event - 33 kV CB close operation with PoW switching - Hedge End



a) Inrush current waveforms b) Corresponding voltage waveform

It is clear from the data that the SynchroTeq relays provide an effective means to minimise inrush current on transformer energisation, resulting in consistently low voltage step change or voltage waveform distortion at the 33 kV busbar which is well within the ER P28 limits.

Following resolution of the issue with the synchronising relay's comms module described in Section 5 'Monitoring - TASS Operation', both TASS trial sites are now operating using controlled PoW switching, and further analysis will be provided in the project closedown report SDRC 9.8 'Knowledge & Dissemination'.

Modelling and Simulation Study

The subsections above provide empirical evidence of the inrush currents and corresponding voltage drops on the 33 kV busbars from transformer energisation events at the TASS trial sites. The modelling work commissioned for the project then extends the analysis to investigate the theoretical maximum possible inrush currents, and the associated impacts on the upstream and downstream networks.

This study used time domain based simulation in PSCAD-EMTDC models together with power quality data monitored during the trials, and provides an assessment of the possible worst case switching conditions together with simulations to replicate transformer energisation events recorded during the TASS trials and analyse the impact on the wider network. The cases assessed are as follows:

- Worst case scenarios
  - Conservative residual flux distribution of +60%, -30%, -30%
  - Representative residual flux distribution of +50%, -25%, -25%
- Simulation of TASS switching events
  - High inrush current event without PoW switching
  - Medium inrush current event without PoW switching
  - Low inrush current event without PoW switching
  - High inrush current event with PoW switching
  - Low inrush current event with PoW switching

The results and key findings are summarised below, and the full report on this study is provided as Appendix F[30].

- Worst Case Scenarios

  This analysis sought to re-evaluate the findings from the technical analysis undertaken during Phase One of the project with regard to the impact of transformer energisation, using data measured during the TASS trials. Accordingly, the theoretical maximum peak inrush current values and assumptions on the most adverse residual flux distribution (determined by the position on the voltage wave at which a transformer was de-energised) have been revised for 15 MVA transformers, as used in the TASS trial substations.

  Two 'worst case' scenarios have been assessed for energisation of 15 MVA 33/11 kV transformers, and these consider the prospective peak inrush currents associated with a conservative residual flux distribution of +60%, -30%, -30% at phase A, phase B and phase C respectively, and a representative residual flux distribution of +50%, -25%, -25%. These residual flux distribution assumptions have been revised from the +80%, 0%, -80% used for the Phase One work in light of research[31] based on empirical studies which indicates that a residual flux distribution of +60%, -30%, -30% will yield the worst case inrush current. The revised conservative residual flux distribution is therefore considered to be more appropriate for assessing the worst case situation associated with TASS switching, with the representative distribution providing sensitivity analysis.

  For the conservative residual flux distribution, the maximum inrush current calculated at Gillingham is around 1.4 kA, which is 5.2 times the rated transformer full load current (262 Amps at 33 kV for a 15 MVA transformer). For this inrush current, the derived maximum voltage drop at the substation's 33 kV busbar is 17%, with the voltage drop at the adjacent upstream 33 kV substations ranging between 9% and 14%. At the 11 kV busbar the voltage drop is around 16%, and at the nearest 132 kV substation the greatest voltage drop is 7%.

  At Hedge End, the conservative residual flux distribution results in a calculated maximum inrush current of 1.5 kA, which is 5.7 times the transformer full load current. The associated maximum voltage drop at the 33 kV busbar is 10%, with the maximum voltage drop at the upstream 33 kV substations ranging between 6% and 9%. The maximum voltage drop at the 11 kV is 10%, and at the nearest 132 kV substation it is 4%.

  Considering the physical health of the transformers, these maximum inrush currents of 5.2 and 5.7 times the transformer ratings at Gillingham and Hedge End respectively are well within design capabilities. Consequently, no winding or mechanical damage to the transformers is expected due to these levels of inrush current.

  As expected, the simulation results for the more representative residual flux distribution of +50%, -25%, -25% show a reduced maximum voltage drop at both the substations and on the upstream and downstream

[30] 'Transformer Energisation Study' report, Mott MacDonald, February 2019

[31] 'Transformer Model for Inrush Current Calculations: Simulations, Measurements and Sensitivity Analysis' (IEEE Transactions on Power Delivery - vol. 25, no. 4), N. Chiesa, B. A. Mork & H. K. Høidalen, October 2010

networks. At the Gillingham 33 kV substation the voltage drop reduces from 17% to 14% using this residual flux distribution, and at the Hedge End 33 kV substation it reduces from 10% to 9%.

A summary of these worst case scenario results is provided in Table 4.

Table 4 - Summary of the worst case scenario analysis

Case Study \ Voltage Drop		Substation Voltage Drop		Network Voltage Drop	
		33 kV Busbar	11 kV Busbar	Nearest 132 kV	Adjacent 33 kV
Gillingham	Conservative Residual Flux	17%	16%	7%	9% - 14%
	Representative Residual Flux	14%	13%	5%	7% - 13%
Hedge End	Conservative Residual Flux	10%	10%	4%	6% - 9%
	Representative Residual Flux	9%	9%	4%	5% - 8%

The results for the theoretical maximum inrush current under the worst case residual flux distribution scenario show significant differences with the values measured at each trial site. Here, the modelled inrush current values are 1362 Amps and 1494 Amps for Gillingham and Hedge End respectively, in comparison to the measured values of 986 Amps and 893 Amps observed at each site respectively. This is attributed to differences between the simulation model and the physical network and performance of individual transformers, including the core saturation characteristics and air-core reactance, which it is not possible to refine.

The detailed simulation results indicate that when considering the worst case residual flux distribution assumed in this study, the probability of exceeding the 3% voltage drop limit specified in ER P28 during transformer energisation is around 83% at Gillingham and around 74% at Hedge End. To avoid exceeding a 3% voltage drop in this case, the peak inrush current experienced would need to be below 458 Amps at Gillingham and 540 Amps at Hedge End.

In Phase One of the project a chart was created to allow the worst case voltage drop for a given transformer and substation situation to be estimated. The chart presents general curves of prospective worst case voltage drop associated with a range of system fault levels at the energising busbar, for various combinations of transformer size and winding connections. By selecting the most suitable curve for the transformer under consideration (based on size and winding connections), the known system fault level can be used to indicate the associated potential worst case voltage drop. Where a specific curve is not suitable, a figure can be estimated by averaging between the closest curves.

This chart has been updated to include curves for 15 MVA YY winding configuration transformers, as commonly used within distribution primary substations, including the TASS trial sites. Whilst the curve for the worst case analysis presented here relates to the revised residual flux distribution assumption, as distinct from the +/-80% residual flux distribution represented in the original curves from Phase One, the additional curves allow the modelled worst case scenario to be compared with the original curves, and with the curve representing the data measured from the highest impact events observed to date during the TASS trials. The chart is presented as an appendix of the 'Transformer Energisation Study' report provided as Appendix F.

- Simulation of TASS Switching Events

  This analysis assesses examples of high, medium and low inrush current TASS transformer energisation events with and without the use of PoW switching for both Gillingham and Hedge End substations.

  To create the simulation model for each site, the switching angle for the high inrush current event without PoW switching was estimated from the time stamp of the measured inrush current data, and the air-core reactance value and residual flux (remanence) were varied until the modelled peak inrush current for this derived switching angle corresponded with the measured value. The air core reactance was then assumed to be a fixed parameter, and the transformer residual flux was iteratively varied to align the modelled results with the measured inrush currents for the medium and low events without controlled switching, and for the high and low events with PoW switching.

  Table 5 summarises the results from the simulations at points across the wider network, and provides a comparison with the voltage drop figures from data recorded during the TASS switching events.

Table 5 - Summary of results from the simulation of TASS switching events

Case Study / Voltage Drop			Substation Voltage Drop			Network Voltage Drop	
			33 kV Busbar		11 kV Busbar	Nearest 132 kV	Adjacent 33 kV
			Measured	Simulated	Simulated	Simulated	Simulated
Gillingham	Without PoW Switching	High	7.89%	11.8%	11.9%	2.0%	10.9%
		Medium	0.98%	3.8%	3.8%	0.5%	3.5%
		Low	-0.16%	0.3%	0.3%	0.0%	0.3%
	With PoW Switching	High	0.74%	0.5%	0.5%	0.1%	0.4%
		Low	0.30%	0.1%	0.1%	0.0%	0.1%
Hedge End	Without PoW Switching	High	4.48%	4.4%	4.3%	1.9%	3.9%
		Medium	0.70%	1.5%	1.5%	0.4%	1.4%
		Low	0.26%	0.5%	0.5%	0.2%	0.5%
	With PoW Switching	High	0.80%	0.5%	0.1%	0.2%	0.5%
		Low	-0.09%	0.0%	0.0%	0.0%	0.0%

Simulation of the highest peak inrush current transformer energisation event without PoW switching at Gillingham (985 Amps) results in a worst case voltage drop at the 33 kV busbar of 11.8%, with the voltage drop at the upstream adjacent 33 kV substations varying between 8.5% to 10.9%. The maximum voltage drop observed at the 11 kV busbar is 11.9%, and at the nearest 132 kV substation is 2%. For the medium (374 Amps) and low (67 Amps) peak inrush current events simulated, the voltage drop at the 33 kV busbar reduces to 3.8% and 0.3% respectively. For the transformer energisation events using PoW switching, for even the high impact event the worst case voltage drop at the 33 kV busbar remains below 0.5%.

At Hedge End, the simulations without PoW switching results in a worst case voltage drop at the 33 kV busbar of 4.4% for the high inrush current event (889 Amps), with the voltage drop at the upstream adjacent 33 kV substations varying between 2.6% and 3.9%. The maximum voltage drop observed at the 11 kV busbar is 4.3% and at the nearest 132 kV is 1.9%. For the medium (407 Amps) and low (163 Amps) peak inrush current events, the voltage drop at the 33 kV busbar reduces to 1.5% and 0.5% respectively. For the transformer energisation events using PoW switching, again even the high impact event worst case voltage drop at the 33 kV busbar remains below 0.5%.

Whilst the measured and simulated figures for the high impact event at Hedge End correspond well at 4.48% and 4.4% respectively, the value from the simulation for Gillingham is 11.8% in contrast to the measured figure of 7.89%. An examination of this difference notes that the fault level calculated using the PSCAD-EMTDC model for this site, created through an ETRAN[32] translation of SSEN's PSS/E network model, is 4.37 kA and is therefore lower than the fault level of 5.06 kA calculated from the PSS/E model. Consequently the PSCAD-EMTDC simulations may derive higher levels of voltage drop associated with the inrush current measured on site.

Further, a simplified PSCAD-EMTDC model has been created to represent the localised network at Gillingham and give a fault level of 5.03 kA, in line with the equivalent figure from the PSS/E model. The simulation of a high impact event using this abridged model results in a voltage drop at the 33 kV busbar of 7.2%, which is in line with the measured figure of 7.89%. The investigations undertaken by Mott MacDonald have not established which aspect of the translation process causes the more extensive PSCAD-EMTDC model to lose consistency with the PSS/E model, however it is acknowledged that the simulation of the wider Gillingham network area presents values in excess of those that would be experienced on site.

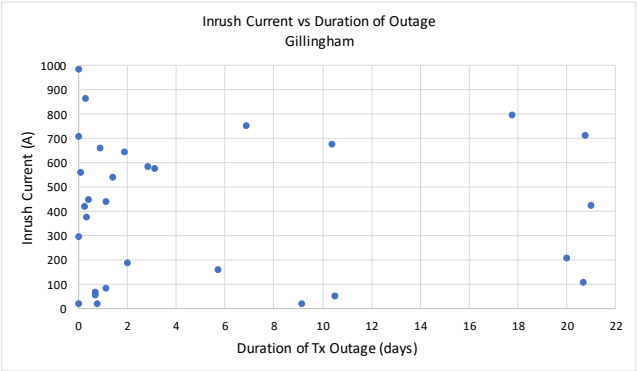
The simulation results presented above indicate that maximum voltage drop limit of 3% specified in ER P28 may be exceeded for high inrush current events at both Gillingham and Hedge substations, however, for transformer energisation events which result in medium or low inrush currents, the majority of events may remain compliant with the P28 limit.

[32] www.electranix.com/software/e-tran-plus

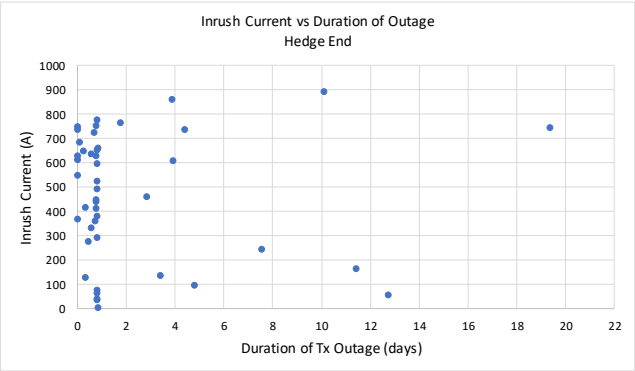
Assessment of the Effect of Transformer Outage Duration on Inrush Current

To investigate whether or not the residual flux within the core of a de-energised transformer may decay with time, the inrush current data and transformer outage durations from the TASS trials have been analysed to assess any potential correlations in outage duration and subsequent inrush current which may indicate a decay in residual flux. Within the TASS trials, the maximum duration of time that a transformer has been switched out is three weeks, with minimum outage durations of a few hours or less. As presented in Figure 17, this comparison does not indicate that a longer duration of transformer outage results in a smaller inrush current on transformer energisation, consequently it cannot be concluded that the residual flux within a transformer core decays over this 21 day time frame.

Figure 17 - Impact of duration of transformer outage on inrush current



a) Gillingham



b) Hedge End

Conclusions & Recommendations Regarding Power Quality Monitoring & the Use of PoW Switching

The power quality data obtained from the switching events during the trials, together with the accompanying analysis and simulation, significantly contribute to the understanding of the impact of TASS transformer energisation on the quality of supply at the primary substations and within the local distribution network.

The statistical analysis of the voltage drop and inrush current values from each TASS transformer energisation event shows that without controlled PoW switching, the probability that any individual event may result in a voltage drop which exceeds the 3% limit defined by ER P28 1989 varies significantly between the two TASS trial sites, with a 10% probability at Hedge End and a 40% probability at Gillingham. The lower probability at the Hedge End substation is primarily associated with the higher network fault level at this site, which results in a lower typical voltage drop. Further, considering the proposed modifications to ER P28, the probability of exceedance at Hedge End reduces to only 2% of the switch events seen to date, although there is little difference in compliance at Gillingham due to the higher magnitude of voltage drop typically experienced at this substation.

The synchronising relays used for the TASS trials are a relatively new item of equipment with no prior deployment on GB distribution networks, and previously SSEN had limited experience of the use of this type of device and mode of

switching. From the data obtained to date, however, it is evident that the PoW functionality delivered by the SynchoTeq relays provides an effective means of ensuring a consistently low level of inrush current during transformer energisation, which maintains the maximum voltage drop well within the ER P28 3% limit.

The simulation work has illustrated the complexities inherent both in translating or creating network models for analysis, and in establishing assumptions associated with aspects of the physical network and specific transformer performance which it is not possible to empirically define. However, the work provides a useful point of reference for consideration of the potential worst case switching scenario, and level of expected voltage variation across the wider network, as the derived figures can be understood to represent a higher impact than may be expected for the modelled sites. Further, the worst case inrush currents calculated within the studies are well within design capabilities for the transformers, thereby supporting the conclusion from Phase One of the project that inrush currents due to TASS switching present minimal risk of damage which may adversely affect transformer asset life.

The overall findings from this analysis and simulation, and the differences observed between the two TASS trial sites with regard to the probability of exceeding a 3% voltage drop, indicate that to maintain best practice compliance with the ER P28 voltage fluctuation limits, PoW switching would be necessary at some TASS sites, for example Gillingham, however other sites may operate acceptably without this controlled switching, such as Hedge End. To differentiate which sites would benefit from PoW switching, the probability of any switching event exceeding the specified limit would need to be considered with regard to both the potential maximum voltage drop during transformer energisation and the expected number of TASS switching events at the site. In addition, reference would need to be made to the guidance that will form part of ER P28 Issue 2 with regard to the acceptable levels of voltage fluctuation and any variations in requirements for different frequencies of events[33].

To provide an estimation of the potential maximum voltage drop for a given site, the chart created to present curves of the prospective worst case voltage drop for various combinations of transformer size and winding connections can be used. The voltage drop associated with the relevant system fault level can be indicated by interpolating between suitable transformer curves, and with reference to the figures recorded for the highest impact TASS switching events. This chart is presented as an appendix of the 'Transformer Energisation Study' report provided as Appendix F.

Consideration of the potential cost for application of PoW switching will be provided with the review of the business case to be included in SDRC 9.6 'Site Performance to Date'.

Power quality data obtained during the TASS trials may be available for further research purposes by emailing enquiries to the project team via lean@sse.com.

[33] at the time of writing proposals for ER P28 Issue 2 include different planning limits for frequent, infrequent and very infrequent events, where the proposed definitions for these events are:

frequent events ≈ more than 4 events per 1 calendar month
infrequent events ≈ 4 events per 1 calendar month
very infrequent events ≈ 1 event per 3 calendar months

5 Monitoring - TASS Operation

This section describes the approaches used to monitor the operation of TASS throughout the trials and validate that the system operates as designed to provide an effective, reliable solution for reducing network losses.

It is aimed at those considering the application of TASS at scale across a given network, and those developing operational review processes to assess technologies during electricity network innovation projects.

TASS continues to successfully control automated switching at the trial substations, demonstrating the system's ability to both reduce losses and respond appropriately to different network situations.

This operational monitoring is presented under the following subsections:

- Data Sources
- TASS Operational Review Processes
- Issues Identified through Operational Review
- Control Room Engagement with TASS
- Conclusions & Recommendations

Data Sources

A number of data sources are monitored to evaluate the performance of TASS and identify any potential issues with the operation of the scheme.

Key TASS information has been incorporated into SSEN's central data historian system, PI, with data obtained in real time via SCADA and displayed in the Distribution Management System (DMS), PowerOn Fusion. The processes for integrating TASS with SCADA and the DMS are detailed in SDRC 9.4 'Initial Learning from Trial Installation and Integration'[34]. Graphical representations of the tracked data can then be accessed via the business's PI ProcessBook and PI Datalink tools.

The data historian and DMS also provide standard operational information of relevance when investigating and assessing the TASS system's response to any issues. This includes network configuration information; asset status indications and alarms; load information; and substation access and switching schedule records.

Data logged within the TASS control device provides a detailed step-by-step record of the signals and decisions processed by the TASS algorithm to supplement the information available within PI. In addition, this gives a back-up data source in the event that a comms issue temporarily prevents SCADA from acquiring data, and the data can be used to validate the precise timings of the TASS events where there may have been a delay in the transmission of data via SCADA.

[34] LEAN SDRC 9.4 'Initial Learning from Trial Installation and Integration', September 2018 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents

This data is retrieved manually from the TASS control devices within the substations every two weeks, or obtained when required for any investigation, and comprises the following three logs:

- event log - operational data such as system statuses, alarms, flags, timers and switching commands issued
- fault log - TASS system faults together with data denoting the cause
- load data - 10 minute average, minimum and maximum values for load measurements

Event and fault log data is used to support the assessment of TASS operation and its responses to different network situations. The load data is used to determine the losses saved due to TASS operation, as presented in Section 6 'Interim Assessment of TASS Performance at the Trial Sites'.

Additional information may also be obtained from other sources within the business as required, such as the site log books held within the substations, and the Real Time Systems (RTS) comms log which records data flows from the substation Remote Terminal Units (RTUs).

TASS Operational Review Processes

The processes put in place to review TASS operation at the trial sites are designed to allow the project team and operational staff to:

- monitor the system's response to different operational situations
- identify and respond to any potential issues with TASS operation
- understand the business's interaction with TASS

Whilst TASS provides an automated system for switching transformers to reduce losses in primary substations, the integration of TASS into the DMS provides network Control Engineers with visibility of the scheme and the capability to remotely manage the system for operational and safety purposes.

TASS commands support the Control Room in responding to operational incidents, and allow the substation to be returned to conventional operation at times of increased operational pressure, for example when a storm is expected. They also allow Control Engineers to remotely suspend TASS operation when someone wants to enter the substation, or if there are reports of a trespasser in the substation. This is important for safety, to minimise the risk of switching or transformer energisation whilst there is someone in the switch room or near the transformers.

Alarms raised by the TASS system are designed to flag an issue with its operation or indicate that a situation has been identified whereby it may not be possible or safe for the algorithm to initiate switching. If a TASS alarm is triggered, the Control Room can review the situation taking into account other information shown in the DMS, and react

accordingly, including restoring the TASS transformer if necessary. Once any situation has been resolved, a Control Engineer can then re-enable TASS and allow the system to resume automated control.

The TASS specific commands, status information and alarms incorporated into the DMS are as follows:

control commands

- Enable TASS/Disable TASS
- Lock TASS/Unlock TASS

status indications

- TASS Enabled/Disabled - TASS has manually been set as not operational by the central Control Room; or certain network alarms/status indications have caused the TASS algorithm to automatically suspend operation - in this case unless there's a fault or other network issue, the algorithm will restore the TASS transformer if it is switched out and then have no further operational control - this equates to a return to conventional substation operation
- TASS Locked - the system has been remotely halted by the Control Room through a command that will not initiate transformer energisation if the TASS transformer is switched out; TASS has automatically locked in response to manual switching (i.e. not initiated by TASS) or use of the Control Isolation Switch in the substation without TASS having first been Disabled or Paused - in this case if the TASS transformer is switched out, it will remain so
- TASS Paused - TASS has been paused manually via the wall box on site - again no subsequent operation will occur, therefore if the TASS transformer is switched out, it will remain so
- TASS Operating T1/T2 - a TASS switching event is in progress
- Amps Away from TASS CoP - provides an analogue signal to indicate how close the substation loading is to the Crossover Point (CoP) which would initiate TASS switching

alarms

- TASS Failed to Operate T1/T2 - a TASS switching operation not been successfully completed; or network data indicate that there may be an operational risk in trying to switch a transformer
- TASS Faulty - there is an internal problem with the TASS device or an issue with its connectivity to substation data, and so the algorithm does not have all the input data needed to make robust switching decisions
- TASS CoP Error - the control device has not switched in the transformer even though the load at the substation has increased above the crossover point where both transformers should be in operation

To validate that the system is working as designed, the operation of TASS is reviewed daily by the LEAN project team, primarily using the PI ProcessBook. All switching events and any alarms raised are recorded in the 'TASS Operational Review Log' created for the trials, and the reason for each operation is identified based on available data. Where any causes are uncertain, additional information is obtained from the TASS control devices on site, or requested from other relevant systems within the business.

The detailed information recorded in the event and fault logs of the TASS control device is reviewed following each site visit to retrieve data. Any anomalies are noted for investigation, with information added to the 'TASS Operational Review Log' as relevant, and the data is then stored for reference or future analysis.

Issues Identified through Operational Review

The processes in place to monitor TASS operation have allowed all potential issues with the system to be swiftly identified. This has been crucial to ensure that the cause of the issue could be ascertained and confirm that TASS operated as necessary to provide an appropriate response.

In each case TASS responded as designed to the SCADA alarms issued by other substation assets, and a relevant TASS alarm was raised in the DMS which the Control Engineer on duty identified and managed as requested during training. The LEAN project team investigated each situation to establish what had happened, and identify and implement anything needed to resolve the issue. These events have provided indispensable live testing of the TASS system, and have demonstrated that TASS was able to quickly identify a problem, halt operation if needed and provide notification in the DMS as designed. The operational principles and responses to different network situations designed into the TASS scheme are presented in SDRC 9.4 'Initial Learning from Trial Installation and Integration'.

The key issues identified during the trials to date are summarised below, and relate to the following devices/systems:

- the comms modules used with the TASS synchronising relays
- the TASS algorithm voltage difference setting
- substation Low Voltage Alternating Current (LVAC) systems
- substation RTU data
- SCADA communications between the substation & Control Room

TASS Synchronising Relay Signals

As reported in SDRC 9.4 'Initial Learning from Trial Installation and Integration', an intermittent issue was experienced at the trial sites whereby 33 kV circuit breaker operation did not occur when required during TASS switching. Additional testing verified that the TASS control device and control algorithm were working correctly, and that the issue related to the signal from the synchronising relays incorporated into the scheme to provide controlled Point on Wave switching. Detailed testing by the device manufacturer pin-pointed this to an error in the firmware of the comms module used with the relay to provide DNP3 communications, with a certain combination of logic status flags preventing a control signal from being processed correctly. Updated firmware was provided accordingly, which the project team were then able to upload to the comms modules at the trial sites.

Prior to the new firmware being installed, the TASS system bypassed the synchronising relays. As reported in Section 4 'Monitoring - Quality of Supply', this mode of operation has provided valuable information for use in assessing any potential impacts on power quality without the use of Point on Wave switching.

TASS Algorithm Voltage Difference Setting

The seasonal increase in electricity demand at one trial site has resulted in more frequent TASS operation from around early November onwards, with the system eventually switching a transformer in every day at around 5.30pm for the evening peak, and then switching back to one transformer when the load drops again after 10pm. This switching has not presented any issues for the system, however this changing demand pattern has also resulted in changes to the voltage levels seen during TASS switching, which revealed a problem with one of the check settings applied within the TASS algorithm.

When switching, the algorithm checks the voltage difference between the transformer being switched back in and the 11 kV busbar prior to operating the 11 kV circuit breaker, to ensure that voltages are within acceptable limits. The algorithm is programmed to halt TASS operation and raise a 'TASS Failed to Operate' alarm where this voltage difference exceeds a specified level, and the value was originally set at 300V. In contrast, the Automatic Voltage Control (AVC) settings at the site allow a voltage difference of up to 330V (11kV +/-1.5%) before the AVC scheme operates and the tap changer acts to brings the voltages more in line. Consequently, on a number of occasions from mid-November TASS halted operation and raised an alarm, even though the voltage difference was within acceptable limits.

To address this and resolve the issue, the voltage difference specified in the TASS control algorithm was revised to 400V (allowing for any issues with accuracy of the readings due to latency in data transfer, etc.), and the new code was tested in SSEN's Protection laboratory, before being uploaded at the two trial sites.

This issue was not seen at the other trial site due to the different characteristics of the load profile at that substation.

Low Voltage Alternating Current (LVAC) System

Primary substations typically have an LVAC system which provides power to auxiliary systems at the site, such as the DC batteries chargers, lighting and heating. The LVAC system takes power from one of the transformers within the substation, and an Automatic Changeover (ACO) scheme transfers the supply to another transformer in the event that the transformer providing the power switches out. Accordingly, ACO operation may be triggered by TASS switching, resulting in increased operation of the scheme and the possibility that where there is an existing issue with the LVAC scheme, TASS operation may bring this to light.

Three issues relating to the LVAC systems have been experienced during the trials, each of which triggered SCADA

alarms which TASS identified and responded to as designed. The TASS response was seen by Control Engineers via the DMS and by the LEAN project team via PI ProcessBook, and a review of the event log and fault log date downloaded from the TASS control device on site identified the specific SCADA alarms which TASS had responded to.

Firstly, it was apparent from the TASS fault log and the site log book (used to record site visits by Field Staff) that the Miniature Circuit Breaker (MCB) for one of the battery chargers on site had tripped three times over the course of a month. On each occasion TASS had responded to the associated SCADA alarms by Disabling itself and raising a 'TASS Failed to Operate' alarm, as this situation may relate to an emerging fault with the protection scheme. At the site in question there are 3 battery chargers, and these will restart each time the LVAC ACO scheme operates. With the seasonal increase in electricity demand, TASS began to switch more frequently, and so more ACO scheme operations occurred, thereby restarting the battery chargers. A site inspection found that the MCB which kept tripping was a 'Type C' with regard to tripping characteristics[35], when in fact a 'Type D' was required (as used for the two other battery chargers) to accommodate the inverter start-up currents seen on some occasions when the battery charger restarts. A new 'Type D' MCB was sourced and installed by the LEAN project team to address this issue.

Secondly, following another situation where TASS had Disabled itself and raised a 'TASS Failed to Operate' alarm, the TASS fault log data indicated that this was also due to a SCADA alarm from the LVAC system, and a site visit found that a fuse for the LVAC ACO scheme had blown. The 2 amp fuse was replaced by the LEAN project team, and around ~20 test operations were run to measure the current drawn by the ACO scheme. The readings were never more than ~0.26 amps, and so it is suspected that the fuse had blown due to being old or faulty rather than experiencing an unacceptably high current, and there have been no further issues with the fuse.

Thirdly, when commissioning the TASS scheme at one of the sites it was found that the LVAC system was set up such that from a comms perspective each LV board was seen independently. Consequently, 'false' alarms would have been raised each time the ACO scheme operated even though the two LV boards were operating correctly in combination. To address this the TASS commissioning team added comms links between the two LV boards, allowing TASS to work correctly on commencement of the trials in June 2018.

However, in December a Field Engineer who attended site to deal with a 'defect' logged with the LVAC scheme found these links between the LV boards, and as that's not usual for this site, attributed this to the reason that a defect had been raised. The associated record in the site log book notes that removing the links would lead to misleading alarms being raised in PowerOn Fusion, and the Field Engineer had contacted the duty Control Engineer to discuss this, but as both believed this to be a valid defect to be resolved, the links were removed with Control accepting the need to return to using judgement when the associated alarms were raised.

Without these links, when TASS next operated it picked up the SCADA alarms now being raised, and so Disabled itself and restored the transformer that had just been switched out, as it's designed to.

[35] see 'MCB Selection' on https://electrical-engineering-portal.com/what-is-the-difference-between-mcb-mccb-elcb-and-rccb

The TASS response was identified by the project team via the PI ProcessBook, and discussed with the associated Field Engineer and Control Engineer. In tracking the defect back, this was found to have been raised prior to the TASS trials commencing, and indeed may even have been raised due to the fact that 'false' alarms were being triggered before the comms links were installed. In addition, these alarms are not necessary for supervision of the substation, since many other valid alarms will be raised if there is a true issue, accordingly only a small number of substations are set up in this way and use these alarms.

Consequently, it was agreed that the links be reinstated to prevent spurious alarms, and allow TASS to continue operating.

A marker in the DMS schematic for the site was also added to note that the associated alarms will not be raised while the links are in place during the TASS trials. With hindsight, the project team acknowledge that this would have been beneficial directly following TASS commissioning.

Remote Terminal Unit (RTU) Data

A situation associated with Control Isolation Switch operation on the RTU in one of the substations caused TASS to Lock itself, and then as the RTU was no longer providing substation data to the TASS control device, a 'Faulty' alarm was raised. As this event occurred in the evening and there is no record of anyone having accessed the site, it is expected that the RTU had automatically reset itself, rather than this situation being linked with activity at the substation which required manual use of the Control Isolation Switch.

The 'Faulty' alarm then cleared itself when the RTU rebooted, and a Control Engineer subsequently Unlocked TASS.

SCADA Communications between the Substation & Control Room

At one site, a number of transformer switching operations were evident through the daily reviews of PI ProcessBook, and data downloaded during a consequent site visit confirmed that these were in response to TASS identifying a sustained loss of comms between the substation and the DMS. In this situation, TASS acts to restore the transformer that is switched out and return the substation to conventional operation over the period that Control Engineers have no visibility of the site.

Though the nature of this issue means that the DMS no longer shows real time data, and instead flags warnings that the data shouldn't be trusted, when SCADA comms are returned data is subsequently transferred to PI, and can then be seen via the PI ProcessBook. The RTS comms log for the site was also reviewed by the project team to verify the loss of comms.

As this issue had also, separately, been identified by the RTS team, they worked to resolve the fault and reliable comms have subsequently been maintained.

Control Room Engagement with TASS

When developing TASS for trial through the LEAN project, the requirements capture process gave detailed consideration to designing a system which aligns with our colleagues' expectations and existing activities.

To evaluate how well the system meets the Control Room requirements for monitoring TASS operation, and to understand any implications associated with this supervision, a feedback form has been issued to each of the Control Engineers. This two-page survey seeks individuals' views on their experience of interacting with the system, their confidence in the system, any changes required, and the general management of the trials and engagement with the project team. This feedback is useful for both informing the wider roll out of the technology and in running similar technical innovation trials in future. The survey form is given in Appendix G.

The responses received indicate that the TASS interface in PowerOn Fusion meets operational requirements well, and that staff are happy with how the system has been implemented.

The Control Engineers have remained engaged and cooperative throughout the TASS trials in swiftly identifying and dealing with issues whilst on duty, in communicating with the project team and in supporting further investigations.

Conclusions & Recommendations on Monitoring TASS Operation

Control Room supervision of the TASS system as part of their overall management of the network is essential for the quick identification and resolution of any issues. This central monitoring via the DMS would therefore need to be continued for wider roll out of the technology. Accordingly, the training material created for use during the project has been developed with consideration to future use, and in a way that will allow other DNOs to easily adapt it for their own use should they also want to implement TASS. As reported in SDRC 9.4 'Initial Learning from Trial Installation and Integration', this material is available to other DNOs as an output from the LEAN project.

The project team's daily reviews of TASS operation via the PI ProcessBook have been necessary during the trials to monitor the operation of the TASS control algorithm and its response to different network situations. It is not expected that such a close level of observation would be required should the technology be rolled out across the business. Rather, any issues would be identified by the Control Room, with appropriate operational resources then drawn in as necessary. Here, and subject to further consideration during future decisions on any roll out of the technology, it is anticipated that issues with the TASS control system would be taken on by the RTS team, and issues with the electrical assets would continue to be addressed by the operational Field Staff.

Data logged on site by the TASS control device would continue to provide useful additional information should any investigations be required. At present, the project team attends site regularly to download the data logs and ensure data is available for analysis during the trials. The need for a member of staff to attend site may continue to be

acceptable if few issues with the TASS system are anticipated, and if it will be possible for a member of the RTS team (or an appropriate colleague) to attend site shortly after any issue is identified to download the data logs. However, for roll out at scale it may be considered more appropriate to establish data transfer via the business's SCADA system, or via an alternative remote data transfer means, should this be shown to be beneficial.

It is expected that the business would continue to monitor the losses saved if TASS is rolled out across the network, with this calculation run annually, or as needed on an adhoc basis, in line with company reporting requirements. Such requirements may relate to environmental reporting, or to the demonstration of a reduction in losses in accordance with our Losses Strategy or any future regulatory Losses Reduction Incentives. Here, the tool for calculating the energy saved at each substation would need to be maintained by the Asset Management & Investment team, with updates made to the transformer specific losses figures in line with any changes to the transformers at a given site, and with the load profiles and TASS switching information applied as relevant to the reporting period in question. Information on the derived savings would then be passed to the Regulatory Reporting team or others within the business as appropriate.

6 Interim Assessment of TASS Performance at the Trial Sites

This section provides an assessment of the performance the TASS technology to date with regard to the automated switching activity seen and the associated reduction in losses.

Over the interim 7 months reported TASS has reduced losses by around 40 MWh in total across the two trial primary substations.

Two subsections are presented:

Data Sources | Interim Summary of TASS Performance & Losses Savings Achieved

Data Sources

The data used to calculate losses savings is taken from the log files held within the TASS control devices at each trial substation. This data includes records of all transformer switching operations together with detailed load measurements.

The switching data indicates the periods of time during which one of the transformers was switched out due to TASS, and the load measurements provide a detailed load profile for the substation in question. This information is used with transformer specific losses figures to determine the energy saved through TASS operation over a given period of time.

Information on the different operational situations encountered and the TASS system's responses to these is drawn from the 'TASS Operational Review Log' created for the trials.

Interim Summary of TASS Performance & Losses Savings Achieved

An initial assessment of TASS performance over the first twelve weeks of operation at the trial sites was presented in SDRC 9.4 'Initial Learning from Trial Installation and Integration'[36]. An update of the key information is presented here, in accordance with the criteria for this SDRC 9.5, and a detailed analysis of the operation, benefits and potential impacts of TASS will be provided in SDRC 9.6 'Site Performance to Date'.

The interim analysis seven months into the TASS trials shows that the system continues to operate as expected to deliver energy savings. At the time of writing, TASS has reduced losses by around 40 MWh in total across the two trial primary substations.

[36] LEAN SDRC 9.4 'Initial Learning from Trial Installation and Integration', September 2018 - available via the ENA's Smarter Networks Portal www.smarternetworks.org/project/sset207-01/documents

A summary of TASS operation up to 15 January 2019 is given in Table 6, with further detail on the performance of the system at the two trial sites provided in the text below.

Table 6 - Summary of TASS trial operation up to 15 January 2019

TASS Operation / TASS Trial Site	Gillingham	Hedge End
Commencement of Full Automated Operation[37]	22/06/2018	08/06/2018
No. of Full Cycle TASS Switching Events[38] (TASS switching out a TX & subsequently reinstating it)	T1 x 15, T2 x 14	T1 x 25, T2 x 26
TASS switching due to substation loading (one TX switched out or switched in to follow demand)	12	74
TASS time based change over events (one TX restored & the other subsequently switched out)	5	2
TASS responses to a comms issue (one TX restored & the other subsequently switched out)	11	1
'TASS Failed to Operate' alarms	1	9
'TASS Faulty' alarms	1	0
'TASS CoP Error' alarms	0	0
Control Room Disable commands issued (TX restored if switched out due to TASS)	10	10
Control Room Lock commands issued	3	2
manual Paused situations	0	1
No. hours one transformer was switched out (h of total h)	4535 of 4993	3338 of 5329
% of time one transformer was switched out	90.8%	62.6%
Losses Saved to date	20.38 MWh	18.71 MWh
Value of Losses Saved to date [39]	£ 986.80	£ 905.90
Associated CO_2 Saving [40]	10.25 tCO_2e	9.41 tCO_2e

At Gillingham, the TASS system has enabled one of the transformers to be switched out for around 91% of the time. This reflects the loading at the substation, with no transformer restoration events seen due to the demand increasing above the Crossover Point, and the twelve load based switching events noted relating to a transformer being switched out after the system had been Enabled. Five time based change over events have been triggered to transfer TASS operation to the alternate transformer following two weeks of continuous operation with one transformer switched

[37] the TASS system was activated at both trial sites on 8 June 2018, however, a stack overflow issue within the RTU at Gillingham then became apparent, leading to TASS perceiving an issue with comms availability - the RTU configuration was subsequently corrected, with full TASS operation commencing at Gillingham on 22 June 2018

[38] reflects a full cycle of TASS switching out a transformer and then subsequently reinstating it, whether due to substation loading, a command from the Control Room, or in response to SCADA data or a loss of comms situation - these figures do not include times when a Control Engineer manually switched a transformer for e.g. outages during transformer condition assessment tests

[39] derived using Ofgem's RIIO-ED1 CBA figure for the value of losses of £48.42 per MWh (rounded to nearest 50p)

[40] derived using Ofgem's RIIO-ED1 CBA figure for the 2016 Electricity GHG conversion factor of 0.503 tonnes per MWh

out, and eleven TASS operations were in response to SCADA comms between the substation and NMC being lost for more than 30 minutes due to an RTS issue at the site, as described in Section 5 'Monitoring - TASS Operation'. Ten switching operations were then due to the Control Room Disabling TASS prior to someone accessing the substation.

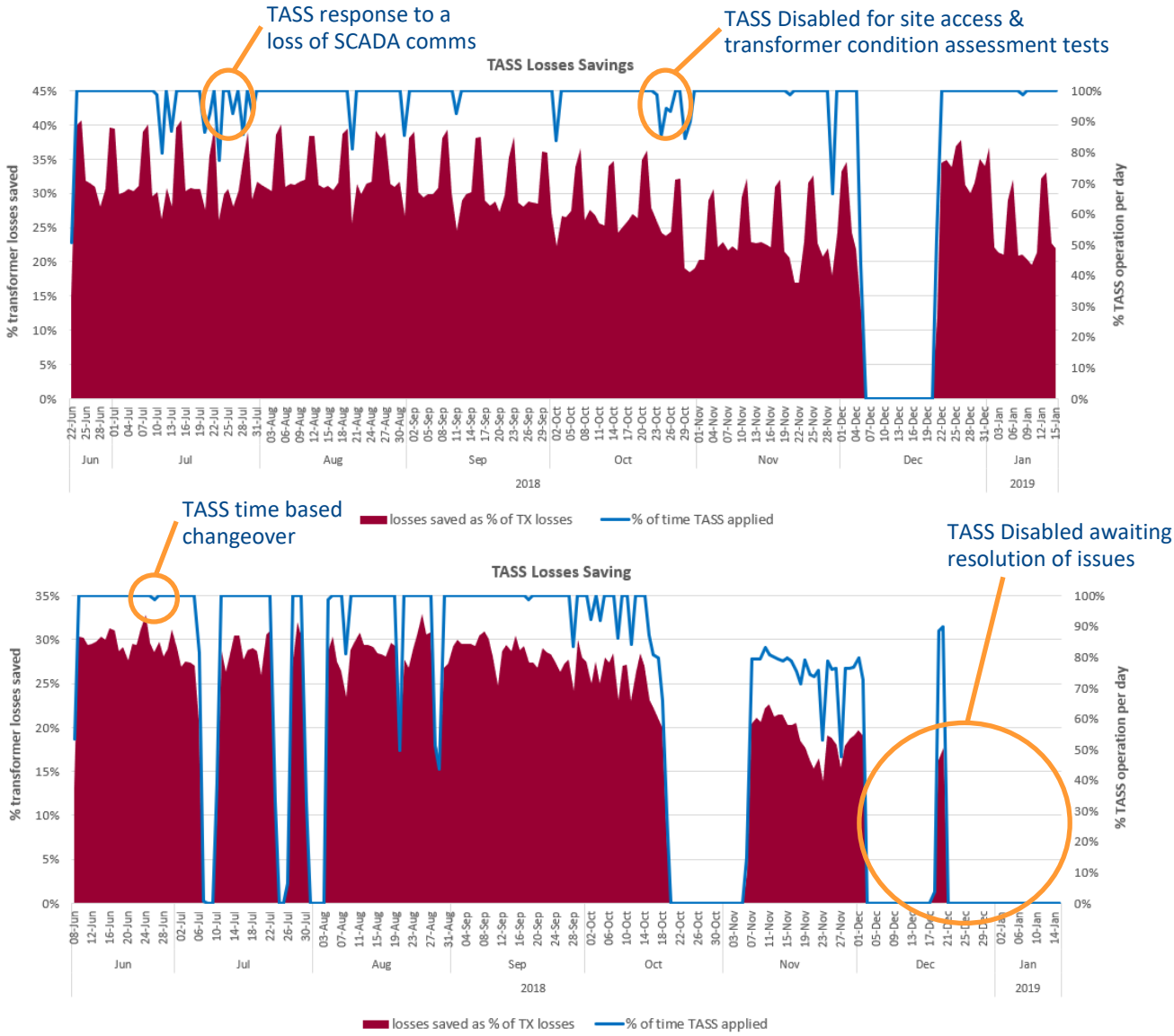
At Hedge End, TASS has allowed the site to run on single transformer for around 63% of the time. This is lower than Gillingham, and lower than the 83% reported in SDRC 9.4 'Initial Learning from Trial Installation and Integration', as TASS was Disabled for 43 days between 2 December and 15 January due to the issues with the LVAC system and the TASS algorithm voltage difference setting also described in Section 5 'Monitoring - TASS Operation'. At this site, the seasonal increase in electricity demand has resulted in more frequent TASS operation from around early November, with the system eventually switching a transformer in every day at around 5.30pm for the evening peak, and then switching back to one transformer when the load drops again after around 10.30pm. Consequently there have been a total of 74 load based switching operations. Two time based change over events have been triggered, and one SCADA comms issues has been experienced at this site to date. Additionally, the Control Room Disabled TASS on ten occasions for site access.

The manual 'Pause' functionality available via the TASS wall box within each substation has been used once at one site, for a period of around 30 minutes. This local non-auto setting provides a back-up option in the event that work must be undertaken within the substation but SCADA comms are lost and it's not possible for the Control Room to remotely Disable TASS, or in the event that someone enters a substation but in error has forgotten to contact the Control Room to request that TASS be Disabled. The Control Room observed the use of the Pause function, and reported this to the project team, however it was not subsequently possible to identify who had been on site or the purpose of the visit.

The 'TASS Failed to Operate' and 'TASS Faulty' alarms from each substation were raised in response to the different operational situations identified by the TASS control algorithm, as described in Section 5 'Monitoring - TASS Operation'.

Charts illustrating TASS operation over the course of the trials to date are provided in Figure 18. In these, the blue line shows the percentage of each day during which a transformer is switched out, to indicate the proportion of time that TASS has been acting to reduce losses, and the red area shows the losses savings (after accounting for system energy use) as a proportion of the transformer losses that would have been experienced without the application of TASS. The charts are labelled to indicate examples of a time based change over event occurring, where the system alternates TASS operation between the transformers in the event that one transformer has been switched out for a two week period; the TASS system response to a sustained loss of SCADA comms; TASS being Disabled by the Control Room to allow access to site; and TASS remaining Disabled for a period of time prior to resolution of the issues described in Section 5 'Monitoring - TASS Operation'.

Figure 18 - TASS operation and losses saved at the two trial sites - Gillingham (top) & Hedge End (bottom)



It can be seen that full TASS operation reduces overall transformer losses by ~30% and ~25% for the two substations respectively. The analysis shows that this equates to just under 0.2% of the energy supplied to customers in each case.

Table 7 then gives the monthly figures for total losses savings, indicating the reductions achieved through full operation of TASS over the course of a month as distinct from the periods when TASS was Disabled for a period of time.

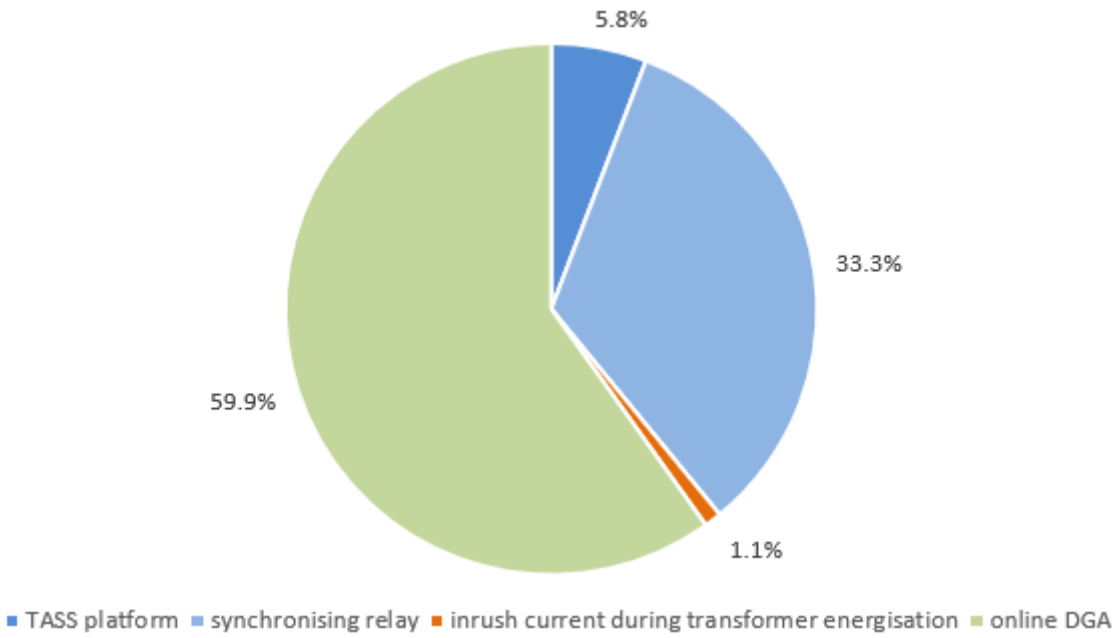
Table 7 - Monthly losses savings from TASS operation up to 15 January 2019

TASS losses savings MWh	June (part month)	July	August	September	October	November	December	January (part month)	**total to date**
Gillingham	1.01	3.52	3.61	3.40	3.09	2.67	1.70	1.38	**20.4**
Hedge End	3.18	3.01	3.66	4.07	2.22	2.22	0.36	0.00	**18.7**

Comparing the losses savings with the figures forecast using the TASS Tool created during Phase One of the project, the energy savings seen at Gillingham to date are around 9% higher than the 7 month equivalent of the forecast figure (18.7 MWh). Differences are to be expected due to variations in load profiles from year to year, but this higher figure also reflects the fact that the substation TASS has seen one transformer switched out for the majority of time, with no transformer restoration due to demand increasing above the Crossover Point. The figure for Hedge End is around 33% lower than the 7 month equivalent of the forecast figure (27.9 MWh), primarily reflecting the fact that TASS was Disabled in December and January prior to resolution of the issues described in Section 5 'Monitoring - TASS Operation'. The TASS Tool will be reviewed and updated taking into account experience gained through development and trial of the technology, and presented in SDRC 9.7 'Network Losses Evaluation Tool'.

Considering the energy used by the equipment installed for the TASS trials, the indicative calculations based on seven months of operation are that the system continues to use around 8 kWh of energy per day per site. This energy use is associated with the TASS platform itself, the synchronising relay, the online DGA monitoring equipment and the inrush currents due to transformer energisation. The energy used equates to an average of 8.7% of the overall energy saving from TASS, with respective figures of 8.0% for Gillingham and 9.4% for Hedge End where TASS remained Disabled though still monitoring and logging data for a period of time in December and January. The figure for energy use drops to around 3.5% excluding the online DGA system being used to monitor the health of the transformers during the trials, with the figures being 3.2% and 3.8% for Gillingham and Hedge End respectively. The relative proportions of energy used by the different components are shown in Figure 19.

Figure 19 - TASS trials - proportional energy use



The ongoing operation of TASS provides clear evidence of how this system can be used to reduce technical losses on the distribution network.

7 Conclusions & Next Steps

This report provides the evidence that SEPD has met the requirements of SDRC 9.5, as set out in the LEAN Project Direction. In line with those requirements, the key topics presented are as follows:

- A review of the techniques used to monitor the trial transformers and assess the effects of TASS switching
- An initial assessment of asset health prior to the installation of TASS and following a period of trial operation
- A review of the electrical impact of TASS switching with regard to network power quality
- Interim feedback on the performance of TASS to date with reference to the automated switching activity seen and the associated reduction in losses

The monitoring and analysis aspects of the TASS trials are essential in managing risks, assessing the performance of the TASS technology, and ensuring that the system maintains compliance with relevant codes and standards. The approaches used have proven to be practicable, effective and thorough in providing a comprehensive understanding of the implications of integrating and operating the TASS scheme with existing network assets.

In addition, the approaches used represent enhanced monitoring and analysis techniques that would bring benefits to wider network operation and investment in the context of improved data management and risk based decision making. The experience from their application during the LEAN project contributes to the consideration of enhanced levels of monitoring as the industry transitions to the world of DSO with increasingly dynamic operation of GB electricity networks.

At this point in time, there is no evidence of any increased risks to asset health due to the deployment of TASS. On this basis, prior to the installation of TASS it is recommended that visual inspections of the substation assets be undertaken. In addition, a suite of pre-installation oil samples, PD surveys and/or transformer condition assessment tests may be considered of value to validate that there are no pre-existing issues with the assets, and to provide a set of reference data for any subsequent tests.

Once the system is operational, the business's standard approaches to asset health monitoring, including scheduled inspections and oil sampling, are expected to be sufficient to monitor any substations where TASS is applied, with more specialist techniques then used if any potential issues are identified which merit further investigation. However, this will be subject to further consideration during future decisions on the potential roll out of TASS technology.

Whilst it is not currently anticipated that an online DGA system would be required as part of the wider roll out of TASS, the use of this technology during the LEAN project has provided valuable insight into the information that can be obtained from such systems, and how the data can be used to evaluate asset health.

Analysis of the power quality data obtained from the TASS transformer energisation events to data indicates that to ensure best practice compliance with ER P28 voltage fluctuation limits, controlled Point on Wave switching would be of benefit for TASS deployment at some primary substations, however at other sites TASS may operate acceptably without controlled switching.

At the time of writing, TASS has been successfully controlling automated switching events for over seven months, operating as designed under a range of different situations. The issues identified and resolved to date do not raise uncertainty over the operation of TASS, rather they have provided indispensable live testing of the TASS system, demonstrating that TASS was able to quickly identify a problem, halt operation if necessary, and provide notification in the DMS as designed.

Next Steps

Subject to the continued successful operation of TASS, the trials will continue until May 2019.

The system will continue to be closely monitored to track the operational scenarios experienced and evaluate how the TASS control algorithm has responded, allowing any modifications or enhancements that could improve the system to be identified.

The assets and systems that TASS interacts with, including transformers, circuit breakers and SCADA, will also continue to be monitored to evaluate any impacts on these due to TASS operation. A further suite of transformer condition assessment tests and PD surveys will be undertaken following the conclusion of the trials, and findings will be presented in the project closedown report SDRC 9.8 'Knowledge & Dissemination'.

Knowledge Sharing

Interested parties are very welcome to contact the LEAN project team with any enquiries via lean@sse.com.

The following companion SDRCs relate to the development and trial of the TASS technology through Phase Two and Phase Three of the project:

- SDRC 9.4 'Initial Learning from Trial Installation and Integration' - comprehensive information on the technology developed, its integration with existing network assets, the operational principles designed into the scheme, and the factors relevant to the scalability and replicability of the system for wider deployment across other network areas, together with an initial assessment of the performance of TASS
- SDRC 9.6 'Site Performance to Date' - a detailed review of the losses savings achieved through TASS operation, and evaluation of both the benefits of the technology and costs of deployment to refine the business case

- SDRC 9.7 'Network Losses Evaluation Tool' - refinement of the tool developed to allow DNOs to undertake a site by site cost benefit analysis on the deployment of the technology, reflecting experience gained from trial implementation
- SDRC 9.8 'Knowledge & Dissemination' - the project closedown report, including consideration of the wider deployment of the technology across the SEPD network if applicable

SDRC 9.4 was published in September 2018, with SDRCs 9.6 to 9.8 to be published over the course of the project as more experience is gained from trial operation.

Targeted engagement and dissemination activities will continue with both internal and external stakeholders to share information and experience. The material available to other DNOs is designed to support their appraisal of TASS and adoption of the technology on their own networks, and to inform choices on enhanced monitoring and analysis approaches to support network operation and risk based asset investment. In addition, the experience gained through the project can be evaluated by product vendors or third party service providers to inform their development of technologies or functionalities relevant to enhanced levels of decentralised control, automation and monitoring as the industry transitions to the world of DSO with increasingly dynamic operation of GB electricity networks.

Appendices

Appendix A	PD Survey reports - SSEN, August 2017 (pre-trial)
Appendix B	Transformer Condition Assessment Test reports - Doble, October 2017 (pre-trial) & October 2018 (mid-trial)
Appendix C	DGA & conventional oil sample results comparison - Camlin, September 2017
Appendix D	12 month DGA trend charts for each TASS trial transformer
Appendix E	SAPIENT reports - Kelvatek (Camlin Group), July 2018 (pre-trial) & November 2018 (mid-trial)
Appendix F	Transformer Energisation Study report - Mott MacDonald, February 2019
Appendix G	TASS Feedback Form issued to SSEN Control Engineers - January 2019

Enquiries regarding these appendices, this SDRC 9.5 report or the LEAN project in general are very welcome via lean@sse.com.