SP ENERGY NETWORKS

Flexible Networks
for a Low Carbon Future

Good Practice Guide to Monitoring

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Executive Summary

Significant changes to existing network design and operation practices are needed in order to meet the requirements of the future distribution network. Distribution networks have traditionally been designed based on a "fit-and-forget" philosophy as good practice where there is only a limited set of representative network metrics available/utilised e.g. the magnitude of peak loading on a secondary substation. This generally does not provide information on the dynamic interactions of the various system states over the course of a year of operation.

Increasing uptake of low carbon technology (LCT) such as heat pumps, electric vehicles and PV along with changing customer consumption patterns will influence load profiles and high density clustering of these technologies due to rollout of electric vehicle charging points for example will lead to rapid, localised load increases. Increased, targeted network monitoring will be required to enable the identification and appropriate response to networks approaching design limits. In parallel, the development of "smart" solutions that provide more rapid, incremental network capacity in comparison to traditional network asset replacement will require additional monitoring to observe and in some cases, manage performance. These include dynamic thermal ratings, flexible network control, dynamic voltage control and generally, greater network automation.

The monitoring that was deployed for the SPEN LCNF Tier 2 Flexible Networks for a Low Carbon Future (Flexible Networks) project was evaluated to draw out learning outcomes and good practice and to develop a robust future network monitoring strategy. This included technical and practical details of monitoring deployment, data acquisition and the application of the monitoring data to improve various business policies and practices. Key monitoring good practice points for future low carbon networks are summarised below.

Monitoring Good Practice – Key Points

- Monitoring specifications should be consistent with required minimum accuracy and reliability, given consideration to scaling across the network at large volumes.
- Practical considerations are also important to ensure an efficient monitoring rollout programme.
- Heuristics based analysis is a powerful technique that can help identify network 'hot-spots' at an early stage.
- Detailed analysis of monitoring data for network trial sites can be used to develop and verify simple rules of thumb for application to the wider network.
- Development of a "common" library will facilitate integration of analysis tools using the same data sources and underlying analysis techniques across planning, operations and connections business processes.
- It is critical to understand the risk associated with a data-based business decision in the context of future load growth increasing rapidly and clustering.

Glossary

AVR	Automatic Voltage Regulator
BAU	Business-As-Usual
CI	Customer Interruptions
CML	Customer Minutes Lost
CT	Current Transformer
DNO	Distribution Network Operator
EV	Electric vehicles
HP	Heat pumps
LCNF	Low Carbon Networks Fund
LCT	Low Carbon Technology
MDI	Maximum demand indicator
NMS	Network management system
OHL	Overhead Line
PV	Photo-voltaic generation devices
SPD	Scottish Power Distribution
SPEN	Scottish Power Energy Networks
SPM	Scottish Power Manweb
THD	Total harmonic distortion

1 Introduction

1.1 Background

Strategic network monitoring is critical to the future efficient design and operation of the distribution network as network requirements become less dependent on historical loading and more dependent on the changing load behaviour of customers in terms of uptake of low carbon technologies.

Network monitoring data can be used in several ways:

i) In "operational" timescales to operate the network in real-time, providing early warning of adverse network changes and guidance on the most favourable reconfiguration during and following faulted conditions. Network data is also utilised for week-ahead outage planning. It can also be used to calculate network performance metrics include CIs and CMLs and respond appropriately to general customer service measures (e.g. voltage complaints).

ii) In "planning" timescales, monitoring data is used to verify that the distribution network performs as designed under both normal and contingency (unplanned outage) conditions. Network performance metrics on these timescales include network utilisation (as a percentage of asset rating), load index, maximum and minimum load/voltage values and distributions, losses and power quality (e.g. harmonics, flicker, voltage unbalance). These are input to the annual network planning/design review process, longer-term network planning and asset management processes. With increased scrutiny for network assets at higher voltage levels due to greater associated risk from maloperation, monitoring data requirements are increased.

The granularity of monitoring across the network is also governed by the value of the monitoring to the DNO. In some instances, there may be a strong economic case for detailed monitoring in specific areas of the network with high loading. This may also provide more general learning that can be applied through simple analysis techniques or "rules-of-thumb" across the wider network where it is not cost-effective to monitor in detail. For example, the impact of clustering of embedded PV generation on the LV network. A rule-of-thumb may be developed to trigger more detailed monitoring when PV uptake reaches a certain level that also takes some consideration of the LV network characteristics.

When deployed and used effectively, network monitoring is a powerful tool that contributes to the techno-economic design and management of a distribution network.

1.2 Objectives

The Good Practice Guide to Monitoring aims to provide an insight into the monitoring that was deployed and evaluated for the SPEN LCNF Tier 2 Flexible Networks for a Low Carbon Future (Flexible Networks) project. The principles of network monitoring and the rationale for the monitoring approach being used for Flexible Networks are described. This includes technical and practical details of monitoring deployment, data acquisition and the application of the monitoring data to improve various business policies and practices.

The Guide also outlines how monitoring can address future challenges due to rapid changes in distribution network loading from LCT uptake. Targeted monitoring will be key to quantifying, characterising, trending and managing varying network characteristics and behaviour.

Learning outcomes on monitoring from other LCNF projects were evaluated and compared with the approach used in Flexible Networks in order to develop a robust future network monitoring strategy. Data analysis techniques and corresponding results in other LCNF projects that were comparable to those in Flexible Networks were also assessed for cross-verification.

1.2.1 Flexible Networks

Network monitoring was installed for Flexible Networks to evaluate the effectiveness of the network innovations being trialled as well as to support the development of improved operations and planning tools. These innovations comprise the following;

- Enhanced Thermal Ratings – Asset loading, ambient temperature and weather (wind)
- Flexible Network Control – Power flows and voltages across the network
- Voltage Regulation – Power flows and voltage across the AVR and the network
- Voltage Optimisation – Power flows and voltage across the network

Detailed secondary substation monitoring was trialled at three network trial areas for approximately 185 secondary substations for Flexible Networks. Further details of the project are contained in Appendix A. Monitoring equipment was also installed at a number of targeted customer locations across LV networks in the trial areas.

One of the focus areas for Flexible Networks was the use of enhanced network monitoring and analysis to create better knowledge and foresight of the changing environment within the business. Enhanced data analysis techniques were developed for primary substation data already collected by SPEN. These included more accurate forecasting of future loading trends based on probabilistic analysis and characterisation of risk associated with high network loading. This significantly increased existing data value to network design and also revealed some additional capacity headroom.

The value of secondary substation monitoring was also assessed in terms of cost-effectively enabling exploitation of additional capacity headroom on the LV network through improved understanding of network characteristics and behaviour. The following characteristics were analysed across the network trial sites;

- Probabilistic secondary substation loading behaviour
- Levels of HV and LV phase imbalance
- Impact of embedded PV on LV network voltage
- Voltage-load relationship for demand

Network characteristics were compared with possible solutions that could be applied to address constraints and to increase capacity headroom. The development and verification of simple analysis techniques and "rules-of-thumb" that can be used to respond more effectively to load changes were also explored. This helped to identify techno-economic solutions for monitoring the wider network.

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[1] *TNEI supporting document 8279-33-01-AVR Location Summary*

2 Fundamental Principles of Monitoring

In order to design a data monitoring system for a distribution network to collect data that is both of value and cost-effective, some fundamental principles of data monitoring should first be considered;

- Measured data is always an approximation to real-world phenomena and how well the phenomena is characterised by the data will depend on the specifications of the monitoring system e.g. data sampling rate, measurement accuracy, monitoring location etc
- What types of measurements are required to best characterise the phenomena? This may be a spot measurement, a measurement of difference between two locations, measurement at a number of locations or a measurement that is only triggered by a particular event.
- What other data is required in order to analyse and/or interpret the measured data and what is the corresponding availability/uncertainty? For example, it may be necessary to know the network connectivity at the time of measurement or secondary substation transformer tap position.
- Are there external influences that may affect the accuracy of the measured data such as environmental factors e.g. temperature, humidity, radio interference? What is the corresponding impact on data accuracy and availability?
- Are error detection and correction algorithms designed appropriately to ensure the required data quality? How is data quality characterised in relation to the measurement and how it is used in business processes?

In designing a monitoring system, it is important to appreciate that there are costs associated with data collection, storage and analysis, so whilst a high specification monitoring solution may provide very high accuracy and reliability, it may also be very costly even when scaled to large volumes. Metrics which quantify or rather specify the quality and risk associated with a data-based decision, essentially the level of uncertainty, can enable the business to make considered decisions on monitoring requirements.

The process of transforming raw measured data from monitoring into value-added learning that can be applied to business decision-making is shown overleaf in Figure 2-1. Uncertainty and error can be introduced at every stage of the process. For example, the methodology for extracting information from the measured data (e.g. extracting the signal from the background noise) through analysis may lead to uncertainty if not well-designed.

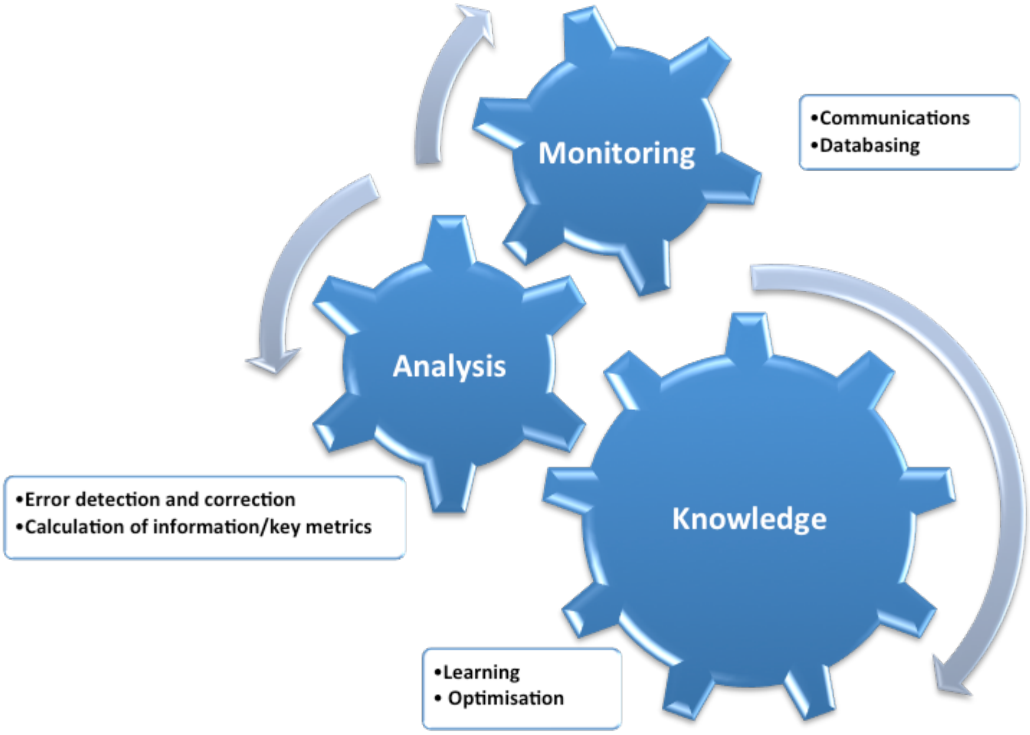

Figure 2-1 Integration of monitoring data

In order to determine minimum monitoring device and communications specifications that are technically and economically acceptable, the trade-off between resolution and extent of monitoring across the network should also be considered. It may be better to have lower resolution data for more of the network than high resolution data for a much smaller area of the network.

Communications and data storage requirements can be reduced by performing some rudimentary or more complex data analysis on-site and only sending back key metrics rather than all raw data. Establishing what data is required in real-time and what data can be packaged or stored for later analysis will also influence communications and database specifications and cost.

Practical considerations such as compatibility of the monitoring device and communications with the NMS and SCADA system and installation e.g. space, access, safety, maintenance and training should also be assessed before rollout.

Monitoring Good Practice – Key Points

- Monitoring specifications should be consistent with required minimum accuracy and reliability.
- Consideration should also be made to scaling across the network at large volumes.
- Metrics which provide a characterisation of the risk associated with a data-based decision should be incorporated.

3 Distribution Network Monitoring

3.1 Existing Monitoring

Details of monitoring typically deployed on the SPEN secondary distribution network at present are described below. Increased levels of monitoring are required at higher voltage levels (132kV and 33kV) from a safety, reliability and network design aspect to ensure that network integrity is maintained. At lower voltage levels (11kV, LV) a more limited set of network measurements are typically recorded and analysed.

The current and voltage on the 11kV busbar and the yellow phase current for the 11kV distributors are usually monitored on primary transformers. These raw measurements are used to construct the following variables;

- Apparent Power (MVA)
- Real Power (MW)
- Reactive Power (MVar)
- Power factor

Each primary substation is polled for new data by the SCADA system on a continuous rolling basis. Measurements are shown in (near) real-time in NMS and are sent at half-hourly intervals to the load database. The NMS also includes analogue limit alarms for primary transformers and 11kV feeders for instances when they exceed rating but not at a sufficient level to trigger protection.

Primary transformers have analogue winding temperature monitors to trigger an alarm in the NMS if the temperature exceeds a set value. Oil analysis or dissolved gas analysis is carried out on an infrequent basis to inform asset management. Transformer tap changer counters are also recorded on a monthly basis as part of substation inspections and if reading trends are atypical, this may prompt further investigation.

Ground-mounted secondary substations in the SPEN network have a maximum demand indicator (MDI). This is manually read on a six monthly basis with total maximum loading and corresponding total three phase current measurements (no timestamp is recorded). Pole-mounted secondary substations typically do not have any monitoring.

Other points in the distribution network where measured data may be available include network automation and protection locations depending on device type and at the premises of large industrial customers and embedded generation (at 11kV and above). Data at automation and protection points is generally only recorded during events which produce a large departure from normal network operating conditions such as a fault and require manual download. A range of raw measurements are recorded depending on the specific device capability.

In specific cases of network issues being identified on the HV or LV network, detailed monitoring may be implemented for a period of time to enable further investigation and diagnostics.

3.2 Flexible Networks Monitoring

A cascade network monitoring approach was applied at the three trial sites. This involved monitoring from the grid infeed level (33kV) down through the voltage levels of the network along selected feeders to monitoring at targeted specific LV customers. This is illustrated in Figure 3 1.

The following monitoring was specifically installed for Flexible Networks;

- Three phase voltage monitoring on primary and secondary transformer busbars and three phase current monitoring on primary transformer 11kV distributors and secondary transformer LV distributors. This enables characterisation of dynamic network loading and voltage behaviour as well as longer term network trends. Specific 11kV feeders were identified in the trial areas and monitoring was deployed to all connected ground-mounted and large pole-mounted secondary substations. This was to allow an evaluation of the benefits from Flexible Network Control including with an AVR and from voltage optimisation as well as an investigation of the impact of small scale embedded generation on load and voltage profiles.
- Conductor temperature and three phase current sensors on 33kV overhead lines, top-oil temperature and winding temperature monitors in primary transformers and external temperature sensors on secondary transformers for analysis of the load/operating temperature relationship.
- Wind speed and direction, ambient temperature and solar irradiance monitoring at primary substations and at four locations along a 33kV OHL circuit. This was to verify a real-time thermal management system for 33kV OHLs and to establish available thermal capacity from primary transformers. Solar irradiance data enabled validation of a simple solar resource assessment model and probabilistic characterisation of PV generation output.
- Single phase voltage monitoring at selected LV customer supply points on the Ruabon network to analyse impact of PV generation on voltage profile along LV feeders.
- Additional three phase load and voltage monitoring at new network control points on the 11kV network to support assessment of suitability for Flexible Network Control.
- Load, voltage, tap change and operational mode monitoring of an AVR installed on an 11kV feeder, to evaluate performance during network backfeeding conditions.

3.2 Flexible Networks Monitoring

Corresponding monitoring specifications for primary and secondary substation monitoring are provided below in Table 3 1. Weather station monitoring specifications are provided in Table 3 2.

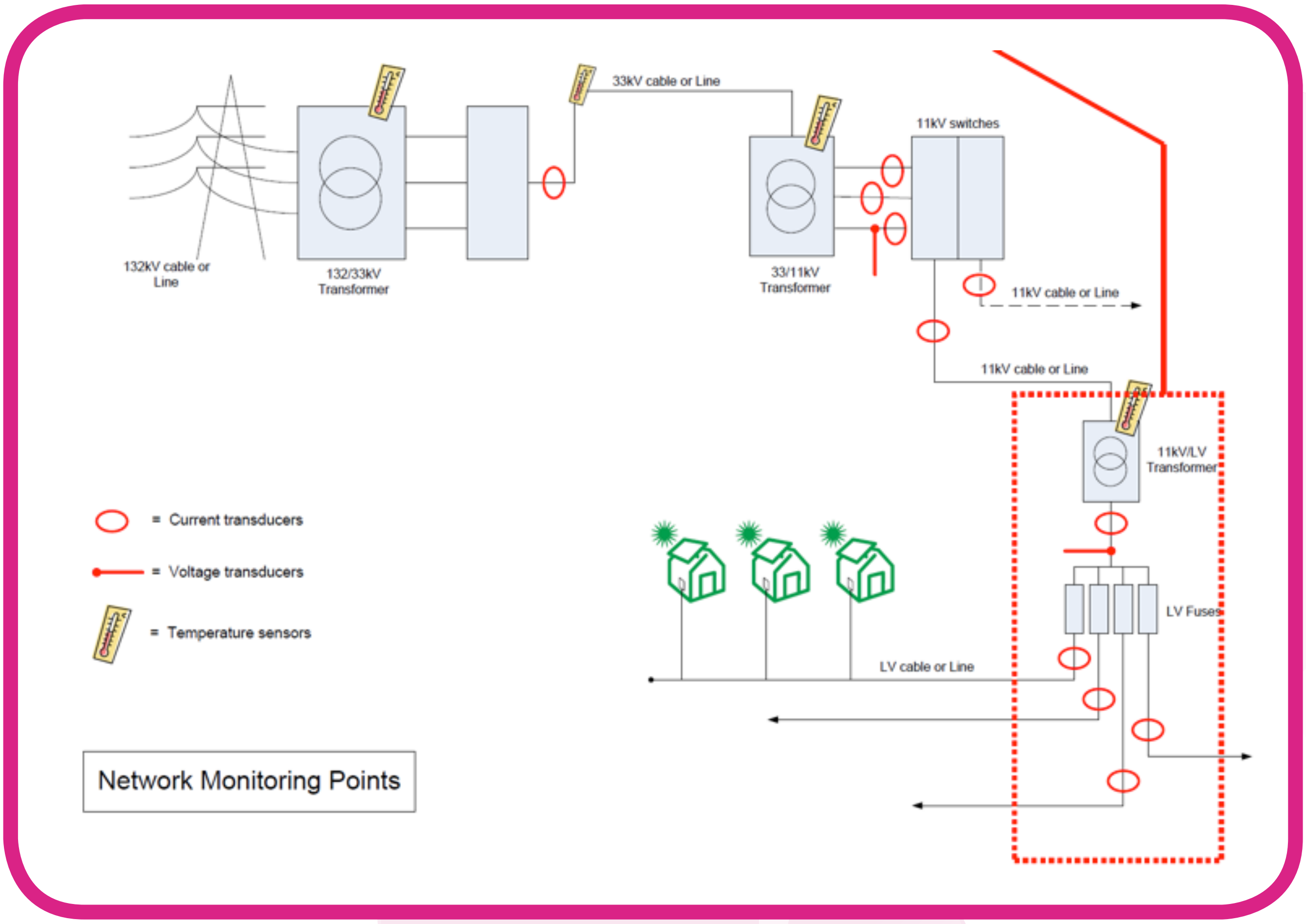

Figure 3-1 Flexible Networks monitoring points

Table 3-1 Monitoring specifications at primary and secondary substations for Flexible Networks

Variable	Resolution	Accuracy
RMS phase voltage	1 minute snapshot	1V
RMS phase current	10 minute snapshot	0.01A
Supply frequency (per voltage set)	10 minute snapshot	
Power factor of each phase (per measured current)	10 minute snapshot	
Real, reactive and apparent loading (per measured current)	10 minute average	1W, 1Var, 1VA
THD (per measured phase)	10 minute average	2 significant figures

3.2 Flexible Networks Monitoring [continued]

Table 3-2 Monitoring specifications at weather stations for Flexible Networks

Variable	Resolution	Accuracy
Ambient Temperature	5 minute average, maximum, minimum, standard deviation	0.01°C
Solar Irradiance	5 minute average, maximum, minimum, standard deviation	0.01W/m2
Wind Speed	5 minute average, maximum, minimum, standard deviation	0.01m/s
Wind Direction	5 minute average, maximum, minimum, standard deviation	0.01°

Current data was recorded at 10 minute intervals with a sign convention to enable representation of reverse flow. This was considered sufficiently frequent enough for comparison with asset ratings due to the associated time constants of heating/cooling. A 1 minute voltage snapshot was selected to enable assessment of voltage variance with transient demand and embedded PV generation load changes. Weather data was measured at intervals of 5 minutes. This is consistent with requirements for the overhead line real-time thermal management system due to the volatility of wind speed and direction.

A number of voltage monitors (single phase voltage, 1 minute snapshots) were also installed along LV feeders with relatively high PV uptake at residential addresses.

Whilst analysis of the monitoring data from trial network areas for Flexible Networks, including development of corresponding analysis tools, was relatively independent of existing business-as-usual planning and operations functions, it was guided by internal stakeholder engagement. This was to facilitate future user buy-in and adoption of the techniques and tools developed. A number of the analysis tools are now integrated into BAU e.g. enhanced transformer thermal rating tool, improved load forecasting and risk characterisation tool.

3.3 Smart Meters

Smart meters are not being investigated as part of Flexible Networks although they are a feature in a number of other LCNF Tier 2 projects. However, it is worth briefly reviewing the wider SPEN strategy for integration of smart meter data into business processes in future.

Smart meters are becomingly increasingly common in industrial, commercial and domestic properties to monitor and reduce energy usage and cost. In the future, it is anticipated that smart meters will be installed in most premises and will not just be static measurement and analysis devices but will include a control system (programmable or via a signal from the supplier) that can automatically switch appliances on and off. It may also be possible for consumers to sell energy back to the grid from energy storage devices including EVs. This is a significant step-change in the amount of data traffic available to the DNO which poses some major challenges including data management, storage, analysis and security.

In the smart meter strategy document submitted as part of the SPEN RIIO-ED1 business plans, an integrated, future-proofed “smart infrastructure” has been defined that will handle data management for all aspects of smart grids and smart meters. This will include a standards based data exchange which facilitates access to all data by any systems which require its use, avoiding complex and fault prone extracts of data from multiple systems.

To progressing towards this, the Grid Analytics trial[2] carried out as part of Flexible Networks provided invaluable learning on what sort of mechanisms and work practices a DNO should put in place to enable efficient use of new smart data by all areas of the business.

3.4 Quantifying Data Value

An assessment of the techno-economic value of monitoring trialled for Flexible Networks was used to inform future network monitoring requirements across SPEN 11kV and LV networks during the RIIO-ED1 regulatory regime and also more widely across GB distribution networks. The high-level process is described below.

In order to develop a business case for the roll-out of a monitoring programme across the distribution network or alternatively, more focussed monitoring under certain network conditions/behaviour, a robust cost-benefit analysis enables evaluation of added value. The cost of monitoring should consider not only the cost of the monitoring equipment itself but also installation, energy usage, communications, maintenance, data storage, training and the cost to analyse the data and apply it in business processes.

Also, in order to identify network areas that need an intervention, it is necessary to monitor more sites than actually need an intervention. This is because monitoring is required to confirm that an intervention is in fact required (and the most appropriate intervention). Over time the monitoring site selection process can be refined to an extent through feedback from this process.

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[1] *SP Energy Networks, SP Energy Networks 2015-2023 Business Plan; Smart Meter Strategy, March 2014.*

3.4 Quantifying Data Value [continued]

The benefits of enhanced distribution network data to the business may be through the following mechanisms;

- Improved knowledge of the network that enables better planning of future network reinforcement requirements
- Improved knowledge of the network that enables a more informed response to future low carbon technology growth
- More informed network management and thus improved performance during both normal and contingency conditions
- Improved knowledge and utilisation of assets leading to optimisation of asset life
- Faster response to generation and load connection applications

This could lead to cost savings potentially achieved through;

- Outright deferral of network reinforcement
- Avoidance of additional costs due to replacing plant reactively
- Application of smart solutions where appropriate to defer conventional network reinforcement
- Reduced CIs and CMLs
- Reduced network losses
- Delayed asset replacement requirements
- Reduced staff time via more efficient network analysis and minimisation of customer complaints
- Reduced carbon costs

4 Monitoring Hardware

The functional specifications of monitoring hardware depend on the requirements of the monitoring to be carried out. This includes practical considerations such as space available for installation of monitoring, access and method of communication. Details of the monitoring hardware that was deployed for Flexible Networks and the rationale for selection are described below.

4.1 Measurement Devices

4.1.1 Rogowski Coils

Rogowski coils were used to measure the LV distributor phase currents in secondary substations. The coils can be installed around existing cable cores or sections of the busbar which generally enables on-line installation without breaking the circuit. This was a key consideration for minimising the need for any circuit reconfiguration and associated CIs and CMLs.

A benefit of the Rogowski coil is that it is a flexible ring and can be fitted in locations where it may not be possible to fit a conventional ring or split current transformer (CT). Measurement accuracy is a function of the concentricity of the coil although this is not a strong dependency. The supply cost is generally higher than conventional CTs but the Rogowski coil can easily be removed and redeployed at other locations once the monitoring programme is complete. This is usually not possible for conventional CTs.

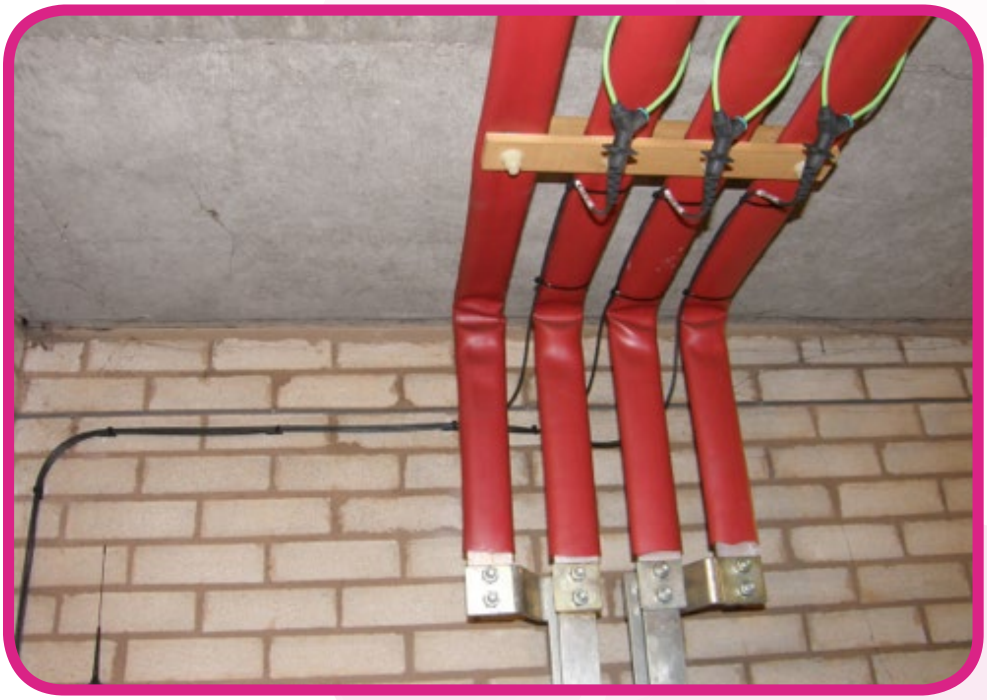

Figure 4-1 Rogowski coil installed in SPM secondary substation

Conventional CTs are commonly installed at SPEN ground-mounted secondary substations on the three phases of the transformer LV tails to provide measurements for MDI monitors. The low cost ring CTs used are slipped over the conductors so require an outage to break the conductor if retrofitted. This can be disruptive to customers depending on the level of network meshing.

There are a range of options for conventional CTs in terms of cost and accuracy and depending on the application. The CTs presently utilised are of a lower class of accuracy and reliability, typically 1A to 5A output.

In primary substations, 11kV distributor yellow phase currents are measured from existing CTs. For Flexible Networks, clip-on CTs were added to measure all 3 phases.

4.1.2 Voltage Clamps

On secondary transformers, the output phase voltages were measured on the 415/240V busbar connections using a newly designed direct 'Drummond' busbar clamp. In primary substations, voltage is already measured directly from the 11kV voltage transformer 110V AC output.

4.1.3 Temperature Measurement

4.1.3.1 Primary Transformers

Top oil temperature was measured with a probe inserted into a pocket within the transformer tank. The monitor also determines the winding temperature by compounding the top-oil temperature with a scaling factor based on the loading from a winding temperature CT.

4.1.3.2 Secondary Transformers

'Tiny tags' were used adjacent to the transformer to monitor the ambient temperature and thereby predict the transformer thermal loading.

4.1.3.3 Overhead Lines

GE FMCT6 line sensors were co-located with the pole mounted weather stations to measure phase current and temperature for each conductor. These are part of GE intelligent line monitoring system.

4.2 Monitors

4.2.1 Current and Voltage Monitors

Current and voltage monitors were installed to collect the measurement data at instrumented SPEN primary and secondary substations within the trial networks. Phase voltage and current were measured directly with frequency, power factor, loading (real, reactive and apparent) and THD calculated on-site from raw voltage and current measurements. Monitors were installed mainly in ground mounted secondary substations and in a selection of larger pole-mounted substations in the three network trial areas. The procured monitors were specified with a 1% or greater accuracy.

A sign convention was designated for loading where positive values indicated demand and negative values indicated generation.

Two monitor types suitable for secondary substations were trialled to assess the wider applicability and cost-benefit case for each including flexibility for redeployment following completion of monitoring programme. The Embedded Monitoring Systems Subnet device, used for primary and secondary substation monitoring, has a wide measurement capability with up to 12 x 3phase monitoring channels if required. The Selex-ES Gridkey, was selected for secondary substation monitoring as it requires less space and was suitable for use on overhead poles.

Collected data was communicated periodically to the data server with on-site data storage and manual download facilities if communications were disrupted.

4.2.1.1 Conventional MDIs

Maximum demand indicators (MDIs) are deployed in existing SPEN secondary substations to measure maximum loading as part of existing network monitoring practice. The functionality of MDIs is described below to enable a comparison with the more detailed current and voltage monitoring deployed for Flexible Networks.

MDIs are typically only installed in ground-mounted secondary substations due to space and access restrictions for smaller pole-mounted secondary substations. Also, ground-mounted secondary substations are usually in urban and suburban locations and generally subject to higher loading than pole-mounted secondary substations so load monitoring is more critical.

MDIs are thermal devices that record single phase current in Amps from the CTs and operate by recording only when the previous recorded value is exceeded. Manual readings and resetting is carried out every six months by SPEN.

MDIs are limited in terms of understanding network loading characteristics because;

- loading for individual secondary substations may peak at different times due to load diversity
- MDIs do not provide any information on peak load duration
- MDIs if not reset after temporary network alteration can give a false reading of the substation loading.

Figure 4-2 – Conventional MDI

4.2.2 LV Voltage Monitors

A Landis & Gyr E650 Smartmeter was installed at LV customer supplies to collect phase voltage measurements. This was a relatively low cost device with remote data communication.

4.2.3 Overhead Line Monitors

A GE Intelligent Line Monitoring system was installed. This included a sensor network gateway (SNG) that collects and transmits both weather station data and conductor current and temperature data to the data acquisition system.

4.3 Practical Considerations

There were a number of practical considerations for installation of monitoring equipment at the three network trial sites, these included;

- Available space restrictions in substation or proposed location of monitoring equipment e.g. monitoring device and device mounting on overhead line pole
- Access to monitoring equipment, other network assets and ancillary equipment for maintenance
- Device reliability versus ease of access
- Safety, particularly if live install is required
- Access to the proposed monitoring location, particularly for rural substations and overhead lines
- Potential CIs and CMLs if an outage must be taken for the install and there is no way to avoid customer interruptions
- Environmental conditions such as weather exposure, temperature range, ventilation and humidity, for example;
    - Will the monitoring device be located in a cabinet?
    - What is the device operating temperature?

Site surveys carried out prior to procurement for Flexible Networks were effective in avoiding potentially costly, unforeseen issues with any of the factors identified above. Space was one of the key considerations for secondary substation monitoring hardware installation. The monitors were specified to be compliant with IP54 which is an electrical device protection class that provides some weather proofing and is suitable for outdoor positioning.

For more details on key learning outcomes from monitoring deployment, “Flexible Networks Monitoring Deployment Guide” contains detailed information on the various considerations to be made when installing monitoring equipment.

4.3.1 Interfacing with Maintenance and Operations

Any new monitoring equipment installed on the distribution network requires training of maintenance crews and engineers that may encounter it during site visits. This can consist of a simple description of what the device is and what it is doing to how to maintain the device and download data from it.

For Flexible Networks, this consisted of safety notices in the substation, where equipment is installed and a company circular which communicated the details to relevant staff.

Monitoring Good Practice – Key Points

- Transducer characteristics need to consider cost, online installation and ability to be deployed in multiple network situations.
- Practical considerations are also important to ensure an efficient monitoring rollout programme.
- Site surveys prior to procurement are effective in avoiding potentially costly, unforeseen installation issues.

5 Communications

The design of the communications system architecture and specification of associated hardware and software is an important consideration for monitoring system cost, accuracy and reliability. For example, a communications platform that is integrated with the NMS is better in terms of reliability but somewhat more costly to deploy than a stand-alone platform using mobile networks.

Some key considerations for the communications system include;

- Level of integration
    - Manual download capability
    - Stand-alone system
    - Integrated with NMS (local/centralised, partial/full)
- Communications medium
    - Wires
    - Radio UHF/VHF/GPRS/3G
- Mode of operation
    - Streamed
    - Discrete
    - Alarms
- Latency – monitoring polling should be consistent with monitor sampling rate and the required mode of operation.
- Fidelity - through the process of data transfer, signal distortion and noise can be introduced which can be removed through advanced signal processing algorithms.
- Reliability - this is linked to the criticality of the data for safe network operation. If measured data is not required in real-time, reliability requirements are reduced. The cost of the communications system will rise with increased reliability however the cost of sending a technician to site to investigate a monitoring issue and/or for a manual data download can also be costly if it occurs frequently in a large population of monitors.
- On-site data storage – cost/frequency of manual download at monitoring sites compared to data storage cost.
- Signals to be sent and received e.g. raw measurements, on-site key metrics, system health status (send/receive/error), remote upgrade of software.
    - It may be possible to pre-process on-site to calculate key metrics (with the option of manual raw data download) to reduce communications requirements.
    - Security – this is particularly important if data is used in real-time and/or from specific customer assets.

The existing SPEN SCADA system ports streamed monitoring data to the NMS which then transfers measurements to the load database at half hourly intervals. It was identified at an early stage in Flexible Networks that the timescales of development work required to integrate the monitoring with existing IT and SCADA systems would be beyond the timescales of the project. Also setting up a permanent change to the company's IT and SCADA for a trial would not be prudent given the risk of changes being necessary when the trial is concluded. Instead, a stand-alone data acquisition system was used which provides greater flexibility and enables a decoupled value assessment of the monitoring communications design to inform and derisk future integration with the NMS and business processes. This recognises that there are likely to be higher levels of local data analysis and intelligence distributed across the network in future to more actively and efficiently manage the volumes of network at primary and secondary level.

Table 5-1 Key communications specifications for Flexible Networks

Feature	Specification
Integration	Stand-alone
Medium	GPRS/3G
Mode	Streamed
Sampling Rate	128 samples per cycle‡
Data Storage	Up to 180 days

‡ems Sub.net

5.1 Data Transmission

Monitors generally performed well in transmitting the data to the acquisition system. GPRS communications were a bit intermittent in some weak signal areas. A signal strength meter was used to identify the best signal level position and at some sites the aerials were repositioned outside the substation enclosure.

A number of monitoring sites required manual download during the monitoring programme due to signal strength intermittency and monitor malfunction issues.

5.2 Data Acquisition

The Nortech iHost data acquisition, storage and analysis platform was used for Flexible Networks as it has a high degree of flexibility and can handle a number of data protocols. Access to the platform is via a remote web link to centrally based servers.

5.3 Database

5.3.1 Structure

Database structure is important to ensuring efficient data access, particularly given the increasing amounts of network data that will be measured, stored and analysed in the future. A poorly designed structure may result in increased data access times leading to user frustration and higher server loading. This was discussed in detail with Nortech to ensure that the design was optimised as much as possible for Flexible Networks data use/analysis requirements. Data files were produced on a daily basis for each substation monitor.

5.3.2 Linkage to other databases

Most network planning and operational business processes that utilise monitored network data also require data from other sources to enable meaningful analysis. SPEN manage and maintain the following relevant databases;

- PI Load database
- Asset database (i.e. SAP, e.g. Supernumber)
- GIS database (i.e. ESRI, e.g. MPAN, URN, Post Code)
- Network connectivity from GE PowerOn Fusion

Currently there is limited linkage between the various databases however this has been considered to an extent within Flexible Networks (see Section 7.5) and is being advanced more widely by SPEN to allow future more integrated use of data within and across business processes.

5.3.3 Storage and Security

Data storage considerations include;

- Size of storage
- Redundancy
  - Back-up frequency
  - Offsite storage
- Installation of uninterruptible power supply

As data storage requirements increase significantly with greater monitoring of the network, the cost-benefit of storage functionality will provide a guide to the most appropriate storage specifications.

Data security will become more critical as the use of data from smart meters and active network management becomes more prevalent.

Monitoring Good Practice – Key Points

- On-site data storage can be used to mitigate communication reliability issues with relatively cheap GPRS communications.
- Database structure design is important to ensuring efficient data access. This may differ for innovation projects compared to wider network rollout.
- Greater integration of databases across the DNO business will be required in the future.

6 Data Analysis

Data analysis transforms raw measured data into meaningful information that can enable an understanding of the phenomena being measured. Data processing of measured values may be carried out either locally at the point of measurement or centrally, and combined with other data from the wider network. Calculation of key metrics can be used to build up an understanding of distribution network characteristics and how these change over time. Analysis can also identify network 'events' which can be informative or alarms to indicate adverse changes in network performance that may require mitigating actions.

Other information such as network connectivity, asset specifications and ratings are usually required to perform the data analysis or interpret the results.

Monitoring data analysis techniques developed as part of Flexible Networks for improved network planning and operation are described in detail below.

6.1 Data Analysis Techniques

The method of data analysis was carefully considered for each variable in order to provide useful results and not introduce additional uncertainty. For example, whilst averaging of data is very useful for identifying trends and characterising behaviour, it can also remove information about the distribution of variables and may mask maxima and minima. The method used was assessed in the context of the final data application to business processes and associated acceptable levels of uncertainty and risk.

Both time-series analysis and heuristic (frequency-based) analysis techniques were utilised for Flexible Networks. The heuristic approach provided an improvement in particular of secondary substation load duration, distribution of solar irradiance and LV voltages to improve understanding of the network characteristics and risk profile. An example of annual secondary substation voltage distribution is shown in Figure 6 1 and can be used to evaluate the probability of high and low voltage conditions due to primary voltage set point changes, loss of load and embedded PV generation or conversely high loading. When presented on a seasonal or annual basis, this can be used to track network voltage trends. This approach deviates from the traditional deterministic approach of network design that focuses purely on maximum demand/minimum generation and minimum demand/ maximum generation scenarios, to enable a more probabilistic network planning philosophy.

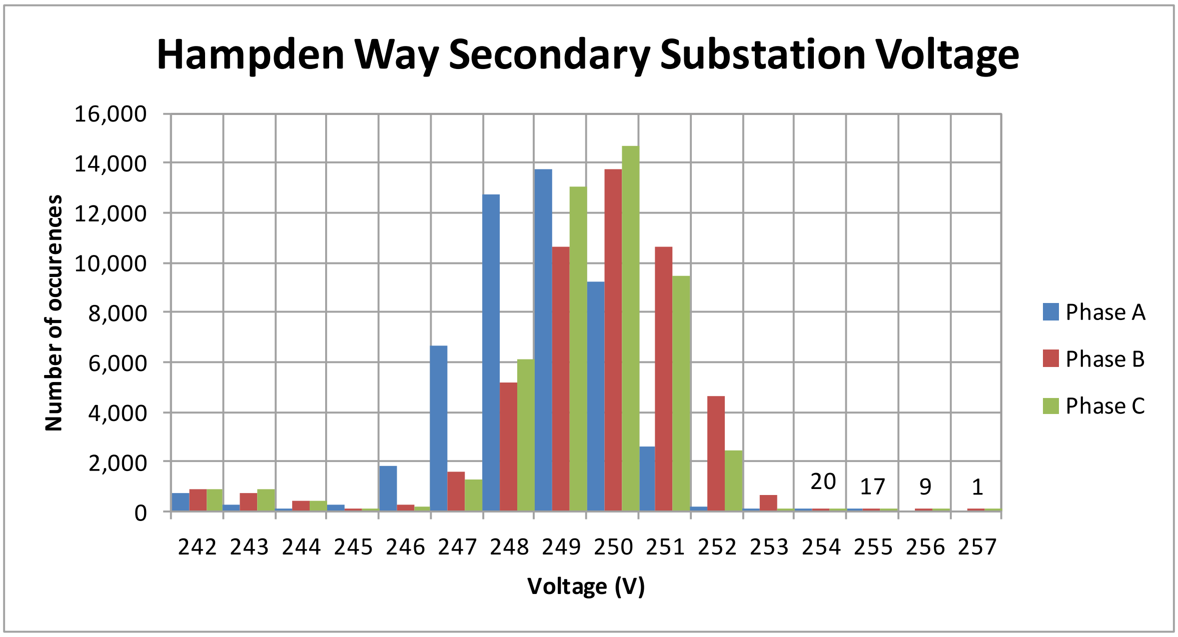

Figure 6-1 Annual phase voltage distribution for Hampden Way secondary substation

6.1 Data Analysis Techniques [continued]

Heuristics based analysis is a powerful technique that can help identify rapid changes on the network or 'hot-spots' at an early stage that may result in P2/6 non-compliance or the exceedance of statutory voltage limits for example. These trends may vary on a daily, seasonal and annual basis. This can then be used to trigger additional monitoring and scrutiny of the affected network area.

For Flexible Networks, the following analysis was carried out on monitoring data;

- Data screening and filtering
- Probabilistic load behaviour of primary and secondary substations
- Correlation of load and voltage profiles across the network from primary substation down to LV feeders
- HV and LV feeder thermal phase imbalance analysis
- Characterisation of minimum demand profiles and voltage distribution for representative residential secondary substations
- Probabilistic distribution of solar irradiance
- Thermal loading of primary transformers and correlation with ambient temperature

These are discussed in more detail below and within a number of reports issued for Flexible Networks.

6.1.1 Data Screening and Filtering

Several tools and processes were developed to monitor the performance of the deployed substation monitors and the quality of the data measurements. This enabled rapid identification and rectification of monitors that were sending back incorrect, incomplete or empty datasets.

6.1.1.1 Data Completeness

Daily monitor data files were reviewed and a colour assigned to each file which represents the level of data which is present with green indicating a full dataset, amber for partial and red for no data. There was an initial process of training the algorithm to determine the full dataset size in kB for each monitor. This identifies issues and trends with communications intermittency or malfunction of monitors for each monitor and also across all Flexible Networks monitors.

This is now implemented in the iHost data acquisition system in the form of a report.

6.1 Data Analysis Techniques [continued]

6.1.1.2 Data Error Detection and Correction

A statistical approach based on short-term forecasting techniques published in the academic literature was trialled for primary substation load measurements. This is based on constructing a forecast from an average load profile for each week of the year, an average profile of the deviation of each measurement point during the day from the daily profile (calculated over the preceding few weeks, with different profiles for different days of the week) and a stochastic element which is forecast based on the error in previously forecast points. The combination of the weekly averaged load from the annual profile and the daily profile gives an 'expected value' for the measured quantity at a particular time, based on the typical annual shape of the load, and its recent behaviour.

Each measured value can be thought of as being composed of the expected value plus a residual difference. The residuals would be expected to correspond to a statistical distribution centred at (or close to zero). The standard deviation of the residuals provides a measure of the extent to which the actual load varies from the expected value, and can be compared to a new measurement in order to determine how well it corresponds to the historical behaviour of the load. Data can then be corrected based on expected load behaviour.

Further details of the approach are contained in "Flexible Networks - Work Package 1_1"[3].

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[3] *TNEI and SP Energy Networks, "Flexible Networks - Work Package 1_1", June 2014.*

6.1.2 Probabilistic Load Behaviour

6.1.2.1 Primary Substations

An improved load forecasting and risk characterisation tool was developed for primary substations based on a probabilistic methodology that minimises the impact of load outliers, due to network load transfer for example3. Percentile half-hourly measured loads other than the P100 value were used i.e. P95, P98, which are less prone to exceptional variation and more representative of underlying loading conditions.

Findings suggest that use of the new methodology represents peak load trends well and provide improvements over the existing forecasting approach. This will help to release capacity headroom where available and improve network reinforcement strategy. The incorporation of local intelligence on new network connections will provide additional enhancement.

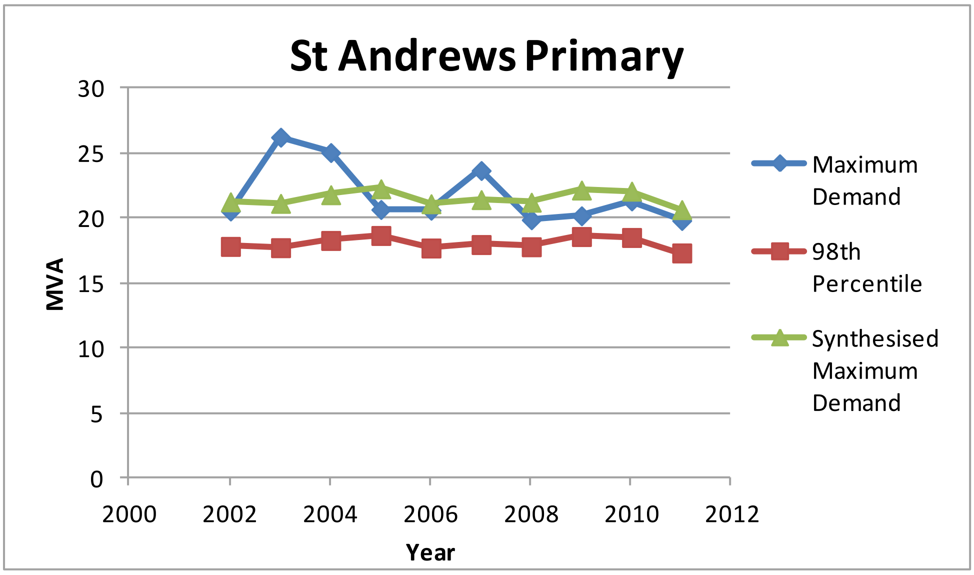

Figure 6-2 St Andrews primary network group load analysis

6.1.2.2 Secondary Substations

Secondary transformer loading data from Flexible Networks was compared with existing MDI data to assess potential for capacity gain based on the load characterisation approach developed for primary substations. Whilst results vary for individual secondary substations transformers, overall there is a small increase in capacity of about 8%.

6.1.3 Network Load and Voltage Characterisation

The correlation of primary substation, HV feeder and secondary substation loading and voltage profiles were analysed to assess network behaviour under high loading and verify robust rules-of-thumb for network modelling[4]. This supported analysis of flexible network control feasibility e.g. potential load transfers, and identification of the optimal location for an AVR to provide voltage boost during network backfeeding.

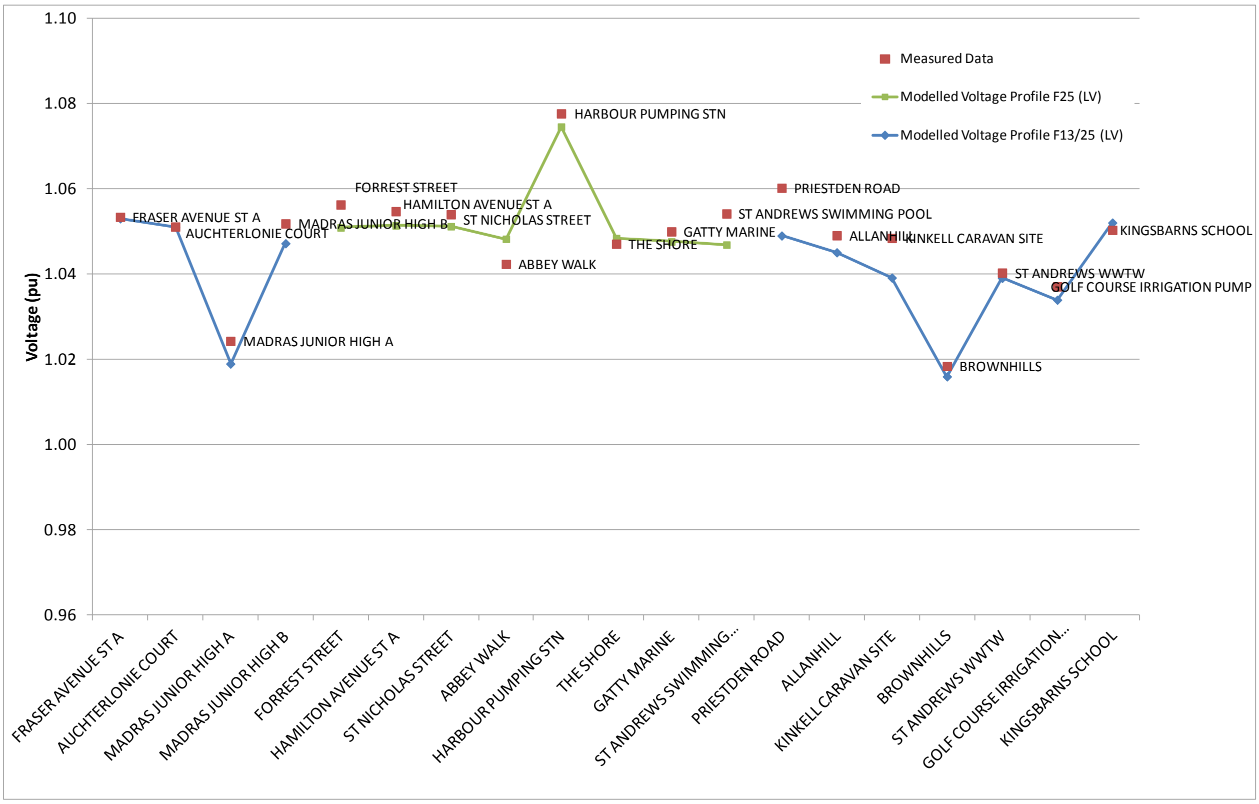

Figure 6 3 Correlation of measured and modelled voltage on LV side of secondary substations along St Andrews HV feeders 25 and 13 (includes consideration of tap position)

Voltage and load at Ruabon primary substation was also analysed during a voltage reduction test to evaluate the voltage dependency characteristics of the load.

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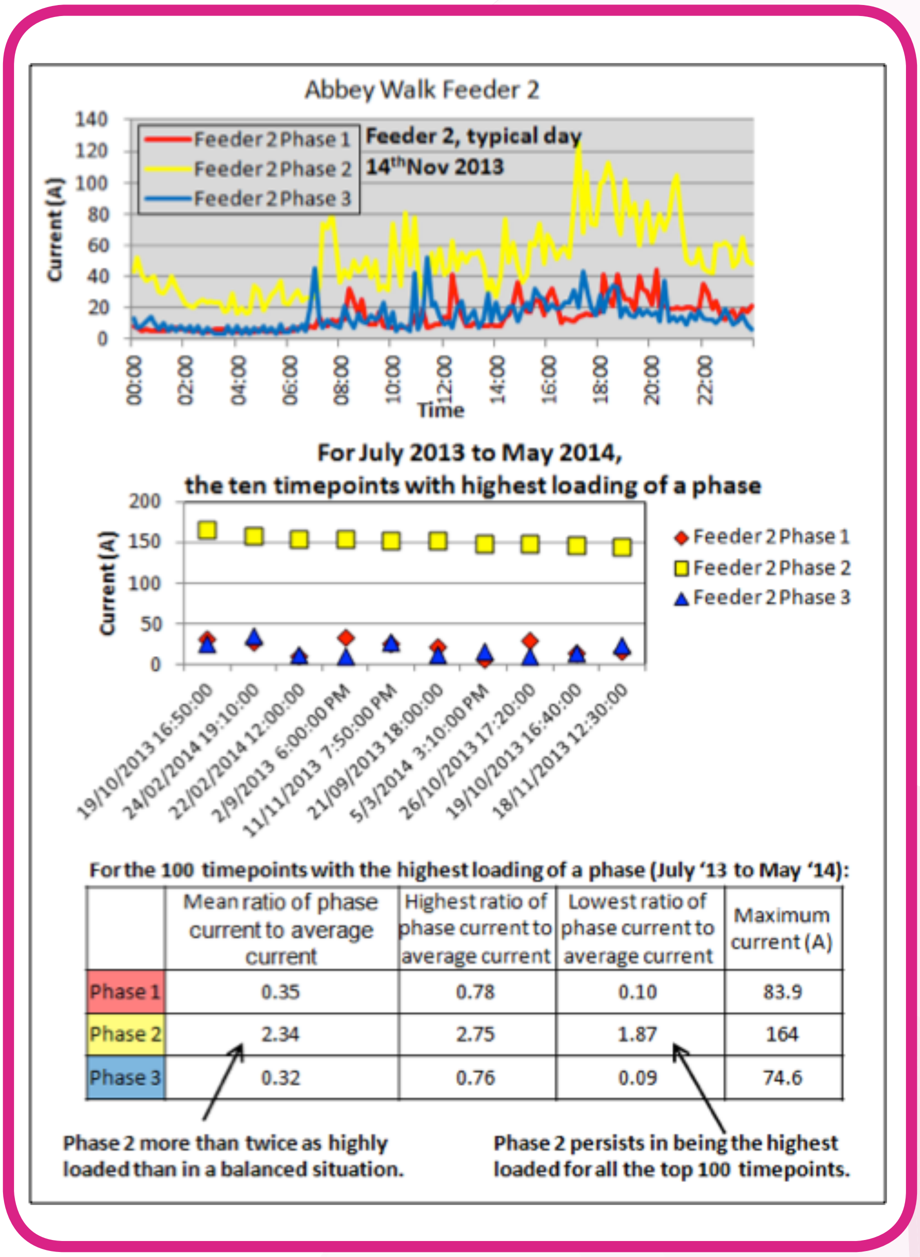
[4] *TTNEI and SP Energy Networks, "Flexible Networks - Future Roadmap for Improvement of HV and LV Network Modelling", July 2015.*

6.1.4 Feeder Phase Imbalance

Thermal loading for primary and secondary substations, and HV and LV feeders was analysed to characterise phase imbalance, focussing on the 100 highest loading timestamps of the most heavily loaded phase to efficiently identify material levels of phase imbalance from large volumes of data . Simple metrics were used to characterise the magnitude and persistence of phase imbalance. This enables an improved consideration of phase imbalance particularly at LV for various network types e.g. suburban, rural.

This also provided learning on reduction of phase imbalance as network voltage level increases. It was also found that secondary substation phase imbalance does not give a very representative indication of LV feeder phase imbalance.



For the 100 timepoints with the highest loading of a phase (July '13 to May '14):

	Mean ratio of phase current to average current	Highest ratio of phase current to average current	Lowest ratio of phase current to average current	Maximum current (A)
Phase 1	0.35	0.78	0.10	83.9
Phase 2	2.34	2.75	1.87	164
Phase 3	0.32	0.76	0.09	74.6

Phase 2 more than twice as highly loaded than in a balanced situation.

Phase 2 persists in being the highest loaded for all the top 100 timepoints.

Figure 6-4 Example of phase imbalance analysis for an LV feeder

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[5] *TNEI and SP Energy Networks, "Flexible Networks – HV and LV Phase Imbalance", July 2015.*

6.1.5 Impact of Embedded PV Uptake

6.1.5.1 Minimum Demand Characteristics

Load was analysed for a number of LV feeders in Ruabon with little or no PV generation connected to characterise the typical residential minimum demand profile expected during summer when embedded PV generation output peaks.

6.1.5.2 Solar Irradiance

The distribution of average and maximum 5 minute solar irradiance was analysed for all three trial networks to inform an embedded PV generation resource assessment model developed and the appropriate peak generation load factor.

6.1.5.3 LV Network PV Hosting Capacity

An improved approach to analysis of available LV network PV hosting capacity was developed based on minimum demand characteristics and PV peak generation load factor that does not require detailed LV feeder measurements[6]. This was validated by comparing load results from network modelling for LV feeders with varying levels of connected PV generation to measured load profiles on several high and low solar irradiance days.

Voltage-load characteristics and voltage distribution at secondary substations and customer locations along LV feeders was also assessed in Ruabon to understand the potential impact on feeder voltage rise from increasing embedded PV.

6.1.6 Example of correlation of modelled and measured LV feeder loading on high solar irradiance day with embedded PV uptake

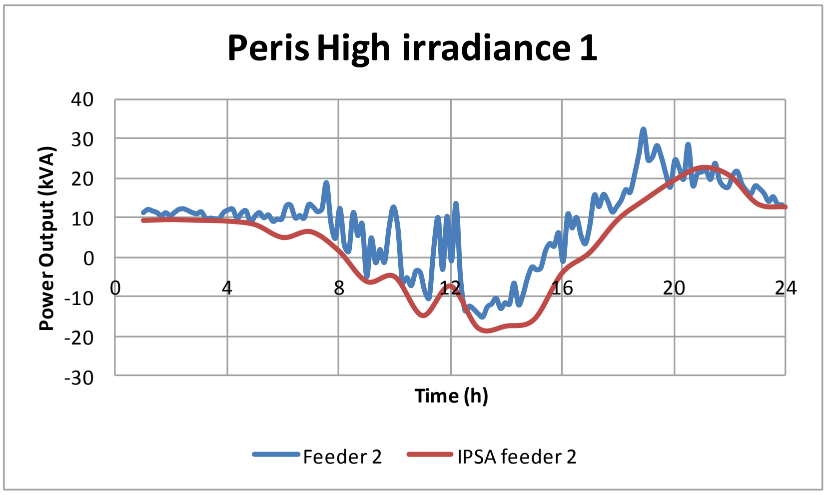

Figure 6-5 Example of correlation of modelled and measured LV feeder loading on high solar irradiance day with embedded PV uptake

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[6] *TNEI and SP Energy Networks, "Flexible Networks - Improved Characterisation of PV Capacity at LV", July 2015.*

6.1.7 Transformer Thermal Loading

An enhanced transformer thermal rating tool based on the industry standard IEC transformer thermal model was developed[7]. This enabled analysis of the relationship between ambient temperature and primary transformer thermal loading under peak seasonal load conditions to release additional capacity. Load related reinforcement could then be deferred with minimal impact on aging.

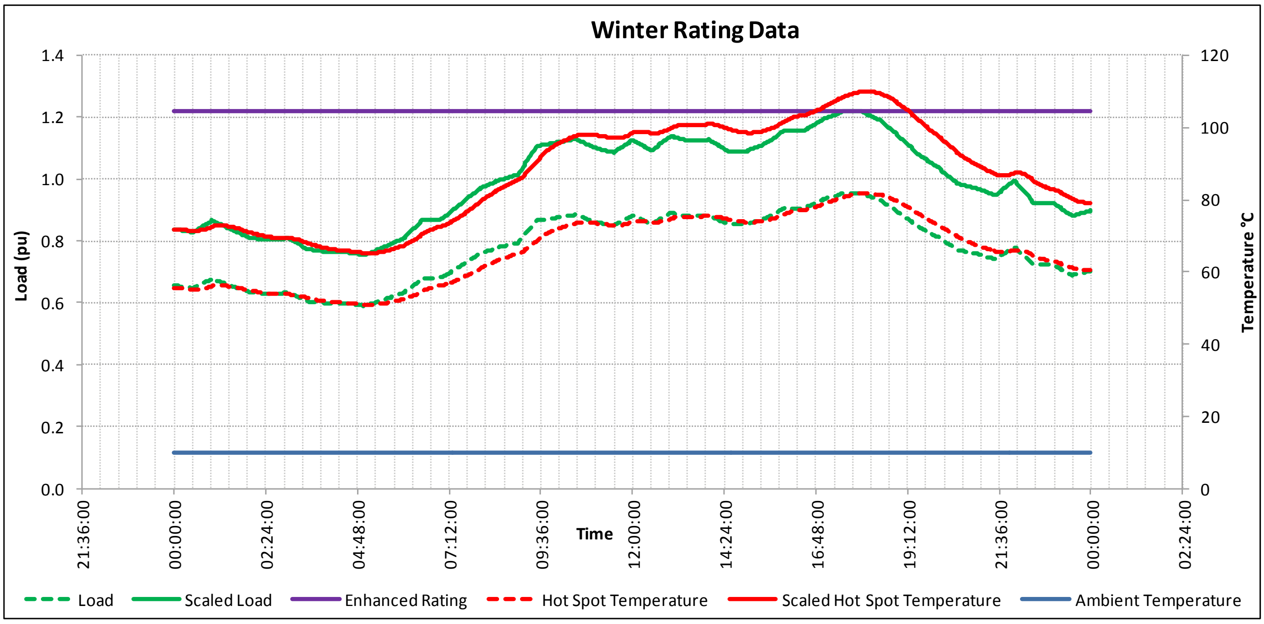

Figure 6-6 Example of output from enhanced transformer thermal rating tool

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[7] *TNEI, "Flexible Networks - Enhanced Transformer Ratings Tool", February 2015.*

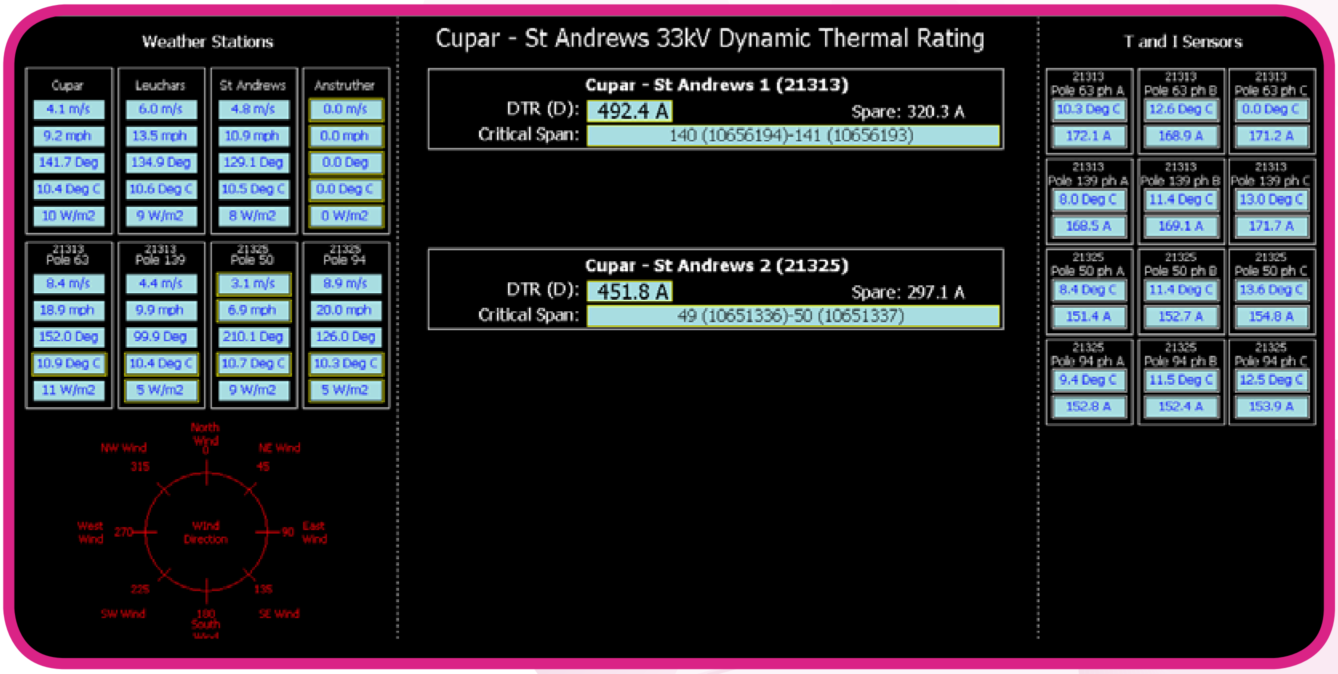
6.1.8 Event Identification

Event identification is critical to the safe and reliable operation of the distribution network. Depending on the metric required, data analysis may be used to provide a simple comparison of measured data with circuit ratings or voltage limits or a more complex analysis may be carried out such as rate of change, or duration assessment. This also generally requires an indication of the network location where the event is taking place and current network running configuration which may require linkage between databases. Event identification can also refer to an event for the monitoring system itself such as status and error detection.

Flexible Networks explored the improvement of day-to-day network operation through event identification including;

- Monitoring and control of the actions of an AVR embedded in the network for management of low voltage during network backfeeding. The AVR was deployed to facilitate flexible network control compared to previous application to connect generation.

  During network switching to facilitate backfeeding, a requirement for safe operation of AVRs is that the tap changer is set to neutral and the unit is taken out of automatic operation. Otherwise damaging circulating currents in the shunt winding can occur. It was recommended to fit all AVR units with telecontrol to enable this.
- Monitoring of a 33kV overhead line circuit through a dashboard interface within PowerOn Fusion NMS, which provides the real-time thermal rating values and all monitored data.



Weather Stations

Cupar	Leuchars	St Andrews	Anstruther
4.1 m/s	6.0 m/s	4.8 m/s	0.0 m/s
9.2 mph	13.5 mph	10.9 mph	0.0 mph
141.7 Deg	134.9 Deg	129.1 Deg	0.0 Deg
10.4 Deg C	10.6 Deg C	10.5 Deg C	0.0 Deg C
10 W/m2	9 W/m2	8 W/m2	0 W/m2

21313 Pole 63	21313 Pole 139	21325 Pole 50	21325 Pole 94
8.4 m/s	4.4 m/s	3.1 m/s	8.9 m/s
18.9 mph	9.9 mph	6.9 mph	20.0 mph
152.0 Deg	99.9 Deg	210.1 Deg	126.0 Deg
10.9 Deg C	10.4 Deg C	10.7 Deg C	10.3 Deg C
11 W/m2	5 W/m2	9 W/m2	5 W/m2

Cupar - St Andrews 33kV Dynamic Thermal Rating

Cupar - St Andrews 1 (21313)
DTR (D): 492.4 A Spare: 320.3 A
Critical Span: 140 (10656194)-141 (10656193)

Cupar - St Andrews 2 (21325)
DTR (D): 451.8 A Spare: 297.1 A
Critical Span: 49 (10651336)-50 (10651337)

T and I Sensors

21313 Pole 63 ph A	21313 Pole 63 ph B	21313 Pole 63 ph C
10.3 Deg C	12.6 Deg C	0.0 Deg C
172.1 A	168.9 A	171.2 A

21313 Pole 139 ph A	21313 Pole 139 ph B	21313 Pole 139 ph C
8.0 Deg C	11.4 Deg C	13.0 Deg C
168.5 A	169.1 A	171.7 A

21325 Pole 50 ph A	21325 Pole 50 ph B	21325 Pole 50 ph C
8.4 Deg C	11.4 Deg C	13.6 Deg C
151.4 A	152.7 A	154.8 A

21325 Pole 94 ph A	21325 Pole 94 ph B	21325 Pole 94 ph C
9.4 Deg C	11.5 Deg C	12.5 Deg C
152.8 A	152.4 A	153.9 A

Figure 6-7 Overhead line dynamic thermal rating control room dashboard (reproduced from RTTR Cupar St Andrews CDR[8])

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[8] *Parsons Brinckerhoff and SP Energy Networks, "2014-12-12 RTTR Cupar St Andrews CDR v01.1", July 2015.*

6.2 User Interface Design

Network planners and operators already manage large amounts of data on a daily basis so before introducing additional new data to be reviewed and assessed, it was important to consider how this would impact their workflow. The user interface design covered not just the data analysis and the visualisation tool itself but also the design/re-design of the business process that utilised the data. This considered training requirements and critically, change management. Some of the key issues that were considered as part of Flexible Networks include;

- Is the data easy to access? Are there any real or likely perceived barriers to access and usage?
- Is this data improving existing business processes or adding a further business process?

A number of successful internal stakeholder engagement workshops were held with network designers and planners to understand and incorporate their views.

6.2.1 Visualisation Tools

GIS data can be used in combination with network monitoring data to visualise distribution network behaviour layered in both space and time. For example, the use of geographical mapping and colour coding of demand, generation, and voltage trends can aid in the identification of network 'hot spots' and provides valuable information to network planners and the connections team.

A pilot study was undertaken by IBM as part of Flexible Networks to develop a Distribution Grid Analytics tool. This utilised GIS data, NMS network configuration data, co-ordinates of monitoring locations and monitoring data. The current network topology can then be visualised through an interface with Google Maps and linkage with analytic tools enable rapid identification of thermally overloaded substations, voltages outside of statutory limits, and phase imbalance[9].

6.3 Risk Management

There is an inherent element of risk associated with the use of network monitoring data for business decisions and the acceptable level of risk will depend on the network voltage level and the applicable standard or engineering recommendation e.g. P2/6. This can be managed by taking a conservative approach to limited measured data, in a "fit-and-forget" manner which has been used in the past.

This has worked well in recent years because, generally, annual load growth rates have been low and reasonably predictable (i.e. within a range of 0.5% +/- 0.5% per annum). However, in the future, the rate of load growth is expected to be much higher, combined with a much greater range in uncertainty if the electrification of transport and heating progresses rapidly. Given the uncertainty in load growth, the traditional conservative approach will lead to greater risk (either increased network risk if load growth is underestimated or increased financial risk if load growth is overestimated).

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[9] *SP Energy Networks, "Flexible Networks Data Analytics Trial CDR", July 2015.*

6.3 Risk Management [continued]

An alternative approach that incorporates improved understanding of network behaviour and (probabilistic) characteristics through greater network monitoring and enhanced data analysis, as explored in Flexible Networks, will increase the techno-economic efficiency of future network design and operation. However, it can also introduce risk due to uncertainties involved in data monitoring and data analysis. Conservative margins provided a buffer for these uncertainties to an extent. Consideration and quantification of monitoring and data analysis uncertainty was an important element of Flexible Networks with internal network planners and control room engineers keen to understand the impact of proposed business process changes on network risk. This informed recommendations on network design and operation policy and practice arising from Flexible Networks[10].

Monitoring Good Practice – Key Points

- A cascade monitoring approach enables an improved understanding of the correlation of network behaviour across voltage levels.
- Heuristics based analysis is a powerful technique that can help identify network 'hot-spots' at an early stage.
- Detailed analysis of monitoring data for network trial sites can be used to develop and verify simple rules of thumb for application to the wider network.
- Consideration of ease of data access/usage and impact on business processes should be made to avoid increasing workload of network planners and control engineers.
- It is critical to understand the impact of data analysis and the associated business process on network risk in the context of future load growth increasing rapidly and clustering.

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[10] *TNEI and SP Energy Networks, "Flexible Networks - Recommendations for Operational Policy and Practice", July 2015.*

7 Future Monitoring Requirements

Future monitoring requirements were developed based on application of the monitoring data at the three Flexible Networks trial sites to facilitate deployment of the innovative network technologies tested and to develop improved planning and operational tools, policy and practices.

It is highlighted that consistency of monitoring specifications across voltage levels was considered to ensure the capture of cascading network behaviour, both downstream and upstream.

7.1 Primary Substations

Phase imbalance on the HV distributors was found not to be significant compared to LV distributors so there is limited value in future detailed monitoring of phase currents and voltages. However, there is a case for monitoring along HV feeders particularly towards feeder ends where load is less diverse[11].

Sampling current at a rate of 10-minutes is preferable as this is closer to the winding time constant of the transformer than half hourly measurements. Also, it is within the timescales of flexible network control and dynamic load shifting. Power factor and power measurements are also on the same resolution, this enables verification of network behaviour through the parameter set.

Analysis was carried out to compare the voltage behaviour characterisation of data for 1, 5 and 10-minute voltage snapshot and 10-minute average sample values[12]. This suggests that actually there is not much difference for the snapshot values provided that the measurements are reliable however the 10-minute average value does differ somewhat. This is the basis for recommendation of a 10-minute snapshot value which is also consistent with the sampling rate of the other parameters.

Table 7-1 Future monitoring specifications for primary substations

Variable	Resolution
RMS three-phase voltage	10 minute snapshot
RMS three-phase HV distributor currents	10 minute average
Power factor of each phase (per measured current)	10 minute average
Real, reactive and apparent loading (per measured current)	10 minute average

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[11] *University of Strathclyde, "Flexible Networks - Report on Assessment of Load Unbalance in HV Feeders", October 2014.*

[12] *University of Strathclyde, "Flexible Networks - Technical Note on Substation Voltage Recording Intervals and Methods", October 2014.*

7.2 Secondary Substations

Whilst there was found to be some benefit from monitoring of individual LV distributor phase currents in terms of identification of significant phase imbalance and clustering of embedded generation, the additional cost of measuring, recording, communicating and storing of this data may not provide the same level of benefit for a wider scale network rollout. A low-cost replacement for existing MDIs which is permanently fitted with a captured-data communication function (a "smart" MDI) would probably give a greater cost/benefit and enable a higher volume of monitoring to be deployed across the network.

Application of the RIIO-ED1 LCT Network Monitoring Strategy[13] will help to identify areas of future LCT clustering and thus candidate areas for network monitoring. Some network areas that are anticipated to have less predictable demand or generation and/or of higher criticality may warrant more detailed data monitoring i.e. LV distributor monitoring. This will also provide data for additional refinement and verification of learning outcomes from Flexible Networks.

Also, detailed LV distributor monitoring with Rogowski coils can be redeployed to other network sites once the monitoring programme is complete. The cost driver for detailed monitoring is the monitoring equipment itself rather than the installation. Data from smart meters will start to be available from around 2018 and this may reduce the need for LV distributor monitoring.

Table 7-2 Future monitoring specifications for secondary substations

Variable	Resolution
RMS phase voltage	10 minute snapshot
RMS phase current on busbar	10 minute average
Power factor of each phase (per measured current)	10 minute average
Real, reactive and apparent loading (per measured current)	10 minute average

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[13] *SP Energy Networks, "RIIO-ED1 LCT Network Monitoring Strategy", March 2014.*

7.3 Weather Stations

Calculation of an enhanced thermal rating for primary transformers based on the IEC 60076-7[14] thermal model can be improved by using ambient temperature measurements in the vicinity unless top-oil temperature measurements are available. Due to the thermal time constants of the transformers, an average temperature measurement over a 10 minute period is appropriate.

Also, installation of a simple low-cost solar irradiance measurement device in network areas with high PV uptake will enable an accurate characterisation of solar irradiance distribution and thus better prediction of LV network PV hosting capacity.

A low cost weather station measuring ambient temperature only or ambient temperature and solar irradiance installed in key locations will enable some regional mapping of weather characteristics. It should be noted that some areas may be close to by UK met office weather stations which can already provide this data (at cost for more detailed measurements).

Table 7-3 Future monitoring specifications for low-cost weather stations

Variable	Resolution
Temperature	10 minute average
Solar irradiance	5 minute average and maximum

It is not cost-effective to install temperature monitoring on all spans of a 33kV overhead line with a dynamic thermal rating management system although direct measurement of conductor temperature helps to minimise risk, particularly for the thermally 'weakest' span although this may change depending on wind conditions (i.e. sheltering). Wind speed and direction measurements at key locations provide input for atmospheric boundary layer modelling and/or state estimation algorithms to enable calculation of thermal loading conditions at all spans of the circuit, identification of the limiting spans and reduction of the need for extensive monitoring. This requires a more detailed monitoring specification.

Table 7-4 Future monitoring specifications for 33kV OHL dynamic thermal ratings

Variable	Resolution
Temperature	5 minute average, maximum, minimum, standard deviation
Solar irradiance	5 minute average, maximum, minimum, standard deviation
Wind speed	5 minute average, maximum, minimum, standard deviation
Wind direction	5 minute average, maximum, minimum, standard deviation

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[14] *IEC 60076-7:2005 Loading guide for oil-immersed power transformers.*

Weather monitoring can be redeployed to other network sites when the monitoring programme is complete however there will additional costs for installation at the new site, particularly for wind measurements. This is because the wind monitoring equipment needs to be installed high enough (e.g. 10m for UK met office anemometers and wind vanes) so as to not be overly influenced by the local topology (trees, buildings).

7.4 Data Acquisition System Functionality

Analysis algorithms that can be implemented in the data acquisition system can enable more efficient data analysis given the following considerations;

- Is the data analysis required frequently?
- And/or is the data analysis required for large volumes of data?

If not, then it is probably more cost-effective to use a bespoke analysis tool. Future data analysis functionality is explored below.

Based on the development of new and improved network planning tools and processes for Flexible Networks, future data acquisition system functionality that would be useful includes;

- Identification of peak loading day for primary transformers and corresponding network group within defined seasonal periods for use in calculating enhanced thermal rating.
- Automatic identification and notification of timestamps when secondary substations are approaching rated capacity and/or close to voltage statutory limits.
- Automatic identification and notification of timestamps when secondary substations are exporting power at significant levels.
- Automatic identification and notification of timestamps when secondary substations are significantly phase unbalanced within a certain margin of cable rating e.g. 80%.
- Seasonal average daily load profiles for substations (to identify LCT clustering).
- Definition of a substation "group" (e.g. along HV feeder) where selected data can be plotted for comparison, to monitor the voltage along an HV feeder with flexible network control for example.
- The ability to present large volumes of data in a histogram to understand the behaviour of the variable in the frequency domain.

7.5 Integration of Analysis Tools

The analysis tools currently in use within SPEN for connections, planning and operations functions are fragmented to a degree although many use the same data sources and underlying analysis techniques. Consideration was made as to how these tools could be efficiently consolidated, including the new analysis tools developed for Flexible Networks. A preliminary functional specification for a "common library" was developed as a result.

A common library would manage the large amounts of data available in the different databases and also the various tools which access them. This common library would be a software based tool, or tools, that allows different users and business functions access to the same information and data processing. The main benefit of this is that it would move users away from having their own individual tools and instead one common set of tools that would be available to all users as well as new analysis tools being immediately accessible to all users. This prevents two different methods of obtaining the same information being used, which can ultimately provide variances in what should be the same result.

7.5.1 Existing approach

There are various existing analysis tools within SPEN for design and operational analysis based on primary network loading data to assist with activities such as operational outage studies, network review, RRP load index, network connection studies and preparation of the LTDS. The PI data historian databases loading data from the NMS.

The current approach for load data processing and analysis is shown in Figure 7 1. This illustrates the number of stand-alone tools that exist for data visualisation and processing and indicates that there is an opportunity for consolidation and greater consistency.

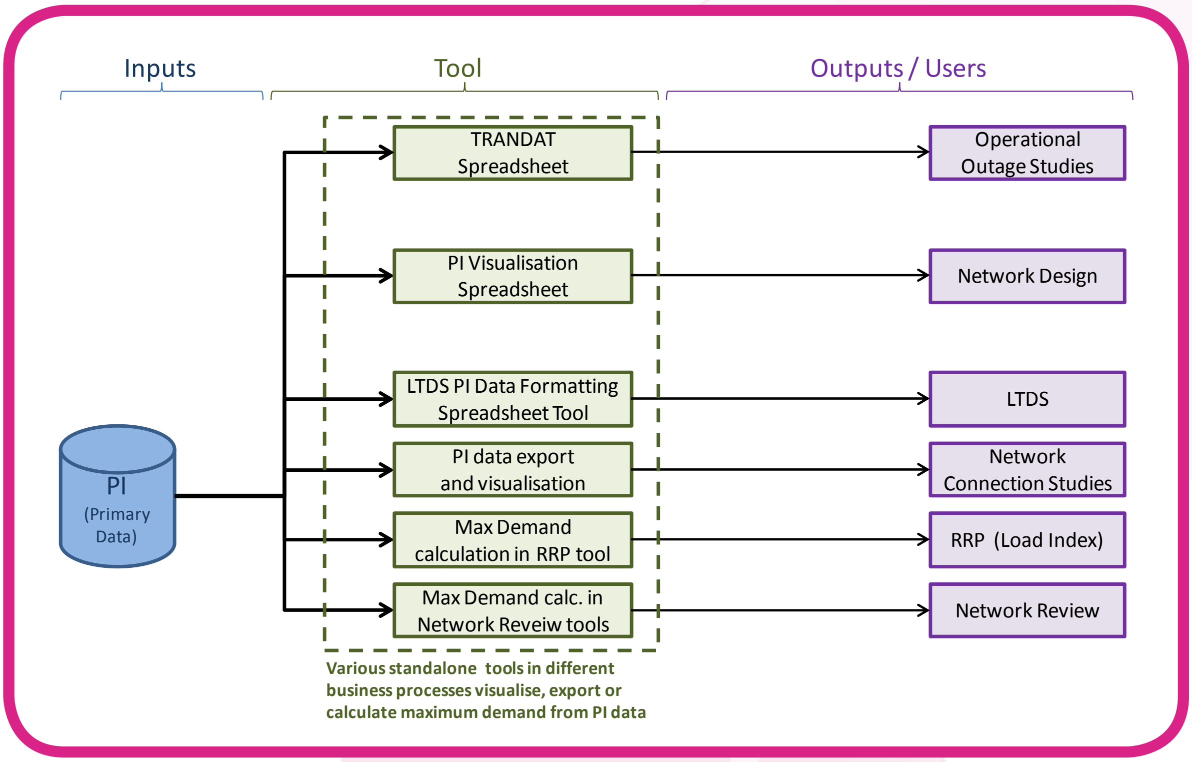

Figure 7-1 Load data analysis approach

7.5.2 Functional Specifications

The common 'library' should meet the following requirements:

- Reduce/remove duplication of code for common functions such as retrieving load data.
- Create shared and standardised procedures and formats for using load data, which can include future data analysis and processing functions.
- Enable tools to be agnostic to load data source.
- Enable easy addition of 'tools' and 'users' to facilitate future use across organisation.

The common library will incorporate the following data analysis features:

- Data processing such as network demand snapshots (summer minimum, winter maximum, annual percentile values), historic annual time series load data, load duration curves, typical daily load profile for a selected duration.
- Data screening features such as filtering 'bad' data, synthesising missing data and provision of a measure of the quality of the data.
- Capability to extend to filtering and analysis of other parameters e.g. voltage, current, weather data.

The common library needs to be flexible to enable it to be easily adapted through amendments and additions to methods and algorithms for data processing, quality checking and data enhancement. Some of these features may alternatively be incorporated directly into the data acquisition software although this may then reduce the flexibility to adapt and refine algorithms as required. This could also potentially be linked to or incorporated with grid analytics in the future as plug-and-play analysis modules.

The proposed common library architecture is shown as a block diagram in Figure 7-2.

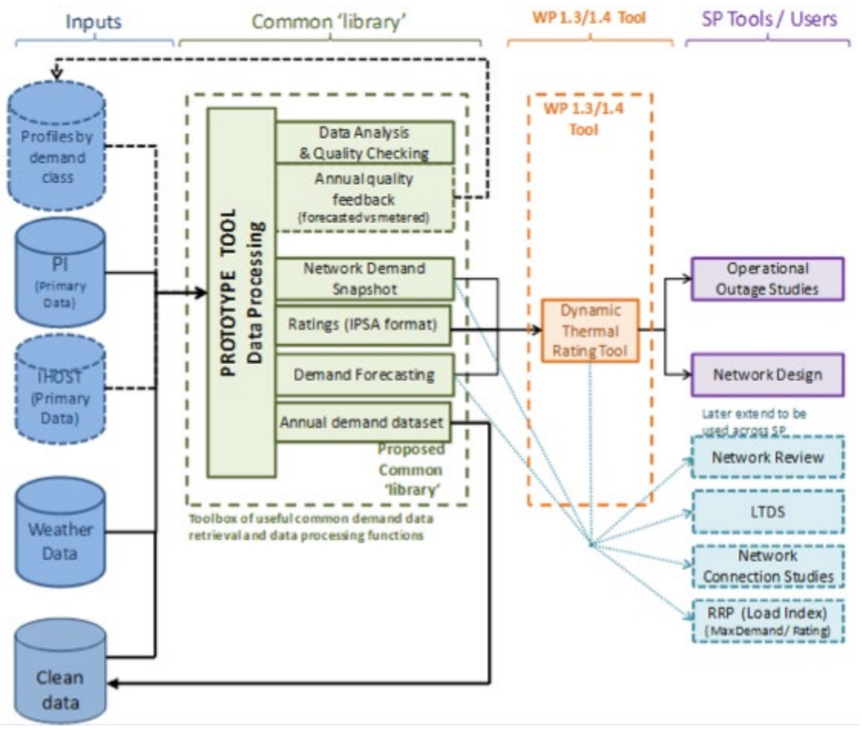

Figure 7-2 Proposed common library architecture with enhanced thermal rating tool example

7.5.3 Common Library Outputs

The outputs from the common library may include the following:

- **Daily load profile** – For a timestamp, return half hourly daily loading data for an asset. For a given year, half hourly loading data during winter maximum and summer minimum.
- **Custom load profile** – For a given start & finish date, return half hourly loading data for the given period and asset e.g. annual or seasonal averages.
- **Asset Data** – For a given asset, return all relevant asset data. An example of this would be returning the rating, cooling type designation, indoor or outdoor etc. for a transformer.
- **Maximum Demand/ Minimum Demand Snapshot** – For a given asset, return a snapshot of maximum demand and minimum demand for a specified year or time period. Aggregation of demand by transformer group will also be possible.
- **Percentile Demand Snapshot** – For a given asset, return a snapshot of a specified percentile demand e.g. 98th percentile, for a specified year or time period. Aggregation of demand by transformer group will also be possible.
- **Demand Time Series Data** – For a given asset, the common library will return demand time series data. Aggregation of demand by transformer group could also be possible.
- **Clean set of Demand Time Series Data** – For each asset and year, a time series dataset will be screened to provide a 'clean' dataset for use in other analysis functions.
- **Asset Ratings** – Asset ratings will be calculated in the common library to provide an asset ratings database in a suitable format for use in power systems software such as IPSA, PSS/E or DigSilent.
- **Load duration curve** – For a given asset, return the load duration curve for a specified period. Aggregation of demand by transformer group will also be possible.
- **Load forecasting** – For a given transformer group, return a future load forecast based on algorithms linked to the common library.
- **HV Loads** – return metered HV load for a particular half hourly period or specified time period.
- **Ambient Temperature** – For a given weather station and time period, return the ambient temperature profile and/or average ambient temperature.
- **Wind speed** – For a given weather station and time period, return the maximum and average wind speed and wind speed distribution.
- **Data quality** – A data quality check could be performed and reported to the user for each data retrieval. Data filtering operations such as number and type of actions e.g. interpolation, and data quality metrics such as number of missing points, number of erroneous reading could be reported.
- **Annual analysis to calculate and report typical daily load profiles by demand class** – This would require classification of each substation into a demand class (e.g. urban, rural). Once this classification database has been created, analysis could be carried out annually to calculate and report typical daily load profiles linked to these demand classes to enable a better understanding of network behaviour as well as identification of trends.

7.6 Future asset data

Recording of tap-settings and changes to tap setting in the data acquisition system will be invaluable for primary and secondary substation voltage control, identifying appropriate network solutions for high PV clustering and understanding implications for network backfeeding.

7.7 Metadata

Whilst not being assessed for Flexible Networks, metadata has been identified by SPEN as a key area of data uncertainty. This is being reviewed and developed during RIIO-ED1 with a number of active projects.

Monitoring Good Practice – Key Points

- A future sampling rate of 10 minutes was specified for average RMS current and RMS voltage snapshot.
- Phase imbalance on HV distributors was found to not be significant compared to LV distributors so there is limited value in future phase monitoring.
- A low-cost replacement for existing MDIs with a captured-data communication function would provide good value, enabling wide network coverage. Network areas anticipated to have less predictable demand or generation and/or of higher criticality may warrant more detailed monitoring of LV distributors.
- Development of a "common" library will facilitate integration of analysis tools using the same data sources and underlying analysis techniques across planning, operations and connections business processes.
- A low cost weather station installed in key locations will enable some regional mapping of weather characteristics.

Appendix A – Flexible Networks for a Low Carbon Future

'Flexible Networks for a Low Carbon Future' is a Scottish Power Energy Networks (SPEN) Tier 2 Low Carbon Network Fund (LCNF) trial project. LCNF Tier 2 projects are awarded annually on a competitive basis to UK Distribution Network Operators (DNO) and are administered through Ofgem.

Flexible Networks will provide the DNOs with economic, DNO-led solutions to enhance the capability of the networks as heat and transport are increasingly de-carbonised resulting in an increase in electricity use. Crucially, these solutions will be capable of being quickly implemented and will help to ensure that the networks do not impede the transition to a low carbon future.

Solutions are needed that can:

- Determine more accurately the capacity headroom while maintaining licence obligations,
- Allow that headroom to be exploited in a safe, reliable and cost-effective manner, and,
- Provide incremental increases in headroom in a timely and cost-effective manner.

Flexible Networks will aim to provide a 20% increase in network capacity through a number of innovative measures. This will enable more customers to make the transition to new low carbon generation and demand technologies. The project involves enhanced monitoring and analysis to better understand and improve existing performance, and the deployment of novel technology for improved network operation and capacity - including dynamic asset rating, network automation, voltage regulation and energy efficiency measures.

To ensure representative and replicable outputs, the project involves three carefully selected trial areas across SP Distribution and SP Manweb licence areas, covering various network topology and customer demographics: St Andrews in Scotland, Wrexham in Wales and Whitchurch in England, see Figure A-1.

The three trial areas have known capacity issues and consequently offer a real opportunity to analyse and implement alternative flexible solutions to network reinforcement. All three sites have different but representative characteristics and customer demographics, and are similar in that they have near-term constraints due to increasing demand and an uptake of low carbon technology. The rapid nature of these changes both imposes a requirement, but also provides the opportunity to trial solutions that are faster and more cost-effective to implement than traditional reinforcement.

Figure A-1 Trial Area Location Map

The specific issues facing these three locations are mirrored across the UK electricity distribution network, and this project will be able to provide generic solutions and recommendations to address these.